Brain and Cognition 79 (2012) 1–11

Contents lists available at SciVerse ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Processing speed and executive functions in cognitive aging: How to disentangle their mutual relationship?

Cédric T. Albinet *, Geoffroy Boucard, Cédric A. Bouquet, Michel Audiffren

CeRCA (CNRS – UMR 6234), Faculty of Sport Sciences, University of Poitiers, France

ARTICLE INFO

Article history:
Accepted 2 February 2012
Available online 2 March 2012

Keywords:
Executive functions
Processing speed
Cognitive aging

ABSTRACT

The *processing-speed theory* and the *prefrontal-executive theory* are competing theories of cognitive aging. Here we used a theoretically and methodologically-driven framework to investigate the relationships among measures classically used to assess these two theoretical constructs. Twenty-eight young adults (18–32 years) and 39 healthy older adults (65–80 years) performed a battery of nine neuropsychological and experimental tasks assessing three executive function (EF) components: Inhibition, Updating, and Shifting. Rate of information processing was evaluated via three different experimental and psychometric tests. Partial correlations analyses suggested that 2-Choice Reaction Time (CRT) performance is a more pure measure of processing speed than Digit Symbol Substitution Test (DSST) performance in the elderly. Hierarchical regression analyses showed that, although measures of processing speed and EF components share mutual variance, each measure was independently affected by chronological age. The unique adverse effect of age was more important for processing speed than for EF. The *processing-speed theory* and the *prefrontal-executive theory* of cognitive aging were shown not to be mutually exclusive but share mutual variance. This implies the need to control for their mutual relationship before examining their unique potential role in the explanation of age-related cognitive declines. Caution has still to be taken concerning the tasks used to evaluate these theoretical constructs.

1. Introduction

There is considerable interest in the area of cognitive and brain sciences in understanding and explaining the age-related declines in cognitive functioning. Numerous theories and models, from neurophysiological perspectives to more behavioral and cognitive perspectives, have been proposed (see Cabeza, Nyberg, & Park, 2005; Reuter-Lorenz & Park, 2010; Schaie & Willis, 2011, for reviews). To date, the most influential and empirically tested models in neuropsychology and cognitive literature are the *processing speed* theory (Salthouse, 1996) and the *prefrontal-executive* theory (West, 1996). Speed of information processing and executive functioning have been thus proposed as theoretical constructs and many researchers have studied them as candidates responsible for mediating (or even explaining), either in whole or in part, the age-related declines in cognitive functioning. As we will review, the conclusions are remarkably mixed: around half of the studies support the slowdown in processing speed and the other half support the decline in executive functions (EF) to be the actual mediator. However, the relationships between these two theoretical models and the tasks used to test them are understudied and poorly understood. It is necessary to determine if speed of information processing and EF are clearly independent, and to elucidate each constructs' explanatory contribution to the understanding of general age-related cognitive decline. The principal objective of the present study is to propose a theory-based, methodological framework concerning the *operationalization* and the measurement of EF and speed of information processing, with the aim of examining their potential mutual relationships.

1.1. The processing-speed theory and the prefrontal-executive theory of cognitive aging

Over the last two decades, the so-called global and local theories of cognitive aging have received considerable attention. On the one side, one of these theories, referred to as the *processing-speed* theory, contends that age-related cognitive declines can be accounted for by a single or *global* mechanism: the generalized slowing of cognitive processing. This generalized slowing is thought to be due in a large part to a diffuse or global deterioration of white matter integrity throughout the brain. On the other side, the *prefrontal-executive* theory states that *local* structural and functional changes in frontal cortex areas lead to specific declines in executive abilities, which in turn lead to more general cognitive deficits.

* Corresponding author. Address: CeRCA, Université de Poitiers, bâtiment A5, 5 rue Théodore Lefebvre, 86000 Poitiers, France. Fax: +33 (0)5 49 45 46 57.
E-mail address: cedric.albinet@univ-poitiers.fr (C.T. Albinet).

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doi:10.1016/j.bandc.2012.02.001

Following years of empirical and theoretical work, Salthouse (1996) proposed the *processing-speed theory* of cognitive aging which assumes that the major factor contributing to the negative age-related effects in fluid cognition measures is a reduction in the speed with which fundamental cognitive operations can be executed (see also Salthouse, 1991, 1994, 2000). Accordingly, this generalized slowing has a detrimental effect not only on the quantitative but also on the qualitative dimension of performance for a variety of cognitive skills. For this author, cognitive performance is degraded because relevant basic cognitive operations are executed too slowly and hence, slowed processing reduces the amount of simultaneously available information needed for higher level processing (see Salthouse, 1996). Recent neuroimaging studies have proposed that a disruption of white matter integrity in the whole brain may be at the core of this generalized slowing (see Gunning-Dixon, Brickman, Cheng, & Alexopoulos, 2009; Penke et al., 2010; Salami, Eriksson, Nilsson, & Nyberg, 2011; but see also Kennedy & Raz, 2009 for clear dissociations between specific cognitive functions and specific white matter regions). Indeed, age-related differences in white matter integrity have been found to influence different measures of cognitive functioning, particularly processing speed (see Madden, Bennett, & Song, 2009 for a review). Since Salthouse seminal work, numerous studies have supported the processing-speed theory and have shown that controlling for processing speed, strongly reduces or even eliminates age differences in such domains as memory (Bryan & Luszcz, 1996; Clarys, Isingrini, & Gana, 2002), general intelligence and reasoning (Hertzog & Bleckley, 2001; Zimprich & Martin, 2002), or spatial abilities (Finkel, McArdle, Reynolds, & Pedersen, 2007; see Verhaeghen & Salthouse, 1997 for a review). Taken together, these results offer a solid foundation for the global approach and for the slowing of processing speed as the key responsible of cognitive aging (see Deary, Johnson, & Starr, 2010 and Rabbitt et al., 2007 for recent development and interpretation).

At the same time, another theoretical model of cognitive aging, the *prefrontal-executive theory*, came from different lines of research and was formalized by West (1996), following the work of Dempster (1992). The rationale for this model is that EF, which are thought to involve higher-order functions of control and coordination of more basic or fundamental cognitive operations (see below) and the anterior brain structures (frontal lobes), are especially sensitive to the effects of normal aging (see Phillips & Henry, 2008). Neuropsychological and neuroimaging studies have shown that an important substrate for executive processes are the frontal lobes, which are the cerebral structure the most vulnerable to the advancing in age (see Raz & Rodrigue, 2006; Raz, Rodrigue, Kennedy, & Acker, 2007; West, 1996). Moreover, Duncan and colleagues (2000) have shown that "*general intelligence derives from a specific frontal system important in the control of diverse forms of behavior*" (p. 457). Given the important age-related declines in these functions as well as their underpinning cerebral structures, the hypothesis of prefrontal-executive decline appears to be also a good candidate for explaining the age effects on cognition. Numerous studies have then documented important age-related decrements in EF (Fisk & Sharp, 2004; Jurado & Rosselli, 2007; see Phillips & Henry, 2008 for a review) and their mediating role in the decline due to normal aging in memory (Clarys, Bugaiska, Tapia, & Baudouin, 2009; Parkin, 1997), strategy and meta-cognition (Bouazzaoui et al., 2010; Taconnat et al., 2006) or activities of daily living (Vaughan & Giovanello, 2010).

