Experimental Aging Research, 32: 263–295, 2006

ISSN: 0361-073X print/1096-4657 online
DOI: 10.1080/03610730600699118

PROCESSING SPEED, ATTENTIONAL CAPACITY, AND AGE-RELATED MEMORY CHANGE

Terry Levitt

Department of Psychology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Jonathan Fugelsang

Department of Psychology, University of Waterloo, Waterloo, Ontario, Canada

Margaret Crossley

Department of Psychology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

This study compared the relative importance (i.e., proportion of shared variance) of attentional capacity and processing speed accounts of cognitive aging to predict age differences in episodic and working memory performance. Right-handed adults ($n = 100$), 18 to 88 years of age, completed measures of attentional capacity (divided attention), processing speed, and episodic and working memory. The results provide little support for the predictive utility of the attentional capacity construct, independent of processing speed ability in accounting for age-specific episodic memory relations. The results are, however, consistent with the notion that attentional capacity mediates aspects of age-related working memory change.

Processing resource theories of cognitive aging posit that there are a small number of relatively broad explanatory mechanisms, mediators, resources, or factors that underlie age-associated changes in

Received 6 September 2004; accepted 28 July 2005.

The authors would like to thank Jamie Campbell, Neil Charness, Laurie Sippola, Norma Stewart, and two anonymous reviewers for comments and helpful suggestions on earlier versions of the manuscript.

Address correspondence to Terry Levitt, 1324 College Drive; Saskatoon, Saskatchewan, S7N 0W5. E-mail: tlevitt@sasktel.net

cognitive functioning (Craik & Byrd, 1982; Hasher & Zacks, 1988; Salthouse, 1990, 1991a, 1992a). One implication of these theories is that controlling for performance on measures that reflect basic processing factor abilities (e.g., attentional capacity, inhibition, processing speed) should substantially attenuate age-associated variance on a variety of age-sensitive cognitive tasks (Hartley, 1993; Salthouse, 1991a, 1992a). Salthouse (1990) argues that for a processing factor to be considered a major age-associated resource, it should account for a substantial proportion (i.e., at least one-third to one-half) of the age-related variance on a variety of cognitive tasks. The present research compares the relative predictive power of estimates of processing speed and attentional capacity, two commonly studied indicators of processing resources, with regard to age-associated declines in episodic and working memory.

Processing Resource Theories

A large body of evidence based on statistical control procedures is consistent with the notion that processing speed plays a major role in mediating relations between age and cognition (for a review see Salthouse, 1996a). Age-associated variance in many age-sensitive cognitive domains (e.g., episodic and working memory, verbal and nonverbal reasoning, verbal fluency, and divided attention) is largely attenuated when variance associated with performance on measures of processing speed is controlled for. To illustrate, in a review of research published between 1988 and 1993 based on samples of at least 200 participants and utilizing several measures of cognition, Salthouse (1993) reported that, on average, almost 16% of the cognition variance was accounted for by age, but that after statistical control of performance on a composite of processing speed measures, this value dropped to between 3% and 4%. In a related study, Salthouse, Fristoe, and Rhee (1996) observed a mean decrease in age-associated variance of 80% after controlling for processing speed performance on a variety of age-sensitive memory, verbal and nonverbal reasoning, and verbal fluency measures. Other analyses have revealed similar reductions using measures of free recall memory (Bryan & Luszcz, 1996; Salthouse, 1995a, 1996b), long-term memory for activities (Earles & Coon, 1994), associative learning (Salthouse & Kersten, 1993; Salthouse, 1994a), continuous associative memory (Salthouse, 1994a, 1994b, 1995b) working memory (Salthouse, 1991b, 1992b, 1995a; Salthouse & Babcock, 1991; Salthouse & Meinz, 1995), visuospatial ability (Salthouse, 1991b, 1994c), matrix, element, and keeping track memory (Salthouse, 1995c), spatial reasoning (Salthouse, 1991b, 1994c), and divided attention ability

(Salthouse, Fristoe, Lineweaver, & Coon, 1995). Clearly, according to Salthouse's (1990, 1996a) criteria, the processing speed factor has achieved "major processing resource" status.

"Attentional capacity" theories focus on age-related reductions in attentional resources as a potential mediator of the relations between age and cognition (Anderson, Craik, & Naveh-Benjamin, 1998; Salthouse, 1994d). Plude and Hoyer (1985) argue that "attentional limitations and age changes in utilizing and allocating attentional resources are important determinants of age-related cognitive decline" (p. 48). Craik and Byrd (1982) propose that a reduction in available mental energy or attentional capacity "is *one* of several major factors underlying declining cognitive efficiency in the elderly" (p. 192). In particular, attention-demanding or cognitively effortful tasks (i.e., intentional, novel, difficult, etc.) will be performed less well with increasing age (Craik & McDowd, 1987; Hasher & Zacks, 1979; Kensinger, Piguet, Krendl, & Corkin, 2005).

Mechanisms, Mediators, and Memory

Processing speed and attentional capacity resource theories provide differing mechanisms for the locus of age-related declines in memory performance. More specifically, both theories provide mechanisms for declines in *episodic* and *working* memory.

Episodic Memory

Concerning episodic memory from a processing speed perspective, Salthouse (1980) argues that older adults may rehearse to-be-remembered information less efficiently than younger adults because they require more time for each rehearsal. Consequently, they complete fewer rehearsals in a given time period compared with younger adults. From an attentional capacity perspective, Craik (Craik, 1983; Craik & Byrd, 1982) argues that attention demanding deep and elaborate encoding of information is necessary for episodic memory task performance (Johnston & Heinz, 1978) and, as a consequence of decreased attentional reserves, older individuals do not adequately encode to-be-remembered events meaningfully.

Working Memory

Salthouse (1992a) reasons that processing speed reduces the efficiency of working memory by limiting the amount of information an individual can simultaneously keep active. As a consequence, higher order abstraction and integration of information is not attainable because the products of early processing dissipate before subsequent processing can be completed. Craik and colleagues (Craik & Byrd, 1982; Morris, Gick, & Craik, 1988) argue that an increase in required mental operations (as occurs when working memory demands are high) will be associated with increased competition for a limited resource pool. Processing limitations associated with high working memory demands require trade-offs between cognitive processes utilized in maintaining information in an active state and cognitive processes required to carry out other mental operations. Older individuals, who presumably have a smaller "resource pool," will be differentially penalized because their attentional capacity is more readily exceeded.

Dual-task methodologies have been used to compare the attentional demands of various tasks (Kerr, 1973) and the attentional capacity differences among individuals (Salthouse, 1991a). Specifically, measures of interference during dual-task performance have been assumed to reflect age-related differences in attentional capacity (Burke & Light, 1981; Craik & McDowd, 1987; Crossley & Hiscock, 1992; Hasher & Zacks, 1979; Morris et al., 1988; Tun, Wingfield, Stine, & Mecsas, 1992; Wickens, Braune, & Stokes, 1987). Although several of the aforementioned studies have examined relations among age, processing speed, and cognition, investigations of age-cognition relations and attentional capacity, as measured within a dual-task program (long used to index individual differences in attentional capacity) are lacking. Indeed, Salthouse (1996a) notes:

> **the processing speed theory . . . has a resemblance to theories attempting to account for age-cognition relations in terms of broad explanatory mechanisms such as processing resources (e.g., Craik & Byrd, 1982) and aspects of attention such as inhibition (e.g., Hasher & Zacks, 1988). Unlike those theories however . . . a large body of evidence based on statistical control and path analysis procedures has accumulated indicating that the construct has a major role in mediating relations between age and cognition (p. 425).**

To be sure, a major problem for researchers who argue that reduced attentional capacity underlies cognitive change with age (e.g., Anderson et al., 1998; Craik & Byrd, 1982; Craik & McDowd, 1987; Crossley & Hiscock, 1992; Macht & Buschke, 1983; McDowd & Craik, 1988; Tun et al., 1992) is the lack of evidence that available measures of attention are significantly related to other measures of cognitive functioning (Madden, 1990; Salthouse, 1991a). Although several studies reveal poorer dual-task performance with age (e.g., Anderson et al., 1998; Craik & McDowd, 1987; Crossley & Hiscock, 1992; Macht & Buschke, 1983; Tun et al., 1992), statistical control procedures have not been used to examine the relationship between these observations and age-related decline on other cognitive measures. As a result, the relevance of these findings to the understanding of age-differences in other cognitive domains remains uncertain.

The Present Study

A primary focus of the present research is to investigate the magnitude of the relation between reduced attentional capacity and age-associated decline in episodic and working memory. Second, this research evaluates which processing resource construct (i.e., processing speed or attentional capacity) provides a better account of age-related variance in episodic and working memory tasks. Third, this research examines the degree to which attenuations in age-related variance are independent of one another after control of performance on divided attention and processing speed tasks. Perhaps there are specific independent relations of processing speed and attentional capacity with age-related episodic and working memory change. In the statistical control approach, this argument would be supported by the observation that dual-task performance predicts a substantial amount of age-related memory variance *after* control of processing speed performance and vice versa.

