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Mediators of Long-Term Memory Performance Across the Life Span

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An individual-differences approach was used to examine the component processes that predict episodic long-term memory performance. A total of 301 participants ages 20–90 received a 7-hr cognitive battery across 3 days. Key constructs hypothesized to affect long-term memory function were assessed, including multiple measures of working memory and perceptual speed. Latent-construct, structural equation modeling was used to examine the relationship of these measures and age to different types of long-term memory tasks. Speed was a key construct for all 3 types of memory tasks, mediating substantial age-related variance; working memory was a fundamental construct for free and cued recall but not spatial memory. The data suggest that both speed and working memory are fundamental to explaining age-related changes in cognitive aging but that the relative contributions of these constructs vary as a function of the type of memory task.

It is well documented that some aspects of memory function differ among adult age groups. Older adults show poorer performance on working memory tasks (Light & Anderson, 1985; Salthouse, 1991a), cued-recall tasks (Craik & McDowd, 1987; Park, Smith, Morrell, Puglisi, & Dudley, 1990), and free-recall tasks (Smith, 1979). Age differences have also often been found on word recognition tasks (Park & Puglisi, 1985; Park, Puglisi, & Sovacool, 1983) and spatial memory tasks (Cherry & Park, 1993; Cherry, Park, & Donaldson, 1993; Park, Cherry, Smith, & Lafranza, 1990), although some researchers have reported no age differences on these tasks (e.g., Sharps & Gollin, 1987). Finally, there are some types of memory processes for which age differences are very small, or not found at all, such as picture recognition (Park, Puglisi, & Smith, 1986; Smith, Park, Cherry, & Berkovsky, 1990), prospective memory (Einstein & McDaniel, 1990), and implicit memory (Light & Albertson, 1989; Park & Shaw, 1992).

There are competing hypotheses about the mechanisms underlying this pattern of findings (Light, 1991). Perhaps the leading hypothesis was proposed by Craik and Byrd (1982), who suggested that older adults had limited "mental energy" and were deficient in self-initiated processing. They noted that older adults performed most poorly on tasks with high processing demands, such as free recall, whereas tasks that demanded fewer resources, such as cued recall and recognition, showed smaller age differences. Their theorizing suggests that tasks such as picture recognition and implicit memory have very low resource demands, so age invariance occurs. Craik and Byrd's construct of mental energy, or processing resource, has frequently been operationalized as working memory (Baddeley, 1986). Working memory can be viewed as the amount of cognitive resource available to store new information and at the same time perform mental operations on either incoming or recently accessed information. Older adults do evince significantly poorer working memory function (Salthouse, 1991a; Salthouse & Babcock, 1991), and there is growing evidence that the age-related variance in many cognitive tasks may be largely mediated through working memory. Salthouse and his colleagues have consistently shown that working memory mediates age differences in a variety of reasoning and other cognitive tasks (e.g., Salthouse, 1991a, 1992a, 1992b, 1993a; Salthouse & Skovronek, 1992). In addition, Stine and Wingfield (1987) reported that working

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memory was associated with 44% of the age-related variance on a speech comprehension task. Hultsch, Hertzog, and Dixon (1990) found that working memory related to age differences in memory for text and words, and Morrell and Park (1993) found it to be a significant predictor of age-related variance on a complex procedural assembly task. Frieske and Park (1993) reported that working memory played a more important role in accounting for age-related variance in recognition of unorganized compared with organized pictures, and Cherry and Park (1993) found it to be an important mediator of age-related variance on a spatial memory task.

Another index of processing efficiency that has been hypothesized to underlie age-related memory differences is a decline in speed of processing. The speed hypothesis has been a pervasive one in the cognitive aging literature and is perhaps the most general of the three hypotheses described. A decrease in speed of processing has been suggested to be a general mechanism underlying age-related differences on virtually all cognitive tasks, including various forms of memory, as well as other abilities such as reasoning, spatial cognition, and fluid intelligence (Birren, 1965; Mayr & Kliegl, 1993; Salthouse, 1985, 1996). According to this view, age-related changes in speed could account for the relationship between working memory and recall.

The speed hypothesis has impressive support in the literature. Salthouse and Babcock (1991) attempted to measure and partition the components of working memory into storage, processing efficiency, and coordination components. They found evidence that processing efficiency (as measured by participants' ability to answer simple math and verbal comprehension questions) mediated most age-related variance in composite measures of working memory. They also reported, however, that age-related deficiencies in processing efficiency were mediated by measures of simple perceptual comparison speed. In their study, the outcome measure was working memory, so it is not known how working memory relates to long-term memory or to other cognitive measures.

In a later study, Salthouse (1993b) collected measures of both perceptual speed (measured by pattern and letter comparison tasks and number and letter transformation tasks) and motor speed (measured by marking and copying tasks) as well as measures of long-term memory in a large sample of adults of all ages. He reported that measures of perceptual speed were associated with 82.6% of the age-related variance in paired-associates learning and free recall. He did not measure working memory in this particular study. Even though previous research by Salthouse revealed working memory to be a primary factor contributing to age differences on cognitive tasks (for a review, see Salthouse, 1992b), he suggested that it is important in subsequent research to determine whether the relationship of speed to memory measures is direct or indirect and mediated through working memory. The finding of Salthouse and Babcock (1991) suggests that the indirect hypothesis is correct. In the present study, we evaluated measures of working memory and speed together to determine their relationships to one another and to measures of long-term memory.

Salthouse (1994) also examined the relationship of perceptual and motor speed to a broad range of cognitive variables. Participants, who were of all ages, were given unlimited time to complete some of the cognitive tasks. Despite the unlimited time, Salthouse reported that measures of perceptual speed were associated with 70–80% of the age-related variance in accuracy on spatial rotation, matrix reasoning, and associative memory tasks. Although Salthouse did not directly implicate working memory as a factor in the observed decrements, his argument suggests that the speed-of-processing variable exerts its effect through working memory. In the present study, we conducted a direct test of this hypothesis by evaluating the role of working memory and perceptual speed jointly on long-term memory.

Extending the work of Salthouse (1993b), Lindenberger, Mayr, and Kliegl (1993) examined the relationship of speed to measures of reasoning, memory, verbal fluency, and knowledge in a large sample of adults ages 60–90. They found that even in very advanced age, speed mediated performance on all measures of cognitive abilities. When the other cognitive abilities were substituted in structural equation models for speed, none of these models fit as well as the speed model. This study, however, did not include working memory as either a predictor or an outcome variable. It is not clear whether working memory would serve as a key mediating construct, in conjunction with speed, to predict the general cognitive abilities or whether it would merely serve as another indicator of general cognitive ability, with variance mediated by speed, an issue that we addressed in the present work.

Other work by Mayr and Kliegl (1993) and Kliegl, Mayr, and Krampe (1994) suggests that a simple speed model of age differences in cognitive function may not be adequate when tasks are more demanding of resources. Mayr and Kliegl found a dissociation of age effects when examining coordinative versus sequential processing complexity in a figural transformation task. They suggested that these represented two separate domains of interindividual differences, with sequential complexity associated with a speed factor and coordinative complexity associated with working memory, providing evidence for a two-factor model in contrast to a pure speed model. In a later study, Kliegl et al. reported that working memory was implicated in age differences associated with higher order tasks such as cued recognition and figural reasoning, but not tasks that focused on figural and verbal scanning. These two studies suggest that speed and working memory might independently contribute to age-related differences in memory function, a hypothesis we tested in the present study. Hultsch et al. (1990) also provided some confirmation of the notion that speed exerts its effect on measures of long-term memory through working memory, although they measured semantic and comprehension speed, rather than perceptual speed. Rabbitt (1993) and Nettelbeck and Rabbitt (1992) also presented evidence that substantial age-related variance in memory function is not accounted for by the construct of speed, suggesting that there is at least one other factor through which age operates.

To summarize, the combined work of Salthouse (1993b, 1994) and Lindenberger et al. (1993) strongly suggests that age differences in perceptual speed are associated with most of the age-related variance on cognitive tasks of many sorts, including memory. At the same time, none of these studies measured working memory, so they do not provide direct tests of the importance of working memory in mediating age-related variance in long-term memory function. Other recent work (Kliegl et al., 1994; Mayr & Kliegl, 1993; Nettelbeck & Rabbitt, 1992; Rabbitt, 1993) suggests that a two-factor model that includes both speed and working memory may be important, particularly for cognitive tasks that involve coordinative functions. The two-factor model has not been tested within the framework of structural equation modeling techniques or across a range of memory tasks. The purpose of the current study then, was to adopt an individual-differences approach to the study of memory and aging and simultaneously to evaluate leading hypotheses about mechanisms underlying memory differences with aging. To do this, we assessed the relationships of working memory, perceptual speed, and age to types of long-term memory function using latent-construct, structural equation modeling. The memory tasks selected for study varied in terms of how resource intensive they were conceptualized to be, with free recall designated the most resource-demanding task, followed by cued recall. Cued recall is assumed to involve less deliberate recollection or effort at retrieval because the cue paired with the to-be-remembered item at encoding is reinstated at retrieval to support retrieval. The third task, spatial recall, is assumed to be even less effortful than free and cued recall (Hasher & Zacks, 1979), and so we studied this as well as implicit memory, which is conceptualized to be almost resource free in both encoding and retrieval demands (Craik, 1986). Thus we hypothesized that the tasks represent a continuum of effort required at encoding and retrieval, with free recall being the least effortful, followed by cued recall, spatial recall, and implicit memory.