Theory-dedicated lines of research have provided empirical evidence for the *processing-speed theory* and to the *prefrontal-executive theory*. A few studies have examined, in the same pool of data, the validity of both speed of information processing and EF as mediators of normal aging on various cognitive domains. However, the results of these studies are remarkably mixed. Clarys and collaborators (Clarys et al., 2002, 2007) and Parkin and Java (2000) found that processing speed emerges as a more fundamental mediator of age-related differences than executive functioning in a number of episodic memory measures. Furthermore, some authors argued against the reality of EF as a distinct construct relevant to the aging literature (Parkin, 1998; Salthouse, 2005; Salthouse, Atkinson, & Berish, 2003). For instance, Salthouse and coworkers have proposed that EF may in fact represent a combination of more well-established cognitive abilities, such as reasoning and perceptual speed. Others showed that controlling processing speed eliminates age differences in central executive functioning (Fisk & Sharp, 2004; Fisk & Warr, 1996). However, almost as many studies reported that executive functioning is a more fundamental factor mediating age-related differences in episodic memory than processing speed (Baudouin, Clarys, Vanneste, & Isingrini, 2009; Bugaiska et al., 2007) or showed that age-related executive decline persists beyond the slowing in processing speed (Keys & White, 2000). Additionally, some studies have shown that processing speed and prefrontal-executive functions are independent contributors to the negative effects of aging on fluid intelligence (Bugg, Zook, DeLosh, Davalos, & Davis, 2006; Charlton et al., 2008; Schretlen et al., 2000).

It is very difficult to draw conclusions from the available research for at least three reasons. First, the great heterogeneity of tasks used to evaluate either processing speed or EF makes the comparison of the results very difficult. Second, there is a lack of clear consensus on the theoretical framework concerning the construct of executive functions and the way to evaluate them as well as processing speed. Third, and most important, the shared commonality between the two constructs has not been adequately studied.

1.2. The need for a theory-based methodological framework

A limitation of past studies is that they used very different tasks or lack a clear theory-based rationale for task selection. Concerning the EF construct, some studies used only one task to infer executive performance; e.g., typically a multi-component neuropsychological test such as the Wisconsin Card Sorting Test (WCST, Bugaiska et al., 2007; Schretlen et al., 2000) or the Tower of Hanoi test (Bugg et al., 2006). Others used the same task to evaluate different executive processes; for instance the Stroop task both for inhibition (Salthouse et al., 2003; Vaughan & Giovanello, 2010) and flexibility (Charlton et al., 2008). These examples point out the need for a clear theoretically-driven framework to explicate the impact of EF on cognitive declines. Despite an extensive neuropsychological literature, the construct of EF has been difficult to operationalize. Executive functions refer to a set of cognitive processes whose principal function is to facilitate behavioral adaptation to new or complex situations, in particular when routines are inappropriate. These are thought to encompass formulation of goal and implementing of strategy, planning, action sequencing and monitoring, mental flexibility, inhibition and updating of working memory (see Bryan & Luszcz, 2000; Jurado & Rosselli, 2007; Rabbitt, 1997 for reviews). It appears thus that EF could be characterized by different fundamental executive processes that traditional neuropsychological tests are unable to clearly separate. Here we adopt the theoretical framework developed by Miyake and coworkers (2000) that proposes that EF is fractionated, with different tasks tapping executive processes that are at least partially independent, yet correlated enough to be a unique construct. Miyake et al. propose a three factor structure. These authors have shown in a college-students population, that EF can be subdivided into three separate components: Inhibition of prepotent responses, Updating of working memory, and mental set Shifting (Miyake et al., 2000). Few studies have examined whether or not this organization of EF is age-independent. Two studies replicated Miyake and collaborators' three-factor model (Fisk & Sharp, 2004; Vaughan & Giovanello, 2010), whereas another identified only two factors including Shifting and Updating but not Inhibition (Hull, Martin, Beier, Lane, & Hamilton, 2008). Again, the number and the nature of the tasks used to assess the different EF components seem to be of critical importance to understand this discrepancy (see Hull et al., 2008 for a discussion).

A limit concerning the EF construct is this problem of task impurity, inherent to the definition of EF in itself. This refers to the fact that it is very difficult to measure directly an EF because it is operating on other cognitive processes (Miyake et al., 2000; Rabbitt, 1997). Accordingly, to address these limitations in the present study, we used nine tasks for assessing the three postulated EF components: Inhibition, Shifting and Updating. By computing a composite score for each EF component, from three different experimental tasks tapping this specific component, we sought a more robust and reliable measure of performance reflecting more selectively the postulated component than each individual experimental task.

The construct of processing speed is much more clearly defined that the one of EF. However, many of the tasks used in past studies have not been very well controlled and often reflect more than pure processing speed. For example, numerous authors (Bryan & Luszcz, 1996; Charlton et al., 2008; Clarys et al., 2007; Parkin & Java, 2000; Salthouse et al., 2003) have used the Digit Symbol Substitution Task (DSST) from the Wechsler adult intelligence scale (WAIS, Wechsler, 1981, 1997) as a measure of processing speed. However, this task is known to involve many other processes than just processing speed; e.g., working memory, visuo-manual coordination, and intelligence (see Parkin & Java, 2000; Piccinin & Rabbitt, 1999; Salthouse, 1992). Moreover, Baudouin et al. (2009) recently showed that the DSST actually involves processing speed and executive processes, particularly in the elderly. These results may explain why DSST performance appears often as the best mediator of age-related cognitive declines. But, as a consequence, it is not possible to isolate the roles of processing-speed and EF in this mediation. Salthouse, 1991, 1994, 1996, 2000 has presented extensive theoretical, methodological, and empirical work on processing speed. He isolated motor speed (with minimal cognitive requirements and reflecting primarily the speed of sensory and motor processes) and perceptual speed (involving various types of cognitive operations, such as comparison, substitution, or transformation, in addition to sensory and motor processes). He argued that perceptual speed is more important than motor speed as a mediator of cognitive aging because it is the speed of central operations that primarily contributes to the relations between age and measures of cognitive functioning (Salthouse, 1994, 1996). However, it is difficult to clearly control what the tasks used to evaluate these constructs (often paper and pencil tasks) really measure in terms of information processing, because they include both motor and cognitive processes, and they do not allow to fully control for the various types of cognitive operations involved. As an illustration of this problem, Salthouse (1994) admitted that motor speed and perceptual speed constructs are not really distinguishable and strongly correlated (i.e., $r = .93$).

