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Elucidating the contributions of processing speed, executive ability, and frontal lobe volume to normal age-related differences in fluid intelligence

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Abstract

One theory of normal cognitive aging asserts that decreases in simple processing speed mediate the age-related decline of fluid intelligence. Another possibility is that age-related atrophic changes in frontal brain structures undermine the functioning of executive abilities, thereby producing the same decline. In this study, we used principal components analysis to derive a measure of fluid–spatial intelligence in 197 normal adults between 20 and 92 years of age. Measures of perceptual comparison speed, working memory, and executive ability, as well as regional brain volumes based on high resolution magnetic resonance imaging were obtained from a subsample of 112 participants. We then conducted a series of hierarchical multiple regression analyses to test whether (1) the processing speed theory, (2) frontal–executive theory, or (3) some combination of these best accounted for age-related variation in fluid intelligence. The results showed that perceptual comparison speed, executive ability, and frontal lobe volume each made significant contributions to a regression equation that explained 57% of the variance in fluid intelligence. These findings suggest that both the processing speed and frontal–executive theory of cognitive aging are partially correct and complement one another. (*JINS*, 2000, *6*, 52–61.)

Keywords: Cognitive aging, Brain MRI, Fluid intelligence, Frontal lobe, Executive ability, Working memory

INTRODUCTION

Age-related declines occur earlier and are more pronounced for cognitive tasks that involve on-line problem-solving and visual–spatial information processing (i.e., fluid–spatial abilities) than for tasks that involve overlearned knowledge and skills (i.e., crystallized–verbal abilities). This "classic aging pattern" (Albert & Kaplan, 1980) has been replicated with many different tests and participant samples (Botwinick, 1967; Schaie, 1983, 1994; Wechsler, 1981). For at least 30 years, it has been argued that the gap between crystallized–verbal and fluid–spatial abilities widens with age because the latter are more dependent on the current integrity of the central nervous system, increasing their susceptibility to the cumulative effects of age-related insults to the brain (Horn & Cattell, 1967).

Numerous studies, however, have shown that age-related differences in fluid ability are greatly attenuated by controlling for simple processing speed (Hertzog, 1989; Schaie, 1989). These findings have given rise to the processing speed theory of cognitive aging, which asserts that normal age-related decrements in the speed with which even simple cognitive processes are executed results in the gradual age-related decline of more complex intellectual abilities (Salthouse, 1996). For example, using hierarchical multiple regression, Salthouse (1991) found that age alone accounted for 17 to 31% of the variability in measures of reasoning among healthy 20- to 84-year-old adults. However, after removing variance associated with simple perceptual comparison speed and working memory, age effects on reasoning were reduced to less than 5% of the explained variance. In fact, only zero to 18% of the variance in fluid intelligence that appeared to be explained by age was *not* mediated by perceptual comparison speed and working memory. Path analyses revealed that the coefficients for paths between (1) age and speed, (2) speed and working memory, (3) speed and

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fluid reasoning, and (4) working memory and fluid reasoning all were larger than coefficients for the direct path between age and fluid reasoning, supporting the inference that age-related differences in fluid ability are mediated primarily by individual differences in simple perceptual comparison speed and working memory.

Here we advance an alternative theory of the classic aging pattern based on evidence that anterior brain structures and executive cognitive abilities appear to be especially susceptible to the effects of normal aging. Using brain magnetic resonance imaging (MRI), Raz (1996) and others have argued that age-related atrophy is more pronounced for the frontal lobes and basal ganglia than for the temporal, parietal, and occipital lobes of the brain. Morphological studies also suggest that the frontal cortex and corpus striatum show greater volume losses with normal aging than do the temporal, parietal, and occipital cortices (Haug, 1985). Executive mental abilities, which include such processes as hypothesis generation, response monitoring, set shifting, and planning, are closely linked to the integrity of prefrontal and striatal brain structures (Kimberg & Farah, 1993; Roberts & Pennington, 1996; Stuss & Benson, 1986). This has led to the argument that more pronounced atrophic changes in frontal brain structures might result in disproportionate age-related decline in executive mental abilities (Veroff, 1980; West, 1996). Consistent with this, many investigators (Albert & Kaplan, 1980; Libon et al., 1994; Mittenberg et al., 1989; Van Gorp & Mahler, 1990; Whelihan & Lesher, 1985) have found age-related decreases in executive abilities, although others have not (Boone et al., 1990). Here we hypothesize that age-related atrophic changes in frontal brain structures undermine the functioning of executive abilities, and that this results in the gradual decline of fluid intelligence. In 95 very healthy adults between 18 and 77 years of age, Raz et al. (1998) recently found that performance on the Wisconsin Card Sorting Test (WCST), a measure of executive ability, correlated more highly with volumetric MRI measures of prefrontal cortex than with limbic, visual, or inferior parietal cortices, lending partial support to this frontal–executive model of cognitive aging. Fristoe et al. (1997), on the other hand, showed that much of the age-related variation in WCST performance, like that seen in measures of fluid reasoning, also is mediated by differences in simple perceptual comparison speed and working memory. They interpreted these findings as consistent with inference that much of the age-related variance in cognitive tasks with putative "localizing" significance is shared rather than unique.

