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# Age differences in item manipulation span: The case of letter-number sequencing

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**ABSTRACT**

The authors report 2 experiments in which they examined age differences in working memory tasks involving complex item manipulation (i.e., letter-number sequencing). In Experiment 1, age differences on tasks involving item manipulation were not greater than age differences on tasks requiring recall of items in the order in which they appeared, suggesting that older adults do not have difficulty with item manipulation per se. In Experiment 2, slower presentation rates increased age differences in item manipulation spans, although age differences at the fastest rate may be attributed to differences in strategy use. In both experiments, age differences were largest when participants were most likely to be remembering familiar sequences, suggesting that older adults may have difficulties dampening the representations of such sequences once they are activated.

Psychologists have long believed that age has little effect on performance of short-term memory tasks requiring mere repetition of items, such as a forward digit span, whereas larger age differences emerge when tasks involve either item manipulation, as in a backward digit span, or divided attention (e.g., Craik, 1977). This belief may be found restated in such authoritative sources as the *Encyclopedia of Cognitive Science* (Kensinger & Corkin, 2003) and the technical manual for the Wechsler Adult Intelligence Scales (WAIS; Psychological Corporation, 1997) and the Wechsler Memory Scale (WMS; Psychological Corporation, 1997). The broad impact of this view is due, in part, to the fact that it fits well with working memory theories that differentiate between storage and executive functions (Baddeley, 1986) and that conceptualize short-term storage tasks as the passive counterparts of more active tasks that place greater demands on executive functions (Groeger, Field, & Hammond, 1999). This active/passive distinction, in turn, gives rise to the expectation that impaired executive functions in older adults lead to greater age differences on working memory tasks that require active manipulation of memory items than on more passive tasks that rely principally on short-term storage.

More recent data, however, have not always supported the idea that the manipulation of items per se is a particular problem for older adults. For example, although larger age differences are evident in alphabet span tasks (in which participants must recall serially presented words in alphabetical order) than in digit span tasks (Craik, 1986), recent evidence from a study by Belleville, Rouleau, and Caza (1998) suggests that this difference is a result of short-term memory deficits in older adults, not a specific problem with item manipulation. Belleville et al. noted that in addition to differing with respect to the manipulation requirement, alphabet span and digit span tasks also differ in the type of memory items (words vs. numbers). When alphabet span was compared with word span, Belleville et al. found no evidence of an age deficit that was related to manipulation of memory items.

Additional evidence against an age deficit in item manipulation comes from studies examining large sets of normative data. Analyses of the standardization data from both the English and French versions of the Forward and Backward Digit Span subtests of the WAIS indicate that, contrary to expectation, the longest series of digits correctly recalled forwards and backwards actually decline with age at equivalent rates (Gregoire & Van der Linden, 1997; Hester, Kinsella, & Ong, 2004; Myerson, Emery, White, & Hale, 2003; Wilde, Strauss, & Tulsky, 2004). Moreover, examination of scores on the Spatial Span subtest of the WMS revealed that scores on the Forward and Backward Spatial Span subtests also decline at equivalent rates, although the rates of decline for these scores are faster than those for the Digit Span subtests (Myerson et al., 2003).

Nevertheless, the hypothesis of an age deficit related to manipulation of working memory items has received some support from further analyses of the third edition of the WMS (WMS–III) by Myerson et al. (2003). These further analyses focused on the Letter–Number Sequencing subtest, which is based on a complex working memory task originally developed for neuropsychological research (Gold, Carpenter, Randolph, Goldberg, & Weinberger, 1997). In both the original and standardized versions of this task, a series of alternating digits and letters are presented (e.g., L 9 F 2), and participants or examinees must recall the digits first, in ascending order, followed by the letters in alphabetical order (e. g., 2 9 F L). Performance on the standardized version included in the WMS–III and in the third edition of the WAIS (WAIS–III) showed a much greater decline with increasing adult age than on either the Forward or Backward Digit Span subtest (Myerson et al., 2003). These results raise the possibility that although older adults may have a problem simultaneously manipulating and maintaining items in working memory, the manipulation required on backward digit span and alphabet span tasks is not difficult enough to reveal such a deficit.

Although the results of the Myerson et al.'s (2003) analysis of the Letter–Number Sequencing subtest are consistent with the hypothesis that age deficits in executive function lead to difficulties in manipulating and maintaining items in working memory, there are alternative interpretations. For example, age differences are larger in letter span than in digit span tasks (Verhaeghen, Marcoen, & Goossens, 1993), and this may contribute to (and potentially explain) the difference between the rates of age-related decline in Letter–Number Sequencing and Digit Span scores. The situation is directly analogous to the comparison of alphabet span and digit span mentioned previously, in which what appeared to be age differences in the participants' ability to manipulate information in working memory were confounded by differences in the types of memory items (Belleville et al., 1998).

The current study, therefore, was designed to examine older and young adults' performance on item manipulation tasks involving letter–number sequencing and to contrast it with their performance on serial recall span tasks involving simple forward recall of series consisting of both digits and letters. In Experiment 1, we tested older and young adults on item manipulation and serial recall tasks in order to determine whether age differences in memory spans were larger when letter–number sequencing was required. In Experiment 2, we tested older and young adults on item manipulation and serial recall tasks with varying presentation rates in order to determine whether the time required for manipulating the memory items influences age differences in performance.

