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Examining the Locus of Age Effects on Complex Span Tasks

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To investigate the locus of age effects on complex span tasks, the authors evaluated the contributions of working memory functions and processing speed. Age differences were found in measures of storage capacity, language processing speed, and lower level speed. Statistically controlling for each of these in hierarchical regressions substantially reduced, but did not eliminate, the complex span age effect. Accounting for lower level speed and storage, however, removed essentially the entire age effect, suggesting that both functions play important and independent roles. Additional evidence for the role of storage capacity was the absence of complex span age differences with span size calibrated to individual word span performance. Explanations for age differences based on inhibition and concurrent task performamce were not supported.

Working memory is a multicomponent system that combines aspects of both storage and processing. The traditional model (Baddeley & Hitch, 1974, 1994) posits two code-specific storage buffers and a central executive. The storage buffers include the phonological loop, which maintains verbal information, and the visuospatial sketchpad, which stores visual and spatial information. The central executive allocates attentional resources to control access to the storage buffers and to perform other processing requirements such as the coordination of concurrent tasks and inhibition of irrelevant information. A recent formulation of the model (Baddeley, 2000) also includes a temporary multimodal storage component called the *episodic buffer*.

It is well established that working memory is negatively affected by normal aging (e.g., Light, 1996; Salthouse, 1990; Verhaeghen, Marcoen, & Goossens, 1993). The type of task most widely used to document these age differences is the complex span task (see Verhaeghen et al., 1993, for a meta-analysis), in which participants perform a processing task while remembering target items (e.g., the final words in a series of sentences) for later recall. Several variants of complex span have all shown age differences (Chiappe, Hasher, & Siegel, 2000; Li, 1999; Lustig, May, & Hasher, 2001; Myerson, Hale, Rhee, & Jenkins, 1999). Studies have also shown that complex span performance can predict age differences in higher order tasks such as language comprehension and episodic memory (e.g., Hess & Tate, 1992; Kwong See & Ryan, 1995).

The reading span task (Daneman & Carpenter, 1980), a common complex span measure, requires the performance of a processing task involving reading and comprehending sets of sentences while remembering the final word of each sentence. Because complex span tasks engage multiple cognitive processes related to working memory, it has been difficult to identify the source (or sources) of the age effect. Declines in complex span tasks may result from impairments in verbal storage capacity, coordination of concurrent tasks (e.g., Engle, Nations, & Cantor, 1990), inhibition of nontarget information (Hasher & Zacks, 1988), and in the case of the reading span task, syntactic processing and semantic integration (e.g., Daneman & Merikle, 1996). Additionally, lower level processing speed (Salthouse, 1996) appears to make an important contribution to performance on these tasks. Whereas various researchers have proposed age differences in each of these constructs as the source of the complex span age effect, there is no consensus as to which are most important. It is the goal of the current study to further investigate this question.

One component function of working memory (Baddeley & Hitch, 1974, 1994) that could account for the complex span age effect is reduced storage capacity for verbal material, both in the phonological loop and in the episodic buffer (Baddeley, 2000). The storage-deficit hypothesis has found support in the findings of age-related declines in word span (e.g., Light & Anderson, 1985; Verhaeghen et al., 1993) and digit span tasks (e.g., Dobbs & Rule, 1989; Gregoire & Van der Linden, 1997; Verhaeghen et al., 1993; but see Belleville, Peretz, & Malenfant, 1995; Fisk & Warr, 1996). Furthermore, although at least one study has found a greater age effect on complex span tasks compared with simple span tasks (e.g., Wingfield, Stine, Lahar, & Aberdeen, 1988), a meta-analysis indicated that age effects on complex and simple word span tasks are of a similar magnitude, suggesting that the additional processing requirements of complex span tests do not increase the age effect (Verhaeghen et al., 1993). As further evidence for the storage-deficit hypothesis, Belleville, Rouleau, and Caza (1998) found that controlling for word span capacity eliminated any further effects of age on an alphabet span task requiring mental manipulation of the words. This suggests again that younger and older adults differ not in their ability to manipulate information in working memory but in storage capacity (see also Babcock &

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Salthouse, 1990). As evidence against the storage hypothesis, however, Gick, Craik, and Morris (1988) found that the reading span age effect remained relatively constant as the number of sentences presented per trial, and therefore the number of words to remember, increased. In sum, although a large number of studies have suggested that reduced storage capacity accounts for some degree of age-related decline in working memory tests, it is still unclear whether storage capacity can completely account for these age differences.

Another component of working memory that may lead to age differences in performance on complex span tasks is the central executive. The central executive carries out a number of functions (Baddeley, 1996), one of which is to coordinate the simultaneous performance of multiple tasks (Baddeley & Hitch, 1974, 1994). Older adults may have reduced proficiency in performing the processing task and the memory task concurrently during complex span tasks. Contrary to this hypothesis, however, Gick et al. (1988) found no difference in the magnitude of the age effect in complex span for divided-attention and single-task span conditions. For paradigms other than complex span tasks, however, there are conflicting data. Whereas some studies have found greater dual-task costs for older adults compared with younger adults (e.g., Salthouse, Rogan, & Prill, 1984), others have found that once single-task performance is equated for the two age groups, older adults are not differentially affected by adding a secondary task (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986; Somberg & Salthouse, 1982).

In addition to coordinating multiple tasks, the central executive also plays a role in inhibiting irrelevant information. Consequently, if older adults have reduced ability to keep irrelevant information out of working memory and to inhibit previously relevant information that has become irrelevant to task goals (Hasher & Zacks, 1988), this may cause working memory to decline. With regard to complex span performance, a decline in the deletion function of inhibition (Hasher, Zacks, & May, 1999) would result in older adults having more difficulty in inhibiting nontarget words once they have been processed and in suppressing interference from previous trials. Support for this explanation comes from a study by Lustig et al. (2001), who in order to examine the role of proactive interference, compared the standard reading span procedure with a modified procedure that begins with larger span set sizes and progressively reduces the set size. It was hypothesized that the “descending” format would reduce proactive interference for the more difficult larger span trials. As predicted, the descending format significantly increased span scores for older adults and eliminated age differences (see also May, Hasher, & Kane, 1999). Also consistent with the inhibition-deficit hypothesis is the finding that age differences on a complex span task are greater when the background material is highly similar to the material to be remembered (Li, 1999). Thus, interference from irrelevant information may be particularly problematic for older adults when it is difficult to discriminate from relevant, to-be-remembered information.

