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Age differences in fluid intelligence: Contributions of general slowing and frontal decline

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Abstract

The current study examined the contributions of general slowing and frontal decline to age differences in fluid intelligence. Participants aged 20–89 years completed Block Design, Matrix Reasoning, simple reaction time, choice reaction time, Wisconsin Card Sorting, and Tower of London tasks. Age-related declines in fluid intelligence, speed of processing, and frontal function were observed. Hierarchical regression analyses showed that the processing speed and frontal function measures accounted for significant variance in fluid intelligence performance, but there was also a residual effect of age after controlling for each variable individually as well as both variables. An additional analysis showed that the variance in fluid intelligence that was attributable to processing speed was not fully shared with the variance attributable to frontal function. These findings suggest that the age-related decline in fluid intelligence is due to general slowing and frontal decline, as well as other unidentified factors.

Keywords: Aging; Fluid intelligence; Frontal function; Processing speed

1. Introduction

In a recent article, Salthouse (2004) makes several observations regarding the "what" and "when" of age-related changes in cognition. He notes that a number of aspects of cognition are detrimentally affected by aging, including processing speed, memory, and reasoning; the negative age trends are often large; and the decline often begins before age 50. At the same time, Salthouse points out that some aspects of cognition (e.g., vocabulary) remain fairly stable from the mid 50s onward. In comparison to what is known about the what and when of cognitive aging, much less is known about what Salthouse calls the "how" of cognitive aging, the mechanisms underlying the cognitive decline. The current study examines the mechanisms that may be responsible for the decline in one aspect of cognition, fluid intelligence.

Fluid intelligence generally refers to reasoning and novel problem-solving ability and is thought to be related to metacognition (Cattell, 1971; Gray, Chabris, & Braver, 2003; Sternberg, 1985). A number of studies, going back to early work by Horn and Cattell (1967), report an age-related decline in performance on fluid intelligence tasks. The existing literature offers several possible mechanisms for the age-related decline in fluid intelligence. Salthouse (1996, 2001a) contends that the age-related decline in a variety of cognitive abilities, including reasoning, can be accounted for by a single mechanism, generalized slowing. By this view, generalized slowing has a detrimental effect on cognitive function in two ways. The first is an inability to effectively execute the component operations involved in a task due to time limitations and the second is the inability to hold information on-line that is necessary for task completion.

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Past aging research on the relationship between fluid intelligence and speed of processing supports the generalized slowing explanation (Hertzog, 1989; Schaie, 1989). In a four-year longitudinal study involving older adults, changes in processing speed strongly correlated with changes in fluid intelligence ($r = .53$; Zimprich & Martin, 2002). About 28% of the age-related variance in processing speed and fluid intelligence was shared variance. In a cross-sectional study, Salthouse (1991) reported that age differences in reasoning ability were significantly attenuated after controlling for processing speed: Across three studies, just 9–29% of the age-related variance in the reasoning measures remained unaccounted for after controlling for variance in perceptual comparison speed. In addition, Bors and Forrin (1995) found that the correlation between age and performance on a fluid intelligence task, Raven's Advanced Progressive Matrices, was non-significant after controlling for mental speed.

A second explanation for age-related cognitive decline relates to the functioning of the frontal lobes. Prefrontal cortex theory (cf. West, 1996) states that goal-oriented functions of the prefrontal cortex (e.g., integrating information, executing complex, sequential behaviors, handling novelty, and inhibiting distracting or interfering information) are most susceptible to age effects because of the neurophysiological changes occurring in this area of the brain. Recent evidence suggests that the frontal lobes are one of the first areas of the brain to be negatively affected by aging. Research has identified decreases in frontal lobe volume (DeCarli et al., 2005; Raz, Torres, Spencer, & Acker, 1993) as well as alterations in frontal cell morphology (Buckner, 2004; Flood & Coleman, 1988; Masliah, Mallory, Hansen, DeTeresa, & Terry, 1993) with age. In addition, the largest age-related reductions in cerebral blood flow have been localized to the frontal and prefrontal areas (Gur, Gur, Obrist, Skolnick, & Reivich, 1987; Mathew, Wilson, & Tant, 1986; Schroeter, Zysset, Kruggel, & von Cramon, 2003; Shaw et al., 1984).

A variety of studies suggest that the frontal lobes are recruited when performing fluid intelligence tasks. Isingrini and Vazou (1997) found, for example, that performance on traditional frontal tasks correlated with measures of fluid intelligence but not crystallized intelligence in a group of older adults. Parkin and Java (1999) showed that fluid intelligence performance accounted for 15–24% of the variance in performance on three tasks of frontal function. Moreover, in a recent functional magnetic resonance imaging study, Gray et al. (2003) found that participants who scored high on a standard measure of fluid intelligence also showed a significantly stronger blood flow response in regions of the frontal cortex (including the lateral prefrontal cortex and anterior cingulate) during a working memory task. This pattern was especially apparent on working memory trials in which interference was high and attentional control was presumably needed to focus on goal-relevant information.