In addition to these constructs, we collected some additional measures, including measures of inhibitory function, which is a construct of some importance in the cognitive aging literature. Hasher and Zacks (1988) hypothesized that age-related differences in cognitive function may occur because older adults have a deficient inhibitory mechanism. This deficit limits their ability to encode relevant target information, because they tend to focus on irrelevant nontarget information. To examine the relationship of inhibitory function to memory performance, we collected two measures of negative priming developed by Tipper (1991) and Hasher, Stoltzfus, Zacks, and Rypma (1991), who considered negative priming effects to be evidence for effective inhibitory function. In addition, we collected measures of verbal ability (i.e., vocabulary) and the ability to perform verbal integration operations. Park, Smith, et al. (1990) suggested that the ability to integrate target information with contextual cues may be an important mechanism accounting for age-related deficiencies on memory tasks. They found older adults to be deficient in integration ability, as did Smith, Park, Earles, and Shaw (1990); Craik and Jennings (1992) also suggested that difficulties in integration operations may underlie age-related differences in memory. Thus this construct seemed worth investigating. Finally, we collected measures of ability to deal with interference (the Stroop task and a reading distraction task developed by Connelly, Hasher, & Zacks, 1991) to determine whether this construct was distinct from inhibition/suppression.

Method

Participants

A total of 301 persons participated in the study. They ranged in age from 20 to 90, with approximately the same number (40–54) of participants representing every decade, with the exception of the 80s, for which there only 23 participants. The participants were community dwelling and were recruited through advertisements placed in newspapers in Athens and Atlanta, Georgia, as well as from existing participant pools at the University of Georgia and the Georgia Institute of Technology. Detailed information about the participants is presented in Table 1. To be eligible for the study, participants had to have corrected vision of 20/30 as measured on a Snellen eye chart and had to pass a color vision screening test (Pseudo-Isochromatic Plates, 1983). Participants had to be willing to provide transportation to the laboratory site and to have a minimum education level of ninth grade.

As can be seen in Table 1, participants of both genders were represented in each decade and did not significantly differ in years of education, verbal ability (as measured by the Wechsler Adult Intelligence Scale—Revised [WAIS–R; Wechsler, 1981] Vocabulary subtest and the Shipley Institute of Living Scale [Shipley, 1986]), or perceived health. The proportion of African American participants was 13%, with ethnicity distributed approximately evenly across age groups. There was a significant effect of age on number of medications being taken, $F(6, 294) = 6.0, p < .001$, with the mean number of medications increasing from .18 in 20-year-olds to 1.87 in 80-year-olds. This participant profile is similar to that reported by Salthouse (1993b), who found that reported health was age invariant in his sample, but that medication use increased with age. Participants received $50 for their participation in this project.

Procedure

We tested participants over 3 days, the first 2 days consisting of individual testing conducted in 2-hr sessions and the third day consisting of group testing with groups of 6 or fewer. For the first 2 days of testing, most tasks were presented on a microcomputer. The third day of testing involved the administration of paper-and-pencil tasks and memory tests involving the presentation of slides. Testing on Day 3 required approximately 3 hr. Participants typically completed the first 2 days of testing on Monday and Wednesday or on Tuesday and Thursday, and then all people tested on these 4 days were scheduled together for the group testing on Friday. Each individual completed all of the testing within 1 week. The order of tasks, as well as testing session, was invariant across participants.

The tasks can be categorized as to whether they were used as indicators of predictor variables or as the outcome measures of memory functioning. We administered a total of 20 tasks across the 3 days. For the majority of the predictor variables, we collected 3 measures of each latent construct hypothesized to be relevant. The latent constructs and the tasks associated with them are described below. The order in which they were presented across sessions and the rationale behind it are described afterwards.

Predictor Variables

The constructs we considered to be potentially important predictors of memory function were working memory, speed, inhibitory function, integration, susceptibility to interference, and verbal ability.

Working memory. We measured working memory using three tasks: the WAIS–R (Wechsler, 1981) Backward Digit Span subscale, a reading span task, and a computation span task. The Backward Digit Span was a straightforward adaptation of the WAIS–R (Wechsler, 1981). The reading span task was adapted from Salthouse and Babcock (1991). We presented the task via computer and required that participants read a series of sentences aloud and answer a simple question about each sentence. At the same time, they were to remember the last word in the sentence just presented and hold this in their memory along with final words from previously presented sentences. Set size for the number of items to be held in memory began with one and increased to seven.

Table 1
Participant Characteristics by Age Group

Age group	*N*	% female	Age *M*	Age *SD*	Education[a]	Health[b]	Medications	WAIS-R	Shipley Institute of Living Scale
20–29	40	40	23.45	2.54	5.36	3.44	0.18	24.6	31.3
30–39	44	75	34.80	2.92	5.57	3.48	0.57	24.4	31.3
40–49	45	64	44.71	3.01	5.64	3.33	1.22	25.1	32.2
50–59	41	68	54.12	3.00	5.39	3.45	1.26	25.1	33.1
60–69	54	54	65.70	2.73	5.81	3.25	2.16	27.5	34.5
70–79	54	59	74.02	2.84	5.69	3.24	1.50	28.0	35.6
80–90	23	61	83.35	2.65	6.00	3.17	1.87	27.6	33.6

Note. WAIS-R = Wechsler Adult Intelligence Scale—Revised.
[a] Participants rated their educational level on the following scale: 1 = *less than 7th grade,* 2 = *8th grade,* 3 = *10th grade,* 4 = *high school degree,* 5 = *some college,* 6 = *college degree,* 7 = *graduate degree.* [b] Participants rated their health on a scale from 1 (*poor*) to 4 (*excellent*).

There were three problems at each level. The task ended when a participant made three consecutive errors. The reading span score was the total number of trials in which both processing and storage were correct up until the trial when the task was terminated.

The computation span task was also adapted from Salthouse and Babcock (1991). Participants saw a simple equation on the screen (e.g., 8 + 4 = ?). They were given three answers and selected the letter of the correct answer on the computer keyboard. At the same time, they were instructed to store in memory the last digit in the equation. After they had given the correct answer in a series of equations, we asked them to recall the string of final digits from the series of equations. The set sizes and number of trials were the same as for the reading span task.

Speed. We used three measures of speed: the Digit Symbol subscale from the WAIS-R and two measures developed by Salthouse and Babcock (1991)—letter comparison and pattern comparison. All were paper-and-pencil tasks.

In the Digit Symbol task, participants were presented with nine geometric figures (line, circle, *L* shape, etc.), each assigned a digit from 1 to 9. They were then shown a series of random digits from 1 to 9 and were to copy the symbol associated with that digit as rapidly as possible onto a scoring sheet. The dependent measure was the number of items completed in 90 s.

In the letter comparison task, participants were presented with pairs of letter strings that consisted of three, six, or nine letters. Their task was to compare the letter strings rapidly and decide whether the strings were the same or different, printing an *S* or *D*. They had 30 s to complete as many items as they could at each level (three, six, or nine letters). The dependent measure was the total number of correct decisions made in the three 30-s periods.

The pattern comparison task was identical to the letter comparison task, except that participants made decisions about whether geometric figures consisting of three, six, or nine line segments were the same or different. There were three 30-s trials, one at each level, and the dependent measure was the total number of correct decisions made in the three trials.

Inhibition. We collected two measures of inhibitory function using negative priming paradigms. One was based on a word-naming task used by Kane, Hasher, Stoltzfus, Zacks, and Connelly (1994), and the other we developed from a procedure involving pictorial presentation used by Tipper (1991).

In the word inhibition task, participants saw pairs of words on the screen, one word printed in red and the other in green. Their task was to name the green word as rapidly as possible and ignore the red word. Voice latency to respond was recorded. Inhibition or negative priming is demonstrated when, across large blocks of trials, there is a somewhat longer latency to name a green word if that word had just been a red word to be ignored on the previous trial. Inhibiting the red word on the first trial delays access to it on the next trial, where it serves as a target. Procedural details were nearly identical to those described by Hasher et al. (1991) and Kane et al. (1994).

The picture inhibition task was similar to that used by Tipper (1991). The main difference between this measure and the word inhibition task was that six concrete pictures from the Snodgrass and Vanderwart (1980) norms were presented as the stimulus set. The target picture was centered on a fixation point, and the picture to be ignored was to the left or the right of the fixation point. The practice block consisted of 15 naming trials. The experimental task had six blocks of 15 trials with control, ignore, and one-picture conditions interspersed within each block.

Integration. There were no standard measures available in the literature to measure the construct integration. In the present study, we defined integration as the participants' ability to provide linkages or mediators for two or more target items, so we used measures of the ability to develop such linkages, as well as the WAIS-R Similarities subscale.

We used a picture integration task based on Smith, Park, Earles et al. (1990) as a measure of participants' ability to integrate information from picture pairs. We presented participants with 36 pairs of concrete objects (taken from Park, Smith et al., 1990) for 15 s per pair and asked them to compose a sentence that integrated the two pictures. Half of the stimuli were related picture pairs, and half were unrelated. Using the scoring scheme developed by Smith et al., we rated the generated sentences on a scale of 0–3 for the quality of the integration.

