EXPLORING HOW THE CENTRAL EXECUTIVE WORKS: A SEARCH FOR INDEPENDENT COMPONENTS

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Although the central executive component of working memory has become a focus of theoretical and empirical interest, its functioning is still poorly specified. The present study explored the factorial structure of a comprehensive sample of executive and working memory tasks assumed to assess the main functions generally attributed to the central executive: coordination, inhibition, long-term memory retrieval, and planning. The aim of the analysis was to identify the various executive abilities underlying these functions. A principal components analysis revealed that several independent capacities contributed to the performance of 65 young adults on the selected tasks: inhibiting prepotent responses in association with long-term memory strategic retrieval, inhibiting distracting information, coordinating storage and processing of verbal information, coordinating storage and processing of visuospatial information and finally, coordinating different processing operations that do not involve storage. This pattern of results suggested the independence of certain control processes and supported the executive fractionation hypothesis. The results also suggested that a theoretical fractionation of the central executive functioning in terms of general functions does not correspond to an empirical reality and that more fine-grained dissociations should be considered.

A currently dominant conception of working memory is the model proposed by Baddeley and Hitch (1974; Baddeley, 1986, 1996) which comprises an attentional control system, the central executive (CE), supplemented by two domain-specific storage subsystems for verbal and visuospatial information. While the CE is certainly the most important component of the working memory model in terms of its general impact on cognition, it paradoxically remains the component whose theoretical status and functioning is the least well known. An initial attempt to specify the CE functioning was made through Baddeley's (1986) functional analogy between the CE and the Supervisory Attentional System (SAS) of Norman and Shallice's (1980) model of attentional control. The CE is then attributed a variety of functions characterized as "attentional" and thought to be involved in tasks that are likely to be impaired in patients with frontal lobe pathology, or more gener-

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ally in dysexecutive patients. Many studies, either clinical or experimental, which examined executive functioning in various populations, suggest the existence of separate control — i.e., executive — functions (e.g., Burgess & Shallice, 1994; Duncan, Johnson, Swales, & Freer, 1997; Letho, 1996; Robbins, James, Owen, Sahakian, McInnes, & Rabbitt, 1997). While the details of the results differ across studies, neuropsychological or correlational dissociations are consistently reported and these findings are used to argue that the functions of the CE (or SAS) are not unitary, but rather fractionated.

In that context, Baddeley (1996) proposed several lines of research for studying the CE, each corresponding to a general function assumed by this component: coordination of two concurrent tasks or mental processes, alternation between response strategies, selective attention, and activation of information in long-term memory (LTM). Note that two of these functions rely more or less explicitly on inhibition: response strategy alternation, where the prior response strategy must be inhibited, and selective attention, where distracting information for the current task must be inhibited. Another important function classically ascribed to the CE is planning (Shallice, 1982, 1988). Planning was not listed by Baddeley as a line of CE research, but he implicitly included it by drawing a functional analogy between the CE and the SAS.

The proposal of Baddeley to fractionate the CE into different functions was meant to provide a research strategy based on conceptual rather than empirical distinctions, and hence the exact nature of the considered functions — i.e., the specific processes they encompass — and their relationships were not clearly specified. Moreover, more fine-grained dissociations within the different CE functions mentioned above have been suggested by several authors (see below), raising questions regarding the empirical relevance of a fractionation in terms of general functions.

The main purpose of the present work is to provide empirical data on the CE functioning by simultaneously taking into account the different functions traditionally ascribed to this component in the literature: coordination, inhibition, retrieval from LTM, and planning. More particularly, this study intends to identify the different executive abilities — determined by one or more executive processes — which underlie the various functions of the CE. The “functions” of the CE are understood here to mean the roles assumed by this component in general cognitive functioning; the “processes” are the mechanisms that ensure those functions; the term “ability” refers to the possibility of mobilizing cognitive resources — that is, of implementing one or more specific processes — in order to execute a given cognitive activity; final-

1 A functional description of a pattern of behaviour that leaves open its anatomical underpinning (Baddeley, 1986).
ly, "executive tasks" are considered to be tasks that involve one or more executive processes.

We focus on coordination, inhibition, retrieval and planning functions because all are considered important CE or executive functions (e.g., Baddeley, 1996; Collette & Van der Linden, 2002; Miyake & Shah, 1999; Rabbitt, 1997; Shallice, 1982) and have been extensively studied in various target populations such as brain-damaged patients, young and elderly adults (e.g., Andrès & Van der Linden, 2000, 2001; Duncan et al., 1997; Letho, 1996; Robbins et al., 1997) and mostly because, envisaged as such, this set of functions allowed us to cover the majority of the studies related to the working memory control system.

Thus, by starting from the lines of research outlined by Baddeley (1996) to which was added the planning function, we reviewed the literature in order to specify the specific processes these functions encompass, the dissociations suggested within these functions and the relationships that have been described. This review is briefly summarized below. Based on this review, a set of tasks commonly used to assess these functions and likely to specifically involve each of the processes they encompass has been selected. A factorial approach was then used in an attempt to determine the different independent factors (i.e., executive abilities) responsible for performance on the selected tasks.

The CE Functions Examined in the Current Study

Coordination. A major function attributed to the CE is the coordination of two concurrent tasks or mental operations (Baddeley, 1986, 1996). This function has been studied originally on patients with Alzheimer's disease whose coordination impairments have been evidenced using dual-task paradigms (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991; Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986) as well as working memory tasks involving the simultaneous storage and processing of information (e.g., Cherry, Buckwalter, & Henderson, 1996; Collette, Van der Linden, & Salmon, 1999). Dual-task paradigms and storage-and-processing tasks have then been widely used to explore the CE's coordinating function in various dysexecutive patients (for a review, see Baddeley, Della Sala, Gray, Papagno, & Spinnler, 1997), and elderly adults (for a review, see Van der Linden, 1994).

Notice that the CE's coordinating function is explored in a very wide range of experimental situations that may involve different executive processes. For example, a distinction was made between coordination tasks - which require the integration of information coming from different sources
– and dual-tasks – which require combining two tasks that are unrelated to each other (e.g., Yee, Hunt, & Pellegrino, 1991; see however Emerson, Miyake, & Rettinger, 1999). In a similar vein, a dissociation between storage-and-processing tasks, and tasks combining two different kinds of processing without storage, have been observed in a brain-damaged patient, suggesting some heterogeneity in coordination deficits (Van der Linden, Coyette & Seron, 1992). Besides these task-type dissociations, dissociations are also reported between verbal and visuospatial storage-and-processing tasks (e.g., Oberauer, Süß, Wilhelm, & Wittmann, 2003; Shah & Miyake, 1996). Moreover, it has been demonstrated that it is the verbal versus visuospatial content that distinguishes these storage-and-processing tasks, not whether the processing applies to the stored information (Vom Hofe & Olivier, 1997). As a whole, these findings suggest the existence of several coordination processes that may determine a family of functions rather than a single unitary function.