Despite the evidence for the inhibition-deficit theory, other studies offer evidence against this explanation. For instance, Schelstraete and Hupet (2002) recently tested the association between age differences on measures of inhibition (i.e., intrusion errors on a reading span task and Stroop interference) and reading span performance. Although interference control contributed to reading span, the inhibition measures could not explain the effect of age. An additional line of evidence against the inhibition-deficit theory is found in a meta-analysis of age differences on working memory tasks. Whereas older adults performed more poorly than younger adults on complex span tasks, the age effects were similar regardless of whether the domains of the memory task and the processing task were the same or different (Jenkins, Myerson, Hale, & Fry, 1999; see also Jenkins, Myerson, Joerding, & Hale, 2000). In sum, there is evidence suggesting a decline in inhibition among older adults; however, there is enough conflicting evidence to question whether it can fully explain age differences on complex span tasks.

Another explanation for age differences on certain complex span tasks (i.e., reading span) is a decline in aspects of sentence processing that depend on working memory, namely syntactic processing and semantic integration (e.g., Just & Carpenter, 1992). These sentence comprehension abilities are related to both the storage and processing aspects of working memory because they involve the maintenance of words and the integration of syntactic structure and meaning of the sentence. Evidence for age-related decline in sentence processing includes findings that greater degrees of sentence complexity differentially reduce both complex span performance (Gick et al., 1988) and memory for prose (Norman, Kemper, Kynette, Cheung, & Anagnopoulos, 1991) in older adults. Furthermore, reduced comprehension of complex sentences in older adults has been attributed to their inability to allocate attentional and memory resources to parts of sentences that are more difficult to comprehend (Stine-Morrow, Ryan, & Leonard, 2000). Recently, Waters and Caplan (2001) found evidence that older adults are differentially affected by syntactic complexity as measured by sentence acceptability judgments and that this measure was correlated with working memory capacity. However, on-line sentence reading measures that required more automatic sentence processing abilities showed equivalent effects of syntactic complexity for older and younger adults and no significant correlations with working memory. Thus, although the evidence is mixed, the results of several studies suggest that older adults may have problems with sentence comprehension. These in turn could contribute to age differences in reading span.

The effect of age on complex span could also be explained by reduced speed of processing in older adults. Salthouse’s (1991, 1996) processing speed theory of cognitive aging is a general model used to account for age differences on many cognitive tasks, including those tapping working memory. Although a generalized reduction in processing speed would be expected to affect cognitive operations at all levels, two mechanisms by which it could affect working memory are to reduce the speed of rehearsal in the phonological loop (Baddeley & Hitch, 1994) and to decrease the availability of information from earlier processing steps (Salthouse, 1996). Many studies have shown that processing speed, commonly measured by perceptual comparison tasks, is associated with a substantial amount of variance on complex span tasks and that age differences on these tasks are largely eliminated after statistically controlling for speed (e.g., Fisk & Warr, 1996; Salthouse, 1994; Salthouse & Babcock, 1991; Verhaeghen & Salthouse, 1997).

A recent study by Park et al. (2002) provides further support for the processing speed theory by using a formal modeling approach. To evaluate the strength of common explanatory constructs related to working memory, Park et al. assessed age-related performance on tasks of sensory functioning, processing speed, short-term memory, working memory, long-term memory, and verbal ability. In addition to supporting the separation of working memory into verbal and visuospatial domains across all age groups, the resulting model pointed to processing speed as the strongest mediator between age and cognitive tasks, including those tapping working memory. Because rates of age-related declines were similar across all cognitive measures, the results supported the hypothesis that slowed speed of processing may be the fundamental construct that drives cognitive reductions in old age. This and many other studies provide strong evidence that the relationship between age and working memory is mediated by an age-related decrease in processing speed (see also Salthouse, 1992). However, there is also some evidence that processing speed might not provide a full account of the complex span age effect (e.g., Gick et al., 1988; Keys & White, 2000).

This review of evidence for and against each interpretation of age differences on complex span tasks highlights the lack of a coherent theoretical account of this phenomenon. One reason for the conflicting data may be the inconsistent use of methodology capable of isolating the source(s) of age differences. Thus, although complex span tasks place multiple cognitive demands on test takers, few studies have independently measured age differences in each task component. A comprehensive approach to the question would assess performance on each task component, determine how well each component that shows age differences predicts the complex span age effect, and explore what combination of predictors can best account for the age differences.

Overview of the Current Experiment

The goal of the current study was to contrast the predictions made by the different hypotheses regarding the age effect on complex span tasks. We included two verbal complex span tasks. The reading span task (RST) required participants to read and verify sentences aloud while remembering the sentence-final words (Daneman & Carpenter, 1980), and the list span task (LST) involved reading word lists aloud and identifying animal names while remembering the list-final words (De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). We focused on identifying the cognitive locus of the age effect in these complex span tasks by examining age differences on the task components that correspond to different working memory functions, either by using independent measures of the components or by comparing tasks that varied only in one component. Statistical regression techniques were also applied to determine which working memory and/or speed-related factors are most successful in explaining the age effect on complex span tasks.

The design of the experiment addressed each of the major hypotheses regarding age differences in working memory. The storage-deficit hypothesis was tested in three ways. First, age differences in word span and complex span were compared. If storage is the critical constraint on age-related complex span performance, there should be similar effects of age on the two types of tasks; however, if complex span components other than storage capacity drive the age effect, there should be larger age differences on the complex spans. Our second test of this hypothesis was to measure each participant's complex span performance at a span size calibrated to his or her word span ability. If storage capacity is critical, then older and younger adults should perform similarly on the complex span tasks when age differences in storage are accounted for in this way. Third, we used word span performance as a predictor of complex span to determine whether it would significantly reduce age-related complex span variance.

We also tested the hypothesis that older adults have reduced central executive resources, resulting in difficulties with concurrent task performance. We compared age differences on the word span task and a dual-task version of word span in which participants read aloud a series of words for later recall while pressing a key whenever they read an animal name (De Beni et al., 1998). If the processing of concurrent tasks affects older adults, then a differential age effect in the dual-task condition would be expected.