One limit concerning the power of the *processing-speed* theory is then how processing speed is defined and experimentally measured. Again, to overcome this limit, we think it is important to use a well-defined theoretical framework and well-controlled experimental tasks. The amount of information given by a stimulus and the rate to process it, measured by the Reaction Time (RT), was formalized mathematically by the *so-called* Hick-Hyman's law (Hick, 1952; Hyman, 1953).[1] Within this framework, we can precisely control the quantity of information one has to process during an experimental RT task. In the present study, we used three different measures of processing speed; a simple auditory RT task (SRT), assumed to measure the speed of only basic sensory and motor processes (the stimulus and the required response are known and prepared in advance); a stimulus-response (S-R) compatible visual 2-choice RT (CRT) task, assumed to measure the speed to process 1 bit of information (see footnote 1); and the DSST from the WAIS III (Wechsler, 1997), assumed to involve both executive and speed processes. Note that, among these three tasks, only the CRT and the SRT allow to clearly quantify the amount of information to be processed (in the case of a 2-choice RT task, 1 bit of information). Concerning the SRT task, one has merely to detect the onset of the stimulus (because the nature of the stimulus, as well as the required response, are known in advance), and thus less than 1 bit of information is processed. Finally, the DSST does not clearly allow to quantify the amount of information to be processed because its performance involves various sensory, motor and cognitive processes, which are difficult to isolate in this paper and pencil task.

The objective of this study was to examine the relationships between measures used to assess two theoretical constructs, processing speed and EF. More specifically, using a theoretically-driven framework, we examined the mutual variance shared by these different measures of processing speed and prefrontal-executive functioning.

2. Material and methods

2.1. Participants

Twenty-eight young adults (11 men, 17 women) from 18 to 32 years of age ($M = 22.7 \pm 3.3$ years) and 39 older adults (17 men, 22 women) from 65 to 80 years ($M = 71.2 \pm 4.4$ years), free of any motor, cardiovascular, or neurological disease, volunteered for this study. Chi-square tests revealed that the proportion of men and women did not differ between the two age groups ($p > .05$). They all had normal or corrected visual acuity and were in good health according to their personal physician. Only the older participants were administered the MMSE and they all scored at least 26 out of 30 ($M = 28.5 \pm 1.2$). This study was approved by the local ethics committee and participants gave their written informed consent. Table 1 presents their demographic characteristics.

2.2. Evaluation of processing speed

2.2.1. Simple Reaction Time (SRT) task

This task was programmed and controlled with ERTS software. Participants had to respond to an auditory stimulus (a 100 ms, 2000-Hz tone) by pressing as quickly as possible a pre-defined key with their right thumb. At each trial, a fixation point (+) was briefly presented (80 ms) followed after a variable preparatory period by the tone. On some trials (catch trials), no tone occurred in order to avoid anticipation. After four training trials, participants performed one block of 40 test trials. The dependent variable was the mean RT for correct responses (*z*-score).

[1] Here we refer to the work of Hick (1952) and Hyman (1953), who mathematically formalized the relation between Reaction Time (RT) and the amount of information to process, based on Shannon and Weaver's mathematical theory of communication (1949). The Hick-Hyman's law states that RT is a linear function of the number of bits of information in the stimulus – with 1 bit of information being given by an event whose probability of occurrence (p) is ½ or 0.5. For instance, in a Choice Reaction Time (CRT) task with 2 stimuli, each having equal probability of occurrence, one has to process 1 bit of information given that $(p) = 1/2$.

Table 1
Characteristics of young and older adult participants.

	Young adults ($n = 28$)		Older adults ($n = 39$)		$F(1,65)$
	M	SD	M	SD	
Age (years)	22.7	3.3	71.2	4.4	2402***
Education (years)	15.6	1.6	12.1	3.9	16.2***
MMSE (max. = 30)	–		28.4	1.4	
Mill-Hill (part B; max. = 44)	33.8	2.9	36.7	5.4	6.8*

Values are mean (M) ± standard deviation (SD).
Note: MMSE = Mini Mental State Examination; Mill-Hill = French version of the Mill-Hill vocabulary scale (Deltour, 1993).
* $p < .05$.
*** $p < .0001$.

2.2.2. Choice Reaction Time (CRT) task

This task was programmed and controlled with ERTS software. Participants had to respond as quickly and accurately as possible to a visually-displayed arrow oriented to the right (>) or to the left (<), by pressing the spatially-compatible key with their right or left thumb (i.e., right thumb for >and left thumb for <). The arrows were displayed on the computer screen until the response was made. At each trial, a fixation point (+) was briefly presented (80 ms) followed after a variable preparatory period by the stimulus. After two training trials, participants performed a 16-trials practice block. Their mean CRT was calculated and displayed. Then, they performed two blocks of 44 test trials, in which they were instructed to try to be faster at each trial than their average RT for the practice block. The dependent variable was the mean RT for correct responses (z-score).

2.2.3. Digit Symbol Substitution Task

This was a subset of the WAIS III (Wechsler, 1997). This task involved a sheet of paper upon which a table of paired digits and symbols was displayed. Below the table were rows of paired boxes. In the upper box a digit was displayed and the participant's task was to fill in the blank lower box with the appropriate symbol from the table. Two minutes were allowed for the task and the dependent measure was the number of correctly completed symbols in that time (z-score).

2.3. Evaluation of executive functions

Participants completed a battery of experimental tasks evaluating EF. All the experimental tasks were computerized (except the Random Number Generation task) and, unless mentioned, were programmed and administered using E-Prime 1.1 software (Psychology Software Tools, Pittsburgh, PA). Below, we briefly present the experimental tasks used in this study. We carefully selected tasks known in the literature to tap each postulated target EF.

2.3.1. Inhibition

2.3.1.1. The Stroop task. The Stroop task (1935) was adapted for administration on a computer and to record individual vocal RT through a microphone. The millisecond-accurate voice key of the E-Prime® Serial Response Box™ was used to record vocal response latencies. Participants were instructed to say aloud the color of a target stimulus as quickly as possible on each trial. The experimenter transcribed participant's verbal responses which were scored offline as correct or incorrect for further data analysis. There were 24 neutral trials (a string of Xs in one of the four possible colors, blue, green, red, yellow), 24 congruent trials (e.g., French word for RED written in the color red), and 24 incongruent trials (e.g., French word for RED written in the color blue), for a total of 72 test trials. After the full explanation of the task and two examples, participants received 12 practice trials before the test trials. The dependent measure was the difference in RTs (ms) between the congruent and incongruent trials for correct responses.

