

A COMPUTERIZED TOOL FOR NEUROCOGNITIVE ASSESSMENT OF EXECUTIVE FUNCTIONS IN ADULTS AND ELDERLIES: PILOT TESTING OF THE EXECUTIVE FUNCTION TOOL-TASK (EF/T-T)

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Executive functions (EFs) play a crucial role in higher cognition, influencing life skills and effective global functioning or dysfunctional developmental trajectories. Despite their significance, EFs assessment primarily relies on tests designed for detecting clinically-significant deficits, limiting their applicability to physiological aging or for profiling supposedly healthy populations. This study introduces the Executive Function Tool-Task (EF/t-t), a screening tool potentially spanning emerging adulthood to elderly age. In a pilot study involving 68 healthy volunteers, we firstly explored its informativity and potential. The EF/t-t includes subtests on verbal learning, memory, cognitive flexibility, attention, and inhibitory control. Partial correlation analyses, accounting for age and education, revealed moderate-to-strong coefficients between subtests, indicating good internal consistency. Also, cluster analysis allowed us to parse out three latent performance profiles. Current findings hint at the potential of the EF/t-t for complementing cognitive screening in presumably preserved adults and elderly people, offering consistent neurocognitive profiling of EFs.

Keywords: Executive functions; Assessment; Computerized testing; Cognitive screening; Cognitive control task.

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Being at the core of higher cognition, executive functions (EFs) are crucial pillars of global functioning across the lifespan. Indeed, EFs allow for flexible adaptation to contextual requests, self-monitoring and self-regulation, and strategic orientation of cognitive resources on ongoing tasks, besides exerting top-down control of sensations, emotions, behavior, and thoughts (Diamond, 2013). Such top-down hierarchical control is also mirrored by the hierarchical structure that defines the neural bases of EFs (Stuss, 2011). According to such organization, cortical prefrontal structures occupy the highest ranks in the hierarchy and regulate other cortical and subcortical structures, as well as neural networks, while also being modulated by feedback loops including regions and nodes that lies outside of the prefrontal cortex and, especially, in subcortical and limbic structures, which create a complex circuit capable of fine-graded control over thought, sensations, perception, emotions, and behavior (Snyder et al., 2015; Stuss, 2011; Zelazo, 2020).

The complex and multifaceted nature of neural basis and functional manifestations of EFs can consistently be found in the EFs unity/diversity models (Diamond, 2013; Duncan et al., 1997; Miyake et al., 2000; Stuss, 2011), now widely used and recognized and originally proposed by Teuber in 1972. The core concept of such model is the contrast between the interconnection and correlation that connote the processes, mechanisms, and skills that constitute EFs due to their common grounding on shared latent traits, and their

functional specificity, expressing different facets of higher cognition and specific subprocesses that can be assessed by using different neuropsychological tests or neurocognitive tasks (Grossi & Trojano, 2013).

Within the unity/diversity model developed by Miyake and colleagues (2000), for instance, EFs are based on three primary functional abilities: inhibition, shifting, and working memory. Inhibition is seen as the manifestation of cognitive control and executive control skills regulating behavior and responses, besides thoughts and inner experiences. Shifting is enclosed within the concept of cognitive flexibility, representing a necessary skill to reorient attention and cognitive resources across different stimuli and tasks thus allowing to flexibly adapt to the environment and generate novel responses to contextual requests. As for working memory, instead, the main focus is on information updating processes and use of such mnemonic and information manipulation space to efficiently integrate different data and support learning and memory. Interestingly, experimental and clinical evidence suggests that such internal structure can be observed across the lifespan, starting from school age to elderly age (Lehto et al., 2003; Miyake et al., 2000; L. Vaughan & Giovanello, 2010).

Besides conceptual differences between various models of EFs, many achievements, experiences, and aspects of human life — in particular as academic and occupational attainments, relationship quality, and physical/mental health — are known to be associated with the degree of integrity and efficiency of EFs, which are considered a valuable protective factor and moderator of life skills, quality of life, and effective global functioning (Balconi et al., 2020; Best et al., 2009; De Panfilis et al., 2013; Hall et al., 2006; Valiente et al., 2013). In addition, EFs are, among the ensemble of human cognitive functions, the domain that shows the most systematic and peculiar pattern of modulation during the lifespan, and especially in the progress from adulthood to elderly age (Cabeza & Dennis, 2013). And again, an impairment of EFs is currently considered one of the primary transdiagnostic features across the lifespan (Balconi et al., 2014, 2015, 2022b; Buckholtz & Meyer-Lindenberg, 2012; Crivelli & Balconi, 2021; Crivelli et al., 2022; Millan et al., 2012; Pagnoni et al., 2022; Snyder et al., 2015), systematically marking different psychopathological pictures. Extensive screening and monitoring of EFs, then, represents a profitable goal for the purpose of self-awareness and self-empowerment and, if needed, prevention and early intervention.

