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A Structural Modeling Examination of the Executive Decline Hypothesis of Cognitive Aging Through Reanalysis of Crawford et al.'s (2000) Data

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ABSTRACT

This study presents a new analysis of data previously published by Crawford, Bryan, Luszcz, Obansawin, and Stewart (2000) examining the role of executive function in age-related declines in general cognitive ability and memory. Although the original authors' question is relevant to understanding the role of executive function in aging, this paper argues that the methods used can be substantially improved to more accurately answer the question. Thus, Crawford et al.'s data are here analyzed using a more parsimonious methodological approach (structural equation modeling), and the results obtained depart from the authors' results but are in line with their original hypotheses. First, for younger individuals, age was differently associated with verbal measures of cognitive ability than with performance measures. Although the relation of age to executive function was stronger than the relation of age to verbal abilities, this difference was not apparent with regard to performance abilities. Second, across samples (i.e., younger and older individuals), memory was not accounted for by cognitive ability but was related to age and executive function. Finally, also across samples, executive function was strongly linked to recall and recognition measures, accounting for the largest variance in memory. These results are discussed in relation to previous findings as well as their theoretical significance for aging research.

The term executive function refers to "... [a] broad range of cognitive skills, such as monitoring one's recent and past performance, generating future goals, inhibiting prepotent overlearned responses, and alternating behavioral patterns in response to feedback'' (Raz, 2000, p. 60). According to this definition, then, executive function is a set of higher order cognitive processes encompassing a wide variety of mental activities. Among these are planning, organizing, divergent thinking, inhibiting, prospective memory, and self-monitoring, as well as aspects of complex behaviors such as social interaction and sexuality.

Executive function has been examined in relation to other cognitive processes (e.g., memory), and various complex behaviors (i.e., intentionality, social behavior). Moreover, executive function and its relationships with other constructs have been studied with particular attention in the context of aging. The present study is an attempt to connect these two approaches. In particular, this study presents new analyses of data previously published by Crawford et al. (2000) in an attempt to clarify the role of executive function in age-related declines in cognitive ability and memory.

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Executive Function and Aging

Research has linked executive function to activation in the prefrontal cortex (PFC), an area responsible for complex functions such as the temporal organization of behavior (Kolb & Whishaw, 1990). The PFC appears to co-ordinate a series of smaller processes that make up complex behaviors, assembling them in the correct order, at the correct time and place, and in response to sensory input. In addition to identifying its physical location in brain physiology, research has described the dependence of executive function on changes in the PFC. In general, it is assumed that executive function is highly sensitive to alterations in the PFC (Kimberg & Farah, 1993). Furthermore, PFC is thought to be one of the most vulnerable areas to aging, in comparison, for example, with the hippocampus, cerebellum, and the temporal, parietal, and occipital cortices, which are less affected by aging processes (Dempster, 1991; Raz, 2000). Such a difference seems to represent a correspondence between ontogenetic chronology and age-related vulnerability. Due perhaps to its complexity, the PFC seems to be the last brain area to develop and the first to degenerate (Raz, 2000).

The high sensitivity of executive function and the PFC to aging has been demonstrated in research. For example, Nagahama et al. (1997) examined potential differences in executive function between younger and older individuals using functional neuroimaging (PET). The researchers found a high negative correlation between the magnitude of activation in the dorsolateral prefrontal cortex (DLPFC) and the number of perseverative errors in the Modified Card Sorting Test (MCST) among older individuals. Moreover, for those commonly activated areas in the two groups, they found a lower magnitude of activation among older participants. Similar age-related differences were reported by Marshuetz, Jonides, Smith, Reuter-Lorentz, and Koeppe (1998) who found activation of left DLPFC to be associated with higher inhibitory demands in younger, but not in older, individuals. Finally, Raz, Gunning-Dixon, Head, Dupuis, and Acker (1998) found that the relationship between the PFC (dorsolateral) and perseverative behavior in the MCST weakened when age was taken into account in the analyses. This was explained from a physiological standpoint; alteration of white matter and loss of gray matter might be independent in their contribution to executive function declines (Raz, 2000). These deficiencies in components of executive function are the most substantial age-related declines described in aging research (Woodruff-Pak, 1997).

To understand age-related declines in executive functions, researchers have focused on the neurobiology of the aging brain. From this standpoint, aging has been associated with both structural and functional changes in the cerebral cortex (see West, 1996; Woodruff-Pak, 1997, for reviews). Structural alterations include (a) reduction in brain volume, notably in the 7th decade of life, possibly due to shrinkage in neuron size and with a larger decline in the frontal cortex and corpus striatum than in other areas of the cortex; (b) neural atrophy, with loss of dendritic processes; (c) reduction in the number of synapses; (d) changes in neurochemistry, involving a reduction in the number of dopamine receptors and the concentration of neurotransmitters; and, (e) increase of pathological structures such as senile plaques, with larger concentration in the frontal and temporal areas in healthy individuals. With regard to functional changes, the main alterations in the PFC associated with aging are: (a) selective decline in regional cerebral blood flow, with greater reduction observed in the frontal cortex, compared with temporal and parietal areas; and, (b) decrease in glucose metabolism, although this finding is not consistent across studies.

Executive Function, Aging, and Memory

The relationship between executive function and aging has also been studied in relationship to other cognitive processes, primarily memory. In this approach, research has tried to describe potential links between these cognitive processes, attempting to identify directionality in the relationship and determine specific roles in aging. An example of this endeavor is the research on prospective memory (i.e., remembering to do something in the future). This type of memory is believed to have a large executive component and is related to the idea of placing the temporal organization of behavior as the central component of executive function (Fuster, 1989). The processes involved in prospective memory have been distinguished from those involved in declarative memory; whereas the former are responsible for manipulating and organizing memory, the latter acquire and store information (Woodruff-Pak, 1997). Consequently, deficits in each type of memory are manifested differently. For example, individuals with impaired memory (e.g., amnesia) from temporal lobe lesions can successfully perform activities demanding prospective memory. Individuals with damaged prospective memory, however, are thought not to be able to perform declarative memory tasks due to impairment in their organizational and retrieval strategies (see Woodruff-Pak, 1997 for a review).

One aspect of prospective memory is remembering the source of information. Source memory is, in part, regulated by the PFC and, thus, is sensitive to lesions in the frontal lobes. Although impairment in this area is thought to lead to deficits in other aspects of memory that are localized in the temporal lobes (Woodruff-Pak, 1997), some research has yielded findings suggesting the contrary. For example, Parkin, Leng, and Stanhope (1988) found that patients with substantial impairment in source memory could perform normally in declarative memory tasks (i.e., recognition and recall of facts). Similarly, Craik, Morris, Morris, and Loewen (1990) found that source recognition and source recall were associated with each other and with performance on the WCST but not with fact recall. The relation of recognition processes to age and frontal lobe functioning was investigated by Parkin and Walter (1992). In this study, participants were shown a list of words and were then asked to perform a recognition test, reporting whether their responses were based on explicit recollection of the words or based on familiarity. The researchers found that whereas recognition based on explicit recollection decreased with age, recognition based on familiarity increased with age. Moreover, the responses of older individuals who used familiarity-based recognition were associated with a greater number of errors on the WCST, indicating a relation between this kind of recognition and frontal lobe functioning.

