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The Elusive Nature of Executive Functions: A Review of our Current Understanding

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Abstract Executive functions include abilities of goal formation, planning, carrying out goal-directed plans, and effective performance. This article aims at reviewing some of the current knowledge surrounding executive functioning and presenting the contrasting views regarding this concept. The neural substrates of the executive system are examined as well as the evolution of executive functioning, from development to decline. There is clear evidence of the vulnerability of executive functions to the effects of age over lifespan. The first executive function to emerge in children is the ability to inhibit overlearned behavior and the last to appear is verbal fluency. Inhibition of irrelevant information seems to decline earlier than set shifting and verbal fluency during senescence. The sequential progression and decline of these functions has been paralleled with the anatomical changes of the frontal lobe and its connections with other brain areas. Generalization of the results presented here are limited due to methodological differences across studies. Analysis of these differences is presented and suggestions for future research are offered.

Keywords Executive Functions · Frontal lobe · Elderly · Children · Development

Despite the frequency with which it is mentioned in the neuropsychological literature, the concept of executive function is one that still awaits a formal definition. Research efforts aimed at exploring the different aspects of this construct have often yielded contradictory findings, resulting in a lack of clarity and even controversy regarding the true nature of executive abilities. The main purpose of this article is to review some of the current knowledge surrounding executive functions and to present the contrasting views generated by this concept. An overview of the myriad definitions and subcomponents believed to make up executive functions is included along with a discussion of the methodological problems associated with the measurement of this construct. The proposed neural substrates of the executive system are examined as well as the evolution of executive functioning over the life-span, from development to decline. Our review on the effects of age on executive function focuses on four distinct and often studied executive abilities, mainly attentional control, planning, set-shifting (Anderson et al. 2001a), and verbal fluency (Fisk and Sharp 2004).

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Overview of the Concept Executive Function

In essence a new concept, executive function was first described as a “central executive” by Baddeley and Hitch (1974) and later defined by Lezak (1983) as the dimension of human behavior that deals with “how” behavior is expressed. Executive functions were conceptualized as having four components: The abilities of goal formation, planning, carrying out goal-directed plans, and effective performance. Lezak added that these behaviors are all necessary for appropriate, socially responsible and effectively self-serving adult conduct. As long as executive functions are intact, a person who has sustained considerable cognitive loss can still continue to be independent and productive (Lezak et al. 2004). Executive abilities are also generally described as high-level cognitive functions believed to be mediated primarily by frontal lobes (Stuss et al. 2002). Luria (1973) identified the frontal lobes as "the essential apparatus for organizing intellectual activity as a whole, including the programming of the intellectual act and the checking of its performance" (p. 340). He conceptualized what currently is referred as executive functions. In fact, the neuropsychological study of executive functions owes much of its origins to the early reports of patients with prefrontal damage (Stuss and Benson 1986).

Definitions abound for the concept of executive functions, as well as for its possible subcomponents and the variables that measure them (see Table 1). Despite the lack of clarity, there exists a relative agreement in terms of the complexity and importance of executive functioning to human adaptive behavior. In a constantly changing environment, executive abilities allow us to shift our mind set quickly and adapt to diverse situations while at the same time inhibiting inappropriate behaviors. They enable us to create a plan, initiate its execution, and persevere on the task at hand until its completion. Executive functions mediate the ability to organize our thoughts in a goal-directed way and are therefore essential for success in school and work situations, as well as everyday living. The concept of morality and ethic behavior also represents an executive function (Ardila and Surloff 2004).

Among the many questions that remain unanswered based on our current understanding of executive functions is the fundamental question of whether there is one single underlying ability that can explain all the components of executive functioning (also known as the theory of unity), or whether these components constitute related, but distinct, processes (non-unity). There seems to be evidence for both a unitary and a non-unitary nature of executive function. Duncan et al. (1996), for instance, suggest that goal neglect is a common mechanism characterizing the nature of deficits present in frontal lobe patients, and that this neglect is highly linked to Spearman's g. These and other authors believe in the existence of a unifying, central factor (i.e., general intelligence or working memory) underlying executive functioning and the organization of goal-directed behavior (Duncan et al. 1996; Parkin and Java, 1999; Kimberg et al. 1997; De Frias et al. 2006).

Godefroy et al. (1999) question the existence of a core factor related to all measure of executive functions by observing that certain patients with frontal lobe injury perform well on some tests purported to assess executive abilities but not on others. Research by these authors provided further evidence for the notion that executive functions depend on multiple, separable control processes and are modular in nature. This hypothesis is supported by a highly consistent pattern across studies showing that the intercorrelation among different executive tasks is low (r= 0.40 or less) and many times lacking statistical significance (Lehto 1996; Miyake et al. 2000; Salthouse et al. 2003). Low correlations can be due to the influence of non-executive processes or to variables that reflect different types of executive abilities instead of a unitary construct (Salthouse et al. 2003).

Miyake et al. (2000) studied three often-postulated aspects of executive functions (shifting, updating, and inhibition) and concluded that, although they are clearly distinguishable, they do share some underlying commonality. Based on the results of their study, the authors stated that executive functions are "separable but moderately correlated constructs," (p. 87) thus suggesting both unitary and non-unitary components of the executive system. The source of commonality among the three executive abilities analyzed in this study still awaits identification but possibilities include a basic inhibitory mechanism and

Table 1 Concepts and components of executive function

Author	Concepts and/or components of executive functions
Lezak (1983)	Volition, planning, purposive action, effective performance
Baddeley and Hitch (1974)	Central executive, phonological loop, visualspatial sketchpad
Norman and Shallice (1986)	Supervisory attentional system
Lafleche and Albert (1995)	Concurrent manipulation of information: cognitive flexibility, concept formation, cue-directed behavior
Borkowsky and Burke (1996)	Task analysis, strategy control, strategy monitoring
Anderson et al. (2001b)	Attentional control, cognitive flexibility, goal setting
Delis et al. (2001)	Flexibility of thinking, inhibition, problem-solving, planning, impulse control, concept formation, abstract thinking, creativity
Hobson and Leeds (2001)	Planning, initiation, preservation and alteration of goal-directed behavior
Piguet et al. (2002)	Concept formation, reasoning, cognitive flexibility
Elliot (2003)	Solving novel problems, modifying behavior in light of new information, generating strategies, sequencing complex actions
Banich (2004)	Purposeful and coordinated organization of behavior. Reflection and analysis of the success of the strategies employed

maintenance of goal and context information in working memory. Other attempts at defining executive functioning from a unitary perspective include the notion of behavioral inhibition constituting the basis for accurate performance in all areas of executive functioning (Barkley 1997) and a combination of inhibition and working memory (Pennington et al. 1996) as the underlying mechanism. The fractioned-but-united nature of executive functions of Miyake et al. (2000) was further examined by Fisk and Sharp (2004) in a study that obtained a fourth factor believed to be a component of the executive system. Using factor analysis, word fluency performance was added as an additional executive process which measures the efficiency of lexical access.