Finally, this research examines how much of the age-related attentional capacity variance (i.e., dual-task variance) is accounted for by the processing speed measures and vice versa. Do these relations overlap completely? Plude and Hoyer (1985) suggest that age changes in dual-task performance can be accounted for by reduced global capacity to support cognitive functioning, a decline in specific resources that increases the demand on global capacity, or by a slowing of speed of processing. Salthouse (1996a) reasoned that with respect to age-related influences, the more fundamental construct should be the one with "a large amount of overlap with the age-related variance in other variables but . . . a smaller proportion of its own age-related variance overlapping with that of other variables" (p. 423). Salthouse et al. (1995) conducted two experiments to investigate the extent of attenuation of age-related dual-task variance after control of single-task or basic measures of processing speed performance. Their results were unequivocal. First, only a few age differences in dual-task performance were observed regardless of which analytical method was employed to control for age differences in single-task performance. Second, the processing speed measures shared a large amount of the age-related variance with performance on the dual-task measures, consistent with the notion that processing speed is involved in age-related dual-task performance changes. Consequently, in this study we examined the mediator potential of performance on each construct (i.e., dual-task performance and processing speed) with respect to how well it accounted for age differences on the other construct.

METHODS

Participants

One hundred right-handed independent community-dwelling volunteers (76 women, 24 men) between 18 and 88 years of age were recruited from local clubs, organizations, housing facilities, and a university research participant pool. All respondents were screened according to the following criteria:

(1) *Visual and auditory acuity.* Participants were required to have normal or corrected to normal vision and audition.
(2) *Physical health and medication use.* Participants who reported generally good health were deemed acceptable for the study. Individuals who reported serious health concerns (e.g., history of heart attack or stroke, rheumatoid arthritis, multiple sclerosis, serious head injury) were not included in this study.
(3) *Intellectual ability.* The National Adult Reading Test (NART; Nelson, 1982) was used to assess intellectual ability. The NART accounts for 66%, 72%, and 33% of the variance in WAIS-R Full Scale, Verbal, and Performance IQ scores, respectively, indicating high criterion validity of the measure, particularly with regard to verbal ability (Crawford, Parker, Stewart, Besson, & DeLacey, 1989). This estimate of verbal intelligence indicates that, on average, our research participants fall approximately 1/2 to 2/3 standard deviations above the mean of their normative age group (see Table 1). In addition, the R^2 value associated with age on the NART was .02 (n.s.) suggesting age-invariant verbal intellectual ability for this sample.

Demographic and health characteristics of the study participants are also summarized in Table 1. Participants had relatively equal amounts of formal education across age groups ($M = 14.1$ years). Cardiovascular difficulties and/or use of medication for hypertension were reported more frequently by older than by younger participants. Overall health ratings were invariant across age, consistent with previous related research (e.g., Salthouse, Kausler, & Saults, 1990; Salthouse, 1993).

Table 1. Means and standard deviations of demographic, verbal ability, and health variables by age decade

Age decade	*n*	Education		NART		Health		Limitation of daily activities due to health		Cardio/blood pres.		Men/women
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
18–29	24	14.6	2.9	32.3	5.1	2.1	1.0	1.3	0.5	0.0	0.0	7/17
30 s	9	14.8	2.0	36.8	5.8	1.9	0.6	1.6	0.7	0.1	0.3	1/8
40 s	14	13.9	2.4	35.5	7.4	1.7	0.7	1.6	0.9	0.0	0.0	1/13
50 s	15	15.5	4.6	39.0	4.4	1.9	1.0	1.5	0.7	0.2	0.4	2/13
60 s	14	14.2	3.5	38.1	7.6	1.8	0.8	1.3	0.5	0.2	0.4	5/9
70 s	10	14.0	2.4	35.3	6.7	2.2	0.6	1.6	0.8	0.3	0.5	6/4
80 s	14	12.1	2.7	35.2	7.1	2.2	0.8	1.8	0.7	0.3	0.5	2/12

Note. Education refers to years of formal education completed. NART refers to the mean score (/50) obtained on the Nation Adult Reading Test. Health represents a self-assessment on a 5-point scale ranging from 1 = excellent to 5 = poor. Limitation of daily activities is on a 5-point scale. Cardio/blood pres. refers to summed score of surgical intervention for cardiovascular intervention and whether or not blood pressure medication is being taken (yes/no responses).

Materials

Each participant was administered a series of tests of episodic memory, working memory, processing speed, and four dual-task combinations. The memory and processing speed measures have been shown to have moderate to high relations with age (Knopman & Ryberg, 1989; Salthouse, 1996a; Wechsler, 1987).

Episodic Memory Measures

To assess episodic memory for verbal discourse and for semantically unrelated word pairs respectively, data from the Logical Memory and the four "difficult" pairs of the Paired Associate subtests from the Wechsler Memory Scale—Revised (WMS-R; Wechsler, 1987) were analyzed. Data from a modified version of the Delayed Word Recall Test (DWRT; Knopman & Ryberg, 1989) were also analyzed; the latter verbal memory test provides repetition and elaborative encoding of a 10-item word list and measures free recall memory following both short and long delays. Finally, data from a visual memory test, the Rey Complex Figure Test were analyzed. This test requires the participant to copy a complex figure and then draw it from memory without prior warning. Performance was scored according to Taylor's criteria as described in Spreen and Strauss (1991). In addition to a short-delay or immediate recall trial, a 30-min delayed recall trial was administered for all episodic memory measures.

Working Memory Measures

Working memory was assessed using two tasks, "Listening Span" and "Computation Span" as described by Salthouse and Babcock (1991). The Listening Span task consisted of oral presentation of sentences in which the participant was required to correctly answer a question about the sentence and remember the last word of each sentence. After completion of a designated number of problems, the participant had to write the target words. In the Computation Span task, arithmetic problems were presented to the participant to correctly solve while remembering the last digit from each problem. Participants then had to write the target digits at the end of each series.

Span estimates represented successful recall and successful performance on the listening and computational tasks. Salthouse and Babcock (1991) report age correlations of $-.47$ for the computation span estimates and $-.52$ for the listening span estimates and note that these measures have high test-retest reliabilities ($r = .90$ for Computation Span; $r = .86$ for Listening Span). Further, Salthouse (1992a) reports that these measures share between 75% and 85% of their age-related variance, suggesting highly similar age-related influences in these measures.

Processing Speed Measures

Processing speed was assessed using the Letter Comparison and Pattern Comparison tests as described by Salthouse (1993). Participants completed two 30-s trials for both tasks. Letter Comparison requires the participant to visually scan two adjacent sets of three, six, or nine letters and to write an "S" to indicate that the adjacent sets were the same and a "D" to indicate that they were different. The dependent measure was the number of correct minus the number of incorrect responses produced within 30 s. The estimated reliability for this test is .83 (Salthouse, 1993).

The Pattern Comparison test requires the participant to visually scan two adjacent sets of line patterns composed of three, six, or nine line segments and then write an "S" if the pattern was the same and a "D" if the pattern was different. The dependent measure was the number of correct minus the number of incorrect responses produced within 30 s. The estimated test-retest reliability for this test is .87 (Salthouse, 1993).

Attentional Capacity Measures

The dual-task trials consisted of four combinations of two oral-output tasks (i.e., letter fluency or serial subtraction) combined with an alternate-key finger tapping or continuous reaction time task. To illustrate the letter fluency task, the experimenter presented a card bearing the letter "S" and instructed the participant to say as many words as possible that start with "S" after the experimenter said, "begin." The participant was told to keep his or her focus on the letter and to continue the task until instructed to "stop." Each participant then completed a 20-s practice trial. Presentation of letter stimuli (i.e., "Y," "T," "L," "A," "Q," "W," "C," "J," "U," "H," "M," "I") was counterbalanced across single- and dual-task trials for each age group. The dependent measure was the number of correct words generated in each 20-s trial.[1]

For the serial subtraction task, participants were verbally presented with a random number between 50 and 99 and then asked to serially subtract by 3's. The experimenter then demonstrated the task and provided the participant with two practice trials. The dependent measure was the number of correct subtractions produced in 20-s trials.

Alternate-key finger-tapping data were collected using a PC keyboard. Using the right index finger, participants were instructed to tap the right- and then left-arrow keys, alternating as quickly as possible. Participants then completed two 20-s concurrent-task practice trials (i.e., tapping paired with letter fluency and then serial subtraction). The dependent measure was the number of taps produced in 20-s trials.