The link between executive function and memory has also been examined by researching spontaneous cognitive flexibility. This term refers to the ability to have a flow of ideas and answers in response to questions. It can be assessed using a word fluency test that allows the participant to initiate the response and differs from reactive flexibility, which is typically assessed by the WCST. Research has identified different relations between these kinds of flexibility and memory types. For example, Parkin and Lawrence (1994) found that memory assessed through release from proactive interference was correlated with spontaneous flexibility but not with reactive flexibility. In contrast, a memory task involving recall difficulty relative to cognition was correlated with reactive flexibility but not spontaneous flexibility. Both types of flexibility, however, were substantially impaired in older adults. Similar findings suggesting different relationships between flexibility and memory were reported by Parkin, Walter, and Hunkin (1995). In this study, the researchers found a correlation between spontaneous flexibility and degree of impairment in spatio-temporal organization among older participants. Degree of impairment, however, was not associated with reactive flexibility, as assessed by the WCST.

The Executive Decline Hypothesis

An overall relation of executive function with other aspects of cognitive aging has been formalized as the ''Prefrontal Cortex Function Theory'' (West, 1996). According to this theory, the PFC is the area of the brain most sensitive to aging. Thus, those cognitive abilities supported by this region should demonstrate earlier and larger age-related declines in cognitive functions than cognitive abilities supported by other regions. West's synthesized model of PFC suggested that executive function has a general function of integrating information temporally. This process involves four aspects, namely, prospective memory, retrospective memory, interference control, and inhibition of prepotent responses. Such a model was found to account for age-related declines in numerous cognitive abilities except for declines in item recall and recognition memory. West (1996) argued that such cognitive processes are best explained by deficits in medial temporal cortices. In this latter statement, West recognized the incompleteness of his model as a neuropsychological theory of cognitive aging.

A more specific version of the role of executive function in cognitive aging has been formulated in relation to memory (Dempster, 1992; Parkin, 1996). This view proposes that age-related declines in memory may be caused by a subclinical and selective decline in executive function. Such a proposition, termed the ''Executive Decline Hypothesis'' of cognitive aging, was recently examined by Crawford et al. (2000). The researchers were interested in examining: (a) whether aging is associated with a selective decline in executive function, compared with deficits in general cognitive ability, and (b) whether declines in executive function mediate age-related declines in memory apart from the variance accounted for by general cognitive ability.

With regard to the first aim, the researchers argued that finding greater age-related declines in executive function than in general cognition would support the selective hypothesis. To examine this question, they used the Wechsler Adult Intelligence Scale – Revised (WAIS–R; Wechsler, 1981) as a measure of general cognitive ability. The WAIS–R was selected for this purpose because it covers a wide range of cognitive domains and because there is evidence that it is relatively insensitive to executive dysfunction. The authors therefore argued that the magnitude of age differences on this measure would provide a useful comparison standard against which any age differences on executive tasks could be evaluated. They used Williams' (1959) significance tests and found the correlations between age and the executive function measures to not differ from the correlations between age and general cognitive ability (i.e., Full Scale and Verbal Scale WAIS–R scores). Contrary to the selective hypothesis, the only exception to this general pattern was the correlation between age and Full Scale ($r = -.28$), which was greater than the correlation between age and Verbal Fluency (a measure of executive function, $r = -.08$). These results depart from the predictions of the first inquiry, thus rejecting the differential decline hypothesis.

In developing their second hypothesis, the investigators built upon previous research suggesting that age-related declines in memory, especially in those tasks dependent upon strategic processes, may be caused by decay of executive function. For example, prior studies had shown that episodic memory was predicted by age only when executive function was not partialled out (Troyer, Graves, & Cullum, 1994) and that free recall performance was predicted by executive function and working memory, but not by processing speed (Bryan, Luszcz, & Pointer, 1999). The mediational role of executive function was examined through a series of hierarchical regression analyses to determine whether executive function accounted for age-related variance in memory over and above that accounted for by general cognitive ability (i.e., Full Scale or Verbal Scale). This procedure was employed separately for each measure of memory (i.e., free recall, recognition, and serial recall). The results of these analyses indicated that executive function and cognitive ability (i.e., Full Scale scores) predicted similar percentages of age-related variance in all the memory tasks, leading the authors to conclude that executive function and cognitive ability both contribute to memory variance. When controlling for Full Scale and Verbal Scores, however, executive function still predicted memory and accounted for additional, albeit modest, age-related memory declines (free and serial recall, not recognition). This was not true when general ability measures were allowed to predict memory after controlling for executive function, suggesting that executive function provides a unique, yet small, contribution to age-related declines in memory.

To interpret the similarity in prediction of age-related memory decline between general ability and executive function, Crawford et al. (2000) argued that perhaps the subtests of the WAIS–R rely on executive processes. Alternatively, they claimed that executive function measures represent general cognitive ability, even those measures assessing verbal ability. To reconcile these views, they asserted that executive tasks need processing speed resources and these might reflect general fluid abilities.

Based on these results and the presumption that ''executive measures may share common variance with fluid intelligence'' (p. 19), the authors decided to examine the relationships between executive function and the WAIS–R scales to see whether these two measures indeed represent a common construct. Their analyses revealed that the WAIS–R subscale exhibiting the largest correlations with age and memory was the Digit Symbol Substitution Test (DSST). Subsequently, this variable was used to examine its relative contribution, as compared with executive function, to age-related declines in memory. The researchers concluded that results of these new analyses indicated that

> [E]xecutive function makes an independent contribution to free recall and serial recall after controlling for the DSST. However, it does not account for additional age-related variance in any memory measure over and above that accounted for by the DSST. Indeed, DSST performance accounted for more of the age-related variance in all three memory measures than did either executive function or general cognitive ability. (p. 21)

This finding was interpreted as supporting the line of research suggesting that processing speed accounts for age-related decline in various memory measures (Salthouse, 1991; Salthouse, Fristoe, & Rhee, 1996).

The Present Study in Relation to Crawford et al.'s (2000) Investigation

Although Crawford et al. (2000) offered some interesting interpretations of their results, there are several limitations to their findings. Some of these limitations are related to the analytic strategies employed. For example, some of their tests of the first hypothesis were based on Pearson correlations alone. Other tests of the second hypothesis relied on a series of hierarchical multiple regression analyses, using different tests for each outcome and, thus, inflating the probability of a Type I error. Other limitations, although embedded in the analytic strategy, are more substantial and involve the methods used to test specific conceptual hypotheses. First, some questions, such as the mediational role of executive function, were examined indirectly, without a straight parsimonious test. Second, performing analyses for each memory task separately did not allow direct comparison among the three measures, or examination of age-related declines in a general ''memory'' construct. Third, although cognitive ability was separated into its verbal and performance components in additional analysis, such a separation was not considered to examine the central question. Rather, the verbal and full scales (i.e., containing the verbal scale) were used leading to a large overlap between them. Distinguishing between the verbal and performance components is important as they represent different theoretical constructs of cognitive ability (i.e., fluid and crystallized abilities) that show distinct variations with age. For example, recent research has indicated how these two abilities follow different trajectories over the life-span and how collapsing such trajectories into a single factor (i.e., general intelligence) is a simplistic and non-tenable hypothesis that obscures the growth and change of cognitive abilities (McArdle, Ferrer-Caja, Hamagami, & Woodcock, 2002).