## EXPERIMENT 1

The primary goal of the first experiment was to determine whether age differences on a working memory task involving item manipulation are larger than age differences in serial recall of the same material. Participants completed four tasks that yielded two measures of serial recall and two measures of item manipulation. Two of the tasks involved only serial recall. In these two tasks, participants had to view and recall either series of alternating letters and numbers (e.g., 7 K 3 B) or grouped series of random numbers and letters, each presented in ascending order (e.g., 3 7 B K). We will refer to the memory spans derived from these tasks as *alternating serial recall* spans and *ordered serial recall* spans, respectively. For the two tasks involving item manipulation, participants always saw a series of alternating letters and numbers (as in the alternating serial recall task) but had to recall the numbers first in ascending order, followed by the letters in alphabetical order (as in the ordered serial recall task). For one of the item manipulation tasks, participants performed only item manipulation trials and were told before the task the order in which they had to recall the items. We will refer to the spans derived from this task as *precued item manipulation* spans. In the other item manipulation task, item manipulation trials were mixed with serial recall trials, and participants were not told how to recall the items until after each series was presented. We will refer to the spans derived from the item manipulation trials of this task as *postcued item manipulation* spans.

In previous research using three of these tasks (all but postcued item manipulation), we found that memory spans in college students were smallest for alternating serial recall and largest for ordered serial recall (Emery, Myerson, & Hale, 2002). That is, digits and letters were better recalled when they were grouped and arranged in a familiar order than when they were presented in a random, alternating order. Spans for precued item manipulation fell between spans for alternating serial recall and ordered serial recall. This presumably occurred because when participants rearranged the letters and numbers in precued item manipulation, the resulting sequence (with items grouped and ordered) was easier to remember than when letters and numbers alternated in sequences. There was, however, a cost to item manipulation, as indicated by the superior recall with ordered serial recall.

If older adults have a particular problem with working memory tasks involving item manipulation, age differences should be larger for precued item manipulation spans than for either of the serial recall spans. Specifically, if older adults have difficulty arranging the items into the easy-to-remember (grouped and ordered) sequence, they would show a smaller benefit of item manipulation relative to alternating serial recall and a larger cost of item manipulation relative to ordered serial recall.

The preceding analysis, however, depends on the assumption that both young and older adults would rearrange the items online (that is, as they are being presented). To encourage participants to do so, we presented the items in the current experiment at a relatively slow presentation rate (one item every 2,500 ms), a rate at which our previous study indicated young adults were able to rearrange the items online. As a check on whether participants in the current experiment manipulated items online, we asked them to perform a postcued item manipulation task in which they were cued only as to whether they should rearrange the letters and numbers after all of the items had been presented. Although participants could choose to manipulate items online in the postcued task, this would require three times as much item manipulation as would waiting until after the cue indicated whether rearrangement was necessary. That is, if they waited for the cue, participants would only have to rearrange items on half of the trials. Alternatively, if they engaged in online manipulation on every trial, on half of the trials they would also have to rearrange the items offline in order to get the items back into their original order for serial recall. Thus, on average, the online strategy would require three rearrangements for every two trials, whereas the offline strategy would require only one. Therefore, we speculated that participants would avoid the online manipulation strategy in favor of the less effortful offline strategy when performing the postcued task.

We compared postcued item manipulation spans with precued item manipulation spans in order to determine whether participants in both age groups were able to rearrange the items as they were being presented. If participants were rearranging the items online during precued item manipulation and reaping the demonstrated benefits of such online rearrangement (Emery et al., 2002), then precued item manipulation spans should be larger than postcued item manipulation spans.

## METHOD

### Participants

Participants in Experiment 1 were 24 young adults and 24 older adults. Young adults (age: *M* = 19.7 years, *SD* = 1.64) were recruited from the Washington University Department of Psychology subject pool and received course credit for their participation. Older adults (age: *M* = 75.6 years, *SD* = 4.26) were recruited from the older adult subject pool and received $10 plus compensation for parking. Two older adults and five young adults did not report their years of formal education. Mean years of education for the remaining participants were 13.4 (*SD* = 1.31) for the young adults and 14.9 (*SD* = 3.07) for the older adults. All participants were administered a modified version of the health questionnaire developed by Christensen, Moye, Armson, and Kern (1992) and were screened for a history of neurological disorder (e.g., stroke, Parkinson's disease), serious illness (e.g., uncontrolled thyroid disease or diabetes, congestive heart failure), current diagnosis of depression, prescriptions for psychotropic medications, and visual problems that would interfere with reading ordinary text even while wearing glasses.

### Apparatus

Stimulus presentation and data collection were controlled by the experimenter using a personal computer and standard keyboard. The tasks were presented using software written in Visual Basic (Version 6.0, Microsoft, Redmond, WA) by Lisa Emery.

### Materials

Memory items—2.5 cm high and printed in a black Arial font—were presented sequentially in a black-outlined square on a gray background in the center of the computer screen. List lengths ranged from 2 to 13 items. List items were randomly chosen from a set of nine digits (1–9) and nine letters (B, F, J, K, L, M, Q, R, and T), selected so as to have minimal phonological similarity. Even list lengths had equal numbers of digits and letters. Half of the odd list lengths had one more digit than they had letters, and the other half had one more letter than digits.

### Tasks

#### *Alternating serial recall*

In this task, each participant saw a series of alternating numbers and letters (e.g., 9, K, 2, T) on each trial, and they were instructed to recall them in the order in which they were presented.