These studies suggest that adult age differences in fluid intelligence are due, at least in part, to age-related decrements in simple perceptual comparison speed and working memory. Thus, our first aim was to test this well-replicated theory of cognitive aging. Less clear is whether adult age differences in fluid intelligence also show an independent relationship with age-related differences in frontal lobe atrophy or executive mental abilities. Thus, our second aim was to test an alternative hypothesis of cognitive aging in which either age-related atrophy of the frontal lobes or age-related differences in executive abilities (or both) would account for significant variance in fluid intelligence. Assuming that the data revealed evidence of a relationship between fluid reasoning and age-related differences in either frontal lobe volume or executive ability, our third aim was to determine whether this relationship was independent of that between fluid ability on the one hand and processing speed and working memory on the other. Finally, our fourth aim was to develop a model of cognitive aging that is parsimonious but explains the maximum amount of age-related variability in fluid intelligence.

METHODS

Research Participants and Procedure

Based on random-digit dialing, we recruited 214 adults from the Baltimore metropolitan area. At the time of initial recruitment each participant was scheduled for a 6-hr evaluation and sent a packet of self-report questionnaires to complete prior to the evaluation. On the day of testing, they gave written informed consent to participate in the study, and then underwent a physical examination, structured psychiatric interview (Schedule for Clinical Assessment in Neuropsychiatry, or SCAN (Wing et al., 1996), laboratory blood studies, structured neurological examination (QNE; Folstein, 1989), brain MRI scan, and neuropsychological testing. Each participant was paid a stipend of $100 at the end of the evaluation. Because this was a study of *normal* rather than *optimal* aging, potential participants were excluded only if they had a history of stroke, head injury with loss of consciousness for longer than 1 hr, dementia, neurological disease (e.g., Parkinson's disease, multiple sclerosis), or current substance dependence, or were living in a nursing home. On this basis 16 persons (7.5% of the initial sample) were excluded from further analysis, as was one other individual who did not complete cognitive testing.

Of the remaining 197 participants, 78% had no ($n = 33$) or *minor* ($n = 120$) health problems, such as hypertension, uncomplicated diabetes mellitus, or major depression in remission, although the remaining 22% ($n = 44$) had *moderate* health problems, such as emphysema, congestive heart failure, prior myocardial infarction, complicated diabetes mellitus, alcohol or drug abuse, or current major depression. These subjects were used to derive measures of crystallized and fluid intelligence based on the principal components analysis (PCA) described in the Results. Consequently, they are referred to as the *PCA subsample* in Table 1.

Finally, measures of frontal lobe and "nonfrontal" cerebral volume were obtained for 112 participants who are described as the *MRI subsample*. Most (84%) of these participants had *no* ($n = 22$) or *minor* ($n = 72$) health problems, although 16% ($n = 18$) had *moderate* health problems. Based not only on the recruitment procedures, but also on the MMSE (Folstein, Folstein, & McHugh, 1975) and IQ scores shown in Table 1, the participants who served in this

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Table 1. Demographic, cognitive, and neuroanatomic characteristics of the study participants

Characteristic[1]	Initial sample (N = 214)	PCA subsample (N = 197)	MRI subsample (N = 112)
Age	59 ± 19	58 ± 19	54 ± 19
Sex (male:female)	97:117	88:109	48:64
Race (W:B:H:O)[2]	173:35:2:4	163:30:2:2	97:13:1:1
Education (years)	13.4 ± 3.4	13.6 ± 3.3	13.5 ± 3.3
Mini-Mental State Exam	28.2 ± 1.9	28.3 ± 1.7	28.6 ± 1.6
Prorated Full Scale IQ	105 ± 15	106 ± 15	105 ± 14
Modified WCST[3]	5.0 ± 1.5	5.2 ± 1.4	5.2 ± 1.4
Brief Test of Attention	13.9 ± 4.3	14.2 ± 4.1	14.9 ± 3.9
Perceptual speed[4]	58.4 ± 17.2	60.0 ± 16.0	62.8 ± 16.1
Frontal lobe volume (cm^3)	N/A	N/A	354 ± 45
Nonfrontal volume (cm^3)	N/A	N/A	666 ± 78

[1]Values expressed as means ± standard deviations unless otherwise indicated. [2]W = White; B = African American; H = Hispanic; O = *other* racial–ethnic background. [3]Category sorts. [4]Sum of items correct on lists of letter and pattern comparison.

study appear to broadly represent normal community-dwelling persons across the entire adult life span.

Brain MRI Protocol and Measurements

Brain MRI scans were performed on a 1.5 Tesla General Electric Signa scanner (General Electric, Milwaukee, WI) using a protocol identical to that described in previous studies by our group (Aylward et al., 1997b). Contiguous 1.5 mm slices were acquired through the entire brain in the coronal plane using a T_1-weighted, three-dimensional spoiled gradient recalled acquisition sequence (SPGR) with a repetition time (TR) of 35 ms, echo time (TE) of 5 ms, flip angle of 45°, and 1 excitation. Field of view was 24 cm, and the image matrix was 256 × 256. Images were transferred via FTP and archived on CD-ROMs.