Some existing research supports a frontal explanation for the decline in fluid intelligence with age. Schretlen et al. (2000) hypothesized 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" (p. 53). Consistent with this view, they found that executive ability and frontal-lobe volume, but not non-frontal volume, significantly reduced the age-related variance in fluid intelligence. Note, however, that processing speed also reduced the age-related variance in fluid intelligence. Moreover, the contribution of executive ability and frontal volume to the decline in fluid intelligence was largely unrelated to the contribution of processing speed. The Schretlen et al. study therefore suggests that reduced frontal functioning and reduced processing speed both contribute to the decline in fluid intelligence with age.

Schretlen et al.'s (2000) study, as described above, is rather uncommon in that it examined both the generalized slowing and frontal explanations of cognitive aging in the same study. Parkin and Java (2000) note that studies of frontal function often do not include tests of speed or fluid intelligence, fluid intelligence studies often do not include tests of speed or frontal function, and speed of processing studies often do not include tests of frontal function or fluid intelligence. As such, most existing studies operate on a confirmatory bias rather than pitting two theories against one another. Here we follow Schretlen et al.'s lead and examine the role of both generalized slowing and frontal function in the age-related decline of fluid intelligence.

2. Overview of the study

The primary goal of the present study was to examine the contribution of age and processing speed to performance on two fluid intelligence tasks, Block Design and Matrix Reasoning. Following Salthouse (2001b; also see Salthouse, 1996), we examined the residual age-related variance in fluid intelligence after statistically controlling for variance on the processing speed measures (simple reaction time, choice reaction time, and processing speed composite). Specifically, we were interested in contrasting the initial age-related variance with the residual age-related variance following the statistical control procedure. If general slowing contributes to the age-related decline in fluid intelligence performance, one would expect a significant reduction in the age-related variance in fluid intelligence after controlling for measures of processing speed. If general slowing fully accounts for the age difference in fluid intelligence, the increment in variance associated with age after control of the processing speed measure should no longer be significant. If, on the other hand, other factors specific to fluid intelligence performance contribute to the age differences in fluid intelligence, one should observe a significant residual effect of age after controlling for processing speed. Such a result would suggest that competing accounts of the age-related decline in fluid intelligence, such as the frontal function account, may be viable. A second goal was therefore to examine the frontal function account more directly. Toward this goal, a subset of the original sample also completed two frontal tasks, the Wisconsin Card Sorting Task and the Tower of London, from which a frontal function composite score was derived. Then, using the statistical control procedure described above, we examined the extent to which frontal function can account for the age-related variance in fluid intelligence. The initial age-related variance in Block Design and Matrix Reasoning was compared to the residual age-related variance following control of the frontal function composite measure and control of both the speed and frontal composites. If factors other than frontal function and processing speed contribute to the age differences in fluid intelligence, one should observe a significant residual effect of age after controlling for frontal function and processing speed. In addition, if frontal function and processing speed account for a unique proportion of the variance in age-related fluid intelligence decline, one would expect a significant residual effect of one of these factors after controlling for the other factor.

The present study has several advantages over past research. First and foremost, we have addressed the concerns of Parkin and Java (2000) by including measures of processing speed, fluid intelligence, and frontal function in a single study, in order to directly contrast more than one account of cognitive aging. Although similar to the work of Schretlen et al. (2000), the present study makes several unique contributions. First, the present study uses different measures of processing speed (simple and choice reaction time) and fluid intelligence (Block Design and Matrix Reasoning) than used in Schretlen et al. and other past studies. This is important in testing the generalizability of past findings. Second, the present study examines the contributions of processing speed and frontal function to age differences in Block Design and Matrix Reasoning separately, rather than examining the contributions of speed and frontal function to an overall index score calculated on the basis of performance on several fluid intelligence tasks. This approach allows us to examine whether the contributions of speed and frontal function are the same or different for different purported measures of fluid intelligence. The present study also differs from Schretlen et al. in its formulation of the frontal function construct. Whereas Schretlen et al. utilize performance on the WCST as their sole indicator of frontal (executive) function, the present study utilizes a composite measure of performance on the WCST and TOL. Salthouse (2001b) emphasizes the importance of including multiple measures of one's theoretical constructs. In addition, multiple measures of the frontal function construct are advantageous given the findings of Miyake et al. (2000). They showed that the WCST and Tower tasks tap into separable executive processes, shifting and inhibition, respectively. Miyake et al. stressed the importance of considering the type of executive process (updating, shifting, or inhibition) represented by frontal "executive" tasks when selecting such tasks as measures of general executive ability. By including measures that tap into more than one executive process, we have enhanced the construct validity of the frontal function measure. An additional advantage of the current study is that we have included a larger sample size than used in some past studies, which is especially important given the statistical control procedure used here (cf. Salthouse, 2001b). With a sufficient number of adults in all age-decades from the 20s to 80s, we were also able to examine developmental changes during adulthood.

