Developing Cognitive Control:

The Costs and Benefits of Active, Abstract Representations

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Abstract

Children show remarkable developments in their ability to decide when and how to flexibly move between a variety of routine and novel activities. While such developments are viewed as adaptive, they may also come with costs. We consider such trade-offs in the development of increasingly active, abstract goal representations supported by prefrontal cortical regions. These developments support key transitions in children's increasingly flexible behavior, but are also resource-demanding, with implications for learning, creativity, and training.

Keywords: reactive control, proactive control, self-directed control, externally-driven control, perseveration, inhibition

“There's no such thing as a free cognitive ability.” Instead, just as in the case of “no free lunch,” there is always a cost even when something appears to be free.

Cognitive abilities help us in certain situations, but they come with costs in the sense of hindering us in other situations. For example, being good at maintaining goals in

working memory can help people to stay on task and avoid distractions (Fukuda & Vogel, 2009; Vogel, McCollough, & Machizawa, 2005). But being good at maintaining goals in working memory can also come with costs, such as a reduced flexibility to shift to new goals or respond to new information in the environment (Friedman, Miyake, Robinson, & Hewitt, 2011; Müller et al., 2007). Thus, there is a cognitive trade-off, between stability on the one hand, and flexibility on the other (Goschke, 2000; Grossberg, 1982). Trade-offs like this one between stability and flexibility are observed across a range of domains (Hills & Hertwig, 2011), including cognitive control versus creativity (Jarosz, Colflesh, & Wiley, 2012; Thompson-Schill, Ramscar, & Chrysikou, 2009; Wieth & Zacks, 2011), exploring new possibilities versus exploiting a particular choice (Cohen, McClure, & Yu, 2007), and learning by building upon expectations (or biases) versus learning in a way that is tied more closely to actual experiences (Doll, Hutchison, & Frank, 2011; known as the bias-variance dilemma in statistics, Geman, Bienenstock, & Doursat, 1992).

These trade-offs can be particularly salient during development, when asynchronies in the development of different cognitive abilities reveal their unique costs and benefits. For example, infants are excellent learners. They can rapidly detect regularities in their environments to bring order to what they see and hear (Gomez & Gerken, 2000; Kirkham, Slemmer, & Johnson, 2002; Romberg & Saffran, 2010). This ability to detect regularities allows infants to quickly learn routines. However, this cognitive ability comes at a price: Infants and children show remarkable limitations in their abilities to break out of habitual ways of thinking and behaving.

For example, after infants repeatedly watch a toy being hidden in one location, they can rapidly detect the regularity of where the toy usually is and learn to search there. Then, even after seeing the toy being hidden in a different location, infants will continue to search in the first location (making the “A-not-B error”, Piaget, 1954). Similarly, children can rapidly learn a habit of sorting cards by one rule (e.g., color), and will then continue to follow this rule even after being instructed to switch to a new rule (e.g. shape; Zelazo, Frye, & Rapus, 1996). Children show this kind of perseveration, or repeating of a routine or prepotent behavior when it is not longer appropriate, in many different situations across development (Baillargeon & Wang, 2002; Carlson, Moses, & Claxton, 2004; Casey et al., 1997; Deak, Ray, & Brenneman, 2003; Diamond, 1991; Morton, Trehub, & Zelazo, 2003; Sharon & DeLoache, 2003; Simpson et al., 2012).

Overcoming such perseveration constitutes an important aspect of development, one that is predictive of success in life years later (e.g., in academic achievement, health, and income; Blair & Razza, 2007; Casey et al., 2011; Moffitt et al., 2011; Young et al., 2009). How do we progress from searching for a toy wherever we last found it, to using information from the environment to flexibly break out of this routine? How do we ultimately progress to deciding on our own when and how to flexibly move between a variety of routine and novel activities, both in the moment and in making longer-term plans, whether for running errands or taking a vacation? How do we achieve these fundamental aspects of what it means to grow up? And given that there is no such thing as a free cognitive ability, what are the implications of the developments that support such changes in cognitive control, particularly for the complementary learning processes that support the quick learning of routines from infancy?

In investigating the development of cognitive control, we and others have focused on the importance of abstract goal representations actively maintained in working memory (Blay & Chevalier, 2011; Bunge & Zelazo, 2006; Friedman et al., 2008; Marcovitch, Boseovski, & Knapp, 2007; Munakata, Snyder, & Chatham, 2012; Towse, Lewis, & Knowles, 2007). Prefrontal cortical regions play a critical role in supporting such goal representations (Miller & Cohen, 2001; Figure 1). These representations are abstract in the sense of coding for higher-order information (e.g., for the goal of sorting cards by color), by coding for shared features across individual examples (e.g., red, blue, orange) while generalizing over differences. Building on this well-established characterization of prefrontal cortical function, we have formulated a unified framework for understanding how these regions support executive functions like inhibitory control (Munakata et al., 2011) and their development (Munakata et al., 2012; Figure 2).

