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Exploratory data analysis of executive functions in children: a new assessment battery

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Abstract

Executive Functions (EF) are fundamental during childhood since they participate actively in such heterogeneous domains as mental and physical health, learning, school performance, and cognitive, social and psychological development. Their evaluation is of interest, both in the field of clinical practice and research. Several criticisms and discussions have been generated regarding the available resources for its measurement, so it is necessary to have evaluation tasks that present adequate psychometric properties and that allow to evaluate each EF with the least possible interference of other processes. This paper aims to present the Tareas de Autorregulación Cognitiva Battery (TAC), a computerized platform designed for independent measurement of inhibition, working memory and cognitive flexibility, as well as obtaining evidence of construct validity from a set of tasks that compose it. 103 children between 9 and 12 years of age from the city of Mar del Plata, Argentina, were assessed. The results of the factor analysis showed a solution of 3 factors, which significantly explain 52.79% of the variance. These results, together with the scientific evidence presented by previous studies, provide empirical support of the validity of the tasks analyzed in the present study. Thus, this study contributes to the literature by presenting a computerized battery for specific and independent assessment of the different executive processes, valid for its application in children.

Keywords Executive functions · Computerized tasks · Exploratory analysis · Children · Tareas de Autorregulación Cognitiva battery (TAC)

Self-regulation is defined as the ability to modulate thoughts, behaviors and emotions to achieve short- and long-term goals and objectives; it is a multifaceted construct wherein executive functions (EFs) play a significant contributing role (Hofmann et al. 2012; Miyake et al. 2000). EFs are defined as a set of higher-order mental processes that contribute to self-regulation in situations where the achievement of a goal requires concentration and where automated responses are inadequate (Burgess and Simons 2005; Diamond 2013; Espy 2004; McCloskey et al. 2009). In this sense, EFs are higher order mental functions that allow self-regulation by supporting important operations in an individual's self-regulatory goal pursuits (Hofmann et al. 2012). EFs are critical during infancy because they actively participate in such heterogeneous domains as mental and physical health, learning, academic performance, and cognitive, social and psychological development (Allan et al. 2016; Blair and Razza 2007; Lui and Tannock 2007; Moffitt et al. 2011; Toll et al. 2011). They are strongly implicated in voluntary and conscious control of thoughts, emotions and behaviors, therefore a decline in EFs may be a key factor within the body of mechanisms contributing to failures in self-regulation Hofmann et al. 2012).

In recent years, numerous studies have analyzed the structure and relationships of the main EFs (Garon et al. 2008; Lehto et al. 2003; Miyake and Friedman 2012). The main question is whether researchers should distinguish among different executive processes (fragmented or multidimensional approach) or whether this is unnecessary (unitary approach). Whereas unitary models maintain that there exists a common factor capable of explaining performance in the various executive tasks (Duncan et al. 1996; Kimberg et al. 1997), the fragmented approach holds that it is necessary to discriminate between different factors based on the assumption of a specific single variance—not shared—for each one of them (Brocki and Bohlin 2004; Diamond 2013). Besides these approaches,

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there is an intermediate stance known as the unity and diversity model of EFs (see Miyake et al. 2000; Miyake and Friedman 2012), that argues in favor of a factor that is common to these processes—that represents unity and explains the correlation between different EF tasks obtained in various studies—and also of specific factors that represent EF diversity and are reflected in the absence of a perfect correlation between the different latent variables extracted in confirmatory factor analysis models.

