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THE EFFECTS OF AGE ON PROCESSING AND STORAGE IN WORKING MEMORY SPAN TASKS AND READING COMPREHENSION

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Background/Study Context: *Declines in verbal working memory span task performance have been associated with deficits in the language processing abilities of healthy older adults, but it is unclear how storage and processing contribute to this relationship. Moreover, recent studies of the psychometric properties of span measures in the general cognitive literature highlight the need for a critical reassessment of age-related differences in working memory task performance.*

Methods: *Forty-two young* (M_{age} = *19.45 years) and 42 older participants* (M_{age} = *73.00 years) completed a series of neuropsychological screening measures, four memory span tasks (one-syllable word span, three-syllable word span, reading span, and sentence span), and a measure of reading comprehension. Each span measure was completed under self-paced and timed encoding conditions. A 2 (age)* × *2 (task type)* × *2 (encoding conditions) mixed-model design was used.*

Results: *(1) Age effects were reliable for both simple and complex span task performance; (2) limiting the available encoding time yielded lower recall scores across tasks and exacerbated age differences in simple span performance; and (3) both encoding condition and age affected the relationship between each of the span measures and the relationship between span and reading comprehension.*

Conclusion: *Declines in both storage and processing abilities contributed to age differences in span task performance and the relationship between span and reading comprehension. Although older people appear to benefit from task administration protocols that promote successful*

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memory encoding, researchers should be aware of the potential risks to validity posed by such accommodations.

Working memory is a limited-capacity short-term memory system responsible for both the immediate processing (manipulation) and storage of information (Baddeley, 1986). The amount of information a person is able to maintain in working memory, or working memory capacity (WMC), is measured with span tasks. Researchers typically rely on two different types of span tasks to assess a person's WMC: simple and complex span tasks (Unsworth & Engle, 2007). Simple span tasks, such as word span, measure storage in working memory, whereas complex span tasks, such as the reading span task (Daneman & Carpenter, 1980), measure both processing and storage in working memory.

In general, complex span tasks have been found to be comparatively better indicators of performance on measures of higher-order cognition, such as reading comprehension (Daneman & Merikle, 1996). There is some dispute about the reason for this finding, but theorists seem to agree that the processing and storage components of complex span tasks better approximate executive processes involved in reading comprehension, such as integrating new and old information stored in long-term memory (Engle, Kane, & Tuholski, 1999; Baddeley, 1986). In the present study, I examined the contribution of age, rehearsal maintenance (keeping information in memory), and task demands to the relationship between memory span performance and reading comprehension for healthy young and older adults.

There is considerable evidence that increased age is typically accompanied by mild to moderate reductions in a person's WMC (Bopp & Verhaghen, 2005). Studies have shown correlations for healthy older adults in which lower working memory span task performance is related to impairments in other verbal activities, such as comprehension for complex sentence structures (Kemper & Liu, 2007; Kemtes & Kemper, 1997; Norman, Kemper, & Kynette, 1992) and discourse (Stine & Wingfield, 1990; Zabrucky & Moore, 1994; although see Light & Anderson, 1985). Thus, declines in WMC may contribute to communication difficulties in advanced age, but it remains uncertain if deficits in storage and processing in working memory independently or collectively contribute to communication failures (MacDonald & Christiansen, 2002; Caplan & Waters, 2002).

Craik and Byrd (1982) postulated that adult age differences in memory performance reflect a decline in the processing resources required for successful encoding (getting information into) and retrieval from memory. For example, studies have shown that although both young and older adults exhibit greater difficulty with tasks that require the active processing and storage of information, age effects are more pronounced on tasks that require both processing and storage as compared with tasks that require mere storage (Morris, Glick, & Craik, 1988; Craik, 1986). Additionally, increasing the processing demands of the task tend to exacerbate age differences in task performance (Glick, Craik, & Morris, 1988). Thus, this theory would predict greater age effects on complex span measures relative to simple span measures, because complex span measures are more taxing on processing resources.

Despite the relative success of the processing resource theory (and others) at explaining age-associated variance in span task performance, a critical reexamination of the effects of age on both span task performance and the relationship between span and verbal cognition is in order. There are several reasons for this recommendation: First, it is uncertain if the variance in span task performance is due to age-associated declines in storage capacity or processing abilities. Second, it is unclear if and how declines in processing and storage uniquely or collectively contribute to reading comprehension difficulties in advanced age (Waters & Caplan, 1996a; 2005). Third, reports from the general cognitive literature indicate that factors other than sample demographics (e.g., age) can affect span task performance. For example, modifications to the presentation of the span levels, task administration procedure, and scoring protocol can change the nature of what span tasks measure and, perhaps more importantly, their predictive power for higher-order cognition (Unsworth & Engle, 2007; Conway et al., 2005; Friedman & Miyake, 2004, 2005).

In the present experiment, healthy younger and older adults completed two simple span tasks (one- and three-syllable word span) and two complex span tasks (reading and sentence span) under self-paced and timed encoding conditions. In addition, all participants completed a standard measure of reading comprehension. To examine the effect of age and task demands on the relationship between memory span and reading comprehension, recall performance for the two age groups was compared on similar span measures with different storage and processing requirements. The one- and three-syllable word span measures were included in the experiment to examine if declines in the phonological capacity of working memory affect older adults word recall performance (Multhaup, Balota, & Cowan, 1996; Baddeley, Thomson, & Buchanan, 1975). The two complex span measures were included to ascertain if age-associated differences in task performance were due to a reduction in the capacity of working memory (Carpenter, Miyake, & Just, 1994) or declines in a specialized memory system for language processing (Waters & Caplan, 2005). Manipulating the encoding condition allowed me to examine (1) if rehearsal processes contribute to age-related differences in span task recall performance and

(2) the effects of both age and task administration on the relationship between span task performance and reading comprehension.