The Remote Associations Test was developed by Mednick and Mednick (1967) and was conceptualized to be a measure of creativity. Participants were presented with three words that did not appear to be related (e.g., *poke, go, molasses*). The participant's task was to produce a fourth word that integrated them (e.g., *slow*).

The WAIS-R similarities subscale consisted of 14 pairs of words. The participant's task was to describe how the pairs were related. The adequacy of the response was scored from 0 to 2 according to the manual.

Interference. We used two measures of interference, both of which assessed participants' ability to ignore competing but irrelevant information. Both tasks relied on the highly automatized process of reading as the source of the irrelevant information.

Participants took the Stroop Color and Word Test (Golden, 1978). They read the words *red, green,* or *blue* when they were printed in incompatible ink colors and also said the color of ink in which a series of *xxxs* were printed. The dependent measure was a proportion that we calculated by dividing the number of Stroop color interference words named in 45 s by the number of colored *xxxs* named in 45 s.

In a reading distraction task modeled after Connelly et al. (1991), participants read stories in which words and phrases that were to be ignored were interspersed in italic with the target text, which was in a plain helvetica font. The dependent measure was the mean reading time required for these stories subtracted from the mean reading time required for stories without the distracting information.

Verbal ability. To assess verbal ability, we administered the WAIS–R Vocabulary test; the Vocabulary section of the Shipley Institute of Living Scale (Shipley, 1986); and an opposites test, adopted from the *Scholastic Aptitude Test (College Entrance Examination Board, 1990)* and developed with permission from the Educational Testing Service. A total of 32 multiple-choice items were presented.

Outcome Measures

We collected four memory measures that we assumed varied in the amount of self-initiated processing required. We assumed that the most processing-intensive task was free recall, followed by cued recall, spatial recall, and a test of implicit memory.

Free recall. Participants received two lists of 25 different words. Within each set of 25 words, there were five categories of words and five exemplars presented per category taken from the Battig and Montague (1969) word norms. Categories were selected from the norms that had 30 or more different items generated by 10 or more participants, with the first 3 responses eliminated (to prevent guessing). The words were presented via a slide projector for 5 s each. We instructed participants to study the words and told them they would be free to recall the words in any order. Recall occurred after each list was presented. The primary dependent measure was the total number of words recalled for each list.

Cued recall. Participants received two lists of 22 different word pairs. For 22 of the target words, the Thorndike and Lorge (1944) frequency counts ranged from 100 to 333, and the other 22 had frequencies of 1,000–3,333. Frequency was balanced across the two lists. We selected a weak associate for each target word from Postman and Keppel's (1970) word norms.

We presented the word pairs on slides at a 5-s rate with the cue in small letters and the target in capital letters. Participants received examples before the experimental trial, and the nature of the retrieval task was demonstrated to them. After each set of words was presented, each cue was presented again for 8 s, and the participants' task was to write down the target associated with it. The dependent measure was the number of target items correctly recalled to cues for each list.

Spatial recall. The procedure for this task was modeled after Park et al. (1983). Participants received 24 words for 5 s each via a slide projector. Each word was located in one of four quadrants on the slide (upper left, lower left, upper right, and lower right). To increase the likelihood that spatial memory would involve minimal self-initiated processing, we did not instruct participants to study location. After acquisition, participants received each word, in a new order, centered on the slide. Their task was to indicate on a 2 × 2 matrix printed in their response book in which quadrant they recalled seeing the word. The dependent measure was the proportion of spatial locations correctly recalled.

Implicit memory. Participants received a stem completion task. The stimuli used were taken from Park and Shaw (1992), and the procedure used was identical to the structural processing task they described for implicit memory. We gave participants a structural processing task for 36 target items. After this, we gave them several distractor tasks and then the stem completion task. Half the items were the target items, and half were nonpresented baseline items. The dependent measure was the number of target items correctly completed minus the number of baseline items correctly completed.

Order of Task Presentation

We presented the tasks in an invariant order. The first 2 days were primarily computer presentations, with a few paper-and-pencil tasks interspersed, as noted below. The third day entailed group testing with stimuli presented via slides or paper-and-pencil tasks. Participants received liberal breaks during all sessions.

On Day 1, participants completed the measures in the following order: (a) the picture integration task, (b) negative priming of pictures, (c) the computation span, (d) the reading distraction task, (e) the WAIS–R Vocabulary subscale, and (f) a demographics questionnaire.

The order of tasks for Day 2 was as follows: (a) the WAIS–R Backward Digit Span subscale, (b) the WAIS–R Similarities subscale, (c) negative priming of words, (d) an awareness questionnaire about the negative priming task, (e) the reading span, (f) the WAIS–R Digit Symbol Substitution subscale, (g) the Stroop task, and (h) the letter comparison task.

The order of tasks for Day 3 was as follows: (a) implicit memory, (b) cued recall, (c) the Shipley Vocabulary test, (d) the pattern comparison task, (e) the opposites test, (f) free recall, (g) the Remote Associations Test, (h) spatial recall, and (i) an awareness questionnaire for the implicit test.

Results

Overview

Preliminary analyses indicated that some of the measures we collected were not suitable for use in measurement models and structural equation modeling. Regrettably, both the inhibition measures and the measure of implicit memory were not suitable for even preliminary inclusion in the development of a measurement model. Negative priming was obtained on the word inhibition task and on the Tipper (1991) picture inhibition task. However, neither the word measure nor the picture measure was reliable, and neither measure had a significant relationship to any other predictor or outcome measure we collected. Thus we did not use the construct inhibition to develop the measurement model. We also had to discard the implicit memory measure, because performance was at floor on the task, with priming rates of 3.6%, so there was insufficient variance in the measure to use it as an outcome measure. Implicit memory was unrelated to any other measure, and the reliability of the measure was only .04.

The constructs that remained for use in the development of a measurement model were speed, working memory, interference, integration, verbal ability, free recall, cued recall, spatial recall, and age. We conducted preliminary analyses on these constructs in the development of a measurement model using a sequential estimation strategy similar to that described by Jöreskog (1993, p. 313). Initial results indicated that the constructs interference, integration, and verbal ability were not suitable for further analysis. The interference and integration constructs were not supported from the indicators we used. In addition, two indicators of the verbal construct proved factorially complex in the measurement models examined. Because of the peripheral nature of the verbal construct, we decided it was best to exclude it. Thus, after these initial analyses, the constructs that remained for inclusion in the development of a measurement model and subsequent structural equation models were speed, working memory, free recall, cued recall, and spatial memory, along with age. It is beyond the scope of the present article to provide detailed information about measures and constructs not used in the measurement and structural equation models. Readers interested in obtaining more detailed information

Table 2
Task Reliability Estimates

Construct/task	Method	Reliability estimate
Speed		
WAIS-R Digit Symbol	Test-retest	.82
Letter comparison	Split half	.94
Pattern comparison	Split half	.94
Working memory		
WAIS-R Backward Digit Span	Test-retest	.83
Computation span	Split half	.90, .84[a]
Reading span	Split half	.86, .86[a]
Free recall	Split half	.85
Cued recall	Split half	.86
Spatial recall	Odd-even	.48

Note. Reliabilities for Backward Digit Span and Digit Symbol were estimated by Wechsler (1981). Reliabilities for computation span, reading span, letter comparison, and pattern comparison were estimated by Salthouse and Babcock (1991). All other reliabilities were estimated using the data from the present study. WAIS-R = Wechsler Adult Intelligence Scale—Revised.
[a] Reliability estimates from Study 1 and Study 2 of Salthouse and Babcock (1991).

about participants' performance on these tasks should contact Denise C. Park. (Salthouse and Meinz, 1995, have already incorporated the Stroop measures collected in this study into an analysis of the relationships among age, inhibition, working memory, and speed.)

Measurement Reliability

Table 2 summarizes the estimates of measurement reliability for all of the measures considered further. We obtained the estimates from a range of sources. For the computation span and reading span measures of working memory, we provide reliability estimates collected by Salthouse and Babcock (1991). Because of the stepped, self-terminating procedure we used to assess working memory in the present study, we could not use odd–even reliability estimates or split-half estimates and for this reason adopted the Salthouse and Babcock norms as the best estimate available. We also used Salthouse and Babcock norms for reliability estimates for the pattern and letter comparison tasks, to avoid the need for test–retest comparisons. Our procedures for these tasks were nearly identical to theirs.

Descriptive Statistics and Missing Data

Of the 301 participants, 92.7% ($n = 279$) provided complete data for all measures used in the confirmatory analyses. Missing data resulted from failure to respond to instructions or failure to complete a task. Because there was no discernible pattern of missing data on these measures, we estimated missing data with a regression approach using available data from measures within each affected construct (Lindenberger et al., 1993, p. 211). Table 3 presents the correlations of variables used in the measurement and structural models after missing data were estimated. The table also contains standard deviations for the variables. We also conducted analyses using listwise deletion of cases missing data and obtained the same pattern of results.

