Intelligence 44 (2014) 64–74

Contents lists available at ScienceDirect

Intelligence

journal homepage:

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

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ARTICLE INFO

Article history:
Received 29 April 2013
Received in revised form 4 February 2014
Accepted 5 March 2014
Available online xxxx

Keywords:
Executive functions
Inhibition
Selective attention
Shifting
Working memory
Ability to learn principles
Children

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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http://dx.doi.org/10.1016/j.intell.2014.03.002
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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 control, regulation, and active maintenance of task-relevant information in service of complex cognition" (Miyake & Shah, 1999, p. 450). It functions like a working space where mental representations coming from different cognitive systems become integrated. The assumption here is that shifting (i.e. shifting back and forth between multiple tasks, operations, or mental sets) is a synergic function that is still undifferentiated at the age of middle-to-late childhood. While WM temporarily stores and updates information, shifting is required to effectively engage in a relevant mental set and to switch among various mental sets elaborating on the information kept in the WM. Functionally, cognitive flexibility demands both functions to be coordinated to solve complex tasks. Later on, during adolescence and adulthood, WM and shifting stay interrelated but become separate (Friedman et al., 2006; Miyake et al., 2000). Apart from the mentioned domains, Anderson's model incorporates two other executive domains, namely goal setting and information processing which are not in the focus of the present study.

The choice of both mentioned domains was based on a theoretical presumption that they are important constituting elements of the ability to change or modify the patterns of cognition as a function of task requirements, i.e. the ability to learn. Because EF never operate independently of other non-executive cognitive systems (Anderson et al., 2005), fulfilling rather a managerial role, it is not possible to measure them in isolation. This is associated with rather low reliability estimates of EF measures (Rabbitt, 1997), leading to the inability to test hypotheses based on error-attenuated correlations of these measures. This fact induced the need to adopt a multiple-indicator latent variable approach to measurement. This approach to measurement models hypothetical attributes to account for relations between observed indicators. This is in order to alleviate the task impurity problem, i.e. to isolate the random error and method variance within each measure and provide a theory-driven explanation of the processes underlying the performance on these tasks. Moreover, the aim was to employ various modalities (verbal, visual) as well as various task complexity levels (from simple to complex) to make sure that the target theoretical construct is the most substantive common denominator of the hypothesized latent variable regardless of the task-specific variance as much as possible.

The present study aimed to test the aggregate hypotheses that: (1) there are domains of attentional control and cognitive flexibility as well as unitary ability to learn problem-solving principles; and (2) the domains of attentional control (inhibition and selection) and cognitive flexibility (WM and shifting) account for a significant amount of variance in the ability to learn problem-solving principles. In the case of the stated hypotheses holding, the aim would be to explore whether the predictive relationship is of substantial importance.

2. Method

2.1. Participants and procedure

The sample comprised 96 typically developing Slovak children, 56 girls and 40 boys, aged between 9 and 10 years (M = 9.7 years; SD = 0.4). The children attended the fourth grade of elementary school. Apart from two children identified as having borderline intellectual functioning, there was no documented history of neurodevelopmental disorders for all the other children. Informed consent for the child's participation in research was obtained from parents.

Every child was tested individually on a battery of 9 tests. Testing took place in the morning in a quiet room, on one occasion lasting approximately 120 min. The administration followed a fixed sequence test procedure designed with the aim to alternate the cognitive modality of the tasks in order to engage the child's interest over the entire testing procedure. Probable sequencing and fatigue effects were not controlled for, which rules out the possibility to interpret normative performances in single tests.

2.2. Measures

Measures of the ability to learn are denoted by (L); those denoted by (AC) and (CF) presumably measure the executive domains of attentional control and cognitive flexibility, respectively.

2.2.1. Seria-Think Instrument (Tzuriel, 1998) (L)

The Seria-Think Instrument (Tzuriel, 1998) is a dynamic test aimed at the ability to learn arithmetic skills based on the operation of seriation. In this task, a child is given a set of cylindrical rods of various lengths and needs to insert them into a wooden cube having 5 rows of five holes differing in depth. The goal was to get series of cylinders with decreasing (pre-test), equal (teaching phase) or increasing (post-test) height using as few insertions of the rods as possible. To devise an effective solution, the child was encouraged to use a special measuring rod to measure the depth of the holes. Pre- and post-test were static measurements with no help provided. In the teaching phase, the child was taught two strategies (arithmetic and perceptual) to solve the complex task. The original procedure of the learning phase (Tzuriel, 1998) lacks a prescribed structure and so the present study utilized an adapted version of Resing's training procedure (Resing, Tunteler, de Jong, & Bosma, 2009). In order to operationalize the ability to internalize mediated problem solving strategies, the post-test score was employed, as recommended by Weingartz, Wiedl, & Watzke (2008). It is thus assumed that the mean number of insertions per row ("Seria-Think" indicator) during the post-test reflect child's modifiability in problem solving domain. Cronbach's α reliability estimate of the pre-test and post-test scores for number of insertions per row in the present study were .70 and .79, respectively.

2.2.2. Test of intellectual potential (TIP; Fabio, 2007) (L)

Rooted in the graduated prompt approach to dynamic testing, TIP is a measure of the ability to learn problem solving principles, culturally adapted and validated by Dzuka, Kovalcikova, and Kocisova (2008). The measure consists of 7 learning items where the child faces novel problem task and 7 transfer items where the child applies what has been learned in the learning phase to new, more complex problem solving (Fabio, 2007). The items (problems) presented in a stimulus booklet cover sequential reasoning (completion of a series of letters and numbers), deductive reasoning (completion of geometrical figures), inductive reasoning (matrices), mental image superimposition, or questions requiring simultaneous coordination of several verbal and visual information. The task is to construct a solution to open-ended questions and identify correct answer among multiple choice questions. The item difficulty was designed to lie beyond the ability level of most children so that the tasks are to be solved with assistance of provided hints, revealing the child's zone of proximal development as defined by Vygotsky (1987). In learning as well as transfer tasks, after giving a wrong answer, the child was supplied with gradual and balanced assistance (from metacognitive through cognitive to solution constructing prompts), progressively disclosing the solution of the problem (Fabio, 2007). A maximum of 5 prompts could be provided for every item. Within the here employed graduated prompt approach, the ability to learn is operationally defined as an inverse function of the number of prompts that children need both in achieving successful independent performance within a problem domain (Learning phase) and subsequently in maintaining and transferring their acquired knowledge to increasingly different problem types (Transfer phase) (Campione & Brown, 1987). The total scores of both, the TIP learning phase ("TIP learning" indicator) as well as TIP transfer phase ("TIP transfer" indicator), were used as indicators of the ability to learn. Obtained internal consistency estimates for the 7 learning phase and 7 transfer phase items were .72 and .71, respectively.