At the same time, however, it has to be acknowledged that traditional neuropsychological tests devised to assess EFs in clinical settings do present some limitation when used to screen and/or profile people who present, so far, a physiological aging process or only report subjective complaints. Indeed, in such cases, the functional impairments that could be observed are often mild and, therefore, could lie undetected by tests that are calibrated to identify moderate-to-severe deficits. This is often due to sensitivity issues linked to the performance metrics that are commonly used in classic paper-and-pencil tests — that is, error rates over a limited set of items/trials — and/or to the simplicity of tasks or test materials. Properly combining traditional tests and neurocognitive tasks that allow capturing even finer-grained performance metrics (such as response times and *d*-prime indices), could represent a feasible solution to overcome the above-noted limitations in applicability of current neuropsychological testing for profiling or screening supposedly healthy people for prevention purposes, in line with recent remarks on computerized neuropsychological assessment in aging (Asensio & Duñabeitia, 2023; Koo & Vizer, 2019; Sozzi et al., 2020; Wild et al., 2008; Zygouris & Tsolaki, 2015). Also, such combination would help overcoming the fragmentation of current approach to cognitive assessment, where different tests apt to investigating single components of EFs are often only juxtaposed without effective integration of their scores. The possibility to have a single tool designed to investigate, via specific subtests, core components of EFs — such as inhibition, attention regulation, working memory, information processing and learning, and cognitive flexibility — and to provide comparable performance metrics and a common profiling for those components would represent a valuable advancement to the actual state-of-the-art in the field.

Moving from those methodological remarks, we here present pilot explorative analyses concerning the feasibility, informativity, and potential of a neurocognitive tool devised to assess higher cognition and EFs in the life span, from emerging adulthood to elderly age. During the development of the tool, we aimed at selecting a set of existing tests and measures that could be quickly administered and scored — thus focusing on usability and ease of administration, besides validity and informativity of the tool — and extensively revised them to overcome intrinsic methodological limitations and to allow for proper combination and comparison of related performance metrics. Also, we focused on tests that could sketch individual profiles of executive control and higher cognition even in healthy people so to complement the standard psychodiagnostics toolbox of professionals, which is so far primarily constituted by tests devised to appraise moderate-severe impairments in clinical settings and, thus, only limitedly suitable to investigate milder deficits in healthy people.

The present pilot work specifically aims at investigating the feasibility, informativity, and robustness of the tool and its ability to outline an integrated profile of the degree of functionality for different components of higher cognition and EFs. At the same time, we wanted to verify the potential ability of the tool to identify different clusters of performers based on the combined outcome of the tool subtests, which could mirror distinct individual profiles connoted by different EFs efficiency levels.

Based on unity/diversity models of EFs, we expected to observe moderate associations between participants' performance at the different tests that constitutes the tool, thus mirroring the internal consistency of the tool itself. Yet, we also did not expect complete and strong correlation across all test performance scores, mirroring their functional diversities and specificity and lack of redundancy. Finally, even if the study is explorative and, then, it is still not possible to postulate strong hypothesis on the screening potential of this novel tool, we also expected to be able to capture different clusters of scores at the tool subtests, thus beginning to parse out different profiles of participants based on the efficiency of their EFs.

METHODS AND MATERIALS

Sample

Sixty-eight healthy volunteers were recruited to test the novel screening battery. Inclusion criteria were: being 18+ years old; having normal or corrected-to-normal vision and hearing. Exclusion criteria were, instead: having positive clinical history for neurology or psychiatric diseases; recent/concurrent diagnosis for cerebrovascular events; having suffered from moderate/severe traumatic brain injury, infectious or inflammatory diseases, neoplastic diseases, or neurodegeneration; clinical instability in the 48 hours prior to the assessment session; and absence of compliance or other transient conditions that could alter the quality of data collection. Table 1 summarizes the sociodemographic characteristics of the sample.

TABLE 1
Sociodemographic characteristics of the sample

	Sample
Group size	68
Sex — M/F (%)	23 (34%)/45 (66%)
Age — Mean (<i>SD</i>); range	37.87 (13.50); 21-60
Education years — Mean (<i>SD</i>); range	15.76 (3.03); 8-21

All participants freely gave their written informed consent for participation in the study. The study and related experimental procedures were reviewed and approved by the Ethics Committee of the Department of Psychology, Catholic University of Milano (Italy) (prot. 2018-th), and comply with the rules and standards of the Declaration of Helsinki and subsequent revisions. In addition, data collection, processing, and storage were conducted in compliance with national and European regulations for privacy and data management/protection.

Procedure

In devising the assessment tool, we had firstly systematically mapped neuropsychological tests and tasks used to profile executive functioning in healthy people and clinical settings, and complemented such mapping with the exploration of available methodological literature on those tests and tasks. Such systematic mapping grounded on a previous research and development work that led to the creation and validation of a computerized battery for fine-grained assessment of executive functions and higher cognition in psychopathology (see Balconi et al., 2022a, 2022b; Crivelli et al., 2022).

After first preliminary testing, procedures and materials have been revised to make them leaner and even more comprehensible. Starting from such preliminary testing and from clinical validation of the extended computerized battery devised to screen executive impairments in psychopathology (Balconi et al., 2022a, 2022b; Crivelli et al., 2022), seven subtests have been finally selected for inclusion in the here presented assessment tool, allowing for the measurement of efficiency of verbal learning and short-/long-term memory, working memory, verbal and nonverbal cognitive flexibility, focused attention, attention regulation and suppression of interference, and inhibitory control. With regard to the here reported testing of the tool, participants were initially recruited via convenience sampling and, subsequently, the sample was increased via snowball sampling.

