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# Verbal Memory Span and the Timing of Spoken Recall

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Prior research indicates that one's memory span approximately equals what one can say in 2 s. However, this refers to pronunciation in separate, subspan tasks. The present research examined speech timing in the memory response in 4-year-olds. It was found that speaking rates depended on list length relative to a subject's span, but that speaking rates for span-length lists were the same for subjects of any span. The results are discussed in terms of a theoretical account that includes the notion of a decaying phonological store (Baddeley, 1986), but also the notion that rapid scanning of items in the pauses within the response (Sternberg, Monsell, Knoll, & Wright, 1978; Sternberg, Wright, Knoll, & Monsell, 1980) may serve to reactivate items before they can decay. Alternative accounts also are discussed. © 1992 Academic Press, Inc.

One of the most intriguing findings of the modern era of memory research is that immediate, serial verbal recall is profoundly time limited. There is a linear relation between a subject's memory span and his or her maximal speech rate for the material to be remembered. One generally can recall as many items as one could pronounce in about 2 s (Baddeley, Thomson, & Buchanan, 1975). This relation holds no matter whether the variance in the maximal rate of speech is obtained by contrasting age groups, individuals within an age group, or sets of words from different languages or from the same language differing in the required pronunciation times (Baddeley et al., 1975; Case, Kurland, & Goldberg, 1982; Hulme, Thomson, Muir, & Lawrence, 1984; Naveh-Benjamin & Ayres, 1986; Nicolson, 1981; Schweickert & Boruff, 1986; Standing, Bond, Smith, & Isely, 1980; Zhang & Simon, 1985). Although Schweickert and Boruff acknowledged the additional importance of nontemporal factors in memory span (e.g., modality-specific sensory memory on one hand and familiarity, grouping, and organization of material on the other), they noted that the temporal factors appear to predominate, so that the rate/span relation is obtained across a wide range of conditions. Finally, Hulme, Maughan, and Brown (1991) found a linear relation with the same slope, but different intercepts, for real words versus nonsense words. These findings suggest that one can reasonably explore the basis of a time relation to memory span separately from other factors in span.

The observed time limit in memory span has involved speech rate estimates from separate pronunciation tasks with subspan lists, rather than measures of speech rate in the memory response itself (with the exception of one study to be discussed later, by Stigler, Lee, & Stevenson, 1986). Amazingly, almost nothing is known about the timing of speech within overt recall and how it is related to memory span. It is perhaps more than coincidental that the correct explanation for the relation between the maximal speech rate and memory span also is still unclear. The present work demonstrates that this relation can be better understood by considering measurements of the timing of spoken recall.

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The most influential account in which articulatory speed is said to influence memory span is the "articulatory loop" model of verbal memory span formulated by Baddeley (1986). The loop includes the set of temporarily activated speech items, collectively termed the "phonological buffer," and an articulation process that can be used either to silently rehearse the items in the buffer or to overtly recall them. The activation of each item was said to decay within about 2 s if the item is not rehearsed. Rehearsal can serve to reactivate items in the phonological buffer, thereby postponing their decay; but it is assumed in the theory that items that have totally decayed cannot be subsequently retrieved for rehearsal during that trial. This simplifying assumption seems reasonable when items are drawn repeatedly from a small set and serial order information is tested because, in that situation, interference between trials should minimize the likelihood of retrieval from other (e.g., long-term episodic) forms of storage (*cf.* LaPointe & Engle, 1990). The faster that one can rehearse the items, the larger the number of items that can be kept active concurrently in a repeating rehearsal loop, which must cycle through all of the items on the list in a time that is limited by the period of decay of items from phonological storage. Thus, the 2-s phonological memory decay period and the reactivation process would account for the finding that subjects can recall about the amount that they can articulate in 2 s.

Within the articulatory loop framework, there are several different possible mechanisms by which articulation rate could influence memory span, and the timing of overt recall has implications for some of these mechanisms. Although the most frequently considered mechanisms involve covert articulatory processes taking place during the initial reception of the list, and although there is some justification for this mechanism at least in older children and adults (Baddeley, Lewis, & Vallar, 1984; Cowan, Cartwright, Winterowd, & Sherk, 1987; Henry, 1991), covert and/or overt articulatory processes taking place during the subject's verbal repetition of the list also may be relevant. Naturally, it is these articulatory processes during output for which the timing of overt recall is of the most obvious relevance.

It does appear that articulatory processes during output affect memory span. For instance, Baddeley et al. (1984) found that word-length effects in the recall of spoken lists could be eliminated by articulatory suppression only if the suppression task extended into the recall period (in a written recall task). Cowan et al. (1992) have shown that word-length effects occur primarily when they involve the lengths of whatever items are to be recalled first. Presumably, repeating these items delays the output of the remaining words on the list, whereas repeating the remaining words naturally does not delay anything else. The role of output is even more critical in children who may be too young to use covert articulatory processes. Henry (1991) found that for 5-year-old children (although not for 7-year-old children), the effect of word length was totally eliminated when spoken recall was replaced by a nonverbal pointing response, which was assumed to have minimized articulatory factors in overt recall.

To begin to explain the possible implications of the timing of verbal recall for memory span, Fig. 1 illustrates two theoretically possible types of mechanism for verbal, serial recall in an immediate memory task. Both mechanisms include Baddeley's assumption that there is a "phonological buffer" or transient source of information about the phonological sequence present in the stimuli. In the first mechanism (Fig. 1A) information is drawn directly from the phonological buffer. It is assumed within this mechanism that neither the speed of the subject's response nor any covert processes that the subject actually carries out in the response period influence the rate of decay of information from the buffer. Successful retrieval from phonological storage