2.2.3. Stroop's tests — verbal and computerized (Delis, Kaplan, & Kramer, 2001) (AC)

Stroop's test measures primarily the inhibition of overlearned response. To measure inhibition in a more complex way using various response modalities, two versions of the Stroop test were employed. The verbal version used was the adaptation of the D-KEFS Color-Word Interference test (Delis et al., 2001) using only the first 3 conditions and 24 items per condition, i.e. color naming, word reading, and color-word interference. The second version was a computerized Victoria version (Mueller, 2010) devised by Regard (1981, as cited in Strauss, Sherman, & Spreen, 2006) with the same structure of test conditions where the same 24 stimuli per condition were presented on a PC screen. Nonverbal response (pressing keys) was required. The test was preceded by a practice phase to enable examinees to get accustomed to the 4 response keys. Both versions were matched having 24 items on each of the three tasks to minimize the learning effects, since there is evidence that shorter test durations may be preferable for identifying individuals who have difficulty with this task (Strauss et al., 2006). The condition 3 vs condition 1 difference score was regarded as an indicator of inhibition in both versions ("Stroop verbal", "Stroop comp" indicators). In contrast to residual scores, difference scores do not partial out the influence of the baseline condition. This was convenient for the present purpose of indicating the general domain of attentional control.

2.2.4. Toulouse–Pieron test (Toulouse & Piéron, 1982) (AC)

This cancelation task measures the ability to distribute selective attention over a longer time period (10 min limit). The task was to look for and mark two randomly placed specific target stimuli among 27 lines of similar distractors, while no searching strategy was proposed. Children were asked to strike corresponding targets as quickly and accurately as possible. The performance in this paper–pencil task is marked by a high perceptual load and places demands on the tenacity of attention. The number of correct signaled target stimuli within the time limit ("Toulouse–Pieron" indicator) was used as the dependent measure.

2.2.5. Tower of Hanoi (TOH) (AC)

Tower of Hanoi has been widely used as a complex measure of planning but it has been shown to tap other factors like inhibition and WM as well (Miyake et al., 2000). It is a complex task that calls for integration of several mental functions. TOH is a puzzle consisting of several disks of various sizes stacked on a base with three pegs. The task is to move the disks according to rules and reach a given goal state. The rules to follow are: move only one disk at a time, and never place a bigger disk onto a smaller one. After demonstrating a sample of correct and illegal moves, the child was given the tower and was presented with 10 items to solve (7 three-disk, 3 four-disk) of increasing difficulty. The task was to move the disks from the initial state to a depicted goal state using the least number of moves possible. There was no test discontinue rule applied; all the items were administered. The trial on an item was terminated (1) if the child had reached three times the minimum number of moves or (2) if the solution took more than three minutes. The composition and complexity of items were based on several studies (Bishop, Aamodt-Leeper, Creswell, McGurk, & Skuse, 2001; Cohen, Bronson, & Casey, 1995). The dependent measure for the TOH was a composite score computed by a set of equations taken from Goel and Grafman (1995). Such a composite score is a function of problem difficulty, number of moves, backward moves, illegal moves and a range constant. In general, the less moves made to solve the item, the higher the score. The reliability estimate of internal consistency in the present sample was $\alpha = .85$.

The assumption in the present study was that, at age 9–10, TOH is still primarily a measure of inhibition and the test performance relies greatly on the ability to restrain any action until a mental plan of several consecutive moves ahead is devised. This dependent measure ("TOH" indicator) was thus conceptualized as an indicator of attentional control.

2.2.6. Trail making test (TMT, Reitan & Wolfson, 1992) (AC, CF)

The TMT test is thought to tap visual attention, psychomotor speed, cognitive flexibility and inhibition (Strauss et al., 2006). It requires the subject to connect encircled numbers in proper order (Part A) and numbers and letters in alternating order (Part B). Part A ("TMT A" indicator) was regarded as an indicator of attentional control. To isolate the effect of interest, i.e. set-shifting variance of Part B and removing all the component effects causally affecting the performance in Part A, an unstandardized residual score variable was computed by regressing Part B onto Part A. Reflecting the difference between observed and predicted value for Part B, this dependent measure ("TMT B residual" indicator) was used as an indicator of cognitive flexibility.

2.2.7. Wisconsin Card Sorting Test (WCST; Heaton, 1981) (CF)

This complex task is usually used as a measure of higher order EF, i.e. flexibility in shifting mental sets and WM (Cohen & Swerdlik, 2009). A computerized version of 64-card WCST was used (Mueller, 2010). It follows the standard revised Heaton et al's procedure (Heaton et al., 1993) and was found to measure the intended construct in a valid way (Piper et al., 2012; Tien et al., 1996). The task requires the examinee to shift cognitive strategies in response to changing environmental contingencies while sorting 64 cards according to an unknown rule. The sorting principle has to be identified just by receiving feedback. The number of correct responses ("WCST" indicator) served as the dependent measure.

2.2.8. Digit span backwards (Wechsler, 1991) (CF)

The backward condition of the WISC III Digit Span (Wechsler, 1991) required examinees to repeat numbers in reverse order from that stated by the examiner. Maximum digit span ("DSB" indicator) was utilized as a measure of WM and, consequently, as an indicator of the cognitive flexibility domain. Internal consistency reliability was shown to be marginally acceptable, at $\alpha = .65$, due to restricted variance in the present sample caused by small age range.

2.2.9. Verbal fluency test (Delis et al., 2001) (CF)

The verbal fluency tests assess the ability to generate words under restricted search conditions and are considered a vital ingredient in the assessment of cognitive flexibility (Anderson, 2002). To that end, the following 60 s conditions were utilized: semantic fluency using categories of animals and boy's names and switching fluency imposing the need to switch between fruits and means of transportation. The score for each condition was the sum of all admissible words generated within the time limit. The procedure on each condition mirrored that used in the D-KEFS battery (Delis et al., 2001) except that, in the switching condition, points were granted only for words being properly switched. To isolate the switching component of cognitive flexibility, an unstandardized residual score was used such that the variance in switching condition accounted for by the semantic condition was removed, serving as the dependent measure for further analyses ("Fluency residual" indicator).

2.3. Initial model

The initial model (Model 1) reflected the hypothesized structure of relationships between latent and manifested variables. The model included two latent variables representing the EF, (1) attentional control including the processes of inhibition and selective attention and (2) cognitive flexibility including WM and shifting. Both domains were modelled to predict an endogenous latent ability to learn problem-solving principles. The proposed latent-indicator relations constituting the measurement models as well as the specification of the initial structural model (Model 1) are shown in Table 1.

2.4. Data analysis

To test if the data fit the proposed underlying causal structure, theoretical models were subjected to structural equation modeling (SEM). SEM was conducted using AMOS 22.0 (Arbuckle, 2013). The maximum likelihood estimation method was used, analyzing the covariance matrix. A significant χ^2 value ($p < .05$) was regarded a sufficient criterion for immediate model rejection, irrespective of approximate fit indices values (see Antonakis, Bendahan, Jacquart, & Lalive, 2010; Hayduk, Cummings, Boadu, Pazderka-Robinson, & Boulianne, 2007). For a non-rejected model, the following approximate goodness-of-fit indices were further examined: the Comparative fit index (*CFI*), the Tucker–Lewis Index (*TLI*), the Root Mean Square Error of Approximation (*RMSEA*), the Standardized Root Mean Square Residual (*SRMR*) and the Akaike Information Criterion (AIC). The usually suggested "rules of thumb" cut-off criteria indicating a well-fitting model were followed: *CFI* and *TLI* > .95, *RMSEA* < .06 and *SRMR* < .08 (Hu & Bentler, 1999). These indices were chosen because of their stability in smaller sample sizes (Brown, 2006; Tanaka, 1987). The estimates of model parameters were interpreted only for the model, for which there was no evidence of misspecification.

