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Working memory updating and the development of rule-guided behavior

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ABSTRACT

The transition from middle childhood into adolescence is marked by both increasing independence and also extensive change in the daily requirements of familial demands, social pressures, and academic achievement. To manage this increased complexity, children must develop the ability to use abstract rules that guide the choice of behavior across a range of circumstances. Here, we tested children through adults in a task that requires increasing levels of rule abstraction, while separately manipulating competition among alternatives in working memory. We found that age-related differences in rule-guided behavior can be explained in terms of improvement in rule abstraction, which we suggest involves a working memory updating mechanism. Furthermore, family socioeconomic status (SES) predicted change in rule-guided behavior, such that higher SES predicted better performance with development. We discuss these results within a working memory gating framework for abstract rule-guided behavior.

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1. Introduction

Rules or *policies* (Badre, 2008; Botvinick, 2008; Bunge, Wendelken, Badre, & Wagner, 2004; Daw, Niv, & Dayan, 2006; Dayan, 2007; Sutton & Barto, 1998) specify the relationship between a context, an action, and an anticipated outcome. Consider the rule given to children: "When indoors, speak in a soft voice, but outside, it is okay to shout". In this example, a representation of the current context (indoor or outdoor) in working memory modulates how one should speak. Importantly, a rule can be more *abstract* to the degree that it determines a set of simpler rules. Extending our example, an older child may learn that the "indoor/outdoor voice" rule only applies when a caregiver is present. In this example, the context ("mom") does not specify the appropriate level of speech but rather which class of rules relating the context to speech is currently appropriate. Sufficiently abstract rules of this sort support adaptive and flexible behavior across a range of circumstances. Here, we focus on the development of rule abstraction from middle childhood through adulthood.

In the lab, rule abstraction can be manipulated in terms of policy order. Consider a task in which one shape indicates one response and another shape a second response (Fig. 1). Here, a single decision based on shape is required to choose a response, and so this task involves 1st order policy. Now, consider that we add a second rule set in which a blue object indicates one response and a red object indicates a second response. As the shape and color rule sets cannot govern responding simultaneously, an additional contextual cue must indicate which set is relevant. Mapping out these decisions results in a two tiered decision tree. Policy abstraction increases with the depth of this decision tree. Notably, the decisions at any level of policy are made more difficult by increasing 'competition', or the number of competing alternatives at a given branch

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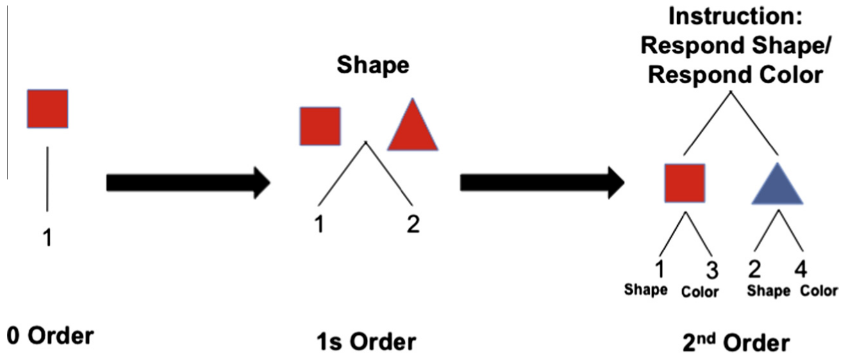

Fig. 1. Schematic of increases in depth, and by necessity width, of decision tree when moving from 0 to 1st and 2nd order policy for action.

point (i.e., increasing the width of the tree). Badre and D'Esposito (2007) developed a set of paradigms to consider behavioral effects of competition at different levels of policy abstraction in adults. Here, we adapt these paradigms to examine the developmental course of these processes.

The developmental literature has examined rule-guided behavior largely through the lens of task switching (Crone, Bunge, Van der Molen, & Ridderinkhof, 2006; Davidson, Amso, Anderson, & Diamond, 2006; Wendelken, Munakata, Baym, Souza, & Bunge, 2012; Yerys & Munakata, 2006; Zelazo, 2006). The Dimensional Change Card Sort (DCCS) has been used to examine very young children's ability to sort cards based on rules (e.g., Zelazo, 2006). In this task, children generally succeed at sorting a red truck based on its color, for example. However, three year-olds fail to subsequently switch rules and sort based on the shape dimension, whereas four year-olds succeed. In older children, Davidson et al. (2006) required participants to switch between two rules, such that correct response was dependent on a single defining stimulus feature. These data showed that even 13 year-olds did not perform at adult levels on this task. Crone et al. (2006) also examined rule-guided behavior using a switching paradigm, but with the addition of 'bivalent' (i.e., 2nd order) relative to 'univalent' rule sets. They found that children and adolescents had greater difficulty with the bivalent rules than univalent rules, especially when switching between rules. These results provide evidence of age-related differences in the capacity to flexibly shift between rules of differing orders of policy. Here, we follow this work by separately manipulating policy level from competition.

Cognitive control depends on working memory to maintain relevant contextual information that can bias thought and action toward a desired goal. It follows that having the right rule or contextual information in working memory is crucial for adaptive responding. Both failing to update relevant information into working memory when it becomes available or failing to maintain it in working memory once it is updated could result in control failures. Thus, cognitive control requires a balance between flexibly updating relevant contextual rule information into working memory (*gating*), and maintaining it there (*maintenance*) stable against interference from irrelevant information (e.g., Chatham, Frank, & Badre, 2014; D'Ardenne et al., 2012; Desimone & Duncan, 1995; Miller & Cohen, 2001). This flexibility/stability paradox seems a particularly difficult problem to solve for the immature developing system. Moreover, perseverative errors, the hallmark of immature cognitive control, could theoretically be attributed to both immature working memory updating or working memory maintenance.

Several models of working memory indicate a solution to these incompatible flexibility and stability demands, where the mechanisms underlying working memory updating or gating are separate from working memory maintenance (Braver & Cohen, 2000; O'Reilly & Frank, 2006). As such, this framework may provide an opportunity for specificity with respect to the precise mechanisms supporting age-related differences in rule-guided behavior in the transition from childhood into adolescence. Indeed, one complication of previous designs that manipulate rule complexity in the developmental literature is that they simultaneously increase overall demands incurred by increased rule complexity (i.e., more abstract policy) *and* maintenance demands among the fan of alternatives (Fig. 1). As such, the developmental course of higher order rule-guided behavior could be a function of updating or gating information into working memory at the level of policy abstraction, at the level of resolving the competition among the increasing fan of options, or some combination. Our work sought to address this question using the paradigms established in Badre and D'Esposito (2007). The potential for specificity and mechanistic insight has broad implications for informing basic science on the topic of the development of rule-guided behavior in this age range, but also fills an important gap with respect to the mechanisms underlying perseverative behavior in a host of developmental disorders, both marked by inefficient cognitive control of thought and action.

Finally, formation of stable rule representations for action is thought to arise through learning mechanisms over childhood (Snyder & Munakata, 2010), and models of the formation of these representations have emphasized the variability of experience as key determining factors (Rougier, Noelle, Braver, Cohen, and O'Reilly (2005). Therefore, we were secondarily interested in the impact of environmental experience in moderating the developmental profile of rule-guided behavior. Socioeconomic status

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