Prior to each series, a green rectangle with the word *START* appeared in the center of the computer screen. When the participant was ready, the experimenter began each trial by pressing the *Enter* key on the computer, at which point the *START* screen disappeared and the presentation of the memory items began. Each item was presented in the center of the computer screen for 1,750 ms, with a 750-ms pause between items. At the end of the series, the participant saw a blue rectangle with the word *FORWARD* on it and heard a low-pitched tone. The participant then recalled the items aloud. The experimenter recorded these items on an answer sheet and also entered into the computer whether the participant's responses were correct.

The first series presented were 2 items long, and the lengths of the series could continue to increase, up to a maximum of 13 items. The series were presented in an ascending format, similar to the Digit Span and Letter–Number Sequencing subtests of the WMS–III. Participants were given three trials at each series length; administration of the trials ended when a participant answered all three trials of a particular series length incorrectly.

*Ordered serial recall*

In this task, each series consisted of a randomly chosen group of ascending numbers, followed by a randomly chosen series of alphabetically ordered letters (e.g., 2, 9, K, T). After the presentation of each series, the participant was to recall the items in the same order in which they had been presented. Other aspects of the procedure were identical to those of the previous task.

*Precued item manipulation*

In this task, each participant also saw a series of alternating letters and numbers (e.g., 9, K, 2, T) on each trial. After the presentation of each series, the participant saw a yellow rectangle with the word *SEQUENCED* on the computer screen and heard a high-pitched tone. The participant was then to recall the numbers first, in ascending order, followed by the letters in alphabetical order (e.g., 2, 9, K, T). Note that although the physical cue to recall the items occurred after the presentation of the items, the recall instructions were given at the beginning of the task, and all series were to be recalled in the same order. Other aspects of the procedure were identical to those in the previous tasks.

*Postcued item manipulation*

In this task, each participant saw a series of alternating letters and numbers (e.g., 9, K, 2, T) on each trial. After the presentation of each series, the participant was asked either to recall the items in the same order in which they were presented or to report the numbers first in ascending order followed by the letters in alphabetical order. The key difference between this task and the precued item manipulation task was that this task encouraged participants to keep all the items in memory and then rearrange them just prior to recall, rather than rearranging the items as they were presented. The cue to recall the items in the order in which they were presented was the appearance on the computer screen of a blue rectangle with the word *FORWARD* on it, accompanied by a low-pitched tone. The cue to recall the numbers in ascending order followed by the letters in alphabetical order was a yellow rectangle with the word *SEQUENCED* on it, accompanied by a high-pitched tone.

In the postcued item manipulation task, participants were given six trials at each series length. Of the six trials, three were serial recall trials, and three were item manipulation trials. The order of the trials within each series length was randomly determined. The lengths of the series ranged from 2 to 13; testing was stopped when a participant missed all three item manipulation trials at a particular series length. Thus, for this task, the span score reflects the length of the longest item manipulation series that a participant could report. [1]

**Task Order and Practice**

There were two possible orders of tasks across participants. All participants performed one of the two serial recall tasks first: Half of the participants in each age group performed the alternating serial recall task first, and half performed the ordered serial recall task first. All participants performed the precued item manipulation task second, followed by the second serial recall task (whichever task they had not already performed). All participants performed the postcued task last to ensure that they were adequately familiar with the task instructions before the trial types were mixed.

In the first two tasks that a participant performed, eight practice trials were presented (two trials with 2-item series, three trials with 3-item series, and three trials with 4-item series) to ensure that the recall instructions were understood. For the second serial recall task, participants received only two practice trials (one with a 2-item series, one with 3-item series) to remind them of the serial recall instructions. For the postcued task, participants received four practice trials: serial recall, 2-item series; item manipulation, 2-item series; serial recall, 3-item series; and item manipulation, 3-item series. For all tasks, participants could repeat the practice trials if needed. We hoped that repeating the practice trials would reduce the possible effect of task-switching difficulties in the postcued task. Among the older adults, 2 requested extra practice on the postcued task, 1 requested extra practice on the alternating task, and 1 requested extra practice on the item manipulation task. None of the young adults requested extra practice.

**Memory Span Calculation**

For each participant, we calculated the memory span using a regression technique to estimate the series length at which the probability of answering correctly was 0.5 (see Jenkins, Myerson, Joerding, & Hale, 2000). We did so by regressing accuracy, *p*(correct), on series length, using the data from the longest series for which the participant answered all three trials correctly through the series length at which testing stopped (i.e., the series length at which the participant answered all three trials incorrectly). We then solved the regression equation for series length with *p*(correct) = 0.5 to determine an individual's span. [2]

**Results and Discussion**

Average memory spans are presented in Figure 1. Significance levels for all statistical tests were set to $\alpha = .05$. A 2 (Age: young vs. older) × 4 (Span: alternating serial recall vs. ordered serial recall vs. precued item manipulation vs. postcued item manipulation) analysis of variance (ANOVA) revealed significant main effects of age, $F(1, 46) = 32.24$, $\eta_p^2 = .41$, and span, $F(3, 138) = 113.21$, $\eta_p^2 = .71$, and a significant Age × Span interaction, $F(3, 138) = 3.73$, $\eta_p^2 = .08$. To determine the nature of this interaction, we conducted three planned contrasts (on the basis of our previously outlined hypotheses) using precued item manipulation spans for comparison.