To investigate an additional manifestation of a reduction in central executive abilities, we examined age-related declines in the ability to inhibit irrelevant information. The primary means of testing the inhibition-deficit theory (Hasher & Zacks, 1988) was to examine intrusion errors during the complex span tasks (i.e., RST and LST). The intrusion measures assessed the deletion function of inhibition (Hasher et al., 1999); if older adults are less able to inhibit the nonfinal words from working memory, their recall should contain a greater proportion of intrusions. In addition, they might be expected to have an especially high rate of animal-name intrusion errors on the LST because these words receive additional processing (De Beni et al., 1998). As another test of the deletion function, we compared age differences on the LST with those on the dual-task word span. These tasks differed mainly in the requirement of the LST to inhibit nonfinal words from working memory. A decline in inhibitory function would be expected to differentially reduce older adults' performance on the LST compared with the dual-task word span, in which all material presented during a trial is relevant to the memory task.

We assessed the hypothesis that a syntactic deficit could explain age differences by comparing the two versions of complex span. The RST and LST differed solely in terms of the syntactic processing requirement, as both required participants to read words aloud and to recall the final word of each sentence or list. If reduced syntactic processing is responsible for complex span age differences, then the age effect should be greater on the RST than on the LST.

The final hypotheses that we tested were related to the processing speed theory (Salthouse, 1996). We included three independent measures of processing speed and compared the effects of age on complex span performance before and after statistical control of performance on these tasks to determine whether they were able to substantially reduce the age effect. As an extension of the processing speed hypothesis, we also considered whether age differences in the speed of processing higher level verbal material, which is determined by lower level speed as well as by language-specific processing speed, might be predictive of complex span performance. Salthouse and Babcock (1991) found that the efficiency of processing the verbal background tests of complex span tasks was a better predictor of the complex span age effect than simple storage and nonmemory task coordination, although not nearly as strong a predictor as lower level processing speed. To test the role of this higher level language processing speed construct in the current study, we independently measured reaction time on the verbal background tasks of the RST and the LST and then tested the relationship of language processing speed to complex span performance and examined the degree of overlap between the higher level and lower level speed constructs.

The main predictions of this experiment were that the complex span age effect would be mostly explained by age differences in working memory storage capacity, higher level language processing speed, and/or lower level processing speed. In addition, we expected that the contribution of lower level speed would be partially independent of the contribution of higher level speed and storage capacity, such that either of these last two would account for unique age-related variance above and beyond that of lower level processing speed. We considered basic processing speed to be the more fundamental cognitive construct because a decline in this lower level ability would arguably affect the efficiency of all cognitive operations (e.g., Salthouse, 1996). In comparison, declines in the other constructs included in the study would affect more specific higher level abilities. On the basis of this logic, we decided to account for the variance associated with lower level speed first in each of our regression analyses. Thus, our strongest predictions were based on explanations involving storage capacity and processing speed. The roles of concurrent processing demands and inhibition ability were also tested, although we had less clear predictions regarding these explanatory constructs.

Method

Participants

Participants included 48 younger adults and 48 older adults (see Table 1 for characteristics of the sample). The younger adults were undergraduate students participating for course credit or payment. The older adults were healthy volunteers who were paid for participation. All participants reported good or excellent health and vision that was normal or corrected to normal. None had a reported history of neurological disorders, uncontrolled hypertension, diabetes, heart attacks, emphysema, kidney disease, or recent severe psychiatric illness, nor were they currently taking psychoactive medication. In addition, no older participants reported excessive alcohol use.

All participants were screened for depression and anxiety by using the Beck Depression Inventory—II (BDI–II; Beck, Steer, & Brown, 1996) and the Beck Anxiety Inventory (BAI; Beck & Steer, 1990). Participants were excluded if they scored above the normal range of 0–13 on the BDI–II and/or above the normal range of 0–9 on the BAI. Thirteen younger adults and three older adults were excluded for this reason and were replaced. There were no age differences in BDI–II or BAI scores. The older adults were also screened for dementia with the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) and all scored above a minimum cutoff score of 28.

Table 1
Characteristics of Participants

Characteristic	Older adults		Younger adults	
	M	*SD*	*M*	*SD*
Age	72.3	5.9	20.1	2.4
Years of education	16.8	2.0	13.9	1.1
MMSE	29.4	0.7	—	—
BDI–II	3.0	3.2	3.1	3.0
BAI	1.2	2.0	2.5	2.2
Shipley–Hartford Vocabulary Test	36.9	2.5	31.0	3.6

Note. Mini-Mental State Examination (MMSE) scores represent the number of points earned out of a maximum of 30. Dashes indicate that MMSE data were not collected for younger adults. Shipley–Hartford Vocabulary Test scores represent the number of correct responses out of a maximum of 40. BDI–II = Beck Depression Inventory—II; BAI = Beck Anxiety Inventory.

Materials

All of the span tasks (RST, LST, dual-task word span, word span) and the language tasks (sentence processing, word-list processing) were presented on a computer monitor. Practice trials were presented to participants prior to each task. On the span tasks, there was a 10-s break between trials to reduce proactive interference. At the end of each span trial, a blue recall screen immediately appeared and participants responded orally. The language tasks involved the presentation of the items sequentially without breaks, and the computer recorded all responses.

Word span task. The word span task required the construction of three trials for each span-level from two to eight, using a total of 105 words. Words selected for the trials were matched to the sentence-final words from the RST (Daneman & Carpenter, 1980) in terms of part of speech, frequency, concreteness, and number of syllables, on the basis of published norms (Kučera & Francis, 1967; Nelson, McEvoy, & Schreiber, 1998; Toglia & Battig, 1978). The words within each trial were chosen to be semantically and phonologically unrelated.

On each trial, words appeared one at a time on the computer monitor for 1 s each. Participants were instructed to read each word aloud and then to recall all the words in order when the blue screen appeared. They were told that it was better to report the material out of order than to not report it at all; however, they were instructed not to say the last item they read as the first word recalled unless it was the only one they could remember. The task began with a span size of two words. After three trials at each level, the span size increased by one until the participant failed at least two out of three trials at a given size. The instructions and procedures for the span tasks followed the reading span procedure of Daneman and Carpenter (1980).