This integrated approach generally identifies working memory (WM), cognitive flexibility and inhibition as the main executive processes (Diamond 2013; Garon et al. 2008; Miyake et al. 2000). Firstly, WM allows the retention and active processing of information. It has been characterized as a complex system with a limited capacity that is comprised of storage components for short-term retention of verbal and visual-spatial information, and an executive component that controls the deployment of atentional resources as well as manipulating, updating and integration of information (Baddeley 2003, 2012; Kane et al. 2004). Secondly, cognitive flexibility is the ability to switch the rules of behavior regulation in order to achieve an objective (Davidson et al. 2006). Lastly, inhibition is the ability to control the interference generated by prepotent tendencies linked to thoughts, behaviors and emotions in order to achieve an objective (Diamond 2013; Introzzi et al. 2016a; Nigg 2000). Some authors distinguish various inhibition types, each one with its own functional properties (Diamond 2013; Friedman and Miyake 2004; Hasher et al. 2007). Inhibition during the first stage of information processing is known as perceptual inhibition. It controls interference generated by environmental distracter stimuli, thus favoring the focusing of attention on relevant stimuli (Diamond 2013).

Challenges in the Measurement of Executive Functions

An issue of special relevance is to consider the challenges that arise as EF are intended to be measured in a valid and independent way (Miyake et al. 2000). The tasks typically used for the evaluation of each process vary as to the extent to which their execution involves other executive processes (impurity problem); this hampers the comparison of results across studies as well as the identification of development patterns for each process (Best and Miller 2010; Miyake et al. 2000). Additionally, the possibility of determining the structure of the EFs through the extraction of factors via factor analysis techniques is biased by the task's degree of impurity. Therefore, it is necessary to design tasks for each EF that present the least possible influence from other executive processes.

The existing EFs tasks are by no means exempt of criticism and debate. Some common issues can be highlighted: the limited number of batteries available to measure the development of each EF (Marino and Alderete 2010); many tasks use a single indicator approach to measure different processes, which makes it difficult to measure each process independently (Miyake et al. 2000); some batteries use overlapping measures, such as the assessment of cognitive inhibition through indices extracted from WM tasks, which creates problems when interpreting test results (Dehn 2008); the evaluation of children by means of simplified versions of tasks that are generally employed with adults, which affects the psychometric validity of the tasks (Garon et al. 2008); and finally, many of the EF tasks present weak confidence and validity levels (e.g., Bishop et al. 2001). These criticisms point to the need for tasks with suitable psychometric properties that make it possible to evaluate each EF with the least possible interference from other processes. To this end, this study introduces the *Tareas de Autorregulación Cognitiva* (TAC; Cognitive Self-Regulation Test Battery; Introzzi et al.'s 2013), a stand-alone computer platform designed to independently measure inhibition, WM and cognitive flexibility in a wide age range, and seeks to obtain evidence of construct validity for the set of tasks that comprise it.

The TAC Battery is comprised of a set of computerized evaluation tasks. It makes possible the exact measure of reaction time (RT) and the percentage of correct responses, and additionally increases the degree of standardization in task administration compared to traditional executive tasks. RT is one of the most widely used variables in the study of cognitive processes, and it is critical to have precise measures, together with control procedures for atypical values, as the use of the arithmetic mean of RTs is influenced by the presence of atypical scores, which add variability to estimates and, consequently, can weaken an instrument's statistical power (Perea and Alagarabel 1999). Each task is based on experimental paradigms widely validated and used in the field of cognitive psychology and neurosciences. Its main advantages are the accuracy, speed and ease with which the user can obtain the different performance indices, the possibility of independently evaluating each process, the format and design of stimuli adapted to the subjects (children, adolescents and adults). The novel aspects are the ease of administration and scoring, its dynamic and user-friendly environment, and the possibility of being used both in the fields of the application of psychology and in that of research. The main characteristics of these tasks is that they have been adapted to reduce to the greatest extent the participation of other executive as well as non-executive cognitive processes (perceptual discrimination, abstract reasoning, etc.), aiming to provide the most precise and purest possible measure of the construct of interest.