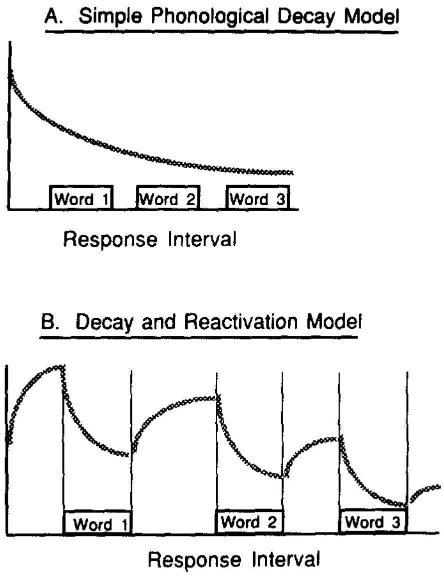


FIG. 1. An illustration of two alternative models of processing during the response period in a memory span task. (A) Phonological memory (dashed line) decays monotonically throughout the response period. All words must be repeated before memory decays. (B) Decay during pronunciation of individual words in the response is partly counteracted by reactivation of items during the pauses between items. Therefore, there is no fixed time limit on memory responding, although the needed information eventually decays.

thus must be completed by the time that the phonological information has decayed, at the fixed rate, beyond a critical level. Related suggestions were made by Broadbent (1958) and Brown (1958). Similarly, Schweickert and Boruff (1986, p. 424) suggested that the "time between presentation and recall of items" may be a critically important variable. Cowan et al. (1992) also suggested this model as the simplest explanation of their observation of word-length effects confined to the lengths of words output first.

Strong empirical predictions can be derived from the mechanism shown in Fig. 1A when it is viewed as one interpretation of the articulatory loop hypothesis. As mentioned above, the ubiquitous finding that a subject can remember about as much as he or she can say in about 2 s, regardless of his or her span, has been accounted for (Baddeley, 1986) with the assumption that phonological memory decays beyond a critical level in about 2 s for normal subjects of all spans (and that individual differences in speech rate determine span differences). Because of the assumption of a fixed decay rate, the total duration of recall for span-length lists would be fixed and therefore uncorrelated with span. Subjects with a higher span would be able to pack more items into the available response period (i.e., prior to complete memory decay) by speaking more quickly. Thus, according to this approach there should be a high correlation between overt response rate and memory span.

Figure 1B illustrates the type of mechanism one gets instead if one accepts the notion of a decaying phonological buffer, but assumes that a more complex recall strategy is going on (involving a decay-and-reactivation cycle rather than monotonic decay). Within this type of mechanism, decay occurs primarily while the subject actually is speaking. In pauses that occur between words in the response, the subject presumably carried out countervailing processes (e.g., mental scanning or covert articulation of items) that tend to reactivate items within the phonological buffer. The net result is to postpone decay and substantially lengthen the period in which the spoken response can continue. Thus, in contrast to the first, monotonic decay mechanism, with a decay-and-reactivation mechanism there should be a correlation between memory span and the *duration* of recall, and not necessarily a relation between memory span and the *rate* of recall.

The monotonic decay interpretation (Fig. 1A) may seem unlikely. For example, it is clear to anyone who has measured memory span that responses often last more than 2 s. However, some version of this model does provide a reasonable first approximation to what little evidence is available. In the only published study I know of in which the duration of spoken recall was examined, Stigler et al. (1986) tested English and Chinese subjects on lists of digits presented in their respective native languages. For the longest lists that each subject could repeat correctly, the response lasted an average of 2.91 s in the English-speaking sample and 2.42 s in the Chinese-speaking sample, a nonsignificant difference (despite the finding that the mean digit span was much higher, and the mean digit duration much shorter, for Chinese than for English). These total response durations are not much longer than Baddeley's 2-s phonological store. The correspondence is even closer if one makes the reasonable assumption that the last word on the list can be pronounced after the store has decayed, provided that it is retrieved before decay is complete.

Nevertheless, the data of Stigler et al. (1986) do not provide conclusive support for the monotonic decay model. There could be very brief pauses between words in the response, during which subjects might engage in high-speed scanning (Sternberg, Monsell, Knoll, & Wright, 1978) that would serve to reactivate items. These brief pauses might not be noticed if they added up to only a small proportion of the response times. Further, the lack of difference between languages in the total response time could be explained by either mechanism shown in the present Fig. 1. Within either mechanism, more memory decay would occur while longer (i.e., English) digits were articulated than while shorter (i.e., Chinese) digits were articulated. Consequently, group differences in the duration of each item in the response could be offset by group differences in the number of items recalled (as was found).

Several departures of the present study from the method of Stigler et al. (1986) make the present work more capable of disconfirming a simple decay mechanism (Fig. 1A) and revealing the decay-and-reactivation mechanism (Fig. 1B) should it be correct. First, the present subjects were 4-year-old children. Any type of covert articulatory activity should be minimized in these subjects, because young children do not spontaneously use the sophisticated memory rehearsal strategies that older subjects use (Flavell, Beach, & Chinsky, 1966; Henry, 1991, in press). Moreover, young children are slower than adults in scanning tasks (Keating, Keniston, Manis, & Bobbitt, 1980) as well as in their maximal rate of articulation (e.g., Hulme & Tordoff, 1989). Therefore, regardless of the exact nature of the covert activity that might occur during the pauses between items in the responses, such pauses probably would be longer and more easily observed in young children than in adults.

A final difference between the present study and that of Stigler et al. (1986) is that, in the present study, individual differences in the timing of responses to a standard word set were observed, rather than group differences based on differential word lengths in two languages. Word length differences could have affected primarily the duration of overt speech, without altering the time to reactivate items during interword pauses. This is especially plausible if the reactivation process during interword pauses is memory scanning, because word length effects are not obtained in scanning studies (Clifton & Tash, 1973; Sternberg et al., 1978). In contrast to word-length effects, individual differences in *span* could reflect differences in the ability to reactivate memory during the interword pauses in the response. Supporting this suggestion, scanning rates are highly correlated with memory span (Cavanagh, 1972). Therefore, if the proposed decay-and-reactivation mechanism is correct, subjects who have higher spans should be the same ones who can reactivate items more efficiently than other subjects, postponing memory decay and extending the permissible duration of their responses beyond what is obtained in other subjects.