3. Method

3.1. Participants

There were 196 participants in the study, ranging in age from 20 to 89 years old. Younger adults were recruited from the student population at the University of Colorado at Colorado Springs and received class credit for their participation or for recruiting older relatives to participate. Older adults were also recruited from local senior citizen organizations in Colorado Springs, Colorado. Volunteers 60 years of age or older received $10 for participation. All participants completed a questionnaire that collected information about demographics, educational history, medical history, and alcohol and drug history. Participants were eliminated from participation if they reported a history or condition of stroke; head injury accompanied by a loss of consciousness; hypertension; diabetes; neurological disorder; current psychiatric diagnosis; current usage of antidepressants or any medication that, based on self-report, might be affecting their thinking; or a medical condition that could interfere with testing. All older adult participants reported that they were in an independent living situation and in fair or good health. In addition, all groups achieved a similar level of education, $ps > .05$. For a description of the demographic characteristics of participants according to age decade, see Table 1.

All participants completed the fluid intelligence and processing speed tasks as part of a larger neuropsychological battery. A subset of 166 participants also completed the Wisconsin Card Sorting Test and Tower of London. The battery of tasks was administered during multiple testing sessions, varying in duration from 1 to 2 h. Numerous breaks were given, especially during the longer sessions, and no more than one lengthy task (20–30 min) was administered per session. Tasks were randomly ordered across participants.

Table 1
Demographic characteristics of the full sample as a function of age decade

	20 s	30 s	40 s	50 s	60 s	70 s	80 s
Number	37	20	24	16	17	52	27
Age							
Mean	22.5	34.1	44.8	53.6	64.4	75.0	82.4
SD	2.8	2.9	2.8	2.4	2.9	2.8	2.3
Education							
Mean	14.8	14.9	15.3	15.7	15.7	14.7	14.9
SD	1.1	1.1	1.5	2.5	2.7	2.4	2.1
% Female	81	75	79	94	59	71	63

3.2. Fluid intelligence tasks

3.2.1. Block Design

The Block Design subtest from the Wechsler Abbreviated Scale of Intelligence (WASI) was administered according to the protocol outlined in the WASI manual (Wechsler, 1999). Participants had to replicate 13 two-dimensional designs using blocks with red, white and red/white sides. The first nine problems used 4 blocks and the last four problems used 9 blocks. Scores were based on completion of the design and the time taken to complete the design, as described in the WASI manual. This task is related to spatial visualization, visual-motor coordination, and abstract conceptualization (Wechsler, 1999). While Block Design is associated with various cognitive processes, increasing literature refers to the task as a fluid intelligence measure due to the involvement of abstract conceptualization and the ability to solve novel problems (Backman, Hill, Herlitz, Fratiglioni, & Winblad, 1994; Emery, Pedersen, Svartengren, & McClearn, 1998; Leaper et al., 2001; Muldoon, Ryan, Matthews, & Manuck, 1997).

3.2.2. Matrix Reasoning

Matrix Reasoning, another task from the WASI, was also administered according to the protocol outlined in the WASI manual (Wechsler, 1999). Matrix Reasoning from the WAIS-III has been found to be a valid measure of fluid intelligence, and correlates with Standard Progressive Matrices at $r = .81$ (Wechsler, 1997). The task consists of four types of problems: pattern completion, classification, analogy, and series completion. Participants were presented 35 test items in a booklet. For each item, they were instructed to look at the presented matrix, and from the five options given, choose the one that best completed the problem. Two sample items were given at the beginning of the task to familiarize participants with the problems. The maximum score on the test was 35, with each item worth one point.

3.3. Speed of processing tasks

3.3.1. Simple Reaction Time Task

The simple reaction time (SRT) task consisted of two segments modeled after a procedure described by Teng (1990). For both segments, participants were shown a series of visual stimuli (left and right pointing arrows) in the center of a computer screen and asked to respond by pressing the appropriate response key on a game pad. Each participant was individually and carefully shown how to use the game pad triggers and participants were informed that they needed to be ready immediately upon the start of the task. The first segment included 16 trials in which the arrow was pointing to the right and participants were to give a right key response. The second segment included 16 trials in which a left-pointing arrow was shown and participants were to give a left key response. Reaction time was recorded for all trials.

