Age-Related Differences in Supervisory Attentional System Functions

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The authors explored the effect of age on executive functions by using 3 tasks (Tower of London, Hayling, and Brixton tests) designed to assess specific executive processes (planning, inhibition, and abstraction of logical rules) that were also sensitive to frontal dysfunction. The performance of elderly participants ($n = 48$) was significantly poorer than that of young participants ($n = 47$) in all 3 tasks. Processing speed, measured by means of a color-naming task, explained some but not all of the age-related differences. These results are discussed in terms of general and specific factors in cognitive aging.

SEVERAL researchers have suggested that cognitive decline in aging is linked to a deficit of executive functions, that is, of those control processes called into action in nonroutine or novel situations (Stuss & Benson, 1986, p. 244). For example, Daigneault, Braun, and Whitaker (1992) found an age-related decline in perseverative and nonperseverative performance on a battery of executive tests, including the Wisconsin Card Sorting Test (WCST), self-ordered pointing, Porteus Mazes, a word association test, verbal and design fluency, and Stroop interference. They concluded that their data support the notion of an age-related decrease in the ability to "regulate behavior on the basis of plans, abstract concepts, environmental feedback or one's own responses" (Daigneault et al., 1992, p. 99). Other recent studies have also sustained the link between cognitive aging and a deficit in executive functions (Brennan, Welsh, & Fisher, 1997; Fristoe, Salthouse, & Woodward, 1997). Impaired executive performances have been shown in elderly people in the area of working memory as well (Daigneault & Braun, 1993; Parkin & Walter, 1991; Shimamura & Jurica, 1994; Van der Linden, Beerten, & Pesenti, 1998; Van der Linden, Brédart, & Beerten, 1994). Finally, a disruption of inhibitory mechanisms has been fairly well documented in elderly people (see Zacks & Hasher, 1994, for a review). Furthermore, executive processes have historically been linked to the frontal lobes (Baddeley, 1986; Shallice, 1988; Stuss & Benson, 1986). This postulate has led a number of researchers to infer a frontal decline in elderly participants (Daigneault & Braun, 1993; Parkin & Lawrence, 1994; Parkin & Walter, 1991, 1992; West, 1996).

However, in a more global conception of age-related deficits, Salthouse, Fristoe, and Hyun Rhee (1996) have questioned the degree of independence of age-related influences on various cognitive measures considered to be sustained by different regions of the brain. They administered a battery of neuropsychological tests to 259 adults aged between 18 and 94 years. Moderate age-related declines were apparent in executive measures (postulated to be specifically sensitive to damage in the frontal lobes, e.g., WCST, trail making test, and verbal fluency), visuo-spatial measures (postulated to be sensitive to the parietal lobes, e.g., Block Design), and mnemonic measures (postulated to be sensitive to the temporal lobes, e.g., Rey Auditory Verbal Learning Test; RAVLT). As expected, most of the measures were found to have moderate negative correlations with age. Nevertheless, much of the age-related variance in a variety of different variables was shared and not all was independent and specific. Indeed, speed measures shared considerable age-related variance with the other measures. An important implication of the results of Salthouse and colleagues is that the age-related effects on the different measures were not exclusively determined by distinct and unique sets of influence. Salthouse and colleagues concluded that inferences about specific or discrete age-related influences should be interpreted with caution until there is confidence that these effects are truly distinct and independent of the general factors such as processing speed (see also Fisk & Warr, 1996, for a similar proposal). However, the hypothetical links between cognitive tasks and brain localization, on which the study of Salthouse and colleagues is based, are not empirically well established (see, e.g., Janowsky, Shimamura, Kritchevsky, & Squire, 1989, for findings showing that Block Design and RAVLT performances, considered by Salthouse and colleagues to be sensitive to parietal and temporal lesions, respectively, are also impaired as a result of frontal lobe lesions).

Our aim in this study was to examine further the hypothesis of a link between cognitive aging and executive functions by using tasks designed to assess specific executive operations and that have been proved to be sensitive to frontal dysfunction. The theoretical framework we used is the control-to-action model developed by Norman and Shallice (1986). This model distinguishes two control-to-action mechanisms. The first one, called contention scheduling, is involved in the routine situations in which actions are automatically triggered. The second one, called the supervisory attentional system (SAS), is a separate mechanism at the highest level of control of action, coping with novelty. This mechanism, which is required in situations where the routine selection of actions is unsatisfactory, is involved in the

genesis of plans and willed actions. Additionally, SAS is conceived as carrying out a variety of processes (Shallice, 1988, 1994). Neuropsychological studies have shown that particular impairments within the general set of SAS operations can be isolated (e.g., Eslinger & Damasio, 1985; Gurd, 1995; Shallice & Burgess, 1993, 1996).