The present study is an attempt to resolve these problems and examine the important conceptual questions addressed by Crawford et al. (2000). To achieve this goal, the original data (i.e., correlation matrix, means, and standard deviations) were reanalyzed using structural equation modeling techniques (SEM). This approach offers advantages particularly relevant to answering the questions at hand. Some of these advantages include: (a) the direct evaluation of hypotheses based on correlations, covariances, or means; (b) the use of direct algebraic specification of a model using ''fixed,'' ''free,'' and ''equal'' parameters; (c) the calculation of ''maximum likelihood estimates'' for free parameters; and, (d) statistical tests of goodness-of-fit using the ''likelihood ratio test'' (LRT) based on the chi-square distribution (McArdle & Prescott, 1992, p. 92). Furthermore, SEM strategies allow simultaneous examination of the relationships among age, executive function, general cognitive abilities, and memory using latent constructs. Based on this examination, alternative models can be compared to determine: (a) what is the pattern of relationships among the constructs that represent the structure of the data more accurately; (b) what are the important factors predicting memory declines; (c) how much variance of the construct is explained; and, (d) the degree of confidence in the results.

METHOD

Participants

Because this paper is based on data previously presented by Crawford et al. (2000), the participants and measures sections are abridged. Further information can be obtained from the original paper.

Two independent samples participated in this study. The first sample consisted of 123 participants (75 females and 48 males) aged 18–75 years ($M = 39.41$, $SD = 13.36$). All the participants were volunteers from a community in Aberdeen (Scotland) with an average of 13.18 years of education ($SD = 2.85$) and without major systemic, neurological, or psychiatric disorders. The second sample consisted of 90 participants (50 females and 40 males) aged 60–89 years ($M = 72.80$, $SD = 6.45$). These participants were also volunteers from a community in Aberdeen with an average of 9.55 years of education ($SD = 1.49$).

Measures (Younger Sample)

General Cognitive Ability

Two measures of general cognitive ability were used, based on the WAIS–R (Wechsler, 1981): a Full Scale measure, based on all the subtests, and a Verbal Scale measure, based on the scores for the verbal subtests.

Executive Function

An overall measure of executive function was used based on the following tests: (a) The Modified Card Sorting Test (MCST; Neslon, 1976), which measures reactive flexibility; (b) The Controlled Oral Word Association Test (COWAT; Benton, 1968; Benton & Hamsher, 1976), also referred to as the letter verbal fluency test, assessing spontaneous flexibility; (c) The Stroop Test (Golden, 1978; Stroop, 1935), which measures proneness to interference; (d) The Tower of London Test (TOL; Shallice, 1982), which measures problem-solving and forward planning; (e) The Cognitive Estimates Test (Shallice & Evans, 1978), which measures formulation, execution, and revision of a cognitive plan; and, (f) The Uses for Common Objects Test (Getzels & Jackson, 1962), which also measures spontaneous flexibility.

Memory Tests

All participants were presented with word lists and then tested for free recall (i.e., freely recall lists of nouns immediately after presentation), serial recall (i.e., from cards displaying one of the previously presented words), and recognition (i.e., of the words presented in the free recall trials).

Measures (Older Sample)

Participants in the older sample completed a battery including measures of: (a) general cognitive ability (i.e., a short form of the Verbal Scale of the WAIS–R including vocabulary, arithmetic, digit span, and similarities subtests); (b) executive function (i.e., the MCST and COWAT tests, and semantic fluency tasks); and, (c) memory (i.e., free recall).

Data Description

Table 1 presents the correlations, means, and standard deviations of all the variables from the two samples, taken directly from the Crawford et al. (2000) original paper. Visual inspection of this table shows, for example, negative correlations of age with all the variables except for cognitive estimates. For the younger sample, these correlations are generally low and range from −.36 to .10. Moreover, Full Scale and Verbal Scale correlate positively with all the variables (r_s ranging from .23 to .62, and from .17 to .62, for Full Scale and Verbal Scale, respectively) and strongly between each other ($r = .92$), which is expected given that the Full Scale includes the Verbal subtests. Among individuals in the older sample, the correlations of age with all the variables are also negative but larger (ranging from −.50 to −.24).

Structural Models of Relationships

To examine the contribution of executive function to age-related declines in memory and the role of executive function in the relationship between general cognitive ability and memory, a model of relations among the variables was specified and tested. The specification of the model emanated directly from the conceptual hypotheses posited by Crawford et al. (2000) as well as from their results. A graphic representation of this model is displayed in Figure 1.

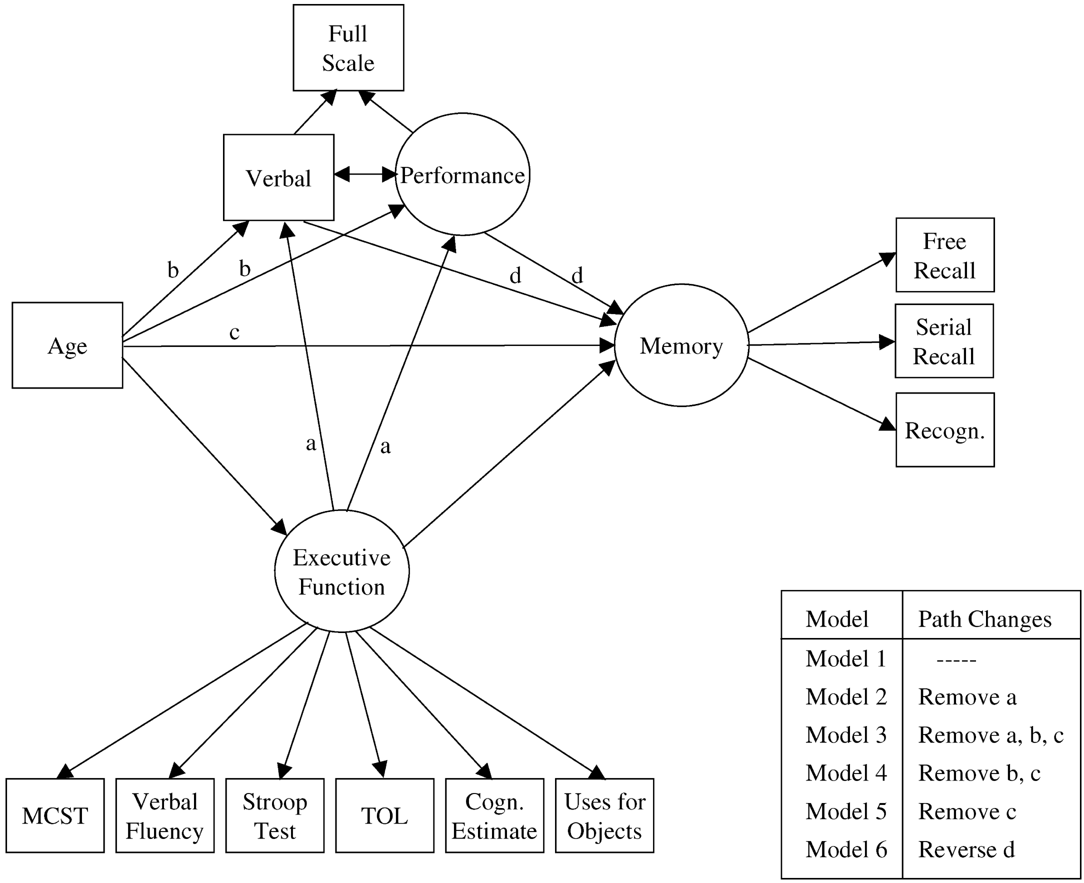
This model makes explicit a number of hypotheses, including: (a) memory is predicted by age, cognitive ability, and executive function; (b) the relations between cognitive ability and age with memory are mediated by executive function; (c) the six executive function tests are best represented by a latent construct that reflects ‘‘executive function;’’ and, (d) the three memory tests are also best represented by their ‘‘memory’’ latent construct. These hypotheses can now be formally tested by comparing this model with theoretically-based alternative ones that specify different patterns of relations among the variables. Following this logic, a series of models positing specific hypotheses, were examined (see legend in Fig. 1). These models included:

Model 1: Described above and representing a baseline against which alternative models can be compared.