It has been hypothesized that it is the cognitive abilities of reasoning and perceptual speed which represent the underlying factors related to all executive functions (Salthouse 1996, 2005) and a close relationship has been established between executive functions and intelligence (Duncan et al. 1995, 1996). Salthouse (2005) observed that performance on two common tests of executive functioning, the Wisconsin Card Sorting Test (WCST) and tests of letter and category verbal fluency were strongly correlated to reasoning ability and perceptual speed. The little common variance shared by these tests was also significantly related to performance on the Ravens Progressive Matrices, suggesting that there is no true executive construct but instead it shares domains with fluid intelligence (Salthouse et al. 2003, 2006; Salthouse 2005). Furthermore, analyses of performance on other traditional measures of executive functioning and on measures of intelligence have concluded that both groups of tests essentially measure general intellectual abilities (Obonsawin et al. 2002). This idea, however, has been challenged by researchers who propose that there exists a distinction between psychometric g and executive functions (Ardila et al. 2000b; Crinella and Yu 2000; Friedman et al. 2006) and that although the function of updating seems to be moderately related to intelligence, other executive functions such as inhibiting and shifting are not (Miyake et al. 2000). Ardila et al. (2000b) found few significant correlations between IQ sores and executive function measures and concluded that psychometric intelligence tests are not appraising abilities that help to organize and direct behavior and cognition. The wide variety of definitions and components believed to make up the executive system reveal that, despite its usefulness for understanding several aspects of human behavior, there is yet no clear agreement about what executive functions are.

Brain Organization of Executive Functions

The study of the neural correlates of executive functioning stems from earlier observations of patients with frontal lesions. Soldiers wounded in war exhibited altered behavior as well as an impaired ability to engage in appropriate actions toward the completion of a goal (Stuss and Benson 1986). Other patients with frontal lesions demonstrated difficulties in self-control and in attentional shifting (Golberg 2001; Lezak et al. 2004). The group of behavioral and cognitive anomalies found in frontal patients became known as the "dysexecutive syndrome" (Baddeley and Wilson 1988) which includes problems in planning, organization, abstraction reasoning, problem-solving, and decision-making (Ardila and Surloff 2004; Norris and Tate 2000; Hobson and Leeds 2001).

Neuroimaging methods have also demonstrated the involvement of the frontal lobe while engaging in executive tasks (see Table 2). Although early observations suggested a homogenous involvement of the frontal lobes, and specifically the prefrontal cortex, executive functions are now accepted to be associated with different regions of the frontal lobes (Stuss and Alexander 2000; Stuss et al. 2002; Koechlin et al. 2000) as well as distributed over a wide cerebral network which includes subcortical structures and thalamic pathways (Lewis et al. 2004; Monchi et al. 2006; Kassubek et al. 2005).

Both the frontal and posterior associative cortices (Collette and van der Linden 2002) have been suggested to mediate functions of the executive system. Wager and Smith (2003) demonstrated in a recent meta-analysis that different executive processes are associated with specific cerebral areas. For example, manipulation of information necessary to perform a dual task most frequently activates the right inferior prefrontal cortex, while the superior frontal cortex is activated the most when information must be continuously updated and when memory for temporal order needs to be maintained. Stuss et al. (2002) suggested an anatomically and functionally cognitive architecture of the frontal lobes based on a decade of neuropsychological research of patients with focal frontal lesions. The right dorsolateral (DL) frontal area was found to be involved in monitoring behavior while the left dorsolateral area is involved in verbal processing. Both the right and left DL frontal areas as well as the superior medial frontal lobe seem to be engaged in tasks that necessitate cognitive switching, while the inferior medial frontal area seems to mediate certain aspects of inhibitory processes of behavior. Approaches that focus on the localization of executive abilities within the frontal lobe have often been criticized in favor of a perspective that emphasizes connectivity between the frontal regions and more posterior and subcortical brain areas. (Parkin 1998; Elliot 2003, Collette and van der Linden 2002).

In a recent review, Royall et al. (2002) stressed the importance of neural circuits comprising the frontal lobes, the basal ganglia and the thalamus for performance on executive tests. The authors identified three important

Table 2 Brain correlates of executive functions using techniques of neuroimage

Executive Function	Areas of increased activation	Test	Technique
Planning			
Morris et al. (1993)	Left PFC	TOL	SPECT
Owen et al. (1996)	Middle DLPFC and head of caudate nucleus	TOL	PET
Dagher et al. (1999)	DLPFC and lateral premotor cortex	TOL	PET
Lazeron et al. (2000)	DLPFC, ACC, cuneus and precuneus, SMG and angular	TOL	fMRI
Goethals et al. (2004)	Right PFC	TOL	SPECT
Wagner et al. (2006)	Rostrolateral PFC	TOL	fMRI
Attentional control			
Siegel et al. (1995)	Medial superior frontal gyrus, lateral inferior temporal gyrus	CPT	PET
Collette et al. (2001)	Left PFC, middle and inferior FL	HT	PET
Nagahama et al. (2001)	Antero-dorsal PFC	WCST	fMRI
–	–		
Gerton et al. (2004)	Right DLPFC and bilateral inferior PL	DS	PET
Fassbender et al. (2004)	Right ventral PFC, right IPL, left putamen, left DLPFC	SART	fMRI
Kaufmann et al. (2005)	DLPFC and AC	Stroop	fMRI
Lie et al. (2006)	Caudal ACC and DLPFC	WCST	fMRI
Cognitive flexibility			
Berman et al. (1995)	DLPFC and temporal and parietal cortices	WCST	PET
Catafau et al. (1998)	Left posterior frontal area and inferior cingulated cortex	WCST	SPECT
Lombardi et al. (1999)	Right dorsolateral frontal–subcortical circuit	WCST	PET
Nagahama et al. (2001)	Postero-ventral PFC	WCST	fMRI
Perianez et al. (2004)	Inferior frontal gyrus, ACC and SMG	WCST	MEG
Hirshorn and Thompson-Schill (2006)	Left inferior frontal gyrus (switching between categories)	VF	fMRI
Verbal/nonverbal fluency			
Frith et al. (1991)	Left DLPFC	VF	PET
Paulesu et al. (1997)	Left inferior frontal gyrus and left thalamus	VF	fMRI
Phelps et al. (1997)	Left inferior frontal gyrus, ACC, superior frontal sulcus	VF	fMRI
Jahanshahi et al. (2000)	Left DLPFC, ACC, superior parietal cortex	RNG	PET
Pihlajamaki et al. (2000)	Left medial TL, RSC, left superior PL	VF	fMRI
Audenaert et al. (2000)	LIPFC (category and letter), RIPFC (category)	COWAT	SPECT

ACC=Anterior cingulate cortex; *COWAT*=Controlled Oral Word Association Test; *CPT*=continuous performance test; *DLPFC*=dorsolateral prefrontal cortex; *DS*=digit span; *FL*=frontal lobe; *fMRI*=functional magnetic resonance imaging; *HT*=Haylings test; *LIPFC*=left inferior prefrontal cortex; *MEG*=magnetoencephalography; *PET*=positron emission tomography; *PFC*=prefrontal cortex; *PL*=parietal lobe; *RIPFC*=right inferior prefrontal cortex; *RNG*=random number generation; *RSC*=retrosplenial cortex; *SART*=sustained attention to response task; *SMG*=supramarginal gyrus; *SPECT*=single-photon emission computed tomography; *TL*=temporal lobe; *TOL*=Tower of London; *VF*=verbal fluency.

circuits which originate in the frontal lobe and send projections to basal ganglia and thalamus: the DL prefrontal circuit is believed to be implicated in the functions of planning, goal selection, set-shifting, working memory and self-monitoring; the lateral orbitofrontal circuit is involved in risk assessment and the inhibition of inappropriate behavioral responses; the anterior cingulate circuit functions in monitoring behavior and self-correcting errors.