My predictions for the outcomes are as follows: First, age effects will be evident for both the simple and complex span tasks (Bopp & Verhaeghen, 2005). Moreover, tasks with greater storage requirements will produce lower recall scores across the two age groups and tasks with greater processing and storage requirements will amplify age differences in task performance (Glick, Craik, & Morris, 1988). Second, I anticipate that limiting the available encoding time will minimize age-related differences in span task recall scores (the total number of words recalled in correct serial order). This prediction is based on previous research that has shown that college-aged adults are more likely to implement rehearsal strategies under self-paced encoding conditions, as compared with timed encoding conditions (Friedman & Miyake, 2004), and that older adults seldom and/or ineffectively use rehearsal strategies when memorizing lists of items (Ward & Maylor, 2005; Harris & Qualls, 2000; Bryan, Luszcz, & Pointer, 1999; Sanders, Murphy, Schmitt, & Walsh, 1980). Thus, it would seem that limiting the available time to implement idiosyncratic rehearsal strategies would produce similar recall performance for both age groups. Alternatively, it is possible that because simple span measures are more sensitive to maintenance rehearsal processes (Unsworth & Engle, 2007), limiting the available encoding time could exacerbate age differences for simple span but not complex span task performance. Finally, I predict that complex span tasks will correlate more strongly with reading comprehension (Daneman & Merikle, 1996); that recall scores for the timed administration of the span tasks will correlate more strongly with reading comprehension because limiting encoding time has been shown to increase the predictive validity of span tasks (Friedman & Miyake, 2004); and that age will effect the relationship between span and reading comprehension.

METHODS

Participants

A total of 84 people participated in the study (42 young adults, 42 older adults). The young adults were 17 males and 25 females. The older adults were 18 males and 24 females. The young adults were recruited from the University of Nevada, Las Vegas psychology subject pool and were awarded class credit for their participation. The older adults were recruited from flyers posted in community centers and received \$20 for their participation. Demographic information is in Table 1. The data reported here were collected between Fall 2006 and Spring 2007.

Table 1. Means (and standard deviations) and *t* test comparisons for the demographic and cognitive screening measures

Measure	Young	Old	*T*
Age in years	19.45 (1.78)	73.00 (4.77)	n/a
Education in years	13.90 (1.20)	15.80 (2.90)	−2.05*
Days between testing sessions	9.45 (5.00)	8.48 (2.86)	1.10
Time taken to complete first session (hh:mm)	1:38 (0:28)	1:38 (0:41)†††	0.00
Time taken to complete second session (hh:mm)	1:44 (0:16)†††	1:54 (0:17)†††	0.82
MMSE	29.05 (1.50)	28.45 (1.48)	1.83
LMI_R	38.88 (9.90)††	36.36 (11.12)	1.08
LMI_T	16.85 (3.52)††	15.67 (3.69)	1.48
LMII_R	25.34 (7.53)†	21.67 (8.85)	2.04*
LMII_T	11.68 (2.81)†	10.48 (3.38)	1.77
LMII_RT	26.05 (2.56)	25.40 (3.12)	1.03
BNT	13.24 (1.54)	14.00 (1.19)	−2.53*
WAIS-VOCAB	45.39 (9.11)†	52.07 (7.57)†	−3.61**
WAIS-BDS	6.48 (1.86)	5.98 (2.23)	1.12
Alpha span	11.64 (2.34)	9.60 (2.47)	3.90**
ND reading comprehension	1.49 (.25)	1.27 (.27)	3.73**

Note. MMSE = Mini Mental State Evaluation; LMI_R = Logical Memory I recall total; LMI_T = Logical Memory I thematic total; LMII_R = Logical Memory II recall total; LMII_T = Logical Memory II thematic total; LMII_RT = Logical Memory II recognition total; BNT = Boston Naming Test; WAIS-VOCAB = WAIS-R vocabulary subtest; WAIS-BDS = WAIS-R backwards digit span; Alpha span = alphabet span; ND reading comprehension = Nelson-Denny reading comprehension.

$^{*}p < .05$; $^{**}p < .01$. $^{\dagger}n = 41$; $^{\dagger\dagger}n = 40$; $^{\dagger\dagger\dagger}n = 37$.

Tasks, Tests, and Materials

All participants were tested on a battery of neuropsychological measures to rule out any signs of cognitive decline or dementia. The background measures included the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975), the Logical Memory I and II subtests of the Wechsler Memory Scale—Revised (WMS-R, Wechsler, 1987), the Wechsler Adult Intelligence Scale—Revised (WAIS-R) backwards digit span (Wechsler, 1981), the WAIS-R vocabulary subtest (Wechsler, 1987), the alphabet span (Craik, 1986), and a computerized version of the 15-item abbreviated Boston Naming Test (BNT; Kaplan & Goodglass, 1972). The MMSE is a brief evaluation measure of dementia. The Logical Memory subtests require participants to listen to short stories and subsequently respond to a series of questions about the stories. The backwards digit span requires participants to view a series of random digit strings and subsequently recall the digit strings in reverse order and is sometimes used as a measure of working memory (Norman et al., 1992). The WAIS-R vocabulary subtest requires the examinee to listen to and orally define 36 unique items. The BNT is a measure of language competence that requires the participant to view and identify a series of pictorial illustrations. The alphabet span task requires participants to view a set of words and recall the words in alphabetical order.