3. Results

3.1. Preliminary analyses

Prior to data analyses, data were screened for missing values, normality and outliers. The screening procedure followed was that recommended by Tabachnick and Fidell (2007). For missing data (0.3%), a regression estimate was imputed. Non-normal variables (according to the significant Kolmogorov–Smirnov measure) were subjected to non-linear transformations (log, sqrt), provided the expectation of normal distribution made sense. To screen for outliers, a matrix of z-scores was created to check that no more than 2 excessive values appeared ($x > M \pm 2SD$). For outlying cases a raw score was assigned that was one unit larger (or smaller) than the next most extreme score in the distribution of the offending variable (Tabachnick & Fidell, 2007).

Table 1
Specification of the structural models.

	Measurement models	Structural model
1	*LV1 Attentional control* BY Stroop verbal, Stroop comp, TMT A, Toulouse–Pieron, TOH. *LV2 Cognitive flexibility* BY WCST, DSB, TMT B residual, Fluency residual. *LV3 Ability to learn* BY Seria-Think, TIP learning, TIP transfer.	*LV2* ON *LV1;* *LV3* ON *LV1,* *LV2.*
2	*LV1 Inhibition* BY Stroop verbal, Stroop comp. *LV2 Selective attention* BY Toulouse–Pieron, TMT A. *LV3 Cognitive flexibility* BY WCST, DSB, TMT B residual, TOH. *LV4 Ability to learn* BY Seria-Think, TIP learning, TIP transfer.	*LV2* ON *LV1;* *LV3* ON *LV2;* *LV4* ON *LV3.*
A	*LV1 Unitary executive functioning* BY all the EF indicators.	
B	*LV1 Attentional control* BY Stroop verbal, Stroop comp, Toulouse–Pieron, TMT A. *LV2 Cognitive flexibility* BY WCST, DSB, TMT B residual, TOH.	*LV2* ON *LV1.*
C	*LV1 Inhibition* BY Stroop verbal, Stroop comp. *LV2 Selective attention* BY Toulouse–Pieron, TMT A. *LV3 Cognitive flexibility* BY WCST, DSB, TMT B residual, TOH.	*LV2* ON *LV1;* *LV3* ON *LV2.*
D	*LV1 Inhibition* BY Stroop verbal, Stroop comp. *LV2 Selective attention* BY Toulouse–Pieron, TMT A. *LV3 Working memory* BY DSB, TOH. *LV4 Shifting* BY WCST, TMT B residual.	*LV2* ON *LV1;* *LV3* ON *LV2;* *LV4* ON *LV2;* *LV3RE* WITH *LV4RE.*

Note: (defined) BY; (regressed) ON; (correlated) WITH; LV = latent variable; RE = residual.

Table 2
Descriptive statistics.

	M	SD	Minimum	Maximum
Stroop verbal	22.21	6.26	8.00	40.00
Stroop comp	0	1	−1.61	2.72
Toulouse–Pieron	111.4	13.52	52.00	131.00
TMT A	38.42	11.99	21.00	102.00
WCST	44.85	7.68	28.00	57.00
DSB	4.33	0.90	2.00	7.00
TMT B residual	0	24.19	−45.50	78.41
TOH	1673	240	613	2131
Seria-Think	10.88	5.05	5.20	37.60
TIP learning	24.27	6.40	4.00	35.00
TIP transfer	24.90	6.19	4.00	34.00
Fluency residual	0	1.96	−5.95	3.83

Table 4
Model test and fit indices.

Model	χ^2	Df	p	CFI	TLI	RMSEA	RMSEA CI	SRMR	AIC
1.	83.7	51	.003	.90	.87	.08	[.05, .11]	.09	138
2.	**51.0**	**41**	**.135**	.97	.96	.05	[.00, .09]	.06	101
A	42.7	20	.002	.82	.75	.11	[.06, .16]	.09	75
B	23.8	19	.203	.96	.94	.05	[.00, .11]	.06	58
C	**19.0**	**18**	**.390**	.99	.99	.03	[.00, .10]	.05	55
D	19.0	16	.273	.98	.96	.04	[.00, .11]	.05	59

Note: (1) Initial structural model. (2) Respecified structural model. Letters represent EF measurement models as follows: (A) Unitary Ef; (B) Attentional control (Inhibition + Selective attention), Cognitive flexibility (WM + Shifting); (C) Inhibition, Selective attention, Cognitive flexibility (WM + Shifting); (D) Inhibition, Selective attention, WM, Shifting.

The next step was to make a preliminary check of the adequacy of the chosen indicators. For the computerized Stroop task, low and sometimes even negative difference scores (in 28 children) between the third and first condition indicated an interfering influence of motor practice effect in associating response keys with colors, masking the underlying inhibition factor. Therefore, the decision was made to compute a factor score indicating overall performance on this computerized test. By means of principal component analysis, a single factor (component) was extracted, accounting for 81% of variance in all three test conditions. The marginally acceptable value of the Kaiser–Meyer–Olkin measure (.66) and a significant Bartlett's test implied the adequacy of such extraction. A regression factor score was computed, checked for normality and then used as an overall test performance indicator.

Table 2 shows descriptive statistics for the raw scores of model variables. Neither significant gender nor even age (2 levels split by median age) differences were found in the model variables.

3.2. Model testing

The first step was to test the fit of the hypothesized initial model (Model 1) where two latent executive domains predict the ability to learn. This initial model did not provide an adequate fit and the present sample provided sufficient power to detect evidence of beyond chance model-data discrepancies. The chi-square value was significant ($\chi^2 = 83.7$; $df = 51$; $p = .003$) which means that the model was not consistent with the data. Subsequent model diagnostics (residual covariances, modification indices, exploratory analyses of the measurement models) revealed the following misspecifications. First, the performance in TOH was not explained by attentional control domain and was found to tap rather the cognitive flexibility domain which implied a stronger WM load than assumed. Second, the Verbal fluency set-shifting indicator did not load on any of the proposed executive domains. Nor did it correlate with other shifting indicators (WCST and TMT residual) and so was dropped from the model. Third, the attentional control latent was not internally consistent and the specification of inhibition and selective attention as separate latents resulted in a significantly better fit. The respecification of the model thus included: (1) the "TOH" indicator assigned as a measure of cognitive flexibility; (2) the "Fluency residual" indicator removed from the model; (3) the attentional control domain split into inhibition factor and the selective attention factor with a defined hierarchical relationship (selective attention regressed on inhibition, inhibition emitting no other paths).

The matrix of zero-order correlations for the indicator variables is presented in Table 3.

Table 3
Correlation matrix.