The subtests included in the current version of the assessment tool was administered by three licensed psychologists trained in psychodiagnostics and neuropsychological testing in a single assessment session that lasted, on average, about 40 minutes. Scoring procedures were standardized (for further information on scoring procedures and calculations, please refer to Balconi et al., 2022a; Crivelli et al., 2022). Yet, the outcomes of testing were scored by an expert examiner and double-checked by a second expert in neuropsychological testing who acted as additional blinded judge.

Materials

The tested assessment tool — labelled Executive Function Tool-Task (EF/t-t) — is, then, constituted by:

1. the Verbal Memory Test (VMT), tapping on verbal learning and short-/long-term memory;
 2. the Working Memory Test (WMT), tapping on transient storage and active processing of information;
 3. the Focused Attention Test (FAT), tapping on detection and selection of target stimuli and inhibition of distracters;
 4. the Verbal Fluency Test (VFT), tapping on cognitive flexibility, lexical access and selection, and set shifting;
 5. the Non-verbal Fluency Test (NFT), tapping on cognitive flexibility, generative, and creative processes based on graphical material, and set shifting;
 6. the Computerized Stroop Task (CST), tapping on attention regulation and suppression of interference;
 7. the Computerized Go/No-go Task (CGT), tapping on inhibitory control and suppression of prepotent responses.
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Performance at the seven subtest is quantified via chronometric, accuracy, and/or error measures, in line with recent suggestions concerning computerized testing in neuropsychology (Asensio & Duñabeitia, 2023; Koo & Vizer, 2019; Sozzi et al., 2020; Wild et al., 2008; Zygouris & Tsolaki, 2015), which are then converted into compound indices mirroring the degree of functionality of the investigated EFs domain. In order to ease the definition of a global profile of strength and weaknesses and in order to make comparison of the examinee's performance at different tests easier, performance indices are converted into the same metric scale, ranging from 0 to 100. For more information on the computation of such performance indices, whose computation algorithms are proprietary, please see Balconi et al. (2022a).

Going down to specifics, the Verbal Memory Test (VMT) — a learning and recall task aimed at investigating encoding and retrieval of verbal information in/from explicit memory — includes, for both immediate and delayed recall, metrics and indices mirroring the number of correctly recalled words, the number of words in the correct position during serial recall, intrusion errors, and repetition errors. The Rey Auditory Verbal Learning Test (Rey, 1958), one of the most widely used neuropsychological tests for immediate and delayed recall of verbal objects, served as the conceptual and methodological foundation for the creation of the VMT. According to previous studies (Andersson et al., 2006; Bravin et al., 2000; Carlesimo et al., 1996; Schoenberg et al., 2006; Vakil et al., 2012), such classic neuropsychological test was effective at identifying memory deficits in a range of clinical conditions. However, a review of the literature revealed some significant problems with the item list included in the Italian version of the test and the test's general structure. In particular, the existence of latent semantic associations between the word list items may facilitate and favor intrinsic encoding processes. Additionally, both concrete and abstract terms are represented in the list's elements despite having distinctive semantic properties and a different representation in the conceptual linguistic system. The words' length also exhibits a lot of variation.

Based on these initial observations and critical notes, we developed a new set of items for the VMT that were chosen from the COLFIS corpus's list of lemmas (Bertinetto et al., 2005) according to strict psycholinguistic criteria: lexical class (nouns), category (concrete), number of letters (4 to 6), and total relative frequency (≥ 100). Additionally, we chose words that did not share any proximal semantic-conceptual networks (e.g., home-school) or have direct latent associations (such as sun-garden-window). Additionally, in the VMT, the examinee is required to complete a serial recall task in order to increase the test's discriminative and sensitive capabilities even in the situation of minor memory function deficiencies.

In the Working Memory Test (WMT) — a test devised to assess the capacity of the brief-term information storage and manipulation space for stimuli presented in auditory modality — the WM span is quantified as the number of items in the longest, correctly reproduced, sequence during a listen-and-repeat task with numeric stimuli. The Digit Backward Test (Hebb, 1961; Wechsler, 1939), one of the most widely used neuropsychological tests for evaluating working memory deficiencies, provided the starting point for development of the WMT. The Wechsler Bellevue Intelligence Scale (Wechsler, 1939) introduced the traditional version of the backward digit paradigm, but in the following years, other variants with different materials, presentation strategies, and scoring algorithms were created. These tests are frequently used in neuropsychological evaluations of a variety of clinical diseases in neurology, including head trauma, stroke, neurodegenerative disorders, and other conditions (Black, 1986; Laures-Gore et al., 2011; Luerding et al., 2008; Sartori & Edan, 2006).