For the continuous reaction time task, a circle was presented in one of four areas of the computer screen (top, bottom, left, right) and the participant was required to press the corresponding arrow key on the keyboard as quickly as possible. Ten milliseconds after each key press a new circle was presented. Each participant completed a 20-s

[1]Letter fluency has been used by a number of researchers as an index of executive performance (e.g., Henry, Crawford, & Phillips, 2005). In order to test the degree to which our sample was at or above age norms for executive functioning, we compared the obtained letter fluency scores from our sample to a published normative data set of 1300 participants ranging from 16 to 95 years (Tombaugh, Kozak, & Rees, 1999). Tombaugh et al. asked participants to generate as many words as they could beginning with the letters F, A, and S. Number of words generated ranged from a high of 43 for the 30s and 40s age decades and declined to 29 for the 80s decade. This represents a 33% drop in performance from the 30s decade to the 80s decade. As noted in Methods, the task incorporated in the current study differed from that of Tombaugh et al. in that participants were given one letter at a time for 20s. An analysis of the averaged responses for the two control letter fluency conditions (see Appendices C and D) reveals that letter fluency scores drop from a high of 8.4 for the 30s decade to 6.6 for the 80s decade. This represents a 23% drop in performance. These data suggest that the older sample may be slightly superior on measures of executive functioning compared to published norms.

practice trial and then two 20-s concurrent-task practice trials (i.e., reaction time paired with letter fluency and then serial subtraction). The dependent measure was the number of correct responses in 20 s. A computer beep signaled the beginning and end of each trial for all tasks.

Procedure

All participants were individually tested by one of two experimenters. The study was described as an attempt to understand what underlies changes in memory with age. To counterbalance the administration of tasks, participants were grouped into three age groups of 33 young (18–41), 33 middle (42–65), and 34 older (66–88) individuals. Within each age group, half of the participants carried out dual-task finger tapping and Computation Span first while the other half carried out dual-task reaction time and Listening Span first. The 12 fluency task letters were broken into three groups of four.

All participants accomplished two blocks of dual-task trials: (a) fluency or serial subtraction and alternate-key finger tapping, and (b) fluency or serial subtraction and continuous reaction time. Each block of trials involved only one of the manual tasks (continuous reaction time or finger tapping) and both oral output tasks. The two blocks were separated by the episodic memory, processing speed, and working memory measures, which were administered in the following order: Logical Memory (I), Verbal Paired Associates (I), Delayed Word Recall Test (I), Rey Complex Figure Test (I), Pattern Comparison, Letter Comparison, Listening Span or Computation Span, Logical Memory (30-min delay), Verbal Paired Associates (30-min delay), Delayed Word Recall (30-min delay), Rey Complex Figure Test (30-min delay), and Listening Span or Computation Span.

Each block of dual-task trials contained 16 experimental trials. The first four single-task trials were (a) right hand tapping or continuous reaction time, (b) letter fluency, (c) serial subtraction, and (d) right hand tapping or continuous reaction time. Eight concurrent-task trials of right hand tapping or continuous reaction time combined with either serial subtraction or letter fluency then followed these single-task trials. Finally, four more single-task trials were completed, in the reverse order. Thus, each participant accomplished four single- and four dual-task trials of each type. Performance was averaged across each trial type. In order to control each participant's allocation of attention during the dual-task trials, the experimenter provided the following instruction: "Because we are measuring your performance on both of the tasks, it is important for you to try as hard as you can on both of them."

The duration of each single- and concurrent-task trial was 20 s. Each block of 16 trials was completed in approximately 20 min. A testing session, including all trials, standardized administration of the verbal ability, episodic memory, and working memory tasks, completion of the health and education questionnaire, and brief rest periods, required between 90 and 120 min.

Dual-Task Scoring

There are currently no clear guidelines regarding a preferred metric for controlling for differences in single-task performance in the interpretation of age differences in dual-task performance (e.g., Guttentag, 1989; Salthouse et al., 1995). Two metrics for indexing dual-task costs predominate in the literature: difference scores between single- and dual-task performance (single-task minus dual-task), and proportion difference scores between single- and dual-task performance ([single-task minus dual-task]/single-task; Guttentag, 1989). Cohen and Cohen (1983) criticize the use of correlational analyses with these variables, arguing that correlations based on such values remain influenced by the relationship between pre-scores and post-scores, or, in this research, by the relationship between single- and dual-task performance. As an alternative to these approaches, Cohen and Cohen advocate residualizing the relationship of the initial measure (e.g., single-task performance) with the subsequent measure (e.g., dual-task performance) and utilizing the residual dual-task measure as it will have no relationship with the initial measure. Because the previous dual-task literature has utilized difference and proportional score metrics, all three approaches were initially used in this study.

As commonly noted in the literature, when an individual carries out two tasks concurrently, there is no assurance that the individual will allocate equal amounts of attention to each task. Because of individual differences in task-specific ability, expectancy, and cognitive operations involved in different tasks, there may be variance in attentional allocation within and across age groups. Indeed, even when participants are instructed to "protect" performance on a particular task, the instructions are not always followed (Kahneman, 1970; Navon & Gopher, 1979). To attempt to deal with this limitation, in addition to instructing participants to exert maximum effort on both tasks, composite measures were created reflecting concurrent performance on both tasks. Dependent measures in each task were converted to *z*-scores that were combined to create a composite performance index. Salthouse et al. (1995) note that this approach is limited by the assumption that measures from each task are equal with respect to their sensitivity and importance. However, it provides a means of integrating the measures of the two tasks into a single index and is thus desirable for the purposes of this study.

Statistical Analysis

The statistical approach used in the current project relies on hierarchical regression analysis to determine the proportion of the age-related episodic and working memory *criterion* variance that can be accounted for by controlling, or adjusting, for the age differences associated with indices of processing resources—hereafter termed *mediator* variables. Salthouse (1991a, 1992a) describes the logic underlying the procedures in detail. Of interest is the relative proportion of shared variance among performance on the dual-task or speed measures and age, and episodic memory or working memory performance.

RESULTS AND DISCUSSION

Dual-task analyses are presented first, followed by interrelations of all measures retained for statistical control analyses. Proportions of age-related variance in episodic and working memory measures after control of performance on speed and attentional capacity measures are then presented, including analyses of unique age-relations between each mediator and criterion variable after control of the other mediator. Proportions of shared age-related variance among the mediators are then examined.

Dual-Task Analyses

Single- and concurrent-task performance rates broken down by age decade are presented in Appendices A through F. Age was measured as a continuous variable for the remainder of the regression analyses. The amount of age-associated variance in the different methods of analyzing dual-task performance was determined from regression equations with age as the single predictor variable. Results of these analyses, in the form of R^2 values related to age, are summarized in Table 2. It is apparent that the age relationships are significant and moderate to major in magnitude with the initial dual-task analyses, but that they are attenuated, in 14 out of 24 cases (final three columns of Table 2), to not significantly greater than zero when

Table 2. R^2 Associated with age for four different methods of analyzing dual-task performance

	Analytical method			
	Dual	**(Single − dual)/single**	**Single − dual**	**Residual**
		Performance on continuous reaction time		
During letter fluency	.503*	.257*	.005	.010
During serial subtraction	.485*	.192*	.057	.007
		Performance on finger tapping		
During letter fluency	.336*	.254*	.177*	.092*
During serial subtraction	.371*	.294*	.247*	.128*
		Performance on letter fluency		
During continuous reaction time	.134*	.048	.029	.102*
During finger tapping	.036	.003	<.000	.012
		Performance on serial subtraction		
During continuous reaction time	.169*	.037	.004	.082*
During finger tapping	.105*	.000	.005	.006

Note. Dual = concurrent task performance rate; residual = residual score from regression equation predicting dual-task performance from single-task performance.

*Significant at the .01 level (two-tailed).

single-task performance is taken into account. Unfortunately, the method of considering single-task performance in the evaluation of dual-task performance creates major differences in the magnitude of the age-associated dual-task relation, and whether or not the relation is significantly greater than zero. For example, estimates of age-related dual-task variance for performance on the continuous reaction time task during concurrent letter fluency range from R^2 age = .257 ($p < .01$) for the analysis on the proportion decrement score, to $R^2 = .005$ (n.s.) for the analysis on the single minus dual difference score. These discrepancies make the interpretation of these results somewhat ambiguous.

The age relations of the composite indices are presented in Table 3. These were created by converting each dual-task trial measure to a z-score and then computing an average for each task combination. The first four rows are the R^2 values related to age for each combination of tasks and the fifth row is made up of the average of each dual-task combination z-score to form a "grand composite," operationalized as an index of each participant's attentional capacity. Inspection of Table 3 reveals that the proportions of variance associated with age in the grand index composite measures are generally higher than the values in the simple composites possibly reflecting increased reliability of the combined measurements. Most of the

Table 3. R^2 associated with age for composite measures for four different methods of analyzing dual-task performance

	Analytical method			
	Dual	(Single − dual)/single	Single − dual	Residual
Continuous reaction time/Letter fluency	.428*	.223*	.026	.085*
Continuous reaction time/Serial subtraction	.429*	.267*	.054	.021
Finger tapping/Letter fluency	.221*	.128*	.079*	.057
Finger tapping/Serial subtraction	.300*	.151*	.095*	.070*
Grand composite index	.435* (85%)	.348* (50%)	.045 (25%)	.057 (43%)

Note. Dual = concurrent task performance rate; residual = residual score from regression equation predicting dual-task performance from single-task performance.