If the data favor the decay-and-reactivation type of mechanism, additional details of the timing of recall would help to further clarify the nature of the mechanism. For example, the rate and quantity of covert articulation or scanning should be reflected in pause times rather than word lengths in the response. Further, the nature of covert activity has implications for the pattern of pause times across serial positions. For example, if subjects scanned the list in serial order during each pause, always starting at Item 1 and terminating when the to-be-pronounced item was reached, the result would be increasing pause times across serial positions. In contrast, if subjects selected each item to be pronounced from a decreasing pool of unused items in phonological memory, the result would be a decrease in pause times across serial positions. There are still other mechanisms for which no such serial position effects would be expected. For example, this would be the case if, during each pause, subjects did an exhaustive search of the list items, if they searched the list items in a random order until the item with the correct serial position tag was found, or if they had to retrieve only a small, fixed subset of the list items adjacent to and including and to-be-pronounced item.

An additional constraint on the possible mechanisms of recall will be provided by evidence on the timing of recall for subspan lists. If each pause is used to process only the upcoming item and not other items on the list, then individual pauses in the response should be just as long for subspan lists as for span-length lists presented to the same subjects. On the other hand, if the processing that goes on during each pause must somehow take into account the other items on the list (or even a subset of them, such as all items remaining to be recalled), then the pauses should be shorter in subspan lists than in span-length lists.

Finally, one manipulation in the present study was designed to take into account that some contributions to memory span are not tied to the rate of speech. Hulme and Tordoff (1989) and Schweickert et al. (1990) both found that lists of phonologically similar items were pronounced as quickly as were phonologically dissimilar items, even though spans were markedly higher for dissimilar lists. These authors proposed that phonological similarity increases the difficulty of retrieving the correct items from the phonological buffer. The phonological similarity variable was included in the present study also, to examine a mnemonic factor thought to be unrelated to speaking rate.

## METHOD

### *Subjects*

The subjects were 44 children between 4 and 5 years of age. The present data consisted of audiotaped recordings from a memory-span determination procedure. The spans for 37 of these subjects were included within Experiments 1 and 2 of Cowan, Saults, Winterowd, and Sherk (1991), who did not report measurements of response timing. Eleven other subjects who had participated in those experiments were excluded from the present sample because the tape recordings were incomplete or inaudible in places. This sample was supplemented with 7 additional subjects who had participated in a pilot study and received the same memory-span procedure as the others.

### *Procedure*

Lists to be recalled were spoken at the rate of one item per second and were to be recalled orally by the subject. For each subject, memory spans for phonologically similar and dissimilar lists were determined both in a control situation in which subjects were unassisted, and in an experimental situation in which subjects were assisted in some way (through either cumulative presentation of the list or repetition of each list item by the subject at the time of presentation). The present study includes only the data from the control condition, which was the same for all subjects.

The words to be recalled were the same as those used by Conrad (1971) and Hulme (1984). Each list of similar words was drawn from the set *rat, cat, mat, hat, bat, man, bag, tap,* and each list of dissimilar words from the set *girl, bus, train, spoon, fish, horse, clock, hand.* Lists of dissimilar and similar words were presented in alternation, starting with lists of two items. Two lists of each type were presented at each list length, and the list length was increased by one item repeatedly until the subject made a mistake on both of the lists of a certain length. For the sake of simplicity, span for either type of list was taken as the number of items in the longest list of that type that the subject repeated successfully. Additional procedural details were reported in Cowan et al. (1991).

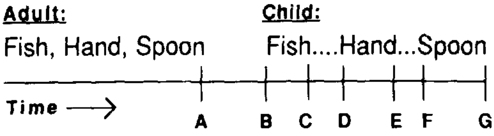
### *Data Reduction*

Timing measures were taken on all trials in which the subject responded without error. Audiotaped protocols were analyzed with the help of an Apple MacIntosh SE microcomputer equipped with MacRecorder waveform editing hardware and software. The recordings were transmitted from the tape deck directly to the MacRecorder digitizer through a wire connection. For each trial, the stimuli and responses were digitized in a single pass and displayed in oscillographic form on the computer screen at a standard magnification. The duration of each segment was determined by using computer mouse clicks to highlight the segment on the screen and then listening to the highlighted portion as another check that word boundaries were accurately determined. The computer provided a digital readout of the beginning and ending locations of the highlighted segment.

In order to characterize the timing of events in the subject's response, eight measures derived from the timing data were used. These derived measures are defined and discussed below and are illustrated for a three-word list in Fig. 2.

*1. Response time.* This is the total time from the end of the stimulis list presentation to the end of the subject's response.

*2. Preparation time.* This is the time from the end of the stimulus list to the beginning of the subject's first word in response.



| | |
|---|---|
| *Response Time:* | G - A |
| *Preparation Time:* | B - A |
| *Pronunciation Time:* | G - B |
| *Speech Time:* | (C - B) + (E - D) + (G - F) |
| *Speaking Rate:* | 3 / (G - B) |
| *Modified Rate:* | 2 / (F - B) |
| *Word Length:* | Speech time / 3 |
| *Interword Pause:* | [(D - C) + (F - E)] / 2 |

FIG. 2. An illustration of a trial with a list length of 3 and eight measures calculated on the basis of speech-timing information.

*3. Pronunciation time.* This is the duration of the response from the beginning of the first word to the end of the last word, that is, the response time minus the preparation time. Pronunciation time could be the critical limiting factor in recall rather than the response time if subjects carry out mental operations that postpone phonological memory decay until the end of the preparatory period.

*4. Speech time.* This is the total amount of time during which the subject actually talked, the pronunciation time minus all interword pauses. The relevance of this measure is that there is an interesting alternative to the pure decay theory of phonological memory in which short-term memory degradation would occur only in the presence of an interfering stimulus (Massaro, 1970). Each item in the response could interfere with all other items when it is being pronounced.

*5. Speaking rate (unadjusted).* This is simply the number of list items divided by the pronunciation time to yield a measure of items per second.