Dual-task word span task. The dual-task word span (De Beni et al., 1998) used 105 animal and nonanimal words matched to Daneman and Carpenter’s (1980) sentence-final words used in the RST in the same way as for the word span task. Animal names were placed randomly in the trials. Three trials were constructed for each span size from two to eight.

On each trial, words were presented one at a time for 1 s each on the computer monitor. Participants were instructed to read the words aloud and to press the *Animal* key whenever they read an animal name. At the conclusion of each trial, participants recalled the words in order when the blue screen appeared. Testing began with a span size of two and increased until the participant failed at least two out of three sets at a given span size.

RST. The RST consisted of 60 sentences between 8 and 12 words long, taken from Daneman and Carpenter (1980). The final, to-be-recalled word in each sentence contained one to three syllables. Half of the sentences were meaningful (i.e., they followed semantic and syntactic rules of English) and half were not. Three trials were constructed for each span size from two to six.

In each trial, sentences were presented one at a time on the computer monitor. Participants read each sentence aloud and made a response as to whether it was meaningful. They pressed a key labeled *Yes* for sentences that were meaningful and a key labeled *No* for sentences that were not. After all sentences in a trial were completed, the blue screen appeared and they recalled the sentence-final words in order. Span size began with two sentences and increased by one sentence after three trials. This process continued until the span size equaled the individual’s word span minus one. At that span size, if a participant was still able to complete more than one out of three trials correctly, testing continued until at least two out of three trials were failed at a given span size. This procedure was adopted so that we could compare age differences in complex span scores with complex span performance calibrated to each individual's simple storage ability. We used the word-span-minus-one level as the criterion rather than actual word span to avoid floor effects in this calibrated complex span measure.

LST. The LST was based on the complex span task used by De Beni et al. (1998) and required the construction of 60 five-word lists, each with zero to two animal names. Words used in this task were selected on the basis of the same criteria as for the dual-task word span. For lists with animal names, the animal words were placed randomly in the lists, including in the final position. Three trials of word lists were constructed for each span size from two to six.

The LST followed much the same procedure as the RST, except that instead of sentences, lists of five words were presented on the screen, arranged horizontally. Participants read the words in each list aloud from left to right while pressing a key labeled *Animal* for each animal name. They pressed a key labeled *End* after reading each list, and at the end of each trial, they saw the blue screen and recalled the final words of the lists in order. The task began with a span size of two, and we used the same procedures as those used in the RST to determine when to terminate testing.

Language processing speed tasks. The two language tasks corresponded to the two complex span background tasks. The test corresponding to the RST was a sentence processing task, which included 20 new sentences from Daneman and Carpenter (1980). Again, half of the sentences were meaningful and half were not. Participants read each sentence aloud and pressed the *Yes* key or the *No* key, depending on whether the sentence made sense or not. For the word-list processing task, corresponding to the background task in the LST, 20 new five-word lists were created by using the same criteria as described for the LST. This task required participants to read each list aloud while pressing the *Animal* key whenever they read an animal name. The *End* key was pressed immediately after reading the last word in each list. For both language tasks, the importance of both speed and accuracy was emphasized. The computer recorded reaction times and accuracy for each trial.

Lower level processing speed tasks. The Pattern Comparison and Letter Comparison tasks (Salthouse & Babcock, 1991), as well as the Digit–Symbol Substitution task (Wechsler, 1997), are paper-and-pencil tests that were administered to measure basic processing speed. In the Pattern Comparison and Letter Comparison tasks, participants were instructed to examine a series of either pattern or letter pairs and decide whether the members of each pair were the same or different. Participants wrote an *S* on the line separating a pair if the two stimuli were the same and a *D* if they were different. For each task, the goal was to complete as many items as possible within 30 s on each of two pages. The score for each task was the total number of correct responses. The Digit–Symbol Substitution task, a subtest of the Wechsler Adult Intelligence Scale—III (Wechsler, 1997), consisted of a piece of paper at the top of which was a key that matched the digits 1–9 with a set of 9 symbols. A series of digits was printed below with an empty box beneath each one. Participants filled in these boxes with the appropriate symbols. Standard administration instructions were used, and the score was the number of items answered correctly in 2 min.

Procedure

Participants were tested individually in sessions lasting approximately 1 hr. Older adults were screened for health problems via telephone prior to the testing session, and younger adults received the health screening at the end of the testing session. Older adults completed the MMSE at the start of the session. There were no other differences in procedure for younger and older adults. The ordering of the tasks was as follows. The word span was administered first to determine the participant's simple span level, which was needed for administering the RST and LST (see the *Materials* section). The order of the remaining computerized tasks was counterbalanced across participants. The lower level speed measures were interleaved with the computerized tasks. The Shipley–Hartford Vocabulary Test (Shipley, 1940), the BDI–II, and the BAI were administered at the end of the testing session.

Results

The RST, LST, word span, and dual-task word span tasks were scored using two methods. For the *span-level* scoring method (Daneman & Carpenter, 1980), participants received 1.0 point for every span size at which they completed at least two out of three trials accurately, and they received an additional 0.5 point if they accurately completed one trial out of three at the next highest span size. For the *items* scoring method (e.g., Chiappe et al., 2000; Lustig et al., 2001; May et al., 1999), we added the total number of target words accurately recalled on fully correct trials. With the age groups combined, the two scoring methods were highly correlated for each of the four span tasks (range of *r*s = .96–.97, $p <$ .001). Because the items scoring method allows for a greater range of scores and because the span-level scoring method at times resulted in floor effects for older adults, we primarily report items scores; however, analyses using span-level scores are reported when they differ from the analyses that used items scores. With few exceptions, the two scoring systems produced similar results.

Older adults scored significantly higher than younger adults on the Shipley–Hartford Vocabulary Test, $t(94) = 8.78$, $p < .05$, partial $\eta^2 = .45$ (see Table 1). With the effect of age removed, vocabulary was significantly correlated with an average complex span score ($r = .33$, $p < .05$). Thus, to remove the effect of verbal ability in all analyses, vocabulary was used as a covariate in analysis of covariance (ANCOVA) procedures and was entered as the first predictor in regression models.