Numbers in parentheses refer to percentage of shared age-related variance among the four simple composites within each calculation metric.

*Significant at the .01 level (two-tailed).

age relations in this table are significant, although there is still a marked disparity in the magnitude of the age-related influence on these scores depending on which metric is considered to control for baseline differences in single-task performance. The only grand composite index, which controls for single-task performance that is significantly greater than zero, is the proportion decrement score. This score has a major relationship with age.

Appropriate Choice of Representative Dual-Task Scores for Subsequent Statistical Control Analyses

It is not reasonable to use the dual-alone measure without control of single-task performance for the statistical control analyses because the R^2 value related to age for the control (or single-task) composite is .377, indicating a substantial amount of single-task variance related to age. It is also argued that the single-dual difference scores and the residual dual score after control for single-task performance should not be retained for the statistical control analyses. Indeed, the R^2 value related to age of .435 in the dual-only condition drops to .057 for the dual-residual score indicating that 87% ([.435 − .057]/.435 = .868) of the age variance in the dual-alone composite is shared with the single-task composite. Further, except for the control letter fluency score in the finger-tapping condition, performance on all of the single-task measures declined with age ($p < .05$; R^2 values ranging from .03 to .81). Retention of the difference scores is also not appropriate because they are not significantly greater than zero for six out of the eight tasks, two out of the four task combination composites, and on the overall grand composite.

The retention of the proportion decrement score, however, is justified for several reasons. First, it places this research in the context of prior studies that have frequently utilized it in the past (Craik & McDowd, 1987; Crossley & Hiscock, 1992; Crossley, Hiscock, & Foreman, 2004; McDowd & Craik, 1988; Salthouse et al., 1995; Somberg & Salthouse, 1982). In addition, the present results reveal that this metric of capacity is clearly age sensitive—a necessary but not sufficient condition of a hypothesized mediator. Further, the proportion score composite has comparable reliability with the processing speed composite (.70 versus .71), a desirable condition for statistical control analyses. However, a cautionary note is provided; because all of the tasks in both studies are measured in terms of responses (e.g., number of taps, words, numbers, key selections) in 20-s time periods, older adults' scores are typically lower than younger adults' scores. Consequently, in these instances the proportion decrement score is a less conservative index of dual-task costs because a smaller difference from single- to dual-task conditions is needed for the same proportion score (Guttentag, 1989). This is not to say that the proportion decrement score is merely an artifact of single-task performance; however, because there is still significant age variance in the proportion score composite ($R^2 = .166$; $p < .001$) after controlling for the influence of single-task performance. The drop from age $R^2 = .348$ to .166 indicates that approximately 52% of the age-related dual-task proportion score variance is shared with single-task performance. Given the aforementioned reasons, only the dual-task proportion decrement score was retained for the subsequent statistical control analyses.

Primary Measures

Composite variables were created for the four constructs (processing speed, attentional capacity, episodic memory, working memory) by averaging *z*-scores for the measures hypothesized to represent each construct. The variables that make up the attentional capacity (dual-task) composites were described above. The remaining constructs and the measures operationalized to represent them are as follows: processing speed (Letter Comparison, Pattern Comparison), working memory (Listening Span, Computation Span), and episodic memory (Logical Memory, Difficult Paired Associates, Delayed Word Recall, Rey Complex Figure Test). Age relations for the mediator and criterion composite variables are plotted as a function of age decade in Figures 1 and 2, respectively. It is apparent that performance on the speed composite gradually and consistently changes with age whereas age-related attentional capacity performance decrements occurred in individuals between ages 18 and 40, and 60 and 88. Performance on the Episodic and Working Memory tasks follow a gradual decline with age. Table 4 contains estimates of the reliabilities, means and standard deviations, and age relations for the primary measures and composite scores. Several of the values indicate satisfactory reliability estimates (i.e., greater than .80). As noted, the reliability estimates for the processing speed composite and dual-task proportion decrement score composite are comparable (.71 versus .70 respectively). It is apparent that the age relationships among the primary measures are significant and moderate to major in magnitude accounting for from 15% (Logical Memory I) to as much as 58% of the variance (Pattern Comparison).

Interrelations of Measures

Correlations computed on measures retained for subsequent analyses are presented in Table 5. The speed composite correlates slightly higher with the episodic memory measures (.68 with episodic memory

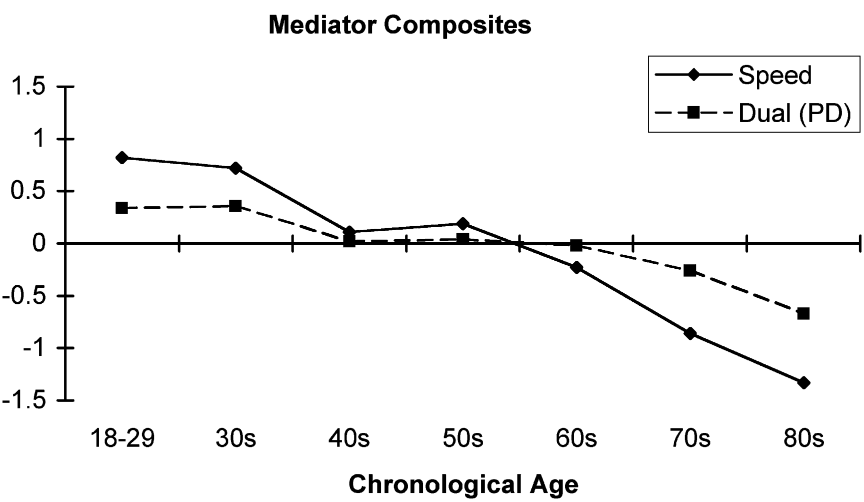

Figure 1. Mean z-sores by decade for the mediator composite variables. Note that the measures have been reflected such that higher z-scores correspond to better performance.

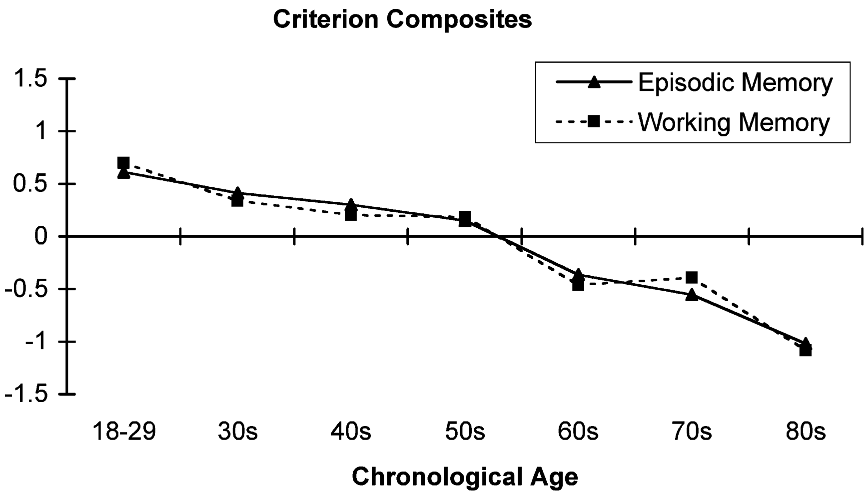

Figure 2. Mean *z*-sores by decade for the criterion composite variables.

composite) than does the dual-task proportion decrement score (–.49), although the two composites have the same correlation with the working memory composite (.51).

Statistical Control Procedures

Results of the statistical control analyses with the mediator composites and individual and composite criterion variables are presented in Table 6. Attenuations of age-related episodic and working memory variance are presented after control of the single-task composite (i.e., average of all *z*-score converted control trials) and reveal a fairly high degree of overlap (67%) among single-task performance, episodic or working memory, and age. Attenuations of age-related episodic memory variance using the processing speed estimate (i.e., Letter Comparison/Pattern Comparison composite) reveal major attenuations in age-related variance (80%) replicating previous work (e.g., Bryan & Luscz, 1996; Salthouse, 1994a, 1995a, 1996b; Salthouse & Kersten, 1993).

The dual-task proportion decrement composite shares just under half (45%) of its age-related variance with the age-related variance in the episodic memory measures. According to Salthouse's (1992a) classification scheme, this percentage attenuation value can be classified as "important" although it is only slightly more than half the attenuation observed after control of the speed composite.