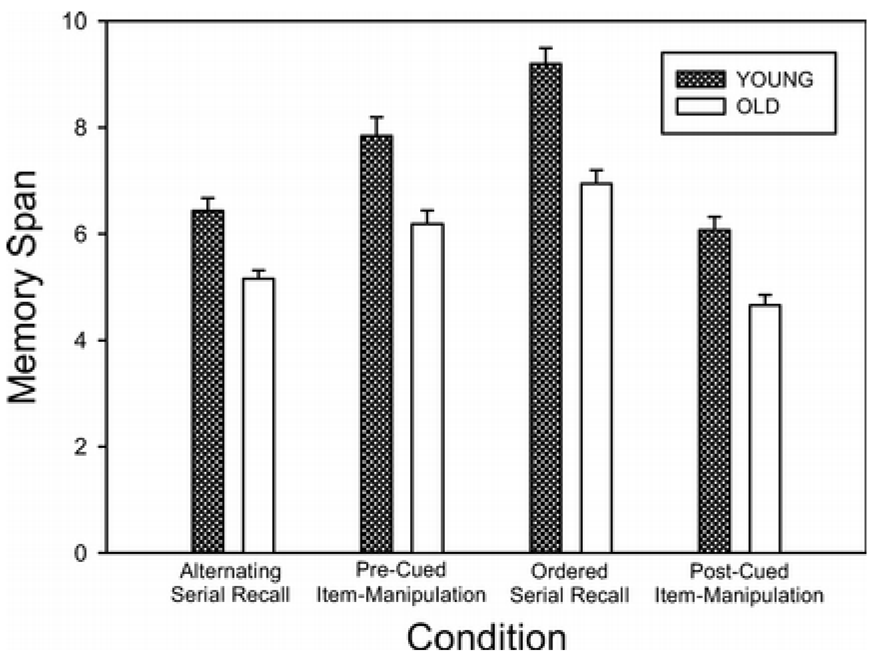


*Figure 1. Memory span (calculated using a regression technique to estimate the series length at which the probability of answering correctly was .5) as a function of task and age in Experiment 1. Error bars represent the standard errors of the mean.*

First, a 2 (Age: young vs. older) × 2 (Span: precued item manipulation vs. postcued item manipulation) contrast yielded a significant main effect of span, $F(1, 46) = 121.52$, $\eta_p^2 = .72$, confirming that postcued item manipulation spans were lower than precued item manipulation spans. Moreover, the absence of a significant Age × Span interaction, $F(1, 46) < 1.0$, $\eta_p^2 = .02$, suggests that both groups benefited equally from rearranging items online rather than offline, after the items had all been presented. Consistent with this view, examination of individual scores revealed that 22 of the 24 young adults and 22 of the 24 older adults had higher precued than postcued item manipulation spans, suggesting that nearly all of the participants in both groups were arranging the items as they were being presented. Taken together, these results suggest that age differences may be equivalent in tasks requiring online and offline manipulation, as long as older and young adults are both using the same strategy. [3]

The second and third contrasts were conducted to determine whether the age difference in precued item manipulation spans was larger than the age difference for either alternating or ordered serial recall spans. The 2 (Age: young vs. older) × 2 (Span: precued item-manipulation vs. alternating serial recall) contrast yielded a significant main effect of span, $F(1, 46) = 44.35$, $\eta_p^2 = .49$, but no Age × Span interaction: $F(1, 46) = 1.00$, $\eta_p^2 = .02$, suggesting that both groups obtained equivalent benefits from reorganizing the memory items. The 2 (Age: young vs. older) × 2 (Span: precued item manipulation vs. ordered serial recall) contrast yielded similar results. The main effect of task was significant, $F(1, 46) = 31.89$, $\eta_p^2 = .41$, but the interaction with age was not, $F(1, 46) = 2.81$, $\eta_p^2 = .06$. Thus for both groups, the costs of having to reorganize the memory items themselves, rather than having the items presented already organized, were statistically equivalent. If anything, the costs for young adults were greater than those for older adults, rather than the other way around (see Figure 1).

Taken together, the results of Experiment 1 suggest that older adults do not have a specific working memory deficit associated with item manipulation. Both age groups appeared to be capable of engaging in the strategy of categorizing and rearranging items online, and age differences in the precued item manipulation task were equivalent to those in each of the serial recall tasks. Thus, the Age × Span interaction that we observed when we analyzed all four tasks was not explained by any of the planned contrasts. A post hoc analysis indicated that this interaction was due to larger age differences in the ordered serial recall task than in the alternating serial recall task, $F(1, 46) = 12.53$, $\eta_p^2 = .21$. As may be seen in Figure 1, having items presented in the prearranged format benefited young adults more than older adults, and this result appears to underlie the significant Age × Task interaction observed in our original ANOVA.

One possible interpretation of this result is that the ordered serial recall task may be associated with more proactive interference than the alternating serial recall task, thereby exacerbating the age difference in memory spans (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). To see where this difference in proactive interference might come from, let us consider a series of six items, three letters and three numbers. There are 567 ways to combine three items from a nine-item set (e.g., the digits 1–9) without repeating any item but only 84 ways to combine them in ascending order. Thus, a series of items on the ordered serial recall task would be more likely to be similar to a preceding series than would a series on the alternating serial recall task. This increased similarity could result in an increase in proactive interference, which would put older adults at a disadvantage on the ordered serial recall task, given their greater susceptibility to such interference. Other interpretations are possible, of course, and we shall return to this issue in the General Discussion.

Other important issues are the rate at which items were presented and the role that processing speed plays in item manipulation spans. In this regard, it should be noted that the WAIS–

III/WMS–III Letter–Number Sequencing subtest and the tasks used in Experiment 1 differ substantially in the rate of item presentation. In the WAIS–III/WMS–III subtest, items are read aloud at a rate of one item every second. In the computerized version of this item manipulation task used in Experiment 1, we presented items visually at the relatively slow rate of one item every 2,500 ms so as to encourage both groups to use the same strategy, manipulating the items as they were presented rather than waiting until the end of the series to do the manipulation.