The unity versus non-unity debate of executive functioning has also permeated to the study of its neural substrates. Both unity and diversity seem to be characteristic of the executive system based on recent neuroimaging data. Collette et al. (2005) using positron emission tomography (PET) found that common areas of the brain are activated by three different executive functions (updating, shifting, and inhibition). These regions included the posterior regions of the left superior parietal gyrus and the right intraparietal sulcus. At a lesser degree, the left middle and inferior frontal gyri were also activated. At the same time, each distinct process activated specific brain regions. Updating processes were associated with bilateral activation of both anterior and posterior areas, while shifting processes activated the parietal lobe and the left middle and inferior frontal gyri. Inhibitory processes were associated with activation of the right orbitofrontal gyrus, but the specificity of this activation was lower than that of shifting and updating. This study by Collette et al. (2005) suggests that parietal areas seem to play a critical role during the performance of executive tasks, and that the executive system is not subserved by the frontal lobe alone, as previously thought. In fact, the parietal areas proved to show more activation than frontal ones. The authors hypothesized that the reason for this lies in the prefrontal areas mediating processes more strategic in nature that are not used the same way by different individuals. In contrast, parietal areas are involved in more basic attentional processes needed for executive performance.

Although the important role of the frontal lobe is not undermined, these results demonstrate that the integrity of the whole brain is necessary for optimal performance on executive tasks (Stuss and Alexander 2000). The pattern of connectivity of the frontal lobes suggests that, although the prefrontal regions might orchestrate behavior, they depend on other areas for input and efficient functioning relies on the quality of information received form other parts of the brain (Anderson et al. 2001b). The current perspective is, therefore, that the frontal lobes represent a multi-faced area of the brain with executive processes likely to involve links between frontal and posterior areas (Stuss et al. 2002) as well as subcortical and thalamic pathways (Baddeley 1998; Royall et al. 2002).

Models and Theories of Executive Function and Brain Organization

Various influential models and theories of executive function have been proposed in an effort to integrate the control processes of the frontal lobe into a coherent framework. Baddeley and Hitch (1974) proposed a model of working memory that included a phonological loop, a visualspatial sketchpad and a central executive responsible for the control and regulation of cognitive processes (Baddeley 2002), such as planning and organization of information (Hobson and Leeds 2001). The phonological system includes a phonological store that is able to hold information for about two seconds and an articulatory loop which maintains the information through rehearsal (Baddeley 1986, 1992). The central executive, on the other hand, is a system of attentional control able to focus and switch attention, but without a storage capacity (Baddeley and Logie 1999). Working memory processes have been known to be mediated by the prefrontal cortex (Eldreth et al. 2006) with the DL prefrontal areas being engaged the most during mental manipulation of information (D'Esposito et al. 1999). Lesions studies have also demonstrated that activation of the superior prefrontal gyrus is triggered by high levels of executive processing (i.e., complex working memory tasks; du Boiseguehenheuc et al. 2006).

The idea of a "central" executive is sometimes understood as proposing a homuncular nature of executive functioning (Zelazo and Muller 2002), but according to Baddeley (1998) this component of working memory does not reject the possibility of a fractionality of the executive with subprocesses that could be (and have been) mapped anatomically (Baddeley 2002). Another criticism is that the model does not allow functional relations among aspects of executive functions, such as planning and self-perception (Zelazo and Muller 2002). Despite its limitations, the working memory model proposed by Baddeley has become one of the most prominent frameworks for the study of executive functions from a cognitive perspective (Miyake et al. 2000).

Another important model in the literature is that of Norman and Shallice (1986), which describes the control of information processing. Their model includes a Supervisory Attentional System (SAS) necessary for situations in which planning for future actions, making decisions and working with novel stimuli are required. A central aspect of this model is the distinction between automatic (routine) and controlled (non-routine) processes. The automatic activation of certain behaviors, such as reading, would not be sufficient for optimal performance in situations that involve planning and decision-making, correction of errors, novel sequencing of actions, or overcoming technical difficulty or strong habitual responses (Shallice and Burgess 1991). The execution of these controlled processes necessitates a supervisory system that is thought to be located in the prefrontal cortex (Shallice 2002). This distinction between controlled and automatic processes, however, is deemed by some authors as insufficient for explaining executive functioning. Stuss and Alexander (2000), for instance, agree with the notion of a SAS made up of distinct parts but question the adequacy of a two-level model (controlled versus automatic) in favor of an idea of multiple levels of control.

Specifically, Stuss (1992) proposed the progressive development in humans of three levels of monitoring mediated by the frontal lobes. The first level includes routine daily activities that are executed repetitively and are automatic and overlearned. These activities are suggested to reflect the actions of the subcortical systems (Slattery et al. 2001). The second level of processing includes executive and supervisory functions which synthesize information to organize goal-directed behavior. The third and highest level of processing is awareness of oneself and the environment. The development of connections between the frontal lobe and the limbic and posterior cortical regions is suggested to mediate the executive and supervisory functions, while self-awareness is believed to reflect the development of the prefrontal region (Slattery et al. 2001).

In order to execute a goal-directed action, the prefrontal cortex must "integrate temporally separate units of perception, action, and cognition into a sequence toward a goal" (Fuster 2002; p. 99). To achieve this, the prefrontal cortex must function in cooperation with subcortical structures and other areas of the neocortex (Fuster 2002). Four cognitive structures, partially controlled by the prefrontal cortex, are essential for temporal integration: attention, working memory, preparatory task set, and response monitoring. These perceptual and cognitive units are linked across time through retrospective and prospective functions which enable the maintenance of information pertaining to a goal and the preparation to act in anticipation of events (Barkley 1997). Similarly, it has been proposed that the frontal lobe is the only cortical region capable of integrating "motivational, mnemonic, emotional, somatosensory, and external sensory information into unified, goal-directed action" (Royall et al. 2002; p. 379).

Zelazo et al. (1997) have taken an alternative approach to the study of executive function, influenced by Luria's idea of "interactive functional systems" (Luria 1973). They conceptualize it as a complex function, or macrostructure, with executive subfunctions that work together to accomplish the higher-order function of solving problems. Four temporally and functionally distinct phases of problem-solving are identified which correspond to different aspects of executive processing: problem representation, planning, execution, and evaluation. The major advantage of this framework is that not only does the outcome of executive functions become evident (i.e., solving the problem or not) but it also allows locating failures of executive functioning in a temporal sequence of problem solving (Zelazo et al. 1997). Complex functions such as those of the executive, according to Zelazo and Muller (2002), cannot be represented exclusively in the prefrontal areas, but require the integrity of other brain areas as well.

In summary, some hierarchical cognitive models (i.e., Baddeley's working memory model and Normal and Shallice's SAS model) support the existence of a central executive that deals with more complex levels of functioning and that reflect prefrontal activity, an idea that is supported by brain damage literature that describes patients with frontal-lobe injury with disorganized and impulsive behavior. Other models such as Fuster's perception-action cycle suggest that the role of the prefrontal cortex is to expand the temporal perspective of the system rather than be an executive interpreter. Moreover, others like Zelazo et al. (1997) reject the approach of the uniqueness of the frontal lobe in the control of executive functions.

Measuring Executive Functions

The ongoing controversy regarding the formal definition of executive functions and the existence of a central executive construct makes the accurate assessment of these functions seem to be an impossible task. Until new methods are developed, however, the study of executive functions must rely on tests that have been historically purported as measuring the functions of the frontal lobe (see Tables 3 and 4 for a description of common executive function tests and batteries). So far, the prevailing approach to the study of executive functions has been described as task-based and this method has been useful in identifying capacities, processes and abilities that are impaired in frontal patients. It has also been viewed as the problem with testing executive functions. The validation on these tests is based solely on the criterion of them being sensitive to frontal lobe damage, while the precise nature of the executive function necessary for the accurate performance on these tasks is unspecified (Miyake et al. 2000).