Age and Task Performance

Participants' performances on the dependent measures, transformed into z scores using the entire sample, are reported in Table 4. We performed regression analyses for each measure using age and the value of age^2 as predictors. The results of these analyses are presented in Table 4. All measures had significant linear relationships with age, and the three measures of speed also had a relation to the age^2 component, as a result of a more pronounced decrease in performance in very late adulthood. It should be noted that these nonlinear effects each accounted for little additional variance and were limited to the measures of perceptual speed.

Measurement Model

An initial measurement model based on the constructs speed, working memory, free recall, cued recall, spatial memory, and the linear and quadratic effects of age is presented in Figure 1. Correlations among these latent constructs are presented in Table 5, and a summary of fit of this measurement model, as well as others tested, is presented in Table 6. We wish to note that in order to treat free recall and cued recall as latent constructs, we had to use the List 1 and List 2 data for each measure as separate indicators of the construct. Because there was only a single indicator of spatial memory, we fixed the error term for this indicator to a value reflecting the estimated unreliable variance of the spatial measure. We recognize that in a pure sense, even using two indicators is not statistically sufficient to identify a construct. We believe, however, that the indicators we used for these recall constructs present unusually clear conceptual, operational, and historical links to the constructs of interest. Therefore, we believe there is little risk that these measures did not assess the different forms of recall they were intended to assess.

The first measurement model (Model 1 in Table 6) examined the possibility that there was a particularly steep decline in performance in the oldest adults, because there was evidence for a significant quadratic trend in this direction on the letter comparison task, the Backward Digit Span subscale, and free recall. Although Lindenberger et al. (1993) did test for nonlinear effects in their sample and did not find them, the age range of the individuals they studied was limited to 70–100 years old. Because of the initial evidence for quadratic trends (Table 4) and because the age range in our study differed from that in Lindenberger et al.'s study, we tested for quadratic effects due to age. Evidence for a significant quadratic trend for age (referred to as age^2) in the measurement model would provide evidence for precipitous decline in late adulthood. To assess the presence of nonlinearity, we constrained the covariance of age with age^2 to zero. We created the quadratic trend for age (age^2 in Table 6) as a residual after age^2 was regressed on age. We subtracted the predicted value of age^2 from this model from the actual age^2 value, creating a residual that was unconfounded with linear age and reflected only quadratic aspects of age.

Although the fit of this initial measurement model seemed

Table 3
Correlation Matrix Used in Measurement and Structural Models

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Age	—												
2. Age^2	.00	—											
3. WAIS-R Digit Symbol	−.63	−.09	—										
4. Pattern comparison	−.65	−.11	.68	—									
5. Letter comparison	−.63	−.09	.71	.73	—								
6. Computation span	−.36	−.09	.43	.43	.42	—							
7. Reading span	−.37	−.05	.37	.39	.40	.63	—						
8. WAIS-R Backward Digit Span	−.20	.03	.31	.33	.43	.42	.51	—					
9. Free1	−.38	−.10	.51	.49	.51	.41	.47	.41	—				
10. Free2	−.39	−.08	.47	.48	.51	.43	.49	.38	.76	—			
11. Cued1	−.34	−.02	.37	.32	.37	.35	.40	.34	.60	.55	—		
12. Cued2	−.30	.02	.35	.33	.38	.38	.40	.35	.65	.59	.76	—	
13. Spatial memory	−.15	−.01	.22	.16	.22	.16	.19	.23	.42	.36	.40	.39	—
SD	19.03	327.30	414.94	12.67	8.63	3.35	2.94	2.38	4.65	4.45	4.77	4.91	3.37

Note. For 22 participants we estimated missing data on some variables. WAIS-R = Wechsler Adult Intelligence Scale—Revised; Free1 = free recall list 1; Free 2 = free recall list 2; Cued1 = cued recall list 1; Cued2 = cued recall list 2.

reasonable, we decided to examine whether the age^2 term was necessary, apart from a possible association with the speed construct. In this second model (Model 2 in Table 6), we constrained the covariances of the age^2 term with all other constructs except speed to zero. This produced a model that, when compared with Model 1, produced an insignificant change in fit, suggesting that age^2 was unrelated to other model constructs besides speed.

To examine whether the effects of age^2 were reliably related to speed, we decided to test another measurement model in which all covariances of the age^2 term with other constructs were constrained to zero. This model was not a significantly worse fit than either Model 1 or Model 2, suggesting that age^2 was not related to the other model constructs. This finding may seem somewhat contrary to the results of the regression analysis, in which each speed measure was related to age^2, in that we now report that the shared common variance of the speed measures was not found to be related to the age^2 term in the measurement model. This is likely because sufficient unique variance in one or more of the measures of speed was related to age^2.

Therefore, we tested a fourth model (Model 4 in Table 6) that simply eliminated the age^2 term altogether. This model produced an adequate fit to the data. On the basis of this model, we retained the constructs speed, working memory, free recall, and cued recall, along with the variables of spatial memory and age, for the testing of the structural equation models.

Structural Equation Models

Before developing a more complex model, we tested an individual model for each of the three types of memory—free recall, cued recall, and spatial recall. This procedure permitted us to determine whether the constructs age, speed, and working memory related to each of the memory variables in a similar or different fashion.

Table 4
Task Performance for Each Age Group

Task	20s	30s	40s	50s	60s	70s	80s	R^2_{Linear}	F^a	$R^2_{\text{Quadratic}}$	F^b
Speed											
WAIS-R Digit Symbol	.90	.65	.29	.05	−.33	−.61	−1.25	.402	201.27**	.009	4.49*
Pattern comparison	.99	.53	.26	.18	−.27	−.67	−1.48	.424	220.09**	.012	6.24*
Letter comparison	.88	.74	.21	.03	−.34	−.53	−1.38	.396	195.90**	.008	3.96*
Working memory											
Computation span	.42	.54	.07	−.08	−.03	−.35	−.88	.127	43.50**	.008	2.66
Reading span	.58	.36	.16	−.06	−.13	−.31	−.85	.140	48.54**	.002	0.86
WAIS-R Backward Digit Span	.52	−.07	.16	−.08	−.11	−.04	−.60	.040	12.38**	.000	0.21
Memory											
Free recall	.62	.33	.24	−.07	−.18	−.18	−1.19	.165	59.28**	.010	3.36
Cued recall	.61	.34	.12	−.23	−.15	−.20	−.74	.117	39.72**	.000	0.01
Spatial memory	.29	.19	−.07	.05	−.09	−.16	−.25	.024	7.21	.000	0.02

Note. WAIS-R = Wechsler Adult Intelligence Scale-Revised.
[a] Degrees of freedom were 1 and 299 for all linear effects. [b] Degrees of freedom were 1 and 298 for all incremental quadratic effects.
$^*p < .05$. $^{**}p < .01$.