3.3.2. Choice Reaction Time Task

The choice reaction time (CRT) task consisted of 32 trials, comprised of 16 trials with left arrows and 16 trials with right arrows presented in pseudorandom order with an inter-stimulus-interval of 1–5 s. In each of four blocks of eight trials, four left and four right arrows were shown. Participants were told that the direction of the arrows would be unpredictable and were instructed to press either the right or left key on a game pad as quickly as possible, according to the direction of the arrow. Each participant was individually and carefully shown how to use the game pad triggers and participants were informed that they needed to be ready immediately upon the start of the task. Accuracy and reaction time were recorded for all trials.

3.4. Frontal function tasks

3.4.1. Wisconsin Card Sorting Test

A computerized version of the Wisconsin Card Sorting Test (WCST) was administered in which participants were required to match a card in the center of the screen with one of four cards located at the top of the screen that served as references (Heaton, Chelune, Talley, Kay, & Curtiss, 1993). The cards were sorted based on a rule that used color (red, green, blue, or yellow), shape (circle, square, star, and cross), or number (one, two, three, or four). Once ten consecutive correct sorts were achieved, the rule was changed without warning and the process repeated until six sets were completed or 128 cards were sorted. The number of categories completed out of six (i.e., the number of times a participant completed 10 consecutive sorts within a category) was the dependent variable.

3.4.2. Tower of London

A computerized version of the Tower of London (TOL) was used, consisting of three 2-move items and six 3-, 4-, and 5-move items for a total of 21 problems (see Davis & Keller, 1998). The number of pegs varied from 3 to 5 with 7 trials given for each type. The TOL requires participants to maneuver balls from a start position to a goal position in as few moves as possible within the following constraints: (1) only one ball may be moved off of a peg at a time, (2) the balls cannot be stacked above the pegs, and (3) the number of balls that can be placed on a peg varies from one to five. Performance was measured by calculating the number of excess moves across the 21 problems. Recent neuroimaging research suggests that the Tower of London is sensitive to frontal function (Dagher, Owen, Boecker, & Brooks, 1999; Lazeron et al., 2000; Owen, Doyon, Petrides, & Evans, 1996).

4. Results

4.1. Fluid intelligence and speed of processing

For all analyses reported in this study, the α level was set at .05. Linear regression analyses revealed significant age-related declines in performance on the Block Design task [$F(1,195) = 66.26$, $p < .001$, $R^2 = .26$, $M = 42.3$, $SD = 15.1$] and Matrix Reasoning task [$F(1,195) = 101.47$, $p < .001$, $R^2 = .34$, $M = 26.2$, $SD = 5.8$]. There were also age-related increases in simple reaction time [$F(1,194) = 26.66$, $p < .001$, $R^2 = .12$, $M = 397$, $SD = 142$], and choice reaction time [$F(1,194) = 68.43$, $p < .001$, $R^2 = .26$, $M = 497$, $SD = 91$]. Accuracy on the choice reaction time task ($M = 29.7$, $SD = 2.9$) did not correlate with choice reaction time ($r = .02$, $p > .10$) or age ($r = -.07$, $p > .10$). As shown in Table 2, all of the key variables of interest correlated with one another.

Using the two independent measures of processing speed, we then examined the extent to which processing speed accounted for age differences in Block Design and Matrix Reasoning performance. To accomplish this, we conducted a forced-entry hierarchical regression analysis with performance on the Block Design or Matrix Reasoning task as the dependent variable, processing speed as the first predictor, and age as the second predictor (cf. Salthouse, 2001b). In the case of Block Design performance, simple and choice reaction time each accounted for significant variance, but age accounted for significant additional variance after statistically controlling for these processing speed measures (see Table 3). Eighty-one percent and 58% of the initial age-related variance remained unaccounted for after control of simple reaction time and choice reaction time, respectively. To illustrate, the initial age-related variance in Block Design was .26, and the increment in variance in Block Design associated with age after control of choice reaction time was .15. Thus, the ratio (.15/.26 = .58) is the proportion of the initial age-related variance that remained unaccounted for after control of choice reaction time.

Similar results were obtained when a composite processing speed measure (the average of z-scores from the simple and choice reaction time tasks) was used as the first predictor, with 65% of the initial age-related variance unaccounted for after control of the processing speed composite. In the case of Matrix Reasoning performance, simple and choice reaction time once again accounted for significant variance, but age accounted for significant additional variance after controlling for these processing speed measures. Seventy-nine, 56, and 62% of the initial age-related variance remained unaccounted for after control of simple reaction time, choice reaction time, and the processing speed composite, respectively.