We investigated age-related differences in three SAS functions: planning, inhibition, and abstraction of logical rules. These SAS functions have already been studied in frontal patients, especially by Shallice and coworkers by means of specific tasks (Burgess & Shallice, 1996a, 1996b; Shallice, 1982). Planning, defined as the capacity to analyze and elaborate possible solutions to a new problem, has been explored with the Tower of London (TOL) test (Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Shallice, 1982), which requires the participant to move an initial arrangement of colored beads presented in a device to match a goal arrangement presented by the experimenter, while making the minimum number of moves. To solve the TOL, that is, to make the minimum number of moves, the participant has to analyze the problem and plan the sequence of moves before starting. This task revealed a planning impairment in patients with frontal damage (Owen et al., 1990; Shallice, 1982). More specifically, frontal patients showed longer initiation and execution times than controls; that is, they were slower to make the first move and to solve the problem. Additionally, they took more moves to solve the problem (see, however, Owen et al., 1990, for results showing normal initiation times in frontal patients).

Inhibition has been recently evaluated in frontal patients by means of the Hayling test (Burgess & Shallice, 1996a). In this task, the participant is presented with sentences in which the last word is missing. What this last word should be is strongly cued by the rest of the sentence. Two sections are presented. In the initiation section of the test (Section A), participants have to complete the sentence by adding the missing word. In the inhibition section (Section B), a word that makes no sense in the sentence context must be produced by the participant. Therefore, the participant has to inhibit the automatic response before generating the new one. In this test, frontal patients were slower in the two sections, suggesting that they were impaired in both processes: initiating an automatic response and inhibiting a dominant response (Burgess & Shallice, 1996a). Moreover, frontal patients made more errors in Section B than control participants, confirming that they are less accurate in the resistance to well-learned responses.

Burgess and Shallice (1996b) conceived the Brixton test to measure the ability to abstract logical rules. This task consists of a series of plates on which 10 circles are presented. One of the 10 circles is filled, and its position changes with each trial. The changes in positions are governed by a series of simple rules that vary without warning, and the participants must predict the filled position on each subsequent trial. In other words, participants answer correctly only when they perform the cognitive integration of the logical rule by abstracting the relation between successive cards. Burgess and Shallice (1996b) administered the Brixton test to frontal patients. The results showed that these patients were impaired in the abstraction of logical

rules. Moreover, frontal patients showed an abnormally high incidence of bizarre responses (responses for which no apparent rationale could be discovered).

To summarize, it has been shown that frontal patients are impaired on the TOL, Hayling, and Brixton tests, which are specifically designed to assess, respectively, planning, inhibition, and abstraction of logical rules. Additionally, Shallice and Burgess (1993) found no correlation between the performance of frontal patients on the Brixton and Hayling tests after control of IQ and age. This suggests that both tests involve different executive processes and confirms the view that the SAS can be fractionated into several independent functions (Shallice, 1988, 1994).

Our aim in the present study was to reexamine the effect of age on executive functions. More specifically, we explored three types of executive processes (planning, inhibition, and abstraction of logical rules) using the same tasks that Shallice (1982) and Shallice and Burgess (Burgess & Shallice, 1996a, 1996b) used in frontal patients: the TOL, Hayling, and Brixton tests. Additionally, we investigated how the three executive tasks are related (i.e., are they related to each other or can they be dissociated?) and to what extent a slowing down of the processing speed can account for the age-related differences in executive abilities.

METHODS

Participants

Participants consisted of 47 young and 48 elderly adults. The young participants (24 men and 23 women) were aged between 20 and 30 years ($M = 22.8$, $SD = 2.8$). Their mean score on the Mill Hill Vocabulary test (French-language adaptation of the multiple-choice synonym subtest; Deltour, 1993) was 35.3 ($SD = 3.6$). The elderly participants (24 men and 24 women) were healthy people living in the community aged between 60 and 70 years ($M = 65$, $SD = 3.9$). Their mean score on the Mill Hill Vocabulary test was 38.1 ($SD = 2.7$). The vocabulary scores of the elderly participants were significantly higher than those of the young participants, $t(93) = -4.32$, $p < .0001$. All participants had completed 12 or more years of schooling. The mean number of years was 14.5 ($SD = 1.3$) for young participants and 15.1 ($SD = 2.2$) for elderly participants. The two groups of participants did not differ with regard to this measure, $t(93) = -1.47$, $p = .146$.

Procedure

The tests were administered following a Latin square procedure.

TOL test.—To evaluate planning capacities, we used Coyette and Van der Linden's (1992) adapted version of Shallice's TOL test (Shallice, 1982). Twelve problems were proposed to each participant. In each problem (see Figure 1) three beads, one red, one green, and one blue, had to be moved from a starting configuration on three sticks of unequal length to a target configuration in a minimum number of moves.