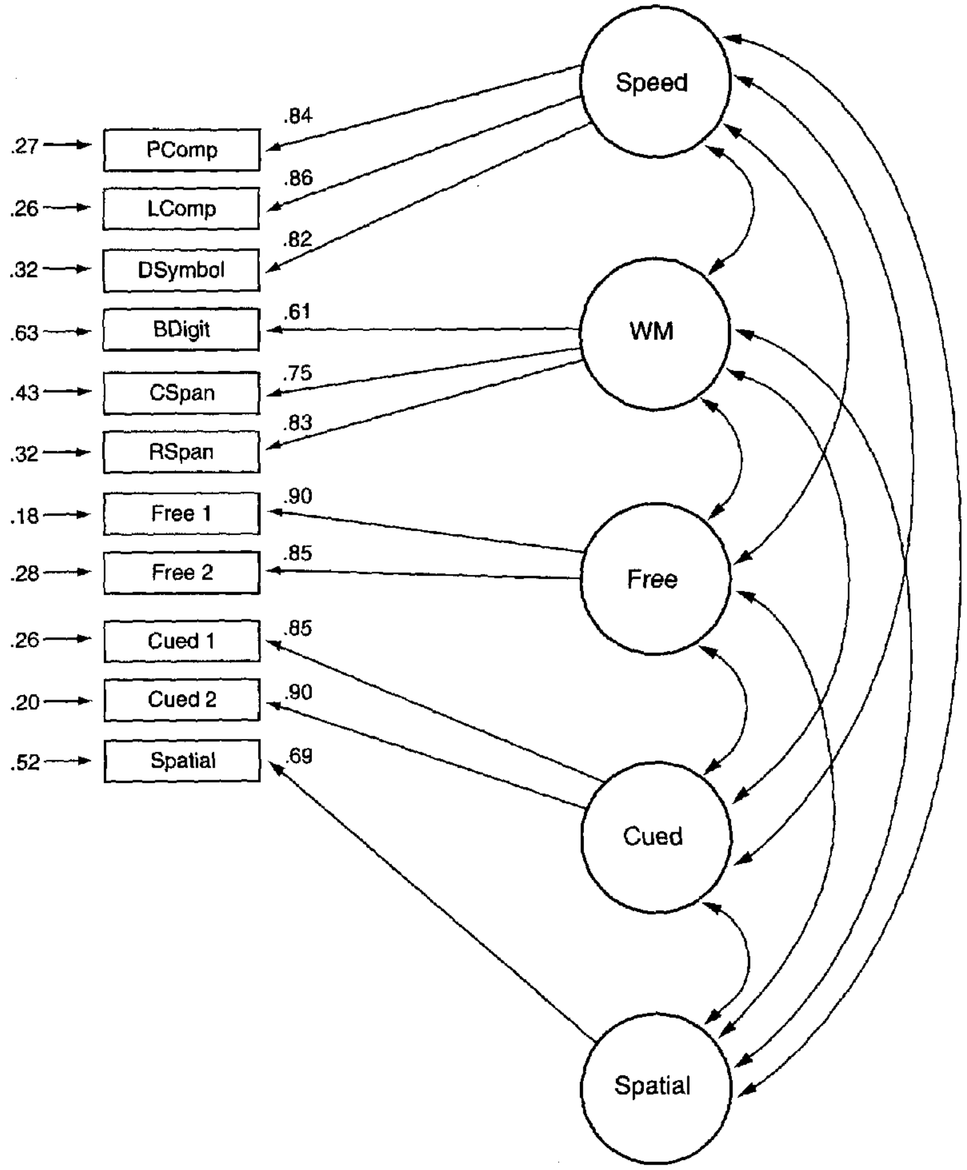

Figure 1. A hypothesized measurement model that includes speed, working memory (WM), free recall, cued recall, and spatial memory constructs with coefficients obtained from a confirmatory factor analysis. PComp = pattern comparison; LComp = letter comparison; DSymbol = Digit Symbol; BDigit = Backward Digit Span; CSpan = Computation Span; RSpan = Reading Span; Free 1 = free recall list 1; Free 2 = free recall list 2; Cued1 = cued recall list 1; Cued 2 = cued recall list 2.

Table 5
Correlations Between Latent Constructs

Construct	1	2	3	4	5	6	7
1. Speed	—						
2. Working memory	.61	—					
3. Free recall	.67	.66	—				
4. Cued recall	.48	.57	.79	—			
5. Spatial memory	.35	.35	.66	.65	—		
6. Age	−.76	−.44	−.43	−.36	−.22	—	
7. Age^2	−.11	−.06	−.11	.01	−.01	.00	—

Because several alternative models were plausible, and because we hypothesized that the relationships among the constructs would not be the same for each type of memory, we fit four nested structural equation models for each type of memory and determined the model of best fit among these four. The basic model and the three variations associated with it are shown in Figure 2. The basic model (Model A in Figure 2) suggests that all age-related variation in memory is mediated by speed and that the effect of speed is partially mediated through working memory. Moreover, speed and working memory, but not age, independently contribute to memory. The second model

Table 6
Summary of Measurement Model Fitting

Model	χ^2	*df*	*p*	NNFI	CFI	RMSEA
Model 1	70.36	48	.019	.98	.99	.04
Speed, working memory, free recall, cued recall, spatial memory, age, age^2 (age^2 correlated with all but age)						
Model 2	77.30	52	.013	.98	.99	.04
Speed, working memory, free recall, cued recall, spatial memory, age, age^2 (age^2 correlated only with speed)						
Compare with Model 1	6.94	4	>.05			
Model 3	81.00	53	.008	.98	.99	.04
Speed, working memory, free recall, cued recall, spatial memory, age, age^2 (age^2 uncorrelated with any constructs)						
Compare with Model 2	3.70	1	>.05			
Model 4	63.96	41	.012	.98	.99	.04
Speed, working memory, free recall, cued recall, spatial memory, age (age^2 omitted)						

Note. *N* = 301 for all models. NNFI = Nonnormed goodness-of-fit index: CFI = comparative fit index: RMSEA = root-mean-squared error of approximation.

(Model B in Figure 2) adds an independent path from age to memory, and the third model (Model C in Figure 2) differs from Model A in that it includes an additional independent path from age to working memory, suggesting that not all age-related variance is directly mediated through speed, as Mayr and Kliegl (1993) have proposed for cognitive tasks requiring coordinative operations. Finally, Model D differs from Model A in that the direct path from working memory to memory is removed, so that only speed makes a direct contribution to memory performance.

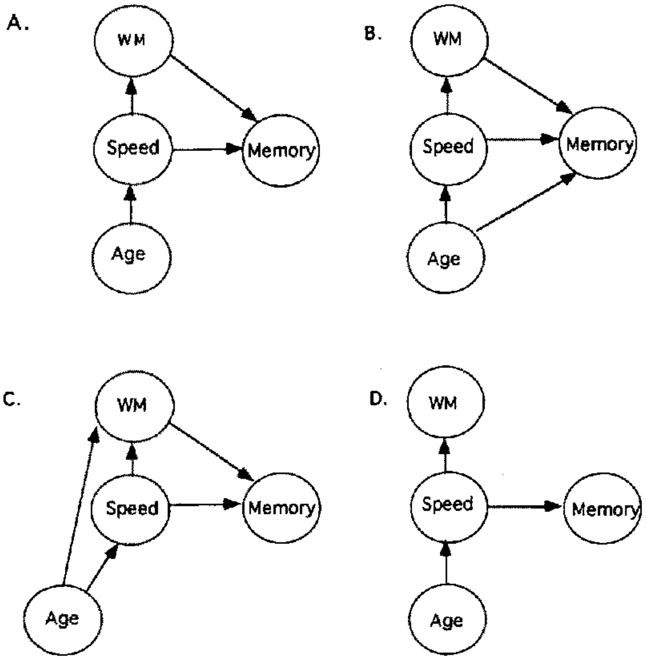

Figure 2. A summary of the structural equation models evaluated for each type of memory. Model A is the basic model, Model B adds a path from age to recall, Model C adds a path from age to working memory (WM), and Model D removes the path from working memory to recall.

The fit of each of these models for each of the three types of memory is presented in Table 7. For each type of memory, Table 7 presents the fit of a correlated-factors model, followed by the basic model. Then the fit of each variant of the basic model is presented, along with a test for the difference between the basic model and alternative models. When the fits of the two models were equivalent, we accepted the simpler model as the model of best fit. For free recall, the model of best fit was Model A, the basic model. In this model, all age-related variance is mediated by the speed construct. There is a strong negative path from age to speed, with speed then positively related to working memory. Both working memory and speed have positive relationships to free recall. It should be noted that although the chi-square was slightly lower for Model B, the direct path from age to free recall was not significant, so Models A and B are actually comparable. Similarly, Model C, a more complex model, did not significantly differ from Model A. With respect to cued recall, the model of best fit was again the basic model. (We discuss direct comparisons across models of cued recall and free recall momentarily when we present a more complex structural equation model.) Finally, for spatial recall, the direct contribution of working memory to the memory outcome measure dropped out. As Table 7 indicates, the model of best fit was Model D, a model in which there is no direct contribution of working memory to spatial memory.

Figure 3 presents a final model that includes all three memory measures as separate outcome variables within a single structural equation model. This model permitted direct comparisons among the three types of memory measures. We formed this model by merging together the models with the best fits for the memory measure individually. In tests leading to this model, there was evidence for substantial covariance among the memory factors free, cued, and spatial recall that was not explained by age, speed, or working memory. After a detailed assessment of model misfit, we decided to address

Table 7
Summary of Model Fitting for Structural Models

Model	χ^2	*df*	*p*	RMSEA	CFI	NNFI
Free recall						
CF: Correlated factors	47.82	22	.001	.06	.98	.97
IF: Independent factors	1,511.85	36	<.001			
A: Basic model (see Figure 3)	51.70	24	<.001	.06	.98	.97
Compare with Model CF	3.88	2	>.05			
B: Add direct path from age to recall	48.13	23	.001	.06	.98	.97
Compare with Model A	3.57	1	>.05			
C: Add direct path from age to working memory	51.18	23	.001	.07	.98	.97
Compare with Model A	.52	1	>.05			
D: Remove path from working memory to recall	84.31	25	<.001	.09	.96	.94
Compare with Model A	32.61	1	<.001			
Cued recall						
CF: Correlated factors	48.52	22	.001	.06	.98	.97
IF: Independent factors	1,428.94	36	<.001			
A: Basic model (see Figure 4)	49.03	24	.002	.06	.98	.97
Compare with Model CF	.51	2	>.05			
B: Add direct path from age to recall	48.93	23	.001	.06	.98	.97
Compare with Model A	.10	1	>.05			
C: Add direct path from age to working memory	48.67	23	.001	.06	.98	.97
Compare with Model A	.36	1	>.05			
D: Remove path from working memory to recall	76.22	25	<.001	.08	.96	.95
Compare with Model A	27.19	1	<.001			
Spatial recall						
CF: Correlated factors	44.74	16	<.001	.08	.97	.95
IF: Independent factors	1,094.26	28	<.001			
A: Basic model (see Figure 5)	45.49	18	<.001	.07	.97	.96
Compare with Model CF	0.75	2	>.05			
B: Add direct path from age to recall	45.11	17	<.001	.07	.97	.96
Compare with Model A	0.38	1	>.05			
C: Add direct path from age to working memory	45.10	17	<.001	.07	.97	.96
Compare with Model A	0.39	1	>.05			
D: Remove path from working memory to recall	49.01	19	<.001	.07	.97	.96
Compare with Model A	3.52	1	>.05			

Note. N = 301 for all models. RMSEA = root-mean-square error of approximation; CFI = comparative fit index; NNFI = nonnormed goodness-of-fit index.

this issue by allowing the residuals of the memory factors to intercorrelate. This seemed the most appropriate course, because our theorizing did not specify how these memory factors might be causally related to one another. Thus, Figure 3 shows direct paths of speed to all measures of memory, as in the individual models, and a direct path of working memory to free recall and cued recall but not spatial memory. This model, as shown in Figure 3, had acceptable fit, $\chi^2(46) = 74.11$, $p < .006$, nonnormed goodness-of-fit index = .98, comparative fit index = .99, and root-mean-square error of approximation = .05. It should also be noted that we tested a path from age to working memory for this model and found it not significant.

