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Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample

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ABSTRACT

This study examined age-related changes in complex executive function (EF) in a large, representative sample (*N*=2036) aged 5 to 17 using the Cognitive Assessment System (CAS; Naglieri & Das, 1997a). Relations between complex EF and academic achievement were examined on a sub-sample (N=1395) given the Woodcock–Johnson Tests of Achievement–Revised (Woodcock & Johnson, 1989). Performance on the three complex EF tasks improved until at least age 15, although improvement slowed with increasing age and varied some across tasks. Moreover, the different developmental patterns in the correlations between completion time and accuracy provide clues to developmental processes. Examination of individual achievement subtests clarified the specific aspects of academic performance most related to complex EF. Finally, the correlation between complex EF and academic achievement varied across ages, but the developmental pattern of the strength of these correlations was remarkably similar for overall math and reading achievement, suggesting a domain-general relation between complex EF and academic achievement.

1. Introduction

A number of studies have focused on the origins of adaptive, goal-directed behavior—commonly referred to as executive function (EF)—in young children (see Garon, Bryson, & Smith, 2008, for a review of early EF development). During early childhood, children develop the ability to ignore distraction (Klenberg, Korkman, & Lahti-Nuuttila, 2001), inhibit prepotent and inappropriate responses (e.g., Carlson & Moses, 2001), shift between different sets of tasks (Zelazo, Müller, Frye, & Marcovitch, 2003a, 2003b), and then integrate these abilities to solve more complex problems (Asato, Sweeney, & Luna, 2004; Bull, Espy, & Senn, 2004; Miyake et al., 2000).

Although these early milestones of EF are important to document, fewer studies examine EF development and its correlates in middle childhood and adolescence (Best, Miller, & Jones, 2009). This later development is highly important, too, as EF is associated with school success in middle (Blair & Diamond, 2008; Blair & Razza, 2007) and late childhood (Sikora, Haley, Edwards, & Butler, 2002; van der Sluis, de Jong, & van der Leij, 2007). What is missing in this literature is a comprehensive look at the relations between EF and academic achievement over a wide age range. The specific relations may vary from one age to another, as EF may be more important during some phases of development than others. The present study is more comprehensive than previous studies in that it included a large sample (N=2036), a wide age range (5 to 17), three EF tasks, nine academic tests (Woodcock–Johnson Tests of Achievement–Revised [WJ-R], Woodcock & Johnson, 1989), and several aspects of performance (accuracy, completion time, and their ratio) on the EF tasks. Moreover, unlike most studies of EF in children, we used an assessment of EF with strong psychometric properties (Cognitive Assessment System [CAS], Naglieri & Das, 1997a). Strong reliability, in particular, is important when examining correlations between tests.

Another reason for using the CAS was that it contains "complex" EF tasks that involve several components of EF and often require the coordination of those components. These three complex EF tasks comprise the CAS Planning scale. "Simple" EF tasks, conversely, attempt to isolate the EF components. (*Note*: There are strong arguments, however, that the EF components, particularly working memory and inhibition, are interactive by nature and cannot be isolated in a cognitive task (Roberts & Pennington, 1996)). The CAS does contain simple EF tasks within another scale, the Attention scale, and a similar analysis of those tasks can be found in Lehman, Naglieri, and Aquilino (2010). Because reading and math are complex skills, their reported correlations with EF likely reflect complex EF skills such as selecting and coordinating several EF components. Finally, we focus on complex EF based on evidence for protracted development through late adolescence (Romine & Reynolds, 2005).

In addition to examining the relations between EF and academic achievement over a broad age range, we had a second goal, of documenting the *form* of EF development (e.g., the magnitude of

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change at different ages), with identical or nearly identical tasks employed across the sample. This examination is important for a) clarifying age differences in EF using a large sample covering a wide age range, and b) identifying aspects of EF development (e.g., accuracy, time to completion) that might underlie age differences in the relations between EF and school performance, which could guide future research on this question.

Based on previous research, we expected EF to improve through the elementary school years and adolescence, though perhaps more gradually during adolescence (Davidson et al., 2006; Huizinga, Dolan, & van der Molen, 2006; Huizinga & van der Molen, 2007; Luciana, Conklin, Hooper, & Yarger, 2005; Somsen, 2007, and see Romine & Reynolds, 2005 for a meta-analysis of EF developmental studies and Best & Miller, 2010, for a review). These behavioral findings align with both structural (e.g., Gogtay et al., 2004) and functional imaging studies (e.g., Casey et al., 1997; Durston et al., 2006) reporting a protracted development of the neural substrate supporting EF.

We examined response time and accuracy separately on the EF tasks in an attempt to provide a more fine-grained analysis of EF development and to seek clues to the developmental processes involved. For example, metacognition—monitoring one's performance and adjusting behavior as needed—appears to be an important mechanism related to EF during the school years (e.g., Crone, Somsen, Zanolie & van der Molen, 2006; Davidson, Amso, Anderson & Diamond, 2006; Somsen, 2007). One way to detect the influence of metacognition is to compare age-related changes in accuracy and reaction time on a task. In one study, Davidson, Amso, Anderson and Diamond (2006) found that both reaction time and accuracy on EF tasks increased from middle childhood to early adulthood, suggesting a speed-accuracy trade-off: Older participants adjusted their reaction times in order to maintain a high level of accuracy, which suggests the influence of metacognition on the development of mature task performance. Note that such developmental patterns suggesting the underlying developmental processes would be less evident when only narrow age ranges are tested.