Three problems were three moves deep, and nine were five moves deep. Moreover, three types of problems were tested: neutral, facilitating, and misleading. Neutral prob-
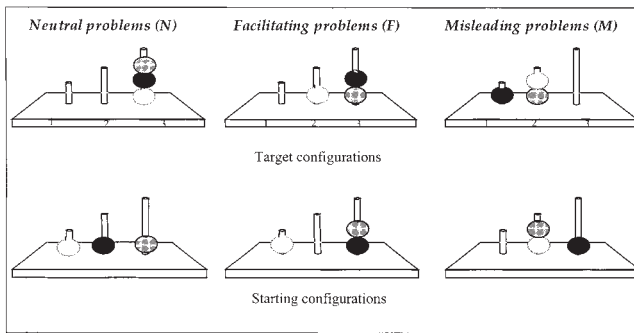
Figure 1. Setup used for the Tower of London test. In these examples, five moves are required to modify the starting configurations into the target configurations. The left configuration represents a neutral problem. The central configuration represents a facilitating problem. In this case, the first move that comes to mind constitutes a good starting step toward the resolution of the problem (i.e., moving the white bead from the shortest stick to the medium one). The right configuration represents a misleading problem. In this problem, a first move comes to mind that seems to point to the resolution of the problem (i.e., moving the black bead from the long stick to the short) but is inadequate because it increases the number of moves necessary to reach the target configuration.

lems could be solved with a simple strategy from the first move. In facilitating problems, a bead could be put into its target position on the first move, and this move would be coherent with the optimal solution of the problem. In misleading problems, a bead could be put into its target position on the first move, but this move would not be coherent with the optimal solution of the problem, therefore increasing the number of subsequent moves necessary to reach the target configuration. In other words, facilitating problems should have a facilitating effect and misleading problems a disrupting effect on performance. Three problems were scheduled for each problem type. The different types of problem were randomly distributed, but the order was always the same for all participants. Participants were asked to solve the problems in the minimum possible number of moves.

The measures derived from the TOL test offered information on both the rapidity of the plan elaboration and its efficacy. Rapidity of the plan elaboration was estimated by the time taken by the participant to start the first move (initiation time). This can also be taken as a measure of impulsiveness. Efficacy of the elaborated plan was measured by the number of moves needed to solve the problem and by the time taken from the first move to the solution of the problem (subsequent time).

Hayling test.—To evaluate participants' capacity to inhibit a prominent response, we created a French adaptation of the Hayling test used by Burgess and Shallice (1996a). It consisted of two sections (A and B), each containing 15 sentences in which the final word was omitted. What this last word should be was strongly cued by the rest of the sentence. The examiner read aloud each sentence. In Section A (initiation/automatic) participants were asked to give as quickly as possible the word they thought fitted the end of the sentence. For example, for the sentence *Most sharks attack very close to the* the correct response should be *coast*. In Section B (inhibition), participants were asked to give a

word that made no sense at all in the context of the sentence. For example, for the sentence *Most cats see well at* participants could give the word *talk*.

Time of response latency was measured in both Sections A and B. Time latency in Section A assessed the participants' rapidity in initiating an automatic answer, and time latency in Section B provided information about the time they took to inhibit the dominant response and find an anomalous one. These latencies were measured with a stopwatch, which was started as soon as the last word of the sentence had been read by the examiner and stopped when the participants began responding. In Section B, we also scored errors to evaluate the efficacy of the strategy elaborated by the participant to give an anomalous response.

Brixton test.—This test evaluated participants' capacity to discover and shift logical rules. To administer the test we used the same material that Burgess and Shallice (1996b) used. The test consisted of series 56 A4-sized pages that were presented 1 at a time to participants. Each page had the same basic template: a 2×5 array of circles numbered 1–10; the only difference between pages was the position of the filled circle. The task of the participant was to predict which circle would be filled on the next page. The correct position could be determined from that on the current page by a simple rule (see Figure 2 for an example), which changed after between 3 and 8 pages. The experiment involved eight rule changes and six different rules. Typical rules were to move to the next lower number or to alternate between Circles 4 and 10. The number of errors made by participants was scored. We examined the nature of the errors to find out whether elderly and young participants differed qualitatively or quantitatively on this task.

Processing speed.—To measure processing speed, we administered a color-naming task. This naming task is a commonly used measure of processing speed in the analysis of cognitive aging (see, e.g., Kwong See & Bouchard Ryan, 1995; Van der Linden et al., 1999). In this task, participants saw 100 colored small rectangles (red, yellow, green, and blue) on a sheet of paper and had to name all the rectangles' color as quickly as possible. The overall color naming time was used as an index of processing speed.

RESULTS

TOL Test

The average number of moves, initiation time, and subsequent time observed in the TOL test are presented in Tables 1 and 2.
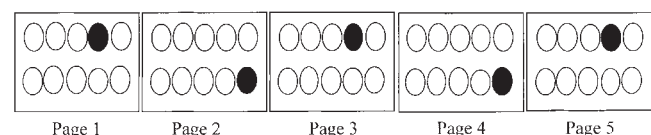

Figure 2. Brixton test. Example of a logical rule consisting in the alternation between filled circles located in Positions 4 and 10. When the participant sees Page 1, he must predict Position 10 for Page 2; when he or she sees Page 2 (Position 10), the participant must predict Position 4 for Page 3, and so on.

Table 1. Tower of London Test: Average Number
of Moves, Initiation Time, and Subsequent Time
in Problems Three Moves Deep

Measure	Elderly Participants	Young Participants	p (Student's t)
Number of moves	3.3 (0.6)	3.1 (0.2)	<.05
Initiation time	4 (3)	2.2 (1.3)	<.01
Subsequent time	6.5 (4.2)	4.3 (1.2)	<.001

Note: Standard deviations are indicated within parentheses.

