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Age-related change in executive function: Developmental trends and a latent variable analysis

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Abstract

This study examined the developmental trajectories of three frequently postulated executive function (EF) components, Working Memory, Shifting, and Inhibition of responses, and their relation to performance on standard, but complex, neuropsychological EF tasks, the Wisconsin Card Sorting Task (WCST), and the Tower of London (ToL). Participants in four age groups (7-, 11-, 15-, and 21-year olds) carried out nine basic experimental tasks (three tasks for each EF), the WCST, and the ToL. Analyses were done in two steps: (1) analyses of (co)variance to examine developmental trends in individual EF tasks while correcting for basic processing speed, (2) confirmatory factor analysis to extract latent variables from the nine basic EF tasks, and to explain variance in the performance on WCST and ToL, using these latent variables. Analyses of (co)variance revealed a continuation of EF development into adolescence. Confirmatory factor analysis yielded two common factors: Working Memory and Shifting. However, the variables assumed to tap Inhibition proved unrelated. At a latent level, again correcting for basic processing speed, the development of Shifting was seen to continue into adolescence, while Working Memory continued to develop into young-adulthood. Regression analyses revealed that Working Memory contributed most strongly to WCST performance in all age groups. These results suggest that EF component processes develop at different rates, and that it is important to recognize both the unity and diversity of EF component processes in studying the development of EF.

Keywords: Executive function; Development; Working memory; Shifting; Inhibition; Structural equation modeling; Wisconsin Card Sorting Task; Tower of London

1. Introduction

Across development, children become increasingly more able to control their thoughts and actions (for a review see: Diamond, 2002). This change has been associated with the development of executive function (EF), which is an umbrella term for various cognitive processes that subserve goal-directed behavior (Miller & Cohen, 2001; see also Luria, 1966; Shallice, 1982). EF is especially important in novel or demanding situations (Stuss, 1992), which require a rapid and flexible adjustment of behavior to the changing demands of the environment (Zelazo, Muller, Frye, & Marcovitch, 2003). EF is thought to rely strongly on prefrontal cortex (PFC), as indicated by studies showing that patients with lesions to PFC perform poorly on tasks such as the Wisconsin Card Sorting Task (WCST; Grant & Berg, 1948) and the Tower of London (ToL; Shallice, 1982; for a review see: Stuss & Levine, 2002). On the WCST, which requires flexible switching between sorting rules, PFC patients typically perseverate, i.e., they persist in sorting according to the rule that was previously correct (e.g., Anderson, Damasio, Jones, & Tranel, 1991; Milner, 1963; Nagahama, Okina, Suzuki, Nabatame, & Matsuda, 2005; Stuss et al., 2000). On the ToL, which requires spatial problem solving by moving balls in order to reach a pre-specified goal, PFC patients require more moves to solve the problem (e.g., Andres & Van der Linden, 2001; Carlin et al., 2000; Morris, Ahmed, Syed, & Toone, 1993; Owen, Downes, Sahakian, Polkey, & Robbins, 1990).

Children show a similar pattern as patients with PFC damage; that is, they also perseverate on the WCST and require more moves to solve ToL problems (Anderson, Anderson, & Lajoie, 1996; Baker, Segalowitz, & Ferlisi, 2001; Chelune & Baer, 1986; Chelune & Thompson, 1987; Heaton, Chelune, Talley, Kay, & Curtis, 1993; Kirk & Kelly, 1986; Lehto, 2004;

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Lehto, Juujaervi, Kooistra, & Pulkkinen, 2003; Paniak, Miller, Murphy, & Patterson, 1996; Welsh, Pennington, & Groisser, 1991). The slow development of EF has been attributed to the protracted maturation of PFC (e.g., Diamond, 2002). Conclusive evidence about the developmental trajectories of the different EF components in relation to the performance on standard neuropsychological EF tasks has yet to be established. In this study, we examined the development of EF component processes by using a multi-group confirmatory factor analysis. Where we have at our disposal multiple indicators of a given latent variable, this approach has the advantage that it allows us to study performance at the level of the latent variables, according to a pre-specified model of EF.