Frontal lobe measurements were made on a Gateway 2000 graphics workstation using software developed by our group (Barta et al., 1997). This allows for the three-dimensional (3-D) reconstruction of images that can then be rotated in any dimension, "painting" landmarks on the surface of the brain, and reconstruction of two-dimensional images in any plane with landmark "paint" remaining on the surface. After "stripping" the brain images of cerebral spinal fluid and nonbrain tissue using a semiautomated thresholding program, the frontal lobes were measured by erasing all brain tissue not included in this region, as defined by rules that are described more fully elsewhere (Aylward et al., 1997a). Briefly, after reconstructing a 3-D image of the brain, the central sulcus was identified, and the pre- and postcentral gyri were "painted" different colors. Scans were then resliced in the axial plane, parallel to the AC–PC line. This was performed at the same resolution with which the scans were obtained, yielding slices that were 0.9375 mm thick. Starting with the most superior slice, and guided by the painted pre- and postcentral gyri, all brain area posterior to the central sulcus was erased on each slice according to the rules developed and described by Aylward et al. In addition, basal ganglia and deep white matter posterior to the diagonal line connecting the central sulcus to the most posterior point of the genu of the corpus callosum in each slice were eliminated. Applying these measurement rules to the MRI scans of 10 healthy adults, Aylward et al. obtained an intraclass correlation coefficient of .99, with a lower 95% confidence interval value of .97. The mean frontal lobe volume obtained by Rater 1 was 366.7 cm^3 (SD = 25.3), compared to 367.0 cm^3 (SD = 23.8) for Rater 2. These values are slightly smaller than those obtained by Andreasen et al. (1994), who used a stereotaxic brain-warping method (M = 387.2; SD = 50.3) on the scans of 90 healthy adults. Values for the present study are shown in Table 1.

Many investigators adjust specific brain MRI measures for either total brain or intracranial volume to insure that group differences or correlations involving particular brain structures do not simply reflect differences in brain size. However, because the frontal lobes comprise roughly one-third of the total brain volume, adjusting for the latter poses a risk of eliminating differences in frontal volume that might well account for variability in cognitive test performance. For this reason, we computed a measure of nonfrontal volume by subtracting the volume of each participant's frontal lobes from his or her total cerebral volume and used both measures for data analyses. Estimates of cerebral volume, in turn, were based on the "stripped" brains, from which brainstem and cerebellum were excluded, using the stereological point-counting method described by Barta et al. (1997). Like the frontal lobe volume measures, these also were based on 1.5-mm, T_1-weighted coronal slices through the entire brain. Using measurement grids of 10 × 10 × 10, such that every 10th pixel was sampled in the coronal, sagittal, and axial planes, the rater determined whether each pixel was in the brain or not, and total cerebral volumes

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were derived from the sum of point counts across the coronal slices that comprised each brain.

Neuropsychological Measures

Each participant was administered Ward's (1990) seven-subtest version of the Wechsler Adult Intelligence Scale–Revised (WAIS–R; Wechsler, 1981). This short form includes the Information, Digit Span, Arithmetic, Similarities, Picture Completion, Block Design, and Digit Symbol subtests. It yields reliable and valid estimates of actual Full Scale IQ scores for adults (Axelrod et al., 1996; Benedict et al., 1992), and valid estimates of Mayo Full Scale IQ scores (Ivnik et al., 1992) for elderly adults (Schretlen & Ivnik, 1996). Five of the WAIS–R subtests were used in conjunction with three other cognitive tests to derive factor measures of fluid–spatial and crystallized–verbal ability. The three other measures included the (1) National Adult Reading Test–Revised or NART–R (Blair & Spreen, 1989), a measure of the ability to read irregularly spelled words, for which the number of correctly read words was recorded, (2) Facial Recognition Test (Benton et al., 1983), a measure of the ability to match pictures of unfamiliar faces under varied lighting conditions, for which the number of correctly matched faces was recorded, and (3) Rey–Osterrieth Complex Figure Test (Rey, 1941/1993), a test of the ability to copy a complex two-dimensional geometric design, for which the number of accurately drawn details was recorded. Scores from these eight tests were used to conduct the principal components analysis (PCA) that yielded measures of crystallized and fluid intelligence.

Three other cognitive tests were used as predictors in a series of multiple regression models. Borrowing from Salthouse (1991), each participant completed four tasks that involved the rapid comparison of letter strings (composed of 3 or 6 letters each) or line patterns (composed of 3 or 6 lines each). The participant was required to indicate whether the letter strings or designs that comprised each pair were identical or different by marking an 'S' or a 'D' in the space between them. The number of correct comparisons made in 30 s was recorded for each task, and these totals were summed to derive a measure of overall perceptual comparison speed. Working memory was assessed using the Brief Test of Attention or BTA (Schretlen, 1997), which involves the presentation via audio cassette of letter–digit strings (e.g., 'M'–'L'–6–'J'–2–9–'B') that range from 4 to 18 stimuli in length. For each of 10 such lists the participant must ignore the numbers and keep a running mental tally of how many *letters* were presented. Then, the same 10 lists are presented again, and the participant is asked to ignore the letters and count how many *numbers* were recited. Finally, Nelson's (1976) modification of the Wisconsin Card Sorting Test, or mWCST (Heaton, 1981), was administered as a measure of executive ability, defined here by the requirements of hypothesis generation and response monitoring. This version of the WCST was chosen because it is shorter than the original, includes test cards that match the stimulus cards in only one of three possible respects (i.e., by the number, color, or design of the stimuli), and is less frustrating to elderly adults. For this task, we summed the number of correct category sorts completed.