	STR-V	STR-C	TP	TMT A	WCST	DSB	TMT B	TOH	FLUE	STI	TIP-L	TIP-T
STR-V	1											
STR-C	$.39^{**}$	1										
TP	$-.35^{**}$	$-.21^{*}$	1									
TMT A	$.25^{*}$	$.22^{*}$	$-.38^{**}$	1								
WCST	$-.30^{**}$	−.18	$.38^{**}$	−.18	1							
DSB	−.10	$-.23^{*}$	$.28^{**}$	−.15	$.45^{**}$	1						
TMT B	.19	.03	−.17	.00	$-.41^{**}$	$-.40^{**}$	1					
TOH	$-.26^{**}$	−.17	$.22^{*}$	−.09	$.50^{**}$	$.34^{**}$	−.17	1				
FLUE	−.09	−.01	.05	$-.25^{*}$	−.04	−.05	.04	.15	1			
STI	.01	−.05	−.15	.03	$-.34^{**}$	$-.23^{*}$	.17	$-.43^{**}$	−.04	1		
TIP-L	−.20	−.09	$.39^{**}$	$-.23^{*}$	$.57^{**}$	$.40^{**}$	$-.27^{**}$	$.44^{**}$	.06	$-.59^{**}$	1	
TIP-T	$-.27^{**}$	−.10	$.36^{**}$	$-.23^{*}$	$.56^{**}$	$.40^{**}$	−.18	$.57^{**}$	.10	$-.63^{**}$	$.78^{**}$	1

Note: N = 96. ** $p < .01$; * $p < .05$ (2-tailed). Intercorrelations of EF measures are marked gray. STR-V = Stroop verbal; STR-C = Stroop computerized; TP = Toulouse–Pieron; TMT A = Trail Making Test A; WCST = Wisconsin Card Sorting Test; DSB = Digit Span Backward; TMT B = Trail Making Test B residual; TOH = Tower of Hanoi; FLUE = Verbal Fluency switching residual; STI = Seria-Think Instrument; TIP-L = Test of Intellectual Potential-learning phase; TIP-T = TIP-transfer phase.

Like in the initial model testing, the respecified model (Model 2) met the requirement of overidentification with $df = 41$. Fitting of the model to the sample covariance matrix converged to an admissible solution. Given the $\chi^2 = 51.0$ with associated probability $p = .14$, the hypothesis of the model's global exact-fit to the data cannot be rejected. The values of approximate fit indices ($CFI = .97$; $TLI = .96$; $RMSEA = .05$, 90% CI [.00, .09]; $SRMR = .063$) were reasonable. Regarding the chi-square test assumption of multivariate normality, this can be deemed as fulfilled ($Kurtosis = 4.2$; $C.R. = 1.2$), since only $C.R. > 2$ suggest significant departure from normality (Arbuckle, 2013). Concerning local fit, a detailed inspection of standardized residual matrix revealed no residual covariance approaching the significance threshold value of ± 1.96 (nonparametric bootstrapping with 2000 samples was performed to estimate standard errors).

In order to test, whether the chosen structure of the EF is really the most adequate and to cast aside the possibly masking effects of the structural relationship to the ability to learn latent, four alternative factorial models of EF were tested. See Table 1 for model specifications and Table 4 for model fit.

Alternative model A where all the EF indicators loaded just on a single latent did not reproduce the observed covariances well; $\chi^2\,(20) = 42.7$, $p = .00$. Moreover, the mean intercorrelation among EF indicators was just $|r| = .21$ (ranging from .01 to .50 in absolute value). The chosen indicators of EF thus exhibit a marked divergence and seem to measure several distinct domains. Model B, defining the domains of attentional control and cognitive flexibility proved to fit the data with $\chi^2(19) = 23.8$, $p = .20$. It follows that every other less parsimonious factor solution will fit the data as well. However, the question here was, whether further partitioning of these two domains provides a significantly better representation of the data. This was the case with Model C, where partitioning attentional control further into inhibition and selective attention latent provided a significantly better fit ($\chi^2_{Diff}\,(1) = 4.8$, $p = .03$) with $\chi^2(18) = 19.0$, $p = .39$, which indicates that the mentioned dimensions of executive functioning are already diverse at around 10 years of age. However, further partitioning of the cognitive flexibility domain into the latent dimensions of WM and shifting (Model D) did not improve the fit given the same $\chi^2 = 19.0$ as for Model C but only with df = 16 and the associated probability of $p = .27$. The drop in df makes the four-factor model less parsimonious (the parsimony ratio $\mathrm{df}_{\mathrm{model}}/\mathrm{df}_{\mathrm{max}}$ for this model equals .57 vs. .64 for the three-factor model) and so there are fewer dimensions along which the model could be tested. The fit did not improve after the addition of the shifting factor, rather to the contrary. Moreover, the free covariance parameter between the residual terms of the WM and shifting latents revealed that they share 85% of variance ($r = .92$). Such a strong overlap in variance clearly indicates that WM and shifting are virtually inseparable at given age. Based upon the foregoing, it could be concluded that in the present sample, there is no empirical evidence speaking against the chosen model (Model 2) as it passed the most stringent disconfirmation procedure available. The data indicate the existence of a three-factor structure of executive functioning (dimensions of inhibition, selective attention and cognitive flexibility) and a unitary factor of the ability to learn problem-solving principles, which contradicts the first hypothesis predicting a two-factor EF structure, since the three-factor solution represented the data significantly better.

3.3. Model evaluation

A non-significant value of the χ^2 for the final model (Model 2, Fig. 1) means that the maximum likelihood fit function was able to find a set of parameters that are consistent with the relations observed in the data.

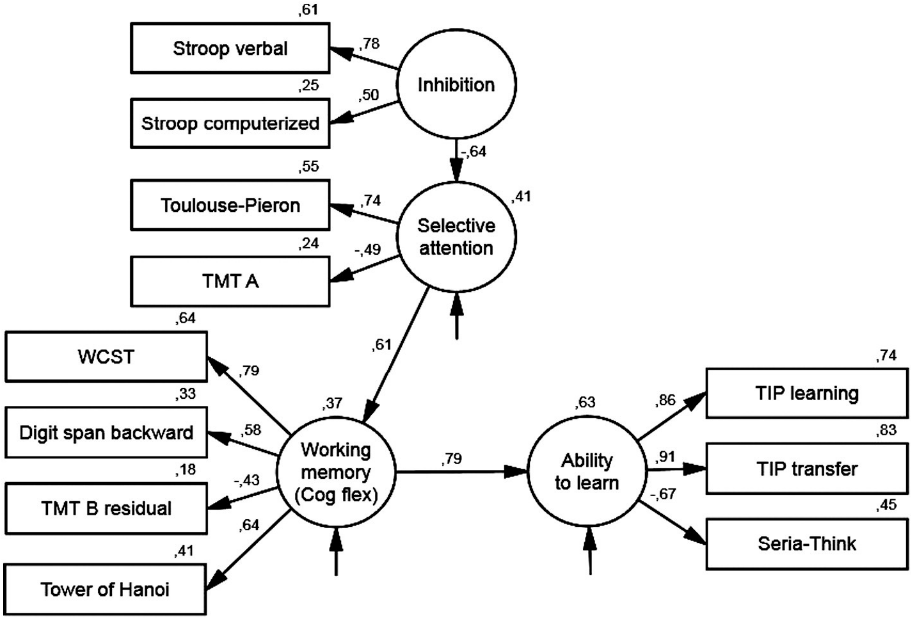

Fig. 1. The respecified structural equation model (Model 2).

