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Do executive functions predict the ability to learn problem-solving principles?

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ABSTRACT

This study examined the relationships between executive functions (EF) and the ability to learn problem-solving principles. It was hypothesized that there are distinct executive domains of attentional control (involving inhibition and selective attention) and cognitive flexibility (working memory and shifting) that predict the ability to learn. Nine to ten year-old children completed a battery of nine tests to provide for multiple-indicator measurement of latent variables. Several alternative models were subjected to structural equation modeling. A three-factor EF structure involving inhibition, selective attention and working memory provided the best fit to the data. Shifting did not emerge as a separate factor and proved to be indistinguishable from working memory. Results indicate a full mediation of inhibition and selective attention effects on the ability to learn via working memory. After controlling for working memory, the paths from inhibition and selective attention to the ability to learn were no longer significant, while working memory accounted for most of the variation in the ability to learn. The findings provide necessary evidence for the hypothesis of a hierarchical structure of EF, where lower-order functions like inhibition and selective attention seem to constitute higher-order functions like working memory which directly determines the efficiency of acquiring novel forms of thinking.

1. Introduction

The term executive functions (EF) refers to a set of mental functions that control and organize cognitive processes. They are thought to be responsible for the synthesis of external stimuli and formation of novel mental forms like patterns of thinking and concepts (Luria, 1976). Although having such integrative function, EF themselves do not seem to form a unitary construct (Friedman et al., 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000). Rather, they are manifested in separate, but interrelated processes of attentional control (inhibition and selection), working memory (WM), self-regulation and planning (Anderson, 2002; Baddeley, 2000; Barkley, 1997; Norman & Shallice, 1986; Zelazo, Carter, Reznick, & Frye, 1997). Even though EF always work in cooperation with lower-order cognitive functions (automatized functions not requiring much effortful control like attention, perceptual encoding, STM or language), this probably does not necessarily hold vice versa; cognitive functions can and often do operate without the involvement of EF, especially in routine situations or when there is no need for adaptive changes (see Anderson, Jacobs, & Harvey, 2005; Norman & Shallice, 1986). However, there are specific conditions in which EF play a crucial role and these conditions involve (1) novel or unfamiliar circumstances, where no previously established response routines exist; (2) where tasks are complex; and (3) where there is a need for integration of information (Shallice, 1988; Walsh, 1987). In the case of deficient executive functioning, these conditions may likely cause cognition to be disorganized. In particular, an individual may not be fully able to focus and

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maintain effortful attention, inhibit stimulus-bound behaviors, hold information in memory while it is being elaborated, plan, generate and implement novel problem-solving strategies or learn from errors (perseverative behavior) (Stuss, 1992; Temple, 1997).

A good example where all of the three mentioned conditions should intersect is learning of problem-solving principles (learning of rules and strategies in complex tasks). This type of learning can be loosely labeled as a process of acquiring novel and modifying established forms of thinking. Such learning is manifested in the ability to successfully transfer the acquired problem-solving skill to a new situation (e.g. Singley & Anderson, 1989). Learning of problem-solving principles employs a synthesis of several lower-level types of learning, works with all three forms of thinking, i.e. concepts, judgments and inferences, and inheres in the production and acquisition of mental operations (Linhart, 1967). Since such an ability to learn requires several cognitive functions to operate efficiently, there is an implied and inherent need for some kind of central regulatory processes to take over the control. This logic clearly implies a significant constituting role of EF in the ability to learn in the sense of being able to acquire and implement problem-solving principles. But would such logic be consistent with reality? What is the individual contribution of single EF to the ability to learn?