RESULTS

Deriving a Fluid–Spatial Ability Index

In order to derive a measure of fluid intellectual ability, we conducted a principal components analysis (with varimax rotation) of the raw scores for the eight cognitive tests listed in Table 2. This analysis yielded two factors whose initial eigenvalues exceeded unity and which accounted for 68% of the total variance. Each of these factors was defined by four variables with factor loadings greater than .70, and no other variables with loadings greater than .35. Because the first factor was defined by scores on the Information, Arithmetic, Similarities, and NART–R, it was labeled Crystallized–Verbal (Gc) Ability. The second factor was defined by scores on Picture Completion, Block Design, Rey–Osterrieth copy, and Benton Facial Recognition. It was labeled Fluid–Spatial (Gf) Ability. Based on these findings, we transformed the scores on each test according to the *Z* distribution, (i.e., with $M = 0$ and $SD = 1$), then derived Gf and Gc Indices by computing the mean of each participant's *z* scores on the four subtests that defined each factor. As expected, Gf Index scores correlated more highly with age ($r = -.56$, $p < .001$) than with education ($r = .32$, $p < .001$), whereas the Gc Index scores correlated more highly with education ($r = .66$, $p < .001$) than with age ($r = .06$, $p > .35$). These findings clearly demonstrate a double-dissociation between age and education on the one hand *versus* type of intellectual ability on the other. As shown in Figure 1, mean Gf Index scores decrease by roughly 1.6 standard deviations between the ages of 20 and 90, whereas Gc

Table 2. Variable loadings on PCA rotated factors that define Crystallized–Verbal and Fluid–Spatial Abilities, and correlations of the resulting index scores with age and education

Variable	Factor 1 Crystallized	Factor 2 Fluid
WAIS–R Information	*.881*	.153
WAIS–R Arithmetic	*.786*	.232
WAIS–R Similarities	*.724*	.302
New Adult Reading Test-Revised	*.870*	.096
WAIS–R Picture Completion	.347	*.730*
WAIS–R Block Design	.335	*.785*
Benton Facial Recognition Test	.007	*.718*
Rey Complex Figure Test	.171	*.803*
Rotation % of variance	36.7	31.1
Index[1] correlation with age	.064	−.561*
Index[1] correlation with education	.660*	.320*

[1]Pearson correlations based on indices derived from the four variables that primarily defined each PCA factor. For these correlations, $* = p < .001$.

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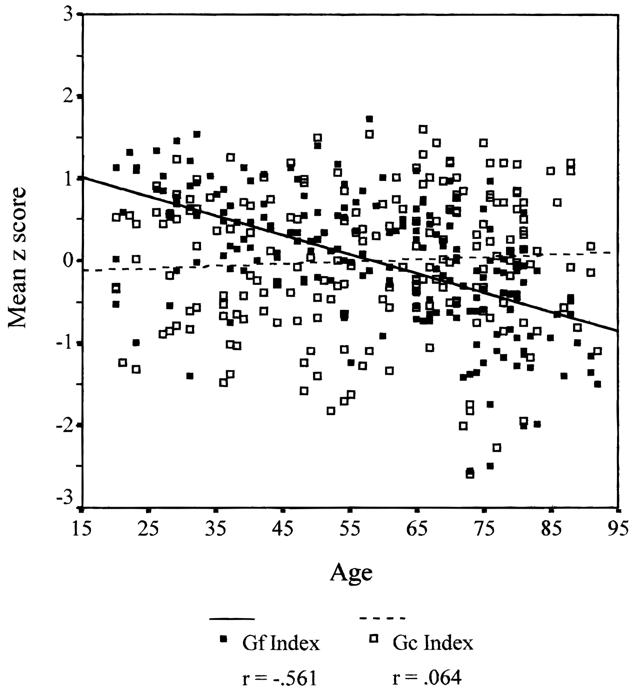

Fig. 1. Crystallized (Gc) and Fluid (Gf) Index scores across the age span.

Index scores increase by about 0.2 standard deviations over the same age range. The Gf Index scores were used for the multiple regression analyses described below.

Multiple Regression Models of Cognitive Aging

In order to test the hypotheses advanced above, we next conducted a series of hierarchical multiple regression analyses.

The processing speed hypothesis

We first tested the processing speed hypothesis of cognitive aging using methods similar to those of Salthouse (1991). When Gf Index scores were regressed on age alone, the resulting model yielded a multiple *R* of .524, thus accounting for 28% of the variance in fluid intelligence. As expected, adding terms for perceptual comparison speed and working memory significantly improved the model fit, increasing the proportion of explained variance to 46%. Contrary to expectation, however, this increase was due entirely to the term for perceptual comparison speed, as the *beta* weight for working memory (.10) was not significant. Also noteworthy was the finding that adding terms for speed and working memory attenuated the *beta* weight for age to a nonsignificant level (i.e., from −.52 to −.11).