1.1. The EF construct

There is ongoing debate about the nature of the EF construct, but one prominent theoretical framework suggests that EF constitutes distinct, yet related, components, with inhibition, updating of working memory, and shifting being foundational components (Friedman et al., 2008; Huizinga et al., 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000; van der Sluis et al., 2007). Based on this multi-componential framework, complex EF tasks, like those used in the present study, likely require some combination of, and coordination of, these EF components (Anderson, 2002; Asato et al., 2004; Bull et al., 2004; Huizinga & van der Molen, 2007; Huizinga et al., 2006; Miyake et al., 2000). The CAS Planning scale contains three such tasks: Matching Numbers, Planned Codes, and Planned Connections. In developing these tasks, EF was operationalized as the ability to prepare multiple steps of action in advance, evaluate those actions (updating of working memory), avoid or suppress non-goal behavior (inhibition), and change course of action if necessary (shifting) (Naglieri, 2005, Naglieri & Das, 2005). On Matching Numbers children must use controlled searches, as opposed to automatic searches (Schneider & Shiffrin, 1977), to find two identical numbers within a row of similar numbers. Since all the numbers within a row contain similar digits and are the same length, the two identical numbers do not "pop out" but must be identified by selecting and employing a controlled search strategy (Das, Naglieri, & Kirby, 1994). Planned Codes is a variation of other substitution coding tasks (also called digit-symbol coding tasks), commonly found in intelligence batteries, which require children to fill in a matrix of incomplete codes based on a decoding key at the top of the page. However, unlike substitution coding tasks that primarily involve children's perceptual speed (e.g., Laux & Lane, 1985), the Planned Codes task does not contain prespecified instructions on how to code (e.g., left to right, top to bottom). Thus, children must consider the problem, select a coding strategy, and monitor its effectiveness, shifting to another coding strategy if necessary (Naglieri et al., 1989). Finally, Planned Connections resembles the classic neuropsychological assessment of frontal lobe functioning, the Trail Making Test (e.g., Reitan, 1971). It requires children to keep a number or letter in mind to find the next number or letter and to shift between executing number and letter searches (Naglieri et al., 1989). As this description indicates, although "Planning" is the umbrella label given to these three tasks, they assess core EF components in the context of achieving task goals.

1.2. EF and academic achievement

Longitudinal research suggests that EF contributes to academic achievement rather than vice versa (e.g., Bull, Espy, & Wiebe, 2008; George & Greenfield, 2005; Hitch, Towse, & Hutton, 2001; Miller & Hinshaw, 2010). Furthermore, EF has been linked to academic achievement in children of various ages with and without specific learning disabilities (see Best, Miller, & Jones, 2009, and Müller, Lieberman, Frye, & Zelazo, 2008, for reviews). Performance on inhibition and working memory tasks, in particular, consistently relates to performance in mathematics and reading (Blair & Razza, 2007; Bull & Scerif, 2001; Protopapas, Archonti, & Skaloumbakas, 2007; St. Clair-Thompson & Gathercole, 2006; van der Schoot, Licht, Horsley, & Sergeant, 2000; van der Sluis et al., 2007). Shifting, on the other hand, does not consistently relate to academic achievement (Espy, McDiarmid, Cwik, Stalets, Hamby, & Senn, 2004; van der Sluis et al., 2007).

As suggested earlier, complex EF tasks that require the coordination of the foundational EFs and the execution and monitoring of a complex sequence of actions should be of particular importance to academic achievement. Only a few studies have examined the link between complex EF and academic achievement, and most of these studies have used the Tower of London (TOL) or Tower of Hanoi (TOH) task. In both tower tasks, children must select and execute a sequence of moves in order to transform an initial pattern of balls located on pegs to a target pattern in a minimum number of moves. In one study (Bull et al., 2008), TOL performance in preschool predicted improvements in both reading and math from age 5 to age 8. The authors reason that early complex EF skills are domain-general rather than domain-specific skills that provide the building blocks for the development of math and reading skills. Another study (Altemeier, Jones, Abbott, & Berninger, 2006) suggests a more nuanced relationship. After controlling for lower-level EF performance, performance on a modified TOH task uniquely predicted the ability to translate previously-taken notes into a report in 3rd graders, but not 5th graders. Tower performance, however, did not uniquely predict the ability to take notes from a written passage in either grade level. The authors suggested that in younger children, report-writing is less automatic and requires more effortful planning and coordination, but it is unclear why complex EF was not a unique contributor to note-taking skills.

In another study (Sikora et al., 2002), children (aged 7–18) with arithmetic difficulties exhibited greater TOL impairment than children with reading difficulties or children with no diagnosed academic difficulty. Although Sikora et al. did not offer any explanations as to why TOL performance would be more closely linked to math performance, they did suggest that the cognitive processes needed for math may differ from those needed for reading. Finally, Cohen, Bronson, and Casey (1995) found that two complex EF tasks (the TOH and Trail-Making task) did not predict 3rd graders' general school performance (as indexed by a composite of reading, language arts, and math grades) but did not examine each school subject separately.