To elaborate the information presented in this model, in Table 8 we present standardized total effects for the model presented in Figure 3. As the data indicate, age and speed had the largest total effect on free recall and the smallest such effect on spatial recall. This finding suggests that age and speed had a greater impact on a memory measure typically conceptualized to be more resource intensive.

A summary of the structural equation modeling suggested the following. First, acceptable fit for all three measures of memory performance was achieved using the constructs age, speed, and working memory. Second, the different types of memory measures did not appear to represent a unitary construct, because they related differently to spatial memory than to free and cued recall. Third, the nature of the relationships of the constructs to memory was orderly and theoretically plausible. Free recall is typically viewed as a more resource-demanding task than cued recall, so it makes sense that more variance would be associated with the resource-based constructs speed and working memory. The constructs' relationship to spatial memory differed from their relationships to free and cued recall, as theoretical models would predict. Working memory, which had a direct path to cued and free recall, did not exert a direct effect on spatial recall, a type of memory conceptualized

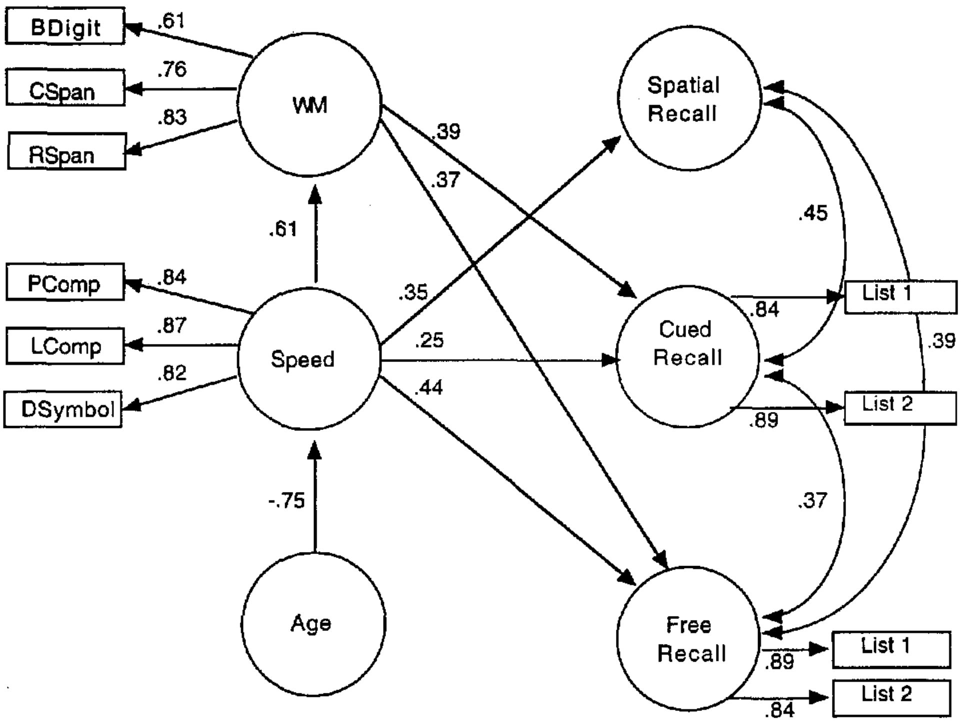

Figure 3. A model that represents all three types of memory—free recall, cued recall, and spatial recall—and the relationships of speed, working memory (WM), and age to them. For each path, the standardized path coefficient is presented. All paths shown were statistically significant. BDigit = Backward Digit Span; CSpan = Computation Span; RSpan = reading span; PComp = pattern comparison; LComp = letter comparison; DSymbol = Digit Symbol. List 1 = recall list 1; List 2 = recall list 2.

to be relatively low in effort, if not automatic (Hasher & Zacks, 1979). The effects of both age and working memory on spatial memory were mediated through speed alone.

Comparison of the Present Data With Salthouse's (1993b) Data

Because Salthouse (1993b) also included measures of speed, memory, and free recall in his study, we compared the fit of his data to the model developed in the present study. It is always desirable to examine the generalizability, or cross-validation, of models, and one way to do so is to inspect the fit of a model on another, independent data set. For this reason, we developed two additional structural equation models that examined the role of age and speed on free recall, comparing data from the present study with Salthouse's data. The measures of speed were the same in the two studies, although the measures of free recall were quite different (Salthouse used 12 words presented at a 2-s rate, whereas we presented participants with 25 words at a 5-s rate). Nevertheless, the models compared favorably, the only difference being that the direct path from age to free recall was negative in the Salthouse data ($p = .05$), whereas ours was weakly positive ($p = .06$). These two models are represented in Figure 4, and the summary statistics for them are reported in Table 9. We hypothesized that the unusual positive relationship we observed from age to free recall was due to the possibility that participants' higher than average vocabulary ability positively influenced free recall. We found that the use of verbal ability as a control variable resulted in the path from age to free recall's becoming negative and significant, in a manner consonant with Salthouse. Although the original path was of marginal significance, we report this because these findings provide some fascinating evidence as to how resource deficits in older adults that result in memory deficits might be moderated by crystallized knowledge.

Table 8
Total Standardized Effects for Combined Structural Model

Memory construct	Age	Speed	Working memory
Free recall	−.50	.62	.38
Cued recall	−.37	.45	.38
Spatial recall	−.26	.35	

Note. Total effects = direct effects + indirect effects.

Speed as a Mediator of General Memory Ability

The models presented thus far suggest that both speed and working memory are important constructs in understanding age-related variance in memory performance and that the relative contributions of these constructs vary as a function of the type of memory under consideration. An alternative approach

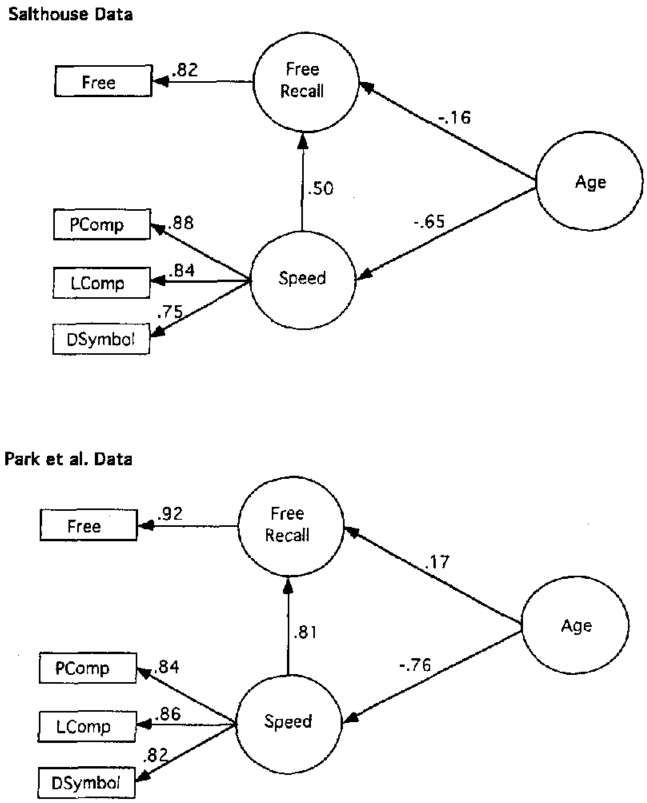

Figure 4. Two models (from Salthouse, 1993b, and the present data) that present the relationship of speed and age to free recall. For each path, the standardized path coefficient is presented. All paths shown were statistically significant. PComp = pattern comparison; LComp = letter comparison; DSymbol = Digit Symbol.

to treating the three types of memory as indicators of individual constructs with different resource requirements is to conceptualize the various types of memory as indicators of a general memory construct. Such an approach was taken by Lindenberger et al. (1993), who treated the individual constructs of reasoning, memory, fluency, and knowledge as indicators of general cognitive ability. They reported that speed alone was a central mediator of age-related variance in such a model and that when the other measures of cognitive ability were individually substituted in the role of central mediator, they showed very poor fit. This provided compelling evidence for speed as a general mediator of age-related variance in cognitive abilities. However, because Lindenberger et al. did not include measures of working memory in their study, we do not know whether working memory might play a joint role with speed as a mediator of general ability, as the models presented thus far would suggest, or whether it might simply serve as another indicator of general ability. The work of Mayr and Kliegl (1993) and Kliegl et al. (1994), however, does suggest that a two-factor model that included speed and working memory might be a better fit for more complex cognitive tasks. Thus, in the present study, we examined whether there was evidence that speed operated as the sole mediator of age effects on general memory function (as Lindenberger et al. reported), and working memory was treated as an indicator of general memory, along with free, cued, and spatial memory. This contrasts with a model in which speed and working memory jointly contribute to the remaining measures of memory function (as the work of Mayr & Kliegl, 1993, and Kliegl et al., 1994, implies).