4.2. Fluid intelligence and frontal function

Additional analyses were conducted using the frontal function measures that were obtained from the subset of 166 participants who completed the Wisconsin Card Sorting Task and Tower of London. Linear regression analyses showed a significant age-related decline in the number of categories completed on the WCST [$F(1,164) = 12.63$, $p < .001$, $R^2 = .07$, $M = 4.8$, $SD = 1.7$] and a significant age-related increase in the number of excess moves on the TOL [$F(1,164) = 6.18$, $p = .01$, $R^2 = .04$, $M = 12.2$, $SD = 12.8$]. There was also a significant correlation between WCST and TOL performance, $r = -.25$, $p = .001$ (see Table 4 for other correlations). A composite measure of frontal function was then derived by averaging the z-scores of the dependent measures from each of the frontal tasks, after rescaling the categories-completed measure so that a greater z-score reflected worse performance. A linear regression analysis revealed a significant age-related decline in frontal function

Table 2
Correlation matrix for the full sample ($n = 196$)

	Age	BD	MR	SRT	CRT
Age	—				
Block Design (BD)	−.51	—			
Matrix Reasoning (MR)	−.59	.65	—		
Simple reaction time (SRT)	.35	−.22*	−.30	—	
Choice reaction time (CRT)	.51	−.35	−.42	.52	—

Note. *$p < .01$; all other correlations are significant at the .001 level.

Table 4
Correlation matrix for the reduced sample ($n = 166$)

	Age	BD	MR	Speed	Frontal
Age	—				
Block Design (BD)	−.48	—			
Matrix Reasoning (MR)	−.56	.63	—		
Speed composite	.42	−.29	−.35	—	
Frontal function composite	.30	−.34	−.48	.35	—

Note. All correlations are significant at the .001 level.

Table 3
Age-related variance in Block Design and Matrix Reasoning before and after control of processing speed measures in the full sample ($n = 196$)

Regression equation	Block Design				Matrix Reasoning			
	R^2	ΔR^2	*SE*	*Tol*	R^2	ΔR^2	*SE*	*Tol*
Age	.26	—	13.1	—	.34	—	4.7	—
Simple reaction time	.05	—	14.8	—	.09	—	5.5	—
Simple reaction time + age	.26	.21	13.1	.88	.35	.27	4.6	.88
Choice reaction time	.12	—	14.2	—	.18	—	5.2	—
Choice reaction time + age	.27	.15	13.0	.74	.36	.19	4.6	.74
Processing speed composite	.09	—	14.4	—	.15	—	5.3	—
Speed composite + age	.26	.17	13.1	.78	.36	.21	4.6	.78

Note. *SE*, standard error of the R^2 estimate; *Tol*, tolerance; all R^2 and ΔR^2 values are significant at the .01 level.

using this composite measure, $F(1,194) = 15.76$, $p < .001$, $R^2 = .08$.

We then examined the extent to which frontal function accounted for age differences in Block Design and Matrix Reasoning performance. To accomplish this, we conducted a forced-entry hierarchical regression analysis with fluid intelligence performance as the dependent variable, the frontal composite score as the first predictor, and age as the second predictor (cf. Salthouse, 2001b). Although the frontal composite measure accounted for a significant amount of variance in Block Design and Matrix Reasoning performance, age accounted for significant additional variance after controlling for frontal function. Seventy percent and 61% of the initial age-related variance in Block Design and Matrix Reasoning, respectively, remained unaccounted for after control of the frontal composite measure (see Table 5).

Additional analyses were then conducted to determine whether the variances in fluid intelligence performance that were attributable to frontal function and processing speed were shared variances. We used a forced-entry hierarchical regression analysis with fluid intelligence performance as the dependent variable, the frontal composite measure as the first predictor, and the processing-speed composite measure as the second predictor. The processing speed composite accounted for significant additional variance in Block Design and Matrix Reasoning performance beyond that of frontal function (total $R^2 = .15$ and .27; incremental $R^2 = .03$ and .04, $p\text{s} < .05$). When we entered processing speed as the first predictor and the frontal composite measure as the second predictor, the incremental variances attributable to frontal function were .07 and .15 for Block Design and Matrix Reasoning, respectively ($p\text{s} < .001$). To test for evidence of an interaction between processing speed and frontal function, a cross-product term (processing speed and frontal function) was entered into the regression model. The interaction was not significant for Block Design or Matrix Reasoning, $p\text{s} > .10$. A follow-up regression analysis that included age as the third predictor showed, however, that age accounted for additional variance in Block Design (total $R^2 = .27$, incremental $R^2 = .13$, $p < .001$) and Matrix Reasoning (total $R^2 = .42$, incremental $R^2 = .16$, $p < .001$) performance beyond that of processing speed and frontal function (see Table 5).

