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Cognitive control in action: Tracking the dynamics of rule switching in 5- to 8-year-olds and adults

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ABSTRACT

Recent studies have suggested that dissociable processes featuring distinct types of inhibition support cognitive control in tasks requiring participants to override a prepotent response with a control-demanding alternative response. An open question concerns how these processes support cognitive flexibility in rule-switching tasks. We used a technique known as reach tracking to investigate how 5- to 8-year-olds (Experiment 1) and adults (Experiment 2) select, maintain, and switch between incompatible rule sets in a computerized version of the Dimensional Change Card Sort (DCCS). Our results indicate that rule switching differentially impacts two key processes underlying cognitive control in children and adults. Adult performance also revealed a strong response bias not observed in children, which complicated a direct comparison of switching between the age groups and reopens questions concerning the relation between child and adult performance on the task. We discuss these findings in the context of a contemporary model of cognitive control.

1. Introduction

We live in a noisy world. To behave adaptively we must be able to select and maintain information relevant to our current goals and suppress irrelevant or misleading information. Given the stochastic nature of our environment, however, our goals are liable to change and information that was previously distracting or misleading can become relevant to the task at hand. Adaptive behavior therefore requires striking a balance between two competing demands. On one hand, we must be able to organize our attention, thought, and action around our current goals in order to counteract distracting or misleading information – a process referred to as *goal shielding*. On the other hand, we must be able to supplant that established structure when new goals emerge – a process known as *switching* (modified from the distinction by Goschke & Dreisbach, 2008).

In the developmental literature, this tension between goal shielding and switching is captured by performance on the Dimensional Change Card Sort (DCCS) (Zelazo, 2006; Zelazo, Frye, & Rapus, 1996; Zelazo, Müller, Frye, & Marcovitch, 2003). In the DCCS, children sort a series of cards that feature one of two bi-dimensional images (e.g., a blue boat or a red truck) into one of two trays. Attached to each tray is a target card that matches each of the sorting cards along one dimension but not the other (e.g., one target card would feature a red boat, while the other would feature a blue truck). In the pre-switch phase of the task, children are instructed to sort the cards according to one of the dimensions (e.g., shape). After sorting a number of cards according to the pre-switch dimension, children are presented with a new set of rules that requires them to sort the cards according to the alternate (post-switch) dimension (e.g., color). The majority of children 5 years of age and older adopt the new sorting strategy, while the majority of 3-year-olds perseverate and continue to sort the cards according to the rules presented in the pre-switch phase.

The DCCS is commonly used to assess the development of cognitive control (also referred to as executive function; Diamond, 2013) and shares a number of characteristics with other prominent measures of cognitive control such as the Stroop task (Stroop, 1935). In the Stroop task, participants identify what color of text a word is written in regardless of the word's meaning. When the meaning of the word cues a different response than the color of its text (e.g., the word "BLUE" written in red text), participants must overcome their bias to classify the word according to its meaning. Similarly, in the DCCS participants must overcome a bias to sort the cards according to whichever strategy was first learned.

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Two key differences separate these tasks. The Stroop task involves a response bias that is developed over years of experience with reading, while the response bias in the DCCS is acquired over the course of a small number of trials. The DCCS also requires participants to switch between different sets of rules, while the standard version of the Stroop task does not. The DCCS thus presents the opportunity to study how a response bias is established in the context of a competing sorting strategy (goal shielding), as well as how this tendency is replaced when a new sorting strategy is introduced (switching).

To outline our argument, we first introduce a prominent model of cognitive control that was developed to account for performance on inhibitory control tasks such as the Stroop (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Dunbar, & McClelland, 1990; Cohen & Huston, 1994; Shenhav, Botvinick, & Cohen, 2013). We then discuss recent research that has used a technique known as reach tracking to target how key processes featured in this model function in children and adults (Erb, Moher, Sobel, & Song, 2016; Erb, Moher, Song, & Sobel, 2017). We propose that reach tracking can be used to investigate how the tension between goal shielding and switching influences the functioning of these processes at different points in development. Finally, we investigate this claim in 5- to 8-year-olds (Experiment 1) and adults (Experiment 2).