The basic speed model, comparable to that tested by Lindenberger et al. (1993), is presented in Figure 5. Lindenberger et al.'s basic model excluded the broken path from age to working memory portrayed in Figure 5. In the basic speed model, working memory was treated as an indicator of general ability, and the fit of this model is presented as model SP1 in Table 10. This model did have reasonable fit overall.

Following Lindenberger et al. (1993; see also Breckler, 1990; MacCallum, Wegener, Uchino, & Fabrigar, 1993), we then tested the centrality of speed in model SP1 with two additional types of analyses that focused on alternative models. The first type of analysis tested for direct effects of age on factors other than speed. For example, a first variation on model SP1 added a direct path from age to the general memory factor and is given as model SP2-1 in Table 10. The overall fit of this model was slightly degraded compared with that of model SP1, but the difference in these models indicated that the added path was not significantly different from zero. We obtained similar results when we added a path from age to free, cued, and spatial recall (Models SP2-3, SP2-4, and SP2-5 in Table 10). However, when we added a path from age to working memory in model SP2-2, there was a significant improvement in fit relative to the basic model, as displayed by the broken path in Figure 5, suggesting that the general ability model with speed as the only central construct was not the model of best fit.

Before proceeding to test an alternate general abilities model that included working memory as a mediator, as the above modeling would suggest, we conducted a second set of analyses similar to those conducted by Lindenberger et al. (1993). The models tested the centrality of speed by exchanging the position of speed with one of the other constructs present in model SP1. The results are displayed in Table 10. First, we switched the roles of working memory and speed, producing model AM-1 which resulted in an unacceptable fit. Thus, working memory could not be used alone as a central mediator of a general memory construct that includes speed. Models AM-2 through AM-4 reversed the role of free recall, cued recall, and spatial recall with speed and, again, did not fit the data well (Table 10). Thus these alternative representations of relations among the constructs did not appear to be tenable models.

Because the model presented in Figure 3 suggested that speed

Table 9
Comparison of the Present Data With Salthouse's (1993b) Data for Age, Speed, and Recall

Model	χ^2	*df*	*p*	NNFI	CFI	RMSEA
Salthouse	11.58	4	.021	.97	.99	.08
Present data	3.63	4	.460	1.00	1.00	.00

Note. N = 305 for Salthouse (1993b) data and N = 301 for present data. NNFI = nonnormed goodness-of-fit index; CFI = comparative fit index; RMSEA = root-mean-square error of approximation.

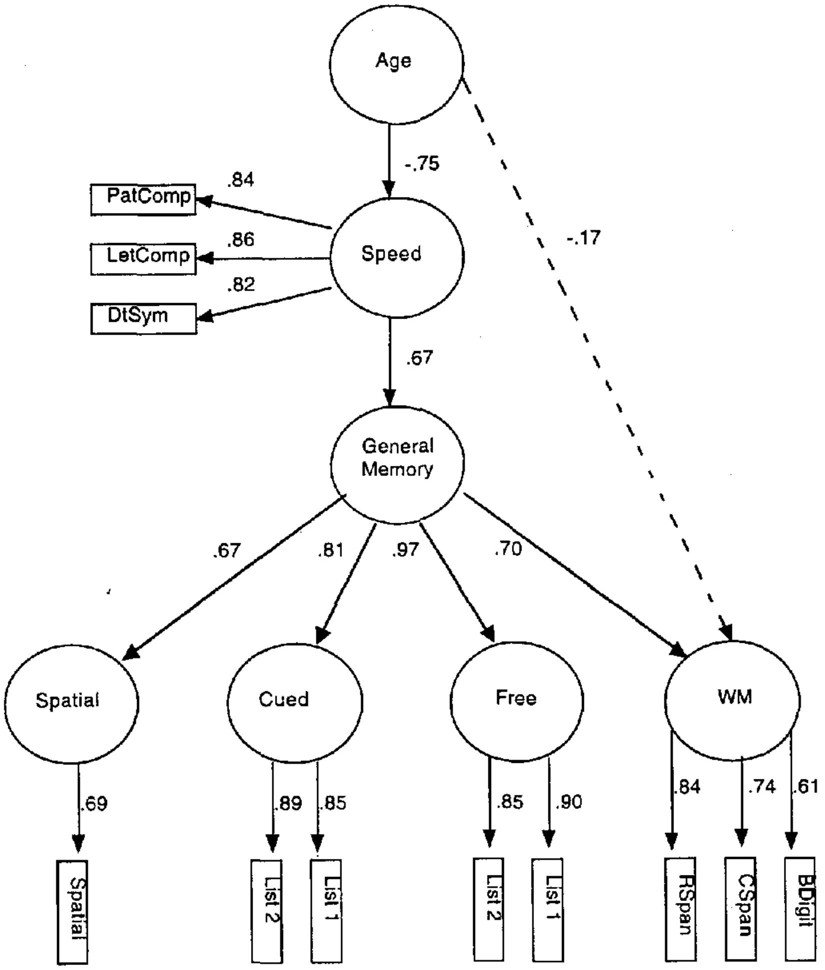

Figure 5. A model (with broken path excluded) in which speed is conceptualized as an indicator of general ability, as in Lindenberger, Mayr, and Kliegl (1993). The broken path represents a variant of the basic model in which age has an independent relationship to working memory (WM). PatComp = pattern comparison; LetComp = letter comparison; DtSym = Digit Symbol; BDigit = Backward Digit Span; CSpan = computation span; RSpan = reading span. List 1 = recall list 1; List 2 = recall list 2.

and working memory jointly contribute to long-term memory function, we fit a final model that was a variant of the basic model (Figure 6). In this model, all age-related variance in memory is mediated through speed, and variance in speed is mediated by working memory. We achieved acceptable fit with this model (Model SPWM-1), as shown in Table 10.

Discussion

The main findings from this research are as follows. First, speed was a central construct in explaining age-related variance in different types of memory performance. Second, working memory was a useful construct in explaining age-related variance in memory function, particularly for more effortful types of memory. The pattern of findings indicated that as memory became more effortful, the contribution of working memory increased. Third, working memory was not merely an indicator of general memory ability, but an important mechanism in its own right for understanding other types of memory; it operated, along with speed, to explain variance in other types of memory and was not simply part of a general memory construct. Fourth, regardless of whether we treated types of memory as separate and independent constructs or as indicators of a single general memory factor, age-related variance was consistently mediated through speed, with working memory making direct contributions to the memory measures. Finally, other constructs that have been hypothesized to be potentially important in understanding age-related variance in memory function were, for various reasons, not useful for the present models.

Mechanisms Underlying Cognitive Aging

The findings reported here are consistent with the work of Salthouse (1993b, 1994, 1996) in that processing speed, as measured by perceptual speed, was a fundamental component of age-related variation in cognitive function. The range of cog-

Table 10
Test of Lindenberger, Mayr, and Kliegl's (1993) Models

Model	χ^2	*df*	*p*	RMSEA	CFI	NNFI
SP1: Basic speed model	96.09	50	<.001	.06	.98	.97
SP2-1: Add age to general memory factor	93.63	49	<.001	.06	.98	.97
Compare with SP1	2.46	1	>.05			
SP2-2: Add age to working memory	88.54	49	<.001	.05	.98	.97
Compare with SP1	7.55	1	<.025			
SP2-3: Add age to free recall	93.06	49	<.001	.05	.98	.97
Compare with SP1	3.03	1	>.05			
SP2-4 Add age to cued recall	95.73	49	<.001	.06	.98	.97
Compare with SP1	0.36	1	>.05			
SP2-5: Add age to spatial memory	93.90	49	<.001	.06	.98	.97
Compare with SP1	2.19	1	>.05			
AM-1: Working memory in place of speed	236.74	50	<.001	.11	.91	.88
AM-2: Free recall in place of speed	225.73	50	<.001	.11	.91	.88
AM-3: Cued recall in place of speed	252.27	50	<.001	.12	.90	.87
AM-4: Spatial memory in place of speed	242.71	50	<.001	.11	.90	.87
SPWM-1: Speed and working memory as causes	82.06	49	.002	.05	.98	.98
Null	2,056.31	66				

Note. $N = 301$ for all models. RMSEA = root-mean-square error of approximation; CFI = comparative fit index; NNFI = nonnormed goodness-of-fit index.

nitive tasks that have been found to have substantial age-related variance mediated by speed is impressive and includes working memory (Salthouse & Babcock, 1991), tests of reasoning and integration (Salthouse, 1993b), paired-associates and free-recall measures of memory (Lindenberger et al., 1993; Salthouse, 1993b), fluency and knowledge (Lindenberger et al., 1993), as well as decision accuracy and decision time (Salthouse, 1994). The present study also included measures of both perceptual speed and working memory as predictor variables, and the results clarified that the role of speed is indeed central but that it operates in part through working memory. This independent contribution of working memory to performance in this study was further elucidated in the modification of the Lindenberger et al. (1993) general ability model (the original model is shown in Figure 5 and the modification is shown in Figure 6), where we treated the types of memory as indicators of a general memory construct. Figure 6 demonstrates that age-related variance works entirely through speed but that speed and working memory jointly contribute to memory function. The finding is congruent with the data of Mayr and Kliegl (1993), Kliegl et al. (1994), and Nettelbeck and Rabbitt (1992) in that it demonstrates the role of an additional factor, working memory, in predicting general memory function. The finding also contrasts with the work of these investigators, however, in that they have reported that a second factor like working memory is needed to explain age-related variance, whereas in the present work, we found that age-related variance works exclusively through speed. It is important to note that the methodologies, tasks, and statistical techniques used in the present study differ substantially from the work of Mayr and Kliegl (1993), Kliegl et al. (1994), as well as Nettelbeck and Rabbitt (1992), so it is not surprising that both congruence with and convergence from their data occur. Generally, the pattern of findings supports a strong speed interpretation of aging effects (Salthouse, 1996), with working memory an important but less central construct.