2.3.1.2. The stop-signal task. This task was adapted from Logan, Cowan, and Davis (1984) and was programmed and controlled using ERTS software package (Beringer, 1994) allowing for millisecond accuracy. Participants were asked to respond as quickly as possible to visual stimuli (> or <, displayed until the response production) by pressing the corresponding key, but to stop (to inhibit) their motor response when an unpredictable auditory signal (a 100 ms, 2000-Hz tone) occurred. Participants performed several blocks of training trials in order to familiarize with the visual and auditory stimuli and the stop-signal task. Then, they performed a block of 84 training trials. Mean RT for correct responses to the visual stimuli were recorded. Finally, participants performed two blocks of 84 test trials. The stop signal occurred at five different delays after the visual stimulus, corresponding to 20%, 40%, 60%, 80%, or 100% of each participant individual mean RT (calculated from the preceding training block). The stop signal occurred on 25% of the trials, equally often at each delay. The dependent measure reflecting Inhibition performance for this task was the mean Stop-Signal Reaction Time (SSRT, see Logan & Cowan, 1984 for detailed computation of this score).

2.3.1.3. The Random Number Generation (RNG) task. This task was developed by Baddeley (1998) and is described more in detail elsewhere (Albinet, Tomporowski, & Beasman, 2006; Miyake et al., 2000). Briefly, participants had to say a number from one to nine aloud each time they heard a computer-generated tone every 1 second, such that they generated a string of numbers that would be as random as possible. The concept of randomness was clearly explained and the importance of maintaining a consistent response timing was emphasized. After a training period, 100 responses were recorded (usually during 100 sec.) and then analyzed using Towse and Neil's RgCalc software (1998). Successful performance on this task requires the efficiency of two executive functions (see Miyake et al., 2000; Towse & Neil, 1998): correct inhibition of overlearned schemas (i.e., counting) and correct updating of working memory (see below). The dependent measure reflecting Inhibition performance for this task was the total Adjacency score. Adjacency (A) describes the distribution of adjacent digits (in ascending or descending series) from the ordinal sequence of alternatives (i.e., 1–2; or 8-7-6) and is expressed as a percentage score. This score is calculated as follows:

$$A = 100 \times (\text{number of adjacent pairs}/\text{number of response pairs}) \quad (1)$$

A scores range between 0% (no neighboring pair) and 100% (only neighboring pairs).

2.3.2. Updating of working memory

2.3.2.1. The verbal running span task. In this task (adapted from Morris & Jones, 1990; see also Van der Linden, Bredart, & Beerten, 1994), lists of six, eight, ten, and twelve consonants were presented on the computer screen at a rate of one letter every two seconds. Participants were not informed about the length of each list before presentation, but they were asked to recall serially the last four items at the end of each list (strict forward serial recall). After four training lists, participants were presented 12 trial lists (three for each length). The dependent measure was the number of letters correctly recalled in the right order (max. = 48).

2.3.2.2. The spatial running span task. This task (adapted from Morris & Jones, 1990) is the spatial *equivalent* of the verbal running span. In this task, participants were presented a 4×4 empty matrix on the computer screen. Sequences of six, eight, ten, or twelve black dots were presented in one of the 16 cases of the matrix (no location was repeated in the same sequence), at a rate of one dot every two seconds. Participants were not informed about the length of each sequence before presentation, but they were asked to recall serially the last four dot's locations at the end of each sequence (strict forward serial recall) using the computer mouse. After four training sequences, participants were presented 12 trial sequences (three for each length). The dependent measure was the number of dots correctly recalled in the right order (max. = 48).

2.3.2.3. The RNG task. This task is the one detailed above. Towse and Neil's (1998) RgCalc software provides several indices of randomness tapping two executive processes (see Miyake et al., 2000; Towse & Neil, 1998). The dependent measure reflecting Updating performance for this task was the Redundancy score (R). R is a measure based on the relative frequency with which individual digits were used and is expressed as a percentage score. An R score of 0% indicates no redundancy (perfect equality of response alternative frequencies), and an R score of 100% indicates complete redundancy (the same response choice is used throughout). Details on the calculus method to obtain this score can be found in Towse and Neil's article.

2.3.3. Shifting

2.3.3.1. Dimension-switching task. This task was a version of the task-set reconfiguration paradigm (Monsell & Mizon, 2006; Rogers & Monsell, 1995). Stroop-like stimuli were presented on the computer screen. Responses to stimuli were right or left index presses made on a button box. The stimuli were the French words for LEFT or RIGHT enclosed in a left or right arrow, and displayed above or below the center of the white screen. In each trial, before stimulus onset, an asterisk was displayed at the location of the upcoming stimulus. After a delay of either 250 or 1750 ms, selected at random, the target stimulus then replaced the cue. Depending on the location of the stimulus, participants were to perform either the word task or the arrow task (counterbalanced across participants). On word-task trials, participants made a button press in the direction indicated by the word. On arrow-task trials, participants responded according to the direction indicated by the arrow. There were two kinds of blocks of trials. On *simple blocks*, the stimulus appeared always on the same location, requiring only to respond to one task at a time. On *mixed blocks*, the stimulus could appear above or below the center of the screen, requiring to switch from one task to another task. During the mixed blocks, the stimulus location was selected randomly, so that the probability of a task switch was 0.5. After two simple blocks of 36 trials and a mixed block of 16 practice trials, participants performed four mixed blocks of 36 trials and again two simple blocks of 36 trials. The dependent measure indexing flexibility in this task was the global switch cost for correct responses, calculated as RT difference (ms) between trials from the simple blocks and task-repeat trials (i.e. a trial n where the relevant task is the same as the task performed in trial $n - 1$) from the mixed blocks.

2.3.3.2. S-R compatibility switching task. This task was another version of the task-set reconfiguration paradigm. In this RT task, stimuli were presented on the computer screen, and responses to stimuli were right or left index presses made on a button box. The target stimulus was an arrow, pointing left or right, surrounded by a frame. Each trial began with the white frame turning red or green. After a period of 1750 or 250 ms, selected at random, the stimulus appeared. Depending on the color of the frame, participants were to press the button located either on the side pointed by the arrow (green frame), or on the opposite side (red frame). During the mixed blocks, the color of the frame was selected pseudo-randomly, so that the probability of a task switch was 0.33. Participants performed four simple blocks of 16 practice trials, followed by two 24-trial mixed blocks of practice, and four mixed blocks of 52 experimental trials. The dependent measure indexing flexibility in this task was the local switch cost for correct responses, calculated as RT difference (ms) between task-repeat trials (i.e. a trial n where the relevant task is the same as the task performed in trial $n - 1$) and task-switch trials (i.e. a trial n where the relevant task is different from the task performed in trial $n - 1$) during the mixed blocks.