*6. Modified speaking rate.* This new measure is the list length minus one, divided by the time from the beginning of the subject's first response word to the beginning, rather than the end, of the subject's last word. The measure is needed because there is a confounding factor in the unadjusted speaking rate measure, if one wishes to compare rates across list lengths. Specifically, for a list containing L items, the ordinary rate is NEWbased on the time taken to produce L words and L-1 interword pauses, which works to the detriment of the rate for longer lists. For example, a subject who consistently produces 0.5-s words separated by 0.2-s pauses would yield an unadjusted rate for 2-word lists of $[2/(0.5 + 0.2 + 0.5)] = 1.67$ items/s, but a rate for 3-word lists of $[3/(0.5 + 0.2 + 0.5 + 0.2 + 0.5)] = 1.58$ items/s. In contrast, the modified rate is based on L-1 items and L-1 pauses. For the subject discussed above, it would yield a common rate of $[1/0.5 + 0.2)] = [2/(0.5 + 0.2 + 0.5 + 0.2)] = 1.43$ items/s, and the same for lists of any length.

*7. Mean word length.* This was the average duration of words in the responses for a particular type of list.

*8. Mean interword pause time.* This was the average time between words in the responses for a particular list type.

## RESULTS

### *Memory Span Distributions*

There was a wide range of variation in performance. On phonologically dissimilar lists, subjects obtained spans of 2 ($N = 2$), 3 ($N = 20$), 4 ($N = 20$), and 5 ($N = 2$). On phonologically similar lists, subjects obtained a much lower distribution of spans, including spans of 2 ($N = 7$), 3 ($N = 30$), and 4 ($N = 7$). The majority of subjects thus achieved a dissimilar span of either 3 or 4, along with a similar span of 3 (for the profile "3, 3", $N = 14$; for the profile "4, 3", $N = 15$). The spans resemble those in other studies with a similar age group and methodology (e.g., Hulme, 1984; Hulme & Tordoff, 1989).

### *Relations between Speech Timing Measures and Span*

A series of correlations was conducted across all 44 subjects, to observe the relation between the memory spans and each of the eight timing measures. The means for each measure and correlations are shown in Table 1, separately for phonologically dissimilar and similar lists. The pattern of correlations, which was almost identical for the dissimilar and similar conditions, illustrates an interesting departure from speech rate measures taken in separate, subspan tasks in previous studies. If subjects sim-

TABLE 1

MEANS AND STANDARD DEVIATIONS ON ALL MEASURES FOR DISSIMILAR AND SIMILAR LISTS, AND CORRELATIONS BETWEEN THE TIMING MEASURES AND MEMORY SPAN

| | List type | | | | | |
|---|---|---|---|---|---|---|
| | Dissimilar | | | Similar | | |
| Measure | Mean | *SD* | *r* | Mean | *SD* | *r* |
| Memory span | 3.50 | (0.66) | — | 3.00 | (0.57) | — |
| Response time | 3.67 | (1.29) | .59** | 3.27 | (1.33) | .53** |
| Preparation time | 0.82 | (0.40) | .11 | 0.95 | (0.66) | .17 |
| Pronunciation time | 2.85 | (1.18) | .60** | 2.32 | (0.93) | .63** |
| Speech time | 2.04 | (0.53) | .82** | 1.68 | (0.50) | .77** |
| Speaking rate | 1.36 | (0.38) | −.26 | 1.42 | (0.43) | −.15 |
| Modified rate | 1.27 | (0.40) | −.23 | 1.32 | (0.50) | −.09 |
| Word length | 0.58 | (0.09) | .11 | 0.56 | (0.11) | .10 |
| Interword pause time | 0.32 | (0.32) | .11 | 0.32 | (0.28) | .00 |

*Note.* For explanations of the measures, refer to Fig. 2 and the accompanying text. Durations are in seconds, and rates are in items per second. All timing measures shown and used in correlations were based on span-length lists only.

** $p < .01$.

ply read information out of a phonological buffer that was limited by the same memory decay function regardless of the subject's level of ability, then one would expect no difference across spans in the pronunciation times (and perhaps not in the total response time either, although that would depend on what happens to memory during the preparatory intervals). One would also expect little or no correlation between these measures and memory span. Instead, however, these correlations were highly significant, as were the correlations between span and speech time (see Table 1).

The means at each span for the three speech measures that were correlated with span are plotted in Fig. 3, for both dissimilar and similar lists. Notice that the mean pronunciation times increased systematically from about 1.5 s for subjects with a span of 2 (on either list type) to over 4 s for subjects with a span of 5. In contrast, the preparation times, interword pause times, and lengths of individual words were not found to be correlated with span (see Table 1). Thus, more capable subjects speak at the same rate as less capable subjects, but respond for a longer time. Notice also that the timing results are quite similar for phonologically dissimilar and similar lists when list length is taken into account (Fig. 3).

If speaking rates during verbal recall played the same role as the speaking rates obtained in separate, subspan repetition tasks in previous studies, then the correlations between recall rate and memory span in the present study should be significant. Instead, these correlations were low and nonsignificant for both the ordinary and the modified speaking rates (Table 1). This indicates that the monotonic memory decay mechanism shown in Fig. 1A cannot be the right one to account for the rate/span correlation reported in the literature in tasks with a separate, subspan measure of speaking rate (see above). More capable subjects apparently have longer to respond, either because they have a slower rate of memory decay or, more likely, because they can reactivate items better than other subjects, postponing decay.

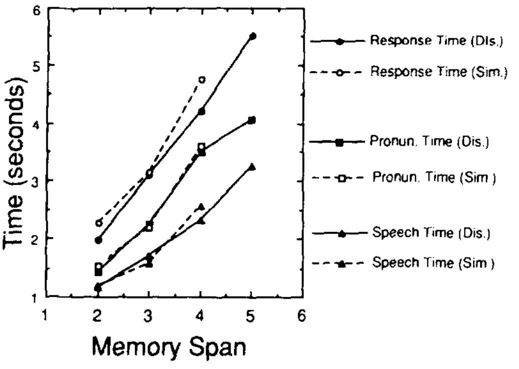


FIG. 3. Means for three speech timing measures calculated for span-length lists, separately for each memory span. Phonologically dissimilar lists, solid lines; similar lists, dashed lines.