Age, Speed, and Memory

The model presented in Figure 3 provides some support for resource views of aging and memory. Craik and Byrd (1982) have hypothesized that older adults are limited in self-initiated processing abilities and that this accounts for memory differences with age. Limitations in self-initiated processing would occur if there were limitations on general processing resources. Salthouse (1991b) suggested that both speed and working memory could be indexes of general processing resources. The present study provides some support for a processing resource view and also elucidates the relationships between types of processing resources. The data presented in Figures 3–6 provide general support for a resource view in that constructs such as speed and working memory, which are hypothesized to be indicators of processing resource, appeared to control age-related variance on memory tasks, as hypothesized. Perhaps of more importance, the models also detail the relationships among age, speed, working memory, and long-term memory. Essentially, the models suggest that perceptual speed is a more fundamental mechanism or resource and that it is speed that mediates age-related variance in working memory, which in turn predicts long-term memory function. The finding that speed is a more fundamental mediator than working memory has been suggested by Salthouse (1992c, 1996). The models also indicate that on tasks typically conceptualized as more demanding, working memory makes independent contributions to long-term memory above and beyond that contributed by speed alone.

It should be noted, however, that free recall, which Craik and McDowd (1987) suggested is more effortful than cued recall, has variance mediated independently by working memory, just as cued recall does. As mentioned earlier, although the models are essentially the same, the total amount of variance accounted for by the constructs appeared to be greater for free recall than for cued recall, an outcome consistent with a resource ap-

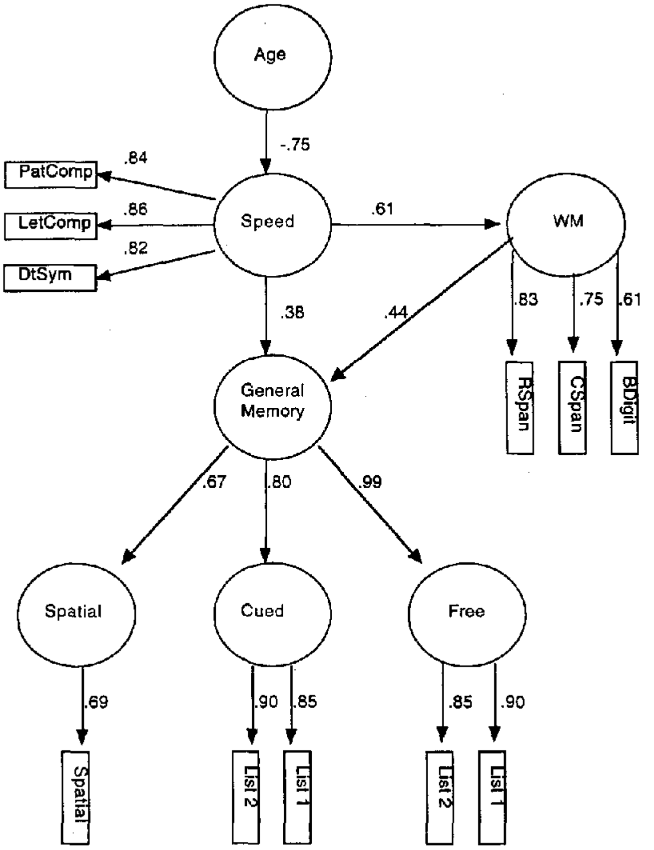

Figure 6. A model in which both speed and working memory (WM) are causes of general memory ability. PatComp = pattern comparison; LetComp = letter comparison; DtSym = Digit Symbol; BDigit = Backward Digit Span; CSpan = computation span; RSpan = reading span; List 1 = recall list 1; List 2 = recall list 2.

proach. In contrast, spatial recall, which has little age-related variance and has been conceptualized to be very low in processing demands (Hasher & Zacks, 1979), does not have a working memory component and is entirely mediated by speed. Thus, these findings suggest that the mechanisms that come into play in long-term memory tasks will vary as a function of task demands in a manner consistent with the resource hypothesis of Craik and Byrd (1982). Working memory is most important on memory tasks that have been conceptualized to be high in resource demands and self-initiated processing.

Further research is needed to examine the mechanisms underlying other types of memory, including prospective and implicit memory. Because implicit memory and prospective memory have generally been viewed as having low resource requirements, one might expect more variance to be associated with speed than with working memory in these tasks. Prospective memory is also an area worthy of future study, because the mechanisms underlying prospective function appear to be different from those associated with other measures of explicit memory (Einstein & McDaniel, 1990). On the other hand, there is little age-related variance on implicit memory tasks (Park & Shaw, 1992), so it would likely be only variance that is not common with age that would predict implicit memory. Generally, the procedures used in the present study appear to be very promising for providing insight into the theoretical mechanisms that control various aspects of memory function and age-related differences in memory, although it is clear that greater refinement in procedures and techniques will be necessary to provide more definitive tests of hypotheses.

Inhibitory Function and Memory

It was disappointing that the present study did not permit an evaluation of the hypothesis that age-related differences in memory function are accounted for by poor inhibitory function. The measure in this study of inhibitory function was a difference score between two priming conditions, and it had low reliability. The negative priming measure did not correlate with any other measures used in the study, and we were unable to include it in any of the models created. It should be noted that Salthouse and Meinz (1995) took a somewhat different tack than we did and operationalized the Stroop task as an indicator of inhibition, reporting strong evidence that most age-related variance associated with the Stroop task was shared with processing speed. They replicated this finding on the data from the present study. However, the relationship of our Stroop data to measures of negative priming was essentially zero. The construct inhibition has assumed an increasingly prominent role in theorizing and speculation about the mechanisms underlying decreased cognitive performance in late adulthood, yet there is no direct evidence linking inhibition as it was conceptualized by Hasher and Zacks (1988) to differences in cognitive performance. There is an urgent need to operationalize this construct in such a way that a reliable measure (or, better yet, multiple measures) of inhibitory function can be developed, so that the importance of this hypothesized mechanism to cognitive tasks can be evaluated.

Other Findings

The other constructs measured in the present study included verbal ability, ability to integrate information, and susceptibility to interference. Although, retrospectively, the inclusion of these measures in the study appears to have been superfluous, they nevertheless served the purpose of providing some evidence that these constructs, as measured in the current study, may not be strong indicators of basic mechanisms underlying differences in cognitive function associated with age. The initial inclusion of many different measures adds confidence to the finding that speed and working memory appear to be basic component mechanisms of memory function and age-related variance associated with memory performance. The finding that high verbal ability may have provided some buffering against age-related decline in free recall (see the discussion of Figure 4) also suggests that crystallized abilities may be important in understanding compensatory mechanisms for age-related processing deficits.

Use of Structural Equation Modeling to Study Aging and Memory

The use of structural equation modeling techniques to elucidate the mechanisms underlying memory function and age-related differences in memory appears to be a fruitful endeavor. The strengths of this approach are that it permits the simultaneous evaluation of competing theoretical views within a single analytical paradigm and provides an account of the relative contributions of different mechanisms to the behavior of interest. In addition, as illustrated in the present work, it also can permit one to examine a theoretical construct at different levels of generality or analysis. In the early structural equation modeling (exemplified by Figure 3), we were able to address specific questions about the role of resources on different types of memory, issues of great importance in understanding practical memory problems and remediation of those problems for older adults. In the later models (exemplified by Figure 6), we treated the types of memory as general indicators of a memory construct. It is important to recognize that when these two different approaches were adopted, we found strong evidence for the integrative nature of the constructs of speed and working memory in understanding aging and memory.

On the other hand, the approach does have limitations. First, it does not provide an easy way to evaluate effects of mechanisms in different experimental conditions (although see Frieske & Park, 1993; Morrell et al., 1993), because of the large number of participants required to develop any single model. Second, the model construction, like most theoretical development, is somewhat subjective. We adopted the approach used by Lindenberger et al. (1993), conducting some limited exploration of theoretically plausible models to ascertain the best of a range of plausible models, as well as to determine how a model that fit one type of memory behavior related to other types of memory. In future research, it would be exciting to adopt a hybrid methodology in which both experimental and individual difference approaches to a problem are adopted. For example, two levels of an independent variable might be investigated (e.g., degree of mental effort) to isolate conditions under which a hypothesized shift in mechanisms underlying a behavior might occur. In summary, careful use of individual-differences techniques has the potential to provide much new information about aging and memory, particularly regarding the relative merits of different theoretical views of memory.

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