Reading comprehension was assessed using the Nelson-Denny Reading Test Form E (Brown, Bennett, & Hanna, 1981). The test consists of eight passages and each is followed by four multiple choice comprehension questions (five answer choices). Due to space constraints on the testing apparatus, one of the eight original passages was omitted from the computerized version of the reading comprehension measure, leaving the final number of passages to seven.[1] Topics range from science to the arts. Participants were allowed 20 min to read as many passages and answer as many question sets as they could.

In the present experiment, the passages and questions were administered electronically on a computer with 14 point Times New Roman font. Participants read each passage silently and, when finished, pressed the space bar to activate the multiple choice comprehension questions. Each comprehension question appeared individually below the reading passage (this procedure is consistent with the original paper-pencil test protocol). Participants entered their choices by selecting the correct answer from a specially labeled set of keys on the keyboard. Once a response was entered, the next question appeared in place of the previous question. All responses were final (e.g., participants could not change their responses for previous items). Responses and reading times were discretely recorded by the computer for subsequent analysis. Each correct response was valued at two points.

Four different span tests were used: (1) word span with one-syllable words, (2) word span with three-syllable words, (3) the Daneman and Carpenter (1980) reading span task, and (4) the Waters and Caplan (1996) sentence span task.

The word span task requires participants to silently read lists of random words and subsequently recall as many of the words as they could in serial order. Two versions of the test were created, using one-syllable words in the first version and three-syllable words in the second (66 one-syllable nouns and 66 three-syllable nouns). Each span level consisted of three unique sets and one trial per set was used. Task stimuli were obtained from the online Kucera and Francis (1967) database from the University of Western Australia MRC Psycholinguistic database. Words were selected based on their properties (nouns), frequency (17 to 38 words per million),

[1]The omitted passage was approximately four paragraphs longer than the seven other passages and consisted of eight questions.

and syllable length (one, three). These words were different than the target words in the other span task measures.

The Daneman and Carpenter (1980) reading span task requires participants to read sets of sentences aloud and, at the end of the set, to recall the last word of each sentence in serial order. The task contained 66 sentences, including six practice sentences. Each span level consisted of three unique sets and one trial per set was used.

The Waters and Caplan (1996) sentence span task requires participants to silently read sets of syntactically normal and complex sentences, decide whether each sentence is plausible, and recall the last word of each sentence at a designated recall period. An example of an acceptable sentence might be *It was the gangsters that broke into the warehouse.* An example of an unacceptable sentence might be *It was the housewife that angered the cigarette butts.* In this example, the target words would be *warehouse* and *butts.* The traditional sentence span task consists of 200 acceptable and 200 unacceptable sentences divided among four different sentence types (cleft subject, cleft object, object- subject, and subject-object). In the present experiment, however, only 66 cleft subject (CS) sentences (i.e., sentences that have been divided into two clauses with the focus on the subject) were used, six of which were practice items. Half of the sentences were acceptable and half of the sentences were unacceptable. Each span level consisted of three unique sets and one trial per set was used.

In contrast to the reading span task (Daneman & Carpenter, 1980), for the sentence span task, participants were instructed to read each sentence silently. In addition, immediately after reading it they were to decide whether the sentence made sense. Participants entered their responses on the keyboard by manually pressing specially labeled "yes" and "no" keys (respectively, the *z* and *m* keys on the keyboard). After a response was entered, the computer advanced to the next sentence or to the recall asterisk at the designated time.

Two parallel forms of each span task were constructed (same items, different order) and they were counterbalanced across testing sessions to control for memorability and deter practice effects. Task stimuli were divided into six randomized spans. Each span was composed of three trials followed by a recall period. The number of to-be-recalled stimuli either increased or decreased with each successive span. For example, one version of the reading span task began with a practice span, followed by Spans 3, 6, 2, 4, and 5. The alternative version began with a practice span, followed by Spans 3, 2, 6, 5, and 4. Thus, in Span 2 the participant recalled three sets of two words, for a total of six words. In Span 3, the participant recalled three sets of three words, for a total of nine words, and so on.

All working memory task stimuli were presented visually to the participants on a personal computer in white 36 point Arial font. For the self-paced encoding condition, participants were allowed to progress through each span task word or sentence at their own pace. The participants would advance to the next word or sentence by pressing the spacebar on the keyboard after they finished reading the presented item. For the timed encoding condition of the span tasks, each word span item appeared for 1000 ms and each reading span and sentence span item appeared for 6000 ms. For the timed version of the sentence span task, after each sentence appeared on the screen, the screen would go blank, at which time the participant was instructed to enter their sentence accuracy decision. Acceptability judgments could only be entered once the sentence disappeared from the computer screen and not sooner.

The end of each span level was signaled by the appearance of a short message on the computer screen ("Go on to the next level?") for which the participant was instructed to press the key marked "yes." The recall period was signaled by the appearance of a white asterisk on the computer monitor. Participants would then recall the words out-loud to the experimenter who would record the responses on a score sheet. All testing sessions were audio-recorded and checked for accuracy by a blind rater. A participant's span score was the total number of words recalled in correct serial order.

Computerized experimental tasks were administered on a Macintosh personal computing system (http://www.apple.com) and programmed using PsyScope 1.2.5 (http://psyscope.psy.cmu.edu/psyscope). All text stimuli were white against a solid black background.