*Reliability of measures*. The absence of a correlation between any particular timing measure in overt recall and memory span possibly could be explained in a more trivial manner, if the reliability of the measures was low enough that a true relation was obscured. In order to examine this possibility, correlations between each subject's performance on dissimilar and similar lists were obtained. The correlation between memory span on dissimilar and similar lists was .55 ($p < .01$), suggesting that some general ability factor contributed to span in both conditions. The speech times also were correlated for the two list types ($r = .61$, $p < .01$). More importantly, though, speaking rates were correlated in the two conditions (unadjusted rate, $r = .38, p < .02$; modified rate, $r = .37$, $p < .02$). Thus, there were stable individual differences in speaking rates within overt recall, even though the rates did not correlate with memory spans. Displaying stable individual differences even more strikingly, the mean lengths of words in the response were highly correlated for the two list types ($r = .81$, $p < .01$). Clearly, the absence of a correlation between mean word length and memory span (Table 1) cannot be attributed to unreliability of the word-length measure.

### *Response Timing in Span-Length versus Subspan Lists*

The present data sample was adequate to examine performance on subspan lists only for subgroups of subjects with a dissimilar span of 3 ($N = 18$), with a similar span of 3 ($N = 27$), and with a dissimilar span of 4 ($N = 17$). The $N$'s are slightly lower than those reported above, because the audiotaped records for subspan trials were incomplete for a few subjects.

*Subjects with a span of 3.* Groups of subjects with a span of 3 on dissimilar and on similar lists were analyzed separately, because the two conditions included some of the same subjects and some different subjects. In each condition, a one-way ANOVA on modified speaking rates was carried out, with list length (two vs three) as a repeated measure. For the dissimilar condition, mean rates were higher for two-item lists than for three-item lists ($M = 1.64$ words/s vs 1.44 words/s, respectively, $F(1,17) = 7.35$, $MS_e = .05$, $p < .02$). For the similar list condition, as well, the results were quite comparable, with means of 1.65 words/s vs 1.45 words/s for two-item lists vs three-item lists, $F(1,26) = 4.99$, $MS_e = .11$, $p < .04$. Analogous effects were obtained for both list types in analyses of the unadjusted response rate, response time, pronunciation time, speech time, and interword pause time (all $p$'s $< .05$). In contrast, analyses of the preparation times and word lengths yielded no differences approaching significance.

*Subjects with a span of 4.* Results for the group with a dissimilar span of 4 were similarly analyzed in one-way ANOVAs with list length (2, 3, and 4) as a repeated measure. The analysis of the modified speaking rate measure yielded a highly significant effect of list length, $F(2,32) = 16.48$, $MS_e = .06$, $p < .001$. The mean rates were 1.58, 1.41, and 1.10 words/s for the three lengths, respectively. Similar analyses revealed effects of list length on the unadjusted speaking rate, response time, pronunciation time, speech time, and interword pause time (all $p$'s $< .001$), the same measures as in the data for subjects with a span of 3.

Newman–Keuls tests on the modified speaking rates indicated that the rates differed in lists of length 2 vs 3 ($p < .05$) as well as 2 vs 4 and 3 vs 4 ($p$'s $< .01$). Thus, the rate difference was not simply a difference between span and subspan lists; it differed also between lists of length span − 1 vs span − 2. For all of the other measures yielding significant effects, the Newman–Keuls comparisons of lists of length 3 vs 4 and 2 vs 4 were significant ($p$'s $< .01$). For most of these measures (speaking rate, response time, pronunciation time, and speech time) the comparison between lists of length 2 vs 3 also were significant ($p$'s $< .05$).

As in the analysis of subjects with a span of 3, the analyses of the preparation times and word durations in subjects with a dissimilar span of 4 yielded no significant effect of list length.

*Comparison across spans and list lengths.* As shown in Fig. 4, when speech rates are compared across groups for lists of span and span − 1 length, subjects with a span of 4 had consistently *lower* speaking rates than subjects with a span of 3. A 2 × 2 ANOVA of modified speaking rates with group (span = 3 vs 4) as a between-subject factor and list length (span vs span − 1 length) as a within-subject factor revealed

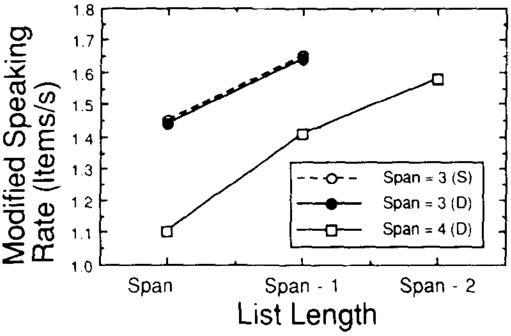


FIG. 4. Modified speaking rates for different combinations of span, list type, and list length (with the last of these expressed as the difference from span length).

significant effects of group, $F(1,36) = 5.32$, $MS_e = 0.24$, $p < .03$, as well as list length, $F(1,36) = 18.97$, $MS_e = 0.05$, $p < .001$, with no significant interaction. The basis of this effect is unclear, but it does demonstrate that speaking rates in the overt responses to span-length lists certainly were not *faster* in subjects with higher memory spans.

### *Detailed Pattern of Timing*

The detailed timing patterns underlying the comparisons of span length vs subspan performance are shown in Fig. 5. The figure shows mean times for each combination of span, list length, and list type. The top two rows of the figure illustrate performance for subjects with a span of 3 on similar lists; the next two rows, for subjects with a span of 3 on dissimilar lists; and the bottom three rows, for subjects with a span of 4 on dissimilar lists. The $X$ axis represents time from the end of the stimulus list presentation. The leftmost white segment within each response strip represents the mean preparation time; the first black segment, the mean duration of the first item in the response; the second white segment, the mean first interitem pause; and so on to the end of the response. The figure clearly illustrates that, for a particular subject group, the slower response rates for lists with more items occurred primarily because the interword pauses increased with list length.