2.3.3.3. The Wisconsin Card Sorting Test (WCST). A computerized version of the WCST was used (see Albinet, Boucard, Bouquet, & Audiffren, 2010 for a full description). The participant's task was to sort a set of cards on the basis of three dimensions (color, shape, and number), which changed periodically but unknown to them (after 10 consecutive successful sorts) during the course of sorting. The task ended when participants achieved six categories or after a maximum of 128 cards. The dependent variable used to evaluate Shifting performance in the WCST was the number of perseverative errors (Berg, 1948).

2.3.4. Composite scores reflecting the three executive functions

Raw scores from each cognitive task were transformed into z-scores (using means and standard deviations for the whole group). When necessary, z-scores were re-coded so that a high score reflected better performance. R score from the RNG task did not correlate with any other measure reflecting Updating, nor with age (no age-related decline). Accordingly, R score from the RNG task was excluded from the Updating composite score and for further analyses (see Fisk & Sharp, 2004 for a similar result). To calculate a composite score for each postulated EF component, a mean score was calculated from the z-scores of the cognitive tasks assumed to reflect the EF component (see Table 2). For each EF component, a Cronbach alpha was computed to assess how well the selected tasks measured a single underlying construct. Alphas for each EF component were moderate to good indicating that each variable measured a one-dimensional latent construct (see Table 2). Table 3 presents the matrix of correlations between Age group, Education and the three EF components.

2.4. Procedure

Each participant was tested individually in a quiet experimental room across two sessions (A and B) on different days separated by a minimum of two days and a maximum of 7 days. Each session lasted about 1.5–2 h. In session A, each participant performed the Stroop task, the DSST, the RNG task, the WCST and the Dimension-switching task. In session B, each participant performed the spatial and the verbal running span tasks, the SRT and CRT tasks, the stop-signal task, and the S-R compatibility shifting task.

Table 2
List of the experimental tasks tapping each Executive Function component and their coefficient alphas of internal consistency.

Executive Function components	Experimental tasks	Cronbach alpha
Inhibition	Stroop task Stop-signal task RNG task	.62
Updating	Verbal running span Spatial running span	.80
Shifting	Dimension-switching task S-R compatibility shifting task WCST	.68

Note: RNG = Random Number Generation; WCST = Wisconsin Card Sorting Test.

Table 3
Correlation matrix between the three executive function components with age and education.

	Age	Education	Inhibition	Updating
Age	–			
Education	−.45***	–		
Inhibition	−.60***	.23ns	–	
Updating	−.71***	.60***	.53***	–
Shifting	−.80***	.50***	.63***	.86***

ns = non significant.
*** $p < .0001$.

Session A and session B were counterbalanced across participants and, within each session, all the tasks were fully counterbalanced across participants. Participants were given short breaks between each experimental task.

2.5. Statistical methods

The data were analyzed in three ways. First, we examined age-related differences in all the individual cognitive measures (*z*-scores), using multivariate analyses of covariance (MANCOVAs) with years of education as a covariate and Age group (two levels) as between-subject factor, separately for each of the three EF components (Inhibition, Updating, Shifting). Second, we assessed the extent to which the different processing speed measures accounted for age-related variance in the three EF components (composite scores), using hierarchical regression analyses. Third, we examined, for each age group separately, the relationships between each processing speed measure and each EF component, using partial correlation analyses. As recommended by Bryan and Luszcz (1996), the "Age group" variable was used rather than chronological age in all the analyses. Participants were divided into two age groups, coded as follows: young adults = 1, older adults = 2.[2] The level of significance was set at $p < 0.05$. Partial estimated effect sizes (η_p^2) were reported for significant results.

3. Results

3.1. Age-related differences in executive tasks and processing speed measures

The results of the MANCOVAs revealed that Age group had a significant negative effect on the inhibition scores (Wilks' lambda = .672; $F(3,62) = 10.\ 1$, $p < .0001$; $\eta_p^2 = .328$), on the updating scores (Wilks' lambda = .515; $F(3,62) = 19.4$, $p < .0001$; $\eta_p^2 = 485$), and on the shifting scores (Wilks' lambda = 427; $F(3,62) = 26.8$, $p < .0001$; $\eta_p^2 = .573$). All the subsequent univariate ANCOVAs conducted on each of the executive tasks revealed a significant effect of Age group (all *p*s < .005).

The results of the MANCOVA concerning the processing speed measures revealed a significant main effect of Age group (Wilks' lambda = .284; $F(3,62) = 52$, $p < .0001$; $\eta_p^2 = .716$). The subsequent univariate ANCOVAs revealed a significant effect of Age group (all *p*s < .0001) for the three tasks. The matrix of correlation for all the cognitive task scores is given in Appendix A. As can be seen, the majority of the correlations between the cognitive scores were significant, making it possible to investigate relationships between the variables. The raw data concerning each cognitive task are detailed in Appendix B.

3.2. Effects of processing speed measures on age-related variance in executive functions

To assess the amount of variance due to each processing speed measure on the age-related variance in each EF component, we performed a series of hierarchical multiple regression analyses, with the number of years of formal education forced as the first step. For each of the three EF components, four models were evaluated. In model 1, age was entered as a predictor to determine the amount of age-related variance in inhibition, updating, and shifting. Model 2 examined whether DSST performance reduced the contribution of age to a non-significant amount. The same procedure was repeated with CRT performance for model 3 and with SRT performance for model 4. Finally, the percentage of the age-related variance (% ARV) accounted for by the mediating variables (i.e., the three measures of processing speed) in the three EF components was calculated using formula (2):

$$\%\text{ARV} = [(R^2 \text{ with age alone} - R^2 \text{ change})/R^2 \text{ with age alone}] \times 100, \tag{2}$$

with R^2 *with age alone* corresponding to the variance accounted for by age after having controlled for education, and R^2 *change* corresponding to the change in R^2 after having controlled for the mediating variable (see Baudouin et al., 2009; Salthouse, 1996). The percentage of ARV explained is reported in the last column of Tables 4–6.

3.2.1. Inhibition

Age predicted 30.8% of the variance in inhibition after having controlled for education (model 1). As can be seen in Table 4, model 2 showed that entering DSST score explained 35.6% of the variance and reduced the age-related variance to a non-significant level of 2.1% ($p = .137$). This means that DSST score accounted for 93.2% of the age-related variance in Inhibition (i.e., $[(.308 - .021)/.308) \times 100]$, see Table 4). Model 3 showed that CRT explained 29.4% of the variance in inhibition and reduced the age-related variance to a lower but still significant level of 4.3% ($p = .04$). Model 4 showed that SRT explained a smaller but significant part of the variance (13.6%) and that the pure age-related variance remained to a significantly high level of 17.5% ($p < .0001$).

3.2.2. Updating

Age predicted 24.5% of the variance in updating after having controlled for education (model 1). As can be seen in Table 5, model 2 showed that entering DSST score explained 21.4% of the variance and reduced the age-related variance to a lower but still significant level of 4.6% ($p < .01$). Model 3 showed that CRT explained 24.4% of the variance in updating and reduced the age-related variance to a lower but still significant level of 2.9% ($p = .03$). Model 4 showed that SRT explained a smaller but significant part

[2] Note that we performed also the analyses with participant's actual chronological age in years and the results were virtually the same.