Experimental Procedure

Testing was completed over two sessions. In the first session, participants signed consent forms, completed a short demographic questionnaire, and completed the screening measures, followed by either the self-paced or timed versions of the working memory span measures (participant assignment to self-paced or timed encoding conditions was randomized across testing sessions). Because the Logical Memory measures are required to be administered at different times, the screening measures were administered in pseudorandom order, such that all participants first completed the Logical Memory I test, then the other screening measures (each administered in randomized order for each participant), and then the Logical Memory II test. After completing the screening measures, the participants then completed the memory span measures (each administered in randomized order for each participant). In the second session, participants completed either the timed or self-paced version of the working memory span measures and the reading comprehension measure (all administered in randomized order for each participant). For all participants, testing sessions were held a minimum of one week apart.

RESULTS AND DISCUSSION

Cognitive Screening Measures

Scores for two younger participants and one older participant were lost. Independent-samples *t* tests were conducted on the young and older adults' scores on the cognitive screening measures. As can be seen in Table 1, although the older adults scored substantially higher on the WAIS-R vocabulary subtest and Boston Naming Task, the younger adults performed comparatively better on several of the other measures. Nevertheless, all participants performed within acceptable limits to be included in the study and no indication of significant neuropsychological impairment was detected within either age sample.

Analysis of Recall Scores for the Simple Span Tasks

The means and standard errors for the span measure scores are presented in Figure 1.

Recall scores for the one- and three-syllable word spans were submitted to a 2 (encoding condition) × 2 (task) × 2 (age) mixed-model analysis of variance (ANOVA). Although the three-way interaction between encoding condition, task, and age was not significant, the interaction between encoding condition and age was significant, $F(1, 82) = 7.62$, $p < .007$, ${\eta_p}^2 = .085$. The younger participants recalled more self-paced, $F(1, 166) = 53.72$, $p < .001$, and timed, $F(1, 166) = 20.36$, $p < .001$, word span items than the older adults. Pairwise comparisons using a corrected Bonferroni procedure indicated significant within-group differences, such that the younger adults self-paced recall ($M = 54.18$, $SD = 5.41$) was significantly better than their timed recall ($M = 49.71$, $SD = 5.97$), $p = .001$. A similar pattern was found for the older participants self-paced and timed recall ($M = 47.18$, $SD = 6.63$ and $M = 45.40$, $SD = 6.66$), $p = .002$, but the observed means were smaller than the younger adults'. Across the age groups, people recalled more words under self-paced condition than the timed condition, resulting in a significant main effect of encoding condition, $F(1, 82) = 40.94$, $p < .001$, ${\eta_p}^2 = .333$.

Both young and older adults recalled more one-syllable than three-syllable word span items, resulting in a significant main effect of

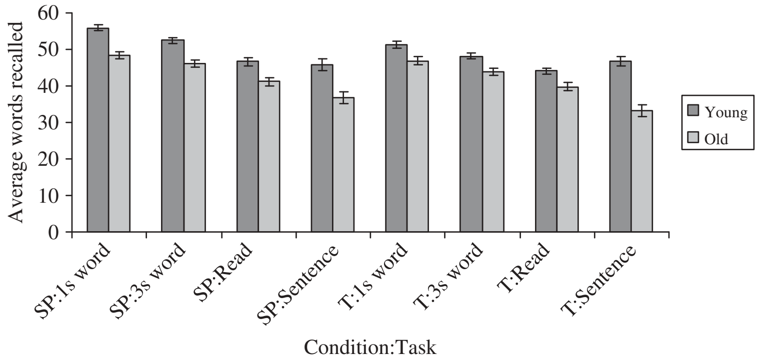

Figure 1. Average number of words recalled for the self-paced and timed encoding conditions of the four memory span measures. Error bars represent standard errors. SP: 1s word = self-paced one-syllable word span; SP: 3s word = self-paced three-syllable word span; SP: Read = self-paced reading span; SP: Sentence = self-paced sentence span; T: 1s word = timed one-syllable word span; T: 3s word = timed three-syllable word span; T: Read = timed reading span; T: Sentence = timed sentence span. Young and older adults' recall scores differed significantly for all measures, all *p*s < .01.

task, $F(1, 82) = 45.96$, $p < .001$, $\eta_p{}^2 = .359$. In addition, the younger adults recalled more words as compared with the older adults, $F(1, 82) = 26.30$, $p < .001$, $\eta_p{}^2 = .243$. The interaction between time and task and task and age was not significant, $F(1, 82) = .04$, $p = .845$ and $F(1, 82) = .50$, $p = .481$, respectively.

In sum, the results of the analysis of the simple span recall scores indicate that healthy aging is accompanied by a decline in storage capacity. The younger adults recalled more one- and three-syllable words relative to the older adults. In addition, limiting the available time to encode the words yielded impaired recall performance for both age groups, and this finding was more pronounced for the older participants (see Figure 1). This finding suggests that age-related decline in encoding strategies contributes to adult age differences in recall performance. Finally, although word length contributed to poorer recall (Baddeley et al., 1975), the older adults were not differentially impaired by this manipulation. Thus, increasing the memory demands of the simple span task failed to elicit greater age effects in recall performance. That the word length effect operated similarly across both age groups seems to further support the notion that older adults rely on phonological rehearsal in a similar manner as the young adults.

Analysis of Recall Scores for the Complex Span Tasks

Recall scores for the reading and sentence span measures were submitted to a 2 (encoding condition) × 2 (task) × 2 (age) mixed-model ANOVA. The three-way interaction between encoding condition, task, and age was significant, $F(1, 82) = 13.24$, $p < .001$, $\eta_p^2 = .139$. Separate ANOVAs were conducted to examine the unique and interactive contribution of each variable on the three-way interaction.