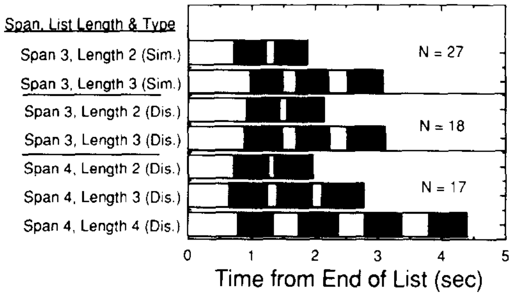


FIG. 5. The detailed timing of recall for every combination of span, list type, and list length. The length of the first white bar represents the mean duration of the preparatory interval; the first black bar, of the first word in the response; the second white bar, of the first interword interval; and so on, through the end of the response.

*Serial position effects on timing.* One motivation to examine serial position effects in timing is provided by Sternberg, Wright, Knoll, and Monsell (1980), in their detailed study of the timing of subjects' speeded pronunciation of short lists following a start signal. They observed that the responses became progressively slower across serial positions. Moreover, the duration changes across serial positions were localized within the words being pronounced, not within the intervals from the end of one word to the beginning of the next. To account for their pattern of results, Sternberg et al. (1980) speculated that the serial position effects had to be explained on the basis of an articulatory command and execution stage of processing, rather than the memory retrieval stage that was used to explain list length effects. If subjects in the present memory span task use similar processes, similar serial position effects should be obtained.

To examine serial position effects in the present data, both word lengths and interword pauses were subjected to one-way ANOVAs with serial position as the within-subject factor. These ANOVAs were conducted separately for various combinations of list type (dissimilar or similar), span (3 or 4), and list length (span, span-1, span-2 if applicable). According to some accounts of covert processing during the pauses between words in the response (described in the introduction), there should be strong serial position effects across successive pauses. However, there were no effects of serial position in any of the analyses for the interword pause times. This matches what Sternberg et al. (1980) found, and it contradicts accounts in which the amount of processing taking place during the pauses increases markedly across serial positions (e.g., always scanning from Position 1 to the current position during the pause) or decreases markedly across serial positions (e.g., rehearsal of all items remaining to be repeated).

Also in keeping with Sternberg et al. (1980), there were serial position effects on word durations. However, the changes were not always monotonic across serial positions and were not consistent across list lengths. Among the analyses of word lengths, the effect of serial position was significant for dissimilar lists of length 3, both in subjects with a dissimilar span of 3, $F(2,38) = 13.61$, $MS_e = 0.005$, $p < .001$, with means of 0.60, 0.51, and 0.61 s in the three serial positions, and in subjects with a dissimilar span of 4, $F(2,38) = 4.89$, $MS_e = .01$, $p < .02$, with means of 0.60, 0.54, and 0.66 s. Newman–Keuls tests showed that, in both groups, the word length in the final serial position was significantly longer than the middle position, $p$'s $< .01$. (For the span = 3 subjects only, the first and middle positions also differed, $p < .01$.) The serial position effect on word length was significant as well for subjects with a similar span of 3 on lists of 3, $F(2,58) = 13.05$, $MS_e = 0.003$, $p < .001$ ($M = 0.51, 0.50$, and 0.57 s). Newman–Keuls tests indicated that the duration of words in the final serial position was significantly higher than in either of the first two positions, $p$'s $< .01$, which did not differ from one another.

In strong contrast to these results on lists of length 3, however, there were no significant serial position effects in lists of length 2 or of length 4. The effects of serial position on word duration for lists of length 3 only might be best interpreted in terms of the conformity of speech production to a hierarchical pattern of rhythm. For example, if there were a tendency to conform to a rhythm pattern that involved pairs of beats, the last word in a 3-word list might be lengthened because it is the sole representative of a higher order node for the final pair of beats. Although this pattern was in no way anticipated, it is consistent with the theory of Martin (1972) and supporting data of Gordon and Meyer (1987). Sternberg et al. (1980) did not separate their serial position data according to list lengths, and one wonders if similarities to the present pattern of data would be observed if they had.

## DISCUSSION

The main outcome of the present study is unequivocal. Unlike a subject's maximal, covert speaking rate, which has been consistently found to correlate with memory span (e.g., Baddeley et al., 1975; Hulme et al., 1984; Schweickert & Boruff, 1986), the rate of overt verbal recall in the present study was unrelated to memory span. There was, however, a strong correlation between the *duration* of recall on span-length lists and memory span. This was the case no matter whether the initial preparatory period was included in the time estimates (response time measure) or excluded from them (pronunciation time measure).

The present measure of speech rate during verbal recall differed from the separate rate measures used in most studies of memory span in two ways. First, the present subjects were not asked to speak as quickly as possible, and second, the present subjects were timed on lists approaching and equalling their memory spans. Theoretically, either of these factors could underlie the difference in results in the two types of procedure. However, Naveh-Benjamin and Ayres (1986) replicated the relation between speech rate and memory span using a rate measure from an unspeeded reading task. Therefore, it seems likely that the memory factor was the more critical factor in the present finding.

The present results have clear implications for the possible mechanisms of recall discussed above. In the first mechanism (Fig. 1A), which was previously suggested by Cowan et al. (1992), Schweickert and Boruff (1986), and Stigler et al. (1986), information is retrieved from a phonological store that decays at a fixed rate. According to this account, retrieval from the store is limited by the store's duration. If the mechanism is to account for the finding that a person can remember about as much as he or she can say in about 2 s (e.g., Baddeley et al., 1975), then it would have to be assumed that the store's duration is about 2 s. Individual differences in memory span would result from how quickly different individuals could talk, so that subjects with a higher span would achieve it by packing more response words into the time available before the transient store decayed. However, the present data clearly indicate that something more was involved. Given that the duration of responses on span-length lists increased steadily with span, to a mean of almost 5 s for subjects with a span of 5 items (Fig. 3), performance could not have been limited by a memory that decayed monotonically in about 2 s in all subjects.

Logically speaking, the data could be consistent with a version of the monotonic decay model in which the duration of the store varies drastically (roughly from 2 to 5 s) among 4-year-olds. However, such a drastic individual difference in a structural component of memory would be unprecedented. Moreover, if this sort of approach were adopted, it still would not provide an explanation for the ubiquitous finding in the literature that subjects can recall about as many items as they can pronounce in about 2 s.