Starting over without a term for age, when fluid ability was regressed on speed and working memory alone, the resulting model yielded a multiple *R* of .673, thereby accounting for 45% of the variation in fluid ability. Thereafter, adding a term for age did not significantly increase the proportion of explained variance ($R^2_{change} = .006$). When this change in R^2 for age is expressed as a percentage of the R^2 for age alone [i.e., $(.006 \div .275) \times 100$], it emerged that less than 3% of age-related effects on Fluid–Spatial ability was *not* mediated by age-related reductions in simple comparison speed and working memory. Nor did adding a term for age substantially reduce the *beta* weight for speed (which decreased from .599 to .532). As before, working memory failed to make a significant contribution to the model fit. As summarized in Table 3, these findings support the processing speed model of cognitive aging except insofar as they failed to show a unique interdependency between working memory and fluid–spatial intelligence, even though their zero-order correlation was highly significant ($r = .51$, $p < .001$).

Table 3. Multiple regression analyses related to the processing speed model of cognitive aging

(Step) Predictor	*Beta*[1]	Mult. *R*	R^2	R^2_{change}	$F_{(change)}$	$F_{(model)}$
Analysis 1						
(1) Age	−.524***	.524	.275	.275	*F*(1,110) = 41.7***	*F*(1,110) = 41.7***
Analysis 2						
(1) Age	−.109; *ns*			.275	*F*(1,110) = 41.7***	*F*(1,110) = 41.7***
(2) WM[2]	.100; *ns*					
(2) Speed[3]	.532***	.678	.459	.184	*F*(2,108) = 18.4***	*F*(3,108) = 30.6***
Analysis 3						
(1) WM[2]	.115; *ns*					
(1) Speed[3]	.599***	.673	.453	.453	*F*(2,109) = 45.2***	*F*(2,109) = 45.2***
Analysis 4						
(1) WM[2]	.100; *ns*					
(1) Speed[3]	.532***	.673	.453	.453	*F*(2,109) = 45.2***	*F*(2,109) = 45.2***
(2) Age	−.109; *ns*	.678	.459	.006	*F*(1,108) = 1.2; *ns*	*F*(3,108) = 30.6***

[1]Refers to *beta* weight at final step in each analysis; [2]WM = working memory as measured by the TA; [3]Speed = perceptual comparison speed.
Note. For all *t* and *F* statistics: *** = $p < .001$; *ns* = not significant.

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The frontal–executive hypothesis

We next tested the frontal–executive hypothesis by using the same general methods as those described above. When Gf Index scores were regressed on age alone, the same multiple R of .524 was obtained. Thereafter, adding terms for frontal lobe and nonfrontal volumes increased the proportion of explained variance from 28 to 38%, and reduced the *beta* weight for age from −.52 to −.44 (as shown in Table 4). Because the *beta* for nonfrontal volume was not significant, we excluded it from further analyses (although including it did not substantially alter any of the subsequent results). We next conducted an analysis in which a term for executive ability was added to a model that included age and frontal lobe volume. As shown in Table 4 (Analysis 3), this increased the R^2 from .374 to .473, thus accounting for 47% of the variance in Fluid–Spatial Ability (nearly identical to the 46% explained by age, processing speed, and working memory). In this model, the *beta* weights for frontal lobe volume (.270, $p < .001$) and executive ability (.324, $p < .001$) were both highly significant. Starting over without a term for age, we regressed Gf Index scores on frontal lobe volume and executive ability, which yielded a multiple R of .578, thus accounting for 34% of the variation in Fluid–Spatial Ability. Then, adding a term for age further improved the model fit and increased the proportion of explained variance by 14% (shown as R^2_{change} of .139 in Analysis 5). Because nonfrontal volume failed to improve the model fit in Analysis 2 (or any other analysis), it was excluded from further analyses. As shown in Table 4, these findings demonstrate that age-related differences in fluid–spatial intelligence depend on both frontal lobe volume and executive ability, even after accounting for the effects of age. In these analyses, including terms for frontal lobe volume and executive ability did not attenuate the relationship between age and Gf nearly as much as including a term for speed of processing in the earlier analysis. When expressed as a percentage of the R^2 for age alone, the change in R^2 due to age *after* removing the variance associated with individual differences in frontal volume and executive ability just exceeded 50%.

In addition to these multiple regression analyses, we investigated two basic assumptions of the proposed theory. The first is that the frontal cortex shows greater volume losses than other brain regions with normal aging. In the present, cross-sectional study this assumption leads to the hypothesis that age will show a significant negative correlation with frontal lobe volume, and that this correlation will exceed the correlation between age and nonfrontal volume. Consistent with this prediction, the Pearson r between age and frontal volume was −.28 ($p = .003$), whereas the correlation between age and nonfrontal volume was −.16 ($p = .10$). The second assumption of the frontal–executive theory is that executive functioning depends, at least in part, on the integrity of frontal–striatal brain structures or circuits. To the extent that this is true, and that differences in regional brain volume reflect variation in brain functioning, one would expect executive ability to correlate more highly with frontal than nonfrontal brain volume in normal aging. Consistent with this, mWCST performance showed a small but statistically significant correlation with frontal lobe volume ($r = .21$, $p = .024$). This was not the case for nonfrontal volume ($r = .05$, $p = .581$).