Hughes and Graham (2002) suggest that one of the obstacles in obtaining reliable measures of executive functioning lies in the difficulty of distinguishing between automatic and controlled actions. These two types of actions, they believe, are at the opposite ends of a continuum. When a person performs a novel task, the processes underlying this performance shift gradually from being controlled to being automatic. A small change in the demands of the task, however, leads to a collapse of the automatic process and the performance becomes, once again, controlled. Another problem that stems from this is the matter of the novelty of stimuli. Measures of executive functions will never be able to reach reliability, according to some authors (Burgess 1997; Denckla 1996) because they are designed to assess the ability to cope with new problems, and the problems cease to be novel after the first administration of the test (Salthouse et al. 2003).

Another measurement problem is that of "task impurity" (Burgess 1997). The execution of the task believed to measure executive functions might, in reality, be triggering non-executive processes unrelated to the task (Hughes and Graham 2002). Tasks that tap on executive processes (for example real-life shopping tasks) are generally very complex and must stress practically all cognitive systems in addition to the executive (Burgess 1997). In order to establish that the deficit presented by a patient is strictly one of the executive system one must be able to identify practically all other non-executive contributions to the task. Yet another problem suggested by Burgess (1997) is that of a low process-behavior correspondence: similar observed behaviors can have quite different causes. Many psychological processes manifest themselves only in one type of situation: our face recognition system, for example, is activated when a subject is shown photos of famous people, but it is not activated when the subject is shown a list of words. Processes of the executive system, on the other hand, become evident in a wide range of situations. Executive functions show, therefore, a low correspondence between process and behavior. An impairment of the executive system can result in a variety of behaviors while, at the same time, a specific behavior can be generated by a variety of impaired processes. Lezak (1983) also identified an obstacle in the utilization of executive function tasks in

Table 3 Tests of executive functions

Test	Reference	Description	Executive function
BSAT	Burgess and Shallice (1997)	The position of a colored circle changes from one page to the next governed by rules unknown to patient who must predict next position	Rule detection
COWAT	Benton and Hamsher (1989)	Patients must produce words beginning with the letter F-A-S	Response generation Inhibition
HSCT	Burgess and Shallice (1997)	In first part, patient responds to incomplete sentences with a word that makes sense. In second part, patient must complete sentence with a word unrelated to the context of sentence	Speed of initiation Response suppression
Stroop	Stroop (1935) Golden (1978)	Word: patient reads a page of color words in black ink. Color: names the ink color of a page of X's. C/W: names the ink words are written on ignoring color word	Inhibition
TMT	Army Individual Test Battery (1944) Reitan (1955)	Subject must connect 25 encircled numbers as fast as possible. In the second part, subject must alternate in connecting encircled numbers and letters	Set shifting Inhibition
TOL	Shallice (1982)	Subjects must move different colored beads across three pegs from an initial configuration to a target position in as few moves as possible	Planning Inhibition
TOH	Simon (1975)	The goal and general procedures are the same as for the TOL but it is more complex in that instead of same size pieces the objects to be re-arranged are five rings of different sizes	Planning Inhibition
WCST	Berg (1948)	Four stimulus cards of different number, color and shape are placed in front of subject. Subject is then given different cards to sort according to an unknown rule that changes without warning	Set shifting Set maintenance Inhibition Rule detection Concept formation
MCST	Nelson (1976)	It is a variant of the WCST that uses only the cards that share a maximum of one attribute with a stimulus card and the participant is told when the sorting rule is changed	Set shifting Set maintenance Inhibition Rule detection Concept formation

There are different versions of these tests and a variety of norm studies (For reviews see Mitrushina et al. 2005; Lezak et al. 2004; Strauss et al. 2006). *BSAT*=Brixton Spatial Awareness Test; *COWAT*=Controlled Oral Word Association Test; *HSCT*=Hayling Sentence Completion Test; *MCST*=Modified card sorting test; *TMT*=Trail Making Test; *TOH*=Tower of Hanoi; *TOL*=Tower of London; *WCST*=Wisconsin Card Sorting Test.

that goal setting, structuring and decision making are behaviors which need to be assessed, yet their assessment is highly structured within the examination. The examiner is the one usually determining when and how the task must be executed without leaving the patients sufficient leeway to analyze and choose alternatives for the completion of the task. It is relatively easy for the test administrator to become a substitute for the frontal lobes of the patient (Stuss and Alexander 2000). Achieving a true "gold standard" for tests of the frontal areas might prove to be an impossible goal since the frontal lobe and its many subcortical connections perform a variety of activities; a problem of the specificity of such tests will appear as both posterior and subcortical lesions can produce frontal test impairments due to extensive connections (Royall et al. 2002).

Tests purported to measure executive functioning, as the ones previously described, are believed by some to represent evidence for a modular nature of executive functions and clinical observations have demonstrated dissociations in performance among executive tasks (Miyake et al. 2000). Some patients may fail on the WCST but not on the Tower of Hanoi (TOH), while the opposite is true for other patients. This dissociation, taken together with the low correlation existent among executive function tasks (r=0.40, or less), makes some clinicians and researchers doubtful of the tests' true ability to measure and quantify the operations of the central executive. It is difficult, however, to determine the construct validity of a group of tests, when the construct itself is ill-defined. By the same token the same test may measure two different components of executive functioning. For example, the

Table 4 Test batteries of executive assessment

Battery/tool	References	Tests included	Executive functions
BADS	Burgess et al. (1998)	Action Program Test, Dysexecutive Questionnaire, Key Search, Modified Six Elements Test, Rule Shift Card Test, Temporal Judgment, Zoo Map Test	Set shifting, planning and goal-directed behavior, estimation abilities, response inhibition
BRIEF	Gioia et al. (2000)	63-Item clinical scale measuring three indexes: Inhibitory self control, flexibility, and metacognition	Inhibition, set shifting, emotional control, planning, organization of goal-directed activity
CANTAB	Huppert et al. (1995)	Big Little Circle, Delayed/Non-delayed Matching to Sample, Motor Screening, Pattern Recognition, Spatial Recognition, Paired Associates Learning, Spatial Span, Spatial Working Memory, Intra/Extra Dimensional Shift, Rapid Visual Information Processing, Reaction Time, Stockings of Cambridge	Set shifting, set maintenance, strategic planning, concept formation, organization of goal-directed activity
D-KEFS	Delis et al. (2001)	Color–Word Interference, Design Fluency Test, Sorting Test, Trail Making Test, Twenty Questions Test, Tower Test, Proverb Test, Verbal Fluency Test, Word Context Test	Response inhibition, verbal and design fluency, concept formation, set shifting, rule deduction, planning, response to feedback, abstract thought
FrSBe	Grace and Malloy (2002)	46-Item rating scale includes three subscales measuring apathy, disinhibition and executive dysfunction	Inhibition, emotional control, organization of goal-directed activity

BADS = Behavioral Assessment of the Dysexecutive Syndrome; *BRIEF* = Behavior Rating Inventory of Executive Function; *CANTAB* = Cambridge Neuropsychological Test Automated Battery; *D-KEFS* = Delis–Kaplan Executive Function System; *FrSBe* = Frontal Systems Behavior Scale.

WCST may assess attention control as well as cognitive flexibility.