Table 1. Pearson Product-Moment Correlations Among the Variables.

Variable	1	2	3	4	5	6	7	8	9	10	11	12
Younger sample (N = 123)												
1. Age	1.00											
2. Full Scale	−.28	1.00										
3. Verbal Scale	−.13	.92	1.00									
4. Free recall	−.23	.32	.28	1.00								
5. Recognition	−.21	.23	.17	.35	1.00							
6. Serial recall	−.36	.32	.27	.33	.27	1.00						
7. MCST categories	−.28	.62	.54	.37	.19	.30	1.00					
8. Tower of London	−.19	.36	.24	.21	.07	.28	.26	1.00				
9. Stroop	−.20	.30	.24	.15	.19	.23	.29	.26	1.00			
10. Verbal fluency	−.08	.52	.52	.27	.23	.19	.39	.24	.27	1.00		
11. Cognitive estimates	.10	.58	.62	.24	.13	.24	.36	.16	.15	.32	1.00	
12. Uses for objects	−.14	.49	.46	.28	.15	.17	.44	.30	.06	.46	.36	1.00
Mean	39.41	112.86	64.46	7.41	6.19	0.53	4.90	26.33	50.37	32.19	4.55	15.49
SD	13.36	21.18	12.66	1.72	0.72	0.07	1.58	4.32	8.57	9.49	3.53	5.91

Variable	1	2	3	4	5	6
Older sample (N = 90)						
1. Age	1.00					
2. Verbal Scale	−.27	1.00				
3. Free recall	−.50	.47	1.00			
4. MCST categories	−.51	.50	.44	1.00		
5. Verbal fluency	−.24	.55	.40	.22	1.00	
6. Semantic fluency	−.37	.57	.49	.42	.59	1.00
Mean	72.80	39.01	18.21	4.60	41.60	42.69
SD	6.45	7.62	4.32	1.67	16.52	12.39



Model	Path Changes
Model 1	-----
Model 2	Remove a
Model 3	Remove a, b, c
Model 4	Remove b, c
Model 5	Remove c
Model 6	Reverse d

Fig. 1. Hypothesized model of structural relationships among the variables and legend representing the alternative models.

Model 2: With no paths between executive function and cognitive ability. This model postulates that age, executive function, and cognitive ability predict memory independently, and is against the mediating hypothesis of executive function.

Model 3: With paths from age to executive function, and from executive function to cognitive ability, but no relations between age and cognitive ability or memory; hence, predicting that all the effects on memory are mediated by executive function. This model is an extreme representation of the mediating hypothesis of executive function.

Model 4: Similar to *Model 3* but with cognitive ability mediating memory predictions. This model examines a hypothesis opposite to the one tested in *Model 3*.

Model 5: With no paths from age to memory; thus, all age-related effects are mediated through executive function and cognitive ability.

Model 6: Similar to *Model 1* but with paths from memory to verbal and performance cognitive abilities, thus reversing the direction of these paths. This model attempts to represent the dynamics of decline in cognitive abilities. It is based on research suggesting that declines in memory may be the "leader" of age-related changes in other variables (McArdle, Hamagami, Meredith, & Bradway, 2000; McArdle, Prescott, Hamagami, & Horn, 1998; Raz et al., 1998; Swanson, 1999).

In addition to integrating the three memory measures into a "memory" common construct, all these models separated Verbal and Performance scales as different components of general cognitive ability.

The data were analyzed using LISREL 8.3 (Jöreskog & Sörbom, 1999). Goodness of fit was assessed examining the chi-square statistic (χ^2), Root Mean Square Error of Approximation (RMSEA) and its probability of close fit $(p < .05)$, and Goodness of Fit Index (GFI).

RESULTS

The Executive Function Decline Hypothesis Among Younger Individuals

Table 2 presents results of the models examining the relationships among age, executive function, general cognitive ability (i.e., Full Scale), and memory. The first model (*Model 1*) is the hypothesized model, predicting direct relationships between memory, executive function, and general cognitive ability with age, independently. Moreover, this model hypothesizes that executive function predicts verbal and performance cognitive abilities, hence, predicting an indirect relation between cognitive ability and memory through executive function.[1] The fit indices indicated that this model provides a good fit ($\chi^2 = 73$, $df = 47$), suggesting that this might be a reasonable representation of the structure of these data. Moreover, this model accounted for a large amount of variance in memory ($1 - \zeta = 74\%$).

The second model removes the path between executive function and cognitive ability, hypothesizing that the relations of age, full scale, and executive function with memory are direct and independent. This model yielded a worse fit ($\chi^2 = 176, df = 49$) compared with *Model 1* ($\Delta\chi^2/\Delta df = 103/2$), thus suggesting this is not likely to be a reasonable representation of these data. Furthermore, the amount of memory variance explained by this model was greatly reduced ($1 - \zeta = 47\%$). The next model (*Model 3*) predicts that the relations of age and general cognitive ability with memory are not direct but mediated by executive function. In other words, this model posits that executive function is the only factor needed to account for variance in memory. As indicated by the fit indices, this model yielded a reasonable fit ($\chi^2 = 102$, $df = 52$), although slightly worse than *Model 1* ($\Delta\chi^2 df/\Delta df = 29/5$) and with a moderate decrease in the variance explained in memory ($1 - \zeta = 43\%$).[2]

Model 4 has the same predictions as *Model 3* but with general cognitive ability as the factor mediating the relationships of age and executive function with memory. This model's fit is also reasonable ($\chi^2 = 94, df = 50$), but still inferior to that of *Model 1* ($\Delta\chi^2/\Delta df = 21/3$). Similarly, the amount of explained variance in memory was reduced ($1 - \zeta = 28\%$). The next model, *Model 5*, reproduced *Model 1* but with the path from age to memory removed. Thus, this model predicted that the relation between age and memory was mediated through general cognitive ability and executive function. The fit of this model turned out to be slightly worse than that of *Model 1* ($\chi^2 = 81, df = 48; df = 48; \quad \Delta\chi^2/\Delta df = 8/1$) with a small decrease in explained variance in

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[1]The path from executive function to cognitive ability becomes a component of the relationship between cognitive ability and memory. This can be demonstrated algebraically as follows:

Let

$$A = A$$
$$B = \beta_{ba} * A + \beta_{bc} * C + e_b$$
$$C = \beta_{ca} * A + e_c$$
$$Y = \beta_{ya} * A + \beta_{yb} * B + \beta_{yc} * C + e_y$$

where $A =$ age, $B =$ cognitive ability, $C =$ executive function, and $Y =$ memory.