Figure 1. A well-established characterization of prefrontal cortical regions in cognitive control, which we build upon in our framework for understanding key developmental transitions in cognitive control. Here we show two distinct pathways, one for finding a toy, the other for naming as many foods as possible in a brief period. **A)** Goal representations (e.g., “Get the toy car”) are maintained in working memory and supported by the sustained firing of neurons in prefrontal cortical regions. **B)** These goal representations provide top-down support, via excitatory connections from prefrontal cortex (green arrows), for relevant options represented in other brain regions, causing goal-appropriate representations (e.g., a toy’s current hiding location) to become more strongly activated. **C)** Representations compete with one another via inhibitory connections (red t-bars), allowing the most active, goal-appropriate representations to win out over alternatives (e.g., the toy’s previous hiding location) and thus guide behavior. In this way, goal representations can support flexible behaviors over habitual ones (as in searching for the toy car). Goal representations can also support selection among multiple competing options, as with the goal of “Think of foods,” which activates the sub-goal of “Think of fruits”; this sub-goal in turn provides top-down support for a more limited pool of food items, helping to resolve the competition and support a choice. By providing top-down support for relevant options in this way, such goal representations could also potentially interfere with more bottom-up learning of regularities in the world. Reprinted from Munakata, Snyder, & Chatham (2012), Sage Publications.

Figure 2. Representational changes supporting the development of cognitive control: Our framework focuses on the role of increasingly robust, abstract goal representations in three key developmental transitions in cognitive control. With development, children’s goal representations become more abstract (from concrete objects to abstract goals, as shown on the x-axis) and more robust to distraction and delay (y-axis). Increasingly robust representations support active maintenance of goals in working memory, which provide top-down support for goal-relevant representations. Increasingly abstract representations support selection from among options, by providing top-down support for a limited pool of competitors. These increasingly robust, abstract goal representations: **1)** support increasingly flexible, goal-appropriate behaviors over habitual ones in response to signals from the environment (e.g., searching for a toy in a new hiding location after seeing it hidden there, and later in development, sorting cards according to a new abstract rule when instructed), **2)** allow such cognitive control to become less externally-driven and more self-directed (e.g., sorting cards according to a new, *self-generated*, abstract rule, and later in development, switching among more abstract, self-generated categories), and **3)** allow such cognitive control to become less reactive and more proactive (e.g., maintaining abstract goals over a sufficiently long period and in the face of distraction to support planning errands or a vacation). Although robust representations (y-axis) could be viewed as most critical for proactive control, and abstract representations (x-axis) could be viewed as most critical for self-directed control, and the two may develop independently, developments in both aspects of goal representation can support increasingly proactive, self-directed control (as shown along the diagonal, and discussed in the Variability Across Tasks section). Thus, these developmental

transitions can occur in concert. The neural bases supporting these developments are discussed in the text. Reprinted from Munakata, Snyder, & Chatham (2012), Sage Publications.

In this chapter, we first describe how the development of abstract goal representations can support three important transitions toward more flexible behavior observed across the first decade of life. Then, we discuss the possible neural bases for such developments, and the potential generalizability of such developments to other aspects of cognition. Finally, we consider the costs of such developments, given that there is no such thing as a free cognitive ability, and the broader implications of costs and benefits in cognitive trade-offs for understanding and potentially influencing children's cognitive control.

TRANSITION 1: FROM PERSEVERATING TO OVERCOMING HABITS WHEN DIRECTED

In the first transition we consider in the development of cognitive control, children become increasingly able to overcome habits in response to signals from the environment, such as an adult showing them or instructing them on what to do. Within our framework, these developments are driven by improvements in children's abilities to actively maintain such information in the service of achieving their goals. For example, infants gradually become better at maintaining concrete information, such as a toy's new hiding location that an adult has pointed out, over delays and distractions. As children develop increasingly abstract representations, they can start maintaining information such as task rules that have been provided for them. These actively-maintained representations provide top-down support for goal-relevant thoughts and behaviors (Figure 1). This kind of cognitive control allows children to respond flexibly to changes in their environment, rather than simply falling back on habits (Figure 2).

We have implemented this framework in biologically-based neural network models (e.g., Chatham, Yerys, & Munakata, 2012; Munakata, 1998; Morton & Munakata, 2002a; Stedron, Sahni, & Munakata, 2005; see also Cohen & Servan-Schreiber, 1992; Marcovitch & Zelazo, 2000), which have shown how increasing abilities to maintain goal-relevant information can lead to improvements in cognitive control. Such models can learn regularities in the environment through changes in connections between processing units, as a result of experience (e.g., Colunga & Smith, 2005; Mareschal, French, & Quinn, 2000; O'Reilly & Munakata, 2000; Rogers & McClelland, 2004). For example, “units that fire together, wire together.” In a model of children’s card-sorting (Figure 3; Morton & Munakata, 2002a), such learning of regularities leads to strong connections developing between units that represent the first rule the model is presented with repeatedly (e.g., color). The model thus develops a prepotent tendency to respond according to that first rule, even when presented with a new rule to sort by, because color-related inputs lead to strong color-related activations, via the strong color-related connections. Overcoming this prepotent tendency requires the active maintenance of a new rule (e.g., shape), which can provide top-down support for relevant exemplars (e.g., trucks and flowers). Thus, increasing the model’s ability to actively maintain goals, via increases in the strength of recurrent connections in the model’s prefrontal rule layer, leads to improvements in flexibility like those observed in children.