Two additional limitations with executive assessment have been identified. First, most of these tests use summary or endpoint scores that do not facilitate the isolation and quantification of specific features of executive functions such as planning, reasoning, and problem solving. Anderson et al. (2002) proposed the implementation of a scoring method that, in addition to summary scores, provides more process-oriented information such as speed, accuracy and strategies. Anderson's group has used this approach successfully with groups of children with frontal-lobe damage (Anderson et al. 1998). The other limitation refers to the poor ecological validity of executive function tests. It is unclear how well performance on these tests reflects problems that the patient might present in real life. Wood and Liossi (2006), for example, found limited ecological validity for four subtests of the Behavioral Assessment of Dysexecutive Syndrome (BADS) battery when used to assess patients following severe head trauma. Odhuba et al. (2005) found moderate correlations between the Hayling and Brixton test scores and the assessment of disability among brain injured patients. To improve the ecological validity of executive tests Chaytor et al. (2006) suggest the addition of functioning and adaptive scales to the traditional tests of executive function in the assessment of brain damaged patients. By the same token, Isquith et al. (2004) describe the benefits of ecological validity of measuring behavior using a behavior rating inventory of executive function for pre-school children with learning disabilities and among children with traumatic brain injury (Gioia and Isquith 2004). Grafman (1999) analyzes the relevance of taking real life scenarios to assess executive functions (i.e., planning) under experimental conditions.

Development of Executive Functions

Denckla (1996) believes that a great deal of the difference between the child and the adult resides in the unfolding of executive functions. The executive system is even responsible for the great differences perceived between the stages of development of the child. Infants, for instance, are mainly stimulus-bound, and react to the present and to events in their immediate surroundings. On the other hand, just a few years older, preschoolers have the capacity of thinking about the past and planning for the future, as well as representing multiple aspects of a problem and choosing the best alternative of action (Zelazo et al. 2004).

Executive functions seem to improve sequentially through childhood, and this improvement seems to coincide with growth spurts in the maturation of the frontal lobes (Anderson et al. 2001a). Such growth periods have been identified between birth and 2 years of age, from 7 to 9 years, and a final spurt in late adolescence, between 16 and 19 years of age (in Anderson et al. 2001b). The frontal lobe, therefore, seems to be relatively immature during childhood and development is believed to continue into early adolescence (Fuster 1993), especially processes such as arborisation, myelination and synaptogenesis. The frontal lobes were originally believed to be "functionally silent" during childhood, but this notion has been abandoned as neuroimaging studies find frontal activation in infants as young as 6 months of age (Chugani et al. 1987).

Hughes and Graham (2002) have identified several difficulties in the accurate assessment of executive functions in children, the most important of which is the child's limited language ability. When task instructions are complex, verbal comprehension in the child is taxed possibly engaging non-executive skills. Many adult executive function tests rely on language abilities (i.e., the Stroop test) and this has prompted the creation of simpler, less verbal versions of common executive tests. A simplified version of the Stroop test, for instance, is the Day/Night task where children are instructed to say "night" to a picture of the sun, and "day" to a picture of the moon (Diamond 2002; Gerstadt et al. 1994).

Development of executive abilities has been shown to occur rapidly through childhood in spurts that have been aligned with the maturation of the frontal lobe (Anderson 2002). Executive development does not appear to occur in a homogenous fashion and different executive abilities have been shown to have different developmental trajectories, with certain executive components not reaching adult competency until late in adolescence (Passler et al. 1985).

Attentional Control

Attentional control is a component of executive function that includes selective attention, sustained attention and response inhibition (Anderson et al. 2002). It has been assessed in infants using the Piagetan A-not-B task or delayed response task (Diamond 2002; Piaget 1954; Zelazo and Frye 1998). Diamond and Goldman-Rakic (1985, 1989) found that infants of 9 months of age are not able to succeed in this task, but that this difficulty is overcome by the age of 12 months. Diamond (2002) explains the A-not-B error as a tendency to reach for A that cannot be inhibited easily by younger infants. They will continually reach for A even when the object is visible in well B (Harris 1974). By the age of 12 months, infants are able to inhibit overlearned responses of reaching for A and switch to a new response set. Other studies found that the greatest period of development of executive abilities, especially inhibition, occurred between 6 and 8 years of age (Passler et al. 1985). Passler et al. (1985) further suggested that by age 10 the child's ability to inhibit attention to irrelevant stimuli, as well as to avoid perseverative errors, was complete with mastery of these skills evident at 12. Marked improvements in inhibition tasks such as the Stop/Signal and Go/No Go tasks have been found between a young group (6–8 years) and an older group (9–12 years) with no additional advancements during adolescence (Levin et al. 1991; Williams et al. 1999). Similar results were found by Brocki and Bohlin (2004) who reported the greatest developmental advances in the inhibition components of executive functioning using the Continuous Performance Test (CPT) occurring between the ages of 8 and 12.

Welsh et al. (1991) argue for a differential development of executive abilities and suggest that the ability to resist distraction is the first executive skill to be acquired around the age of 6, reaching adult levels of impulse control around 10 years of age. A curious increase in impulsivity has been found by some authors to occur around the age of 11, although, in general, children at this age are able to regulate and monitor their actions well (Anderson et al. 1996).

Studies investigating the progression of executive functions through adolescence have demonstrated an increased attentional capacity and speed of processing during this period (Anderson et al. 2001a). A study by Anderson et al. (2001a) proposed the possibility of a growth spurt in these domains around the age of 15. Gender effects were also present with boys showing better performance than girls in tasks life Digit Span during childhood, with this pattern reversing during early adolescence. This crossover was found to occur around the age of 11, and further studies into the gender differences of executive development are required.

Planning

Planning refers to the ability to identify and organize the steps and elements needed to achieve a goal (Lezak et al. 2004). Planning is a multifaceted activity that requires complex cognitive demands (Grafman 1999). Hudson et al (1995) found that children as young as three are able to construct different types of verbal plans, such as planning for familiar events. This simple type of planning is different to that found in children of 7 to 11 years who show strategic behavior and reasoning abilities leading to more organized and efficient planning (Levin et al. 1991). A recent meta-analysis also demonstrated that planning showed its greatest period of development between the ages of 5 and 8, and that improvements in performance continued well into the early adulthood period (Romine and Reynolds 2005). Welsh et al. (1991), on the other hand, believe planning behavior to be among the last abilities developed by children, with maturation occurring around the age of 12. Similar results were found by Anderson et al. (1996) who studied children's performance on the Tower of London (TOL) task and found that younger children made more errors and achieved fewer correct responses than older ones. These authors found that planning skills reach adult levels between the ages of 9 and 13, with performance on the TOL test rather stable during adolescence (a regression to simpler strategies between the ages of 12 and 13 was reported by Anderson et al. 2001a).

Set Shifting

Set shifting or cognitive flexibility refers to the ability to switch rapidly between different response sets (Anderson 2002). It has been estimated that this ability emerges in children between the ages of 3 and 5 when using simple switching tasks (Espy 1997). As the task rules increase in complexity, however, the child will show more errors in flexibility. Zelazo and Frye (1998) pointed out the development of rule-use in early childhood, considering this an important aspect of executive functioning. These authors developed the theory of Cognitive Complexity and Control (CCC), according to which age-related changes in the acquisition of executive skills during childhood can be attributed to changes in the maximum hierarchical complexity of the rules that the child can formulate and apply when solving a problem. According to this theory, 3-year-old children can hold one set of rules in mind during a sorting task if, for example, they are asked to sort by color ("If red, then it goes here; if blue, then it goes here"). Three year-olds, however, are not capable of reflecting on more than one set of rules and cannot switch from one set to the other; for example, if the rule changes and they are now required to sort by color ("If red, then here; if blue, then here") or by shape ("If car, then it goes here; if flower, then it goes here"). Until children are able to reflect on a more complex rule system, then errors like perseveration in rule use will occur. Other authors, however, suggest that children around the age of 7 still struggle with sorting tasks when they have to maintain multiple dimensions in mind and switch between them (Anderson et al. 2001b). This ability improves considerably between the ages of 7 and 9 and continues to improve until adolescence (Anderson 2002; Zelazo and Frye 1998).