Table 4. Multiple regression analyses related to the frontal–executive model of cognitive aging

(Step) Variable	*Beta*[1]	Mult. *R*	R^2	R^2_{change}	$F_{(change)}$	$F_{(model)}$
Analysis 1						
(1) Age	−.524***	.524	.275	.275	F(1,110) = 41.7***	F(1,111) = 41.7***
Analysis 2						
(1) Age	−.435***	.524	.275	.275	F(1,110) = 41.7***	F(1,110) = 41.7***
(2) FL vol.[2]	.288***					
(2) NonFL vol.[3]	.059; *ns*	.613	.376	.101	F(2,18) = 8.7***	F(3,108) = 21.7***
Analysis 3						
(1) Age	−.392***					
(1) FL vol.[2]	.270***	.611	.374	.374	F(2,109) = 32.6***	F(2,109) = 32.6***
(2) Exec. ability[4]	.324***	.688	.473	.099	F(1,108) = 20.3***	F(3,108) = 32.3***
Analysis 4						
(1) FL vol.[2]	.369***					
(1) Exec. ability[4]	.372***	.578	.334	.334	F(2,109) = 27.3***	F(2,109) = 27.3***
Analysis 5						
(1) FL vol.[2]	.270***					
(1) Exec. ability[4]	.324***	.578	.334	.334	F(2,109) = 27.3***	F(2,109) = 27.3***
(2) Age	−.392***	.688	.473	.139	F(3,108) = 28.5***	F(3,108) = 32.3***

[1]Refers to *beta* at end of final step in each model; [2]FL vol. = frontal lobe volume; [3]NonFL vol. = total cerebral volume minus frontal lobe volume (excluded from Analyses 3–5 because it consistently failed to improve the model fit; [4]Exec. ability = category sorts on the mWCST.
Note. For all t and F statistics: *** = $p < .001$; *ns* = not significant.

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A comprehensive model of cognitive aging

Our third aim was to determine whether the dependence of fluid–spatial intelligence on frontal volume and executive ability would remain after accounting for the relationship between fluid ability and perceptual comparison speed. Failure to find evidence of a unique interdependency would support the contention by Fristoe et al. (1997) that much of the age-related variation in executive ability, like fluid intelligence, is mediated by differences in perceptual comparison speed. Thus, again using hierarchical multiple regression, we tested the hypothesis that individual differences in frontal lobe volume and/or executive ability would explain significant variance in fluid–spatial intelligence after accounting for the effects of age and simple perceptual comparison speed. A related aim was to derive a model of cognitive aging that combines elements of both the processing speed and frontal–executive hypotheses.

As shown in Table 5, entering terms for perceptual comparison speed, executive ability, and frontal lobe volume all improved the model fit, and doubled the proportion of explained variance in Gf Index scores that was explained by age alone from 28% to 57%. The final *beta* weights for speed, frontal volume, and executive ability all remained significant, whereas that for age did not. Though not shown in Table 5, the subsequent addition of terms for sex, race, years of education, working memory, and nonfrontal volume all failed to improve the model fit. These findings clearly demonstrate that the dependency of fluid–spatial intelligence on frontal lobe volume and executive ability remains even after accounting for the dependency of fluid–spatial intelligence on perceptual comparison speed. Importantly, adding terms for frontal lobe volume and executive functioning caused only a partial reduction of the *beta* weight for perceptual comparison speed after accounting for age effects (i.e., from .58 to .44), indicating that their contributions to fluid intelligence are largely dissociable from that of processing speed.

Assuming that frontal lobe volume might influence executive ability either directly or via its impact on perceptual comparison speed, we conducted a final set of analyses. First, executive ability was regressed on frontal lobe volume alone, which yielded a weak but significant model whose multiple R was .213 [$F(1,110) = 5.2$, $p = .024$]. Then, adding a term for perceptual speed increased the multiple R to .329, improved the model fit [$F(2,109) = 6.6$, $p = .002$], and reduced the initial *beta* weight for frontal lobe volume to a nonsignificant level (from .21 to .13). When the order of variable entry was reversed, the multiple r for processing speed alone was .306 [$F(1,110) = 11.3$, $p = .001$]. Thereafter, adding a term for frontal lobe volume increased the multiple R only to .329, resulting in an R^2_{change} of .015, which was not significant. These findings suggest that most (67%) of the variance in executive ability that initially was explained by individual differences in frontal lobe volume appears to be mediated by perceptual comparison speed.

DISCUSSION

Several findings emerged from this study. Based on a principal components analysis of the cognitive test results produced by 197 broadly representative, community-dwelling adults between 20 and 92 years of age, we derived measures of Crystallized–Verbal (Gc) and Fluid–Spatial (Gf) Abilities. As expected, Gc showed a strong positive correlation with years of education but only a nonsignificant positive correlation with age. Conversely, Gf showed a moderately strong positive correlation with education and an even stronger negative correlation with age. These findings are precisely what Horn and Cattell's (1967) theory of fluid and crystallized intelli-

Table 5. Multiple regression analyses related to a comprehensive model of cognitive aging