It is also possible to consider a version of the monotonic decay model in which there would be memory decay only while the subject is pronouncing a word and neither decay nor reactivation during the interword pauses (i.e., an output interference approach that would be similar to a model of memory interference developed by Massaro, 1970). However, this leads to the prediction that the summed duration of all words in the response (i.e., the total time of output interference) should be constant across individuals. This was not the case; the summed duration (speech time measure) was found to be strongly correlated with memory span.

At first glance, the present data would appear to be at odds with the findings of the only other published study in which the timing of recall was measured. Specifically, Stigler et al. (1986) tested digit span in English- versus Chinese-speaking adults and found a marked Chinese-speaking advantage on digit span (and on subjects' maximal articulation rates for digits), but still no difference between languages in the duration of spoken recall. Response durations had similar distributions in the two language groups, with a mean of under 3 s in each.

The present data, the data of Stigler et al. (1986), and the prior data on maximal speech rate and memory span all can be accommodated by an account that involves a decay-and-reactivation type of mechanism during overt recall, as shown in Fig. 1B. Within such an account, phonological memory would decay while subjects repeat a word, but would be reactivated to some extent in the pauses that occur between words in the response. The difference between the present data and those of Stigler et al. can be explained on the basis of differences in the degree to which the variables examined influence decay versus reactivation.

Word length is one variable that clearly affects decay (Cowan et al., 1992). It extends the duration of each word within the spoken response and therefore imposes longer periods of decay for lists composed of longer words. Because of this additional decay of memory for lists composed of longer words, spans would be lower for longer words. Thus, the longer word durations in the response would not necessarily result in longer total response times. In the case of Stigler et al. (1986), the word length manipulation in fact altered individual word durations in the response, but not the total response durations.

In contrast to duration of words in the response, the duration of pauses between items in the response might not be affected by word length manipulations. The reactivation process could be similar to mental scanning of a memory set, and several studies have demonstrated that word length does not affect the rate of scanning (Clifton & Tash, 1973; Sternberg et al., 1980).

Individual differences in memory span would have very different implications for recall than word length does. Cavanagh (1972) has demonstrated that the mental scanning of items is highly correlated with memory span. It is also clear that the maximal rate of speech is highly correlated with memory span (Baddeley et al., 1975; Hulme & Tordoff, 1989; Schweickert & Boruff, 1986). Therefore, it seems almost certain that the rate of reactivation in interword pauses in the response would be correlated with memory span (assuming that reactivation consists of covert articulation, mental scanning, or some combination of both of these). Faster reactivation would tend to counteract memory decay, permitting a longer response. In contrast to the reactivation rate, though, the duration of words in the response need not be correlated with memory span. There could even be factors that tend to lengthen the duration of words in the response in more capable subjects, such as an attempt to speak clearly, which would cancel out any tendency toward increasing speed of word pronunciation in more capable subjects.

The rough equivalence of pause times in span-length lists for subjects of all spans does not necessarily contradict the thesis that processing in these pauses is faster for subjects with a higher span. Bear in mind that the amount of processing to be done during the pauses would be, according to many accounts (see below), proportional to the number of items in the list. For example, a subject with a span of $X$ may carry out processing during the pauses only half as fast as a subject with a span of $2X$ (e.g., a subject with a span of 2 may scan both items in a span-length list in about the same amount of time that a subject with a span of 4 can scan all 4 items in a span-length list).

In sum, word lengths would affect word durations in the response, whereas the subject's span would be related to the rate of reactivation of items in the interword pauses in the response. This would account for the finding of no word length effect on total response duration at span (Stigler et al., 1986) together with the present finding of a strong positive relation between memory span and the total response duration at span. Thus, two factors that are related to memory span (word length and individual differences in certain processing speeds) are suggested to have different, separable implications for span.

### *List Length Effects, Serial Position Effects, and Accounts of Covert Processing in Span Tasks*

One key point that remains unclear within the theoretical account offered above (Fig. 1B) is the nature of the reactivation process that occurs in pauses within the response. Several additional findings of the present study may shed light on this unanswered question. First, it was found that the rate of responding was faster for lists of span − 1 length than for span length, and faster still for lists of span − 2 length. The slowing in speaking rate as the list length increases toward the subject's span occurred because of increases in the interword pauses rather than increases in the length of words in the response. This finding closely confirms and extends the generality of what Sternberg et al. (1978, 1980) found in tasks with adult subjects in which a list of 1 to 5 items was to be pronounced as quickly as possible on each trial following a ready signal. As in the present study, the speaking rate decreased monotonically with the number of items in the list, and this effect of list length was localized in the interword pauses rather than word durations.

Another finding of the present study was that there was no effect of serial position on pause duration. This favors accounts in which the amount of processing accomplished during the pauses stays about the same while the subject's response progresses from one word to the next. The finding of no serial position effect on pause times matches what Sternberg et al. (1980) found in a study of the speeded repetition of subspan lists.

At least two types of more detailed accounts of covert processing during pauses in the present task are possible given the present data, and these will be described below.

*Memory scanning account.* The type of account of scanning that Sternberg et al. (1978, 1980) developed on the basis of the speeded pronunciation of subspan lists (including a large body of converging evidence) can be adapted to account for the present data also. Within that account, each item is represented in short-term storage with a serial position tag, but the order in which the items are scanned in memory is random. The subject cannot read out the items in the correct serial order but must scan them in search of the correct serial position tag. It is assumed that items remain in short-term storage even after they are selected (i.e., that the set size does not shrink across serial positions). The larger the number of items in the list, the longer will be the average scan time for each target. The data are insufficient to determine if the scan is exhaustive or self-terminating.

The application of the scanning account to memory span performance could make sense of the finding (Cavanagh, 1972) that span is correlated with scanning speed, if one adds the assumptions that scanning serves to reactivate items that are scanned and that these items otherwise decay from transient storage. Faster scanners would reactivate more items in a comparable amount of time, thus counteracting decay more efficiently and permitting a longer response, containing more items, in these faster scanners. When a supraspan list is encountered, however, the subject presumably cannot scan all of the items quickly enough to reactivate them before they decay. A longer pause duration would not help, because some items would decay while other items were being reactivated by the scanning process. Finally, each subject's scanning rate would apply also to subspan lists, so that list length effects would be based on the number of items that the subject must scan at his or her personal rate.