We computed *t*-test comparisons on these different measures observed in the easiest problems (three moves). Elderly participants made significantly more moves to solve the problems, $t(93) = -2.322$, $p < .05$. They also took more time to initiate the first move, $t(93) = -3.73$, $p < .001$, and they took more time to solve the problem once the first move was realized, $t(93) = -3.43$, $p < .001$. Moreover, when we examined the subsequent time divided by the number of moves taken, to take into account the fact that elderly participants required more moves to solve problems, elderly participants were significantly slower than young participants, $t(93) = -3.29$, $p < .005$.

For problems requiring five moves (Table 2), we performed a two-way 2 (Group) $\times$ 3 (Type of Problem: neutral, facilitating, or misleading) ANOVA on the number of moves. This ANOVA revealed one main effect of group $F(1,93) = 5.329$, $p < .05$, showing that elderly participants took significantly more moves to solve the problems. There was also a significant main effect of type of problem, $F(2,186) = 20.932$, $p < .0001$. Newman-Keuls post hoc comparisons revealed that the number of moves was equivalent between neutral and misleading problems but was greater for neutral and misleading problems than for facilitating problems. There was no significant Group $\times$ Type of Problem interaction, $F(2,186) = 0.662$, $p = .517$.

Two-way 2 (Group) $\times$ 3 (Type of Problem) ANOVAs were carried out on the initiation and subsequent times. For the initiation time, the analysis showed one main effect of

Table 2. Tower of London Test: Average Number of Moves,
Initiation Time, and Subsequent Time

Measure	Elderly Participants	Young Participants	p (ANOVA, Effect of Group)
Number of moves			
5N	8.5 (2.5)	7.7 (2.3)	<.05
5F	6.5 (1.8)	6.3 (1.7)	
5M	8.7 (3)	7.7 (2)	
Initiation time			
5N	5.4 (3.1)	3.6 (3.1)	<.01
5F	5.3 (3.2)	3.3 (2.6)	
5M	5.5 (4.3)	3.3 (2.6)	
Subsequent time			
5N	21.8 (12.2)	16.2 (10.7)	<.001
5F	16.9 (12.5)	11.1 (4.5)	
5M	24.2 (13.8)	15.6 (7.2)	

Notes: 5N = neutral problems, five moves deep; 5F = facilitating problems, five moves deep; and 5M = misleading problems, five moves deep. Standard deviations are indicated within parentheses.

age, $F(1,93) = 10.42$, $p < .01$, but no significant effect of type of problem, $F(2,186) = 0.38$, $p = .682$, or of interaction, $F(2,186) = 0.4$, $p = .674$. For the subsequent time, significant effects of age, $F(1,93) = 18.25$, $p < .0001$, and of type of problem, $F(2,186) = 11.37$, $p < .0001$, were observed. Post hoc comparisons (Newman-Keuls) on the type of problem showed that neutral and misleading problems were similar but differed from facilitating problems. However, no significant interaction between these two factors was observed, $F(2,186) = 0.82$, $p = .442$. In sum, the analysis on the measures of time revealed that elderly participants needed significantly more time to initiate and complete the sequence of moves to solve the problems. Moreover, this difference was equivalent for the three types of problems. Insofar as elderly participants took more moves to solve the problems, the differences in the subsequent time could be due to the higher number of moves taken by elderly participants. Therefore, a two-way ANOVA was also carried out on subsequent time divided by the number of moves. This analysis revealed that a significant age effect existed, $F(1,93) = 15.36$, $p < .0001$. However, the significant effect of type of problem disappeared, $F(2,186) = 2.19$, $p = .128$. The interaction between these factors was not significant, $F(2,186) = 1.51$, $p = .224$. These results suggest that elderly participants took more time solving the problem, independent of the higher number of moves taken.

Hayling Test

The average response latencies (sum of latencies across 15 trials in seconds, as in Burgess & Shallice, 1996a) in Section A of the Hayling test were 10.37 ($SD = 3.7$) and 11.91 ($SD = 5.8$) for young and elderly participants, respectively. The same measure in Section B was 39.03 ($SD = 19.6$) and 58.91 ($SD = 32.4$). The 2 (Group) $\times$ 2 (Section) ANOVA revealed a significant age effect, $F(1,93) = 14.1393$, $p < .001$, a significant effect of section, $F(1,93) = 190.2077$, $p < .0001$, and a significant interaction between these two factors, $F(1,93) = 11.1896$, $p < .01$. Post hoc comparisons (Newman-Keuls) on the interaction revealed that elderly participants were significantly slower than the younger participants to give the answer in Section B ($p < .001$) but not in Section A ($p = .6938$).

The 1,425 responses (95 participants $\times$ 15 sentences) were classified by two raters who were blind to the purpose of the study. They agreed on 76.5% of these responses. The results presented are the average of the two ratings. The same results were observed when each rating was analyzed individually.