Table 4. Estimated reliability and age relations for primary dependent variables

	Estimated reliability	*M*	*SD*	Age R^2
Letter Comparison	.83[a]	10.4	2.7	.470*
Pattern Comparison	.87[a]	17.5	4.7	.578*
Delayed Word Recall (I)	—	6.1	2.0	.404*
Delayed Word Recall (II)	—	6.3	2.3	.501*
Logical Memory (I)	.74[d]	23.7	7.0	.150*
Logical Memory (II)	.75[d]	18.8	7.7	.190*
Difficult Paired Association (I)	—	7.0	3.1	.313*
Difficult Paired Association (II)	—	2.8	1.2	.368*
Rey Complex Figure Test (I)	—	17.1	6.8	.342*
Rey Complex Figure Test (II)	—	16.7	6.7	.406*
Listening Span	.86[e]	3.2	1.3	.385*
Computation Span	.90[e]	3.3	1.8	.314*
Processing speed composite	.71[c]	—	—	.573*
Single-task composite	.90[c]	—	—	.377*
Dual-task composite	.70[c]	—	—	.348*
Episodic memory composite	.85[c]	—	—	.529*
Working memory composite	.83[c]	—	—	.400*
NART	.98[f]	35.7	6.5	.023

Note. I = first recall; II = second recall; processing speed composite = average of Letter Comparison and Pattern Comparison; single-task composite = composite of performance on control task measures; dual-task composite = composite of proportional ([single – dual]/single) decrement scores; episodic memory = composite of I and II trials of Delayed Word Recall, Logical Memory, Difficult Paired Associates, and Rey Complex Figure Test; working memory composite = composite of Listening Span and Computation Span; NART = National Adult Reading Test.

[a]Estimated test-retest reliability derived by using Pearson correlation.
[b]Value from Snow, Tierney, Zorzitto, Fisher, and Reid (1989).
[c]Estimated intercorrelation of scores using Cronbach's Alpha.
[d]Value from Wechsler (1987).
[e]Value from Salthouse and Babcock (1991).
[f]Value from Crawford, Parker, Stewart, Besson, and De Lacey (1989).
*Significant at the .01 level (two-tailed). — = no scores available.

Attenuations of age-related variance in the working memory measures after control of the speed composite are somewhat discrepant between the two working memory measures. The percentages of shared variance are 57% and 72% on the Listening and Computation Span measures, respectively. Interestingly, the dual-task proportion composite shares the same percentage (57%) of age-related variance with the Listening Span measure as the speed composite although it shares somewhat less with the Computation Span measure (58% versus 72%). This might be because the processing component of the Computation Span task is more demanding in that the participant

Table 5. Correlation matrix for performance measures

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Letter Comparison	—																	
2. Pattern Comparison	.83	—																
3. Delayed Word Recall (I)	.55	.57	—															
4. Delayed Word Recall (II)	.60	.63	.86	—														
5. Logical Memory (I)	.46	.45	.52	.51	—													
6. Logical Memory (II)	.48	.46	.58	.57	.91	—												
7. Delayed Paired Association (I)	.45	.46	.51	.58	.44	.54	—											
8. Delayed Paired Association (II)	.51	.49	.57	.61	.43	.48	.72	—										
9. Rey Complex Figure (I)	.43	.55	.45	.51	.44	.44	.53	.53	—									
10. Rey Complex Figure (II)	.46	.60	.48	.54	.46	.46	.52	.49	.93	—								
11. Listening Span	.45	.45	.54	.56	.44	.49	.48	.46	.42	.44	—							
12. Computation Span	.45	.48	.45	.47	.36	.40	.40	.37	.38	.40	.75	—						
13. Single task	.67	.75	.50	.55	.50	.54	.48	.49	.46	.47	.53	.53	—					
14. Processing speed	.96	.96	.59	.65	.47	.49	.48	.52	.51	.55	.47	.48	.74	—				
15. Dual-task	–.51	–.61	–.38	–.46	–.35	–.32	–.33	–.32	–.42	–.45	–.50	–.45	–.44	–.59	—			
16. Episodic memory	.63	.67	.79	.83	.75	.79	.77	.77	.77	.78	.61	.52	.64	.68	–.49	—		
17. Working memory	.48	.50	.53	.55	.43	.47	.47	.44	.43	.45	.93	.93	.56	.51	–.51	.60	—	
18. Age	–.69	–.76	–.64	–.71	–.39	–.44	–.56	–.61	–.58	–.64	–.62	–.56	–.61	–.76	.59	–.73	–.63	—

Note. I = first recall; II = second recall; single task = composite of performance on control task measures; processing speed = average of Letter Comparison and Pattern Comparison; Dual task = composite of proportional ([single – dual]/single) decrement scores; episodic memory = composite of I and II trials of Delayed Word Recall, Logical Memory, Difficult Paired Associates, and Rey Complex Figure Test; working memory = composite of Listening Span and Computation Span.

Table 6. Proportions of age-related variance before and after control of performance on attentional capacity and speed measures

	Age alone R^2	After single task R^2 change	After dual task R^2 change	After speed R^2 change	After dual task and speed R^2 change
Episodic memory					
Delayed Word Recall (I)	.404*	.176* (.56)	.256* (.37)	.085* (.79)	.084* (.79)
Delayed Word Recall (II)	.501*	.218* (.56)	.293* (.42)	.112* (.78)	.103* (.79)
Logical Memory (I)	.150*	.010 (.93)	.050 (.67)	.002 (.99)	<.001 (.99)
Logical Memory (II)	.190*	.018 (.91)	.090* (.53)	.009 (.95)	.008 (.96)
Difficult Paired Association (I)	.313*	.110* (.65)	.201* (.36)	.090* (.71)	.087* (.72)
Difficult Paired Association (II)	.368*	.150* (.59)	.265* (.28)	.110* (.70)	.109* (.70)
Rey Complex Figure Test (I)	.342*	.147* (.57)	.175* (.49)	.090* (.74)	.073* (.79)
Rey Complex Figure Test (II)	.406*	.196* (.52)	.213* (.48)	.110* (.73)	.092* (.77)
		$M = .66$	$M = .45$	$M = .80$	$M = .81$
Working memory					
Listening Span	.385*	.142* (.63)	.165* (.57)	.166* (.57)	.120* (.69)
Computation Span	.314*	.091* (.71)	.133* (.58)	.088* (.72)	.063* (.80)
		$M = .67$	$M = .58$	$M = .65$	$M = .75$
Composites					
Episodic memory	.529*	.181* (.66)	.299* (.43)	.105* (.80)	0.94* (.82)
Working memory	.400*	.132* (.67)	.170* (.58)	.142* (.65)	.102* (.75)
		$M = .67$	$M = .51$	$M = .73$	$M = .79$

Note. Single task = composite of performance on control task measures; dual task = composite of proportional ([single − dual]/single) decrement scores; Speed = average of Letter Comparison and Pattern Comparison; I = first recall; II = second recall; episodic memory = composite of I and II trials of Delayed Word Recall, Logical Memory, Difficult Paired Associates, and Rey Complex Figure Test; working memory = composite of Listening Span and Computation Span.

is required to work out the simple arithmetic problem with no aid from the answer sheet. For the Listening Span task, however, the statement that is read to the participant (from which the participant must determine the answer to the question that follows) includes the answer to the question and consequently the participant only needs to recognize the answer from the answer sheet and select it. Consequently, how fast an individual is able to perform simple arithmetic problems might have a greater influence on the more demanding Computation Span task. The age-related variance on the dual-task proportion decrement score overlaps similarly with the age-related variance on both working memory tasks; it shares an average of

58% of the age-related variance in those measures—an important influence relying on Salthouse's (1992a) classification.

Unique Contributions of Attentional Capacity and Speed

The unique predictive utility of each hypothesized mediator with regard to age-related episodic and working memory change was assessed by controlling for each mediator, and then examining the change in R^2 with age on the criterion variables after the second mediator was entered into the regression equation.[2] Table 6 shows the proportion of age-related episodic and working memory variance after controlling for the attentional capacity scores and the speed score, and Table 7 shows the percentage of unique age-related episodic and working memory variance specific to each mediator. For the episodic memory measures, the results are consistent when examining additional age-associated variance accounted for by the attentional capacity proportional composite after control of the speed composite because the values only range from an additional 0% to 5% unique shared variance. The proportions of age-related working memory variance accounted for by attentional capacity performance after control of speed performance are higher, ranging from 8% for the Computation Span measure to 12% for the Listening Span measure. Overall, the average percentage of additional age-related memory variance on the episodic and working memory composites accounted for by utilizing the proportional dual-task metric is 6%. This indicates that there is very little *average* overlap among age, episodic or working memory, and attentional capacity performance that is not shared with performance on the speed measure.

The results are quite different when considering additional age-related episodic and working memory variance accounted for by the speed composite after controlling for attentional capacity performance. On the episodic memory measures, an additional 37% of age-related variance is accounted for after control of the dual-task proportion decrement score. The results with the working memory measures are less impressive in that only an average of 17%

[2]We also examined the degree to which the criterion and mediator variables interacted with age. To do this, we created four interaction terms that represented the interaction between working memory and dual-task performance, working memory and processing speed, episodic memory and dual task performance, and episodic memory and processing speed and regressed these interaction terms on age. These additional analyses revealed that the interactions between the mediator and the criterion variables did not account for any additional variance over and above that of the criterion and mediators alone (largest $t = 1.01$, $p = .315$). These additional analyses demonstrate that the criterion and mediator relationship was homogenous as a function of age.