In literature, studies of relationships between the system of EF and the ability to learn are still rather scarce. Several studies in the normal population were carried out mostly with samples of adolescents or adults in order to ascertain the relationship (e.g. Adler, et al., 2011; Barenberg, Berse, & Dutke, 2011; Duff, Schoenberg, Scott, & Adams, 2005; Entwistle, Leavell, & Fierstien, 1996; Hallett & Grafman, 1997; Roderer, Krebs, Schmid, & Roebers, 2012; Sasaki, 2009; Tremont, Halpert, Javorsky, & Stern, 2000). However, the focus in all the studies was on lower-order types of the ability to learn (priming, psychomotor learning, verbal learning and associative learning). It can be noted that there is still a gap in our understanding of how and to what degree EF operate and interact when it comes to a more complex ability to learn and internalize new tools of thinking, i.e. principles and strategies needed to solve problems in cognitive domains. Such understanding is especially important in school-aged children since the ability to learn is a crucial constituent of education as such.

1.1. The present study

Examining the question of whether some of the variation in the child's ability to learn problem-solving principles could be attributed to executive functions required some conceptual issues to be resolved. The first one was to define the latent structure of both theoretical concepts. The second fundamental issue that followed was how to measure them.

There is probably no unitary ability to learn that would operate throughout all the content domains. Learning a language, motor skills, faces, or telephone numbers probably do not rely on a single mechanism. However, there may be a single and specific latent ability to learn problem-solving principles. To substantiate and test such an assumption, an observation of performance in several problem tasks was needed in order to infer the underlying latent dimension. Measurement of the ability to learn posits a logical requirement of learning as an inherent part of the testing situation itself. In recent decades, there has been growing concern about the suitability of formerly used static measures to assess the ability to learn. By construction, more traditional static approaches do not reflect potential intra-individual variability. Although such an estimate requires inducing "change" to the testing situation (Dzuka & Kovalcikova, 2008), this variability is regarded a part of error variance here. This conceptual incompatibility resulted in the development of the dynamic assessment paradigm (see Feuerstein, Feuerstein, Falik, & Rand, 2002; Sternberg & Grigorenko, 2002). Testing using dynamic assessment leads us to explore the change in the examinee's ability if an opportunity is provided (Sternberg & Grigorenko, 2002). In dynamic assessment, a teaching phase or feedback is provided which is expected to induce learning, leading to a transfer of newly learned in similar tasks. Several dynamic assessment models have been proposed to date (Budoff, 1972; Campione & Brown, 1987; Carlson & Wiedl, 1978; Feuerstein et al., 2002). In the present study, the two most frequently used approaches to the measurement of the ability to learn were chosen, i.e. the pre-test–intervention–post-test approach (Tzuriel, 2001) and the graduated-prompt approach (Campione & Brown, 1987). It was assumed that such a specific kind of learning ability must follow the same dimension regardless of the measurement approach should it have real ontological foundation.

In early childhood, executive functioning has been shown to follow a single dimension where the executive domains are undifferentiated (Brydges et al., 2012; Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011). Later on, at around the age of 9, EF is reported to become differentiated, forming a structure of interrelated domains (Lehto et al., 2003). From that age on, the developmental sequences of EF seem to become related but separate from one another (Klenberg, Korkman, & Lahti-Nuuttila, 2001). However, the precise rate at which these abilities develop, get differentiated and mature is rather unclear (McAuley & White, 2011).

The objective of the present study was to test a factorial EF structure involving two specific interrelated latent domains as defined in Anderson's "Executive control system" model (Anderson, 2002). The first, executive domain of attentional control can be conceptualized as a goal-directed ability to consciously focus on a target stimulus and simultaneous regulation of internal and external interference factors. Constituted by the processes of inhibition and selective attention (ensuring correct response selection), this domain is presumed to function as a precondition for all the higher executive as well as non-executive cognitive processes (Barkley, 1997; Pennington & Ozonoff, 1996). Although served by a common prefrontal network, inhibition and selective attention are known to be separate constructs (Goghari & MacDonald, 2009). However, it is expected that these two functions are still undifferentiated at the age of middle-to-late childhood and they form an internally consistent construct. The second domain, namely cognitive flexibility entails (1) working memory, i.e. the ability to concurrently process multiple sources of information, and (2) shifting, i.e. the demand-sensitive mental capacity to shift between response sets. The assumption that the cognitive flexibility domain includes both mentioned functions is also inherent in Anderson's (2002) "Executive control system"model. Working memory is "involved in the