In contrast, the faster presentation rate used in the WAIS–III/WMS–III Letter–Number Sequencing subtest may force a difference in strategy between the older and the young adults. That is, at this rate, more older adults than young adults may wait until the end of a series to manipulate the items rather than manipulating them as they appear. Because the presentation rate used in Experiment 1 was relatively slow, age differences in the precued item manipulation task may have been reduced relative to previously reported differences in the WAIS–III/WMS–III Letter–Number Sequencing subtest (Myerson et al., 2003). Experiment 2 was designed to explore this possibility.

## EXPERIMENT 2

The data from Experiment 1 provided no evidence of a specific age deficit in the participants' ability to manipulate items in working memory. It is possible, however, that as the presentation rate becomes faster, older adults may be less able than young adults to manipulate the items online. This could result in an apparent age-related deficit in the ability to manipulate items in working memory that is actually due to an age-related deficit in processing speed.

Salthouse (1996) proposed two mechanisms by which age differences in speed of processing may account for age differences in cognition. One, the limited time mechanism, suggests that age differences occur because older adults may not have enough time to complete processing operations. The other, the simultaneity mechanism, suggests that age differences occur because older adults cannot keep memory contents active for processing. Both of these mechanisms may operate when participants must remember and rearrange memory items. For example, because older adults may take longer to manipulate memory items, they may be unable to do so online at faster presentation rates and thus would be deprived the benefits of an ordered series (limited time mechanism). In addition, because of the amount of time required to manipulate items, they may lose some of the items during the manipulation process (simultaneity mechanism).

Taken together, one might expect that these mechanisms would lead to larger age differences if memory items were presented at faster rates, whereas smaller age differences would be observed at slower presentation rates. Accordingly, the role of processing speed was examined in Experiment 2, in which older and young adults performed the (alternating) serial recall span and the (precued) item manipulation span tasks at three different presentation rates.

## METHOD

### Participants

Participants in Experiment 2 were 24 young adults and 24 older adults. Young adults (age: *M* = 19.8 years, *SD* = 1.18) were recruited from the Washington University Department of Psychology subject pool and received course credit for their participation. Older adults (age: *M* = 77.3 years, *SD* = 4.21) were recruited from the older adult subject pool and received $10 plus compensation for parking. Three older adults and 1 young adult did not report their years of education; mean years of education for the remaining participants were 13.9 (*SD* = 1.34) for the young adults and 14.5 (*SD* = 2.59) for the older adults. All participants were screened for health conditions as described in Experiment 1.

### Apparatus and Materials

Stimulus presentation and data collection, as well as the construction of the stimulus lists, were the same as in Experiment 1.

### Tasks and Procedure

In both the (alternating) serial recall task and the (precued) item manipulation task, participants saw a series of alternating numbers and letters presented one by one in the center of the computer screen. In the serial recall task, participants had to report the items in the order in which they appeared; in the item manipulation task, participants had to report the numbers first, in ascending order, followed by the letters in alphabetical order. Each task type (serial recall and item manipulation) was presented at three different presentation rates: fast (750 ms per item, with a 750-ms pause between items), medium (1,750 ms per item, with a 750-ms pause, the same presentation rate that was used in Experiment 1), and slow (2,750 ms per item, with a 750-ms pause). The remaining procedures were identical to those in the alternating serial recall and precued item manipulation tasks described in Experiment 1.

The tasks and conditions were counterbalanced for order across participants. Specifically, the span tasks were blocked by presentation rate and alternated by task type, with the serial recall task occurring first in each block and with each presentation rate (fast, medium, and slow) used in each position (first, second, and third) an equal number of times. This resulted in six presentation orders, with 8 participants (4 older and 4 young) per order.

In the first two memory tasks that a participant performed, eight practice trials were presented (two trials of 2-item series, three trials of 3-item series, and three trials of 4-item series) to ensure that the recall instructions were understood. For the remaining conditions, the participant received two practice trials (one of 2-item length and one of 3-item length) to remind them of the recall instructions. As in Experiment 1, participants could repeat the practice trials if needed. One older adult requested extra practice in the fast condition of the serial recall task, and 1 requested extra practice in the medium condition of the serial recall task. No young adults requested extra practice.

### Memory Span Calculation

Memory spans were calculated as described in Experiment 1.

### Results and Discussion

Average memory spans for the three conditions of each task are presented in Figure 2. As before, significance levels for all statistical tests were set to $\alpha = .05$. As may be seen, and contrary to expectation, age differences on the item manipulation task actually became larger as the presentation rate decreased. We conducted a 2 (Age: young vs. older) × 2 (Span: serial recall vs. item-manipulation) × 3 (Presentation Rate: fast vs. medium vs. slow) ANOVA on the memory span data. The ANOVA revealed significant main effects of all three variables: age, $F(1, 46) = 71.49$, $\eta_p^2 = .61$, span, $F(1, 46) = 65.00$, $\eta_p^2 = .59$, and presentation rate, $F(2, 92) = 34.54$, $\eta_p^2 = .43$. Two of the second-order interactions were also significant: Age × Span, $F(1, 46) = 14.09$, $\eta_p^2 = .23$, and Span × Presentation rate, $F(2, 92) = 29.98$, $\eta_p^2 = .40$. These second-order interactions were qualified by a significant three-way interaction among age, span, and presentation rate, $F(1, 92) = 4.13$, $\eta_p^2 = .08$.