These simulations of our framework have led to counterintuitive predictions that have been confirmed. For example, children who perseverate in sorting cards according to an old rule (e.g., sorting a red truck based on color) nonetheless seem to know where the cards should go; they correctly answer questions such as “Where do trucks go in the

Figure 3. A simplified version of a neural network model (Morton & Munakata, 2002a) and five inputs corresponding to a trial in Zelazo et al.'s card-sorting task. The model demonstrates how improvements in goal maintenance can lead to improvements in cognitive control, and leads to counterintuitive predictions about knowledge-action dissociations (where children seem to know what they should be doing but fail to act accordingly), reaction times, and generalization. Adapted from Morton & Munakata (2002a).

shape game?" (Zelazo et al., 1996). Our framework explains such apparent knowledge-action dissociations, where children seem to know what they should be doing but fail to act accordingly, in terms of the strength of required goal representations (e.g., to sort by

shape). A weak representation is sufficient to support the correct response when no information is presented that is relevant to the old rule (as with questions that focus on the new rule). In this case, the strong connection weights that can bias attention to the prior rule do not drive behavior, because no input is coming into them. In contrast, a stronger representation is required to overcome conflict when information relevant to the old rule is presented (as with cards that include both color and shape information). In this case, input about the old rule comes into the strong connection weights that have been built up by prior use of this rule, which strongly biases attention to the old rule and requires a stronger representation of the new rule to support the correct response. We thus predicted that apparent knowledge-action dissociations should disappear when measures are equated for conflict (e.g., sorting a red truck, and answering "Where do red trucks go in the shape game?"). This prediction has been confirmed (Munakata & Yerys, 2001; see also Morton & Munakata, 2002b), challenging the characterization of children as showing "knowledge-action" dissociations, and highlighting the importance of goal representations in overcoming conflict.

Two additional counterintuitive predictions from simulations of our framework came from the fact that goal representations provide top-down support to speed responses and support generalization to new situations. Specifically, strongly representing a new abstract rule such as shape (as flexibly-switching children are thought to do) should speed the processing of thoughts and behaviors related to shape, and allow this rule to be applied to novel shapes. Thus, although all children can correctly answer simple questions about what they should be doing (e.g., "Where do trucks go in the shape game?"), children who flexibly switch between rules should answer such questions faster

than children who persevere with old rules. In addition, although children who persevere seem dramatically stuck on old behaviors (e.g., sorting red and blue cards), they should not generalize their behaviors to new stimuli (e.g., instead sorting orange cards randomly), whereas flexibly-switching children should generalize their behaviors to new stimuli. Both predictions have been confirmed (Blackwell, Cepeda, & Munakata, 2009; Kharitonova, Chien, Colunga, & Munakata, 2009; Kharitonova & Munakata, 2011), highlighting the importance of the strength and abstractness of children's goal representations in their developing cognitive control.

TRANSITION 2: Reactive to Proactive Control

Developmental theories have traditionally assumed that children are simply less-skilled versions of adults in terms of how they activate goal representations. For example, in the classical A-not-B task, infants have been thought to succeed by *proactively* maintaining the location of a hidden toy until they are allowed to search for it - thereby demonstrating a capacity for proactively maintaining goal-relevant information that is similar to, but less robust than, that of adults (e.g., Diamond, 1991; Munakata, 1998). However recent work indicates that children may instead utilize a qualitatively different and *reactive* form of cognitive control, which is recruited on a more as-needed basis (Andrews-Hanna et al., 2011; Chatham, Frank, & Munakata, 2009). The developmental transition from reactive to proactive control can be understood as arising from developmental improvements in the ability to robustly maintain goal representations.

This developmental transition can be observed in a child-adapted version of the AX continuous performance task (AX-CPT). In this task, a target response is provided to a frequent sequential pair of stimuli (“A” followed by “X”), whereas a nontarget response is provided to all other stimulus pairs (Braver, Gray, & Burgess, 2007). The first stimulus in each pair can be proactively maintained and used to prepare subsequent responses - a strategy adopted both by adults and by 8-year-old children. However, younger children (3-year-olds) show a distinctly *reactive* pattern, with no sign of such proactive maintenance of the first stimulus in each pair. Instead, 3-year-olds retrieve the identity of the first item only when it is needed; that is, only when an “X” stimulus appears.

These stark and sometimes counterintuitive age differences are visible in this task in errors, reaction times, and effort (Chatham et al., 2009). For example, owing to their use of proactive control, 8-year-olds show comparatively *greater* difficulty when the “A” stimulus is followed by a “Y” stimulus, relative to other trials. Three-year-olds find such trials comparatively easier: their lack of proactive anticipation can actually lead to performance improvements, because they are not erroneously preparing the (incorrect) target response. On the other hand, 3-year-olds show more difficulty than older children even when the first stimulus (a “B”) fully determines the subsequent response—as though children of this age cannot behave proactively even in this unambiguous situation. Effort, as indexed by pupil diameter (Beatty & Lucero-Wagner, 2002) is relatively greater among 3-year-olds rather late in each trial - only after the second stimulus in a pair is presented - as though they are reactively engaging effortful control processes only at that point. By contrast, 8-year-olds tend to exert more effort earlier in the trials, soon

after the first stimulus is presented, consistent with their use of more proactive control processes (Chatham et al., 2009).

Qualitative changes of this kind can, nonetheless, emerge from more gradual and quantitative changes; specifically, we suggest that this developmental shift in the temporal dynamics of cognitive control emerge from gradual improvements in the ability to actively and robustly maintain abstract information (Figure 2). Proactive control may not be expressed by younger children, even when future demands are perfectly predictable, because delay and distraction disrupt the active maintenance of information by children of this age. But as the robustness of active maintenance improves with development, it becomes increasingly sufficient for withstanding delays and distractions, and thus capable of supporting proactive control.