(Step) Predictor	*Beta*	Mult. *R*	R^2	$R^2_{(change)}$	$F_{(change)}$	$F_{(model)}$
Analysis 1						
(1) Age	−.524***	.524	.275	.275	$F(1,110) = 41.7$***	$F(1,110) = 41.7$***
Analysis 2						
(1) Age	−.126; *ns*	.524	.275	.275	$F(1,110) = 41.7$***	$F(1,110) = 41.7$***
(2) Speed[1]	.580***	.673	.453	.178	$F(1,109) = 35.4$***	$F(2,109) = 45.1$***
Analysis 3						
(1) Age	−.144; *ns*	.534	.275	.275	$F(1,110) = 41.7$***	$F(1,110) = 41.7$***
(2) Speed[1]	.483***	.673	.453	.178	$F(1,109) = 35.4$***	$F(2,109) = 45.1$***
(3) Exec. ability[2]	.278***	.723	.523	.070	$F(1,108) = 15.8$***	$F(3,108) = 39.4$***
Analysis 4						
(1) Age	−.116; *ns*	.534	.275	.275	$F(1,110) = 41.7$***	$F(1,110) = 41.7$***
(2) Speed [1]	.440***	.673	.453	.178	$F(1,109) = 35.4$***	$F(2,109) = 45.1$***
(3) Exec. ability[2]	.248***	.723	.523	.070	$F(1,108) = 15.8$***	$F(3,108) = 39.4$***
(4) FL vol.[3]	.224***	.753	.567	.044	$F(1,107) = 10.8$***	$F(4,107) = 35.0$***

[1]Speed = perceptual comparison speed; [2]Exec. ability = correct category sorts on the mWCST; [3]FL vol. = total cerebral volume minus frontal lobe volume. Entering terms for sex, race, years of education, WM, and NonFL vol. failed to improve the model fit after the final step of Analysis 4.
Note. For all t and F statistics: *** = $p <.001$; *ns* = not significant.

gence predicts, and provide further evidence in support of the "classic aging pattern" (Albert & Kaplan, 1980). Both the factorial purity of the two factors that emerged from the principal components analysis and their double-dissociation with age and education support the inference that the obtained Gc and Gf Indices represent reliable and valid measures of Crystallized–Verbal and Fluid–Spatial Ability.

Using the Gf Index as a measure of fluid–spatial reasoning, the results of our first pair of multiple regression analyses strongly supported the processing speed theory of cognitive aging (Salthouse, 1996). The finding that age alone accounted for 27.5% of the variance in Gf Index scores is well within the range of 17 to 31% reported by Salthouse (1991). Further, replicating the results of Salthouse, we found that entering terms for perceptual comparison speed and working memory markedly reduced the amount of variance in Gf explained by age. The only respect in which these results differed from some previous reports involved our failure to find a relationship between working memory and fluid–spatial ability after removing the variance explained by comparison speed from both. One possible reason is that our test of working memory shared an inordinate proportion of variance with the measure of perceptual comparison speed. However, in two of three reported studies, Salthouse (1991) also found that working memory did not explain significant incremental variance in fluid reasoning after accounting for the effects of perceptual comparison speed, suggesting that the latter is primarily responsible for age-related declines in many cognitive abilities (Hertzog, 1989).

Several findings also support the frontal–executive theory of cognitive aging. For example, both age and executive ability showed significant correlations in the predicted directions with frontal lobe volume, whereas neither correlated significantly with nonfrontal volume. In addition, using the Gf Index to measure fluid–spatial intelligence, a series of multiple regression analyses revealed that adding terms for individual differences in executive ability and frontal lobe volume increased the proportion of explained variance in Gf Index scores beyond that attributable to age alone (from 28% to 47%). Adding these terms did not reduce the explanatory power of age alone to nearly the same extent as adding a term for processing speed. Thus, whereas less than 3% of the variance in Gf Index scores initially accounted for by age effects was *not* mediated by perceptual comparison speed and working memory, about half of the age-related variance in Gf Index was *not* mediated by individual differences in frontal lobe volume and executive ability. The fact that both executive ability and frontal lobe volume explained significant unique variance in the dependent variable also suggests that their contributions were at least partly nonredundant. This is interesting because differences in executive ability often are linked to the functioning of frontal–striatal brain structures or circuits (Kimberg & Farah, 1993; Roberts & Pennington, 1996). Based on their presumed relationship, one might expect executive ability and frontal lobe volume to account for overlapping variance in Gf, with the result that only one would appear to explain significant unique variance when both were entered into a regression model. Yet we found that differences in both improved the model fit. Though not predicted by the frontal–executive theory, neither does this finding contradict it. Rather, it suggests that executive functioning and frontal lobe volume contribute to differences in fluid intelligence via mechanisms that extend beyond their own interrelationship. This is not surprising in light of evidence that the frontal lobes are not the exclusive province of executive abilities, or *vice-versa* (Anderson et al., 1991; Baddeley, 1998). Indeed, although executive functioning correlated more strongly with frontal than nonfrontal brain volume in the present study, the correlation was weak ($r = .21$). Raz et al. (1998) found a stronger correlation ($r = -.42$) between WCST perseverative errors and a volumetric measure of the prefrontal cortex. Perhaps the variance in Gf that is explained by a more specific regional frontal lobe measure, such as the dorsolateral prefrontal cortex, would show greater overlap with the variance attributable to executive functioning.

Having found support for both the processing speed and frontal–executive theories of cognitive aging, perhaps the most important finding of this study was their complementarity. Specifically, an exploratory stepwise multiple regression analysis revealed that perceptual comparison speed, executive functioning, and frontal lobe volume all made significant unique contributions to a model that accounted for nearly 57% of the variance in fluid–spatial intelligence. Based on their R^2 estimates, the processing speed and frontal–executive models each explained significantly less variance in Gf (46 and 47%, respectively). The fact that adding terms for executive ability and frontal lobe volume only attenuated the *beta* weight for processing speed from .58 to .44 suggests that the mechanism(s) by which differences in executive ability and frontal volume influence fluid–spatial intelligence are largely unrelated to decrements in speed.