The errors were classified by the two raters into one of three possible categories: responses that were actual completion-response received an error score of 3; responses that were semantically connected to the sentence in some way received an error score of 1; and responses unrelated to the sentence, as required by the task instructions, received an error score of 0 (Table 3). The proportions of the different types of response were analyzed. The analyses revealed that elderly participants committed more Type 3 errors, $t(93) = -10.76$, $p < .001$, and gave fewer Type 0 responses, $t(93) = 2.283$, $p < .05$, than young participants. The groups

did not differ significantly on Type 1 responses, $t(93) = -1.29$, $p = .199$. In addition, we calculated an error score by adding the error points. Under these conditions, the average error score was 6.8 ($SD = 3.4$) for elderly participants and 4.8 ($SD = 2.6$) for young participants. This difference between performances was statistically significant, $t(93) = -3.28$, $p < .01$, showing that elderly participants globally made more errors.

Brixton Test

The overall number of errors made by the different participant groups and proportion of total errors of each type are shown in Table 4. Like Burgess and Shallice (1996b), we considered three possible types of errors. The first type (I) was the perseverations at the stimulus-response or the set level. The second (II) was the application of the other rules that were previously relevant. The third (III) was bizarre responses and guesses, that is, responses that could not be included in first or second type because no apparent rationale could be discovered. In the original study, Burgess and Shallice (1996b) considered that control participants could not make Type III errors. Indeed, they considered that all responses given by these participants were rationally driven and that only patients could produce bizarre responses and guesses. In the present study, in which no patients were involved, we took the position that both young and elderly participants can produce responses for which no underlying logical reasoning or strategy can be identified.

A t test carried out on the total number of errors showed a significant age effect, $t(93) = -5.907$, $p < .0001$, indicating that elderly participants made significantly more errors on the test than the young. Finally, it appeared that the two groups did not differ with regard to the proportion of errors of each type: Type I, $t(93) = -.638$, $p = .525$; Type II, $t(93) = -.671$, $p = .504$, and Type III, $t(93) = 1.219$, $p = .226$.

Role of Processing Speed

To examine the role of age and processing speed on the different measures of executive control (Salthouse, 1996), we first analyzed performance on the color-naming task. Elderly participants were slower than young participants, 66.9 s ($SD = 13.7$) versus 54.2 ($SD = 9.2$), respectively, $t(93) = -5.29$, $p < .0001$. We then included processing speed in a correlational analysis (Salthouse, 1992) to exam-

ine the relative role of age and slowing down on the different executive measures. This analysis (see Table 5) confirmed that executive tasks shared a significant proportion of their total variance with age. This proportion appeared to be more important for some tasks, particularly for the Brixton test.

When processing speed was controlled, the correlations between executive functions measures with age decreased importantly. However, they were still significant for the Hayling and Brixton error scores. These results were confirmed when we controlled the response latency in Section A of the Hayling test ($r = .29$, $p < .005$, between age and Hayling error score, and $r = .44$, $p < .00001$, between age and Brixton error score) rather than the performance on the color-naming task. In consequence, the processing speed seemed to be an important mediator between age and some (particularly the TOL test), but not all, measures of executive performance.

Fractionation of the SAS

Finally, we examined the question of the interrelations between the three executive tasks to explore to what extent the results obtained in elderly people converge with the idea of fractionating the SAS (Shallice & Burgess, 1993). In other words, our purpose in this analysis was to evaluate the hypothesis according to which the SAS fulfills different independent functions (Shallice, 1988, 1994; Shallice & Burgess, 1993, 1996).

Table 4. Brixton Test: Total Errors and Error Types Across Groups

Error Type	Young Participants	Elderly Participants	p (Student's t)
Total number of errors	10.7 (35)	18 (7.8)	.0001
Type I			
Absolute number	3.4 (2.3)	5.5 (3.2)	
Percentage of total errors	30.7 (16.3)	32.7 (15.5)	.525
Type II			
Absolute number	4.4 (2)	7.7 (3.5)	
Percentage of total errors	42.5 (18.2)	44.6 (12.9)	.504
Type III			
Absolute number	2.9 (2.2)	4.8 (5)	
Percentage of total errors	26.8 (18)	22.6 (15.8)	.226

Note: Standard deviations are indicated within parentheses.

Table 3. Hayling Test: Average Number and Proportion of Errors

Response Type	Young Participants	Elderly Participants	p (Student's t)
Errors (scored 1)			
n	3.6 (1.9)	4.1 (1.7)	
Proportion	24.39 (13.1)	27.39 (11.3)	.199
Errors (scored 3)			
n	0.4 (0.5)	0.9 (1)	
Proportion	2.7 (3.15)	6.04 (64)	<.001
Correct responses (scored 0)			
n	11 (2.1)	10 (2)	
Proportion	72.8 (14.1)	66.42 (13.2)	<.05

Note: Standard deviations are indicated within parentheses.

Table 5. Correlations with Age Before (A) and After (Partial Correlations, B) Control of Processing Speed

Measure	A, Age	B, Age–Processing Speed
Tower of London test		
Initiation time 5N	.22*	.15
Subsequent time 5N	.22*	.10
Total moves	.22*	.08
Hayling test		
Latency in Section B	.35***	.19
Section B score	.33**	.28**
Brixton test score	.49***	.42***

Note: 5N = neutral problems, five moves deep.
*$p < .05$; **$p < .01$; ***$p < .001$.