Table 4
Hierarchical multiple regression analyses related to education, age, measures of processing speed and inhibition.

Model	R^2	R^2 change	% ARV explained in Inhibition
Model 1			
Education	$.053^{ns}$		
Age	.361	$.308^{***}$	
Model 2			
Education	$.053^{ns}$		
DSST	.409	$.356^{***}$	
Age	.430	$.021^{ns}$	93.2
Model 3			
Education	$.053^{ns}$		
CRT	.347	$.294^{***}$	
Age	.390	$.043^{*}$	86
Model 4			
Education	$.053^{ns}$		
SRT	.189	$.136^{**}$	
Age	.364	$.175^{***}$	43.2

Note: DSST = Digit Symbol Substitution Test; CRT = Choice Reaction Time; SRT = Simple Reaction Time, % ARV = percentage of age-related variance.
ns = non significant.
* $p < .05$.
** $p < .005$.
*** $p < .0001$.

Table 5
Hierarchical multiple regression analyses related to education, age, measures of processing speed and updating.

Model	R^2	R^2 change	% ARV explained in Updating
Model 1			
Education	$.354^{***}$		
Age	.599	$.245^{***}$	
Model 2			
Education	$.354^{***}$		
DSST	.568	$.214^{***}$	
Age	.614	$.046^{**}$	81.2
Model 3			
Education	$.354^{***}$		
CRT	.598	$.244^{***}$	
Age	.627	$.029^{*}$	88.2
Model 4			
Education	$.354^{***}$		
SRT	.472	$.118^{***}$	
Age	.604	$.132^{***}$	46.1

Note: DSST = Digit Symbol Substitution Test; CRT = Choice Reaction Time; SRT = Simple Reaction Time, % ARV = percentage of age-related variance.
** $p < .005$.
*** $p < .0001$.

of the variance (11.8%) and that the age-related variance remained to a significantly high level of 13.2% ($p < .0001$).

3.2.3. Shifting

Age predicted 41.8% of the variance in shifting after having controlled for education (model 1). As can be seen in Table 6, model 2 showed that entering DSST score explained 42.6% of the variance and reduced the age-related variance to a lower but still significant level of 4.9% ($p < .01$). Model 3 showed that CRT explained 42.7% of the variance in shifting and reduced the age-related variance to a lower but still significant level of 4.5% ($p < .01$). Model 4 showed that SRT explained a smaller but significant part of the variance (17.5%) and that the age-related variance remained to a significantly high level of 24.5% ($p < .0001$).

In summary, the results of the hierarchical multiple regression analyses showed that DSST performance explained the major part

Table 6
Hierarchical multiple regression analyses related to education, age, measures of processing speed and shifting.

Model	R^2	R^2 change	% ARV explained in Shifting
Model 1			
Education	$.245^{***}$		
Age	.653	$.418^{***}$	
Model 2			
Education	$.245^{***}$		
DSST	.671	$.426^{***}$	
Age	.720	$.049^{**}$	88.3
Model 3			
Education	$.245^{***}$		
CRT	.672	$.427^{***}$	
Age	.718	$.045^{**}$	89.2
Model 4			
Education	$.245^{***}$		
SRT	.420	$.175^{***}$	
Age	.666	$.245^{***}$	41.4

Note: DSST = Digit Symbol Substitution Test; CRT = Choice Reaction Time; SRT = Simple Reaction Time, % ARV = percentage of age-related variance.
** $p < .005$.
*** $p < .0001$.

of the age-related variance in the executive composite scores, representing 93.2%, 81.2%, and 88.3% of the age-related variance in inhibition, updating, and shifting, respectively. Moreover, when controlling for DSST, there was no more significant effect of age on inhibition. CRT also explained a strong portion of age-related variance in EF, representing 86%, 88.2%, and 89.2% of the age-related variance in inhibition, updating, and shifting, respectively. However, after having controlled for CRT, the effect of age still remained significant for all the EF components. Finally, SRT accounted for a small portion of age-related variance in all executive composite scores (between 41% and 46%), and the effect of age on the three EF components remained important.

3.3. Relationships between DSST, CRT, and executive functions

Both DSST performance and CRT explained a large amount of the age-related variance in all three EF components. As mentioned in the introduction, it may be that correct performance on these tasks (notably DSST) requires utilization of some executive components, especially for the older adults. The structure of the DSST and the CRT task was investigated by examining the relationship between the three EF components and both DSST and CRT, following the procedure of Baudouin et al. (2009). To isolate any independent relationship, we performed, separately for the two age groups, partial correlations between DSST scores and inhibition, updating and shifting scores after partialling out the number of years of education and the CRT scores. The same procedure was applied to examine the partial correlations between CRT performance and the three EF components after partialling out the number of years of education and the DSST scores. In the young adults group, no significant correlation (all *ps* > .05) was observed between DSST scores and the three EF components, but there was a significant partial correlation between CRT and the shifting score ($r = .44$, $p < .05$). For the older adults group, there was no significant partial correlation between CRT and any EF component (all *ps* > .05), but DSST scores significantly correlated with the inhibition score ($r = .38$, $p < .05$), the shifting score ($r = .39$, $p < .05$), and were marginally correlated with the updating score ($r = .29$, $p = .08$), after having controlled for the CRT scores.

These results strongly suggest that, in the older population, DSST performance does involve executive control, but not CRT performance. On the contrary, in the younger adults group, CRT

Table 7
Hierarchical multiple regression analyses related to education, age, executive Function components and Choice Reaction Time.

Model	R^2	R^2 change	% ARV explained in CRT
Model 1			
Education	.151**		
Age	.679	.529***	
Model 2			
Education	.151**		
Inhibition	.415	.264***	
Age	.694	.279***	47.3
Model 3			
Education	.151**		
Updating	.472	.321***	
Age	.702	.230***	56.5
Model 4			
Education	.151**		
Shifting	.631	.480***	
Age	.731	.100***	81.1

Note: % ARV = percentage of age-related variance; CRT = Choice Reaction Time.
** $p < .005$.
*** $p < .0001$.

performance was found to involve some shifting processes. As such, the CRT task should be interpreted as a purer measure of processing speed than the DSST, particularly for older adults. In order to verify whether age remained a significant predictor of CRT, even after having controlled for executive performance, we decided to perform a series of hierarchical multiple regression analyses, in the same manner as we did for the three EF components. As can be seen in Table 7, age predicted 52.9% of the variance after having controlled for education (model 1). Models 2, 3 and 4 showed that entering Inhibition score or Updating score or Shifting score, respectively, accounted for a substantial portion of the variance (from 26.4% to 48%). However, the age-related variance on CRT remained to a significantly high level, explaining between 10% and 27.9% of the variance (all *ps* < .0001).