TRANSITION 3: Externally-Driven to Self-Directed Control

While children are increasingly able to break out of habits by actively maintaining goals, they are first able to behave flexibly when they are provided with exogenous (externally-driven) goals (e.g. switching from playing to putting away toys when told). Only later are children able to succeed in switching using endogenous (internally-generated) goals (e.g. turning off the TV and starting their homework on their own; Luria, 1959; Vygotsky, 1962). For example, 4-year-olds can switch between two rules for sorting cards (e.g. by shape and color) when an adult tells them the new rule (e.g. “Now we’re going to play the color game!”) (Zelazo et al., 1996). However, when children are not told the new rule, and instead are simply asked to sort cards in “a new way”, even 6-year-olds may perseverate on the old rule (e.g., Jacques & Zelazo, 2001; Smidts, Jacobs,

& Anderson, 2004). When control must be even more self-directed, adult levels of performance are not reached until late adolescence (e.g. Kave, Kigel, & Kochva, 2008). For example, in the verbal fluency task participants are asked to say as many items as they can in one minute from a category (e.g. animals). In order to generate many words participants must both cluster (produce words within semantic subcategories) and switch (shift between subcategories). Children often fail (e.g. naming five zoo animals and declaring there are no more animals), even though they know many more items (e.g. many other types of animals).

What makes such self-directed flexibility more demanding and later to develop than externally-driven flexibility? One possibility is that self-directed control requires selecting among many options. In externally-driven tasks, participants are told what to do and/or when to do it, so selection demands are minimal. In contrast, when there are multiple options, competition among them must be resolved in order to select a response, a process that is time-consuming and relies on prefrontal cognitive control mechanisms (e.g. Hirshorn & Thompson-Schill, 2006; Snyder, Banich, & Munakata, 2011). For example, in the verbal fluency task, participants must select *when* to switch (e.g. when more zoo animals are unlikely to be retrieved) and *what* to switch to (e.g. which of many animals to say next).

Abstract, categorical representations may support self-directed flexibility by reducing these selection demands. Abstract representations provide top-down support for relevant category members, making it easier to select a response (Figure 1). For example, instead of selecting from all category members (many competing responses), abstract representations can limit competing items to the small pool in the subcategory

(e.g. the ten zoo animals the child knows), or to the small pool of other subcategories (e.g., pets, farm animals, or ocean animals) when switching. Thus, whether planning errands or a vacation, actively maintaining abstract representations of our goals (e.g., going to the grocery store and the hardware store, as opposed to buying milk, nails, and bread) should guide the selection processes that are critical for self-directed behavior.

A role for abstract representations in supporting self-directed flexibility is supported by the finding that giving children some initial support in activating such abstract representations helps them subsequently switch on their own. When children are provided with subcategory examples designed to induce the use of abstract representations (e.g. “pets are animals”) before completing verbal fluency, they endogenously switch among subcategories more than children given examples (e.g. “a hamster is an animal”) (Snyder & Munakata, 2010). This benefit also extends to subcategories that were not provided. The transition from exogenous to endogenous control can thus be understood partly in terms of the development of increasingly active, abstract goal representations (Figure 2). As children develop increasingly abstract representations, these should help them to control and sequence their own behavior without strong environmental support.

NEURAL BASES AND GENERALIZABILITY

There are clearly many benefits to improvements in cognitive control, as captured in the preceding sections describing the role of active, abstract representations in increasingly flexible, proactive, self-directed control. What are the neural bases supporting these developments? And how might these developments support

improvements in other aspects of cognition, including response inhibition, working memory updating, and prospective memory?

Neural Bases

These developments likely reflect effects of learning and brain maturation, both within prefrontal cortical regions and in the development of large-scale, distributed networks of brain regions. For example, the formation of increasingly abstract goal representations may be supported by the maturation of anterior prefrontal cortex, and by the building of representations from the bottom-up through learning about the world, with the formation of more concrete representations providing the foundation for the formation of more abstract representations (Bunge & Zelazo, 2006). Similarly, the increasing ability to maintain representations of currently relevant information over delays and distractions may be supported by both maturational changes in prefrontal cortical regions and associated networks for sustaining neuronal firing (Braver et al., 2007; Edin, Macoveanu, Olesen, Tegnér, & Klingberg, 2007; Morton, Bosma, & Ansari, 2009) and by learning processes that detect the utility of maintaining goal-relevant information (e.g., O'Reilly & Frank, 2006).

Knowledge of frontostriatal circuitry has supported detailed computational models of these systems, providing insights into how they are uniquely specialized to support processes such as proactive control, and how they can go awry in diseases such as Parkinson's (Hazy, Frank, & O'Reilly, 2007). The substrates supporting reactive control are less specified. The substrates for reactive control could be the same as those for proactive control, but become activated as needed rather than in preparation for

cognitive control. Alternatively (or additionally), reactive control could tap regions critical for memory retrieval, such as the hippocampus.

Future work identifying relevant neural regions, and their associated connectivity, functionality, and developmental changes, should inform an understanding of the types of learning and maturation that support improvements in cognitive control. Moreover, interactions among frontal, hippocampal, and striatal systems are likely both cooperative and competitive (e.g., Ashby & Maddox, 2010; Daw, Niv, & Dayan, 2005), in ways that may lead to cognitive trade-offs that are relevant for development. We return to this point after considering the generalizability of our framework.

Generalizability to other domains

Our framework for understanding transitions from reactive, externally-driven cognitive control toward proactive, self-directed control may be sufficiently general to relate to phenomena across a number of domains. Below, we describe its potential relevance for domains like inhibition, working memory, and prospective memory.