**Inhibition.** Inhibition is considered an important executive function (Norman & Shallice, 1980; Rabbitt, 1997) and the CE functioning has been associated with several aspects of inhibitory control (Baddeley, 1996; Miyake & Shah, 1999). Thus, the CE is considered to be involved in tasks requiring the suppression of a prepotent response in, for example, a random-generation task (Baddeley, 1996) or the Hayling test (Burgess & Shallice, 1996). These tasks are commonly used to assess inhibition abilities in various target populations (e.g., Andrès & Van der Linden, 2000, 2001; Brugger, Monsch, Salmon, & Butters, 1996). The CE is also thought to be implicated whenever a response or plan of action becomes ineffective in the course of an activity and needs to be changed as in sorting tests such as the Wisconsin Card Sorting test (Milner, 1963; Nelson, 1976), or in alternation tasks like the Trail-Making test (Reitan, 1958). A deficit on these tasks is manifested by perseveration with an inappropriate response mode and is generally associated with frontal pathology (for a review, see Fery, 1999). Finally, the capacity to attend selectively to one stream of information while discarding others – the classic phenomenon of selective attention – is considered an important function assumed by the CE (Baddeley, 1996; Kane & Engle, 2000). Selective attention is probably one of the most widely explored aspect of inhibitory control, specifically in older adults who are consistently found to be more distracted by extraneous environmental stimuli than are younger adults across a number of different paradigms such as the Stroop task (e.g., Spieler, Balota, & Faust, 1996), and the negative priming paradigm (e.g., Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994). Oversensitivity to interference has been demonstrated in various dysexecutive patients using similar or variants of these paradigms (e.g., Collette, Van der Linden, Delrue, & Salmon, 2002; Richer, Décary, Lapière, Rouleau, Bouvier, & Saint-Hilaire, 1993).
It appears that various tests are used to operationalize the inhibitory processes commonly associated with the CE functioning. This raises the question whether such processes determine a single unitary function or whether these are better characterized as a family of functions as suggested by a number of researchers (e.g., Hasher, Zacks, & May, 1999; Kok, 1999; Nigg, 2000). This latter view is supported by the finding of dissociations between inhibition tasks (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994) and by the recent demonstration, at the level of latent variables, of separate inhibitory functions (Friedman & Miyake, 2004). Also Consistent with this view is the interpretation of the results Miyake, Friedman, Emerson, Witzki, Howerter and Wager (2000) recently reported. These authors used latent variable analysis to examine the relations among three often postulated executive functions (mental set shifting, inhibition of prepotent responses, and updating the contents of working memory). They concluded that these three functions, although clearly separable, were moderately correlated, and proposed at least two explanations to account for these intercorrelations: one is that the critical factor common to these functions is their demand for controlled attention conceived as a domain-free capacity involved in all situations requiring to maintain active working memory representations in the face of interference and distraction (see Kane & Engle, 2003); the other is that they all involve some form of inhibitory control, which is considered by some authors as a central player in general cognition that assumes multiple functions (e.g., Hasher et al., 1999). Notice that these two interpretations are not mutually exclusive, since they both have an inhibitory flavor which emphasizes the lack of specification of the concept of inhibition.

Retrieval from long-term memory. The CE is also thought to play a critical role in controlled LTM search and retrieval processes (Baddeley, 1996; Conway & Engle, 1994; Rabbitt, 1997). Verbal fluency tasks are typically considered to call upon such processes (Baddeley, Lewis, Eldridge, & Thomson, 1984; Rosen & Engle, 1997, 1998), and are widely used as a measure of CE function in various dysexecutive patients (e.g., Perret, 1974; Troyer, Moscovitch, Winocur, Leach, & Freedman, 1998) and in the normal elderly (see Bryan & Lusczcz, 2000, for a review).

However, there exists several verbal fluency tasks and there is some discrepancy in the literature regarding their equivalence in terms of underlying processes. Some studies have found evidence of dissociations between letter and semantic fluency tasks, implying distinct underlying processes (e.g., Martin, Wiggs, Lalonde, & Mack, 1994; Tomer & Levin, 1993). However, Vilkki and Holst (1994) who examined letter, semantic and alternating fluency tasks in anterior and posterior lesioned individuals found no performance differences between the letter and semantic tasks, but rather on the
alternating fluency task, suggesting that processes involved in verbal fluency tasks may vary according the type of retrieval cue proposed and/or the need to shift between retrieval cues.

Planning. Finally, planning is considered to be a major function of the SAS and has mainly been studied in the framework of Norman and Shallice's (1980) model of attentional control. Planning ability has been widely examined in several dysexecutive populations using various complex problem-solving tasks such as the Tower of London task (e.g., Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Shallice, 1982), mazes tasks (e.g., Mack & Patterson, 1995; Porteus & Kepner, 1944) and arithmetic problem-solving tasks (e.g., Luria, 1978).

Planning certainly involves more than one aspect of executive function, including formulation of a plan, monitoring and regulation of the responses intended to carry out the plan, and the verification that the responses have their intended effect (Lezak, 1995; Luria, 1978). In a recent study, Kafer and Hunter (1997) found no correlations between performance on several tests generally thought to call upon planning and problem-solving abilities leading the authors to reject the hypothesis that the tasks measure a unidimensional concept, planning. Such findings also raise doubt regarding the unity of the concept of planning.

Relationships Between the CE Functions Under Study

Little research has related these CE functions to one another. Nevertheless, a distinction between coordination and inhibition abilities has been observed in a group of patients with Alzheimer’s disease (Collette et al., 1999). Indeed, a principal components analysis indicated that the patients’ performance on a series of executive tasks loaded mainly on two factors defined as representing (1) inhibitory processes, and (2) the coordination between storage and processing operations. Moreover, these authors showed that performance on each factor was related to different cerebral areas. The results obtained by Miyake et al. (2000) are consistent with this distinction. Indeed, these authors showed that the three isolated functions (shifting, inhibition and updating) differentially contributed to performance on complex executive tasks. Interestingly, the dual-task was the only complex task that was not related to the three target executive functions, suggesting that the simultaneous coordination of multiple tasks relies on an ability that is distinct from the three studied functions.

On the other hand, there is a wealth of data demonstrating a specific relationship between inhibition and controlled retrieval abilities. Although evidence for such a relationship comes from various research domains such as
long-term memory (e.g., Anderson & Spellman, 1995; Radvansky, 1999), working memory capacity (e.g., Rosen & Engle, 1997, 1998) and aging (e.g., Hasher, Quig, & May, 1997), all of these authors consider LTM controlled search and retrieval to be closely tied to the necessity of inhibiting automatically activated information that is irrelevant or has just become so.

To sum up, the CE is clearly implicated in coordination, inhibition, controlled retrieval, and planning functions. However, these functions are neither clearly defined, nor precisely operationalized, given the diversity of the processes implicated and the range of tests used to assess them. Moreover, little information is available as to their interrelationships. Considering the dissociations reported within the different functions of the CE, it is not clear whether a theoretical fractionation into general functions as envisaged by Baddeley (1996) has an empirical basis. The studies have included a limited set of executive tasks and/or functions and differ widely at a theoretical level (definition and choice of the studied tasks and/or functions) as well as at a methodological level (different populations, wide variety of experimental paradigms). As such, a clear identification of the abilities underlying the different facets of the CE functioning is not yet available. One way to address this issue is to study the CE functions simultaneously in the same group of participants, as we propose here.