Table 5
Age-related variance in Block Design and Matrix Reasoning before and after control of processing speed and frontal function measures in the reduced sample ($n = 166$)

Regression equation	Block Design				Matrix Reasoning			
	R^2	ΔR^2	*SE*	*Tol*	R^2	ΔR^2	*SE*	*Tol*
Age	.23	—	13.3	—	.31	—	4.5	—
Frontal composite	.12	—	14.2	—	.23	—	4.8	—
Frontal composite + age	.27	.16	12.9	.91	.42	.19	4.2	.91
Frontal composite	.12	—	14.2	—	.23	—	4.8	—
Frontal composite + speed	.15	.03*	14.0	.88	.27	.04	4.7	.88
Frontal + speed + age	.27	.13	13.0	—	.42	.16	4.2	—

Note. SE, standard error of the R^2 estimate; *Tol*, tolerance; all other R^2 and ΔR^2 values are significant at the .01 level.
* $p < .05$.

5. Discussion

The primary purpose of the current study was to examine existing hypotheses regarding the decline in fluid intelligence in older adulthood. Following Parkin and Java's (2000) suggestion, we included measures of processing speed, frontal function, and fluid intelligence in the same study. As observed in past studies, we found an age-related decline in fluid intelligence as measured by Block Design and Matrix Reasoning tasks. Hierarchical regression analyses were then used to test the generalized slowing and frontal function explanations of this age effect. One key finding was that processing speed accounted for a significant proportion of the variance in fluid intelligence. Note, however, that for both measures of fluid intelligence, the effect of age was still significant after statistically controlling for processing speed. This finding is consistent with other studies (e.g., Salthouse, 1991; Schaie, 1989) in showing that generalized slowing partially accounts for the age-related decline in fluid intelligence, but one or more other factors seem to contribute as well.

Our results differ from those obtained by Bors and Forrin (1995), however, who found that the correlation between age and Raven's Advanced Progressive Matrices became non-significant after controlling for mental speed. This may partially reflect differences in sample size. Bors and Forrin's study was based on 63 participants, only 13 of them aged 60–80. Salthouse (1991) used a sample size comparable to ours and did observe a significant residual effect of age. This effect was, however, smaller in magnitude than that observed here. In Salthouse's study, the age-related variance in fluid ability (as measured by the Shipley Abstraction Test and Raven's Advanced Progressive Matrices), after controlling for processing speed, was 13% of the initial age-related variance. In the current study, the age-related variance in Block Design and Matrix Reasoning performance after controlling for the processing speed composite measure was 65 and 56%, respectively, of the initial age-related variance.

One possible reason for the difference in the magnitude of the residual age effect across studies may be the use of different fluid intelligence measures. Bors and Forrin (1995) and Salthouse (1991) both included Raven's Advanced Progressive Matrices as a fluid intelligence measure, whereas we used Block Design and Matrix Reasoning. Note, however, that performance on the Matrix Reasoning task strongly correlates with performance on Standard Progressive Matrices ($r = .81$; Wechsler, 1997). Also note that we obtained similar results with both of our measures of fluid intelligence. Thus, the choice of fluid intelligence measures appears to be an unlikely source of the differences across studies.

Another possible reason for the differences across studies may be the use of different processing speed measures. We used simple and choice reaction time as measures, Salthouse (1991) used letter and pattern comparison tasks that measured the speed of same/different judgments, and Bors and Forrin (1995) included a composite of simple and choice reaction time, speed of memory access on a Sternberg task, and speed of same/different judgments. Bors and Forrin noted that their simple and choice reaction time measures were highly correlated (rs = .58 and .61) with response time on their same/different judgment task, and suggested that the reaction time and judgment tasks reflect, at least in part, a single speed factor. Nonetheless, one could argue that there are multiple mechanisms whereby processing speed affects performance on fluid intelligence tasks (cf. Hertzog, Raskind, & Cannon, 1986), and that by virtue of including a variety of processing speed measures, Bors and Forrin's composite is the only one that taps into these multiple mechanisms. Perhaps this is why Bors and Forrin's study was the only one to eliminate the effect of age on fluid intelligence by statistically controlling for processing speed. Their null result may also reflect the smaller sample size and limited number of older adults in their study (i.e., just 13 adults aged 60 and above compared to 96 in the current study), so additional research is needed.

A second key finding of the present study was that performance on the frontal-function tasks also accounted for a significant proportion of the age-related variance in fluid intelligence. Moreover, the processing speed composite measure accounted for significant additional variance in fluid intelligence beyond that of frontal function (and frontal function accounted for significant additional variance beyond that of processing speed). Thus, the variance in fluid intelligence that was attributable to frontal function was not fully shared with the variance attributable to processing speed. These results suggest that there were independent contributions of generalized slowing and frontal decline to the age-related changes in fluid intelligence, as was observed by Schretlen et al. (2000) using different measures of speed, frontal function, and fluid intelligence.