Consequently, it makes sense to interpret the estimated model parameters what would not have been the case had the model test failed (Antonakis et al., 2010; Bollen, Kirby, Curran, Paxton, & Chen, 2007; Hayduk et al., 2007).

Established fit of the model provides a more solid ground in order to precisely track down the identity of the latents. When considering the factor loadings, the inhibition latent gained most of its meaning from "Stroop verbal" requiring response inhibition in verbal modality. The factor loading pattern is similar in selective attention latent with "Toulouse–Pieron" indicator (reflecting the ability to maintain vigilant focus and avoid distractions) defining the identity of the construct. The TMT A indicator that involves also motor speed got a weaker loading.

In case of cognitive flexibility latent, pattern of high correlations among "WCST", "TOH" and "DSB" indicated a much stronger working memory identity (considering the WCST is also known to involve shifting). When trying to pinpoint the weakest element of the cognitive flexibility latent, it was the "TMT residual" that stood out, although the loading did not constitute a significant misspecification. Following the respecification (Model 2), "TMT residual" remained the only pure measure of shifting within the cognitive flexibility domain with the other three indicators likely having a stronger WM load. The other reason can be that the residual score, like any difference score, incorporates the unreliability of both subtests (TMT A and TMT B) especially if they are correlated, which was the case here ($r = .55$). Moreover, in light of similarly low loading of "TMT A" on selective attention factor, performance in TMT in general is likely influenced by the confounding effect of visual perception or motor control, causing the underrepresentation of the target latent dimension.

However, there is substantial empirical evidence that makes the presence of shifting variance within the modelled factor doubtful. First, there was a near-zero loading of another purified indicator of shifting, namely the "Fluency residual" on the cognitive flexibility factor. Second, the model test of the EF structure involving shifting as a separate factor (Model D) did not fit the data better than the more parsimonious model, mainly because the WM and shifting factors were nearly collinear. Third, the WM factor was remarkably stable, i.e. the loadings of the WM indicators (DSB and TOH) proved to be virtually invariant to the presence of the shifting indicators within the WM factor (DSB loading did not change, TOH loading changed by .01). Consequently, all these indications led to the conclusion that the common variance shared by these four indicators, and thus the identity of the latent, is attributable to WM.

Regarding the ability to learn, it was "TIP transfer" that proved to be in control of the identity of this latent since it measures whether learning has occurred and whether the child is able to apply learned solution strategies to new problems.

The structure of relationships between the four measurement models is articulated by the structural model, the diagram of the estimated structural regression model being illustrated in Fig. 1. The results show that the modelled domains of executive functioning accounted for 63% (R^2) of the variation in the ability to learn (R^2 95% *CI* [.51, .74]). The bivariate correlations between the EF (inhibition, selective attention and WM) and the ability to learn were $r = -.31$ (negative due to inverse scaling of the inhibition latent), $r = .48$ and $r = .79$, respectively. However, the regression path coefficients did not follow such a pattern. This was due to a full mediation effect. As can be seen in Fig. 1, after controlling for WM, the paths from inhibition and selective attention to the ability to learn were no longer significant. The moderate bivariate correlations of inhibition and selective attention with the ability to learn thus seem to be caused by the variance shared with WM.

Inhibition predicted only selective attention with $\beta = -.64$. The total indirect effect on the ability to learn was at .31. Selective attention predicted WM ($\beta = .61$), and .79 of that effect was transferred to the ability to learn, with indirect effect = .48. The mediation effects (1) inhibition on WM mediated by selective attention and (2) selective attention on the ability to learn mediated by WM were also confirmed by the Sobel test, $z = -4.0$, $p < .001$ and $z = 6.0$, $p < .001$, respectively.

Once a child's status on the latent continuum of WM was known, knowing about its attentional control processes of inhibition and selective attention thus seemed to tell little about whether the child is a good learner in the present sample. Based on these results, the hypothesis assuming a significant predictive relationship of modelled EF domains towards the ability to learn problem-solving principles was accepted.

4. Discussion

The aim of the present study was to examine the relationship between executive functioning and the ability to learn problem-solving principles by means of a latent variable modeling approach. Concerning the structure of executive functioning, it was found that a three-factor model (inhibition, selective attention and working memory) fitted the data well, indicating a non-unitary nature of the construct at the age of 9–10. As was also concluded by Miyake et al. (2000), there is now accumulated evidence that executive function measures are not homogeneous in the sense that different EF contribute differentially to performance on these tasks. The intercorrelations among EF tasks found in the present study were markedly higher than those reported by Miyake et al. (2000), for instance, and approximate those reported by Brydges, Reid, Fox, and Anderson (2012), or St Clair-Thompson and Gathercole (2006). This may be simply due to sampling variation but more likely due to the fact that Miyake et al. studied a sample of undergraduates, while the latter two studies employed children aged 9 to 12, respectively. Given that the (at first unitary) EF system is known to become a system of separate functions with a rather modular character during development, the expectation of stronger relationships among EF tasks in a sample of children is reasonable.

Further exploration of the EF structure revealed that a factorial structure found in adolescents (Lehto et al., 2003; Miyake et al., 2000) that involves both, WM and shifting as separate latents did not fit the data. The following inspection of the models did not provide support for the existence of a distinct shifting dimension, because shifting proved to be collinear with WM at the age of 9–10 years. This is in line with the findings of St Clair-Thompson and Gathercole (2006) who also failed to identify shifting even with more simple tasks, since all the WM and shifting indicators fell along one latent dimension suggesting that shifting may still not be differentiated from its primary components (WM and inhibition) at this age and thus not so developed (Senn, Espy, & Kaufmann, 2004).

Regarding the ability to learn, there were concerns that various dynamic assessment measures might measure distinct abilities to learn (Karpov, 2008), loading on distinct latent dimensions. In the current study, all the dynamic measures loaded on a single latent despite the fact that they were of diverse modalities.

The results of this individual differences study indicate that out of three postulated EF, it is only the WM that is in a tight predictive relationship to the ability to internalize novel patterns and strategies of thinking. Previous research suggests that such a pattern is development-specific. In pre-school children, it is the inhibition that determines the performance in complex problem-solving tasks, whereas the WM starts to be more important in older children (Senn et al., 2004). Moreover, a very similar pattern was found for the relationship between EF and intelligence in late adolescence (Friedman et al., 2006). When controlling for the EF intercorrelations, only WM remained related to Gf and Gc (.74 and .79, respectively), while inhibition and shifting paths to Gf and Gc became nonsignificant. Friedman et al.'s findings were replicated also with 11–12 years old children (Duan et al., 2010). Here, it is to be noted that WM was proven to account for almost all associations between Gf and Gc, rendering the covariance between their residual trivials (Brydges et al., 2012; Friedman et al., 2006) which might suggest that the process by which Gf is transformed into Gc is mediated by WM (Brydges et al., 2012), irrespective of age. Conceding that the process of Gf–Gc transformation might be attributable to the ability to learn, these findings align with the results of the present study, where working memory explained 63% of the variation in the higher-order ability to learn.