The WMT was updated with new items using one-digit natural numbers, controlling for the internal structure of the sequences to prevent the presence of ordered digit chunks and to avoid chunks composed of contiguous even (or odd) numbers in order to address some critical issues regarding the structure of sequences that were pointed out during the critical analysis of the pertinent literature. The WMT also asks the test taker to mentally manipulate the information stored in the temporary buffers (i.e., before being created,

the sequence of numbers must be rearranged in descending order), increasing the cognitive effort and letting to measure the effectiveness of working memory.

The Focused Attention Test (FAT) — a decoding task based on symbols and numbers aimed at assessing the integrity of focused attention processes, identifying relevant stimuli while ignoring distracters — includes total number of responses, number of correct decoding answers, and number of decoding errors as performance measures. The FAT was created starting from a review of the most-diffused neuropsychological tests used to evaluate the efficiency of focused attention and, in particular, the Symbol Digit Modalities Test (Smith, 1973). This test, which was modelled after the Wechsler Digit Symbol Test (Wechsler, 1939), is believed to evaluate several aspects of attention as well as working memory and information processing abilities (Shum et al., 1990). According to several studies (Owens et al., 2018; van Walsem et al., 2018; Wu et al., 2020), several categories of neurology patients performed poorly on the Symbol Digit Modalities Test, and their performance was worsened by concurrent anxiety or depression (Goretti et al., 2014; Joosub et al., 2017). Also, the original test's score is known to be modified by practice, age, education, gender, and cultural factors (Kennepohl et al., 2004; Roar et al., 2016; Strauss et al., 2006).

We have carefully revised the internal structure of the test and implemented novel graphical symbols, so to avoid graphics that could have recalled mathematical operators that, when combined with numerical digits, might have triggered implicit facilitating associations. Additionally, the encryption key was revised so to prevent graphically similar signs from being next to one another, hence preventing any facilitation effect brought on by implicit learning of the sequence.

The Verbal Fluency Test (VFT) — a test devised to investigate the integrity of lexical access and selection mechanisms via phonemic rule, and cognitive flexibility when dealing with verbal material — quantified performance in terms of total number of correct words, intrusion errors, and repetition errors. Verbal fluency tasks are likely the most diffused methods for assessing higher executive function in both neurology and psychiatric departments since it requires executive control over cognitive processes such as selective attention and inhibition, set shifting, and self-monitoring (Patterson, 2011). Starting from the original version of the Controlled Verbal Fluency Task (Borkowski et al., 1967), numerous variants of the verbal fluency test have been developed based on different languages and letter sets (e.g., Kavé, 2005; Kosmidis et al., 2004; Novelli et al., 1986; Pena-Casanova et al., 2009; Raoux et al., 2010). Such tests proved to be valid and sensitive in identifying deficits of cognitive flexibility and impairment of verbal EFs in the presence of frontal lesions or dysfunctions (Alvarez & Emory, 2006; Davidson et al., 2008; Henry & Crawford, 2004; Metternich et al., 2014), as well as neurodegenerative disorders, mild cognitive impairment, neurodevelopmental disorders, and depressive syndromes (Andreou & Trott, 2013; Libon et al., 2009; Obeso et al., 2012; R. M. Vaughan et al., 2018). Yet, validation studies present a remarkable variability of core factors modulating examinees' performance (Ardila et al., 2000; Auriacombe et al., 2001; Loonstra et al., 2001).

Since the critical study of available data mostly revealed methodological flaws in the selection of the stimulus letters, which was frequently made at random, we paid particular attention to this when developing the new version of the VFT. In particular, in the current revision of the phonemic verbal fluency test, the stimulus letters have been chosen in accordance with the following principles in order to minimize potential biases caused by the randomly choosing the stimulus letters and to the consequent differences in the extension of the related vocabulary in different languages: two consonants and one vowel; at least 10.000 lemmas for consonants and 25.000 for the vowel in the reference vocabulary (De Mauro's New Dictionary of the Italian Language); and at least as many lemmas in the Italian vocabulary beginning with the three newly chosen stimulus letters as there were for the original letters.

The Non-verbal Fluency Test (NFT) — a drawing task devised to test the integrity of generative and creative processes and the efficiency of cognitive flexibility mechanisms with visual-spatial material — allow to assess the examinees' performance in terms of total number of drawings, number of original non-repeated drawings, number of drawings designed according to a recognizable strategy (e.g., series of at least three drawing that highlight a rotation, progressive addition or semantic strategy), and number of errors due to repetition or violation of test rules. The NFT grounds on a methodological revision of the few neuropsychological tests developed to evaluate cognitive flexibility and fluency via nonverbal material and, in particular, of the Five Point Test (Regard et al., 1982). Several studies show that such test is sensitive to brain damage and, in particular, to structural and functional alterations of the frontal lobes (Goebel et al., 2013; Hansen et al., 2017; Lee et al., 1997; Tucha et al., 1999).

A review of the test materials and an update to some scoring criteria were produced as a consequence of the critical analysis of pertinent literature and of preliminary testing of the tool. In order to maximize the contrast between the figure and background, the matrices in the revised version of the NFT are constituted by five squared dots. Also, a third example configuration has also been added to make it clear to the examinee that even drawings made up of independent lines (such as two parallel lines) are acceptable for the test's aims. Finally, the employment of strategies for creating graphic configurations is a significant area of interest in the revised NFT, as it is seen as a particularly important component in assessing the effectiveness of high-order EFs. Because of this, the criteria for identifying strategies in test answers have been expanded to include the use of rotation rules (serial replication of the same graphic configuration rotated around its central point), enumeration rules (serial replication of similar graphic configurations created by adding or removing traits), and semantic-conceptual rules (e.g., the sequential reproduction of the letters of the alphabet or of graphic patterns representing numerical digits).