Let's also set the following assumptions:

$$\mathcal{E}[A, e_b] = 0, \mathcal{E}[A, e_c] = 0, \mathcal{E}[A, e_y] = 0,$$
$$\mathcal{E}[B, e_c] = 0, \mathcal{E}[B, ey] = 0, \mathcal{E}[C, e_b] = 0, \mathcal{E}[C, ey] = 0,$$
$$\mathcal{E}[Y, e_b] = 0, \mathcal{E}[Y, e_c] = 0,$$
$$\mathcal{E}[e_b, e_c] = 0, \mathcal{E}[e_b, e_y] = 0, \mathcal{E}[ec, e_y] = 0,$$
$$\mathcal{E}[A, A] = v_a.$$

Then, the expected covariation between cognitive ability and memory:

$$\mathcal{E}[Y, B] = \beta_{yc}\beta_{ca}\beta_{ba}v_a + 2\beta_{yb}\beta_{ba}\beta_{ca}v_a + \beta_{yb}(\beta_{ba})^2 v_a + \beta_{ya}\beta_{ba}v_a + \beta_{yb}(\beta_{bc})^2(\beta_{ca})^2 v_a + \beta_{ya}\beta_{bc}\beta_{ca}v_a + \beta_{yc}(\beta_{ca})^2\beta_{bc}v_a$$

where β_{bc} is the beta coefficient of the path from executive function to cognitive ability.

This structural component, in addition to the nonperceptible indirect effect of executive function on memory, and the increased variance explained by the model, demonstrates the role of the path between executive function and cognitive ability in the relationship of cognitive ability and memory.

[2]An alternative model to *Model 3* was assessed in which the paths from age to cognitive ability (i.e., verbal and performance) were retained. This model yielded better fit than *Model 3* ($\chi^2 = 88, df = 50$), but still relatively worse than *Model 1* ($\Delta\chi^2/\Delta df = 11/3$).

Table 2. Model Fit Comparison.

Model	χ^2	*df*	RMSEA	*p* (close fit)	GFI	$\Delta\chi^2/\Delta df$
Younger sample ($N = 123$)						
Model 1 (hypothesized)	73	47	.063	.24	.91	–
Model 2 (independent effects)	176	49	.120	.00	.85	103/2
Model 3 (executive function only)	102	52	.089	.01	.88	29/5
Model 4 (cognitive ability only)	94	50	.077	.06	.89	21/3
Model 5 (no age → memory)	81	48	.067	.17	.91	8/1
Model 6 (memory → cognitive ability)	73	47	.063	.24	.91	–
Older sample ($N = 90$)						
Model 1 (hypothesized)	22	6	.176	.01	.92	–
Model 2 (independent effects)	69	7	.269	.00	.84	47/1
Model 3 (executive function only)	33	9	.173	.00	.89	11/3
Model 4 (cognitive ability only)	60	9	.250	.00	.82	38/3
Model 5 (no age → memory)	22	7	.160	.01	.92	0/1
Model 6 (memory → cognitive ability)	23	7	.160	.01	.92	–

memory ($1 - \zeta = 67\%$). The final model, *Model 6* reproduced the initial model but with the direction of the paths between memory and cognitive ability reversed; in this model the former construct was hypothesized to predict the latter. Not surprisingly, this model yielded identical fit to *Model 1* ($\chi^2 = 73, df = 47$), as it estimated the same parameters.

Table 3 presents the parameter estimates from *Model 1* and *Model 6*. The estimates from *Model 1* indicate that age was negatively related to the performance component of cognitive ability, memory, and executive function ($\beta s = -.24$, $-.41$ and $-.21$, respectively). Furthermore, the relationship of age to cognitive ability (i.e., both verbal and performance) was also mediated through executive function ($\beta s = -.18$, and $-.15$, respectively). These findings are in line with the mediational role hypotheses of executive function but the small path coefficient between age and executive function, as compared with those of memory or performance, does not support the differential decline hypothesis. A graphic display of these results is presented in Figure 2.

The particular relationships of cognitive ability and executive function with memory were also different. Whereas none of the cognitive ability components was predictive of memory (*t* values $=$ -1.49 and -1.33, for verbal and performance, respectively), executive function was strongly associated with memory scores, in fact being the strongest predictor of memory ($\beta = 1.36$). The paths from executive function to the verbal and performance cognitive abilities were substantial ($\beta s = .85$ and .73, respectively), suggesting a strong relation between these constructs. Furthermore, adding this path to the model improved substantially both the model fit, as compared with alternative models, and the amount of explained variance in memory. For example, when compared with a model of independent effects (*Model 2*), the percentage of explained variance in memory increased from 47% to 74%, suggesting that a substantial amount of modeled variance in memory was due to the relation between executive function and cognitive ability. This finding, again, provides support for the mediational role of executive function in age-related memory declines.

The results from *Model 6* are very similar to the ones from *Model 1*, reflecting comparable interrelations among the constructs (see Table 3 and Figure 3). The parameter estimates from this model indicate moderate paths from age to performance ability and memory ($\beta s = -.35$ and $-.34$), and a slightly smaller path to executive function ($\beta = -.21$). Similarly, this model suggests strong relations between executive function and cognitive ability ($\beta s = 1.09$, and .93, for verbal and performance, respectively), executive function and memory ($\beta = .64$), as well as imperceptible relations between memory and cognitive

Table 3. Parameter Estimates for the Hypothesized Model (*Model 1*) and Alternative Model with Best Fit in Younger Sample (*Model 6*).

Variable	*Model 1*		*Model 6*	
Factor loadings	λ	$\theta\epsilon$	λ	$\theta\varepsilon$
EF → MCST	.68	.54	.68	.54
EF → Verbal fluency	.59	.65	.59	.65
EF → Stroop Test	.34	.88	.34	.88
EF → Tower of London	.40	.84	.40	.84
EF → Cognitive estimate	.63	.61	.63	.61
EF → Uses for objects	.56	.68	.56	.68
Memory → Free recall	.61	.63	.61	.63
Memory → Serial recall	.60	.64	.60	.64
Memory → Recognition	.47	.78	.47	.78
Direct relations	β	*t* value	β	*t* value
Age → Verbal ability	.05	.74	−.08	−.67
Age → Perf. ability	−.24	−3.60	−.35	−3.21
Age → Memory	−.41	−2.98	−.34	−3.09
Age → Ex. func.	−.21	−2.02	−.21	−2.02
Verbal ability → Memory	−.52	−1.49	–	–
Perf. ability → Memory	−.38	−1.33	–	–
Ex. func. → Verbal ability	.85	7.36	1.09	4.37
Ex. func. → Perf. ability	.73	6.87	.93	4.13
Ex. func. → Memory	1.36	2.37	.64	4.11
Memory → Verbal ability	–	–	−.38	−1.37
Memory → Perf. ability	–	–	−.32	−1.26
Indirect relations	β	*t* value	β	*t* value
Age → Verbal ability	−.18	−2.01	−.05	−.38
Age → Perf. ability	−.15	−2.00	−.05	−.39
Age → Memory	−.07	−0.61	−.14	−1.86
Ex. function → Memory	−.64	−1.47	–	–
Disturbances	ζ	*t* value	ζ	*t* value
Verbal ability	.29	4.01	.23	2.30
Perf. ability	.33	4.91	.29	3.32
Ex. function	.95	3.99	.95	3.99
Memory	.26	1.13	.38	1.95

ability (t values $= -1.37$ and -1.26, for verbal and performance, respectively).