Recently, a series of studies have tested the internal and external validity criteria for a number of the TAC Battery's tasks (Richard's et al. 2017a, b, c). There are also studies that have analyzed the internal validity criteria associated with maturation changes with age (Canet-Juric et al. 2015; Introzzi et al. 2016b; Richard's et al. 2017c). However, there still remains the matter of exploring the whole performance of the tasks that comprise the TAC Battery. The objective of this study is to contribute evidence in this regard, by conducting an exploratory factor analysis of the main performance indices of each one of these tasks in children.

Method

Participants

A non-probabilistic incidental sample of 103 children with ages ranging from 9 and 12 (M = 10.84 SD = 0.88), of both sexes (48 girls and 55 boys, 47% and 53% respectively), all of them residents of the city of Mar del Plata, Argentina, was assessed. 18.79% of the children's families were of the mid- to high-socioeconomic status (SES), 49.10% were of the mid-SES; and the remaining 31.20% of the mid- to low-SES, according to the Two Factor Index of Social Status (Hollingshead 2011). To discard the presence of a clinical population, the *Guía de Observación Comportamental* (GOC; Behavior Observation Guide) (Ison and Fachinelli 1993) was used.

Ethical Considerations

To participate in this study, authorization from the children's parents was required via a signed informed consent form. Participation was voluntary and the children were free to cease participating whenever they wanted to do so. The form assured that the data would remain confidential and that the results would only be used for research purposes in accordance with National Law 25.326 on the protection of personal data and the "Guidelines on ethical conduct in the Social Sciences and Humanities" developed by the Ethics Committee of CONICET (2857–06), Argentina's National Science and Technical Research Council. This research followed the procedures recommended by the American Psychological Association (APA 2010).

Materials

***Batería de Tareas de Autorregulación Cognitiva* (*TAC*; Cognitive Self-Regulation Test Battery; Introzzi et al. 2013)** This test battery is composed of a set of tasks, designed to evaluate independently each executive process (see Introduction). In this study, tasks that evaluate perceptual inhibition, WM and cognitive flexibility were used.

1. ***Perceptual inhibition task.*** This task is based on the conjunction search experimental paradigm proposed by Treisman and Gelade (1980). On each trial, the participant must identify the presence or absence of a target stimulus among a variable set of stimuli that act as distracters (4, 8, 16 and 32 stimuli). The distracters share one of the target's two perceptual traits: color or form. This fosters visual similarity among stimuli and generates the interference effect required in order to activate perceptual inhibition. The target is a blue square with sides of 0.8 cm, and the distracters are blue circles with a diameter of 0.8 cm and red squares with sides of 0.8 cm. Each trial begins with the presentation of a centered fixation cross for 200 ms. Then stimuli are randomly presented in an undisplayed matrix of 7 X 6 cells (width: 9.5 cm, height: 8 cm). Stimuli remain on display until the participant responses. The task presents a practice block (10 trials), followed by three blocks, each one consisting of 40 trials (10 trials per number-of-distracters condition: 4, 8, 16, 32). The target is present in half of the trials on each condition. Participant must respond as quickly and as precisely as possible by pressing the "Z" key if the target is present and the "M" key if it is absent. The tests are randomly distributed, making the target's presence/absence unpredictable; similarly, the locations of the stimuli on the screen are also randomly distributed. The percentage of correct responses (CR) and the average RT (calculated from CRs) in the condition with 32 distracters were used as indicators of perceptual inhibition ability. This condition presents the greatest interference at the perceptual level and places the greatest demand on inhibition.
2. ***WM Tasks.*** The tasks used are based on the dual paradigm and are an adaptation of the procedures in Logie et al. (1990) and Hale et al. (1997). Dual tasks require that the subject simultaneously execute two tasks: a primary and a secondary task. The first task implies the maintenance of stimuli in short-term memory. The secondary task serves as interference and is aimed at interrupting any type of strategy that can facilitate maintaining the primary task's information. The thinking behind the dual paradigm is that there is a limited set of working memory resources that can be shared between the primary and secondary tasks, and this leads to decreased performance. There are four tasks in total: two verbal (a single verbal task, a primary verbal task with a secondary verbal task) and two spatial tasks (a single spatial task, a primary spatial task with a secondary spatial task). In the primary tasks, a series of items are shown on the screen one by one (numbers in the verbal task and a matrix in the spatial task), followed by a recall signal. In the secondary verbal task, participants are to say aloud the color of each item. In the secondary visual-spatial task, participants are to indicate the color of each item by touching or using a cursor to point to the color on a

palette located to the right of the stimulus being presented. The maximum number of elements recalled in each task is taken as an indicator of WM capacity.