The Computerized Stroop Task (CST) — a neurocognitive task devised to investigate the integrity of attention regulation processes and of mechanisms allowing for the control of interference due to semantic incongruence in verbal material — included, as performance measures for congruent and incongruent stimuli, response times, response accuracy, and number of omitted responses. The Stroop task was originally developed as a tool to quantify the processing speed of complex information and the cognitive cost of interference (Stroop, 1935). The design and development of the novel CST task were, then, guided by the critical analysis of relevant literature concerning the paper-pencil and computerized versions of the Stroop test and, in particular, focused on the selection of optimal timings for stimuli presentation, intertrial interval, and response windowing.

The Computerized Go/No-go Task (CGT) — a neurocognitive task specifically devised to assess executive control and response inhibition — quantifies examinee's performance in terms of response times, accuracy, number of omitted responses, number of false alarm responses, and the d' sensitivity measure. The most diffused tasks devised to investigate and quantify the ability to suppress prepotent — though useless, irrelevant, or dysfunctional — thoughts or behaviors, such as the stop-signal task and the go/no-go task, grounds on inhibitory control processes that manifest themselves through response selection or response stopping. Since its first definition, the Go/No-go Task took the form of an experimental paradigm used to study attention and inhibitory control mechanisms and their neurophysiological correlates (Donders, 1969; Huster et al., 2013). Factors such as the relative frequency of Go and No-go stimuli, the duration of the trial, or the inter-stimulus interval affect the level of inhibitory control required by the task and, then, the interpretation of performance measures (Leblanc-Sirois et al., 2018; Wessel, 2018; Young et al., 2018).

The creation of the CGT was based on a revision of available evidence on applications of the Go/No-go paradigm for the evaluation of cognitive control skills and inhibitory mechanisms, which resulted mostly experimental in their nature. In particular, critical remarks focused, even in this case, on the selection of

optimal timings and ratio for stimuli presentation, intertrial interval, and response windowing. For more information on the internal structure, stimuli, and software development concerning the above introduced tests and tasks, please see Balconi et al. (2022a).

Data Analysis

In order to explore the robustness and validity of the internal structure of the novel assessment tool, associations between performance metrics for each subtest of the tool have been explored by partial correlation tests controlling for age and education. Cohen (1988) norms were used to interpret correlation strength. Threshold for statistical significance was set to $\alpha = .05$. The outcomes of partial correlation analyses have been checked against the false discovery rate by applying the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995), so to minimize the risk of interpreting results biased by potential multiple testing errors.

In addition, cluster analysis based on performance indices and metrics at the tool subtests was used to identify the ability of the tool to identify potential latent performance groups among participants. Specifically, to explore latent clustering structure grouping different subtypes of participants, a hierarchical agglomerative cluster analysis with Ward's method as a linkage method and Euclidean distance as a similarity measure was conducted.

Subsequently, the identified hierarchical clustering solution was refined by applying a nonhierarchical partitioning clustering model to the data. Going down to specifics, we used a K-means clustering model based on Hartigan-Wong method (Hartigan & Wong, 1979) with fixed solution to improve the cluster fit while minimizing potential biases in initial assignment of centroids¹ and datapoints. This two-stage sequential approach allows to benefit from the strengths of the individual clustering procedures while limiting their weaknesses. Indeed, the hierarchical cluster analysis (CA) provided starting partitions for the subsequent partitioning analysis, thus guarantying unambiguous solutions on the basis of meaningful starting points. Then, the nonhierarchical partitioning CA revealed the optimal categorization of cases since the clustering outcome is repeatedly computed until no further improvement is possible. This also allowed computing optimized cluster-specific centroids and the distance of each respondent to the cluster centroid.

RESULTS

Table 2 reports the full matrix for partial correlations between subtests' compound indices and performance metrics, including correlation coefficients and probability values. As for the two-step cluster analysis, the optimal number of clusters was determined by visually inspecting the dendrogram, that is, the graphical representation of how individual cases are arranged into the clusters produced by hierarchical clustering. By taking into account the arborization of the dendrogram and the distribution of cases across clusters, we selected the three-cluster as the more robust and potentially meaningful. This was also supported by the fact that further splitting the identified clusters would have only resulted in adding smaller clusters that could have been only limitedly informative. Then, the distribution of cases across clusters in the three-cluster solution and histograms concerning the profile of performance indices in each cluster were qualitatively assessed to appraise the chosen clustering solution. Such a solution presented peculiar, distinct, and well-separated patterns of clustering variables and, therefore, plausibly identified different subtypes of examinees.