Table 7. Percentage of unique age-related memory variance after control of speed and attentional capacity mediators

	Speed after dual task	Dual task after speed
Episodic memory		
Delayed Word Recall (I)	43	0
Delayed Word Recall (II)	38	2
Logical Memory (I)	33	0
Logical Memory (II)	43	1
Difficult Paired Association (I)	36	1
Difficult Paired Association (II)	42	0
Rey Complex Figure Test (I)	30	5
Rey Complex Figure Test (II)	30	4
	M = 37	*M* = 2
Working memory		
Listening Span	12	12
Computation Span	22	8
	M = 17	*M* = 10
Composites		
Episodic memory	39	2
Working memory	17	10
	M = 28	*M* = 6

Note. Dual task = composite of proportional ([single − dual]/single) decrement scores; speed = average of Letter Comparison and Pattern Comparison; I = first recall; II = second recall; episodic memory = composite of I and II trials of Delayed Word Recall, Logical Memory, Difficult Paired Associates, and Rey Complex Figure Test; working memory = composite of Listening Span and Computation Span. *M* = mean value.

additional age-related working memory variance is accounted for by the speed composite after control of the dual-task proportion decrement score. Considering this metric of controlling for dual-task performance, speed and attentional capacity performance are closer in terms of the magnitude of their importance as mediators in the working memory domain. Notably, there are "small" (.12 and .08) and "small" and "interesting" (.12 and .22) proportions of unique age-related variance shared with the attentional capacity and speed measures, respectively, suggesting some distinct age-related influences in working memory. Overall, when considering the composite episodic and working memory constructs, the speed composite accounts for four times more age-related variance on the criterion variables.

Overlap of Mediators

To investigate the possible role of each mediator in the age-differences of the other mediator, hierarchical regression analyses were conducted to examine the proportion of variance associated

Table 8. Proportions of shared age-related variance in mediator constructs

	Age alone R^2	After speed R^2 change	After dual task R^2 change
Dual task	.348*	.049* (.86)	—
Speed	.573*	—	.257* (.55)

Note. Speed = average of Letter Comparison and Pattern Comparison; dual task = composite of proportional ([single − dual]/single) decrement scores.

*Significant at the 0.01 level (two-tailed). Numbers in parentheses refer to the proportion of shared age-related variance among mediating and criterion variables.

with age in the retained attentional capacity measure after control of performance on the speed composite, and vice versa. The results are presented in Table 8 and reveal major attenuation (86%) in dual-task variance after controlling for processing speed; however, the remaining age-variance in the dual-task proportion decrement score was significantly greater than zero ($R^2 = .049$; $p < .01$). The attenuation in age-related speed variance was smaller (55%) for the proportion decrement score. Thus, these results support the conclusion of Salthouse et al. (1995) that the decrement in dual-task performance may be strictly an artifact of slower speed of processing. However, although the attenuation in age-related dual-task performance after control of speed performance is major, there is significant residual age-related dual-task variance that is independent of performance on the speed composite.

GENERAL DISCUSSION

The results of this study do not support the attentional capacity construct (measured as dual-task performance) as an independent mediator of age-related *episodic* memory change. Although the proportion decrement score attenuations are classifiable as "important" (Salthouse, 1992a), the attenuations were not independent of the processing speed estimates. Because there was no relationship found between dual-task performance and episodic memory performance independent of processing speed, the assertion that poorer memory performance with age may be attributed to age-related reductions in processing resources (e.g., Craik & McDowd's, 1987) is not supported. By contrast, performance on the processing speed composite accounted for almost as much age-related episodic variance (37% versus 45%) as dual-task performance *after* controlling for dual-task performance. Consequently, it is more parsimonious to interpret age-related differences in episodic memory in terms of processing speed. As such, the notion that processing speed ability might be a central factor in age-related episodic memory change is supported in the present study.

The second major conclusion based on these statistical control results is that both the attentional capacity and processing speed constructs can be viewed as major and independent mediators of age-related *working* memory change. The percentage attenuations of each mediator on the working memory composite measure are comparable (65% for speed of processing; 58% for attentional capacity proportion decrement score). Further, examination of the unique age-related working memory variance after control of each mediator reveals 17% additional variance accounted for by speed after statistical control of the dual-task proportion decrement score and 10% additional variance accounted for by the dual-task score after control for speeded performance. Consequently, a small proportion of the variance in these measures is independent in its overlap with age and working memory. There appears to be an age-sensitive aspect of the working memory tasks, independent of processing speed ability, that demands the attentional effort measured in a dual-task paradigm.

Finally, the results regarding the mediational potential of each processing resource with respect to the other provide strong evidence for substantial mediation of dual-task performance by speed of processing, whereas the reverse is not true. However, as there was significant residual age variance in the dual-task proportion decrement score, the notion of complete age-related dual-task mediation through processing speed ability is not supported.

The assessment of age-related decrements in dual-task performance is not currently governed by explicit mathematical and theoretical justifications for controlling for single-task performance. As described here, interpretations of dual-task performance changes with age depend on the control procedure used. When analyses on dual-task scores across different methods for controlling for baseline differences in single-task performance yield congruent results, strong conclusions can be made. However, Craik and McDowd (1987) observed only a marginally significant ($p = .10$) age-related effect of memory retrieval on a choice reaction time task (proportion decrement score) compared with a highly significant ($p < .005$) effect of age on the absolute difference score. Anderson, Craik, and Naveh-Benjamin (1998) also reported varying results. The present dual-task results were even more discrepant and thus lead to a more complicated and inconsistent interpretation of the valid magnitude of attentional effects.

If the proportion decrement score is deemed appropriate, this study provides some support for the validity of the attentional capacity construct as a mediator of *working* memory performance. However, these findings need to be replicated using the same as well as alternative measures of working memory. For example, the sentence verification component of Baddeley and Hitch's (1974) working memory task and of Daneman and Carpenter's (1980) working memory task was observed to be age sensitive by Morris et al. (1988) and by Gick, Craik, and Morris (1988), respectively. Thus, age differences on that aspect of the task should be uniquely predicted by independent measures of dual-task performance.

Craik and Salthouse (1992) identify five age-sensitive cognitive domains (i.e., attention, memory, knowledge representation, reasoning and spatial abilities, and language). Accepting that the proportion decrement score of dual-task costs reflects true age differences in attentional resources, future dual-task studies should examine the magnitude of shared variance among age, dual-task performance, and other age-sensitive cognitive domains. A processing resource is defined as a factor that is relevant for performance across a variety of cognitive tasks (Salthouse, 1991a). Broader application of the attentional capacity construct to multiple cognitive domains is needed with investigations of how limitations in attentional capacity influence cognitive performance.

Mediators and Mechanisms of Cognitive Aging

These data clearly demonstrate strong relations among memory, processing speed, and age. Nevertheless, caution is required when speculating about underlying cognitive mechanisms. This requirement primarily arises from two nonmutually exclusive sources. First, speculations regarding the underlying causal relationship when using regression-based analyses can be misleading. Although these data are consistent with the interpretation that slower speed of processing causes poorer cognitive performance with age, they do not directly provide evidence in support of this causal relationship. That is, evidence of shared relations do not, on their own, constitute evidence that a direct causal relationship exists. However, as Cohen and Cohen (1983) point out, "causation manifests itself in correlation, and its analysis can only proceed through the systematic analysis of correlation and regression" (p. 15). This notwithstanding, future research should attempt to develop methodologies that directly measure the causal influences mediating age-related changes in attentional capacity, processing speed, and cognition.

Second, there are a number of noncognitive variables that have also been shown to be related to age, which may or may not be directly related to attentional capacity and/or processing speed. These noncognitive variables range from simple physical metrics such as grip strength, blood pressure, and expiratory volume (e.g., Cook et al., 1995; Elias, D'Agostino, Elias, & Wolf, 1995) to more complex sensory processes such as visual and acoustic sensory processing (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Lindenberger, Scherer, & Baltes, 2001; Salthouse, Hambrick, & McGuthry, 1998). These findings have been taken to challenge the regression approach in general, and the processing speed as mediator approach in particular, as a general model of cognitive decline with age.

Concerning the simple physical variables (e.g., grip strength), numerous studies have demonstrated that processing speed accounts for significantly more variance of age-related cognitive decline than physical decline. For example, Salthouse (1993) compared measures such as time to copy numbers or letters (i.e., motor speed, reflecting "tasks with minimal cognitive requirements," p. 723) with timed cognitive measures requiring "cognitive or mental operation speed" (p. 736) or perceptual speed with respect to attenuation of age related cognitive variance. The results show an average attenuation of about 57% of age-cognition relations after control for performance on the motor measures, but 86% attenuation after control of performance on the perceptual speed tasks. In addition, in the current study, simple tapping speed (a measure of noncognitive motor performance) accounted for only 25% of age variance (see Appendix B). Taken together, these data provide support for processing speed as a stronger predictor of cognitive aging than the less cognitively involved simple physical variables.