Verbal Fluency

Verbal initiative and productivity is an executive function that is frequently tested by using verbal fluency tasks (Lezak et al. 2004). Two conditions can be used: phonemic (letter) and semantic (category) fluency. Phonemic verbal fluency requires the subject to retrieve words that begin with a particular phoneme or letter (e.g., F), while semantic verbal fluency requires the subject to name words that belong to a particular category (e.g., animals). Successful performance on word fluency tasks requires executive functions such as inhibiting words that do not conform to the rules of the task (Anderson et al. 2002). In addition, verbal fluency tests are believed to be among the most sensitive to dysfunction of the frontal lobe (Stuss and Benson 1986).

Brocki and Bohlin (2004) found a significant improvement in verbal fluency to occur at two points during development: around the ages of 8 and 12 years old. Verbal fluency is one of the executive abilities most difficult to test in young children due to their lack of phonological awareness. On the F-A-S subtest of the Controlled Oral Word Association Test (COWAT) where children must generate words based on a set of rules (words beginning with letters F, A and S), it is not uncommon for children to say words like "elephant" when prompted to generate words beginning with letter A (Anderson 2002). It is generally found that children perform better at category fluency tasks than on letter fluency tests, with the latter reaching maturity at a slightly older age (Hurks et al. 2006; Riva et al. 2000; Klenberg et al. 2001). Matute et al. (2004) found that by ages 14 to 15 children reach an adult level in semantic fluency tasks but not in phonemic fluency, suggesting that the measurement of the developmental trend of the fluency dimension is task-dependent. Parental or caregivers' educational level has also been strongly correlated with fluency measures, with low parental education associated with a low fluency performance in children over a 60-s period (Hurks et al. 2006; Ardila et al. 2005).

In summary, all components of executive function show an improvement with age during infancy and childhood. The progression of executive function however, is not the same for all executive components. The first to emerge, by the child's first year is the ability to inhibit overlearned behavior, allowing the child increased attentional control over the environment; the ability to inhibit task-irrelevant information, however, shows its greatest development later between the ages 6 and 10. Other executive skills such as planning and set-shifting seem to develop, by age 3 with significant improvement after age 7. Verbal fluency is last to emerge and is significantly influenced by environmental factors. All functions continue to improve until adolescence. The sequential progression of these functions in children has been paralleled with the maturation of the frontal lobe and its connections with other brain areas.

Executive Dysfunction and Developmental Disorders

Difficulties in executive function are prevalent in certain developmental disorders including phenylketonuria (Welsh et al. 1990), Tourette's syndrome (Pennington and Ozonoff 1996), ADHD (Barkley 1997) and autism (Hughes et al. 1994). All of these conditions, which have been associated with abnormal activity of the frontal lobe (Dickstein et al. 2006; Girgis et al. 2007; Schmitz et al. 2006; Yoon et al. 2007) produce difficulties with executive performance. Much research has been conducted especially in ADHD and autism since they constitute disorders with very noticeable executive deficits. Impairments in executive behavior in autism, for example, both in the school-aged and adult population, include those in the area of planning and mental flexibility, while inhibitory control is not impaired in all cases (Hill 2004). In the case of ADHD, the main executive problem lies in inhibitory control and the suppression of overlearned responses such as in the Stroop test and the Stop/Signal task (Pennington and Ozonoff 1996; Desman et al. 2006). Both autistic and children with ADHD also demonstrate problems with planning future actions as measured by the TOL task (Hughes et al. 1994; Scheres et al. 2004). Children with Tourette's demonstrate deficient performance on verbal fluency tasks like the COWAT (Anderson 2001) while studies of other executive abilities have yielded mixed results (Ozonoff et al 1998).

Environmental factors have also been suggested to have an effect on the development of executive functioning. In a study by Ardila et al. (2005), children's scores on executive tests taken from a neuropsychological battery correlated significantly with the level of education of the parents. Specifically, about 5 additional years of parents' education made a significant contribution to the executive performance of the child.

Executive Functions in the Aging Population

Literature on age-related changes in executive functioning is still scarce, and results are often times contradictory. A better understanding of the effects of aging on executive functions is important and meaningful, however, since it has been estimated that age-related deficits in executive functions are associated with, and can be predictive of, decline in the functional living skills of the elderly (Grigsby et al. 1998). Cahn-Weiner et al. (2000) reported that executive tests, when compared to tasks that involve different cognitive domains, are more predictive of decline in instrumental activities of daily living in older individuals. It has also been suggested that, as long as executive skills are intact, a person can remain independent and productive even after sustaining other forms of cognitive loss (Lezak et al. 2004). Tests purported to measure executive functioning can also be predictive of future development of mild dementia (Nathan et al. 2001), Alzheimer's disease (Rapp and Reischies 2005) and poor performance on such tasks has been correlated with an increased risk for accidents in elderly drivers (Daigneault et al. 2002). The executive system has been associated with so many skills necessary for adaptive human behavior, that a thorough understanding of these functions is important and meaningful. There are data to suggest that there is a relationship between aging and changes in the abilities mediated by the executive system (West 1996; Plumet et al. 2005; de Luca et al. 2003; Keys and White 2000; Mejia et al. 1998; Fisk and Sharp 2004), but the specific nature of this relationship remains to be clarified.

In the same way that maturation of the prefrontal cortex has been connected to the development of executive functions, the decline in executive functions at the other end of the life span has been associated with anatomical changes in the brain during normal aging. The human brain is believed to undergo a gradual reduction in volume that begins during early adulthood (Miller et al. 1980). Some brain areas known to be vulnerable to the effects of aging are the hippocampus and prefrontal regions (Salat et al. 2005). Furthermore, the difference in the degree of reduction between the frontal cortex and other areas such as the temporal, parietal and occipital cortices is significant, with a reduction in the latter areas of about 1 and 10–17% in the frontal cortex (Haug and Eggers 1991). This vulnerability of the frontal lobes to the effects of aging implies an age-related vulnerability to the functions of the frontal lobes as well, and is consistent with the "frontal-lobe hypothesis of aging" (West 1996). Hughlings Jackson was an early advocate of the idea that phylogenetically newer parts of the brain, like the frontal lobes, were particularly susceptible to damage (in Greenwood 2000). This idea evolved into a theory that states that early decline of the frontal lobes during normal aging accounts for cognitive difficulties often times observed in the elderly (but see Greenwood 2000).

Greenwood (2000) evaluated the frontal aging hypothesis by examining functions mediated by parts of the brain other than the frontal lobes. The author does not believe that the physical decline of the frontal lobe plays such an important role in cognitive deficits since volumes in the temporal and parietal lobes are lost as well, although to a lesser degree. The localizationist approach of the frontal-aging hypothesis, the notion that a specific area of the brain mediates a specific set of behaviors, is abandoned for a more network-based theory of cognitive aging, where aging has an effect of altering the dynamics within processing networks (Greenwood 2000). Recent evidence shows that the frontal lobes are not universally affected by age has raised additional questions about the frontal-aging hypothesis (Band et al. 2002).