Logic of the Study and Task Selection

The present study is a first attempt to bring together the main functions of the CE (coordination, inhibition, LTM retrieval and planning) by exploring the factorial structure of a comprehensive sample of executive and working memory tasks assumed to assess these functions. The goal of such an analysis is to isolate in the most specific manner the different executive abilities – determined by one or more executive processes – that underlie performance on the selected tasks.

Therefore, tasks were chosen according to the processes they are assumed to involve and as a set, the selected tasks allowed us to cover all of the processes involved in the functions examined in the current study. With a very few exceptions, they were a strict replication of tasks available in the literature and commonly used in cognitive and neuropsychological studies to explore executive functioning. Although each of the chosen tasks is most commonly associated with the assessment of a particular function (e.g., the Stroop task is typically considered an inhibition task whereas, maze is considered a planning task), a characteristic often reported regarding executive tasks (e.g., Rabbitt, 1997) which is reflected in our task analyses (see hereafter), is that most of them tap more than one CE function leading to some overlap between the
executive processes they involve. Consequently, in order to determine the individual contributions to overall performance of each targeted executive process, the tasks were chosen such that each one was either mainly associated with a specific process or with a specific combination of processes, and when possible each target process was implemented in at least two tasks. The dissociations reported in the literature served to guide our sampling of relevant executive processes and provided the basis for our task selection.

**Coordination.** Given that the coordination function may encompass several different mechanisms, the present study included various coordination tasks according to the processes they putatively involve: a task that combines storage and processing of verbal information (backward verbal span task) as well as a task that combines the same operations but on visuospatial information (backward visuospatial span task), a task combining different processing operations without storage (dual-processing task), and a task combining different storage operations without processing (dual-storage task).

**Inhibition.** Our task selection had to take into consideration the possibility that there might be separate inhibitory mechanisms. A specific set of inhibition tasks was selected because, as a set, they call upon all of the inhibition processes classically associated with the CE. Thus, the random letter generation task was chosen because it is traditionally associated with inhibition of a highly automated response; it is also thought to involve switching retrieval strategies, that is, the inhibition of a strategy that is no longer operational (Baddeley, 1996). The Hayling test (Burgess & Shallice, 1996) was selected because it requires inhibiting a prepotent response with controlled retrieval of information from memory. The Trail-Making test (Reitan, 1958) was chosen because it is thought to mainly require alternating between two response strategies and hence inhibiting the previous strategy which has become ineffective. Finally, we included the Stroop test (1935), which is typically regarded as belonging to the family of interference paradigms, where the selection of target information is disrupted by the presence of distracting information; it is also considered as a prototypical inhibition-of-a-prepotent-response task; and finally, this task is also thought to involve inhibiting a prior response mode that has become ineffective in a specific condition which requires alternating between reading and naming.

**Retrieval from long-term memory.** Several verbal fluency tasks (letter, semantic and alternating) were used to assess the retrieval function, since there is no consensus regarding their equivalence in terms of underlying processes. These tasks were chosen because they are typically considered to involve executive processes that ensure strategic searching and retrieval from LTM (Baddeley et al., 1984), and also because they are thought to involve inhibitory processes, since once an item is produced, it has to be actively inhibited or it will keep coming back to adversely affect the rest of the task.
(Rosen & Engle, 1997, 1998). In the alternating fluency task, which in addition requires shifting between two retrieval cues, inhibition of the preceding response mode has to take place after each item is produced.

**Planning.** Our task selection included planning tasks that vary according to the specific operations that need to be planned. We used arithmetic problem solving and maze tasks typically used in clinical neuropsychology to explore planning processes (Gil, 1996; Lezak, Le Gall, & Aubin, 1994). These tasks are also believed to involve storage-and-processing operations: problem solving requires participants to carry out numerical processing while remembering particular pieces of information (Salthouse & Babcock, 1991), and maze tasks require a strategic search while simultaneously keeping track of the location of the goal (Mack & Patterson, 1995).

Viewed as such, this set of tasks allowed us to cover the majority of the targeted processes involved in the CE functions.

**Statistical Analysis**

The method used to study the data's factorial structure was principal components analysis (PCA) which reduces a large number of variables to a smaller number of components. PCA is particularly recommended when the researcher has no specific hypothesis regarding the nature and the number of factors (Lebart, Morineau, & Piron, 1996; Tabachnick & Fidell, 2001), which is the case in the present study. The only hypothesis that may be formulated in the light of the findings from the literature is that a fractionation of the CE functioning in terms of general functions as proposed by Baddeley (1996) appears rather unlikely. Indeed, as mentioned earlier, findings from the literature do not yet provide a necessary empirical basis for developing a theoretical model that specifies either the nature or organisation of the various CE functions. In attempting to generate a tenable theoretical model, a first step is to analyse data from the same subject population on a series of tasks involving a large set of executive processes. PCA provides productive tool in this exploratory venture.

**Method**

**Participants**

Sixty-five young adults (30 male and 35 female) participated. All were students (age 16–32 years, mean = 23.87 ± 3.6 years) at the University of Poitiers, France.
Materials, Design, and Procedure

Backward verbal span task (second part of the digit-span test\textsuperscript{2}, Wechsler, 1991). Participants had to recall increasingly long series of digits (presented orally at a pace of one digit per second) in the opposite order to their presentation. The test consisted of series of 2 to 7 digits with two trials per length, making 12 series in all. The dependent measure was the number of correctly recalled series.

Backward visuospatial span task (second part of the visual-span test\textsuperscript{3}, Wechsler, 1991). Participants had to reproduce increasingly long sequences of taps (presented at a pace of one tap per second) in the opposite order to their presentation. The test consisted of sequences of 2 to 7 taps, with two trials per length, making 12 sequences in all. The dependent measure was the number of correctly recalled sequences.

Dual-processing task. This task was devised to compare situation C, where two types of processing occurred at the same time (in a text, detect words belonging to a given semantic category and detect a given letter) to situations A and B, where each type of processing was done alone (A: detect words in the fruit category; B: detect the letter “h” in a meaningless string of letters). In all three parts the texts contained 1030 to 1080 characters, 10 target items (parts A and B) or 10 target items of each type (part C). In all three parts the number of target items correctly detected was recorded, along with the total time to execute the task, and the proportion of items correctly detected per unit of time was then calculated for each part. This score thus took into account both accuracy and speed of processing. The ratio between the score on the dual-processing task (C) and the mean score on the separate processing tasks (A and B) calculated with the formula $C/((A+B)/2)$, served as the dependent measure. This measure ranged between 0 and 1, a score close to 1 indicating that the subject performed similarly on the dual-processing and single-processing tasks.

Dual-storage task (adapted from Loisy & Roulin, 1992). Participants were presented with a 6 x 6 matrix containing one-syllable words and had to recall the words by writing them in their respective locations in an empty matrix. Five matrices containing an increasing number of words (from 3 to 7 words) were presented in succession. The matrix presentation time was a function of the number of words it contained (5 seconds per word). There was no time

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\textsuperscript{2} The participants also took the first part of the test (recall in same order as presentation), which gave us a forward digit span score to use as a control measure in the data analysis.