In contrast to the simple physical variables such as grip strength, which typically show moderate age relations, more complex physical variables such as visual and auditory sensory processing have been shown to possess larger age relations. For example, Lindenberger, Baltes, and colleagues (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Lindenberger et al., 2001) have demonstrated in a number of studies that sensory processes such as degradation of hearing and vision can account for as large a percentage of cognitive declines with age as processing speed. Indeed, Salthouse et al. (1998) also noted that sensory processing and processing speed share a large amount of age-related variance. Furthermore, as is evidenced by the data contained within the current study, the cognitive criterion and mediator variables were all highly correlated and thus share a large amount of common variance (see Table 5). Based on these findings, one might speculate that the commonality may be attributed to broad general mechanisms that have an overarching physical, cognitive, and neuroanatomical basis. Theoretical advances on the relationship between working memory and episodic memory are consistent with this approach (see Park et al., 1996; Verhaeghen & Salthouse, 1997, for examples of how working memory mediates long-term memory performance). Further, as elucidated by Park et al., (1996) and demonstrated in this study, the relative contributions of indices of general processing resources (e.g., speed, attentional capacity, etc.) in explaining age-related changes in cognition (e.g., episodic memory) will vary as a function of the type of task and metric used to operationalize general processing resources and to measure the criterion and mediator variables.

One possible candidate for a broad general mechanism that has received much recent attention is executive processing (e.g., Salthouse, Atkinson, & Berish, 2003) and concomitant changes in frontal lobe function and structure as a function of age (e.g., Davidson & Glisky, 2002; Stuss, Craik, Sayer, Franchi, & Alexander, 1996; Van Petten et al., 2004). Here, numerous studies have linked working memory and episodic memory age-related changes to deficits in supervisory executive functioning and associated frontal lobes digenesis. Concerning the current data, one can envision a common role of executive processing in both the criterion variables (i.e., working memory and episodic memory) and the mediator variables (i.e., processing speed and attentional capacity). The degree to which processing speed either underlies, or is mediated by, executive processing is an important avenue for future research. To this end, combined behavioral and neuroimaging techniques may help elucidate the degree to which these processes are related by determining the degree to which they rely on common or unique underlying neural circuitry.

REFERENCES

Anderson, N. D., Craik, F. I. M., & Naveh-Benjamin, M. N. (1998). The attentional demands of encoding and retrieval in younger and older adults: 1. Evidence from divided attention costs. *Psychology and Aging*, *13*, 405–423.

Baddeley, A. D. & Hitch, G. J. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–90). San Diego, CA: Academic Press.

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

Bryan, J. & Luszcz, M. A. (1996). Speed of information processing as a mediator between age and free-recall performance. *Psychology and Aging*, *11*, 3–9.

Burke, D. M. & Light, L. L. (1981). Memory and aging. The role of retrieval processes. *Psychological Bulletin*, *90*, 513–546.

Cohen, J. & Cohen, P. (1983). *Applied multiple regression/correlation analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Cook, N. R., Albert, M. S., Berkman, L. F., Blazer, L. F., Taylor, J. O., & Hennekens, C.H. (1995). Interrelations of peak expiratory flow rate with physical and cognitive function in the elderly: MacArthur Foundation Studies of Aging. *Journal of Gerontology: Medical Sciences*, *50A*, 317–323.

Craik, F. I. M. (1983). On the transfer of information from temporary to permanent memory. *Philosophical Transactions of the Royal Society, London, Series B*, *302*, 241–359.

Craik, F. I. M. & Byrd, M. (1982). Aging and cognitive deficits: The role of attentional resources. In F. I. M. Craik & S. Trehub (Eds.), *Aging and cognitive processes* (pp. 191–211). New York: Plenum.

Craik, F. I. M. & McDowd, J. M. (1987). Age differences in recall and recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 474–479.

Craik, F. I. M. & Salthouse, T. A. (Eds.). (1992). *The handbook of aging and cognition*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Crawford, J. R., Parker, D. M., Stewart, L. E., Besson, J. A. O., & DeLacey, G. (1989). Prediction of WAIS IQ with the National Adult Reading Test: Cross-validation and extension. *British Journal of Clinical Psychology*, *28*, 267–273.

Crossley, M. & Hiscock, M. (1992). Age-related differences in concurrent-task performance of normal adults: Evidence for a decline in processing resources. *Psychology and Aging*, *7*, 499–506.

Crossley, M., Hiscock, M., & Foreman, J. B. (2004). Dual-task performance in early dementia: Differential effects for automatized and effortful processing. *Journal of Clinical and Experimental Neuropsychology*, *26*, 332–346.

Daneman, M. & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

Davidson, P. S. R. & Glisky, E. L. (2002). Neuropsychological correlates of recollection and familiarity in normal again. *Cognitive, Affective, & Behavioral Neuroscience*, *2*, 174–186.

Earles, J. L. & Coon, V. E. (1994). Adult age differences in long-term memory for performed activities. *Journal of Gerontology: Psychological Sciences*, *49*, P32–P34.

Elias, M. W., D'Agostino, R. B., Elias, P. K., & Wolf, P. A. (1995). Neuropsychological test performance, cognitive functioning, blood pressure, and age: The Framingham Heart Study. *Experimental Aging Research*, *21*, 369–391.

Gick, M. L., Craik, F. I. M., & Morris, R. G. (1988). Task complexity and age differences in working memory. *Memory & Cognition*, *16*, 353–361.

Guttentag, R. E. (1989). Age differences in dual-task performance: Procedures, assumptions and results. *Developmental Review*, *9*, 146–170.

Hartley, J. T. (1993). Aging and prose memory: Tests of the resource-deficit hypothesis. *Psychology and Aging*, *8*, 538–551.

Hasher, L. & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General*, *108*, 356–388.

Hasher, L. & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *The psychology of learning and motivation*, *22*, 193–225.

Henry, J. D., Crawford, J. R., & Phillips, L. H. (2005). A meta-analytic review of verbal fluency deficits in Huntington's disease. *Neuropsychology*, *19*, 243–252.

Johnston, W. A. & Heinz, S. P. (1978). Flexibility and capacity demands of attention. *Journal of Experimental Psychology: General*, *107*, 420–435.

Kahneman, D. (1970). Remarks on attentional control. *Acta Psychologia*, *33*, 118–131.

Kensinger, E. A., Piguet, O., Krendl, A. C., & Corkin, S. (2005). Memory for contextual details: Effects of emotion and aging. *Psychology and Aging*, *20*, 241–250.

Kerr, B. (1973). Processing demands during mental operations. *Memory and Cognition*, *1*, 401–412.

Knopman, D. S. & Ryberg, S. (1989). A verbal memory test with high predictive accuracy for dementia of the Alzheimer type. *Archives of Neurology*, *46*, 141–145.

Lindenberger, U. & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging*, *9*, 339–355.

Lindenberger, U., Scherer, H., & Baltes, P. B. (2001). The strong connection between sensory and cognitive performance in old age: Not due to sensory acuity reductions operating during cognitive assessment. *Psychology & Aging*, *16*, 196–205.

Macht, M. L. & Buschke, H. (1983). Age differences in cognitive effort in recall. *Journal of Gerontology*, *38*, 695–700.

Madden, D. J. (1990). Adult age differences in attentional selectivity and capacity. *European Journal of Cognitive Psychology*, *2*, 229–252.

McDowd, J. M. & Craik, F. I. M. (1988). Effects of aging and task difficulty on divided attention performance. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 267–280.

Morris, R. G., Gick, M. L., & Craik, F. I. M. (1988). Processing resources and age differences in working memory. *Memory and Cognition*, *16*, 362–366.

Navon, D. & Gopher, D. (1979). Task difficulty, resources, and dual task performance. In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 297–315). Hillsdale, NJ: Lawrence Erlbaum Associates.

Nelson, H. E. (1982). *National adult reading test*. Windsor, UK: Nfer-Nelson.

Park, D. C., Smith, A. D., Lautenschlager, G., Earles, J. L., Frieske, D., Zwar, M., & Gaines, C. L. (1996). Mediators of long-term memory performance across the life span. *Psychology and Aging*, *11*, 621–637.

Plude, D. J. & Hoyer, W. J. (1985). Attention and performance: Identifying and localizing age deficits. In N. Charness (Ed.), *Aging and human performance* (pp. 47–99). New York: Wiley.

Salthouse, T. A. (1980). Aging and memory: Strategies for localizing the loss. In L. W. Poon, J. I. Fozard, L. Cermak, D. Arenberg, & L. W. Thompson (Eds.), *New directions in memory and aging* (pp. 47–65). Hillsdale, NJ: Lawrence Erlbaum Associates.

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review*, *10*, 101–124.