To examine the effect of task and age on complex span task performance, recall scores were submitted to a 2 (task) × 2 (age) mixed-model repeated-measures ANOVA. The two-way interaction between task and age was significant, $F(1, 166) = 28.87$, $p < .001$, $\eta_p^2 = .148$. Follow-up tests of simple effects indicated that the younger adults recalled more reading and sentence span items, relative to the older adults, $F(1, 166) = 19.15$, $p < .001$, $\eta_p^2 = .103$ and $F(1, 166) = 51.78$, $p < .001$, $\eta_p^2 = .238$. Pairwise comparisons for the within-group effect of age on task performance indicated that although the younger adults' reading and sentence span scores did not differ significantly, $p = .283$, the older adults recalled more reading span items ($M = 40.49$, $SD = 7.50$) than sentence span items ($M = 34.94$, $SD = 10.70$), $p < .001$.

To examine the effect of encoding condition and age on complex span task performance, recall scores were submitted to a 2 (encoding condition) × 2 (age) mixed-model repeated-measures ANOVA. Superior recall was observed for self-paced span task condition as compared with timed condition, $F(1, 166) = 10.04$, $p < .002$, $\eta_p^2 =.057$. The younger adults recalled more self-paced ($M = 46.20$, $SD = 9.24$) and timed ($M = 45.45$, $SD = 7.47$) items, relative to the older adults (respectively, $M = 38.95$, $SD = 9.54$ and $M = 36.48$, $SD = 9.60$), resulting in a significant main effect of age, $F(1, 166) = 39.16$, $p < .001$, $\eta_p^2 = .191$. However, the interaction between encoding condition and age was not significant, $F(1, 166) = 2.88$, $p = .092$

To examine the effect of encoding condition and task on complex span performance, recall scores were submitted to a 2 (encoding condition) × 2 (task) repeated-measures ANOVA. People recalled more items under the self-paced task condition, relative to timed condition, resulting in a significant main effect of encoding condition, $F(1, 83) = 7.61$, $p < .007$, $\eta_p^2 = .084$. People recalled more reading span items as compared with sentence span items, resulting in a significant main effect of task, $F(1, 83) = 8.07$, $p < .006$, $\eta_p^2 = .089$. However, the interaction between encoding condition and task was not significant, $F(1, 83) = .46$, $p = .499$.

The results of the analysis of the complex span recall scores indicates that the majority of the variance in span task performance was driven by the interaction between age and task. First, the young adults recalled more reading and sentence span task items than the older adults, which suggests that age differences in complex span task recall were due to declines in how older persons store and process information in working memory. Second, whereas the older adults recalled more reading than sentence span items, there was no significant difference between the young adults' reading and sentence span recall, which suggests that the requirements of the sentence span task were more cognitively taxing on the older adults than those of the reading span task.

The results also indicate that encoding condition contributed to the variance in complex span task recall scores, but it did not interact with age. The old adults recalled fewer items in the self-paced and timed encoding conditions relative to the young adults. This finding suggests that although the older adults had difficulty balancing the processing and storage requirements of the complex span measures, they were not differentially impaired by the encoding manipulation. Thus, both age groups benefited from the self-paced encoding condition, relative to the timed encoding condition.

It is noteworthy that although the younger adults reading and sentence span recall scores did not differ significantly, the older adults' scores did. Although the storage requirements are similar for both the tasks, the processing requirements are different. Therefore, it seems plausible that the sentence verification component of the sentence span task was more taxing on the older adults' ability to maintain the target items in memory as compared with reading the sentences out-loud, as in the reading span task. If so, then this raises the possibility that the older adults sacrificed recall performance by devoting their attention to the processing component of the sentence span task. Confirmation of a trade-off between storage and processing would be evidenced by the lack of an age effect on the sentence judgment scores. Alternatively, it is possible that the combined storage and processing components of the sentence span task were taxing for the older adults, in which case the older adults would exhibit both lower recall performance (as demonstrated here), as well as impaired sentence judgment performance.

A key feature of the sentence span task is that storage (sentence final word recall), processing (accuracy for the sentence verification component), and processing speed may be assessed independently (for a more detailed discussion of this point; see Waters & Caplan, 1996, 1996a). To examine the potential for processing and storage trade-offs, an analysis of the sentence span sentence judgment scores was conducted.

Analysis of Sentence Span Sentence Judgment Scores

Sentence span accuracy scores were submitted to a 2 (encoding condition) $\times$ 2 (age) mixed-model ANOVA. People's sentence judgments were more accurate in the self-paced encoding condition ($M = 60.76$, $SD = 3.18$) as compared with the timed encoding condition ($M = 59.83$, $SD = 4, 71$), $F(1, 82) = 4.86$, $p < .030$, $\eta_p{}^2 = .056$. However, the two age groups did not differ in their sentence judgments, $F(1, 82) = .24$, $p = .622$, and the interaction between encoding condition and age was not significant, $F(1, 82) = 1.84$, $p = .179$.

The main finding from the analysis of the sentence span judgment scores was that older adults performed similarly to the younger adults, which suggests that the older participants did indeed devote greater resources to the processing component of the sentence span measure and, consequently, recalled fewer target items. To examine the possibility of speed-accuracy trade-offs in sentence plausibility judgments, additional analyses were conducted on the response times to the sentence plausibility component of the sentence span task. If the older participants were slower to respond to the sentence plausibility component of the sentence span task relative to the young participants, this would suggest a slowing in the speed at which they are able to process the sentences (Salthouse, 1996). Alternatively, if no age differences are found for the sentence plausibility response times, this would suggest that older adults' sentence span performance was impaired by declines in working memory (Waters & Caplan, 2005).