3. ***Cognitive flexibility task.*** This is a change task based on the Simon paradigm (Simon and Rudell 1967) which was previously used with arrows as stimuli (see Davidson et al. 2006). It requires participants to quickly and precisely alternate between two rules. The task used in the present study uses fingers instead of arrows, in order to increase the familiarity of the stimulus and facilitate the association between the stimulus and the location of the response. The task begins with a fixed cross that appears in the center of the screen and remains fixed throughout the entire task; the stimuli appear equidistant to the left or right of the cross. The interval between stimuli is 500 ms. Each stimuli remains on screen for 750 ms, during which time participants are to respond. There are two types of trials: congruent and incongruent. In congruent trials, a hand appears on the left or right side of the screen pointing straight down, indicating to the participant that they are to press the key ipsilateral to the location of the stimulus (when the stimulus appears on the left side they are to press the "S" key and when it appears on the right side they are to press the "L" key). In incongruent trials, a hand appears on the right or left side of the screen, with a finger pointing diagonally towards the opposite side. Participants are to press the key opposite to where the stimulus is located. Therefore, if the stimulus appears on the left side of the screen, participants are to press the "L" key, and if the stimulus appears on the right side of the screen, they are to press the "S" key. There are three types of blocks: congruent, incongruent and mixed. The task begins with the congruent block, in which only congruent trials are presented. This is followed by the presentation of the incongruent block, which only presents incongruent trials. Finally, the mixed block is presented. This block specifically demands task-switching, as congruent and incongruent trials are randomly presented, thus requiring the participant to rapidly switch between responses. Accordingly, this study used the percentage of correct responses and the mean response time in the mixed block as the performance indicators.

***Guía de Observación Comportamental* (*GOC;* Behavior Observation Guide; Ison and Fachinelli 1993)** This scale is administered to teachers. It allows detecting the presence of behavioral disorders, through the assessment of type and frequency of symptoms of inattention and problematic behaviors in children between 5 and 13 years of age. It consists of seven sub-scales, where the teacher must indicate the option that best describes the child's behavior in terms of frequency ("Never", "Sometimes" or "Often"). The GOC presents adequate levels of internal consistency (Ison and Fachinelli 1993).

All of the computerized tasks were administered on a portable laptop computer with a high-resolution 14-in. screen and with the Windows 7 operating system. The TAC platform provides feedback to help resolve tasks; therefore, the intervention of researchers is limited to giving instructions and accompanying the children in case they deviate from the established objectives of the task.

Procedure

The sample was evaluated with the tasks of the *TAC* Battery over the course of two 25-min individual sessions that took place in classrooms equipped for this purpose. The tasks were administered by researchers who were especially trained for that purpose. Before beginning each task, instructions were provided orally by the researchers and were simultaneously displayed on the computer screen. Researchers assured that children understood the purpose of each task and allowed questions to be made. Students were reminded that they were able to withdraw if they desired to do so, and that they could take a break between tasks if they felt tired. Previously, informed consent was obtained and the socioeconomic status scale was administered to parents and/or tutors. Additionally, the teacher responsible for each child was administered the *GOC*.

Data Analysis

The analyses were conducted using the SPSS V23 software. First, a series of descriptive analyses were performed to determine the distribution of the variables under study for the total sample. Second, an Exploratory Factor Analysis (EFA) was then conducted to evaluate the internal structure (construct validity) of the *TAC* Battery tasks.