Although our findings suggest that processing speed and frontal function both contribute to the age-related decline in fluid intelligence, they also show that there is a significant effect of age on fluid intelligence above and beyond these two factors. One possibility suggested by the literature is that a decline in working memory ability also contributes to the effect of age on fluid intelligence. Salthouse (1991) and Schretlen et al. (2000) both found that the age-related variance in fluid intelligence was non-significant after controlling for both processing speed and working memory. It is not clear, however, whether working memory would contribute to the age-related decline in fluid intelligence independent of the frontal-function measure used here, given that working memory measures often correlate with performance on the WCST and TOL, and given that working memory has been associated with the functioning of the prefrontal cortex (cf. Kane & Engle, 2002). Nonetheless, there is reason to suspect that working memory may make an independent contribution. According to Miyake et al. (2000), the WCST and Tower tasks used to develop the frontal function composite appear to tap into the executive processes of shifting and inhibition, respectively. However, our frontal function composite does not include performance on a task that taps into a third executive process identified by Miyake et al., what they refer to as updating. Miyake et al. found that updating is an executive process that is separable from shifting and inhibition and that updating relates to working memory performance. Thus it is possible that the frontal function measure used here does not capture working memory, thereby accounting for the differences in the magnitude of the residual age-related variance observed across studies. Additional research is needed to address this question.

Overall, we concur with Salthouse (2004) that more research is needed on the "how" of cognitive aging—the mechanisms underlying the effects of age on cognition. Part of the allure of Salthouse's (1996) generalized slowing account is its potential to explain age-related changes across a variety of cognitive functions. Although the current study suggests a slowing mechanism can not, by itself, account for the age-related decline in fluid intelligence, it is yet to be determined if any other single-factor theory can do so. It may well be the case that the pattern of age-related decline in cognitive function is too complex to be explained by a single-factor theory. The current study adds to a growing body of literature suggesting that multiple factors, including generalized slowing, may be necessary to provide the most complete explanation of the "how" of cognitive aging (Bugg, DeLosh, Davalos, & Davis, in press; Kwong See & Ryan, 1995; Persad, Abeles, Zacks, & Denburg, 2002; West & Baylis, 1998).

References

Backman, L., Hill, R., Herlitz, A., Fratiglioni, L., & Winblad, B. (1994). Predicting episodic memory performance in dementia: Is severity all there is? *Psychology & Aging, 9*, 520–527.

Bors, D. A., & Forrin, B. (1995). Age, speed of information processing, recall, and fluid intelligence. *Intelligence, 20*, 229–248.

Buckner, R. L. (2004). Memory and executive function in aging and AD: Multiple factors that cause decline and reserve factors that compensate. *Neuron, 44*, 195–208.

Bugg, J.M., DeLosh, E.L., Davalos, D.B., Davis, H.P. (in press). Age differences in Stroop interference: Contributions of general slowing and task-specific deficits. *Aging, Neuropsychology, and Cognition*.

Cattell, R. B. (1971). *Abilities: Their structure, growth, and action*. Boston: Houghton-Mifflin.

Dagher, A., Owen, A. M., Boecker, H., & Brooks, D. J. (1999). Mapping the network for planning: A correlational PET activation study with the Tower of London task. *Brain, 122*, 1973–1987.

Davis, H.P., Keller, F.R., 1998. Colorado assessment test manual. Colorado Springs: Colorado Assessment Tests.

DeCarli, C., Massaro, J., Harvey, D., Hald, J., Tullberg, M., Au, R., Beiser, A., D'Agostino, R., & Wolf, P. A. (2005). Measures of brain morphology and infarction in the framingham heart study: Establishing what is normal. *Neurobiology of Aging, 26*, 491–510.

Emery, C. F., Pedersen, N. L., Svartengren, M., & McClearn, G. E. (1998). Longitudinal and genetic effects in the relationship between pulmonary function and cognitive performance. *Journals of Gerontology Series B-Psychological Sciences & Social Sciences., 53*, 311–317.

Flood, D. G., & Coleman, P. D. (1988). Neuron numbers and sizes in aging brain: Comparisons of human, monkey, and rodent data. *Neurobiology of Aging, 9*, 453–463.

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience, 6*, 316–322.

Gur, R. C., Gur, R. E., Obrist, W. D., Skolnick, B. E., & Reivich, M. (1987). Age and regional cerebral blood flow at rest and during cognitive activity. *Archives of General Psychiatry, 44*, 617–621.

Heaton, R. K., Chelune, G. J., Talley, J. L., Kay, G. G., & Curtiss, G. (1993). *Wisconsin card sorting test manual: Revised*. Odessa FL: Psychological Assessment Resources.

Hertzog, C. (1989). Influences of cognitive slowing on age differences in intelligence. *Developmental Psychology, 25*(4), 636–651.

Hertzog, C., Raskind, C. L., & Cannon, C. J. (1986). Age-related slowing in semantic information processing speed: An individual differences analysis. *Journal of Gerontology, 41*, 500–502.

Horn, J. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologia, 26*, 107–129.