1.1. Cognitive control and reach tracking

Cohen and colleagues present a model of cognitive control in which performance on the Stroop task can be understood to involve two distinct processing pathways: an automatic pathway that is attuned to word meaning and a control-demanding pathway that can be directed to attend to text color (e.g., Botvinick et al., 2001; Cohen & Huston, 1994; Cohen et al., 1990; Shenhav et al., 2013). On incongruent trials (e.g., ‘‘BLUE” written in red text), the automatic pathway generates strong activation in favor of the response cued by word meaning while the control-demanding pathway generates relatively weak activation in favor of the response cued by text color. In order to ensure that the appropriate response is ultimately selected, cognitive control is required to sway response activations in favor of the response supported by the control-demanding pathway.

In the model, cognitive control is supported by three central components (Shenhav et al., 2013). The monitoring component (associated with the dorsal anterior cingulate cortex) registers conflict stemming from the co-activation of the competing responses. In light of this conflict, the specification component identifies the appropriate course of action given one's current goal (e.g., responding according to text color in the Stroop task). The specification component has also been linked to a *response threshold adjustment process* involving a directed global form of inhibition in which signals of conflict from the monitoring component raise one's threshold to initiate a response by temporarily halting motor output (Cavanagh et al., 2011; Frank, 2006; Munakata et al., 2011). This process has been proposed to allow additional time for the third component – the regulation component (associated with the lateral prefrontal cortex) – to implement a *controlled response selection process* by providing strong top-down support in favor of the appropriate pathway (Shenhav et al., 2013). In addition to increasing activation along the control-demanding pathway, top-down support from the regulation component has been proposed to suppress activation in the automatic pathway through a process of competitive inhibition involving lateral inhibitory connections between the pathways (Munakata et al., 2011).

One of the strengths of this model is that it provides a framework for considering how the components and processes underlying cognitive control function across different timescales. At the timescale of a single trial, the model offers an account of how conflict is detected, motor output is inhibited, the appropriate goal is specified, and top-down support is allocated. At the timescale of multiple trials, the model has been used to account for trial sequence effects in which qualities of one trial influence performance on a subsequent trial (e.g., Botvinick et al., 2001; Shenhav et al., 2013). At the timescale of years, one can consider how components of this model change across development. In the case of the Stroop task, for example, the pathway attuned to word meaning becomes automatized as children learn to read. This automation, in turn, increases the demands placed on cognitive control when the automatic response is inappropriate (i.e., incongruent trials).

In recent work, Erb and colleagues (Erb et al., 2016, 2017) have used a technique known as reach tracking to investigate how key processes underlying cognitive control function across different timescales in response conflict tasks such as the Stroop. In contrast to button-press measures of accuracy and response time, recording the path that a participant's hand travels to reach a response target provides a detailed image of how processes across perception, cognition, and action unfold over time (Song & Nakayama, 2009). Erb et al. (2016, 2017) proposed that two of the measures afforded by reach tracking – *initiation time* (the time elapsed between stimulus onset and movement onset) and *curvature* (the degree to which a response deviates from a direct path to the selected target) – can be used to target the functioning of the response threshold adjustment process and controlled response selection process, respectively. On this view, initiation time indexes the degree of motoric stopping experienced before a movement is started, with higher response thresholds generating longer periods of motoric stopping and, consequently, longer initiation times. Curvature reflects the controlled response selection process by capturing the degree of competition between co-active responses over the course of the movement, with larger curvatures indicating greater pull toward a competing response before top-down support is recruited in favor of the appropriate response.

Consistent with their proposal, Erb et al. (2016) observed different patterns of effects in initiation time and reach curvature in the Stroop task and the Eriksen flanker task. Crucially, the effects observed in initiation time and curvature conformed to the same patterns of effects linked to the response threshold adjustment process and controlled response selection process in previous electrophysiology and functional neuroimaging research (Kerns et al., 2004; Shenhav et al., 2013; Sheth et al., 2012). In a subsequent study targeting the development of cognitive control, Erb et al. (2017) found that reach curvature but not initiation time revealed age-related gains in flanker task performance between childhood and adulthood, suggesting that the response threshold adjustment process and controlled response selection process follow different developmental trajectories.

1.2. Linking this model of cognitive control to the DCCS: The current study

The tasks used in the reach tracking studies reviewed above featured preexisting response biases and did not require participants to switch between different rule sets. Consequently, these tasks did not enable the researchers to investigate the cognitive and developmental dynamics underlying the tension between goal shielding and switching. In the current study we address this gap by using manual reach tracking to investigate how children and adults establish, maintain, and then supplant a response bias in a computerized version of the DCCS.

How might the model of cognitive control introduced above be applied to the DCCS? Let us assume that competing sorting strategies in the DCCS (e.g., matching by color or shape) can be mapped