The Executive Function Decline Hypothesis Among Older Individuals

The next set of analyses examined the relationships of age, executive function, cognitive ability, and memory among older individuals (i.e., sample from Study 2 in Crawford et al., 2000). This examination was done in the Crawford et al. study based on research suggesting that executive function decline may not be manifested until older ages (Woodruff-Pak, 1997). To test this inquiry in the current study, the same models examined with the initial sample were fitted to the data from the new sample ($N = 90$; see Table 2). For these data, the models with best fit were *Model 1* (hypothesized model; $\chi^2(6) = 21.6$), *Model 3* (executive function alone; $\chi^2(9) = 32.9$), and *Model 5* (no direct relation between age and memory; $\chi^2(7) = 21.7$). Of these, *Model 5* yielded the best relative fit, also increasing the amount of explained variance in memory ($1 - \zeta = 53\%$, compared with 49% and 45%, for *Model 1* and *Model 3*, respect-

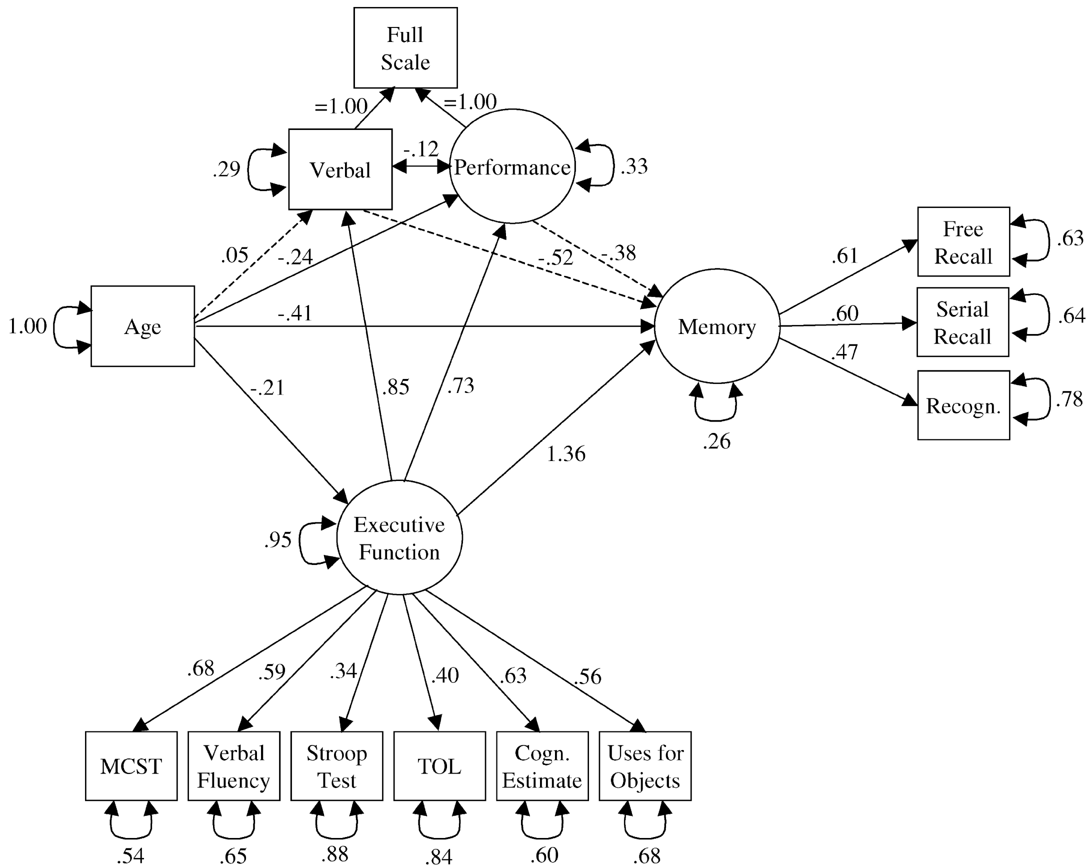

Fig. 2. Standardized parameter estimates from *Model 1* for the younger sample.
Note. Continuous lines indicate accurately estimated coefficients (t value $> \pm1.96$). Discontinuous lines indicate inaccurately estimable coefficients (t value $< \pm1.96$).

ively). Finally, based on this *Model 5*, a new model was fitted reversing the path between memory and cognitive ability. This model also yielded a reasonable fit ($\chi^2(7) = 23.0$).

Table 4 presents the parameter estimates from *Model 5* and *Model 6* fitted to this older sample. The results from *Model 5* indicate that, for this sample age was positively related to cognitive ability (i.e., short version of WAIS–R Verbal Scales) and negatively related to executive function. This finding is in line with Crawford et al.'s (2000) hypothesis of a differential age decline between cognitive ability and executive function. Furthermore, free recall was not related to age (β fixed $= 0$) or cognitive ability ($t < 1.96$), but strongly associated with executive function ($\beta = 1.01$), indicating that, for this sample, memory decline could be predicted by executive function alone. Estimates from *Model 5* are depicted in Figure 4.

Similar to the results with the younger sample, executive function was predictive of cognitive ability. The incorporation of this path in the model improved the overall fit, increased the amount of explained variance in memory, and added an indirect effect of age on cognitive ability through executive function ($\beta = -.61$). Comparably, age was also related to memory through executive function ($\beta = -.49$). Together, these results provide support for the hypothesized mediational role of executive function in age-related memory declines.

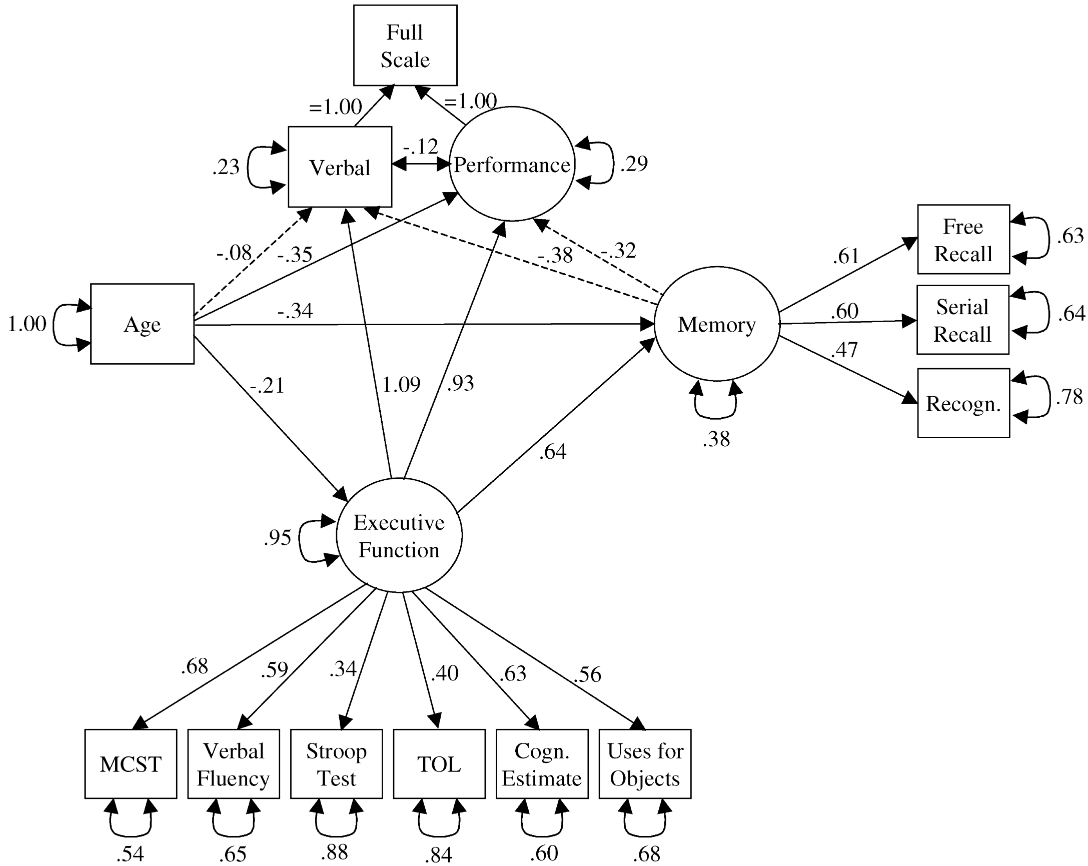

Fig. 3. Standardized parameter estimates from *Model 6* for the younger sample.
Note. Continuous lines indicate accurately estimated coefficients (t value < ±1.96). Discontinuous lines indicate inaccurately estimable coefficients (t value < ±1.96).