It is important to keep in mind that this is an account of processing during the pauses only. By itself, it cannot explain the word length effect on memory span, because word-length effects have not been obtained in scanning studies (Clifton & Tash, 1973; Sternberg et al., 1978). Word-length effects might be accounted for, at least partly, by the duration of the pronunciation of words in the response (Cowan et al., 1992), possibly in combination with rehearsal effects during reception of the list (Baddeley et al., 1984). It would be interesting to further examine performance in the presence of a nonverbal response such as those used by Henry (1991). With such a response, memory span might be most equivalent not to the amount that subjects can pronounce in 2 s (Baddeley et al., 1975; Hulme & Tordoff, 1989; Schweickert et al., 1990), but to the amount that subjects can scan in about 240 ms (Cavanagh, 1972).

One minor problem for the scanning account is that a significant effect of list length on preparation time was obtained in the research of Sternberg et al. (1978), but not in the present study. Although the present preparation times may simply have been too variable to show such a relationship (see above), it is also possible that preparatory processes differ for novel lists approaching span length (in the present study) versus lists that can be more easily recalled (in Sternberg's procedure). This question cannot be resolved with the present data set.

*Processing capacity account.* A different explanation of the processing in the pauses within the responses in the present study involves the assumption that individual differences in mnemonic ability reflect differences in the availability of a general processing capacity, as in the theories of Pascual-Leone (1970) and Case (1972). According to those theories, a general processing capacity or storage space must be used both to hold items in short-term storage and to perform operations on those stored items. The processing capacity available for the short-term storage of items is whatever capacity is not used up by the operational schemes needed for the task to be performed. The available capacity presumably increases with development, either because the total capacity increases with development or because the available capacity gets used more efficiently (for a discussion of these possibilities see Kail, 1990).

In the present study, the subject must hold all items in storage while searching for the one that should be pronounced next. The larger the number of items being held, the smaller would be the processing capacity available for the search process itself. The search process could be slower when conducted with less free processing capacity (i.e., as the subject's span is approached) and impossible when the available processing capacity falls below a certain threshold (span exceeded). According to this account, capacity would directly determine span (i.e., the list length at which the subject cannot hold all of the items in memory and still carry out the necessary operations). Speed-of-processing differences related to span (e.g., the effect of list length on pause durations) would be byproducts of the amount of free capacity as a function of list length.

*Distinguishing between the accounts.* Arguing against the processing capacity account, Sternberg et al. (1978, 1980) reported that the duration of responding was insensitive to a memory load that was independent of the primary, speeded pronunciation task. Still, it remains possible that the finding does not apply to a memory span situation and therefore that the capacity account is correct in that situation.

Thus, at present, both scanning accounts and capacity accounts of the data remain theoretically possible, although the data of Sternberg et al. (1978, 1980) together with the relatively close correspondence between those findings and the present observations of timing in a memory span task favor the scanning account. The key question is what the nature of the most fundamental individual difference is. Does processing speed determine memory capacity, or vice versa? This is a difficult question that has not easily yielded to experimental investigation. For example, an attempt to raise memory span by training children to pronounce the relevant word set more quickly (Hulme & Muir, 1985) had little chance to succeed because the valiant attempt to increase pronunciation speeds failed.

A tractable research strategy for the near future might be to test assumptions of particular models of each type. For example, one important issue is the type of the covert processing that occurs between words in the response. Is this process limited to mental scanning as Sternberg's account suggests, or does it consist at least partly of covert rehearsal? This question can be addressed by examining the effect of word length on the timing of spoken recall. Whereas considerable evidence indicates that the time it takes to pronounce a word affects the speed of covert rehearsal (Baddeley, 1986), other evidence just as clearly indicates that this factor makes no difference in mental scanning for the sake of retrieval (Clifton & Tash, 1973; Sternberg et al., 1978). A scanning-only account predicts no effect of word length on interword pauses in the response.

One reason to suspect that scanning rather than covert rehearsal is occurring during interword pauses is that there is not enough time to do very much covert rehearsal. It is clear that covert rehearsal proceeds at about the same rate as the maximal rate of overt pronunciation (Landauer, 1962). Judging by the maximal speech rate/

memory span relation obtained by Hulme and Tordoff (1989), the present subjects (who had a mean span of 3.5 items on dissimilar lists) should be rehearsing at the rate of about 330 ms/item. If they were to rehearse all items in a span-length list, it should therefore take an average of about 1.17 s. In contrast, the actual mean interword pause was only 320 ms. The estimated time that it would take for children to scan all of the items is much more reasonable. Specifically, inserting the present memory span into the relation between scanning rate and memory span reported by Cavanagh (1972) would lead to a scanning rate estimate of 72 ms/item. (The reasonableness of this estimate is strengthened by the fact that an estimate of 55 ms/item was obtained for 8-year-olds, the youngest age tested, by Keating et al., 1980). Given the present scanning estimate, subjects could scan a span-length (3.5 item) list in an estimated 252 ms, close to the obtained mean interword pause time of 320 ms.

### *Summary and Conclusions*

The articulatory loop theory of Baddeley (1986) has been useful as a "grand theory" that has the generality and flexibility to account for a wide spectrum of results. However, as such, its future usefulness depends on how carefully the theory can be articulated. One aim should be to specify in greater detail the mechanisms of short-term memory storage, decay, and activation in particular tasks. The present research has attempted this by examining the timing of spoken recall in a memory span task with 4-year-old children. The finding that the timing of spoken recall does not bear the same relation to memory span as does the timing of pronunciation in separate, low-load repetition tasks helps to clarify the operation of memory decay and activation. The data suggest that the theory of memory span based on a transient phonological store (Baddeley, 1986) is appropriate, but it may have to appeal to models of memory scanning (Sternberg et al., 1978, 1980) in order to account for the way in which retrieval and reactivation of items occurs during pauses within the response. Obtaining a more complete data base on response timing should be a high priority for the near future, as it may improve our understanding of memory span.

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