The alpha level was set at $p = .05$. We report partial η^2 as a measure of effect size. Partial $\eta^2 = .01$ represents a small effect; partial $\eta^2 = .06$, a medium effect; and partial $\eta^2 = .14$, a large effect (Cohen, 1988).

Age Differences on Complex Span Tasks

Before testing our hypotheses, we compared performance on the two complex span tasks. In doing this, we also tested whether the age effect was different for the two versions of complex span. A 2 (type of complex span: RST, LST) × 2 (age) ANCOVA with vocabulary as a covariate was computed. As expected, there was a significant effect of age, $F(1, 93) = 23.60$, $MSE = 55.96$, $p < .05$, partial $\eta^2 = .20$, indicating overall better performance by younger adults. There was no effect of complex span type and no interaction of complex span type and age. Vocabulary was a significant covariate, $F(1, 93) = 11.64$, $MSE = 55.96$, $p < .05$, partial $\eta^2 =$ .11, but did not interact with other variables.

The correlation between the two complex span tasks with age partialed out was significant ($r = .53$, $p < .001$). Because the pattern of age-related performance was similar for the RST and the LST, mean complex span scores were used in all subsequent analyses that compared complex span tasks with other tasks or those that used variables to predict complex span.

Analyses Relating to the Storage-Deficit Hypothesis

Performance on the word span task showed significant age differences, $t(94) = 3.78$, $p < .05$, partial $\eta^2 = .13$, with younger adults performing better than older adults (see Table 2). To com-

Table 2
Means and Standard Deviations on Span Tasks Using Items Scores for Each Age Group

	Older adults		Younger adults	
Span measure	*M*	*SD*	*M*	*SD*
Reading span task	8.88	5.82	13.13	8.31
List span task	8.38	5.20	11.60	5.90
Word span	34.77	9.28	42.83	11.51
Dual-task word span	37.88	11.19	47.42	13.67

Table 4
Means and Standard Deviations of the Proportions of Intrusion Errors on the Reading Span Task (RST) and the List Span Task (LST)

	Older adults		Younger adults	
Type of intrusion error	*M*	*SD*	*M*	*SD*
RST intrusions	.06	.06	.05	.06
LST intrusions	.09	.08	.06	.06
LST animal intrusions	.02	.05	.01	.02

pare the magnitude of age differences on simple versus complex span tasks, a 2 (type of span: word span, average complex span) × 2 (age) ANCOVA was computed with vocabulary as a covariate. There was a trend toward a main effect of span type, $F(1, 93) = 3.59$, $MSE = 41.28$, $p = .06$, partial $\eta^2 = .04$; a significant main effect of age, $F(1, 93) = 28.92$, $MSE = 90.11$, $p < .05$, partial $\eta^2 = .24$; and a significant interaction of the two variables, $F(1, 93) = 5.24$, $MSE = 41.28$, $p < .05$, partial $\eta^2 = .05$. The word span scores were somewhat higher than complex span scores, younger adults performed better than older adults, and the interaction indicated larger age differences in word span compared with complex span. There was also a significant effect of the vocabulary covariate, $F(1, 93) = 10.60$, $MSE = 90.11$, $p < .05$, partial $\eta^2 = .10$, but no significant interactions with other variables.

We also compared younger and older adults' complex span performance at each individual's word-span-minus-one level. The dependent variable in this analysis was the number of sentence- or list-final words correctly recalled at the word-span-minus-one level divided by the maximum number of words that could have been recalled at that level (see Table 3). A 2 (type of complex span: RST, LST) × 2 (age) ANCOVA was computed with vocabulary as the covariate. There was no effect of span type or of age and no significant interaction between the two variables. There were also no significant effects or interactions involving the vocabulary covariate.

Analyses Relating to the Concurrent-Task-Deficit Hypothesis

Older adults performed significantly worse on the dual-task word span compared with younger adults, $t(94) = 3.74$, $p < .05$, partial $\eta^2 = .13$ (see Table 2). To assess whether the addition of a concurrent task to a memory storage task increased age differences in memory span, a 2 (type of word span: single task, dual task) × 2 (age) ANCOVA was calculated with vocabulary and mean word-list processing reaction times as covariates. The word-list processing covariate, as measured by the mean reaction time to read and respond to animal names in the word-list processing task, was included to control for baseline performance in this component of the dual-task word span. The results showed no effects of word span type, although the main effect of age was significant, $F(1, 92) = 9.77$, $MSE = 192.61$, $p < .05$, partial $\eta^2 = .10$, indicating lower performance on both tasks by older adults. There was no significant interaction between age and task type. There was a trend toward a main effect of the vocabulary covariate, $F(1, 92) = 3.40$, $MSE = 192.61$, $p = .07$, partial $\eta^2 = .04$, but it did not interact with other variables. The effect of the word-list processing covariate was significant, $F(1, 92) = 6.18$, $MSE = 192.61$, $p < .05$, partial $\eta^2 = .06$, but it did not interact with other variables.

Table 3
Means and Standard Deviations of Proportions of Recall on the Reading Span Task and the List Span Task at the Word-Span-Minus-One Level

	Older adults		Younger adults	
Complex span task	*M*	*SD*	*M*	*SD*
Reading span task	.64	.16	.66	.16
List span task	.59	.21	.62	.19

Analyses Relating to the Inhibition-Deficit Hypothesis

We first examined the proportion of intrusion errors on the RST and LST. *Intrusion errors* were defined as nontarget words from the current span trial that were erroneously recalled as target words.[1] This proportion was computed by dividing the total number of nonfinal words recalled by the total number of words recalled (see Table 4). In separate *t* tests, no age differences in these scores were found for either complex span task. We next examined age differences in a subset of LST intrusion errors, the animal names that were erroneously recalled. This score was calculated by dividing the number of intrusion errors that were animal names by the total number of words recalled. In a *t* test, the proportion of animal intrusion errors did not show age differences (see Table 4). The overall proportion of intrusion errors and the proportion of animal intrusion errors across both age groups were extremely low, however, so it was difficult to assess age trends.