\textsuperscript{3} The participants also took the first part of the test (recall in same order as presentation), which gave us a forward visuospatial span score to use as a control measure in the data analysis.
limit for recall. The dependent variable was the number of words recalled in their correct location.

Random letter-generation task (Baddeley, 1966). Participants had to produce a sequence of letters as randomly as possible, at a pace set by a metronome (30 and 60 ticks per minute). Standard random-generation instructions were given (Baddeley, 1966). Two conditions were proposed in succession: generate a letter every 2 seconds for 100 seconds, then every second for 50 seconds. Thus, at most, 50 letters had to be produced per condition. A single score that took into account both the redundancy in the sequence (that is, the relative frequency with which each letter and each digram was produced) and the tendency to produce stereotyped strings (that is, alphabetic stereotypes and familiar acronyms) which are considered the two most important aspects of random performance (e.g., Baddeley, 1966; Baddeley, Emslie, Kolodny, & Duncan, 1998), was calculated for each condition. From the total number of letters produced, one point was subtracted every time a letter was produced more than three times (for example, if the same letter was produced 5 times, 2 points were subtracted), and one point was taken away for every letter in a sequence of two or more consecutive letters that formed an acronym. From the total number of digrams produced (digrams were obtained by pairing every two consecutive letters, making at most 49 digrams per condition), one point was taken away for each repeated and each stereotyped digram (two adjacent letters in the alphabet). The dependent variable was the total number of points obtained from both conditions.

Hayling test. We used a computerized French version (Fournet, personal communication) of the procedure devised by Burgess and Shallice (1996). It has two parts (A and B), each consisting of 15 incomplete sentences with the last (highly predictable) word omitted (e.g., “One cuts meat with a … ”). In part A (initiation), participants had to say a word that completed the sentence properly, as quickly as possible. In part B (inhibition), they had to quickly say a word that was not related in any way to the sentence. The sentences were presented orally through a loudspeaker in the computer, and response times (RTs, in ms) were recorded using a voice key. Three sample sentences were proposed before each part of the test. The dependent measure was the difference between the average RTs of sentences from part B and the average RTs of sentences from part A.

Trail-Making test (Reitan, 1958). In part A, participants had to connect numbers (1 to 25) in increasing order and as fast as possible. In part B, they had to connect numbers (1 to 13) and letters (A to L) by alternating between numbers and letters to form the following sequence: 1 - A - 2 - B, etc. The dependent measure was the time difference between the two parts (in seconds).
Stroop test (adapted from Stroop, 1935). The version used had three parts, A, B and C. In all cases, the stimulus cards contained 160 names of colors (blue, green, yellow, red). In part A, the color names matched the color of the ink used to print them, whereas in part B, the words and colors no longer matched. Parts A and B both had two conditions in which participants were given one minute to respond as quickly as possible by (1) reading the words (A: simple reading, B: reading with interference), and then (2) naming the color of the ink (A: simple naming, B: naming with interference). In part C (shifting), the stimuli were presented as in the interference condition, except that some of the words were boxed and the participant had to alternate between naming the color (of the boxed words) and reading (the unboxed words). A short practice session was run before testing in each condition. The number of words correctly read and/or named in one minute was noted for each condition of the three parts (the scores obtained on part A reflected reading and naming speed). Two dependent measures were used: the Stroop effect in the naming condition (Stroop “naming”), which was the score on naming-with-interference (B) minus the score on simple naming (A); and a shifting index (Stroop “shifting”), which was the difference between the score on part C and the mean score on the simple reading and simple naming conditions of part A.

Verbal fluency tests. Participants had to generate words that started with the letter “s” for the letter fluency test, and words that belonged to the animal category for the semantic fluency test. For the alternating fluency test, participants had to alternate between the furniture category and the boys names category. The dependent measures were the number of words generated in one minute in the first two cases and the number of word pairs produced in one minute in the last case, minus the number of errors and repetitions.

Arithmetic problem-solving test (adapted from Luria, 1978; Luria & Tsvetkova, 1967). After an initial sample problem was proposed, participants were successively presented with four problems\(^4\) that had to be solved as quickly as possible. Participants began by reading the problem statement aloud, at their normal reading pace but without pausing. The reading aloud guaranteed that the participant would read the problem statement correctly and completely before trying to solve it. The timing began as soon as the participant finished reading and the timer was not stopped until the correct answer was given. The problem statement remained visible and could be

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\(^4\) An example of one of Luria’s arithmetic problems (1978): A pedestrian gets to the train station in 30 minutes. A cyclist goes 3 times as fast as the pedestrian. How much time does the cyclist take to get to the station?
referred to at any time. The dependent measure was the mean solving time on the whole set of problems (in seconds).

Maze task (Wechsler, 1996). The mazes used were taken from Wechsler’s battery of tests for children, which includes a series of ten mazes of increasing difficulty. We used the last three (the most complex) and presented them in the original order (the first one served as an example). The participants’ task was to start at the center and get out of the maze as quickly as possible, without lifting the pencil off the paper. The dependent measure was the mean time taken on the last two mazes (in seconds).

General Procedure

All participants were tested individually in a session of about an hour and a half. The presentation order of the different items, trials, and conditions within tasks, if any, was either originally fixed or determined randomly and then held constant for all participants. Similarly, the testing order of the fourteen tasks was fixed for all participants in order to minimise any measurement error due to participant by order interaction. The testing order was as follows: dual-processing task, dual-storage task, verbal fluency tests, backward verbal span task, backward visuospatial span task, random letter-generation, problem solving, maze, Trail-Making test, Stroop test, and Hayling test.