TABLE 2

Partial correlation matrix between subtests' compound indices and performance metrics, including correlation coefficients and probability values

		VMT Immediate	VMT Delayed	WMT	FAT	VFT	NFT	CGT RT	CGT Acc	CGT FA	CGT Omiss	CGT <i>d'</i>	CST Acc	CST RT	CST Omiss	
VMT Immediate	Coefficient	1.00														
	<i>p</i>	.														
VMT Delayed	Coefficient	.78	1.00													
	<i>p</i>	< .001	.													
WMT	Coefficient	.25	.27	1.00												
	<i>p</i>	.049	.032	.												
FAT	Coefficient	.32	.30	.26	1.00											
	<i>p</i>	.012	.018	.044	.											
VFT	Coefficient	.16	.25	.33	.32	1.00										
	<i>p</i>	.211	.052	.009	.012	.										
NFT	Coefficient	.27	.22	.26	.28	.32	1.00									
	<i>p</i>	.036	.077	.042	.027	.010	.									
CGT – RT	Coefficient	-.07	-.04	-.14	-.17	-.01	-.27	1.00								
	<i>p</i>	.605	.758	.290	.201	.939	.040	.								
CGT – Acc	Coefficient	-.03	-.06	.13	.47	.01	.18	.01	1.00							
	<i>p</i>	.796	.676	.328	< .001	.959	.181	.928	.							
CGT – FA	Coefficient	.07	.05	-.05	-.33	.04	.01	-.33	-.62	1.00						
	<i>p</i>	.592	.693	.688	.011	.792	.993	.008	< .001	.						
CGT – Omiss	Coefficient	-.02	-.01	-.05	-.43	-.14	-.28	.20	-.87	.23	1.00					
	<i>p</i>	.903	.963	.724	< .001	.301	.031	.124	< .001	.071	.					
CGT – <i>d'</i>	Coefficient	-.05	-.03	.06	.44	.04	.12	.09	.93	-.77	-.75	1.00				
	<i>p</i>	.730	.806	.639	< .001	.772	.345	.509	< .001	< .001	< .001	.				
CST – Acc	Coefficient	.16	.31	.19	.42	.36	.09	.06	.27	-.19	-.28	.31	1.00			
	<i>p</i>	.234	.019	.161	.001	.005	.512	.663	.038	.153	.028	.015	.			
CST – RT	Coefficient	-.28	-.30	-.35	-.64	-.12	-.07	.30	-.20	.14	.22	-.22	-.42	1.00		
	<i>p</i>	.031	.020	.006	< .001	.363	.586	.021	.125	.278	.095	.093	< .001	.		
CST – Omiss	Coefficient	-.15	-.16	-.39	-.50	-.25	-.12	.04	-.41	.27	.45	-.46	-.77	.56	1.00	
	<i>p</i>	.244	.222	.003	< .001	.057	.365	.746	.001	.038	< .001	< .001	< .001	< .001	.	

Note. VMT = Verbal Memory Test; WMT = Working Memory Test; FAT = Focused Attention Test; VFT = Verbal Fluency Test; NFT = Non-verbal Fluency Test; CST = Computerized Stroop Task; CGT = Computerized Go/No-go Task; RT = response times; Acc = accuracy; FA = false alarms; Omiss = omissions; *d'* = *d*-prime. Statistically significant correlations are highlighted in bold.

Figure 1 depicts the final cluster composition, their segregation, and the distance between final cluster centroids, resulting from the nonhierarchical partitioning clustering model. Figure 2 reports average values for the standardized clustering variables (i.e., the performance indices and metrics, for which RT and error-related ones have been inverted in order to be easily readable in comparison with positive performance metrics such as accuracy and correct responses).

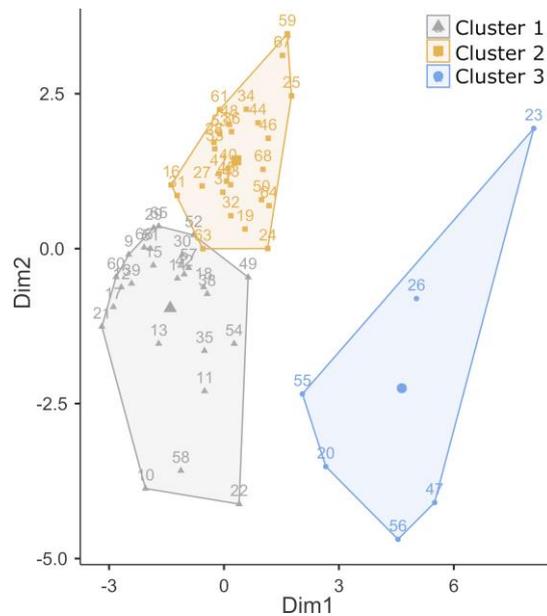


FIGURE 1

Note. Cluster plot depicting the final cluster composition, their segregation, and the distance between final cluster centroids, resulting from the nonhierarchical partitioning clustering model. Larger symbols (triangle, square, or circle) for each cluster identify the cluster centroid.