4. Discussion

The principal purpose of the current study was to examine relationships between different measures that have been used to support two competing theoretical constructs that account for cognitive aging: processing speed and executive functions. Several measures were used to evaluate, in samples of young and older adults, three EF components identified by Miyake and collaborators' factorial structure (2000). The contribution of processing speed obtained from three different measures was also investigated. As in previous studies, our results showed that chronological age has a detrimental effect on all the cognitive measures used to assess EF and processing speed. Different patterns of relationships between the measures of EF and processing speed were found as a function of chronological age; however, a significant portion of age-related deficits in all three EF components was accounted for by a slowing in information processing as measured by CRT.

Concerning the EF construct, we used several measures to examine participants' performance at the level of composite scores rather than at the level of individual tasks in order to have more reliable and robust estimates of construct. A previous study by Fisk and Sharp (2004) used a similar approach with latent variables, to examine the effects of normal aging on executive performance and processing speed. However, it should be noted that they used only one single task (the WCST) to reflect the shifting component as well as one single task (the random letter generation task) to reflect the inhibition component. It was then important to verify if their results can be generalized with a more comprehensive examination of EF. Consistent with Fisk and Sharp's results, we found that the measure of redundancy (*R*) from our RNG task did not correlate with the other measures reflecting updating of working memory and was not affected by age. Together, these results raise questions concerning this measure as a relevant index of updating. Also consistent with their results, we showed that the performance for the three EF components thought to reflect inhibition, updating and shifting, was impaired in the aged population. Contrary to their results, we found our EF components to be moderately to strongly correlated; ranging between .53 and .86 compared to −.20 to .20 reported by Fisk and Sharp. These results are similar to those correlations reported by Salthouse et al. (2003) and Vaughan and Giovanello (2010) in the same context (from .61 to .94). This pattern of results can be interpreted in two ways. The fact that executive processes seem less dissociable in older adults (the correlations between the same latent constructs in Miyake et al.'s college students study ranged between .42 and .63) may reflect the functional *dedifferentiation* phenomenon and suggests that as we age, cognitive abilities become more correlated (see Baltes & Lindenberger, 1997; Hertzog & Bleckley, 2001; Li, 2002). Such an explanation would imply a lesser number of EF components in the older population. This was indeed the case in Hull et al.'s (2008) study, but not in Fisk and Sharp (2004) and Vaughan and Giovanello (2010) studies. As discussed below in this section, more studies should be dedicated to the clarification of this particular point.

Alternatively, one must acknowledge that a careful inspection of the correlation matrix displayed in Appendix A shows that the correlations between tasks reflecting different EF components are often greater than the correlations between tasks measuring the same EF component. This important point, already discussed more in detail in Salthouse et al. (2003), raises the question of the low specificity of the tasks used to assess EF and more generally of the discriminant validity of the EF construct. It is very difficult to extract the pure EF component of an experimental task due to the non-executive, idiosyncratic aspects of the task and also because multiple EF components may be involved in the performance of the same task. More work is still needed, in our opinion, to better design tasks or procedures aimed at measuring specific EF components as well as the relationships between various EF components.

Although a full discussion about the relationship between executive functions and frontal lobes is beyond the scope of this article, we shall partly address this question. Historically, lesion and neuropsychological studies have closely linked functional changes in executive performance with specific structural alterations in the frontal lobes (for a full discussion, see Jurado & Rosselli, 2007; Phillips & Henry, 2008; Rabbitt, 1997). This has led many researchers to use the terms executive tasks and frontal lobe tasks interchangeably and served as a basis for the prefrontal-executive theory. However, recent neuroimaging and behavioral studies have clearly shown a great heterogeneity in the cerebral areas involved in the performance of executive tasks and that different EF components involve specific patterns of brain activity (see Collette, 2004; Collette, Hogge, Salmon, & Van der Linden, 2006; Collette et al., 2005, for reviews). Although a key role of the prefrontal and frontal cortices cannot be underestimated, these studies emphasize the importance of posterior areas, mainly the parietal cortex, as playing a critical role in executive performance (Collette et al., 2006). This modern view of a more distributed neural network, underpinning different EF components raises questions about the relevance of using executive tasks to assess the prefrontal-executive theory of cognitive aging.

Concerning the three measures of processing speed, in accordance with Salthouse (1994, 1996), we think the SRT to reflect essentially sensory and motor processes, with a weak contribution of higher cognitive processes, and we showed that it contributed very little to the relations between age and executive functioning. Supporting Baudouin et al.'s (2009) findings, we showed, on the basis of partial correlations (see Section 3.3), that older adults' DSST performance clearly involves inhibition, shifting, and, to a lesser extent, updating beyond processing speed and other putative processes. This implies that DSST performance is not an index of simple processing speed. Based on the literature and our results, it seems that CRT provides the most rigorous and informative data on processing speed. The 2-CRT has unique advantages because the computational characteristics of the task enables researchers to measure the amount of information and the rate of processing, leading to control for baseline levels of processing. In our study, older adults' performance on this task was shown not to involve executive processes and thus provided a clear index of relation between processing speed and EF components.

As for younger adults, however, we found a significant partial correlation ($r = .44$, $p < .05$) between 2-CRT performance and task switching performance (see Section 3.3). It should be stressed that performing any cognitive task requires a subset of representations and cognitive processes to be selected and organized – a task-set (Allport, 1987; Rogers & Monsell, 1995). Both CRT and switching tasks require the ability to control a task-set where manual responses to visual stimuli are produced according to arbitrary stimulus-response rules. Within this framework, it is conceivable to find a relationship between task switching and CRT performances.

Thus, on the one side, one measure of processing speed, the DSST, involved executive processes only for older adults but not for the younger ones, and on the other side, a second processing speed measure, the CRT task, involved some executive control only for the younger adults but not for the older ones. Therefore, it appears that, depending on chronological age, different cognitive processes are more or less involved in the performance of the same task. This finding raises the question of structural invariance in cognitive abilities as a function of age (see Hertzog & Bleckley, 2001). The question of potential qualitative changes in the structure of cognitive factors as a function of aging should be carefully examined and controlled in future studies.

The results of the hierarchical regression analyses revealed that processing speed, as measured by CRT, removed a substantial portion of the age-related variance in all the three EF components (more than 85%), but that the contribution of age to the executive performance remained significant. It can be noted that, before controlling for CRT performance, the effect of chronological age seemed to be more important for shifting than for inhibition and updating (see Tables 4–6), but after controlling for processing speed, the remaining age-effect appeared virtually equivalent for the three EF components.