Results

Atypical values in each performance index were analyzed and a limit of ±2 *SD* from the mean was established; extreme values beyond ±2 *SD* were replaced with the corresponding limit value (see Table 1).

An EFA was conducted using the Maximum Likelihood (ML) method with *Varimax* rotation to evaluate the internal structure of the *TAC* Battery tasks. This method of factor extraction was used due to compliance with the assumptions of multivariate normality and absence of outliers (Fabrigar et al. 1999). Performance indices with factor loadings ≥ .40 were extracted. The Kaiser-Meyer-Olkin (*KMO*) test for sampling adequacy value was .53. The Bartlett's test statistic was significant ($X^2 = 47.765$, $df = 28$,

Table 1 Principal executive performance indices for the total sample

Task	Index	N	Mean	SD	Min.	Max.	As.	Ks.
Perceptual inhibition	Precision	103	84.57	11.23	52	100	−.98	.73
	Mean RT	103	1590.18	419.84	928	2613	.61	−.38
Verbal WM	Span without interference	103	6.03	1.04	3	8	−.44	−.03
	Span with interference	103	4.28	1.16	2	7	−.01	−.35
Spatial WM	Span without interference	103	5.28	1.17	3	8	.13	−.57
	Span with interference	103	3.94	1.17	2	7	.00	−.59
Cognitive Flexibility	Precision	103	97.51	3.34	88	100	−1.32	.84
	Mean RT	103	576.95	87.48	349	811	.37	.10

$p = .011$). These results indicate that the data is suited for factor analysis (Hair et al. 1999). A three-factor solution was obtained, which significantly explains 52.79% of the variance. The rotated factor matrix is shown in Table 2. Factors were grouped in the following manner:

Factor 1 – Perceptual Inhibition (20.38%): Mean RT in condition with 32 distracters, Precision in condition with 32 distracters.
Factor 2 – Cognitive Flexibility (17.57%): Precision in mixed block, Mean RT in mixed block.
Factor 3 – WM (14.83%): Verbal WM without interference, Verbal WM with interference, Spatial WM without interference.

Discussion

The objective of this study was to explore the factorial structure of the set of tasks that are part of the *TAC* Battery. These tasks were especially designed to independently measure three executive processes: perceptual inhibition, WM and cognitive flexibility. The results of the EFA converged into a three-factor solution, which significantly explains 52.79% of the variance. The first factor summarizes the variance in perceptual inhibition indices (precision and mean RT). The second factor groups the variance in cognitive flexibility indices (precision and mean RT). Lastly, the third factor summarizes the variance in verbal and spatial WM tasks (both with and without interference). These results, together with the scientific evidence contributed by previous studies (see Introduction), suggest that the *TAC* Battery constitutes a valid instrument to measure the three executive processes that are identified by most researchers in the literature (Garon et al. 2008; Miyake et al. 2000).

Table 2 Factor loadings of the performance indices

Task	Index	Factor		
		1	2	3
Perceptual Inhibition	Precision	**.78**	−.14	.13
	Mean RT	**.53**	.31	−.12
Verbal WM	Span without interference	.19	−.13	**.43**
	Span with interference	−.13	−.13	**.41**
Spatial WM	Span without interference	−.10	.07	**.50**
	Span with interference	.06	.04	.16
Cognitive Flexibility	Precision	−.07	**.63**	−.01
	Mean RT	.08	**.40**	−.14

factorial loadings ≥.40 presented in bold

Extraction Method: Maximum Likelihood. Rotation Method: Varimax with Kaiser Normalization

The executive functions of WM, inhibition and cognitive flexibility are interrelated (Diamond 2013), resulting in various difficulties when it comes to assessing each one of them independently. For example, the Wisconsin Card Sorting Test, a typical task used to measure cognitive flexibility, presents a high WM and inhibition load in its execution (Thorell et al. 2009). Unlike this and other tasks typically used, the cognitive flexibility task of the *TAC* Battery requires participants to maintain a single behavior-regulation rule (respond with the key the finger is pointing to, independent of the stimuli's location), which reduces the intervention of WM in its execution. Further, although inhibition does participate in its execution, its intervention occurs at the prepotent response (ipsilateral) level, and not at the rule-change response level, which reduces its participation. This implies that the visual key provided by the stimulus (a finger pointing in the direction of the response) reduces intervention of the inhibitory process. This could address why the cognitive flexibility task has an independent factor load of WM and inhibition.