The final test of the inhibition-deficit hypothesis involved a comparison between the LST and the dual-task word span task (see Table 2). This 2 (type of span task: LST, dual-task word span) × 2 (age) ANCOVA showed an effect of span type, $F(1, 93) = 3.61$, $MSE = 56.38$, $p = .06$, partial $\eta^2 = .07$, with higher scores on the

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[1] An identical pattern of results was found when intrusion errors were scored to include intrusions from all previous span trials. The number of intrusion errors combined for the RST, LST, and LST animal-name intrusion measures increased only by a total of four words for younger adults and by seven words for older adults when across-trial intrusions were included.

dual-task word span. There was also a main effect of age, $F(1, 93) = 26.07$, $MSE = 119.54$, $p < .05$, partial $\eta^2 = .22$, with better performance by younger adults, and an interaction of the span task and age, $F(1, 93) = 7.25$, $MSE = 56.38$, $p < .05$, partial $\eta^2 = .07$. The interaction reflected greater age differences in the dual-task word span task scores compared with the LST scores. There was a significant effect of the vocabulary covariate, $F(1, 93) = 9.85$, $MSE = 119.54$, $p < .05$, partial $\eta^2 = .10$, but no interactions with other variables.

Analyses Relating to the Processing Speed Theory

Significant age differences were found on all speed-related measures (see Table 5). For the lower level processing speed tasks, older adults completed fewer items correctly than younger adults on the Pattern Comparison, $t(94) = 6.00$, $p < .05$, partial $\eta^2 = .28$; Letter Comparison, $t(94) = 7.80$, $p < .05$, partial $\eta^2 = .39$; and Digit–Symbol Substitution tasks, $t(94) = 12.06$, $p < .05$, partial $\eta^2 = .61$.

On both higher level language tasks, the reaction times were significantly faster for younger adults than for older adults—sentence processing task: $t(94) = 2.33$, $p < .05$, partial $\eta^2 = .06$; word-list processing task: $t(94) = 4.62$, $p < .05$, partial $\eta^2 = .19$. Levels of accuracy on both tasks were high ($M = .98$, $SD = .04$), and *t* tests showed no age differences in either task (see Table 6). With age partialed out, the correlation of the sentence processing and word-list processing reaction times was significant ($r = .61$, $p < .001$).

Predictors of Complex Span Performance

A series of hierarchical regression models tested the hypotheses that controlling for task components that showed significant age differences would substantially reduce the age effect on complex span tasks. To this end, we computed separate regression analyses with performance on the simple storage measure, the higher level language measures, and the lower level processing speed measures as individual complex span predictors. We then explored a hierarchical combination of lower level processing speed with each of the task components as predictors of complex span performance. The concurrent task and inhibition measures were not included as predictors because they failed to show a differential effect of age. All regression models were computed with vocabulary as the first predictor. The mean score on the two complex span tasks was used as the dependent variable in each analysis (see Table 7 for correlations among predictors and complex span tasks).

Table 5
Means and Standard Deviations of Scores for the Lower Level Processing Speed Tasks

	Older adults		Younger adults	
Lower level speed task	*M*	*SD*	*M*	*SD*
Pattern Comparison	32.5	5.2	40.6	7.8
Letter Comparison	20.6	3.6	27.7	5.2
Digit–Symbol Substitution	62.8	12.2	89.5	9.3

Note. Scores on the Pattern Comparison and Letter Comparison tasks represent the number of correct responses in 1 min. Digit–Symbol Substitution scores represent the number of correct responses in 2 min.

Table 6
Means and Standard Deviations of Reaction Times (RTs) and Accuracy Levels on the Sentence Processing and Word-List Processing Speed Tasks

	Older adults		Younger adults	
Language task	*M*	*SD*	*M*	*SD*
Sentence processing				
RT	4,380	879	3,968	853
Accuracy	.98	.04	.97	.04
Word-list processing				
RT	4,079	950	3,314	643
Accuracy	.98	.04	.99	.03

Note. RTs are presented in milliseconds. Accuracy levels represent the proportions of correct responses.

We computed a preliminary regression model with age as the sole predictor of average complex span score. This model, as expected, showed age to be a significant predictor, accounting for 20.2% of the variance ($p < .05$). Subsequent regression models included the experimental tasks as primary predictors, followed by age, allowing us to compare the amount of variance accounted for by each task with effects of age alone (see Table 8 for regression results).

The first of these regression models used word span as a predictor of complex span performance, followed by age. The results showed that word span performance was highly predictive of complex span performance, accounting for 31.2% of complex span task variance ($p < .05$). Age was still a significant predictor, however, accounting for an additional 5.4% of the variance ($p < .05$). Compared with the age-only model, adding word span as a predictor reduced the age effect by 73.3%.

The second regression model tested the ability of higher level language processing to predict complex span performance. This model included the mean of the reaction times for the sentence and word-list processing speed tasks as the first predictor, followed by age. The language task reaction time was a significant predictor, accounting for 13.7% of the variance ($p < .05$). However, age was still a significant predictor of complex span score, accounting for an additional 9.6% of the variance ($p < .05$). Compared with the age-only model, controlling for the language tasks reduced the age effect by 52.5%.

The lower level speed tasks were used to predict complex span in the next model, followed by age. All three speed tasks were entered as a group in one level of the regression model, and accounted for 26.3% of complex span variance ($p < .05$). The age variable, however, still contributed 4.2% of the variance ($p < .05$). Controlling for the simple speed tasks reduced the age effect by 79.2% compared with the age-only model.

The subsequent set of hierarchical regression models tested the prediction that lower level processing speed, plus one of the task components, would render the age effect nonsignificant. The first regression model included the lower level speed measures, followed by word span and then age. As noted above, the simple speed tasks, entered as a group, were associated with 26.3% of the

Table 7
Correlations Among Variables With Age Group Partialed Out

Variable	1	2	3	4	5	6	7	8	9	10	11
1. Mean complex span	—										
2. RST	.91**	—									
3. LST	.84**	.53**	—								
4. Dual-task word span	.56**	.46**	.54**	—							
5. Word span	.50**	.44**	.44**	.64**	—						
6. Sentence processing	−.25*	−.22*	−.22*	−.21*	−.26*	—					
7. Word-list processing	−.27**	−.24*	−.23*	−.23*	−.35**	.61**	—				
8. Pattern Comparison	.05	.09	−.02	.09	.05	−.26*	−.24*	—			
9. Letter Comparison	.34**	.34**	.24*	.18	.15	−.20	−.19	.44**	—		
10. Digit–Symbol Substitution	.19	.19	.14	.11	.07	−.35**	−.32**	.37**	.60**	—	
11. Vocabulary	.33**	.23*	.37**	.24*	.25*	−.29**	−.31**	.13	.11	.08	—