For the TOL test, the neutral-type problems were selected because no interaction between age and type of problem was observed when ANOVAs were carried out. As in Shallice and Burgess (1993), the error scores of the Hayling and Brixton tests were taken into account. Finally, the latency in Section B of the Hayling test was also considered. In sum, five measures of performance representing planning, inhibition, and rule anticipation functions were taken into account:

1. Initiation time in the TOL neutral problems that required five moves.
2. Subsequent time in the TOL neutral problems that required five moves (weighted by the number of moves).
3. Hayling error score.
4. Latency in Section B of the Hayling test.
5. Brixton error score.

A unique significant correlation was observed, first of all between the Hayling error score and the initiation time of the TOL test ($r = .40$, $p < .001$) in the young adults, and then in the elderly group between the subsequent time of the TOL test and the Brixton error score ($r = .33$, $p < .01$). Considering the total sample, there were significant correlations between initiation and subsequent time of the TOL test ($r = .27$, $p < .01$), between subsequent time of the TOL test and the Brixton error score ($r = .31$, $p < .01$) and between the Hayling and the Brixton error scores ($r = .31$, $p < .01$). When we performed partial correlation analysis by statistically controlling the general effect of age (Salthouse, 1992), we found a reduction of the correlations between the initiation and subsequent time of the TOL test ($r = .23$, $p = .01$) and between the subsequent time of the TOL test and the Brixton error score ($r = .23$, $p = .01$). Moreover, the correlation between the Hayling and Brixton error scores was no longer significant.

DISCUSSION

Our aim in this study was to reexamine the effect of age on executive functions. We addressed this question by using executive tasks inspired by the theoretical framework of Norman and Shallice (1986). Additionally, the extent to which processing speed could explain age-related differences in executive abilities was examined.

The results show that elderly people present impaired performance on the executive tasks specifically designed by Shallice and coworkers (Burgess & Shallice, 1996a, 1996b; Shallice, 1982) to assess some of the SAS functions, especially planning, inhibition, and abstraction of logical rules.

First, the results on the TOL test reveal that, like frontal patients (Shallice, 1982), elderly participants took more moves than young participants to solve the problems and were significantly slower on the two time measures examined, that is, initiation and subsequent times. However, partial correlations showed that controlling for processing speed significantly attenuated age-related differences in the TOL test. This result suggests that at least one part of the age-related difficulties in planning is related to a more general factor, namely the speed with which elementary operations are realized.

Second, on the Hayling test, elderly participants were

slower compared with young participants on Section B but not on Section A (unlike frontal patients, who were slower also in Section A; Burgess & Shallice, 1996a). Moreover, elderly participants made more errors than young participants and particularly more inhibition errors (actual completion response or error score of 3). The observed dissociation between Sections A and B tackles directly the contention scheduling/SAS (or automatic/controlled) distinction proposed by Normal and Shallice (1986): An age difference is observed in the controlled process allowing to inhibit a dominant response but not in the production of an automatic response. The results are consistent with Zacks and Hasher's (1994) view that some of the age-related differences in cognition may be explained by a deficiency in inhibitory mechanisms. However, a puzzling result is that although elderly participants showed an inhibition deficit on the Hayling test, they were not particularly disrupted by misleading problems of the TOL. This suggests that the inhibitory mechanisms involved in the analysis and elaboration of a plan are not affected by age and that the inhibitory processes involved in the TOL and Hayling tests are independent. These results might indicate that the suppression of a mental representation stored in long-term memory and strongly triggered by the context of the sentence (in the Hayling test) demands a greater allocation of attentional resources than the suppression of a move that has no long-term memory representation. These findings suggest that the attentional graduation of inhibitory resources is important, as suggested by Arbuthnott (1995), and confirm the view that there exist multiple inhibitory mechanisms that are not affected in the same way by age (see Connelly & Hasher, 1993). A last important result concerning the executive function of inhibition was that the differences between young and elderly participants in the error score remained after processing speed had been statistically controlled for.

Finally, our results on the Brixton test reveal a significant global influence of aging on the ability to discover and apply logical rules. Contrary to frontal lesions (Burgess & Shallice, 1996b), aging increases the level of error for each error type similarly, not specifically for responses not driven by logical rules (bizarre responses). Therefore, although they made more errors, elderly participants applied logical rules to their responses. It seems, then, that the difference between frontal patients and elderly participants is that performance of elderly participants is more directed by logical rules. This result suggests that the process of rules identification is affected by age in a weaker and less specific way than by frontal lobe lesions. Moreover, the age effect persisted even after statistical control of the processing speed.

Our present findings confirm and extend the results reported in previous studies of cognitive aging (Daigneault & Braun, 1993; Daigneault et al., 1992; Kramer, Hahn, & Gopher, 1999; Parkin & Walter, 1991, 1992; Shimamura & Jurica, 1994): Elderly persons are impaired on tasks assessing executive functions. Our findings also suggest that processing speed, measured by a color-naming time, constitutes an important mediator between age and cognitive performance. However, processing speed explains only partially the performance on the executive measures, because it does not contribute to the age-related differences on the Hayling and

Brixton error scores. This suggests that some age-related differences in executive tasks are linked to more specific factors than processing speed (see also Kramer et al., 1999; Spieler, Balota, & Faust, 1996). More generally, a productive approach of cognitive aging taking into account both common (or shared) and specific (or unique) age-related influences is needed.