Some authors have argued that those cognitive abilities subsumed under executive functions are the most sensitive to age decline. They have been seen to decline earlier when compared with abilities in other cognitive domains, and some authors even suggest a return to an almost child-like level of performance by age 64 (de Luca et al. 2003). Due to the seemingly fractionated nature of executive functions, decline has not been found to be homogenous, and for some executive functions such as cognitive flexibility, decline has been proposed by some studies to have a late onset of about age 70 years (Boone 1999) while other studies believe this decline to occur at a much younger age (Robbins et al. 1998; Daigneault et al. 1992; Daigneault and Braun 1993).

Increasing age has been found to correlate with decline in the performance of executive functions, but it has often been difficult to differentiate this decline from a general decline in cognitive abilities (Crawford et al. 2000). The empirical basis for the relationship between age and executive functioning has been difficult to establish due to contradictory research results and skepticism by some authors of a specifically executive deficit in aging. Age differences in executive functioning have been attributed, for instance, to a general slowdown in the rate at which information is activated within the working-memory system, further arguing that no specific deficits in the central executive occur as a consequence of aging (Fisk and Warr 1996). One objection to the theory of executive decline in aging is the claim that information processing speed underpins many of the age-related changes in cognitive ability (Fisk and Sharp 2004). When processing speed is controlled for, age-related deficits in tasks such as random letter generation (Fisk and Warr 1996) and the WCST have been reduced in significance. Psychomotor speed has also been purported as a variable underlying the age-related changes in executive functions. Keys and White (2000), however, studied the relationship between psychomotor speed, age and executive abilities and found there is a unique effect of age on the executive abilities of set formation and set shifting beyond that accounted for by psychomotor speed. Their results do not support a theory of processing speed as the sole contributor to age-related deficits in cognition. The contribution of age to executive functioning was found to vary considerably across different tasks; executive function tasks vary greatly in their complexity, and age will affect various tasks differently. Further research using a variety of tasks within the same group is still needed.

Experience, although difficult to quantify experimentally, has been found to contribute to the performance of older adults in real-life-type problem solving tasks that often necessitates the involvement of executive processes (Crawford and Channon, 2002). In a study by Crawford and Channon (2002), younger participants performed better than older ones in abstract tasks of executive functioning such as the WCST, TMT and the Hayling Sentence Completion Task, but older individuals showed an increased ability to produce high-quality solutions in a real-life problem solving task. The study found that the older group utilized a different set of strategies to solve problems when compared to their younger counterparts, and the use of these strategies led to better performance.

While some authors find education to be a variable that affects the age-related decline in executive functioning, with low education exacerbating age effects and high education associated with more successful aging, (Van der Elst et al. 2006; Grigsby et al. 2002), others find education to be a poor predictor of executive performance (Manly et al. 2005; Hashimoto et al. 2006). Plumet et al. (2005) utilized a sorting task (MCST) and found that distractive errors were exhibited at the same rate in participants over the age of 70, regardless of level of education attained. According to these authors, there seems to be an age-related difficulty in keeping attention focused on the relevant sorting rule which is independent of any cultural factor. Similar conclusions were reached by authors using the TOL test (Rönnlund et al. 2001; Glosser and Goodglass 1990), but not by others when measuring performance on a Stroop paradigm (Van der Elst et al. 2006). The applicability of a theory of the protective effects of education on cognitive functioning (Dahua et al. 2005; Springer et al. 2005) remains to be understood in terms of the relationship between education and executive abilities. Variables such as education and experience, among others, seem to contribute differentially to executive abilities in the aging population and these interactions need to be further studied. Recently Bialystok et al. (2004) proposed bilingualism among other mediating variables of the aging process of certain executive functions.

In summary, different executive abilities have been proposed to decline differently with increasing age, and changes in some brain areas, in particular the frontal lobes have been associated with it. The mediation of environmental variables to this vulnerability has also been suggested. In the following paragraphs the age-related effects on some specific executive functions are presented.

Attentional Control

It has been proposed that difficulties with inhibition and attentional control can account for many of the cognitive changes associated with aging. Hasher and Zacks (1988) proposed the inhibitory deficit theory of cognitive aging, which tries to explain a wide range of age-related difficulties in cognitive functioning by a deficit in the inhibitory control system. This framework aims to explain the difficulties experienced by older individuals find at restraining task-irrelevant information as well as prepotent responses, and getting rid of irrelevant information from working memory (Hasher and Zacks 1988; Hasher et al. 2001; Lustig et al. 2001).

Utilizing tests such as the CPT, Stroop, and Haylings, researchers have generally found age-related deficits in attentional control and inhibition when comparing old and young groups (Belleville et al. 2006; Haarmann et al. 2005;

Mani et al. 2005; Rekkas 2006; Rush et al. 2006; Van der Elst et al. 2006). The influence of age on inhibition is apparent, even after controlling for the effects of processing speed (Andrés and Van der Linden 2000).

Planning

A decreased ability to regulate behavior in accordance to a plan, and difficulty in the grasping of abstract concepts was found by Daigneault et al. (1992) in an adult population younger than 65. Similar results were found by Zook et al. (2006) who noticed less accuracy on the TOL task in adults starting at the age of 60. Contrary results reported by Davis and Klebe (2001) suggest that age does not affect planning abilities measured by the TOH task until the eight decade of life. Brennan et al. (1997) utilized the TOH test to measure executive abilities among young, young-old and old-old groups. Similar executive capacities were found among the young and young-old group when compared to the old-old group on the three-disk tasks of the TOH test. However, as problem complexity increased in the four-disk task with an additional disk and longer move sequences, younger adults showed a significantly superior performance when compared to both the young-old and old-old groups, with average ages of 65 and 75 years old, respectively. These findings are consistent with the hypothesis that there are age-related differences in executive functions, and also introduce the importance of task complexity. Among the errors commonly seen in elderly participants on a tower task are an increase in moves to reach a solution, and an increase in rule violations. (Rönnlund et al. 2001). Although it is generally agreed that age has an effect on planning, the age of onset of the deficit is yet unclear and conflicting results might stem from the type of task used.

There is some recent evidence suggesting that age differences in planning tasks decrease or disappear if instead of using based planning tasks (TOL), they use material that is more familiar to the participants (Garden et al. 2001). Phillips et al. (2006) indicate no age differences between a senior and a young sample in a planning task that investigates the ability to plan a work schedule. The authors concluded that when more ecologically valid tasks are used, adults are able to selectively attend to task-relevant information which may compensate for the possible age-related changes in cognitive resources.

Set Shifting

Results from studies investigating other components of executive functions such as set shifting have also found variation in results. A lack of statistical significance was reported in a study examining the performance of two groups of elderly individuals, a young-old group (55–70) and an old-old group (71–85), on the WCST (Mejia et al. 1998). Haaland et al. (1987) also found that older participants committed fewer perseverative errors and achieved more categories than younger ones; decline was only observed after the age of 80. Perseverative errors occur when the participant continues to sort according to a previously unsuccessful principle and may reflect an inability to shift set.

Axelrod and Henry (1992) found that a significant increase in perseverative errors was observed after age 60. Similar findings are reported by Crawford et al. (2000) who found a significant age-related decline among a sample aged 60–75 years when compared to a younger group (18–60) using a modified version of the WCST the Modified Card Sorting Test (MCST). Other studies posited that older adults become progressively susceptible to errors of perseveration in WCST-like tasks because of deficient abilities in the formation of new hypothesis regarding changing rules and deficient abilities in set-shifting (Ridderinkhof et al. 2002).