The proportion of variance explained approaches than that reported by Duff et al. (2005), for instance, on a mixed clinical sample where two executive domains shared 55–60% of variance in verbal and visual learning. Suchlike associations are necessary, though certainly not sufficient evidence to allow the drawing of causal inferences. Even with a theoretical backing, the causal directions among defined concepts are arbitrary and rest on an untested assumption that higher order functions (e.g. WM) are an emergent manifestation of the interaction between several other lower-order processes (e.g. inhibition, selective attention and STM). Such an assumption still does not guarantee that the values of the path estimates are exactly correct, because the model latents are almost certainly not truly exogenous. There is thus a very likely threat of endogeneity (see Antonakis et al., 2010), i.e. there are minor misspecifications due to omitted variables exercising a causal effect on both predictor and outcome variables. For example, measures of RT's and within-subject variability in processing speed might have been relevant, because it has been shown to impact mental processes at each subsequent higher level including WM and Gf (Demetriou et al., 2008) by increasing the number of representations that can be processed in immediate memory (Coyle, 2013).

However, based on present findings, it is reasonable to infer that inhibition, selective attention and WM are important constituents of the ability to learn, although the former two only indirectly, mediating the acquisition of novel cognitive patterns. The alternate explanations of spurious correlation, reverse causal direction or bidirectional relationships lack empirical and theoretical support so far.

Employing both simple and complex tasks, it was found that the ability to learn is indirectly determined by the attentional control processes of inhibition and selective attention, mediated by WM. It means that those three functions are not hierarchically equal, but one being a subsystem (involved in the functioning) of other. The specification of this inter-individual pattern of relationships also reflects the intra-individual development of EF, which was shown to develop sequentially, from inhibitory control to selective attention and finally to higher EF like WM, and shifting or planning later on (Klenberg et al., 2001).

These findings are also in line with several theories of executive functioning. According to some theoretical frameworks (Barkley, 1997; Pennington & Ozonoff, 1996) inhibition and its interaction with working memory, is considered a driving force for the development of executive functioning. Deficient functioning may thus trigger a cascade of behavioral deficits (Knight & Grabowecky, 1995). Inhibition is a part of the Supervisory attention system (Norman & Shallice, 1986) which takes control when overlearned schemata do not suffice to cope with stimuli demands. In a similar manner, the “Executive control system” model by Anderson (2002) defines attentional control domain (inhibition and selective attention) as a fundamental EF component which influences the functioning of all the other EF domains. As was found, effective WM also seems to be dependent on attentional control processes, which is consistent with the hypothesis that they make use of the same limited-capacity pool of resources (Roberts & Pennington, 1996). Consecutively, WM has been conceptualized as a constituent of higher-order cognition (Baddeley, 2000), as was also found in several other studies (e.g. Bacon, Handley, Dennis, & Newstead, 2008; Daneman & Carpenter, 1980; Engle, Tuholski, Laughlin, & Conway, 1999; Seigneuric & Ehrlich, 2005).

4.1. Limitations

The current study has several limitations that deserve mention. First, all the conclusions apply exclusively to the cognitive domain and cannot be extended to affective domains of executive control and problem-solving, which might eventually be of greater ecological validity. Nor do the findings translate directly to other kinds of learning ability. Second, the data gave rise to a three-factor EF structure, but it does not imply that EF is inherently a three-factor structure. As can be seen in EF research in general, the identified structure of EF depends not only on the age of the studied population but partly also on the conceptual choice of EF measures. Third, given the dynamic character of the EF structure during development, the present findings probably do not apply to other age groups, because the relations among the EF are known to change over the course of development, particularly as they are recruited for complex tasks (see Best, Miller, & Jones, 2009). The relations might thus be of different magnitude, possibly giving rise to a qualitatively different structure. It is also possible that the magnitudes of the structural relations between defined EF domains and the ability to learn are at their peak right at the age around 10 years where the EF are no longer unitary (Lehto et al., 2003), but the cognition still lacks a more modular character typical for later age. Fourth, from the statistical viewpoint, SEM ought to be seen rather as a disconfirmatory technique because, by definition, the accept-support hypothesis test (χ^2) does not allow for a strong confirmatory tone, however it is a strong way to rule out models that significantly ill-fit the observed sample covariance matrix. The reason is that the chi-square that empirically tests the model has a reduced power to detect minor discrepancies between the model and the data in other than very large samples (Bollen, 1989) and, generally, there may always be other models fitting the data equally well. As was noted by Bollen (1989, p. 68), “If a model is consistent with reality, then the data should be consistent with the model. But if the data are consistent with a model, this does not imply that the model corresponds to reality”. The point estimates of model parameters should also be considered an approximation to true values. Estimates based on larger samples would more likely be affected by regression to the mean. Lastly, as in every relational design study, one must consider the general statistical maxim that between-subjects results should not be interpreted as a commonplace in a within-subjects sense (Borsboom, 2005). In this regard, the latent structure as well as the strength of association between involved constructs does not have to hold for an individual child. More research is also needed to learn whether such structures are invariant in various groups differing in their ability to learn. The composition and involvement of cognitive and executive functions that constitute the ability to learn might well be quite different in e.g. groups of struggling and gifted children.

Despite these suggested limitations, it can be concluded that current results provide support for the claim that executive functioning (via WM) exerts a strong influence on the ability of higher-order learning. This is especially true for school-aged children where cognitive deficits may hamper the attainment of needed learning objectives. Understanding of the executive functions involvement in the learning processes might thus possibly help to identify the underlying deficits of poor learners and devise more effective educational intervention strategies with the explicit goal of enhancing the ability to learn.

Acknowledgment

This work was supported by the Slovak Research and Development Agency under the Contract No. APVV-0281-11 (Executive functions as a structural component of the ability to learn: assessment and stimulation, principal investigator Iveta Kovalcikova).

References

Adler, M., Holster, T., & Golden, C. (2011). Does executive functioning influence verbal learning? *Archives of Clinical Neuropsychology*, *26*, 525-525. http://dx.doi.org/10.1093/arclin/acr056.

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, *8*, 71–82. http://dx.doi.org/10.1076/chin.8.2.71.8724.

Anderson, V., Jacobs, R., & Harvey, A. S. (2005). Prefrontal lesions and attentional skills in childhood. *Journal of the International Neuropsychological Society*, *11*, 817–831. http://dx.doi.org/10.1017/S1355617705051052.

Antonakis, J., Bendahan, S., Jacquart, P., & Lalive, R. (2010). On making causal claims: A review and recommendations. *The Leadership Quarterly*, *21*, 1086–1120. http://dx.doi.org/10.1016/j.leaqua.2010.10.010.

Arbuckle, J. L. (2013). *IBM SPSS Amos 22 User's Guide.* Armonk, NY: IBM.