Both the proactive and the self-directed nature of adult-like control, and its origins in more reactive and environmentally-driven forms of control, may have straightforward applications to the domain of response inhibition, where prepotent or ongoing motor actions must be stopped (Aron, 2011). For example, adult subjects might recruit inhibitory control over such actions proactively in situations where accuracy is emphasized over speed, but might recruit inhibitory control more reactively (if at all) when speed is prioritized over accuracy. And, it is well known that great care must be taken in response inhibition tasks (e.g., Stop Signal task; Logan, Cowan, & Davis, 1984) to exogenously specify that subjects should allocate equal priority to speed and accuracy;

accuracy is otherwise endogenously prioritized over speed (Morein-Zamir, Hommersen, Johnston, & Kingstone, 2008).

Proactive and self-directed control are also likely relevant to the domain of working memory updating, which refers to the processes of monitoring incoming information, and adding, deleting, or replacing information actively maintained in working memory (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). First, the contents of working memory can be managed both proactively - e.g., by selectively updating working memory only with information that will be most behaviorally-relevant - and more reactively, by selecting among the items in working memory only those that are currently most behaviorally-relevant (e.g., Kriete & Noelle, 2011). Second, working memory updating can also be driven by internally-generated goals - for example, during explicit hypothesis testing, where attention should be directed to features of hypothesized importance - or can instead be driven by more purely environmental factors, such as stimulus salience.

The distinctions between reactive and proactive control, and between externally-driven and self-directed control, are also likely to apply to the capacities that enable execution of delayed intentions (e.g., to buy milk on the way home from work at the end of the day) - a complex ability known as prospective memory. A contentious debate has surrounded the extent to which prospective memory is supported by the proactive monitoring of the environment for opportunities to enact the delayed intention, versus those “spontaneous retrieval” processes that are reactively triggered when intention-related stimuli are experienced (Einstein et al., 2005). These dual mechanisms for prospective memory might be productively understood as arising from proactive and

reactive control; for example, monitoring for goal-relevant cues (e.g., a store, when the goal is to buy milk) could be particularly reliant on proactive control, while relying on such cues to serve as reminders taps reactive control (Einstein et al., 2005). In addition, adults can engage self-directed control by selecting relatively arbitrary stimuli (such as the cliché of a string to tie around your finger) to serve as a subsequent *external* cue for retrieving an intention. Such mnemonics have not thoroughly investigated in the domain of prospective memory. Our framework not only highlights such under-explored phenomena, but also offers a clear developmental approach for assessing the relative contributions of proactive monitoring and more reactive spontaneous retrieval processes to prospective memory.

Future research should address the possible domain-generalty of both proactive and self-directed control, and the extent to which they may interact in a number of domains. Our framework highlights under-explored phenomena in such domains, and suggests that developmental studies may prove useful for disentangling distinct mechanisms that may contribute to a range of behaviors. Proactive and self-directed control might even developmentally dissociate across cognitive domains, thereby providing insight both into the developmental trajectory of these abilities, and the multiplicity of mechanisms supporting them. Proactive and self-directed processes may thus be important not only for characterizing developmental transitions in cognitive control, but also potentially for more comprehensively characterizing the multiple facets of adult-like cognitive control.

AT WHAT COST?

Neural developments that support increasingly active, abstract representations in flexible, proactive, self-directed control may lead to improvements in a variety of domains, as described above. However, given our argument that there's no such thing as free cognitive control, we next turn to considering costs in the development and use of cognitive control. We focus on three issues: adaptiveness, learning regularities, and creativity.

Adaptiveness of cognitive control modes

While proactive, self-directed control is more characteristic of adults than children, and thus would seem to be more advanced, it may not be the optimal form of control for children, or even for adults in some circumstances. For example, proactive control is resource-demanding, given its reliance on effortful maintenance of information in working memory and sustained firing of prefrontal neurons (Braver et al., 2007; Braver, 2012; Cohen, Lewis-Peacock, & Norman, 2012). Thus, reactive control can be a better default strategy, particularly when it is unclear what aspects of the environment will be most useful for guiding future behavior (Locke & Braver, 2008), when distraction is so likely to occur that the resource-demanding process of active maintenance is unlikely to succeed (Cohen et al., 2012), or when even habitual behaviors are likely to yield adequate reward. For example, when children who are capable of proactive control engage in a secondary task that may interfere with active maintenance of information for a concurrent primary task, they appear to default to a reactive approach to the primary task over a proactive approach (Blackwell & Munakata, 2013). Adults similarly default to a reactive approach to a primary task when a concurrent secondary task is highly demanding (Cohen et al., 2012). Thus, to the extent that the features listed above (e.g., likelihood of distraction and adequacy of habitual behaviors) characterize the world of

the child, their use of reactive control may in fact be highly adaptive.

Similarly, self-directed control requires actively maintaining abstract goals and selecting among competing options, and thus is effortful and time-consuming, and requires sufficient knowledge about how to prioritize goals. Adults have to manage their own goals and behaviors without being told what to do (that's part of what it means to be an adult), so self-directed control is critical for adults. Children, on the other hand, have adults to provide external support for guiding their behavior. It is likely adaptive for children to rely on these external (adult) cues, rather than their own endogenous goals, not only because it is more efficient but also because they have not yet learned enough about the world to endogenously select appropriate goals and behaviors.