Note. RST = reading span task; LST = list span task.
* $p < .05$. ** $p < .01$.

variance ($p < .05$). The word span task accounted for an additional 16.6% of the variance in this model ($p < .05$). Including lower level processing speed as the first predictor approximately halved the contribution of simple storage to complex span performance, and the combination of lower level speed and storage rendered the contribution of age-related variance nonsignificant. Compared with the age-only model, these predictors reduced the age effect by 95.5%. We cannot, however, strongly conclude that these two constructs completely eliminated the age effect because the corresponding analysis using the span-level scoring method for complex span measures showed a small amount of significant remaining age-related variance.[2] Although there is some discrepancy in results, both scoring methods resulted in a substantial reduction of the complex span age effect after statistically controlling for lower level speed and storage capacity.

Table 8
Results of Hierarchical Regression Analyses Predicting Mean Complex Span Score Using Items Scores

Predictor	R^2	Increase in R^2	F	*df*
Vocabulary	.000	.000	0.03	1, 94
Age	.203	.202	23.60**	2, 93
Vocabulary	.000	.000	0.03	1, 94
Word span	.313	.312	42.27**	2, 93
Age	.367	.054	7.88**	3, 92
Vocabulary	.000	.000	0.03	1, 94
Mean language processing RT	.138	.137	14.82**	2, 93
Age	.233	.096	11.49**	3, 92
Vocabulary	.000	.000	0.03	1, 94
Lower level speed	.263	.263	10.83**	4, 91
Age	.306	.042	5.49*	5, 90
Vocabulary	.000	.000	0.03	1, 94
Lower level speed	.263	.263	10.83**	4, 91
Word span	.429	.166	26.21**	5, 90
Age	.438	.009	1.39	6, 89
Vocabulary	.000	.000	0.03	1, 94
Lower level speed	.263	.263	10.83**	4, 91
Mean language processing RT	.297	.034	4.34*	5, 90
Age	.331	.034	4.50*	6, 89

Note. RT = reaction time.
* $p < .05$. ** $p < .01$.

A final model was computed by using lower level processing speed as the first predictor, followed by average reaction time for the language tasks and then age. The lower level processing speed tasks were associated with 26.3% of the complex span variance ($p < .05$), and although the variance associated with the language tasks was substantially reduced compared with the model without the simple speed tasks, it accounted for an additional 3.4% of complex span variance ($p < .05$). With the addition of these two predictors to the model, the age effect was reduced by 83.2% compared with the age-alone model. The age effect remained significant, however, accounting for 3.4% of the variance ($p < .05$).

Because our regression analyses up to this point supported the importance of both lower level processing speed and storage capacity in the complex span age effect, we computed a post hoc regression model that explored the contribution of lower level speed to word span. This model, which included vocabulary, lower level speed tasks, and age as hierarchical predictors of word span, showed that lower level speed accounted for 12.9% of unique variance ($p < .05$). Age still contributed an additional 7.0% of unique variance to the model ($p < .05$). For comparison, age alone accounted for 18.3% ($p < .05$) of word span variance. Compared with the age-only model, the addition of the speed tasks to the regression equation decreased the age effect by 61.7%.

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[2] The hierarchical regression model with lower level processing speed, word span, and age as predictors of complex span performance showed slightly different results when the span-level method of scoring was used, in that age was still a significant predictor after accounting for lower level speed and word span, adding an additional 2.8% of variance to the model ($p < .05$). Including the lower level speed measures and the word span as predictors reduced the age effect by 89.3% compared with the regression model using span-level scores with age as the sole predictor. Due to this discrepancy, we cannot positively conclude that storage capacity and lower level speed eliminate the age effect; however, the age effect was reduced substantially, supporting our conclusion of significant and unique contributions of storage in working memory and of lower level speed to the complex span age effect.

Discussion

Complex span tasks are commonly discussed in the cognitive-aging literature as tests of working memory (e.g., Jenkins et al., 1999; Verhaeghen et al., 1993), but it is unclear which aspects of the tasks are responsible for age differences. This experiment focused on the role of each function of working memory that contributes to complex span performance, as well as the roles of two levels of processing speed. Age differences in complex span were assessed by using two variations of the task, the RST (Daneman & Carpenter, 1980) and the LST (De Beni et al., 1998). Independent measures of simple storage capacity in working memory, concurrent task performance, higher level language processing speed, and lower level processing speed were included to determine which components of complex span tasks were responsible for the age effect. Complex span intrusion errors were assessed to explore the role of inhibition.

Results showed that, consistent with previous research (e.g., Verhaeghen et al., 1993), older adults scored significantly lower on both complex span tasks compared with younger adults. In addition, significant age differences were found on the word span tasks and on both types of processing speed tasks. In discussing the contribution of each task component to age differences in complex span, we first consider the explanations that were rendered less plausible, followed by a discussion of the theoretical explanations that were most strongly supported.

We did not find any support for the hypothesis that the effect of age on complex span results from reduced central executive functioning. Two such predictions were that either decreased ability to coordinate concurrent tasks or failures to inhibit irrelevant information could account for age differences. When the ability to coordinate the memorizing and processing components of the task was assessed, however, age effects on the single-task and dual-task versions of the word span task were similar. Thus, there was no evidence that older adults were differentially affected by the addition of a dual-task requirement to a word recall task. Because the LST required the same concurrent processing as the dual-task word span (i.e., animal-name identification), it is unlikely that carrying out a secondary task contributed to LST age differences. These conclusions are consistent with several previous studies (e.g., Somberg & Salthouse, 1982).