DISCUSSION

The different analyses of this study yielded a consistent pattern of results with relevance for research in cognitive aging. First, across samples, age was associated differently with cognitive ability than with executive function. The relationship of age to the verbal component of cognitive ability was imperceptible for younger participants and positive for older participants. Among the younger participants, the relationship between age and performance ability was negative. The relation of age to executive function, however, was negative for the two samples. The difference in the particular relations of age to verbal cognitive ability and executive function is in line with Crawford et al.'s (2000) initial hypothesis positing such different associations but departs from the researchers' actual findings. Using a series of comparisons between pairs of correlations, Crawford et al. found no differences between the correlations of age with the executive function tests and the correlations of age with cognitive ability, with the exception of the MCST among the older participants. The results of the current analyses, however, indicate that the relation of age to the nonverbal component of cognitive ability is substantially different than the relation of age to the verbal scale, and that this relation does not seem to be larger than the one between age and executive function. This latter finding does not support Crawford et al.'s initial

Table 4. Parameter Estimates for the Models with Best Fit in Older Sample.

Variable	*Model 5*		*Model 6*	
Factor loadings	λ	$\theta\varepsilon$	λ	$\theta\varepsilon$
EF → MCST	.63	.60	.64	.60
EF → Verbal fluency	.60	.64	.58	.66
EF → Semantic fluency	.69	.52	.67	.55
Direct relations	β	*t* value	β	*t* value
Age → Cog. ability	.34	3.25 .	41	2.86
Age → Ex. function	−.59	−4.55	−.63	−4.95
Cog. ability → Memory	−.38	−1.60	–	–
Ex. function → Cog. ability	1.03	5.87	1.28	3.83
Ex. function → Memory	1.01	3.64	.73	5.28
Memory → Cog. ability	–	–	−.26	−1.28
Indirect relations	β	*t* value	β	*t* value
Age → Cog. ability	−.61	−4.79	−.69	−4.37
Age → Memory	−.49	−5.47	−.46	−5.28
Ex. function → Memory	−.39	−1.50	–	–
Disturbances	ζ	*t* value	ζ	*t* value
Cog. ability	.23	2.53	.11	1.06
Ex. function	.65	3.07	.26	2.97
Memory	.47	4.46	.42	4.63

differential decline hypothesis but represents more accurately the relationship between age and cognitive ability. Examining cognitive ability using the verbal and full scales, while ignoring performance, might have avoided capturing the complexity of this relation in the Crawford et al. study.[3]

In addition to being negative across the two samples, the relation of age to executive function was stronger among older individuals, resembling the results from Crawford et al.'s (2000) study, although this difference was not formally tested. Considering that the executive function measures used with the older sample consisted primarily of verbal and semantic fluency, it is possible that differences in executive function between the samples might reflect different strategies used by older and younger participants when performing fluency tasks. Previous research has observed that older adults have more difficulty switching to new semantic categories than younger adults do when performing semantic fluency tasks (Troyer, Moskovitch, & Winocur, 1997).

The second pattern of findings relates to predictors of memory. For both younger and older participants, memory was not accounted for by cognitive ability. This was the case regardless of the component of cognitive ability considered (i.e., verbal or performance). The relationship of age to memory, however, was manifest. For younger individuals, age was negatively and directly related to memory. For the individuals in the older sample, such a negative association was not direct but mediated through executive function. The findings from the younger sample are consistent with research linking age directly to memory, regardless of possible mediators such as processing speed (Salthouse et al., 1996) or a

[3] Additional examination of the differential age-related deficit between executive function and cognitive ability was conducted by comparing models that: (a) constrained the paths from age to cognitive ability and to executive function to be invariant, and (b) relaxed that constraint. For the younger sample, such an equality slightly worsened the fit both when considering a cognitive ability composite ($\Delta\chi^2/\Delta df = 6.4/1$) and when separating verbal and performance ($\Delta\chi^2/\Delta df = 13.1/2$) cognitive abilities. For the older sample, an invariant hypothesis was highly untenable ($\Delta\chi^2/\Delta df = 40/1$).

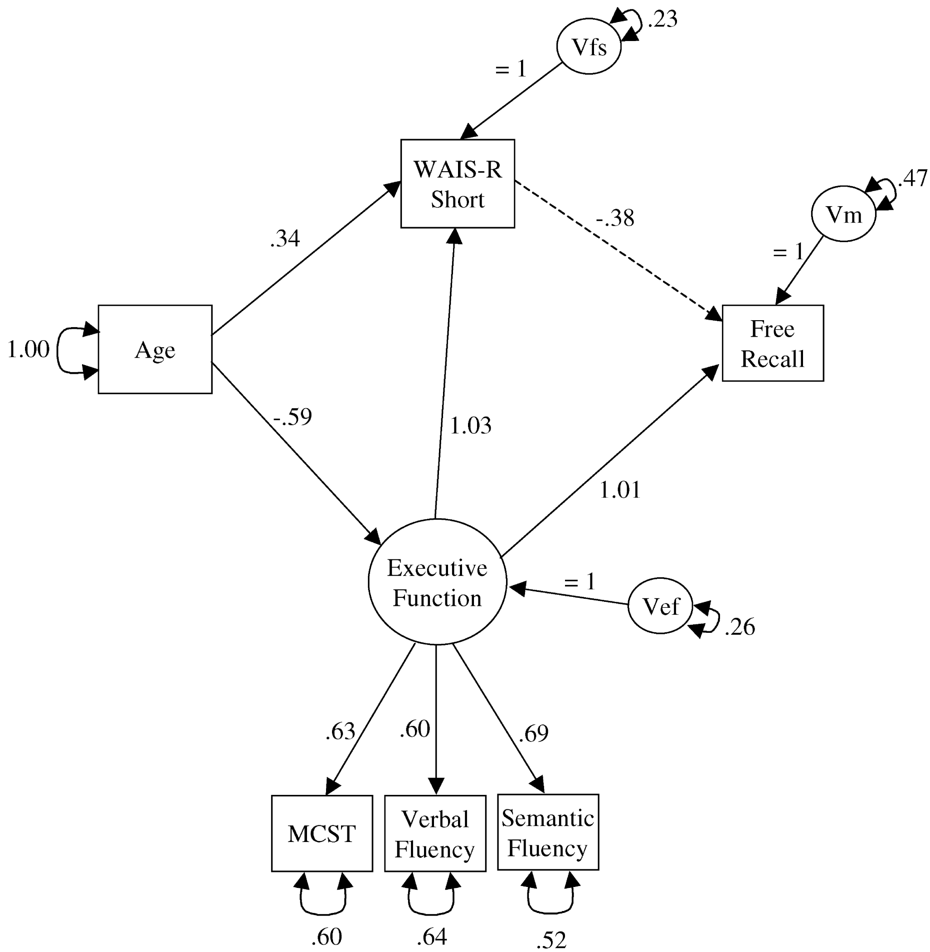

Fig. 4. Standardized parameter estimates from *Model 5* for the older sample.
Note. Continuous lines indicate accurately estimated coefficients (t value $> \pm 1.96$). Discontinuous lines indicate inaccurately estimable coefficients (t value $< \pm 1.96$).