Isingrini, M., & Vazou, F. (1997). Relation between fluid intelligence and frontal lobe in older adults. *International Journal of Aging and Human Development, 45*, 99–109.

Kane, M. J., & Engle, R. W. (2002). The role of the prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review, 9*, 637–671.

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

Lazeron, R. H. C., Rombouts, S. A. R. B., Machielsen, W. C. M., Scheltens, P., Witter, M. P., Uylings, H. B. M., et al. (2000). Visualizing brain activation during planning: The Tower of London test adapted for functional MR imaging. *American Journal of Neuroradiology, 21*, 1407–1414.

Leaper, S. A., Murray, A. D., Lemmon, H., Staff, R., Dreary, I., Crawford, J., et al. (2001). Neuropsychologic correlates of brain white matter lesions depicted on mr images: 1921 aberdeen birth cohort. *Radiology, 221*, 51–55.

Masliah, E., Mallory, M., Hansen, L., DeTeresa, R., & Terry, R. D. (1993). Quantitative synaptic alterations in the human neocortex during normal aging. *Neurology, 43*, 192–197.

Mathew, R. J., Wilson, W. H., & Tant, S. R. (1986). Determinants of resting regional cerebral blood flow in normal subjects. *Biological Psychiatry, 21*, 907–914.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100.

Muldoon, M. F., Ryan, C. M., Matthews, K., & Manuck, S. (1997). Serum cholesterol and intellectual performance. *Psychosomatic Medicine, 59*, 382–387.

Owen, A. M., Doyon, J., Petrides, M., & Evans, A. C. (1996). Planning and spatial working memory: A positron emission tomography study. *European Journal of Neuroscience, 8*, 353–364.

Parkin, A. J., & Java, R. I. (1999). Deterioration in frontal lobe function in normal aging: Influences of fluid intelligence versus perceptual speed. *Neuropsychology, 13*, 539–545.

Parkin, A. J., & Java, R. I. (2000). Determinants of age-related memory loss. In T. Perfect & E. A. Maylor (Eds.), *Models of cognitive aging: Debates in psychology* (pp. 188–203). London: Oxford University Press.

Persad, C. C., Abeles, N., Zacks, R. T., & Denburg, N. L. (2002). Inhibitory changes after age 60 and their relationship to measures of attention and memory. *Journal of Gerontology: Psychological Science, 57B*(3), P223–P232.

Raz, N., Torres, I. J., Spencer, W. D., & Acker, J. D. (1993). Pathoclisis in aging human cerebral cortex: Evidence from in vivo MRI morphometry. *Psychobiology, 15*, 21–36.

Salthouse, T. A. (1991). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science, 2*, 179–183.

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

Salthouse, T. A. (2001a). Structural models of the relations between age and measures of cognitive functioning. *Intelligence, 29*, 93–115.

Salthouse, T. A. (2001b). A research strategy for investigating group differences in a cognitive construct: Application to ageing and executive processes. *European Journal of Cognitive Psychology, 13*, 29–46.

Salthouse, T. A. (2004). What and when of cognitive aging. *Current Directions in Psychological Science, 13*, 140–147.

Schaie, K. W. (1989). Perceptual speed in adulthood: Cross-sectional and longitudinal studies. *Psychology and Aging, 4*(4), 443–453.

Schretlen, D., Pearlson, G. D., Anthony, J. C., Aylward, E. H., Augustine, A. M., Davis, A., et al. (2000). Elucidating the contributions of processing speed, executive ability and frontal lobe volume to normal age-related differences in fluid intelligence. *Journal of the International Neuropsychological Society, 6*, 52–61.

Schroeter, M. L., Zysset, S., Kruggel, F., & von Cramon, D. Y. (2003). Age dependency of the hemodynamic response as measured by functional near-infrared spectroscopy. *Neuroimage, 19*, 555–564.

Shaw, T. G., Mortel, K. F., Meyer, J. S., Rogers, R. L., Hardenberg, J., & Cutaia, M. M. (1984). Cerebral blood flow changes in benign aging and cerebrovascular disease. *Neurology, 34*, 855–862.

Sternberg, R. J. (1985). The holey grail of general intelligence. *Science, 289*, 399–401.

Teng, E. L. (1990). The 3RT test: Three reaction time tasks for IBM PC computers. *Behavior Research Methods, Instruments, & Computers, 22*(4), 389–392.

Wechsler, D. (1997). *WAIS-III administration and scoring manual*. San Antonio, TX: The Psychological Corporation.

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. San Antonio, TX: Harcourt Brace Jovanovich.

West, R. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*(2), 272–292.

West, R., & Baylis, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging, 13*(2), 206–217.

Zimprich, D., & Martin, M. (2002). Can longitudinal changes in processing speed explain longitudinal age changes in fluid intelligence? *Psychology and Aging, 17*, 690–695.