Bacon, A. M., Handley, S. J., Dennis, I., & Newstead, S. E. (2008). Reasoning strategies: the role of working memory and verbal–spatial ability. *European Journal of Cognitive Psychology*, *20*, 1065–1086. http://dx.doi.org/10.1080/09541440701807559.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*, 417–423. http://dx.doi.org/10.1016/s1364-6613(00)01538-2.

Barenberg, J., Berse, T., & Dutke, S. (2011). Executive functions in learning processes: Do they benefit from physical activity? *Educational Research Review*, *6*, 208–222. http://dx.doi.org/10.1016/j.edurev.2011.04.002.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*, 65–94. http://dx.doi.org/10.1037/0033-2909.121.1.65.

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive functions after age 5: Changes and correlates. *Developmental Review*, *29*, 180–200. http://dx.doi.org/10.1016/j.dr.2009.05.002.

Bishop, D. V. M., Aamodt-Leeper, G., Creswell, C., McGurk, R., & Skuse, D. H. (2001). Individual differences in cognitive planning on the tower of Hanoi task: Neuropsychological maturity or measurement error? *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, *42*, 551–556. http://dx.doi.org/10.1017/S0021963001007247.

Bollen, K. A. (1989). *Structural equations with latent variables.* NY: Wiley.

Bollen, K. A., Kirby, J. B., Curran, P. J., Paxton, P. M., & Chen, F. N. (2007). Latent variable models under misspecification — Two-stage least squares (2SLS) and maximum likelihood (ML) estimators. *Sociological Methods & Research*, *36*, 48–86. http://dx.doi.org/10.1177/0049124107301947.

Borsboom, D. (2005). *Measuring the mind: Conceptual issues in contemporary psychometrics.* Cambridge, UK: Cambridge University Press.

Brown, P. T. A. (2006). *Confirmatory factor analysis for applied research.* NY: Taylor & Francis Group.

Brydges, C. R., Reid, C. L., Fox, A. M., & Anderson, M. (2012). A unitary executive function predicts intelligence in children. *Intelligence*, *40*, 458–469. http://dx.doi.org/10.1016/j.intell.2012.05.006.

Budoff, M. (1972). Measuring learning potential: An alternative to the traditional intelligence test. *Studies in learning potential*, *39*. Cambridge, MA: Research Institute for Educational Problems.

Campione, J. C., & Brown, A. L. (1987). Linking dynamic assessment with school achievement. In C. S. Lidz (Ed.), *Dynamic assessment: An interactional approach to evaluating learning potential* (pp. 82–109). NY: Guilford Press.

Carlson, J. S., & Wiedl, J. H. (1978). Use of testing-the-limits procedures in the assessment of intellectual capabilities in children with learning difficulties. *American Journal of Mental Deficiency*, *82*, 559–564.

Cohen, G. N., Bronson, M. B., & Casey, M. B. (1995). Planning as a factor in school achievement. *Journal of Applied Developmental Psychology*, *16*, 405–428. http://dx.doi.org/10.1016/0193-3973(95)90027-6.

Cohen, R. J., & Swerdlik, M. E. (2009). *Psychological testing and assessment: An introduction to tests and measurement.* Boston: McGraw-Hill.

Coyle, T. R. (2013). Effects of processing speed on intelligence may be underestimated: Comment on Demetriou et al. (2013). *Intelligence*, *41*, 732–734. http://dx.doi.org/10.1016/j.intell.2013.06.003.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466. http://dx.doi.org/10.1016/s0022-5371(80)90312-6.

Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *Delis–Kaplan executive function system.* San Antonio: The Psychological Corporation.

Demetriou, A., Mouyi, A., & Spanoudis, G. (2008). Modeling the structure and development of g. *Intelligence*, *5*, 437–454. http://dx.doi.org/10.1016/j.intell.2007.10.002.

Duan, X., Wei, S., Wang, G., & Shi, J. (2010). The relationship between executive functions and intelligence on 11-to 12-year-old children. *Psychological Test and Assessment Modeling*, *52*, 419–431.

Duff, K., Schoenberg, M. R., Scott, J. G., & Adams, R. L. (2005). The relationship between executive functioning and verbal and visual learning and memory. *Archives of Clinical Neuropsychology*, *20*, 111–122. http://dx.doi.org/10.1016/j.acn.2004.03.003.

Dzuka, J., & Kovalcikova, I. (2008). Dynamicke testovanie latentnych ucebných schopnosti. *Ceskoslovenska Psychologie*, *52*, 366–377.

Dzuka, J., Kovalcikova, I., & Kocisova, L. (2008). Dynamicka diagnostika inteligencie deti zo socialne znevyhodnujuceho prostredia pomocou testu intelektoveho potencialu R. A. Fabiovej. *Psychologia A Patopsychologia Dietata*, *43*, 253–261.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, *128*, 309–331. http://dx.doi.org/10.1037//0096-3445.128.3.309.

Entwistle, P. C., Leavell, C. A., & Fierstien, J. (1996). Verbal learning and executive functioning. *Archives of Clinical Neuropsychology*, *11*, 388. http://dx.doi.org/10.1093/arclin/11.5.388.

Fabio, R. A. (2007). *TIP. Test d'intelligenza potenziale.* Gardolo-Trento, Italy: Erickson.

Feuerstein, R., Feuerstein, R. S., Falik, L. H., & Rand, Y. (Eds.). (2002). *The dynamic assessment of cognitive modifiability*. Israel: The ICELP Press.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., Defries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science*, *17*, 172–179. http://dx.doi.org/10.1111/j.1467-9280.2006.01681.x.

Goel, V., & Grafman, J. (1995). Are the frontal lobes implicated in "planning" functions? Interpreting data from the Tower of Hanoi. *Neuropsychologia*, *33*, 623–642. http://dx.doi.org/10.1016/0028-3932(95)90866-P.

Goghari, V. M., & MacDonald, A. W. (2009). The neural basis of cognitive control: Response selection and inhibition. *Brain and Cognition*, *71*, 72–83. http://dx.doi.org/10.1177/1073858407299288.

Hallett, M., & Grafman, J. (1997). Executive function and motor skill learning. *International Review of Neurobiology*, *41*, 297–323. http://dx.doi.org/10.1016/S0074-7742(08)60357-8.

Hayduk, L. A., Cummings, G., Boadu, K., Pazderka-Robinson, H., & Boulianne, S. (2007). Testing! Testing! one, two, three — Testing the theory in structural equation models! *Personality and Individual Differences*, *42*, 841–850. http://dx.doi.org/10.1016/j.paid.2006.10.001.

Heaton, R. K. (1981). *A Manual for the Wisconsin Card Sorting Test.* LA: Western Psychological Services.

Heaton, R. K., Chelune, G. J., Talley, J. L., Kay, G. G., & Curtis, G. (1993). *Wisconsin Card Sorting Test (WCST). manual revised and expanded.* Odessa: Psychological Assessment Resources Inc.

Hu, L. T., & Bentler, P. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling*, *6*, 1–55. http://dx.doi.org/10.1080/10705519909540118.