Even adults, who can effectively employ proactive, self-directed control, may find it more effortful to do so (Braver et al., 2007; Forstmann, Brass, Koch, & Cramon, 2005). For example, when adults must endogenously determine what task to switch to, compared to when they were exogenously cued as to what task to perform, they were slower to switch and more strongly recruited the frontal-parietal network involved in cognitive control (Forstmann et al., 2005). Similarly, proactive control strategies more strongly recruit prefrontal cognitive control areas during the delay period of working memory tasks (albeit with the benefit that participants are able to respond more quickly; e.g. Speer, Jacoby, & Braver, 2003). Thus, it may still be optimal for adults to rely on reactive, externally-driven control in some circumstances. This may be particularly adaptive when otherwise goals would have to be maintained over a long period of time and in the face of distraction (making proactive control difficult) and there would be many options to select among (e.g., many work tasks or errands) making self-directed

control difficult. For example, many people set up calendar alerts on their phone or computer, allowing them to rely on externally-driven, reactive control to switch between important tasks. Reducing reliance on proactive, self-directed control can even save lives: for example, surgical checklists that prompt members of the medical team to complete important safety steps at the appropriate times substantially reduce complications and mortality (de Vries, Prins, & Crolla, 2010).

One direction for future research is to identify whether there is a form of "cognitive meta-flexibility" that enables different types of control to be used in different tasks or contexts, and how such an ability might develop. For example, proactive control can be encouraged among adults when good performance is strongly rewarded (Locke & Braver, 2008), but it is unclear whether children might demonstrate a similar form of meta-flexibility as a function of expected reward. Conversely, proactive control could be advantageously abandoned in favor of more reactive strategies when the resource demands of attempted active maintenance outweighs its probable success. For example, distractors are known to decrease the expression of proactive control in adults (Frank, Santamaria, O'Reilly, & Willcutt, 2007). Similarly, in the voluntary task switching paradigm (in which participants choose what task to complete on each trial), self-directed control is reduced when participants are under a concurrent working memory load (Demanet, Verbruggen, Liefoghe, & Vandierendonck, 2010), or have little time to prepare (Arrington, 2008); under these conditions participants instead rely on external cues. However, it is currently unknown whether these findings represent simple disruptions of proactive and self-directed control or more strategic adoptions of reactive

and externally-driven control, and whether children might be capable of this kind of meta-flexibility.

Learning regularities

Improvements in executive function may bring some cost in learning regularities in the world, given that top-down goals (e.g., to search where a toy was just hidden) can override the learning of regularities (e.g., regarding the toy's most frequent hiding location); (Thompson-Schill et al., 2009; Maddox, Love, Glass, & Filoteo, 2008). Children's limited abilities to strongly maintain goals may account for why children are better than adults at finding constant patterns in inconsistent evidence (Ramscar & Yarlett, 2010; Thompson-Schill et al., 2009). Because adults are able to strongly maintain active and abstract goal representations, they are able to override habits that have developed through experience. This is an advantage in many tasks, but in tasks that require learning the most frequent pattern from inconsistent input it can be a disadvantage. For example, in language learning (e.g. learning that plural nouns usually end in -s, even though some do not), adults perform poorly because they probability match, producing each form as frequently as it occurs in the (noisy) input (Thompson-Schill et al., 2009). In contrast, young children (under age 4), who cannot overcome prepotent, habitual responses, tend to over-match (always picking the most frequent response) rather than probability matching (Derks & Paclisanu, 1967; Thompson-Schill et al., 2009). This leads them to over-generalize at first (e.g. saying "mouses" instead of mice), but also to learn the dominant form more quickly than adults (Ramscar & Gitcho, 2007).

How strongly adults can maintain information in working memory can also influence the balance between learning regularities and imposing top-down goals. For

example, adults who are better at maintaining the instruction that a particular stimulus is most likely to be rewarded are actually worse at learning regularities about what stimuli are *actually* rewarded more (Doll et al., 2011). Thus, there may be an inherent trade-off between promoting cognitive control processes that improve goal-directed behavior and processes such as language and convention learning.

These tradeoffs could involve competitive interactions between a prefrontal system for learning abstract, rule-based information, and striatally-mediated learning of more concrete regularities. For example, models of category learning posit a cooperative role of the frontal cortex and the hippocampus in the learning of abstract rule-based categories (Ashby & Maddox, 2010) - similar in kind to those we have argued support the active and self-directed use of cognitive control. By contrast, these systems may compete with the striatally-mediated learning of categories defined more by the concrete relation among specific features (Ashby & Maddox, 2010). Such competitive interactions are hypothesized to yield a trade-off between the acquisition of abstract, rule-based categories and learning about more concrete regularities.

Creativity

There may also be a trade-off between cognitive control and creativity (Chrysikou & Thompson-Schill, 2010; Thompson-Schill et al., 2009). Specifically, it has been proposed that in healthy adults, abstract mental models of a task, supported by prefrontal cortical regions, provide top-down support to screen out peripheral information; while this is useful in many situations, during creative problem-solving such attentional control may cause only the responses that initially appear most task-relevant to be considered (e.g., Chrysikou & Thompson-Schill, 2010; Jarosz et al., 2012; Wiley & Jarosz, 2012).

For example, when trying to solve a remote associate problem (e.g., what word could go with *pie*, *luck*, and *belly*?; Bowden & Jung-Beeman, 2003a), strong cognitive control may unproductively focus attention on strong associates (e.g., *apple* for *pie*), screening out weakly-associated words. Nor will employing cognitive control to switch among such strong associates lead to the correct solution. Rather, it is necessary to allow multiple weakly-associated words to come to mind in a bottom-up manner, until the solution is recognized (in this case, *pot*). Indeed, people generally experience solutions to such problems as an ‘aha! experience’ rather than as resulting from effortful, controlled thought processes (e.g., Bowden & Jung-Beeman, 2003b). Thus, the absence of strong cognitive control (e.g., during development) may improve performance on tasks that benefit from a more diffuse attentional state which allows more weakly associated alternative representations to be considered (e.g., Chrysikou & Thompson-Schill, 2010; Jarosz et al., 2012; Wiley & Jarosz, 2012).