Additionally, the visual conjunction search paradigm on which the perceptual inhibition task is based also makes it possible to control for the effect of WM and cognitive flexibility in its execution. Given that inhibition allows for controlling interference generated by prepotent tendencies to achieve a goal, this control requires actively maintaining the necessary behavior-regulation rules; thus, WM is interrelated with inhibition. The execution of this inhibition task implies the participant to carry out two behavior-regulation rules (indicate with separate keys the presence or absence of a target); therefore, it is necessary to control for the effect of WM. As these rules remain constant, cognitive flexibility does not participate in the task's execution.

The WM tasks without interference do not call on the active intervention of inhibition or cognitive flexibility. However, the WM tasks with interference present a low-level of demand on both of these processes. This implies a reduced demand on cognitive flexibility. Although they require the participant to alternate between two tasks, this does not require a change in the rules. Over the course of the task, the participant is to always remember a verbal or spatial stimulus, then constantly realize a secondary task, and finally reiterate the stimuli in the order in which they were presented. Secondly, these tasks generate controlled intervention of perceptual inhibition. The information to be recalled enters the participant's attention focus (without interference from other stimuli) and the participant knows that the information will be relevant when the time comes to respond, and for this reason the control of the interference generated by the secondary task requires less cognitive effort.

As for the limitations of this study, it is important to point out that performance on the visual-spatial WM task with interference does not contribute significantly to any of the three factors, although it does present a slightly greater factorial load in the first component (WM). On this point, previous studies indicate that the variation in performance in verbal and visual-spatial WM tasks are grouped in a single factor for children between 8 and 13 years of age (Lehto et al. 2003). In any event, there is a clear need to further analyze this visual-spatial process with larger samples. At the same time, it would be interesting to broaden the age range in order to conduct a parallel factor analysis by age group; this would require a larger sample that could be subdivided in such a way as to assure a minimum number of participants per age group. Facing these empirical limitations would contribute to the validation of the TAC Battery and provide evidence in favor of the underlying EFs conceptual model.

The results of the present study encourage the development of practical application of the battery. Previous studies suggest that it is appropriate for discriminating children with a diagnosis of ADHD from others showing typical development (Richard's et al. 2017b). Future studies may consider this battery's validity for the diagnosis of disorders related to alterations in executive functioning, such as obsessive compulsive disorder (Snyder et al. 2015) or pathological gambling (van Timmeren et al. 2017). Moreover, having instruments to assess each EF independently is a key issue in designing interventions that are tailored for each cognitive profile.

In closing, this study contributes to the literature by presenting a computerized evaluation battery for the different executive processes that is valid for use with children up to 12 years of age. Although this study has only explored the factorial structure of a set of tasks, the results add to those reported in previous studies by the same authors. Thus, this strengthens the evidence of validity for the tasks that comprise the *TAC* Battery for its use in school-age children. Currently, there are a set of studies being developed aiming to extend the use of this battery to other stages of the life cycle, and obtaining evidence of different types of validity. This work must consider the limitations in this study, to deepen the evidence in this regard.

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Compliance with Ethical Standards

All procedures performed in this study were in accordance with the ethical standards of the National Scientific and Technical Research Council of Argentina, and with the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from the children's parents, and each participating child gave his assent to participate in the study.

Conflict of Interest The authors declare that they have no conflict of interest.

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