Response times for the sentence span sentence verification component were submitted to a 2 (encoding condition) × 2 (age) mixed-model ANOVA. The interaction between encoding condition and age was marginally significant, $F(1, 82) = 3.71$, $p = .057$, $\eta_p{}^2 = .043$. Both age groups were faster to enter their responses in the timed encoding condition ($M_{young} = 1.25$ s, $SD_{young} = .68$ and $M_{old} = 1.99$ s, $SD_{old} = 1.40$) as compared with the self-paced encoding condition ($M_{young} = 5.44$ s, $SD_{young} = 1.78$ and $M_{old} = 5.51$ s, $SD_{old} = 1.32$), and the young adults were faster to respond in the timed condition relative to the older adults response times in the self-paced condition, ps $= .001$. None of the other comparisons were significant, $p = 1.00$.

The primary motivation for analyzing the sentence span sentence judgment scores and response times was to ascertain if older adults' impaired recall performance was due to trade-offs between processing and storage and speed and accuracy. It was found that young and older adults performed similarly within both encoding conditions. This outcome suggests that although working memory capacity limitations impaired the older adults' ability to successfully balance both maintaining target items in memory and responding to the sentence verification component, they were not differentially impaired by age-related declines in processing speed (Salthouse, 1996).

In addition, it was found that participants performed better on the sentence verification component in the self-paced encoding condition and were faster entering their responses in timed encoding conditions. Coupled with the previous finding that both groups recalled more complex span task items in the self-paced encoding condition of the complex span tasks relative to the timed encoding condition, the observed effect of encoding condition on the sentence judgment component accuracy and response times suggests that disruptions in the rehearsal of complex span tasks affects both storage and processing performance. However, the lack of a significant interaction between the age and encoding condition variables indicates that older adults' processing performance was not differentially impaired by limiting the available encoding time.

Bivariate Correlations Between the Recall Scores for the Simple and Complex Span Tasks

To examine the effects of age, encoding condition, and task demands on the relationship between the span task measures, separate Pearson correlation coefficients were calculated for each of the age groups span task recall scores (see Tables 2 and 3). For both age groups, limiting the encoding time of the span tasks appears to have reduced the magnitude of the correlations between the recall scores for each of the measures (with the

Table 2. Bivariate correlations between self-paced (top) and timed (bottom) span scores for the younger participants

Measure	1s word span	3s word span	Reading span	Sentence span
1s word span	—	.57**	.47**	.50**
3s word span	.64**	—	.57**	.48**
Reading span	.28	.33*	—	.79**
Sentence span	.35*	.27	.56**	—

Note. 1s word span = one-syllable word span; 3s word span = three-syllable word span. *$p < .05$; **$p < .01$.

Table 3. Bivariate correlations between self-paced (top) and timed (bottom) span scores for the older participants

Measure	1s word span	3s word span	Reading span	Sentence span
1s word span	—	.66**	.52**	.66**
3s word span	.78**	—	.56**	.60**
Reading span	.30	.48**	—	.70**
Sentence span	.52**	.60**	.53**	—

Note. 1s word span = one-syllable word span; 3s word span = three-syllable word span. *$p < .05$; **$p < .01$.

exception of the relationship between one- and three-syllable word span recall), by a factor of approximately .20 for the young and .13 for the older adults. Within-group correlation coefficients for the span scores were submitted to separate tests of significance for dependent correlations for each age group using DEPCOR (Silver, Hittner, & May, 2006). Although the correlations between younger adults' self-paced reading and sentence span ($r = .79$) and timed reading and sentence span ($r = .56$) differed significantly (Dunn and Clark $z = 2.33$, $p = .02$), this pattern of correlations was not observed for the older participants' complex span scores, $z = 1.73$, $p = .08$. None of the other correlations differed significantly, all ps $> .05$. Tests for significance of independent correlations were conducted on the correlation coefficients for the young and older adults' span scores using Fisher's r to z test (Cohen, Cohen, West, & Aiken, 2003); however, none of the correlations differed significantly between the two age groups, all ps $> .05$.

It is noteworthy that the results of the correlational analyses suggest that limiting the available time for participants to use rehearsal strategies reduced the correlations between the recall scores for the complex span measures (Friedman & Miyake, 2004). For both age groups, the magnitudes of the correlations between self-paced recall scores for both of the simple and both of the complex span tasks were relatively similar, with a combined average of $r = .53$ for the reading span and $r = .56$ for the sentence span. However, limiting the encoding time of the span tasks reduced the overall correlations between simple and complex span recall scores to a combined average of $r = .35$ for the reading span and $r = .44$ for the sentence span. Interestingly, the correlation coefficients between the older adults' timed word and sentence spans were somewhat higher, relative to the younger adults'. Collectively, these outcomes suggest that both individual difference variables, as well as experimental manipulations contribute to the relationship between recall scores for simple and complex span tasks (Unsworth & Engle, 2007).

Nelson-Denny Reading Comprehension

t tests were conducted on the young and older participants' passage and question reading times and reading comprehension performance on the Nelson-Denny reading comprehension measure. Although the young ($M = 61.68$ s, $SD = 20.60$) and older ($M = 67.13$ s, $SD = 19.37$) adults' average passage reading times did not differ significantly, $t(82) = -1.25$, $p = .22$, the younger adults' average question reading times ($M = 14.85$ s, $SD = 4.89$) were significantly faster than the older adults' average question reading times ($M = 18.94$ s, $SD = 7.70$), $t(82) = -2.91$, $r^2 = .09$, $p < .005$.