Results

Description of Participants’ Performance

Descriptive statistics for the variables in the study are presented in Table 1. The hypothesis of a normal distribution could not be rejected for the dual-processing, dual-storage, semantic fluency, alternating fluency, random letter-generation, and the Stroop variables (see Table 1: Shapiro-Wilk normality test, 1965). For the other variables, the Shapiro-Wilk test results led us to reject the normal distribution hypothesis. However, the distributions of these variables had an unimodal shape, and all were centered and sufficiently discriminatory to be input into the planned analyses. When the data recording allowed it, internal reliability estimates for the tasks included in the PCA were obtained using the split-half correlation, adjusted by the Spearman-Brown prophecy formula. As seen in Table 1, the reliability estimates were relatively low (except for the backward verbal span, random letter-generation and Hayling tasks), which is a characteristic often reported for executive tasks (see Miyake et al., 2000).
Table 1. Descriptive Analysis of the Variables in the Study (N = 65)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Shapiro-Wilks W</th>
<th>Reliability*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual-processing</td>
<td>0.56</td>
<td>0.11</td>
<td>0.32</td>
<td>0.90</td>
<td>0.97</td>
<td>0.62</td>
</tr>
<tr>
<td>Dual-storage</td>
<td>17.63</td>
<td>3.02</td>
<td>10</td>
<td>24</td>
<td>0.98</td>
<td>0.44</td>
</tr>
<tr>
<td>Letter fluency</td>
<td>13.17</td>
<td>3.50</td>
<td>7</td>
<td>22</td>
<td>0.96*</td>
<td>n.p</td>
</tr>
<tr>
<td>Semantic fluency</td>
<td>20.83</td>
<td>4.29</td>
<td>11</td>
<td>31</td>
<td>0.98</td>
<td>n.p</td>
</tr>
<tr>
<td>Alternating fluency</td>
<td>7.07</td>
<td>1.60</td>
<td>3</td>
<td>11</td>
<td>0.95</td>
<td>n.p</td>
</tr>
<tr>
<td>Backward verbal span</td>
<td>7.87</td>
<td>2.02</td>
<td>4</td>
<td>12</td>
<td>0.95 **</td>
<td>0.76</td>
</tr>
<tr>
<td>Backward visuospatial span</td>
<td>9.52</td>
<td>1.22</td>
<td>7</td>
<td>12</td>
<td>0.93**</td>
<td>0.53</td>
</tr>
<tr>
<td>Random letter-generation</td>
<td>65.10</td>
<td>9.14</td>
<td>44</td>
<td>85</td>
<td>0.99</td>
<td>0.72</td>
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<tr>
<td>Problem solving</td>
<td>51.50</td>
<td>30.68</td>
<td>9.89</td>
<td>136.17</td>
<td>0.94 **</td>
<td>0.45</td>
</tr>
<tr>
<td>Maze task</td>
<td>73.77</td>
<td>34.82</td>
<td>35.38</td>
<td>207.45</td>
<td>0.83 **</td>
<td>0.60</td>
</tr>
<tr>
<td>Trail-Making test</td>
<td>29.65</td>
<td>13.28</td>
<td>10</td>
<td>72.50</td>
<td>0.93 **</td>
<td>n.p</td>
</tr>
<tr>
<td>Stroop naming</td>
<td>-78.96</td>
<td>15.97</td>
<td>-115</td>
<td>-39</td>
<td>0.98</td>
<td>n.p</td>
</tr>
<tr>
<td>Stroop Shifting</td>
<td>-96.90</td>
<td>14.47</td>
<td>-140</td>
<td>-63.50</td>
<td>0.99</td>
<td>n.p</td>
</tr>
<tr>
<td>Hayling test</td>
<td>1751.98</td>
<td>1215.82</td>
<td>86.94</td>
<td>4949.51</td>
<td>0.94 **</td>
<td>0.83</td>
</tr>
</tbody>
</table>

* Internal reliability estimates were obtained using the split-half correlation adjusted by the Spearman-Brown prophecy formula.  
* p < .05; ** p < .01; n.p = not possible to compute, unfortunately the reliability estimates could not be calculated for these tasks because of the way we recorded the data at the time the experiment was run (mostly because there was only one RT or one measure per condition).

Study of the Relationships Among the Variables

For ease of interpretation, the directionality of the dependent measures was adjusted so that larger numbers always indicated better performance. The correlations between the variables are presented in Table 2.

The examination of the correlations between variables according to their order of administration in the test battery suggests that the testing order did not have a critical effect on the correlation patterns5.

---

5 Taking the variables in groups of five according to their order of administration, we can see that the correlations among the first five variables (dual-processing, dual-storage, letter fluency, semantic fluency and alternating fluency) were nonsignificant except for the two fluency variables (r(63) = 0.46, p<.01). Similarly, no significant correlations were obtained between the five middle variables (backward verbal span, backward visuospatial span, random letter-generation, problem-solving and maze) except for the backward visuospatial span and maze variables (r(63) = 0.36, p<.01), nor between the last four variables (Trail-Making, Stroop naming, Stroop shifting and Hayling test) except for the two Stroop test variables (r(63) = 0.52, p<.01). This means that tasks performed close to each other were not more correlated than were tasks performed far apart.
<table>
<thead>
<tr>
<th>Variables</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<th>10</th>
<th>11</th>
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<tr>
<td>Backward verbal span</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Backward visuospatial span</td>
<td></td>
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<td></td>
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<td></td>
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<td>-0.11</td>
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<tr>
<td>Dual-processing</td>
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<td>-0.13</td>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Dual-storage</td>
<td>-0.03</td>
<td>0.18</td>
<td>0.02</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Random letter-generation</td>
<td>-0.14</td>
<td>0.02</td>
<td>-0.01</td>
<td>0.31*</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Hayling test</td>
<td>0.19</td>
<td>0.11</td>
<td>-0.14</td>
<td>-0.02</td>
<td>0.43**</td>
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<tr>
<td>Trail-Making test</td>
<td>-0.17</td>
<td>0.22</td>
<td>-0.04</td>
<td>0.07</td>
<td>-0.06</td>
<td>-0.05</td>
<td></td>
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</tr>
<tr>
<td>Stroop naming</td>
<td>0.27*</td>
<td>-0.11</td>
<td>-0.15</td>
<td>0.26*</td>
<td>0.24</td>
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<tr>
<td>Stroop shifting</td>
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<td>-0.02</td>
<td>-0.13</td>
<td>0.21</td>
<td>0.17</td>
<td>0.01</td>
<td>-0.05</td>
<td>0.52**</td>
<td></td>
<td></td>
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<tr>
<td>Semantic fluency</td>
<td>0.14</td>
<td>-0.20</td>
<td>0.03</td>
<td>0.03</td>
<td>0.55**</td>
<td>0.36**</td>
<td>-0.10</td>
<td>-0.02</td>
<td>0.08</td>
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<td>Letter fluency</td>
<td>0.27*</td>
<td>-0.07</td>
<td>0.08</td>
<td>0.04</td>
<td>0.25*</td>
<td>0.37**</td>
<td>-0.006</td>
<td>-0.003</td>
<td>-0.09</td>
<td>0.46**</td>
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<tr>
<td>Alternating fluency</td>
<td>0.22</td>
<td>-0.18</td>
<td>-0.05</td>
<td>-0.04</td>
<td>0.12</td>
<td>0.18</td>
<td>-0.01</td>
<td>0.08</td>
<td>0.01</td>
<td>0.22</td>
<td>0.13</td>
<td></td>
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<tr>
<td>Problem solving</td>
<td>0.22</td>
<td>-0.04</td>
<td>0.07</td>
<td>0.16</td>
<td>-0.07</td>
<td>-0.01</td>
<td>-0.03</td>
<td>0.18</td>
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<td>-0.05</td>
<td>0.10</td>
<td>-0.002</td>
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</tr>
<tr>
<td>Maze task</td>
<td>-0.20</td>
<td>0.36**</td>
<td>0.09</td>
<td>0.16</td>
<td>-0.13</td>
<td>-0.03</td>
<td>0.27*</td>
<td>-0.14</td>
<td>-0.18</td>
<td>-0.03</td>
<td>0.05</td>
<td>-0.28*</td>
<td>0.15</td>
</tr>
</tbody>
</table>