The second aspect of central executive functioning that failed to explain age differences in complex span was inhibition. The inhibition-deficit hypothesis (Hasher & Zacks, 1988) would predict that the age effect on complex span tasks can be explained by a decline in the deletion function of inhibition, which removes words from working memory that need not be remembered (Hasher et al., 1999). We tested this hypothesis by measuring the proportion of intrusion errors on both complex span tasks and the proportion of animal-name intrusion errors on the LST. Because the animal names received additional attention during the LST, the inhibition-deficit hypothesis might predict that older adults would have particular difficulty inhibiting these words from working memory. Although there were floor effects in the intrusion measures, the age effects were not significant and there was no evidence in either age group that nontarget words were overtly confused with target words in working memory. Another test of the deletion function involved comparing the dual-task word span with the LST. Both had the concurrent task requirement to respond to animal names, but unlike the LST, the dual-task word span did not require the inhibition of any words. Contrary to the predictions of the inhibition-deficit hypothesis, age differences were no larger on the LST than on the dual-task word span. Taken together, our findings provided no evidence that inhibitory inefficiency drives the complex span age effect. These results place a potential limitation on the applicability of the inhibition-deficit hypothesis in explaining age differences in working memory.

Another hypothesis that was not supported by the current results is that age differences on the RST are due to an age-related syntactic processing decline. Processing syntax requires working memory in order to briefly store earlier parts of the sentence and to integrate the structure and meaning of the sentence. If older adults have difficulty processing sentences, then we would expect a larger age effect on the RST, which required sentence comprehension, compared with the LST, which required reading word lists and responding to animal names. Contrary to this hypothesis, the results showed equivalent age effects on the two tasks. This suggests that the type of verbal background task used in complex spans does not have an effect on age differences, and it also supports the idea that syntactic processing involves an automatic type of working memory that is not necessarily affected by aging (Waters & Caplan, 2001). Although the RST sentences did not have particularly complex syntactic structures, there was no evidence in the context of this complex span task that older adults' difficulty with comprehension and syntax contributed to their lowered performance. In summary, we failed to find support for explanations of complex span age differences based on the central executive functions of concurrent task coordination and inhibition, nor did we find support for the hypothesis that a decline in syntactic processing drives the age effect.

Turning now to the hypotheses that were supported, we found evidence that a reduced ability to store verbal material in working memory contributes to older adults' lowered complex span performance. Age differences in complex span were no greater than those in word span, suggesting that word span and complex spans capture a similar amount of age-related variance that is presumably related to storage capacity. In addition, a comparison of complex span performance of younger and older adults by using span sizes calibrated to their individually determined word span scores showed no effect of age on the complex span tasks. Also consistent with the storage-deficit hypothesis was the finding that word span performance was a significant predictor of complex span. This suggests that the ability to store information in working memory is strongly related to, and predictive of, complex span performance. Previous studies have also provided support for the storage-deficit hypothesis (e.g., Belleville et al., 1998; Verhaeghen et al., 1993).

Another hypothesis supported in the current study concerned the role of processing speed. The processing speed construct is an attribute of information processing that influences performance in many cognitive domains. In the context of working memory, it has been hypothesized to affect the rate of information rehearsal and the amount of information available for current use from previous processing steps (Salthouse, 1996). In the current experiment, the lower level speed measures showed age differences and were significant predictors of complex span performance. The findings indicate that older adults' reduced lower level processing speed can account for most of the age-related variance on complex span tasks.

With respect to the speed of higher level language processing, one hypothesis was that older adults might be slower to process language-based materials, resulting in decreased complex span scores. Although higher level language processing depends in part on the speed of processing at the perceptual level, it can be differentiated from the lower level speed construct because it also involves the processing of meaningful verbal material. In the current study, older adults were slower to respond on higher level language tasks. More importantly, the language tasks were significant predictors of complex span, and controlling for them reduced the age effect by about half. Although these tasks were strong predictors of complex span performance, they explained considerably less age-related variance than the lower level speed tasks. This pattern of findings not only provides support for Salthouse's (1996) theory regarding the explanatory power of lower level processing speed but also suggests that age-related changes in higher level functions may involve some nonspeeded components that do not show age-related decline or some highly automatic language-based skills that do not show age-related reductions in speed.

Our results to this point indicate that although storage capacity, language processing efficiency, and lower level processing speed were individually significant predictors of complex span performance and although each reduced the age effect substantially, none rendered it nonsignificant. We therefore tested hierarchical combinations of lower level processing speed with storage capacity and higher level language processing to determine whether they could fully account for age differences in complex span. The regression results indicated that including the lower level speed tasks and the language tasks as predictors resulted in a substantial reduction of, but not elimination of, the complex span age effect. However, when the lower level speed tasks and the word span task were included as predictors, the age effect was rendered nonsignificant. Thus, although both combinations of variables substantially reduced the age effect, the strongest explanation of complex span age differences was based on independent contributions of storage capacity and lower level processing speed.

Because our results suggested the importance of both speed and storage in explaining the complex span age effect, we further explored the degree of independence between them. Lower level processing speed was a significant predictor of word span; however, age still made a significant contribution above and beyond speed. Therefore, although processing speed is related to word span ability, the results of this post hoc analysis support the conclusion that verbal storage capacity is a distinct factor and not just a function of processing speed.

Taken together, our results indicate that storage capacity is the working memory function that best explains age differences on complex span tasks. In terms of the Baddeley and Hitch (1974, 1994) model of working memory, this suggests that constraints on verbal storage in the phonological loop and possibly in the episodic buffer (Baddeley, 2000), and not the functions of the central executive, are the critical determinants of age-related complex span task performance. Constructs related to processing speed, in particular the speed of lower level perceptual processes, are also important in explaining the age effect in complex span. Higher level language processing speed overlapped with the lower level processing speed measures but also made a unique contribution to the complex span age effect. This could be due to the storage requirement of speeded language tasks or to the additional slowing of older adults' processing of meaningful and complex verbal materials.

In conclusion, complex span tasks are extensively used in the cognitive-aging literature as measures of working memory and also as predictors for higher order cognitive abilities. Considering the multiple cognitive demands of these tasks and the conflicting evidence in the literature over which components are most predictive of age differences in complex span performance, it is important to systematically examine which theoretical constructs have the most empirical support. Overall, the three major conclusions of this study are that (a) storage capacity explains most age differences on complex span; (b) lower level processing speed accounts for as much of the age-related complex span variance as storage and for about half of the contribution of storage to complex span performance; and (c) the two constructs together are successful in explaining essentially all the complex span age effect. Although it is clear that there are several sources of age differences on complex span tasks, the results of this study suggest that storage capacity is the most predictive working memory–specific function and that lower level processing speed is a more general ability strongly associated with age-related complex span performance.

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