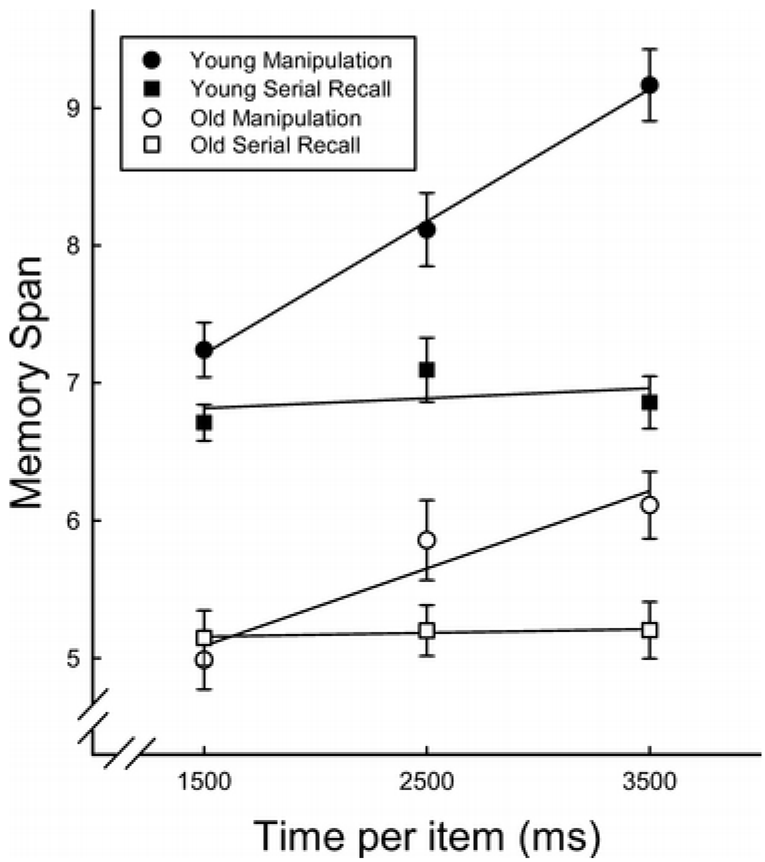


*Figure 2. Memory span (calculated using a regression technique to estimate the series length at which the probability of answering correctly was .5) as a function of presentation rate, task, and age in Experiment 2. Circles represent spans on the item manipulation task; squares represent spans on the alternating, serial recall task. Error bars represent the standard errors of the mean, and the straight lines are the linear regression lines.*

To examine the basis for this three-way interaction, we conducted two within-subjects contrasts. The first of these revealed that there was no significant main effect of presentation rate (interitem interval) on serial recall spans, $F(1, 46) = 1.80$, $\eta_p^2 = .04$ and no interaction between age and presentation rate for serial recall spans, $F(1, 46) = 1.10$, $\eta_p^2 = .02$. The second revealed a significant linear trend in item manipulation spans, $F(1, 46) = 101.26$, $\eta_p^2 = .69$, that interacted significantly with age, $F(1, 46) = 6.97$, $\eta_p^2 = .13$. This interaction reflects the fact that for the young adults, the slope of the regression of span on interitem interval was 0.96 items per second, whereas for older adults, the corresponding slope was only 0.56 items per second (see Figure 2). There was no significant polynomial trend or interaction.

Although age differences in item manipulation span were not largest at the fastest presentation rate, as had been expected, one result was clearly consistent with the hypothesis that older adults may be unable to manipulate memory items online at fast presentation rates and thus may be deprived the benefits of an ordered series under such conditions. Specifically, we found no significant difference between older adults' memory spans on the serial recall and item manipulation tasks at the fast presentation rate, $F(1, 23) = 0.79$, $\eta_p^2 = .03$. In contrast, younger adults' item manipulation spans were already significantly greater than their serial recall spans at this presentation rate, $F(1, 23) = 6.19$, $\eta_p^2 = .21$. Examination of the data from individual participants provided further support for this hypothesis. At the fast presentation rate, only 9 of the 24 older adults had item manipulation spans that were longer than their serial recall spans, whereas 17 of the 24 younger adults did. In contrast, at the medium presentation rate, more than two thirds of the participants in each age group had item manipulation spans that were longer than their serial recall spans (17 older and 17 young adults), and by the slow presentation rate, this had increased to more than four fifths of each group (20 older adults and 23 young adults).

This finding suggests that an online rearrangement strategy was spontaneously adopted by most participants, regardless of their age, when the presentation rate was relatively slow. When the items were presented at a relatively fast rate, however, the older and young groups differed either in the number who used this strategy or in the number who were able to use it effectively, or both. These alternatives are, of course, not mutually exclusive, because individuals' inability to profit from a strategy may lead them to abandon it, particularly if the strategy is an effortful one, as online rearrangement is likely to be. In either case, the increase in older adults' item manipulation spans as the interstimulus interval increased from 1,500 to 2,500 ms may reflect a qualitative change as well as a quantitative one, whereas the increase in younger adults' spans may represent a primarily quantitative change. In contrast, when the interstimulus interval increased from 2,500 to 3,500 ms, approximately equal numbers of participants in each group appeared to have used and benefited from the online rearrangement strategy.

