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N2 amplitude as a neural marker of executive function in young children: An ERP study of children who switch versus perseverate on the Dimensional Change Card Sort

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ABSTRACT

To explore the neurocognitive mechanisms underlying individual differences in executive function during the preschool years, high-density electroencephalography (EEG) was used to record event-related potentials (ERPs) from 99 children (between 35 and 54 months of age) during performance on the Dimensional Change Card Sort (DCCS), a widely used measure of executive function in which participants are required to sort bivalent stimuli first by one dimension and then by another. ERP analyses comparing children who switched flexibly (passed) to those who perseverated on post-switch trials (failed) focused on the N2 component, which was maximal over fronto-central sites. N2 amplitude was smaller (less negative) for children who passed the DCCS than for children who failed, suggesting that the N2, often associated with conflict monitoring, may serve as a neural marker of individual differences in executive function. Implications for learning and education are discussed.

Executive function refers to the deliberate, top-down neurocognitive processes involved in the regulation of thought, action, and emotion – processes such as cognitive flexibility, inhibitory control, and working memory (Miyake et al., 2000). Individual differences in executive function in childhood have been found to predict important developmental outcomes, including math and reading skills in preschool and the early school grades (e.g., Blair and Razza, 2007), and SAT scores in adolescence (e.g., Shoda et al., 1990). Indeed, executive function is often a better predictor of achievement than is IQ, and teachers often report that the most important determinant of classroom success in kindergarten and early school grades is the extent to which children can sit still, pay attention, and follow rules (e.g., McClelland et al., 2007).

Children with poor executive function may be at a disadvantage in educational contexts for a number of reasons, including poor attention, poor emotional control, an increased likelihood of causing behavioral disruptions, and teachers' diminished expectations of children's success. From a cognitive perspective, however, it has also been suggested that children with better executive function may approach learning opportunities in a more reflective, self-directed way that allows them to be goal-directed and proactive in seeking out new information instead of learning in a more passive, incremental fashion (Marcovitch et al., 2008). For example, children who are more likely to reflect upon and monitor their own knowledge may display greater cognitive flexibility and be better able to override the influence of habits or predispositions that interfere with learning.

It is now well known that executive function undergoes particularly marked changes between the ages of 3 and 6 years (Zelazo et al., in press), just as children face sharp increases in the demands placed on their self-regulation

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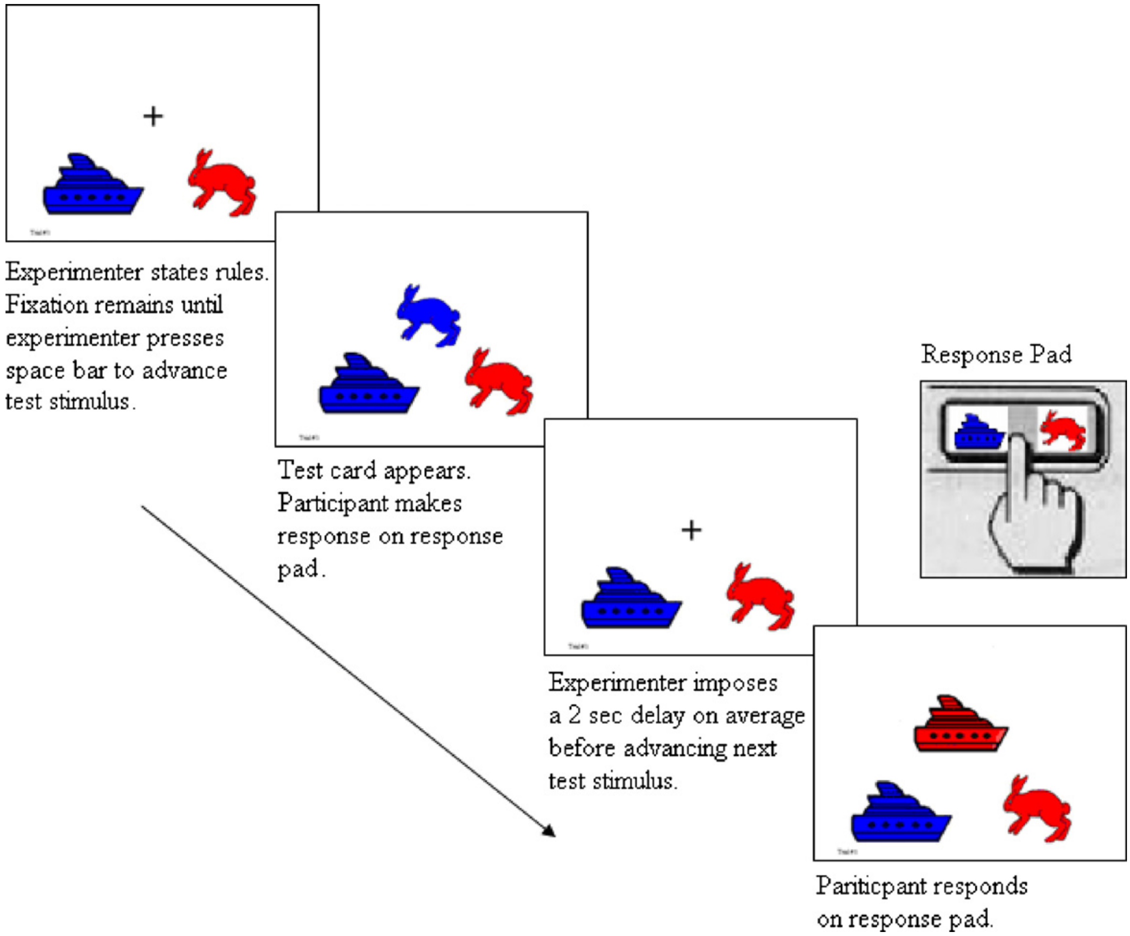