Salthouse et al. (2000) found no true direct age-effect on the two versions of the Connections Test (a test analogous to the Trail Making Test; TMT). They found that all age-related effects were mediated through influences of perceptual speed. Wecker et al. (2005), on the other hand, found that advancing age is associated with poorer performance on tasks of cognitive switching, such as the TMT, even after controlling for component skills required by those tasks like visual scanning and motor and perceptual speed.

In summary, set shifting as measured by different neuropsychological tests seems to be affected by age but there is a discrepancy on the age at which this decline starts. Discrepancies may be explained by the methodologies used by the studies, such as continuous age grouping rather than younger versus older group, and variation in sample sizes. In some studies the sample size of the older group is very small. For example, in the study of Crawford et al. only 11 participants were included in the oldest group. These differences make comparisons across studies difficult.

Verbal Fluency

Similar to findings with other executive measures, conflicting results are found when studying the influence of age on verbal fluency. Some authors find no age influences in performance on verbal fluency tests (Crawford et al. 2000; Keys and White 2000; Parkin et al. 1995) and suggest that this task relies on a large verbal knowledge base which is usually well-maintained with increasing age. Results from a study by Fisk and Sharp (2004), for instance, indicate a lack of evidence of an age-related decline in word fluency and random letter generation tasks. A deficit was only found when a dual-task situation was presented. On the other hand, Brickman et al. (2005) reported a linear decline in fluency tests as age increased. According to these authors and others (Auriacombe et al. 2001; Crossley et al. 1997), the rate of the decline was greater for category fluency when compared to letter fluency. Older individuals tend to produce fewer numbers of words and an increased number of intrusions and perseverations which are independent of the semantic category used (Rodriguez-Aranda and Martinussen 2006).

Rodriquez-Aranda and Martinussen (2006) did a meta-analysis to compare literature on the variation in performance on phonemic fluency tests in the elderly, and found a clear age effect. The results suggested an improvement from the 20s to the 40s, and then a slow decline continuing until the late 60s. From then on, a rapid decline is seen through the late 80s. The authors noted that one possible confound in some studies involving elderly groups is the lack of screening for dementia. It is also relevant to note that of the 26 studies reviewed for this meta-analysis, 11 did not report education by group. The effect of education on fluency tasks has been well established (Acevedo et al. 2000; Ardila et al. 2000; Ostrosky-Solis et al. 2007), and educational attainment has a clear effect on performance in favor of the highly educated group (Plumet et al. 2005). It seems reasonable to assume that poor control of educational level and other socioeconomic variables might be a possible confound on some of the fluency studies. Other suggested explanations for the conflicting results in phonemic verbal fluency include cohort effects and the nature of a cross-sectional design (Piguet et al. 2002).

In summary there are age-mediated changes across different domains of executive functions. This decline, however, does not seem to follow the same pattern across domains. For example, while the difficulties of older participant in inhibiting irrelevant information seem to be seen in all studies independently of the task used, the decreased ability to plan seems to be task-dependent, with complexity and familiarity of task becoming mediating variables. Problems with set shifting and a decrease in category fluency appear to be other relevant changes with age. Findings suggest that the greatest decline of these executive abilities happens late in life around age 80 years old. Generalization of the these results, however, need to be taken with caution due because most of the studies used cross sectional designs with, in most cases, small sample sizes per age group (n less than 30). One additional difficulty in the generalization of the results on age-related changes is that the tests used for executive function, depend on other abilities for successful performance. For example, the TOL is used to measure the ability to plan, but other abilities such as working memory, visuospatial memory, and inhibition are important for effective performance (Lezak et al. 2004).

Conclusions and Future Research

A variety of definitions and components of the executive system were described on this review to illustrate the lack of clarity regarding this concept. The diversity of definitions for executive functions support the complexity of this concept that encompasses many integrated components (i.e., planning and organization, behavior initiative, implementation of strategies for problem solving, self control, thought process flexibility, monitoring of behavior, etc.), thereby weakening the notion of a unitary concept. This fragmentation of executive functions is also found in their relation to the frontal lobes (Stuss and Alexander 2000). Different executive function processes are linked with dissimilar prefrontal areas. Although it has been accepted by most researchers that the prefrontal cortex plays a critical role in executive functioning, research evidence supports the importance of other brain regions (subcortical and posterior cortex) in the integration (or association) of information and the regulation of emotion, thought, and action. The role of the prefrontal area has been interpreted by some as that of inhibitory control (Stuss and Alexander 2000) while others argue this is a simplistic interpretation (Zelazo and Muller 2002).

This review provided evidence of the vulnerability of executive functions to the effects of age over lifespan. This does not mean, however, that the developmental changes in executive functions in seniors and children are equivalent. Moreover, we do not propose that the processes of development and decline are the same. As suggested by Span et al. (2004) different patterns of age effects occur during childhood and senescence. These authors found that the speed of responding on executive tasks is more vulnerable to the effects of advancing age in seniors than in children, when the performance on these tasks is compared with the efficiency of performance on non-executive tasks. Furthermore, Span et al. (2004) suggest that there may be a difference in the way these two age groups perform executive tasks. For example, children might focus more on speed than accuracy. Conversely, seniors may focus more on accuracy than speed.

The results that emerged from the studies reviewed here also demonstrate that both the development and the decline of executive functions are heterogeneous, since some executive abilities develop and decline earlier than others. There are, however, important potential methodological limitations to these studies that should be mentioned. First, the majority of the studies follow a cross-sectional design and very few are longitudinal, making it difficult to demonstrate a pattern of development across the life span. As noted earlier, conclusions from some of these studies should be taken with caution since the importance of mediating variables such as level of education were not taken into consideration. Moreover, the observation that differences in performance in executive functions appear to be affected by the type of task or the demands of the task limits the generalization of some other studies. Further research is needed that focuses on the extent to which different executive functions are differentially affected by age using longitudinal designs and controlling for socio-economic variables.

The current review also points out some important limitations of executive function assessment, such as the lack of correlation among executive tests which raises questions on construct and ecological validity. New models of assessment of executive function (Isquith et al. 2004) recommend the inclusion of ecologically valid evaluations of executive dysfunction and provide an important bridge toward understanding the relationship between deficits in cognitive tests and difficulties in an individual's everyday adaptive functioning. This assists the definition of targets for intervention. The ability of executive tests to also predict functional and independent living in the aging population deserve attention so that the assessment of executive functions will be included in regular examinations, with the aim of predicting possible problems in functional independence. Within the context of an ever-growing aging population, the nature and extent of the decline in executive functions need to be identified in order to find measures to prolong independent living.

Another assessment problem is that many widely used measures of executive functioning are complex and involve a wide range of skills, thus complicating efforts to identify specific processes. New scoring methods that include qualitative and processes analysis have been proposed (Anderson et al. 2002).

The function of the executive system is still an uncharted area that necessitates further research on many of its aspects. The association observed between executive deficits, and neurodegenerative and developmental disorders as well as many medical conditions warrants additional investigation on the applicability of executive tests to better predict disability when compared to tests based on other cognitive domains (Royall et al. 2002). In the area of developmental disorders, a better understanding of executive functioning would lead to the development of better rehabilitation techniques to allow children t, not only perform better in school and later at work, but also be able to thrive socially.

Despite the importance of discerning whether executive functions are one or many, whether they are based on abilities of processing speed or fluid intelligence, or whether the available tests measure them accurately, it is imperative to understand that 'executive functions' is a useful label to describe many human abilities that allow us to engage in independent and purposive behavior. More research needs thus to be focused on the crippling effects of executive deficits and to possible treatments.

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