With respect to the WAIS–III/WMS–III Letter–Number Sequencing subtest, in which memory items are presented at a rate (1 per second) that is close to that used in the fast condition of this experiment, the present results suggest that older adults may be much less likely than young adults to adopt an online rearrangement strategy on this subtest. Moreover, because use of an online strategy may lead to larger spans than are possible with an offline rearrangement, as shown in Experiment 1, the consequence may be the pronounced age-related deficit observed on this subtest of the WAIS–III/WMS–III (Myerson et al., 2003). [4]

We would note that this interpretation suggests an important corollary to the limited time and simultaneity mechanisms proposed by Salthouse (1996). As Salthouse suggested, when tasks are not self-paced, as is true of most working memory tasks, age-related slowing can lead to poorer performance because all of the processing required cannot be completed in the time allotted (limited time mechanism). Alternatively, slowing can lead to poorer performance because all of the information required to perform a given working memory task cannot be kept active, given the greater time required for performance of secondary tasks or for further processing of memory items (simultaneity mechanism). The present results highlight the fact that age-related slowing can also lead to poorer performance for a different but related reason. That is, rather than using the same strategy as younger adults use (albeit less efficiently), older adults may adopt a less efficient strategy in response to slowing because it is the only one feasible given the constraints of a slower processing system.

Even though some older adults appear to have shifted from an offline to an online strategy as the presentation rate became slower, this does not explain the reason that age differences on the item manipulation task grew larger, contrary to expectations based on the processing speed hypothesis. As will be elaborated in the General Discussion, the explanation for this finding may rest in age-related differences in processes that participants used in the interface between primary and secondary memories, which may influence performance more as time pressure is eased.

With respect to the age-related difference in participants' serial recall spans, it is likely that this is a result of the impact of age-related slowing on the length of the articulatory loop, which reflects both the covert rehearsal rate and the rate at which the representations of memory items decay (Baddeley, 1986; Baddeley, Thomson, & Buchanan, 1975). Previous research has shown that older adults have slower speech rates than do young adults, and speech rates are closely related to span length (e.g., Multhaup, Balota, & Cowan, 1996). Slowing the presentation rate may give participants more time to perform operations such as item manipulation, but it cannot alter the size of the articulatory loop. Therefore, under normal conditions, varying the presentation rate over the range from 1.5 to 3.5 s per item should not affect serial recall memory spans. Performance in the item manipulation task, however, may not be limited by articulation rate because ordered items (e.g., 1, 2, 3) may constitute familiar “chunks” or sequences. As highlighted in the General Discussion, the activation of representations of these sequences in long-term memory may enable participants to evade the temporal constraints imposed by articulation rate or the length of the articulatory loop (Baddeley & Hitch, 1974).

## GENERAL DISCUSSION

In two experiments, we examined age-related differences on a working memory task that required manipulation of the memory items. Overall, the results of these two experiments do not support the hypothesis of a specific age deficit in the ability to manipulate items in the working memory and are consistent with recent research using other, less complex item manipulation tasks (Belleville et al, 1998; Gregoire & Van der Linden, 1997; but see Bopp & Verhaeghen, 2005).

In Experiment 1, age differences on the precued item manipulation task were not larger than those on either of the two serial recall tasks. In addition, age differences were equivalent for pre- and postcued item manipulation spans, suggesting that age differences in tasks requiring manipulation of items are equivalent for online and offline manipulation, as long as both young and older adults are using the same strategy. Apparent age deficits in item manipulation may emerge at faster presentation rates, however, because older adults may be forced to use an offline strategy when young adults are able to use an online strategy. Although our evidence is indirect, this was what appears to have occurred in the fast condition of Experiment 2, and this explanation could explain our previous finding with regard to age differences on the Letter–Number Sequencing subtest of the WAIS–III/WMS–III (Myerson et al., 2003). However, age differences in processing speed cannot fully explain the age differences on the item manipulation task in Experiment 2 because these differences actually grew larger as the presentation rate became slower. This finding suggests that as time pressure decreases, both overall performance and age differences may be influenced by other factors. To elaborate on these other potential sources of age differences on our item manipulation task, we must first consider why recalling memory items was easier on some tasks in this study than it was on others.

One notable finding was that item manipulation spans were consistently larger than those for (alternating) serial recall of the same material, as long as the item manipulation procedure allowed the items to be rearranged online (i.e., as they were presented). This finding, which was observed in both young and older adults in both of the experiments in the present study, is especially striking because it is unlike what is found with most other working memory tasks (e.g., backward digit span). The reason that the item manipulation spans were longer than the alternating serial recall spans is most likely because in the item manipulation task, participants had to rearrange the items so that they were more memorable, as indicated by the particularly long spans in the ordered forward recall condition of Experiment 1.

Previous research would suggest that the reason such ordered lists are more memorable is because sorting and ordering the items makes them more familiar—that is, reorganizing the items may make it possible to use long-term or secondary memory to supplement the primary, short-term verbal store. This could be done in multiple (mutually nonexclusive) ways at various points in the process, from encoding to reporting the memory items. For example, the reorganization of memory items at encoding may facilitate *chunking* (Baddeley, 2000; Miller, 1956), which in turn may increase the covert articulation rate of the items, because these familiar chunks are well practiced. At the retrieval end of the process, the reorganization of memory items may facilitate *redintegration*, the process by which items are identified from their degraded traces (Hulme, Roodenrys, Schweickert, & Brown, 1997; Schweickert, 1993). Not only are familiar items themselves easier to identify, but the presence of familiar sequences enables one item to prime another.

For present purposes, the most important question is whether such mechanisms are equally helpful to older and young adults. Recalling again the results of Experiment 1, we believe that the answer appears to be no: The only significant Age × Task interaction in Experiment 1 indicated that older adults did not benefit as much from ordered serial recall as did young adults. This lessened benefit may explain why, in Experiment 2, the young adults benefited significantly more than the older adults from a decrease in presentation rate. That is, the young adults may have benefited more from having additional time in the item manipulation condition simply because having a sorted and ordered list produces a greater increase in memorability for younger adults.