*p < .05; **p < .01

A first glance at the correlation matrix showed that overall, there were very few significant correlations (14 out of a possible 91). As might be expected, correlations within functions were not particularly higher than correlations between functions. Indeed, for the tasks involving coordination processes (dual-processing, dual-storage, backward verbal span and backward visuospatial span), no significant correlations were obtained. Tasks with coordination of storage and processing of different kinds of material (verbal vs. visuospatial) were not correlated, nor were those involving the simultaneous coordination of two processing operations or two storage operations. For the tasks requiring inhibition processes, there were two main groups of highly correlated tasks. The first group included random letter-generation (RLG), semantic fluency (SVF), letter fluency (LVF), and the Hayling test (HT) \[ r_{RLG,SVF}(63) = 0.55, p < .01; r_{RLG,LVF}(63) = 0.25, p < .05; r_{RLG,HT}(63) = 0.43, p < .01; r_{HT,SVF}(63) = 0.36, p < .01; r_{HT,LVF}(63) = 0.37, p < .01; r_{SVF,LVF}(63) = 0.46, p < .01]. The second group included the two Stroop test conditions \[ r(63) = 0.52, p < .01]. Moreover, no significant correlations were obtained between the alternating tests involving prior response-mode inhibition, i.e., the alternating fluency test, the Trail-Making test, and the shifting condition of the Stroop test. For the tasks involving controlled activation in memory, there was a significant correlation between the letter and semantic fluency tests \[ r(63) = 0.46, p < .01]. In contrast, no significant association was obtained between the letter and semantic fluency tasks and the alternating fluency task. Finally, the correlation was nonsignificant between the two
tasks that involved planning processes (problem-solving task and maze task).

Search for Underlying Abilities

A PCA was applied to these data. We retained all variables except the letter fluency task\(^6\). Contrary to what has been observed in some populations and which led us to include both measures in the study, the letter and semantic fluency tasks were here significantly correlated, making it not very useful to include both in the factor analysis. Thus, 13 variables were included in the PCA, which provided a satisfactory participant-to-variable ratio (Gorsuch, 1983).

Determining the number of factors. The first criterion taken into consideration to determine the number of factors to extract was Kaiser-Guttman rule (Kaiser, 1960), which excludes factors with eigenvalues less than 1, because from a variance perspective such factors are not as important as an observed variable. This first criterion led to a five-factor solution\(^7\). The five-factor solution adequacy was confirmed by examination of the residual correlation matrix in the five-factor solution as well as in the four, the three, the two and the one-factor solutions (see Appendix). Thus, both the residual analyses and the Kaiser-Guttman rule suggested a five-factor solution.

Examining the retained factorial solution. The five-factor solution obtained is presented in Tables 3a (eigenvalues and percentage of explained variance) and 3b (eigenvalues and loadings after varimax orthogonal rotation\(^8\)). The decision criterion for the meaningfulness of the correlations between variables and factors vary among researchers (Tabachnick & Fidell, 2001). For these data, we chose to follow Gorsuch's method (1983; see also Stevens, 1996); this author proposed taking the critical value of a correlation

\(^6\) When combined into a single variable representing the performance obtained on both fluency tasks, the semantic fluency task had the highest correlation with the combined variable \(r(63) = 0.88, p<.01\); versus \(r(63) = 0.82, p<.01\) with the letter fluency task) indicating it is a better indicator of the processes shared by the corresponding tasks.

\(^7\) Note that another often used criterion is the scree test (Cattell, 1966). However, results of the scree test are less obvious (and reliable) when each factor does not have several variables with high loadings and/or when the sample size is not very large (Gorsuch, 1983), which is the case in the present study. It is then more appropriate to perform several factor analyses, each time specifying a different number of factors, and to examine the residual correlation matrix (Tabachnick & Fidell, 2001) which is obtained by subtracting the reproduced correlation matrix from the observed correlation matrix.

\(^8\) Adequacy of rotation was confirmed by presence of simple structure in the loading matrix (see Table 3b) and by examination of pairwise plots of factor loadings following orthogonal rotation that also indicated simple structure (Tabachnick & Fidell, 2001).
coefficient for a given level of significance and to double it. Given our sample size, loadings greater than .488 at the .05 level of significance, and loadings greater than .634 at the .01 level of significance, met our criterion. Therefore, loadings in excess of .488 were considered significant, and loadings in excess of .634 were considered particularly high.

<table>
<thead>
<tr>
<th>Table 3a. Eigenvalue and Percentage of Explained Variance for the Five-Factor Solution before Orthogonal Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factor</strong></td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Factor 1</td>
</tr>
<tr>
<td>Factor 2</td>
</tr>
<tr>
<td>Factor 3</td>
</tr>
<tr>
<td>Factor 4</td>
</tr>
<tr>
<td>Factor 5</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Table 3b. Results of the Principal Components Analysis with Varimax Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
</tr>
<tr>
<td>Backward visuospatial span</td>
</tr>
<tr>
<td>Maze task</td>
</tr>
<tr>
<td>Trail-Making test</td>
</tr>
<tr>
<td>Stroop naming</td>
</tr>
<tr>
<td>Stroop shifting</td>
</tr>
<tr>
<td>Dual-storage</td>
</tr>
<tr>
<td>Random letter-generation</td>
</tr>
<tr>
<td>Semantic fluency</td>
</tr>
<tr>
<td>Hayling test</td>
</tr>
<tr>
<td>Problem solving</td>
</tr>
<tr>
<td>Backward verbal span</td>
</tr>
<tr>
<td>Dual-processing</td>
</tr>
<tr>
<td>Alternating fluency</td>
</tr>
<tr>
<td><strong>Eigenvalue</strong></td>
</tr>
<tr>
<td><strong>Explained Variance (%)</strong></td>
</tr>
</tbody>
</table>

* *p < .05; ** *p < .01

**Factor 1** was highly loaded by the backward visuospatial span and maze tasks, and in the second place by the Trail-Making test. The backward span task requires manipulating a sequence of taps retained in memory in order to be reproduced backwards. The maze task involves processing visuospatial information about current moves through the maze while keeping track of the location of the goal. The Trail-Making test implies alternating between connecting letters and numbers spread across a sheet of paper, which requires visuospatial processing ability. Thus, the most salient characteristic shared
by these tasks appears to be the ability to simultaneously maintain and manipulate some visuospatial information.

Factor 2 was highly loaded by the Stroop “naming” and the Stroop “shifting” conditions, and in the second place by the dual-storage task. In the two Stroop test conditions, the selection of target information is disrupted by the presence of distracting information and therefore the subject has to resist interference and inhibit information that is irrelevant. The dual-storage task requires simultaneously maintaining an increasing number of words and their respective locations. Analysis of this task suggested that another underlying component might be an ability to resist interference; specifically, words and locations from previous trials have to be classified as irrelevant and suppressed since they are likely to interfere with the recall of currently relevant items. Although it seems reasonable to consider that both tasks involve some inhibitory control, it is not clear whether the required inhibitory processes are of the same kind; in the Stroop task, irrelevant information is present in the external environment with explicit instructions to resist interference, whereas in the dual-storage task irrelevant items are mentally represented and inhibition of prior information is implicit. Thus in both cases inhibition prevents irrelevant information from entering into the focus of attention, although in one case it is a classical selective attention process, and in the second, it is more a question of an internally focused selective attention process. Although conceptually separable, the two types of inhibition may be somewhat related, which might have led to the moderate contribution of the dual-storage task on this factor. Therefore, this factor was interpreted as reflecting the ability to resist interference i.e., the ability to inhibit irrelevant information so as to enable efficient processing of relevant material.