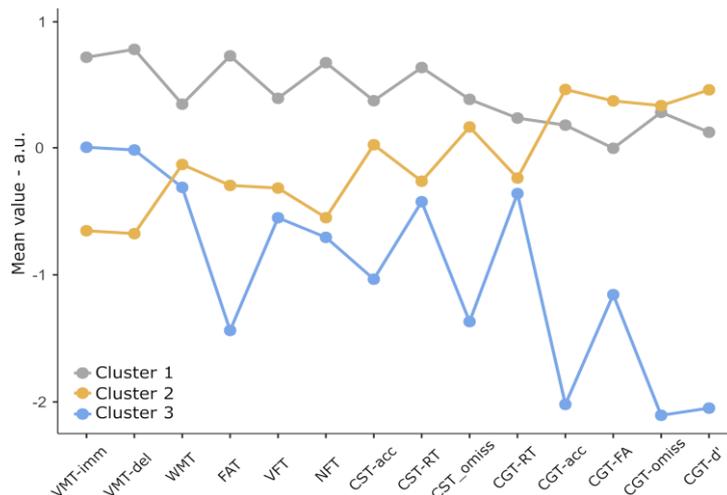


FIGURE 2

Average values for the standardized clustering variables grouped by cluster

Note. VMT = Verbal Memory Test; WMT = Working Memory Test; FAT = Focused Attention Test; VFT = Verbal Fluency Test; NFT = Non-verbal Fluency Test; CST = Computerized Stroop Task; CGT = Computerized Go/No-go Task; Acc = accuracy; RT = response times; Omiss = omissions; FA = false alarms; d' = d' -prime.

DISCUSSION AND CONCLUSIONS

We here present a pilot explorative study investigating feasibility, informativity, and potential of a neurocognitive tool — the Executive Functions Tool-Task (EF/t-t) — devised to assess higher cognition and EFs in the life span, from emerging adulthood to elderly age. The design of the tool was guided by the purpose of creating a brief battery of subtests that could be easily used by professionals to assess executive control and higher cognition even in healthy people. Such potential application was specifically pursued to enrich the standard psychodiagnostics toolbox of professionals, which is so far primarily constituted by tests devised to appraise moderate-severe impairments in clinical settings and, thus, only limitedly suitable to investigate milder deficits in healthy people.

Descriptive and inferential analyses highlighted: (i) the capability of the tool and its subtests to provide consistent outcomes for neurocognitive profiling, as shown by multivariate analysis highlighting three distinctive latent clusters among the examinees; (ii) the seemingly irrelevant contribution of age to the composition of performance clusters and related members' profile; (iii) moderate-to-strong associations between performance indices and metrics of the subtests included in the tool, even after controlling for age and education, suggesting good internal consistency across subtests.

As for the cluster analysis — as noted above — a latent three-cluster structure was observed starting from multivariate analysis of participants' performance data. Specifically, each of the three clusters presented peculiar, distinct, and well-separated patterns for the clustering variables and therefore plausibly identified different subtypes or profiles of examinees, which seem to correspond to different degrees of efficiency with regard to the investigated cognitive domains. In particular, the emerging profiles were labelled: High-Performers (Cluster 1), Mid-Performers (Cluster 2), and Low-Performers (Cluster 3).

Participants in Cluster 1 — the High-Performers — obtained top performances at the computerized Stroop task, especially when looking at chronometric measures of information processing efficiency (response times), as well as at the focused attention test, at immediate and delayed recall for the Verbal Memory Test, and at the Non-verbal Fluency Test. Then they also obtained remarkable performances (greater than or around 0.5 standard deviation above the sample mean) at the Go/No-go Task, Working Memory Test, and Verbal Fluency Test. This profile of strength with no extreme pitfalls suggests that people in Cluster 1 had finely honed mechanisms supporting both the efficacy of EFs and attention regulation, as well as their efficiency, as pointed out by the optimal chronometric indices of performance at the computerized tasks and the high performance at the focused attention test.

Participants in Cluster 2 — the Mid-Performers — represent the largest group of examinees, connoted by mostly average performances across the subtests. No performance index, on average, clearly stand out for its excellence or flaws — with accuracy, control of false alarms and omissions, and *d*-prime index of the computerized Go/No-go Task as the highest metrics (even though around or lower than 0.5 standard deviation above the sample mean), and with performance at the Verbal Memory Test and Non-verbal Fluency Test as the lowest metrics (even though around 0.5 standard deviation below the sample mean). Generally, this average profile and, especially, its relative weak/strong points might suggest that people in Cluster 2 are challenged by memory tasks and do not particularly excel in any specific subtest, but might share a cautious approach to assessment tasks that favor response accuracy over readiness and time efficiency.

Finally, Cluster 3 (the smallest of the three latent groups) — the Low-Performers — gathers participants who showed the globally worse performances at most of the subtests. Besides average performance metrics for the immediate and delayed recall of the VMT, all other performance indices suggest a reduced efficiency of EFs with respect to the sample's average profile. Specifically, people in this cluster showed their worst performances at the focused attention task, in accuracy and control of omissions at the computerized

Stroop task, and in accuracy, d -prime, and control of false alarms and omissions at the computerized Go/No-go Task (all around or lower than 1 standard deviation below the sample mean). Low performance was also observed in Verbal and Non-verbal Fluency Tests. Taken together, such observations might suggest that the most efficient EFs processes concern learning and memory, while efficient control of cognitive resources, response inhibition, and regulation of attention are the weakest skills.