A final point of this article concerned the fractionation of the SAS. Partial correlation analysis in which we controlled the general effect of age gave rise to a disappearance of correlations between Hayling and Brixton tests. This confirms that the SAS can be fractionated into different independent executive functions, as already suggested by Shallice (1988, 1994) and Shallice and Burgess (1993, 1996), on the basis of dissociations in frontal patients.

Globally, these age-related differences in executive functions are consistent with the studies showing a frontal decline in elderly persons. For example, in the study of Raz and colleagues (1997), age-related structural differences in the human cerebral cortex were examined in 148 healthy volunteers (aged 18–77 years) using in vivo evidence from magnetic resonance imaging. The most substantial age-related decline was observed in the volume of the prefrontal gray matter (4.9% per decade). Smaller or no age-related differences were found in the other regions, including hippocampal formation and prefrontal white matter. Additionally, Raz, Gunning-Dixon, Head, Dupuis, and Acker (1998) observed that age-related shrinkage of the prefrontal cortex might specifically mediate age-related differences in executive functions such as flexibility (evaluated by the WCST). Researchers should conduct studies to relate the age-related differences on TOL, Hayling, and Brixton tests and frontal dysfunction.

A limitation of the present study concerns the general issue of the relation between executive measures and underlying constructs such as inhibition or planning (Burgess, 1997). First, executive tasks are less pure measures than non-executive ones. Because they are assessed by complex and multidetermined tasks, nonexecutive factors such as sensory deficits can affect age-related differences in executive functions to some extent. For example, it could be argued that sensory deficits contributed to the age-related differences (Baltes & Lindenberger, 1997) observed in the current study. However, age-related differences in peripheral processes (e.g., vision) are shown in some but not all aspects of vision. Thus, HaegerstromPortnoy, Scheck, and Brabyn (1999) observed that, whereas under conditions of reduced contrast or luminance spatial vision measures can show some age-related differences, high-contrast acuity is well maintained with aging. It would be difficult to see how this specific deficit could explain the age-related differences observed in the tasks administered in the present study, which required clearcut perceptual discrimination only (e.g., only primary colors were used in the TOL test).

Second, the relative lack of correspondence between behavior and putative cognitive processes in executive functions (e.g., Phillips, 1997) can sometimes lead to difficult interpretations of age-related differences in executive tasks. In this vein, if we consider, for example, the age-related differences in latency times of Section B of the Hayling test

taken alone (without considering the result that elderly participants make more inhibition errors), it is difficult to distinguish between a diminution of the capacity to generate nonstereotypical responses and a difficulty in inhibiting strong stereotypical responses. Researchers should conduct studies to break down the complex executive tasks into their different cognitive components and to understand which particular cognitive processes (e.g., working memory) could contribute to the age-related differences observed in executive functions.

References

Arbuthnott, K. D. (1995). Inhibitory mechanisms in cognition: Phenomena and models. *Current Psychology of Cognition, 14,* 3–45.

Baddeley, A. D. (1986). *Working memory.* New York: Oxford University Press.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging, 12,* 12–21.

Brennan, M., Welsh, M. C., & Fisher, C. B. (1997). Aging and executive function skills: An examination of a community-dwelling older adult population. *Perceptual and Motor Skills, 84,* 1187–1197.

Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 81–117). Oxford, England: Psychology Press.

Burgess, P. W., & Shallice, T. (1996a). Response suppression, initiation and strategy use following frontal lobe lesions. *Neuropsychologia, 34,* 263–273.

Burgess, P. W., & Shallice, T. (1996b). Bizarre responses, rule detection and frontal lobe lesions. *Cortex, 32,* 241–259.

Connelly, S. L., & Hasher, L. (1993). Aging and inhibition of spatial location. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1238–1250.

Coyette, F., & Van der Linden, M. (1992). Elaboration d'une épreuve d'évaluation adaptée de la Tour de Londres [Development of an adapted version of the TOL test]. Unpublished study.

Daigneault, S., & Braun, C. M. J. (1993). Working memory and the self-ordered pointing task: Further evidence of early prefrontal decline in normal aging. *Journal of Clinical and Experimental Neuropsychology, 15,* 881–895.

Daigneault, S., Braun, C. M. J., & Whitaker, H. A. (1992). Early effects of normal aging on perseverative and non-perseverative prefrontal measures. *Developmental Neuropsychology, 8,* 99–114.

Deltour, J. J. (1993). Echelle de vocabulaire Mill Hill de J. C. Raven. [Raven Mill Hill Vocabulary Scale] Braine-le Chateau, Belgium: Editions l'Application des Techniques Modernes.

Eslinger, P. J., & Damasio, A. (1985). Severe disturbance of higher cognition after bilateral frontal lobe ablation: Patient EVR. *Neurology, 35,* 1731–1741.

Fisk, J. E., & Warr, P. (1996). Age and working memory: The role of perceptual speed, the central executive, and the phonological loop. *Psychology and Aging, 11,* 316–323.