One young adult and seven old adults did not read all seven passages in the allotted time (20 min), and were thus unable to answer the comprehension questions for those passages. Therefore, ratio scores (total points earned divided by the number of questions actually answered) were calculated for all participants. Independent-samples *t* tests confirmed that there was a statistically significant difference between young and older adults' ratio scores, $t(82) = 3.73$, $r^2 = .15$, $p < .001$, with lower accuracy for the older adults as compared with the younger adults.

Bivariate Correlations Between Span Scores and Reading Comprehension

Separate Pearson correlation coefficients were calculated to examine the relationship between recall scores and reading comprehension. In contrast to previous research that has shown complex span task performance to be more strongly correlated with reading comprehension (Daneman & Merikle, 1996), recall scores for all of the span tasks were significantly associated with scores on the reading comprehension measure and none of the correlation coefficients differed significantly, all *p*s > .05.[2] This outcome indicates that both storage alone (as measured by the simple span measures) and storage and processing together (as measured by the complex span tasks) contribute to the relationship between span and verbal cognition. In addition, I expected that recall scores for the timed encoding condition of the span measures would be more strongly associated with reading comprehension, relative to the scores for the self-paced encoding condition (Friedman & Miyake, 2004). However, as evidenced from the overall pattern of correlations in Table 4, although there was some variation in the magnitude of the correlation coefficients, recall scores for all of the span measures were significantly correlated with reading comprehension and none of the correlations differed significantly, all *p*s > .05. This outcome suggests that encoding condition did not affect the relationship between span and reading comprehension.

The patterns of correlations for the young and older adults are somewhat puzzling and, due to the relatively low sample sizes, should be interpreted with caution. Nevertheless, there are a couple of interesting features about the pattern of young and old correlations. First, whereas no significant correlations emerged for the younger adults, the older adult's word span scores were significantly associated with reading comprehension. This

[2]Studies have shown that span task scoring procedure affects the magnitude of the relationship between span and verbal cognition (Friedman & Miyake, 2005; Waters & Caplan, 2003). The span task scoring procedure used in the current study (total words recalled) was selected based on the recommendations of Friedman and Miyake (2005) who reported that it was a more reliable span metric than other scoring methods.

Table 4. Bivariate correlations between memory span and reading comprehension

Measure	$r_{overall}$	$r_{self\text{-}paced}$	r_{timed}	r_{young}	r_{old}	$r_{youngsp}$	r_{youngt}	r_{oldsp}	r_{oldt}
1s word span	**.42**	**.46**	**.30**	.14	**.39**	.13	.12	**.46**	.27
3s word span	**.45**	**.39**	**.44**	.23	**.42**	.16	.24	.34	**.46**
Reading span	**.33**	**.33**	**.29**	.21	.25	.20	.18	.26	.20
Sentence span	**.38**	**.33**	**.40**	.19	.27	.19	.16	.22	.30

Note. 1s word span = one-syllable word span; 3s word span = three-syllable word span. $r_{overall}$ = correlation between the span measures and reading comprehension for all participants; $r_{self\text{-}paced}$ = correlation between self-paced span task recall and reading comprehension for all participants; r_{timed} = correlation between timed span task recall and reading comprehension for all participants; r_{young} = correlation between the younger adults' span task recall and reading comprehension; r_{old} = correlation between the older adults' span task recall and reading comprehension; $r_{youngsp}$ = correlation between the younger adults' self-paced span task recall and reading comprehension; r_{youngt} = correlation between the younger adults' timed span task recall and reading comprehension; r_{oldsp} = correlation between the older adults' self-paced span task recall and reading comprehension; r_{oldt} = correlation between the older adults' timed span task recall and reading comprehension.Correlations in bold: $p < .01$.

suggests that at least some of the variance in the relationship between age, span, and reading comprehension is due to deficits in storage. The second interesting aspect of the pattern of correlations is that older adults' self-paced one-syllable and timed three-syllable word spans were significantly associated with reading comprehension. This finding suggests that disruptions in rehearsal processes (e.g., word length effects) cause simple span measures to behave like complex span measures, in terms of the relationship between span and measures of higher-order cognition and that this pattern is enhanced by limiting the available encoding time.

In sum, the results of the correlation analyses indicated that both storage and processing, and to a lesser degree age, contribute to the relationship between span and comprehension. In addition, it would seem that age-related changes in storage may contribute more to the variance in the relationship between span and verbal cognition than processing and storage. Finally, the findings reported here seem to be in agreement with Unsworth and Engle's (2007) proposal that the relationship between span performance and reading comprehension is affected by task, experimental variables, and characteristics of the sample.

GENERAL DISCUSSION

In the present experiment, healthy young and older adults completed four memory span measures, including two simple span tasks (one- and three-syllable word span) and two complex tasks (reading and sentence span).

Participants completed each measure under self-paced and timed encoding conditions. Additionally, participants also completed the Nelson-Denny reading comprehension test.

The prediction that age effects would be evident for both the simple and complex span measures was confirmed. Across tasks, the younger adults recalled more items than the older adults, which suggest that declines in both storage and processing in working memory contributed to the age differences in recall performance. In addition, it was found that increased task demands exacerbated the age-related differences in recall performance for the complex span tasks, but not the simple span tasks. Older adults' recall errors were significantly greater for the sentence span task, relative to the other measures. In addition, it was found that the young and old adults performed similarly on the sentence span sentence judgment component, indicating that the older adults had greater difficulty balancing the processing and storage requirements of the sentence span task. Consistent with Craik and Byrd (1982), these findings suggest that age-related declines in processing may have contributed to the variance in complex span task recall scores.