Factor 3 was highly loaded by the random letter-generation task, the semantic fluency test, and the Hayling test. Correct performance on these tasks requires both inhibition of a dominant response that may be automatically activated in working memory, and controlled retrieval from LTM. The random letter-generation task involves inhibiting the natural tendency to produce letters in alphabetical order while strategically searching in LTM (for example, in order to produce a letter that does not come after the one just given). Likewise, the verbal fluency test requires inhibiting the automatic activation of preexisting semantic associations and/or previously produced items while conducting a controlled search to access new items. Finally, in the Hayling test, sentences must be completed with an unrelated word, which requires inhibiting a highly predictable word while actively searching for a word that fits with the instructions. Therefore, this factor appears to be linked to the ability to implement processes that inhibit a prepotent response, in association with LTM retrieval processes.

Factor 4 was highly loaded by the arithmetic problem-solving task and the
backward verbal span test. The backward span task requires manipulating a series of digits held in memory in order to recall them backwards. The arithmetic problem-solving task involves manipulating numerical data while maintaining the results of the successive steps in order to make the calculations required to solve the problem. Thus, the characteristic shared by the two tests that loaded on this factor appears to be the ability to simultaneously maintain and manipulate some verbal (numerical) information.

Finally, Factor 5 differed from the other factors detected, because only one variable contributed significantly to this factor: the dual-processing task. This task is the only one that requires coordinating two different types of processing without storage. The fifth factor may therefore represent the ability to coordinate different types of processing when no memory storage is involved.

We must be cautious in interpreting factors defined by only one or two variables (Tabachnick & Fidell, 2001), as is the case here for Factors 4 and 5. However, the three first factors were unaffected by the presence or the absence of a fourth and/or a fifth factor in the retained factorial solution. Moreover, variables that loaded significantly on Factor 4 did not load significantly on Factors 1 to 3 regardless of the retained solution. Furthermore, the dual-processing task loaded significantly only on Factor 5. Although Factor 5 was poorly defined, we must keep in mind that performance on the dual-processing task was independent of Factors 1 to 4.

**Discussion**

In this study, our goal was to determine what independent factors (i.e., what distinct abilities) might underlie performance on a series of tasks, selected because as a set, they potentially call upon all the processes assumed to be involved in the functions classically attributed to the CE.

First, the very small number of significant intercorrelations and the emergence of several independent factors obtained in the present study support the idea of a fractionation of the CE functioning. This result is in line with a number of studies demonstrating neuropsychological or correlational dissociations of executive functioning in various target populations, including brain-damaged patients (e.g., Burgess & Shallice, 1994, 1996; Duncan et al., 1997), young adults (Letho, 1996; Miyake et al., 2000), and elderly adults (e.g., Robbins et al., 1997).

Second, an interesting result of our study is that a theoretical fractionation of the CE functioning in terms of general functions (coordination, inhibition, LTM retrieval and planning) as originally proposed by Baddeley (1996), does not seem to correspond to an empirical reality. Indeed, our findings indicate
that the functions attributed to the CE may not each represent a unified single, independent ability, but rather each function relies on several distinct abilities; these findings suggest more fine-grained dissociations within the considered functions.

Indeed, the results suggest that several independent abilities may accomplish a coordination function. In light of the nonsignificant correlations between the different coordination tasks, it is legitimate to conclude that different abilities are in fact at play, depending on whether what has to be coordinated is two different processing operations without storage, two different storage operations without processing, or a storage operation and a processing operation. The fact that higher correlations were obtained between different tasks involving the same type of material (backward verbal span and problem-solving tasks; backward visuospatial span and maze tasks) than between similar tasks performed on different material (backward verbal and visuospatial span tasks; verbal and visuospatial planning tasks) suggests that the kind of task material (verbal vs. visuospatial) plays a key role in the correlation patterns. This point of view is compatible with the findings of Vom Hofe and Olivier (1997), who showed that the verbal versus visuospatial content is a determinant in the distinction of storage-and-processing working memory tasks, not whether the processing pertains to the stored material.

Further supporting the separability between verbal and visuospatial storage-and-processing abilities, the results of our factor analysis showed an opposition between a verbal factor (Factor 4) and a visuospatial factor (Factor 1). One can argue that this opposition does not simply reflect a separation in the related slave systems (Baddeley, 1986; Baddeley & Hitch, 1974), but rather a separation within the CE. We actually examined the relationships between the tasks that load on these two factors and the forward parts of the span tasks, which were included as control measures of verbal and visuospatial storage abilities. We found that the forward visuospatial span task was not significantly correlated with any task that contributed to Factor 1 (backward visuospatial span task, maze test, and Trail-Making test). The forward verbal span task was significantly correlated with the backward verbal span task ($r(63) = 0.40, p<.01$) while not with the problem-solving task, which are the two tasks that contributed to Factor 4. These findings suggest that the makeup of Factors 4 and 1 cannot be interpreted solely in terms of the verbal versus visuospatial storage ability, but that it is more a question of an ability to coordinate both storage and manipulation operations that bear on verbal versus visuospatial information. Similarly, Shah and Miyake (1996) showed that beyond the role played by the storage requirement, the nature of both the processing and storage requirements is responsible for the dissociations they observed between verbal and visuospatial storage-and-processing working memory tasks (see also Bayliss, Jarrold, Gunn, &
Baddeley, 2003). Moreover, we note here that, although it requires verbal processing, the dual-processing task did not load significantly on Factor 4, which indicates that the need to process verbal information is not the only determinant of this factor.

The body of findings obtained in this study thus suggest that the coordination function of the CE may be handled by at least two distinct abilities, depending on the nature of the material stored and manipulated (verbal vs. visuospatial). The factor analysis pointed up a third coordination ability, however the related factor (Factor 5) was loaded by a single task (dual-processing task) which was the only one to involve coordinating different processing operations without storage. Further research would be needed to verify whether several dual-processing tasks load on a single factor determining such a specific coordination ability. In any case, the dual-processing task's unique loading on a factor independent of Factor 1 and 4 is in line with studies where performance patterns have differed according to whether what has to be coordinated is processing and storage, or processing alone (Van der Linden et al., 1992).

Concerning the planning function, the results did not indicate that a single ability underlies performance on planning tasks. Similarly, using confirmatory factor analysis, Kafer and Hunter (1997) failed to show that four tests known to call upon planning ability measure the same construct. In the present study, each of the planning tests (problem-solving and maze tasks) was found to be associated with a different coordination test (backward span test), which contributed to the emergence of two independent factors (Factors 1 and 4). Thus, the need to simultaneously store and manipulate information may have been responsible for the clustering observed. One possible explanation for this result is that the tasks chosen did not actually assess planning ability. Although the current study cannot disprove this possibility, we may argue that the face validity of these tasks (indexed by their wide clinical use) suggests that they do measure some planning ability (Gil, 1996; Lezak et al., 1994). In addition, research has shown that they are sensitive to executive dysfunction in clinical populations (e.g., Luria, 1978; Mack & Patterson, 1995). A more promising explanation - which has been raised by other authors (Kafer & Hunter, 1997; Miyake et al., 2000) - may be that planning is such a complex construct that it is not easily measured by any one task. If this is the case, then the tasks we chose might have assessed only some aspect of this complex construct, namely, the ability to coordinate the storage and manipulation of information.