As a whole, these findings are consistent with Keys and White's results (2000), who showed that age-related executive decline cannot be explained solely in terms of slowing of processing speed. In the present study, we used a more comprehensive and theoretically-driven evaluation of executive and processing speed processes. Our results support the view that processing speed can contribute to age-related deficits in cognition, but it is not the sole contributor of cognitive declines. Age makes a unique contribution to changes in EF performance beyond the one accounted for by the slowing in processing speed. This contribution is modest (ranging between 3% and 4.5%, depending on EF component) but significant and suggests a direct and measurable executive decline in normal aging. On the other side, age makes also a direct and unique contribution to changes in processing speed, as measured by CRT, even after having controlled for EF influence. This unique effect of age on processing speed was more important than the one on EF components (from 10% to 28%, depending on which EF component was controlled for, see Table 7). Thus, one might say that both processing-speed theory and prefrontal-executive theory can explain parts of the effects of normal aging on cognition, and that neither can be viewed as the sole contributor. Our conclusions support those of Bugg et al. (2006) and Schretlen et al. (2000). We extended the literature base by showing that most of the age-related variance in executive performance is shared with processing speed. Our results suggest that future research should control for the contribution of general slowing in executive performance before examining its mediating role in the aging of cognitive abilities, because an important part of this mediation could be due to non-executive components of the performance; and *vice-versa* when examining the mediating role of processing speed in cognitive aging.

Some limitations concerning this study require consideration, however. The relative small sample size prohibited from performing a principal components analysis in order to confirm the factorial structure of our three EF components. Hence, the three-component model of executive functions assumed in this paper is essentially derived from previous studies' results and should be confirmed before a definitive conclusion can be made. The Redundancy score from the RNG task did not correlate neither with the two other measures of updating, nor with age, and was thus not included in the composite score of updating. As a consequence, this composite score was based on only two different measures. Also, the WCST perseveration score did not correlate significantly with one of the two other measures of shifting. These limits lessen the *generalizability* of our results and reflect again the challenge of measuring executive functions. It will be important in future research to overcome these limitations with a larger sample size and by using factor analysis to verify the construct validity as a function of chronological age and to increase the internal consistency of the tasks used. It would have been also informative to compare our CRT measure with the more traditional paper-and-pencil perceptual speed tasks used in the literature (see Salthouse, 1994, 2000). Future research should examine if this approach (i.e., controlling for the mutual relationship between EF and processing speed) is useful to better understand the effects of normal and pathological aging on various domains of cognitive functioning.

To conclude, two important findings are emphasized and have theoretical and methodological implications. First, caution should be taken concerning the neuropsychological and experimental tasks used to assess theoretical constructs. We recommend that the DSST should no longer be viewed as a simple measure of information-processing speed. Second, the measures used to assess the processing-speed theory and the prefrontal-executive theory of cognitive aging were shown not to be mutually exclusive and share mutual variance. This implies the need to control for their mutual relationship before examining their unique potential role in the explanation of age-related cognitive declines. The present study adds to the growing body of research emphasizing the importance of a multivariate approach in the understanding of the complex relationships between cognitive domains and brain aging (see Head, Rodrigue, Kennedy, & Raz, 2008; Rabbitt et al., 2007).

Acknowledgments

This work was supported by grants from Région Poitou-Charentes and the University of Poitiers. The authors greatly thank Prof. Phillip D. Tomporowski for his valuables comments on an earlier version of this manuscript.

Appendix A

See Tables 8 and 9.

Table 8
Correlation matrix between age, education and all the cognitive tasks (*z* scores).

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Age group	–												
2. Education	−0.45***	–											
3. DSST	−0.82***	0.46***	–										
4. CRT	−0.82***	0.39**	0.80***	–									
5. SRT	−0.55***	0.06^{ns}	0.48***	0.54***	–								
6. RNG Adjacency	−0.49***	0.14^{ns}	0.56***	0.49***	0.47***	–							
7. Stroop interference	−0.50***	0.34**	0.50***	0.48***	0.22^{ns}	0.54***	–						
8. Signal Stop RT	−0.36**	0.04^{ns}	0.37**	0.35**	0.17^{ns}	0.26*	0.24*	–					
9. RNG Redundancy	−0.12^{ns}	−0.03^{ns}	0.15^{ns}	0.05^{ns}	0.03^{ns}	0.05^{ns}	0.25*	0.06^{ns}	–				
10. Verbal running span	−0.54***	0.55***	0.55***	0.53***	0.23^{ns}	0.25*	0.45***	0.18^{ns}	0.12^{ns}	–			
11. Spatial running span	−0.76***	0.53***	0.70***	0.72***	0.47	0.53***	0.56***	0.23^{ns}	0.04^{ns}	0.67***	–		
12. Global switch cost	−0.74***	0.39**	0.75***	0.76***	0.47***	0.42**	0.42**	0.42**	0.08^{ns}	0.60***	0.79***	–	
13. Local switch cost	−0.60***	0.31*	0.59***	0.59***	0.33*	0.38**	0.36**	0.20^{ns}	0.12^{ns}	0.55***	0.49***	0.48***	–
14. WCST errors of perseveration	−0.54***	0.46***	0.57***	0.52***	0.31*	0.54***	0.44***	0.12^{ns}	−0.12^{ns}	0.56***	0.70***	0.58***	0.20^{ns}

Note: DSST = Digit Symbol Substitution Test; CRT = Choice Reaction Time; SRT = Simple Reaction Time; RNG = Random Number Generation; WCST = Wisconsin Card Sorting Test.
ns = non significant.
* $p < .05$.
** $p < .005$.
*** $p < .0001$.

Table 9
Means and standard deviations of raw scores on the cognitive tasks for the young and older adult groups.

	Young adults (n = 28)		Older adults (n = 39)		F[a]
	M	*SD*	*M*	*SD*	
DSST (number)	93.04	11.96	57.77	12.25	98.4***
CRT (ms)	335.37	30.49	475.62	57.69	105.5***
SRT (ms)	195.56	24.82	248.75	48.86	32.9***
RNG Adjacency (%)	34.25	6.46	43.94	9.85	19.6***
Stroop interference (ms)	183.31	72.11	297.43	113.12	13.6***
Signal Stop RT (ms)	216.65	43.64	256.10	56.81	10.7**
Verbal running span (number)	40.14	4.44	30.72	8.95	11.4**
Spatial running span (number)	39.61	6.03	20.36	9.60	57***
RNG redundancy	1.34	0.69	1.57	1.06	1.6^{ns}
Global switch cost (ms)	144.37	134.20	659.25	288.26	55.4***
Local switch cost (ms)	44.80	35.96	171.81	106.66	26.3***
WCST errors of perseveration (number)	8.68	2.57	18.26	9.45	12**

Note: DSST = Digit Symbol Substitution Test; CRT = Choice Reaction Time; SRT = Simple Reaction Time; RNG = Random Number Generation; WCST = Wisconsin Card Sorting Test.
^{ns} = non significant.
[a] Based on ANCOVAs, with number of years of Education as covariate.
** $p < .005$.
*** $p < .0001$.

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