Previous research has shown that limiting the available time to implement rehearsal strategies yields lower recall scores on complex span measures (Friedman & Miyake, 2004). Additionally, it has been demonstrated that older adults do not use rehearsal strategies as consistently or effectively as younger adults (Ward & Maylor, 2005; Harris & Qualls, 2000; Bryan et al., 1999; Sanders et al., 1980). Therefore, I expected that limiting the available encoding time would minimize age-related differences in recall performance, but this prediction was not confirmed. Although both age groups recalled fewer items under the timed encoding condition (Friedman & Miyake, 2004), the younger adults recalled more span items under both encoding conditions relative to the older adults. However, the interaction between encoding condition and age was significant only for the simple span measures. First, these results indicate that older adults do rely on rehearsal strategies to maintain target items in memory, but it also suggests that they may use them differently or do not use them as effectively as compared with younger adults (Ward & Maylor, 2005) and were therefore differentially impaired by limits on the available encoding time. Second, that the effect of encoding condition was more pronounced for the older adults' simple span task recall indicates that maintenance rehearsal may contribute to storage deficits associated with span task performance (Baddeley, 1986). However, the finding that encoding condition did not differentially impair the older adults' complex span performance is consistent with previous studies that have shown that despite age differences in task performance, young and older adults are equally adept at generating effective encoding strategies, such as maintenance rehearsal (Bailey, Dunlosky, & Hertzog, 2009). On the whole, these outcomes both support and extend Unsworth and Engle's (2007) position that simple span measures are more sensitive to maintenance rehearsal than complex span measures by showing that developmental differences in rehearsal also affect task performance.

The results of the correlational analyses were surprising. Limiting the presentation rate of the span tasks reduced the magnitude of the association between the recall scores for most of the span measures. Age also contributed to the relationship between the recall scores for the span measures, as indicated by the comparatively stronger associations between simple and complex recall scores for the older adults. Perhaps most surprising was the finding that older adults' simple span was significantly associated with reading comprehension. This outcome is not necessarily unprecedented. First, previous aging studies have found that word span recall predicted reading comprehension better than reading span (e.g., Light & Anderson, 1985). Second, experimental variables, administration, and individual differences can affect the relationship between span and measures of higher-order cognition (Unsworth & Engle, 2007). For example, disruptions in phonological rehearsal (e.g., word length) can cause simple span measures to behave like complex span measures. Indeed, the pattern of bivariate correlations between the span recall scores and the reading comprehension scores indicated markedly stronger associations between older adults' three-syllable word span. Moreover, other studies have shown that nontraditional span presentation order affects the relationship between age, memory span, and performance on other verbal measures (Lustig, May, & Hasher, 2001). In addition, it is possible that the within-group sample size may have also contributed to the relatively low correlations between the span scores and reading comprehension scores (Cohen et al., 2003). Nevertheless, the outcomes for the present experiment suggest that declines in the storage capacity of older adults contribute to the relationship between span task performance and measures of verbal cognition.

Prior research has shown that older adults benefit from environmental supports during cognitive testing, such as protocols that promote self-initiated processing or minimize working memory demands (Park, 2000; Craik & Byrd, 1982). That the older adults benefited from additional time to encode strings of information but were not differentially impaired when both processing and storage were taxed is consistent with this line of research (e.g., Craik & Rabinowitz, 1985; Morris et al., 1988) and highlights the value of allowing older people more time to effectively encode information when memorizing information.

Given the finding that encoding condition exerted some influence on the older adults' span task performance, is it possible that other extraneous variables might have exacerbate the observed age-related differences in cognitive task performance? For example, did the computerized presentation of the measures contribute some variance to the span task recall scores? It is unlikely that participants were confused about how to enter their responses, because in addition to receiving explicit instructions about which keys to press, the required keys were specially labeled and/or were easily identifiable (e.g., the spacebar). Moreover, because the participants verbally recalled the span task items, it is not possible that experience with keyboards or typing affected their recall performance (relative to situations in which the participants type their responses). Thus, it is unlikely that computing experience or proficiency contributed to the reported outcomes.

Another possibility is that the observed age differences were due to how well the participants were able to perceive (and therefore store and process) the span task items. For example, recent studies have shown that even when participants are matched for visual abilities, adult age differences in cognitive task performance are exacerbated by differences in the luminance of the presentation (Seichepine et al., 2011). The effortful hypothesis (Rabbitt, 1968; Gao, Stine-Morrow, Noh, & Eskew, 2011) proposes that people must exert more cognitive effort to store and/or process information presented from a perceptually degraded signal and, as such, are more likely to perform at a level that is not reflective of or comparable to the level of performance that would have been observed if the information had been presented from a normal quality stimuli. Because visual perception was not measured for the current study, it is difficult to rule out this possibility. However, if the perceptual quality of the stimuli were an issue in the performance of the current samples, then it likely would have yielded systematic differences in the performance of both age groups (Gao et al., 2011).

Collectively, the outcomes from the present experiment suggest that both storage and processing and storage contribute to adult age differences in span task performance, as well as the relationship between age, memory span, and reading comprehension. In addition, it is recommended that researchers attempt to control extraneous sources of influence on span task performance, such as administration protocols that enable participants to use idiosyncratic strategies, as this was found to interact with the effects of age, especially on the simple span measures. Finally, further research is needed to examine how specific relevant working memory–associated processes, such as search and retrieval from memory (Unsworth & Engle, 2007; Mogle, Lovett, Stawski, & Sliwinski, 2008), contribute to adult age differences in span task performance and the relationship between span and higher-order cognition.

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