Finally, the inhibition function appears to be fulfilled by different abilities, depending on the processes required by the task. Our analysis points to two independent abilities that perform an inhibition function (Factor 2 and 3). One of these two abilities was also involved in controlled LTM retrieval.
Thus, Factor 3 can be considered to reflect a capacity that associated two kinds of processes: controlled LTM retrieval, and inhibition of information automatically activated in working memory. These two types of processes indeed appear to be tightly linked in the three tasks that contributed the most to the emergence of this factor: verbal fluency, Hayling test, and random generation. Significant relationships between these tests have been noted elsewhere in the literature, and the interpretations proposed to account for them focus on the inhibition they demand (e.g., Baddeley et al., 1998; Collette et al., 1999). The clustering of these three tasks on the same factor (distinct from another factor determined by inhibition processes without associated controlled search processes – Factor 2 – see below), suggests that strategic retrieval is most likely related to the necessity of inhibiting automatically activated but irrelevant information (activation induced by the very nature of the task), as if the “deactivation” of this mental representation were a necessary step in accessing and retrieving new items. This viewpoint is in line with many studies that clearly demonstrate the involvement of inhibition in controlled memory retrieval, both of information that is irrelevant, but activated automatically (upon presentation of a cue and/or a previously retrieved item), and of already retrieved information that has become irrelevant (e.g., Anderson & Spellman, 1995; Hasher et al., 1999; Radvansky, 1999; Rosen & Engle, 1997, 1998). Thus, controlled memory retrieval and the inhibition of activated, but irrelevant information jointly imply the same ability, at least in this sample.

The second factor associated with the inhibition function (Factor 2) was determined by the interference conditions of the Stroop test and the dual-storage task, which were thought to involve inhibitory processes without requiring strategic search and retrieval from LTM. Although inhibitory processes involved in these tasks may seem rather different, it has nonetheless been argued that they may be in some way related to one another, since in both tasks inhibition prevents irrelevant information to enter the focus of attention.

The present results thus suggest different types of inhibitory mechanisms: those associated with controlled searching and retrieval, whose role would be to inhibit prepotent responses that may be automatically activated in working memory, and those associated with selective attention, whose role would be to prevent distracting information from interfering with processing. This interpretation is consistent with previous conceptual distinctions of inhibition-related functions (e.g., Hasher et al., 1999; Kok, 1999; Nigg, 2000), and with empirical studies that suggest that different inhibition tasks tap separable processes (Friedman & Miyake, 2004; Kramer et al., 1994).

As a whole, this study suggests that the different facets of executive functioning rely, at least in part, on distinct abilities reflecting the existence of
independent though interactive executive processes: inhibiting a prepotent response with controlled retrieval, inhibiting distracting information, coordinating the storage and processing of verbal information, coordinating the storage and processing of visuospatial information, and possibly, coordinating different processing operations without storage. These distinct abilities, each determined by one or more executive processes, may cooperate in ensuring the efficiency of the functions traditionally ascribed to the CE of working memory.

One important finding that must be stressed is that the inhibition-related abilities were found to be independent of the coordination-related abilities. This result concurs with Collette et al.’s (1999) data, which indicated that inhibition and coordination are two independent aspects of executive functioning. Thus, the current exploratory analysis supports the hypothesis of a dissociation between coordination and inhibition functions, and suggests moreover that each of them rely on distinct abilities which may reflect distinct coordination-related functions (notably according to the nature of the material to coordinate) and distinct inhibition-related functions (notably depending on the processes required by the situation). Although the present study illustrates the benefits of the classical factor-analytic approach for defining more accurate research axes and assessment tools, we are aware of the weaknesses of such techniques for theorizing about the organisation of executive functioning (Miyake et al., 2000). This is why the structure of the CE functioning hypothesized on the basis of the present data should be regarded as a starting point for further research.

To conclude, the present study raises the question of executive assessment as the tasks often used in cognitive and neuropsychological studies to assess similar abilities – as they are assumed to involve comparable processes – may not necessarily rely on a same ability (i.e., are not associated with the same factor). For example, both the alternating fluency and the Trail-Making tasks involve shifting processes; likewise, the problem-solving task and the maze task both involve planning processes, however they are associated with different factors. This study also stresses the need to take into account the interrelationships between the different operations required for a participant to carry out a given activity, and to consider the possibility that success in a given task may necessitate the joint implementation of different executive processes (e.g., controlled LTM retrieval would jointly implicate activation and inhibition processes). A fine-grained analysis of executive functioning based on a breakdown into elementary processes inevitably runs up against a number of obstacles, such as the problem of selecting suitable tasks to assess the targeted process(es), but it is nonetheless a worthwhile research endeavor. The present study is but a first step in this direction.
References


Intelligence, 31, 167-193.


Appendix

Adequacy of the Different Factor Solutions (One, Two, Three, Four, and Five-Factor Solution) to the Data: Residual Analyses and Percentage of Explained Variance

<table>
<thead>
<tr>
<th></th>
<th>One-Factor Solution</th>
<th>Two-Factor Solution</th>
<th>Three-Factor Solution</th>
<th>Four-Factor Solution</th>
<th>Five-Factor Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of correlations correctly reproduced: % residuals &gt; .101</td>
<td>53.84</td>
<td>47.43</td>
<td>34.61</td>
<td>30.76</td>
<td>25.64</td>
</tr>
<tr>
<td>Accuracy of reproduction of the correlation coefficients (off-diagonal elements):</td>
<td>.119</td>
<td>.106</td>
<td>.083</td>
<td>.080</td>
<td>.072</td>
</tr>
<tr>
<td>Mean (standard deviation) of the absolute values of the residuals</td>
<td>(.078)</td>
<td>(.073)</td>
<td>(.057)</td>
<td>(.058)</td>
<td>(.052)</td>
</tr>
<tr>
<td>Accuracy of reproduction of the variables (diagonal elements):</td>
<td>.815</td>
<td>.680</td>
<td>.553</td>
<td>.450</td>
<td>.365</td>
</tr>
<tr>
<td>Mean (standard deviation) of the absolute values of the residuals</td>
<td>(.140)</td>
<td>(.160)</td>
<td>(.218)</td>
<td>(.150)</td>
<td>(.129)</td>
</tr>
<tr>
<td>Explained variance (%)</td>
<td>18.46</td>
<td>32.12</td>
<td>44.87</td>
<td>54.83</td>
<td>63.46</td>
</tr>
</tbody>
</table>

Note. The residual correlation matrix is obtained by subtracting the reproduced correlation matrix from the observed correlation matrix. Adequacy of the reproduction of the correlation matrix was estimated following Gorsuch (1983) and Tabachnick and Fidell (2001).