Fig. 1. Sequence of events for the computerized version of the Dimensional Change Card Sort.

(e.g., as they transition to school). A widely used measure of executive function during these years of rapid change is the Dimensional Change Card Sort (DCCS; Zelazo, 2006; see Fig. 1). In the standard version of this task, children are shown two target cards (e.g., a blue rabbit and a red boat) and asked to sort a series of bivalent test cards (e.g., red rabbits and blue boats) first according to one dimension (e.g., color) and then according to the other (e.g., shape). Regardless of which dimension is presented first, most 3-year-olds sort correctly on the pre-switch trials but then perseverate during the post-switch trials, continuing to sort test cards by the first dimension despite being told the new rules on every trial, and despite correctly answering questions about the post-switch rules. By 5 years of age, most children switch flexibly (e.g., Bialystok, 1999; Bohlmann and Fenson, 2005; Brace et al., 2006; Diamond et al., 2005; Dick et al., 2005; Kirkham et al., 2003; Kloo and Perner, 2005; Munakata and Yerys, 2001; Zelazo et al., 2003). The DCCS shows excellent test-retest reliability during this age range (*ICCs* = .90–.94; Beck et al., 2011).

How best to explain children's performance on the DCCS is currently a matter of debate. According to the Cognitive Complexity and Control theory-revised (CCC-r; Zelazo et al., 2003), for example, children who perseverate on the DCCS have difficulty reflecting on their rule representations and formulating a hierarchical rule system that resolves the conflict inherent in the bivalent stimuli. The rapid development of self-reflection during the preschool years allows children to understand that they know two different ways of approaching the task: "If I'm sorting by color, then the red rabbits go here; but if I'm sorting by shape, then they go there." This approach suggests that performance on the DCCS should provide a measure of self-reflection, or monitoring one's rule knowledge, that will predict the efficiency of later learning. In contrast to the CCC-r theory, other approaches emphasize other cognitive processes, such as the need to maintain rules in working memory (e.g., Morton and Munakata, 2002) or to inhibit attention to pre-switch rules (e.g., Kirkham et al., 2003).

Regardless of how one characterizes the processes that make it possible for children to switch on the DCCS, however, there is general agreement that these processes depend importantly on neural networks involving lateral prefrontal cortex, as shown in several recent neuroimaging studies using the DCCS (Moriguchi and Hiraki, 2009; Morton et al., 2009; Waxer and Morton, 2011a). In the single study to date to examine preschoolers, Moriguchi and Hiraki (2009) used near-infrared spectroscopy (NIRS)