Fristoe, N. M., Salthouse, T. A., & Woodard, J. L. (1997). Examination of

age-related deficits on the Wisconsin Card Sorting Test. *Neuropsychology, 11,* 428–436.

Gurd, J. M. (1995). Frontal dissociations: Evidence from Parkinson's disease. *Journal of Neurolinguistics, 9,* 55–68.

Haegerstrom-Portnoy, G., Scheck, M. E., & Brabyn, J. A. (1999). Seeing into old age: Vision function beyond acuity. *Optometry and Vision Science, 76,* 141–158.

Janowsky, J. S., Shimamura, A. P., Kritchevsky, M., & L. R. (1989). Cognitive impairment following frontal damage and its relevance to human amnesia. *Behavioral Neuroscience, 103,* 548–560.

Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: Explorations of executive control processes in the task switching paradigm. *Acta Psychologica, 101,* 339–378.

Kwong See, S. T., & Bouchard Ryan, E. (1995). Cognitive mediation of adult age differences in language performance. *Psychology and Aging, 10,* 458–468.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. (Center for Human Information Processing Technical Report No. 99, rev. ed.). In R. J. Davidson, G. E. Schartz, & D. Shapiro (Eds.), *Consciousness and self-regulation: Advances in research,* (pp. 1–18). New York: Plenum Press.

Owen, A. M., Downes, J. D., Sahakian, B. J., Polkey, C. E., & Robbins, T. W. (1990). Planning and spatial working memory following frontal lobe lesions in man. *Neuropsychologia, 28,* 1021–1034.

Parkin, A. J., & Lawrence, A. (1994). A dissociation in the relation between memory tasks and frontal lobe tests in the normal elderly. *Neuropsychologia, 32,* 1523–1532.

Parkin, A. J., & Walter, B. (1991). Aging, short-term memory, and frontal dysfunction. *Psychobiology, 19,* 175–179.

Parkin, A. J., & Walter, B. (1992). Recollective experience, normal aging, and frontal dysfunction. *Psychology and Aging, 7,* 290–298.

Phillips, L. H. (1997). Do "frontal tests" measure executive function? Issues of assessment and evidence from fluency tests. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 191–213). Oxford, England: Psychology Press.

Raz, N., Gunning-Dixon, F. M., Head, D., Dupuis, J. H., & Acker, J. D. (1998). Neuroanatomical correlates of cognitive aging: Evidence from structural magnetic resonance imaging. *Neuropsychology, 12,* 95–114.

Raz, N., Gunning-Dixon, F. M., Head, D., Dupuis, J. H., McQuain, J., Briggs, S. D., Loken, W. J., Thorton, E., & Acker, J. D. (1997). Selective aging of the human cerebral cortex observed in vivo: Differential vulnerability of the prefrontal gray matter. *Cerebral Cortex, 7,* 268–282.

Salthouse, T. A. (1992). *Mechanisms of age-cognition relations in adulthood.* Hillsdale, NJ: Erlbaum.

Salthouse, T. A. (1996). The processing speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428.

Salthouse, T. A., Fristoe, N., & Hyun Rhee, S. (1996). How localized are age-related effects on neuropsychological measures? *Neuropsychology, 10,* 272–285.

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society of London, B, 298,* 199–209.

Shallice, T. (1988). *From neuropsychology to mental structure.* Cambridge, England: Cambridge University Press.

Shallice, T. (1994). Multiple levels of control processes. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance IX* (pp. 395–420). Cambridge, MA: MIT Press.

Shallice, T., & Burgess, P. (1993). Supervisory control of action and thought selection. In A. D. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awarenes and control. A tribute to Donald Broadbent* (pp. 171–187). Oxford, England: Oxford University Press.

Shallice, T., & Burgess, P. (1996). The domain of supervisory processes and temporal organization of behavior. *Philosophical Transactions of the Royal Society of London, B, 351,* 1405–1412.

Shimamura, A. P., & Jurica, P. J. (1994). Memory interference effects and aging: Findings from a test of frontal lobe function. *Neuropsychology, 8,* 408–412.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and adults and in individuals with dementia of the Alzheimer type. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 461–479.

Stuss, D. T., & Benson, D. F. (1986). *The frontal lobes.* New York: Raven Press.

Van der Linden, M., Beerten, A., & Pesenti, M. (1998). Age-related differences in random generation. *Brain and Cognition, 38,* 1–16.

Van der Linden, M., Brédart, S., & Beerten, A. (1994). Age-related differences in updating working memory. *British Journal of Psychology, 85,* 145–152.

Van der Linden, M., Hupet, M., El Ahmadi, A., Feyereisen, P., Schelstraete, M.-A., Bestgen, Y., Bruyer, R., Lories, G., & Seron, X. (1999). Cognitive mediators of age-related differences in language comprehension and verbal memory performances. *Aging, Neuropsychology and Cognition, 6,* 32–55.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120,* 272–292.

Zacks, R. T., & Hasher, L. (1994). Directed ignoring. Inhibitory regulation of working memory. In D. Dagenbach & T. Carr (Eds.), *Inhibitory mechanisms in attention, memory and language* (pp. 241–264). San Diego, CA: Academic Press.