Interestingly, age seems not to be a factor modulating the composition of the clusters. Indeed, age ranged between 21 and 60 years in High-Performers (Cluster 1), between 22 and 59 years in Mid-Performers (Cluster 2), and between 23 and 58 years in Low-Performers (Cluster 3). Such first observations, which we acknowledge would benefit from further deepening and cross-test with a different sample, might be put under test by investigating the role of third so far untested factors such as individual cognitive reserve or inter-individual differences in the use of compensation mechanisms across the lifespan (Cabeza & Dennis, 2013).

As for partial correlation analysis, performance indices and metrics developed to provide a synthetic representation of the global functionality of the investigated EFs components show varying levels of inter-correlation. Notably, such variability in the significance and strength of associations between subtest performance indices mirrors, at the same time, the relative independence of the constructs investigated in the different subtests, as well as the functional proximity of some of them more than others. The strength of correlation coefficients is, as expectable, large for the indices concerning immediate and delayed recall performance at the VMT. Again, correlations coefficients between the performance indices relating to the subtests dedicated to focused attention (FAT), working memory (WMT), and verbal and non-verbal fluency (VFT and NFT) resulted generally moderate. Performance metrics derived from the CST and CGT tasks also showed a selective scenario of moderate/strong associations with the other subtests — among which with the FAT, WMT, and NFT — and large associations between different metrics within the subtest (e.g., between accuracy and omissions at the CST). Such a scenario is consistent with the peculiar nature and structure of the two neurocognitive tasks with respect to the digitalized neuropsychological tests and the specificity of the functional correlates they investigate. Indeed, while the computerized version of the Stroop and of the Go/No-go tasks was born to be delivered via computer and designed — since their beginning — to benefit from the advantages of computerized administration (e.g., fixed and controlled timings, precision in capturing chronometric performance indices), the digitalized tests for verbal memory, working memory, focused attention, and cognitive flexibility are computerized evolutions of neuropsychological tests originally not devised to be administered via PC. The digitalization process surely has made even such latter subtests more informative — providing, as an example, automated capturing and scoring of specific behaviors — yet they remain adaptations of selected paper-and-pencil tests, chosen for their functional correlates and robustness.

Notably, the observed pattern of correlations between performance indices, together with the evidence for consistent latent clusters emerging from the integrated outcomes of all subtests, also deposes in favor of the actual complementarity of digitalized tests and computerized tasks, notwithstanding their specificities. Indeed, it seems that all selected tests/tasks play a role in qualifying the profile of integrity and efficiency of examinees' EFs and contribute to outlining different individual profiles. At the same time, while the evidence base associated to traditional tests provides robustness and a solid background to the tool, their combination with computerized tasks improves its flexibility and sensitivity even in case of milder alterations of EFs efficiency.

It is finally worth noting that the subtest whose performance index showed the highest number of significant associations with performance metrics at other subtests is the focused attention one (FAT), which showed significant moderate associations to: immediate and delayed recall at the VMT; WMT; verbal and non-verbal fluency (VFT and NFT); accuracy, false alarms, omissions, and d' at the CGT; and accuracy, RTs, and omissions at the CST. While we acknowledge that such empirical observation might be worth

further and focused investigations, a first preliminary interpretative hypothesis might ground on the transversal and basic role of focused attention mechanisms for every other cognitive process and function (Knudsen, 2018; Mashour et al., 2020; Petersen & Posner, 2012), given that selecting relevant information and managing/not considering distracters is crucial for more complex elaboration on task-relevant information and more complex processing steps.

To conclude, while the present pilot study was explorative and aimed at presenting and discussing first evidence concerning a computerized assessment tool for EFs, current findings already allowed to highlight a few interesting features of the tool — which could be worth further focused investigations — and hint at its potential for complementing cognitive assessment even in healthy or presumably preserved adults and elderly people. Nonetheless, we acknowledge that present findings would benefit from replication with ampler samples, especially if connoted by a priori segmentation based on gender and age decades in order to systematically extend observations across the life-span. Also, they would benefit from further testing and integration with additional parallel neuropsychological and psychometric tests to assess convergent/divergent validity and to empirically compare the diagnostic performance of the tool with respect to other existing series of tests or batteries. In addition, predictive validity of the tool and related measures should become object of specific investigation via follow-up studies focused on re-test, where the administration of the tool is complemented by additional ecological and psychometric assessment of higher cognition and EFs to allow for exploring its generalized predictive potential. Again, behavioral data could be complemented with objective neurofunctional markers of cognitive performance (e.g., event-related potentials or task-related modulation of cortical blood perfusion as measures by fMRI or fNIRS) to further test the sensitivity of the subtests and of their performance indices. Furthermore, future developments could focus on complementing the tool with synchronized collection of psychophysiological and/or neurofunctional data, so to explore anatomical-functional associations of specific components of EFs, even based on relevant literature on functional cortical localizations.

NOTE

1. In cluster analysis, a centroid is the center point of a cluster, representing the mean position of all the datapoints within that cluster. It serves as a reference point for assigning new data points to the cluster during iterative algorithms like K-means clustering.

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