In short, our findings support both the processing speed and frontal–executive theories of cognitive aging. More importantly, they demonstrate that neither theory alone yields a model that accounts for as much variance in fluid–spatial intelligence as is explained by a model that takes the core predictors from each theory into account. These results point to the need for a unification of the processing speed and frontal–executive theories of cognitive aging. Any such unifying account of the "classic aging pattern" must recognize that whatever mechanisms link age-related decline in fluid intelligence to decrements in processing speed, executive ability, and frontal lobe volume are at least partly independent. Consistent with Salthouse (1996), our data support the inference that age primarily affects fluid–spatial intelligence indirectly, via its impact on simple processing speed. The data also suggest that age affects Fluid–Spatial Ability indirectly via its impact on frontal lobe volume and executive functioning, but that both of these affect Fluid–Spatial Ability independent of age. Finally, the obtained results suggest that much of the variance in executive ability that is related to frontal lobe volume appears to be mediated by differences in perceptual comparison speed. These interrelations are depicted below in Figure 2.

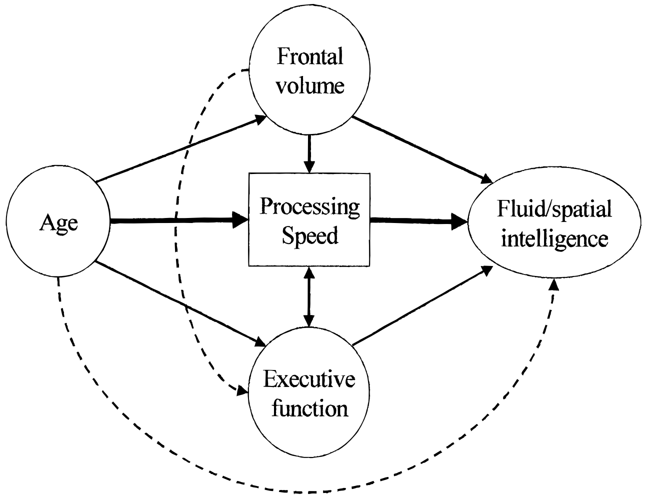

Fig. 2. An hypothetical model of individual differences in fluid–spatial intelligence. Arrows reflect presumed directions of influence. Line thicknesses represent the strength of association between variable pairs. Dashed lines represent relationships that are markedly attenuated by other terms in the model. Thus, as described in the text (and shown in Tables 3 and 5), for example, the relationship between age and fluid–spatial intelligence is greatly attenuated by controlling for simple perceptual comparison speed.

The present results point to several directions for future research. For example, given that processing speed appears to be a powerful predictor of fluid intelligence, and that accounting for differences in both executive ability and frontal lobe volume has little impact on this relationship, an obvious question is, "What accounts for age-related decrements in processing speed?" From a neuroanatomic perspective, other brain structures (e.g., total white matter volume), longitudinal changes in regional brain volume, and other morphometric characteristics warrant consideration. Another possibility is that decreases in processing speed reflect normal age-related changes in cerebral blood flow, glucose metabolism, or activation in response to cognitive challenge, as age effects have been demonstrated by all of these methods (Madden & Hoffman, 1997).

Several limitations of this study also require consideration. First, it should be noted that the findings reported here were based on cross-sectional rather than longitudinal analyses. Thus, they represent an attempt to draw inferences about age-related *changes* based on adult age *differences* in both mental abilities and neuroanatomy. Until verified with longitudinal analysis, we cannot exclude the possibility that cohort effects (e.g., secular improvements in nutrition, education, etc. between the oldest and youngest participants) magnified the observed age differences in cognitive functioning or regional brain volumes. Worth noting in this connection, however, was the fact that prorated Full Scale IQ scores, which are age-adjusted and therefore should not correlate with age, actually showed a modest positive correlation with age (Pearson $r = .28$, $p = .003$). This suggests that the older participants were, if anything, more intelligent than the younger ones. This could offset secular improvements enjoyed by the latter, and thereby constrain the age-related "decline" demonstrated by our cross-sectional sample to a level that is more characteristic of longitudinal studies.

The second potential basis on which this study might be criticized was our decision not to correct frontal lobe and nonfrontal volume for total intracranial volume, height, or sex. The rationale for such a criticism is that the contribution of frontal lobe volume to fluid intelligence could simply reflect individual differences in total brain volume. As noted earlier, we believe that such corrections are not warranted when the brain structures under study are large. The fact that we included measures of nonfrontal brain volume, which is nearly twice the volume of the frontal lobes, argues against this criticism on rational grounds. The finding that frontal lobe volume showed a larger partial correlation with fluid intelligence than did nonfrontal volume argues against it on empirical grounds.

Bearing in mind that this was a cross-sectional study, and that individual differences in total brain volume (and perhaps other brain regions) almost certainly correlate with fluid intelligence, we believe that these findings begin to elucidate the elements of a more comprehensive theory of the "classic aging pattern" than previously has been articulated.

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