Salthouse, T. A. (1991a). *Theoretical perspectives on cognitive aging*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Salthouse, T. A. (1991b). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science*, *2*, 179–183.
Salthouse, T. A. (1992a). *Mechanisms of age-cognition relations in adulthood*. Hillsdale, NJ: Lawrence Erlbaum Associates.
Salthouse, T. A. (1992b). Influence of processing speed on adult age differences in working memory. *Acta Psychologica*, *79*, 155–170.
Salthouse, T. A. (1993). Speed mediation of adult age differences in cognition. *Developmental Psychology*, *29*, 722–738.
Salthouse, T. A. (1994a). Aging associations: Influence of speed on adult age differences in associative learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*, 1486–1503.
Salthouse, T. A. (1994b). The nature of the influence of speed on adult age differences in cognition. *Developmental Psychology*, *30*, 240–259.
Salthouse, T. A. (1994c). How many causes are there of aging-related decrements in cognitive functioning? *Developmental Review*, *14*, 413–437.
Salthouse, T. A. (1994d). The aging of working memory. *Neuropsychology*, *8*, 535–543.
Salthouse, T. A. (1995a). Influence of processing speed on adult age differences in learning. *Swiss Journal of Psychology*, *54*, 102–112.
Salthouse, T. A. (1995b). Selective influences of age and speed on associative memory. *American Journal of Psychology*, *108*, 381–396.
Salthouse, T. A. (1995c). Differential age-related influences on memory for verbal-symbolic information and visual-spatial information. *Journal of Gerontology: Psychological Sciences*, *50B*, P193–P201.
Salthouse, T. A. (1996a). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403–428.
Salthouse, T. A. (1996b). General and specific speed mediation of adult age differences in memory. *Journal of Gerontology*, *51B*, P30–P42.
Salthouse, T. A. & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology*, *27*, 763–776.
Salthouse, T. A. & Kersten, A. W. (1993). Decomposing adult age differences in symbol arithmetic. *Memory and Cognition*, *21*, 699–710.
Salthouse, T. A. & Meinz, E. J. (1995). Aging, inhibition, working memory, and speed. *Journal of Gerontology: Psychological Sciences*, *50B*, P297–P306.
Salthouse, T. A., Atkinson, T. M., & Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology: General*, *132*, 566–594.
Salthouse, T. A., Fristoe, N., & Rhee, S. H. (1996). How localized are age-related effects on neuropsychological measures? *Neuropsychology*, *10*, 272–285.
Salthouse, T. A., Hambrick, D. Z., & McGuthry, K. E. (1998). Shared age-related influences on cognitive and noncognitive variables. *Psychology and Aging*, *13*, 486–500.
Salthouse, T. A., Kausler, D. H., & Saults, J. S. (1990). Age, self-assessed health status, and cognition. *Journal of Gerontology: Psychological Sciences*, *45*, P156–P160.
Salthouse, T. A., Fristoe, N., Lineweaver, T. T., & Coon, V. E. (1995). Aging of attention: Does the ability to divide decline? *Memory and Cognition*, *23*, 59–71.

Snow, W., Tierney, M., Zorzitto, M., Fisher, R., & Reid, D. (1989). WAIS-R test-retest reliability in a normal elderly sample. *Journal of Clinical & Experimental Neuropsychology*, *11*, 423–428.

Somberg, B. L. & Salthouse, T. A. (1982). Divided attention abilities in young and old adult. *Journal of Experimental Psychology: Human Perception & Performance*, *8*, 651–663.

Spreen, O. & Strauss, E. (1991). *A compendium of neuropsychological tests*. New York: Oxford University Press.

Stuss, D. T., Craik, F. I. M., Sayer, L., Franchi, D., & Alexander, M. P. (1996). Comparison of older people and patients with frontal lesions: Evidence from word list learning. *Psychology & Aging*, *11*, 387–395.

Tombaugh, T. N., Kozak, J., & Rees, L. (1999). Normative data stratified by age and education for two measures of verbal fluency: FAS and animal naming. *Archives of Clinical Neuropsychology*, *14*, 167–177.

Tun, P. A., Wingfield, A., Stine, C. A. L., & Mecsas, C. (1992). Rapid speech processing and divided attention: Processing rate versus processing resources as an explanation of age effects. *Psychology and Aging*, *7*, 546–550.

Van Petten, C., Plante, E., Davidson, P. S. R., Kuo, T. Y., Bajuscak, L., & Glisky, E. L. (2004). Memory and executive function in older adults: relationships with temporal and prefrontal gray matter volumes and white mater hyperintensities. *Neuropsychologia*, *42*, 1313–1335.

Verhaeghen, P. & Salthouse, T. A. (1997). Meta-analyses of age-cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. *Psychological Bulletin*, *122*, 231–249.

Wechsler, D. (1987). *Wechsler memory scale—revised manual*. San Antonio: Psychological Corporation.

Wickens, C. D., Braune, R., & Stokes, A. (1987). Age differences in the speed and capacity of information processing: A dual-task approach. *Psychology and Aging*, *2*, 70–78.

Appendix A. Mean continuous reaction time rates: Control and during letter fluency or serial subtraction by age decade

		Control		During letter fluency		During serial subtraction	
Age decade	*n*	*M*	*SD*	*M*	*SD*	*M*	*SD*
18–29	24	34.43	4.12	23.94	6.91	20.19	6.13
30 s	9	33.25	3.75	22.14	6.73	17.97	4.08
40 s	14	27.82	4.15	15.39	3.28	12.29	3.68
50 s	15	27.98	2.96	15.47	4.30	13.40	3.01
60 s	14	26.32	3.58	15.09	5.30	13.14	3.15
70 s	10	22.58	5.31	10.58	5.81	9.57	3.43
80 s	14	19.68	2.54	8.13	1.88	7.55	1.73

Note. Control age $R^2 = .640$ ($p < .01$).

Appendix B. Mean finger tapping rates: Control and during letter fluency or serial subtraction by age decade

		Control		During letter fluency		During serial subtraction	
Age decade	*n*	*M*	*SD*	*M*	*SD*	*M*	*SD*
18–29	24	90.70	12.15	82.03	13.96	83.13	13.84
30 s	9	90.14	17.20	84.19	15.88	84.08	15.93
40 s	14	84.64	15.77	76.36	16.92	75.46	18.57
50 s	15	89.88	10.58	78.03	12.70	78.58	12.25
60 s	14	83.25	13.46	73.02	19.16	69.14	20.85
70 s	10	71.13	15.07	57.28	24.86	55.03	26.79
80 s	14	67.88	11.38	39.00	20.00	38.00	17.42

Note. Control age $R^2 = .245$ ($p < .01$).

Appendix C. Mean letter fluency rates in the continuous reaction time series: Control and during continuous reaction time by age decade

		Control		During continuous reaction time	
Age decade	*n*	*M*	*SD*	*M*	*SD*
18–29	24	7.35	1.74	6.66	1.57
30 s	9	8.39	.89	7.03	1.61
40 s	14	7.11	2.27	5.86	1.55
50 s	15	8.03	2.00	6.75	1.49
60 s	14	7.11	1.70	5.88	1.79
70 s	10	6.50	1.89	5.40	1.32
80 s	14	6.64	1.68	4.95	1.33

Note. Control age $R^2 = .036$ ($p = .06$).

Appendix D. Mean letter fluency rates in the finger tapping series: Control and during finger tapping by age decade

		Control		During finger tapping	
Age decade	*n*	*M*	*SD*	*M*	*SD*
18–29	24	7.17	1.93	6.56	1.75
30 s	9	8.17	2.35	7.86	1.87
40 s	14	7.43	1.88	6.71	2.40
50 s	15	7.37	1.73	7.35	1.60
60 s	14	7.54	2.23	6.84	1.57
70 s	10	6.75	2.04	6.20	1.92
80 s	14	6.18	1.03	5.48	1.37

Note. Control age $R^2 = .027$ ($p = .10$).

Appendix E. Mean serial subtraction rates in the continuous reaction time series: Control and during continuous reaction time by age decade

		Control		During continuous reaction time	
Age decade	*n*	*M*	*SD*	*M*	*SD*
18–29	24	14.85	5.50	9.89	2.83
30 s	9	14.44	7.89	9.92	5.76
40 s	14	12.93	5.11	9.30	3.84
50 s	15	14.27	3.29	8.88	1.68
60 s	14	13.18	3.74	8.27	2.66
70 s	10	12.40	3.89	7.78	2.40
80 s	14	9.93	3.88	6.00	1.95

Note. Control age $R^2 = .090$ ($p < .01$).

Appendix F. Mean serial subtraction rates in the finger tapping series: Control and during finger tapping by age decade

		Control		During finger tapping	
Age decade	*n*	*M*	*SD*	*M*	*SD*
18–29	24	14.58	4.73	12.76	4.48
30 s	9	12.56	8.11	11.97	7.19
40 s	14	13.43	4.69	11.11	4.15
50 s	15	14.20	2.78	12.50	2.95
60 s	14	13.32	4.23	11.59	3.34
70 s	10	11.95	3.24	10.63	3.27
80 s	14	9.11	3.58	7.91	2.93

Note. Control age $R^2 = .010$ ($p < .01$).