Supporting this theory, some evidence suggests that experimental manipulations and individual differences that reduce cognitive control can sometimes lead to better performance on creative problem solving tasks. For example, people are better at solving creative problems when they are moderately intoxicated (Jarosz et al., 2012), tested at their non-optimal time of day (e.g., morning for ‘evening people’; Wieth & Zacks, 2011), when woken from REM sleep (which decreases prefrontal cortical arousal; Stickgold, Scott, Rittenhouse, & Hobson, 1999), or even have lateral prefrontal lesions (Reverberi, Toraldo, D’Agostini, & Skrap, 2005), all of which presumably reduce cognitive control.

However studies that have directly examined the association between cognitive control and creativity have reported both positive and negative correlations (often within

the same study, depending on the task; e.g., Gilhooly & Fioratou, 2009; Ricks, Turley-Ames, & Wiley, 2007; Scibinetti, Tocci, & Pesce, 2011; White & Shah, 2006; see Wiley & Jarosz, 2012 for a review). One possible explanation for these mixed results is that all problem solving may involve both insightful (creative) and analytic (cognitive control demanding) aspects, with the balance between these processes depending on the task and the phase of problem solving (Ormerod, MacGregor, & Chronicle, 2002). Specifically, while disengaging prefrontal control processes may be beneficial for generating creative ideas, cognitive control needs to be re-engaged to effectively evaluate the quality of those ideas (Ellamil, Dobson, Beeman, & Christoff, 2011). Thus, while children seem remarkably adept at generating many creative possibilities that might not occur to adults, they may have more difficulty realizing which of those possibilities is actually likely to solve a problem.

COSTS AND BENEFITS

Thinking about the relative benefits and costs of improvements in cognitive control has implications for attempts to train children to improve their cognitive control, and for understanding the variability that children show in their cognitive control.

Training

Given the importance of executive functions, many researchers have investigated whether their development can be accelerated, or whether effective alternative approaches can be encouraged. The answer is yes in both cases. However, much less emphasis has been placed on the potential costs of such attempts to improve children's executive functioning. Is the training of executive function worth any associated cognitive costs? The answer may depend on many factors, including the nature of the training.

For example, some aspects of executive function, such as working memory, reasoning, inhibition, and monitoring, can be improved in children (Flook et al., 2010; Jolles & Crone, 2012; Klingberg et al., 2005; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). The activities that lead to such improvements are diverse (as reviewed in (Diamond & Lee, 2011), and include computerized training, school curricula, games, aerobics, and martial arts. Our framework suggests that such training works in part by supporting the use of abstract goal representations. In this case, we would expect training to also improve children's proactive, self-directed cognitive control. Our framework also suggests additional ways of helping children to become more self-directed: by teaching them more abstract, categorical labels for activities, e.g. ‘‘play time’’, ‘‘getting ready to go outside’’ rather than just their component activities (‘‘putting on your coat’’), to aid them in switching from one activity to another. Such teaching of abstract representations may be particularly helpful for children who have particular difficulty engaging in self-directed control, such as children with autism spectrum disorders (e.g., Mackinlay, Charman, & Karmiloff-Smith, 2006) and attention deficit/hyperactivity disorder (ADHD, e.g., Siklos & Kerns, 2004), who cannot easily switch among tasks on their own, without external cues. These types of efforts to improve executive functions may benefit children who are struggling, in important ways (e.g., in school settings). However, programs to improve executive functions may come with cognitive costs, in terms of adaptiveness, learning, and creativity. For example, the use of proactive control may be wasteful of mental resources if it is unclear what information should be maintained in order to succeed at a task; instead, the use of reactive control may be better suited for discovering that information. In addition,

increased or accelerated use of executive functions may limit learning and creativity, as discussed in preceding sections.

In cases where children's endogenous, proactive control is insufficient to guide their behavior, another strategy would be to try to encourage alternative approaches. For example, children's ability to shift from old habits can also be dramatically improved by scaffolding them to build up new habits through practice (e.g., Brace, Morton, & Munakata, 2006). This approach taps children's reliable learning of regularities, without directly targeting their executive functions. These new habits are thus unlikely to generalize well, because they are based on more stimulus-specific representations (Kharitonova et al., 2009; Kharitonova & Munakata, 2011). For this same reason, this approach of building new habits is also less likely to confer costs in adaptiveness, learning, and creativity.

Another possible strategy is to encourage reactive control before children can effectively employ proactive control. For example, children could be provided with cues that encourage them to recall instructions when needed, instead of being provided with instructions that require children to plan in advance. This approach may be more successful than trying to encourage proactive strategies directly; indeed, young children who use (or are trained to use) proactive memory strategies such as rehearsal can sometimes show worse memory performance than their peers (Bjorklund, Miller, Coyle, & Slawinski, 1997; Miller & Seier, 1994). And when young children can be encouraged to utilize rehearsal strategies, they will often abandon these strategies upon follow-up (Keeney, Cannizzo, & Flavell, 1967) or fail to extend them to novel tasks - suggesting that training of this kind fails support the endogenous recruitment of proactive control.