It is possible, of course, that the answer as to why a differential benefit is observed with sorted and ordered memory items is to be found not in mechanisms that produce the benefit but in other aspects of the tasks used in the present study. For example, letter–number sequencing appears to involve a number of executive functions, most notably item manipulation and set switching between types of items (letters and numbers), that might contribute to the age differences observed on this task (Myerson et al., 2003). As outlined below, however, the results do not indicate a specific age-related deficit in these functions.

In Experiment 1, the cost of engaging in item manipulation was revealed by the finding that ordered serial recall spans were larger than item manipulation spans. However, this cost was no larger for older adults than it was for young adults. In addition, spans for the alternating serial recall task, which required set switching at encoding and again at recall, were also smaller than those for the ordered serial recall task, which required the least set switching of any of the tasks used. This result could be interpreted in terms of either a cost from set switching or a benefit from ordered items, but in either case, the age difference for ordered serial recall spans (which involved minimal switching) was significantly larger than that for alternating serial recall spans (which involved switching after every item). In Experiment 2, moreover, the largest age difference in item manipulation spans was observed at the slowest presentation rate, yet Friedman and Miyake (2004) have argued that executive functions are most required when individuals must encode items under time pressure.

Another possible factor that may contribute to the size of the age-related differences on the item manipulation tasks is proactive interference, because of older adults' problems with removing previously relevant information from working memory (Lustig et al., 2001). As we noted in Experiment 1, repeated sets of grouped and ordered items are likely to be similar to each other and more likely to cause built-up proactive interference. Likewise, in both experiments, once the items that made up a series presented on the item manipulation task were rearranged, the sequence could have been more similar to preceding rearranged series. That is, we assume that as the presentation rate in Experiment 2 became slower, more people were able to rearrange the items online, replacing the alternating sequence with the more interference-prone ordered sequence and thereby creating problems to which the older participants were particularly susceptible. Nevertheless, it should be noted that for both groups, any difficulties with proactive interference or inhibitory difficulties were apparently outweighed by the benefits of rearranging memory items into an ordered sequence.

Finally, there is an additional and related potential source of the increased age difference in item manipulation spans as presentation rate decreased. It could be that the benefit from ordered items arose because ordered items activated representations of familiar series in long-term memory. When presentation rates were decreased, this may have allowed time for greater activation of such long-term representations, but it may also have caused increasing difficulties for older adults because of their problems dampening such activation once it occurs (Oberauer, 2001; Zacks, Radvansky, & Hasher, 1996). That is, the more that older adults benefited on one series of items, the more difficulty they may have had on the following series.

Although performance on working memory tasks involving item manipulation (e.g., letter–number sequencing and the backward digit and spatial span tasks) tends to decrease with age (e.g., Myerson et al., 2003), the present findings suggest that this is not because older adults have a general problem manipulating information in working memory. Rather, the general implication of the present findings is that the source of the age-related difference on a working memory task involving manipulation of memory items may be specific to the item manipulation task under examination. In the item manipulation task used in the present study, both strategy (online vs. offline manipulation) and the memorability of ordered series appear to play a greater role in age differences than item manipulation per se. This suggests that, in some cases at least, a better understanding of age differences in working memory may arise from a careful examination of the constituent processes involved in a particular task rather than from the comparison of performances on different tasks.

**NOTES**

1. The decision to stop testing once all three item manipulation trials of a series length were answered incorrectly, rather than when all six trials of a series length were answered incorrectly, was made to reduce possible frustration for the participants. Participants were unaware of the stopping criterion and unaware that only the item-manipulation trials “counted” in this task.
2. All analyses were also conducted using the number of correct trials (the measure used in the WAIS–III/WMS–III subtests) as the dependent variable. The results of these analyses were consistent with those reported here.
3. We assumed that in the postcued test, both older and young adults would remember the items in serial order until they were given the cue to rearrange them, and thus postcued alternating serial recall spans should be equivalent to spans for (precued) alternating serial recall in both age groups. A post hoc comparison of alternating serial recall spans to spans derived from the postcued serial recall trials supported this assumption: Neither the main effect of cueing (pre vs. post) nor the Cueing × Age Group interaction was significant (both *F*s < 2, both $\eta_p^2$s = .04). Postcued serial recall spans may be slightly underestimated, because testing often stopped before a participant had missed all three postcued serial recall spans (see Footnote 1). Nevertheless, given the comparatively large and significant difference between pre- and postcued item manipulation spans, we believe our assumptions regarding the postcued task are valid, although converging evidence could be provided by presenting items too quickly for online manipulation by either group.
4. We note that a 2 (Age: young vs. old) × 2 (Task: serial recall vs. item-manipulation) ANOVA on the data from the fast presentation rate yielded a significant Age × Task interaction, $F(1, 46) = 6.10$, replicating our results for the WMS–III data (Myerson et al., 2003). When the same ANOVA was conducted on the data from the medium presentation rate (the same rate used in Experiment 1), the Age × Task interaction was not significant, $F(1, 46) = 1.19$, replicating the results of the alternating versus item manipulation contrast performed in Experiment 1. This further supports the hypothesis that differences in presentation rate and the potential consequences for the use of the online arrangement strategy in older adults were factors in the differences between the Myerson et al. (2003) results and those reported for Experiment 1.

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