1.1. Decomposition of executive function

A major theoretical issue concerns the organization of EF. It has been suggested that EF is unitary, i.e., it does not include distinct sub-functions or sub-components. This means that the cognitive and behavioral impairments seen after PFC damage can be explained entirely in terms of one dysfunctional system (e.g., Cohen & Servan-Schreiber, 1992; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kimberg, D'Esposito, & Farah, 1997). For example, Kimberg et al. (1997) posited that all deficits in PFC function can be attributed to deficits in working memory. In contrast, others view EF as multi-faceted (non-unitary). These authors argued that EF involves several discrete cognitive processes that have a relatively focal neural representation (e.g., Baddeley, 1986; Stuss, Shallice, Alexander, & Picton, 1995; see also Teuber, 1972). The multi-faceted nature of EF is suggested by behavioral studies incorporating batteries of widely used EF tasks. These studies yielded low or non-significant correlations between tasks and exploratory factor analysis yielded multiple factors (Brocki & Bohlin, 2004; Culbertson & Zillmer, 1998; Lehto, 1996; Levin et al., 1996; Pennington, 1997; Robbins et al., 1994; Welsh et al., 1991).

Neuroimaging studies provide evidence in support of the multi-faceted nature of EF, as different components of EF are seen to rely on different parts of PFC. For example, the ability to maintain information in working memory has been found to recruit mostly lateral PFC (Narayanan et al., 2005; Smith & Jonides, 1999). In contrast, switching between tasks is thought to rely on medial PFC (Crone, Wendelken, Donohue, & Bunge, 2005; Rushworth, Walton, Kennerley, & Bannerman, 2004). Finally, the ability to inhibit responses was found to rely on orbitofrontal cortex (e.g., Aron, Robbins, & Poldrack, 2004; Roberts & Wallis, 2000). Thus, different regions within PFC subserve different components of goal-directed behavior.

At this point, it should be noted that the problem of "task impurity" hinders the interpretation of results reported in behavioral and neuroimaging studies using multiple EF tasks. Task impurity refers to the fact that a single indicator (operationalization) of a given construct (e.g., Working Memory) can rarely, if ever, be viewed as a pure measure of that construct. Most measures are contaminated by random error and systematic error (see Kline, 1998, p. 55). The task impurity problem is highly relevant to EF research, as the manifestation of EF components invariably involves other (non-EF) cognitive processes (e.g., Miyake et al., 2000).

Miyake et al. (2000) presented one way to address the task impurity problem. They proposed using multiple tasks to measure each EF component and adopting a latent variables approach to extract the variance common to those tasks. Latent variables (as incorporated in structural equation models; SEM) refer to what is shared among tasks that are assumed to tap a given EF. The latent variable approach minimizes the task impurity problem, and is therefore especially informative in developmental studies (e.g., Nunally & Bernstein, 1994, p. 85). Using confirmatory factor analysis, Miyake et al. (2000) examined the separability of three frequently postulated EF components: "Working Memory", "Shifting", and "Response Inhibition" (henceforth: Inhibition). Miyake et al. (2000) focused on these three EF components because: (1) they are well-circumscribed, lower-level functions that can be operationalized in a fairly precise manner; (2) they can be studied using commonly used tasks; and (3) they have been implicated in the performance of more complex EF tasks, such as the WCST and ToL. Miyake et al. (2000) tested healthy young-adults on multiple tasks tapping Working Memory, Shifting, and Inhibition, and several standard, but complex, neuropsychological tasks, including the WCST and the Tower of Hanoi (similar to the ToL). The results showed that, although moderately correlated, Working Memory, Shifting, and Inhibition were separable constructs (see also Fisk & Sharp, 2004). Moreover, the EF component processes differentially predicted performance on the complex neuropsychological tasks. For example, Shifting predicted WCST performance, whereas Inhibition predicted ToH performance.

1.2. Development of executive function

Developmental studies using standard neuropsychological tasks have shown that EF has a protracted course of development, beginning in early childhood and continuing into adolescence. However, these EF tasks are subject to distinct developmental trajectories. For example, on the WCST, analysis of perseverative errors indicates that the performance of children is comparable to that of young-adults by 12 years of age; however, analysis of failure-to-maintain set indicates that children do not reach adult levels of performance until 13–15 years of age (e.g., Chelune & Baer, 1986; Chelune & Thompson, 1987; Levin et al., 1991; Welsh et al., 1991). Similarly, on the ToL task, performance based on errors appears to continuously improve from middle childhood into young-adulthood; however, when performance is based on both errors and time, adult levels of performance may be attained as early as 13 years of age (Baker et al., 2001; see also Levin et al., 1996).

There is a growing body of research indicating differential trends in the development of EF component processes.[1]

[1] A growing body of research appeared recently, focusing on EF in pre-school aged children (e.g., Carlson, Mandell, & Williams, 2004; Diamond, Briand,