more general common factor (Salthouse & Ferrer-Caja, 2001). The results from the older sample, on the contrary, depart from Salthouse et al.'s findings, especially considering the substantial number of older individuals in their sample (i.e., $n = 90$, ages 60–94). Finally, the relation of executive function to memory was consistent across samples. For all individuals, executive function was strongly linked to recall and recognition measures. This was, indeed, the strongest path leading to memory measures. Together, these results indicate that, for this group of individuals, memory was best accounted for by executive function. These findings support Crawford et al.'s (2000) initial predictions yet deviate from the researchers' results in their first study, which indicated that cognitive ability and executive function accounted for similar amounts of age-related variance. Moreover, the findings from the older sample are in line with Troyer et al.'s (1997) study, in which the relationship between age and memory was entirely mediated by executive function.

The third finding is the relation of executive function to general cognitive ability. In all the analyses, adding a path from executive function to cognitive ability resulted in improved model fit and increased explained variance in memory. This link was included to examine the mediational role of executive function and its direction was dictated by the literature suggesting that executive function is a higher order process that might play a role in general cognitive functioning (Kolb & Whishaw, 1990; Woodruff-Pak, 1997). In fact, across the samples and regardless of the measure of cognitive ability (i.e., verbal WAIS–R scale, performance WAIS–R scale, or shortened verbal WAIS–R scale), executive function was strongly associated with cognitive ability. Furthermore, this link contributed to the relation of age to cognitive ability and helped to account for a substantial amount in explained variance of memory. These findings provide support for the hypothesis explored by Crawford et al. (2000), that age-related declines in memory may be due to selective decline of executive function (Dempster, 1992).

Most of the models considered here were based on the conceptualization of Crawford et al.'s (2000) hypotheses. As an alternative, however, a model was presented reversing the direction of relationships between cognitive ability and memory. This conceptualization was motivated by literature suggesting that declines in memory may lead to age-related changes in other variables (McArdle et al., 1998, 2000; Raz et al., 1998; Swanson, 1999). Considering the cross-sectional nature of this study, recognizing this directionality was not possible and, thus the merit of the models must be evaluated on conceptual grounds. Once again, longitudinal data involving several measurements are needed to accurately identify "leading" and "lagging" indicators in these dynamic relationships (McArdle et al., 1998, 2000).

In addition to this pattern of consistent findings, there are several results that deserve further explanation. For example, all the analyses conducted here considered a linear relation of age to all the constructs. This was due to the lack of availability of correlations using higher order age functions. Although it would be interesting to examine these higher order functions, the linear age models tested here yielded a reasonable fit. Furthermore, Crawford et al. (2000) found that the relation of age to cognitive measures did not depart from linearity. Similarly, McArdle and Prescott (1992) found linear relations of age and WAIS–R measures to fit better than either quadratic or cubic age functions. A caveat for this interpretation refers to the cross-sectional nature of the data used in these studies, as well as the limited age range of the participants in the present investigation. Recent research using longitudinal data has demonstrated that the trajectories describing different cognitive abilities over the life-span require more complex age functions (McArdle et al., 2002).

Another finding needing clarification is the relationship of age to general cognitive ability. Among younger participants, this pattern was expected; that is, a non-substantial relation between age and verbal measures, and a negative relation between age and performance scales. For older individuals, however, the path between age and cognitive ability (i.e., using a shortened version of the verbal WAIS–R scale) was positive. This finding might be the result of slightly more years of education for the "very old" group (i.e., 80–89 years). In addition to these interpretations, the "expected" negative relation of age to cognitive ability was modeled through executive function. Thus, it is possible that the strong relation of executive function to cognitive ability might have suppressed the association between age and cognitive ability.

Several limitations to the findings of this study are in order. First, the models examined here hypothesized that the different executive function measures represented the same latent construct. This assumption was not strongly supported in the younger sample. For example, as indicated by their small loadings and large uniquenesses, the Stroop Test and Tower of London measures might not represent the same underlying construct that the other measures. That is, although part of a common executive process, it is possible that these two variables may tap some unique function (i.e., inhibition), as it was found by Miyake et al. (2000). This and other possible unique functions (e.g., shifting, and updating) may relate differently to cognitive abilities and memory. We did not explore this issue in our analyses because of the limited number of executive function measures. Although we cannot formally distinguish different processes driving the relation between executive function and cognitive ability in our findings, the correlations suggest that cognitive ability was most strongly related to verbal and nonverbal reasoning, and flexibility (i.e., MCST categories, verbal fluency, and cognitive estimates) and only weakly related to measures of planning, interference, or inhibition (i.e., Stroop Test and Tower of London).

Good discussions on the validity of executive function measures are available elsewhere (Bryan & Luszcz, 2000; Miyake et al., 2000; Rabbitt, 1997). For example, Bryan and Luszcz argue that there is little evidence for a pure construct of executive function. By definition, they assert, this construct taps a range of functions and thus tests of executive function do not reliably correlate with each other, even when purportedly measuring the same ''construct'' (e.g., inhibition). In addition, they point to the difficulty of distinguishing between executive and non-executive tasks, thus becoming a problem for anyone trying to pin down the construct. From both substantive and methodological standpoints, additional research is still needed to provide evidence of executive function as a valid construct (McArdle & Prescott, 1992; Salthouse, 2001) and to examine ''the unity and diversity'' of executive functions (Miyake et al., 2000).

A similar point could be made about memory. The recognition measure had a small loading and large uniqueness. Moreover, the measures used here are limited and do not capture other types of memory (e.g., logical memory, long-term-retrieval, and prospective memory). Of all the memory measures, free recall had the largest correlations with the executive function variables. As discussed in the original report by Crawford et al. (2000), performance in free recall might rely on the use of strategies to encode and retrieve information. Thus, the nature of this task may be responsible for the strong relation between executive function and memory.

Second, consistent measures across samples are required to conduct invariance analyses in order to formally compare parameters and interpret findings more accurately. Due to discrepancy in the measures between the two samples as well as differences in the scaling of some of the common measures (e.g., free recall, verbal fluency, etc.), invariance analyses could not be conducted. Third, the samples used in this study were small; this might present a problem for adequate estimation in structural equation modeling. Several parameter estimates yielded *t* values barely reaching accuracy (i.e., 1.96 at the .05 significance level) and, more important, large confidence intervals. Larger samples are needed to yield stable estimates and accurately determine the direction and magnitude of relationships. Finally, as mentioned above, longitudinal data are needed to more fully examine aging processes, especially to capture their dynamic nature and their role in cognitive functioning changes.

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