Karpov, Y. (2008). Do all dynamic assessment techniques assess learning potential? *Journal of Cognitive Education and Psychology*, *7*, 411–418. http://dx.doi.org/10.1891/194589508787724132.

Klenberg, L., Korkman, M., & Lahti-Nuuttila, P. (2001). Differential development of attention and executive functions in 3-to 12-year-old Finnish children. *Developmental Neuropsychology*, *20*, 407–428. http://dx.doi.org/10.1207/S15326942DN2001_6.

Knight, R. T., & Grabowecky, M. (1995). Escape from linear time: Prefrontal cortex and conscious experience. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1357–1371). Cambridge, MA: MIT Press.

Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*, 59–80. http://dx.doi.org/10.1348/026151003321164627.

Linhart, J. (1967). *Psychologie uceni.* Praha: Statni pedagogicke nakladatelstvi.

Luria, A. R. (1976). *The working brain: An introduction to neuropsychology.* NY: Basic Books.

McAuley, T., & White, D. A. (2011). A latent variables examination of processing speed, response inhibition, and working memory during typical development. *Journal of Experimental Child Psychology*, *108*, 453–468. http://dx.doi.org/10.1016/j.jecp.2010.08.009.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49–100. http://dx.doi.org/10.1006/cogp.1999.0734.

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* Cambridge: University Press.

Mueller, S. T. (2010). PEBL: The psychology experiment building language (version 0.11) [computer experiment programming language]. Retrieved Aug 2010 from. http://pebl.sourceforge.net

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In R. J. Davidson, G. E. Schwartz, & D. E. Shapiro (Eds.), *Consciousness and self-regulation*, *Vol. 4*. (pp. 1–14). NY: Plenum Press.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry*, *37*, 51–87. http://dx.doi.org/10.1111/j.1469-7610.1996.tb01380.x.

Piper, B. J., Li, V., Eiwaz, M. A., Kobel, Y. V., Benice, T. S., Chu, A. M., et al. (2012). Executive function on the Psychology Experiment Building Language tests. *Behavior Research Methods*, *44*, 110–123. http://dx.doi.org/10.3758/s13428-011-0096-6.

Rabbitt, P. (1997). Introduction: Methodologies and models in the study of executive function. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 1–38). East Sussex, UK: Psychology Press Ltd.

Reitan, R. M., & Wolfson, D. (1992). *Neuropsychological evaluation of older children.* Tucson, AZ: Neuropsychology Press.

Resing, W. C. M., Tunteler, E., de Jong, F. M., & Bosma, T. (2009). Dynamic testing in indigenous and ethnic minority children. *Learning and Individual Differences*, *19*, 445–450. http://dx.doi.org/10.1016/j.lindif.2009.03.006.

Roberts, R. J., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, *12*, 105–126. http://dx.doi.org/10.1080/87565649609540642.

Roderer, T., Krebs, S., Schmid, C., & Roebers, C. M. (2012). The role of executive control of attention and selective encoding for preschoolers' learning. *Infant and Child Development*, *21*, 146–159. http://dx.doi.org/10.1002/icd.738.

Sasaki, T. (2009). The role of the central executive in associative learning. *Psychologia*, *52*, 80–90. http://dx.doi.org/10.2117/psysoc.2009.80.

Seigneuric, A., & Ehrlich, M. -F. (2005). Contribution of working memory capacity to children's reading comprehension: A longitudinal investigation. *Reading and Writing*, *18*, 617–656. http://dx.doi.org/10.1007/s11145-005-2038-0.

Senn, T. E., Espy, K. A., & Kaufmann, P. M. (2004). Using path analysis to understand executive function organization in preschool children. *Developmental Neuropsychology*, *26*, 445–464. http://dx.doi.org/10.1207/s15326942dn2601_5.

Shallice, T. (1988). *From neuropsychology to mental structure.* Cambridge, UK: Cambridge University Press.

Singley, M. K., & Anderson, J. R. (1989). *The transfer of cognitive skill.* Harvard, UK: Harvard University Press.

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *The Quarterly Journal of Experimental Psychology*, *59*, 745–759. http://dx.doi.org/10.1080/17470210500162854.

Sternberg, R. J., & Grigorenko, E. L. (2002). *Dynamic testing: The nature and measurement of learning potential.* Cambridge: Cambridge University Press.

Strauss, E. H., Sherman, E. M. S., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary.* NY: Oxford University Press.

Stuss, D. T. (1992). Biological and psychological development of executive functions. *Brain and Cognition*, *20*, 8–23. http://dx.doi.org/10.1016/0278-2626(92)90059-U.

Tabachnick, B. G., & Fidell, L. S. (2007). *Using multivariate statistics.* Boston: Pearson/Allyn & Bacon.

Tanaka, J. S. (1987). How big is big enough? Sample size and goodness of fit in structural equation models with latent variables. *Child Development*, *58*, 134–146. http://dx.doi.org/10.2307/1130296.

Temple, C. M. (1997). *Developmental cognitive neuropsychology.* NY: Taylor & Francis Group.

Tien, A. Y., Spevack, T. V., Jones, D. W., Pearlson, G. D., Schlaepfer, T. E., & Strauss, M. E. (1996). Computerized Wisconsin Card Sorting Test: Comparison with manual administration. *Kaohsiung Journal of Medical Sciences*, *12*, 479–485.

Toulouse, É., & Piéron, H. (1982). *Toulouse–Piéron test manual.* Madrid: Tea Editiones.

Tremont, G., Halpert, S., Javorsky, D. J., & Stern, R. A. (2000). Differential impact of executive dysfunction on verbal list learning and story recall. *Clinical Neuropsychologist*, *14*, 295–302. http://dx.doi.org/10.1076/1385-4046(200008)14:3;1-P;FT295.

Tzuriel, D. (1998). *Seria-Think Instrument. Instruction manual.* Ramat Gan, Israel: Bar-Ilan University.

Tzuriel, D. (2001). *Dynamic assessment of young children.* New York: Kluwer Academic/Plenum Press.

Vygotsky, L. S. (1987). *Thinking and speech.* NY: Plenum Press.

Walsh, K. W. (1987). *Neuropsychology: A clinical approach.* NY: Churchill Livingstone.

Wechsler, D. (1991). *WISC-III: Wechsler Intelligence Scale for Children: Manual.* San Antonio: Psychological Corp.

Weingartz, S., Wiedl, K. H., & Watzke, S. (2008). Dynamic Assessment of Executive Functioning: (How) Can We Measure Change? *Journal of Cognitive Education and Psychology*, *7*, 368–387. http://dx.doi.org/10.1891/194589508787724088.

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology*, *44*, 575–587. http://dx.doi.org/10.1037/0012-1649.44.2.575.

Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A., Chevalier, N., & Espy, K. A. (2011). The structure of executive function in 3-year-olds. *Journal of Experimental Child Psychology*, *108*, 436–452. http://dx.doi.org/10.1016/j.jecp.2010.08.008.

Zelazo, P. D., Carter, A., Reznick, I., & Frye, D. (1997). Early development of executive function: A problem–solving framework. *Review of General Psychology*, *1*, 198–226. http://dx.doi.org/10.1037/1089-2680.1.2.198.