The consequences of approaches to encourage less mature forms of cognitive control are unclear, however. On the one hand, encouraging less mature forms of cognitive control could delay the development of more mature forms. On the other hand, encouraging the use of reactive control could bolster the learning of regularities (e.g., about what information should be maintained in order to succeed at a task), which will be important for the efficient use of proactive control.

Variability Across and Within Tasks

A child can perform quite differently across and within different tasks meant to measure the same cognitive abilities (“horizontal décalage,” in Piagetian terms). Such variability can shed light on the processes supporting behavior and development (Munakata, 2001; Siegler, 1996). In the case of children’s developing cognitive control, our framework suggests that such variability arises in part from the interdependence of active and abstract representations (Munakata et al., 2012). Here, we also consider the adaptiveness of distinct types of cognitive control at different ages and across different situations.

Depending on the task, the shift from reactive to proactive control could seem complete by infancy (Diamond, 1985), 8 years (Chatham et al., 2009; Lersbach & Reimer, 2010), or post-adolescence (Andrews-Hanna et al., 2011; Finn, Sheridan, Kam, Hinshaw, & D’Esposito, 2010). For example, the use of reactive control seems to persist well into the second decade of life given that adolescents less strongly recruit neural regions associated with proactive control in a sustained fashion than adults (Andrews-Hanna et al., 2011), and may instead recruit the hippocampus during working memory

tasks (Finn et al., 2010). At the same time, even infants appear capable of utilizing proactive control in simplified tasks, such as those requiring search for a hidden toy (Piaget, 1954). Infants' performance rapidly deteriorates with increases in the delay between the hiding of the toy and the time when children are allowed to search for it (e.g., Diamond, 1985), which would seem to indicate that infants are proactively maintaining the hidden toy's location (even if only for a short time). Similarly, shifts from externally-driven to self-directed control are observed from childhood through adolescence, across different tasks (Jacques & Zelazo, 2001; Kave et al., 2008; Siklos & Kerns, 2004). For example, 7-year-olds can reliably sort cards "in a new way" without being told what dimension to switch to (Smidts et al., 2004), while the ability to switch in a self-directed manner among subcategories during the verbal fluency task continues to improve through adolescence (e.g. Kave et al., 2008).

Further, more and less mature forms of control could be employed in varying amounts within the same task. For example, the use of proactive control can expose task-relevant information to significant interference from ongoing events in the environment. Control could then be (reactively) increased, so as to minimize distraction throughout the remainder of the task. These kinds of dynamics could underlie phenomena like post-error and post-conflict slowing - situations where an inadequate recruitment of proactive control is reactively remedied, even on the very next trial. Similarly, when subjects are free to select a task to perform, their choices are nonetheless swayed by the environment in a manner that varies with preparedness (Arrington, 2008), indicating that both self-directed and externally-driven control mechanisms might compete at any given time.

Thus proactive and self-directed control can be present in varying degrees alongside more reactive and environmentally-driven forms of control.

One potential source of such variability is based on what is adaptive at different ages and across different situations. Given how resource-demanding proactive control is, due to its reliance on the sustained firing of prefrontal neurons, it may be more adaptive to engage it when it is very clear what information should be maintained in order to succeed in a given situation. Thus, reactive control might be used until the repeated reactivation of a relevant prior experience has been followed by reward so often that this regularity has been learned by posterior or subcortical substrates - substrates that can then subsequently trigger the maintenance of predictive information in a more fully proactive mode. Proactive control should thus emerge earliest in highly concrete contexts (e.g., in dealing with physical properties of objects in the world), where such temporal regularities are most clearly present. For example, proactive control might emerge earliest in relatively concrete domains, like object permanence: rewarding objects regularly persist despite visual occlusion, and thus provide a robust learning signal for posterior and subcortical substrates in driving the maintenance of occluded objects. In contrast, proactive control may emerge much more gradually in situations where the linkage between prior information and future reward is more indirect and abstract. Thus, proactive control may emerge later in card sorting tasks than in object permanence tasks because substantially more experience with the world is required to learn that abstract verbal labels (e.g., color) can refer to sets of features (e.g., red and blue) that in turn identify rewarded relationships between objects (cards).

Similarly, the extent to which self-directed control is adaptive may vary by age and situation. Because children know less about the world and are generally more constrained in their opportunities to manage their own goals and behaviors, relative to adults, it may often be more adaptive for them to rely on external support for guiding their behavior rather than effortfully maintaining abstract goals in the service of selecting among competing options for self-directed control. This might explain why some of the earliest forms of self-directed control are observed in simple tasks with relatively few options to select among and with low demands on world knowledge (e.g., Jacques & Zelazo, 2001), while self-directed control shows a more prolonged trajectory in more complex tasks with greater demands on selection processes and on world knowledge (e.g., Kave et al., 2008).

CONCLUSION

Developing cognitive control is a fundamental aspect of development -- one that allowed each of us to move on from being a perseverating child, and one that predicts important elements of success in life. We have focused on the roles of increasingly active and abstract goal representations, in allowing us to respond flexibly to new situations, and to engage cognitive control in preparation for needing it rather than only in the moment, and based on our assessment of this need rather than requiring signals from the environment. However, we have emphasized throughout the chapter that these abilities do not come for free. They are costly in terms of effort, knowledge required, and potential interference with learning and creativity. Viewing these fundamental developmental transitions in terms of such trade-offs should allow us to better understand

children's struggles, the high variability in their behavior across different situations, and the potential benefits and costs of attempts to accelerate the development of children's executive functions.

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