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The Differential Maturation of Two Processing Rates Related to Digit Span

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Recent studies have proposed that rapid-speaking durations predict short-term memory spans. However, N. Cowan et al. (1998, *Journal of Experimental Psychology: General,* **127,** 141–160) found *two* separate types of processing durations related to digit span for children in Grade 1 (7–8 years), Grade 3 (9–10 years), and Grade 5 (11–12 years): rapid-speaking durations (thought to index the rate of covert articulation) and the durations of interword pauses in the memory span task responses (thought to index the rate of short-term memory retrieval). The present analysis additionally establishes the differential maturation of those two durations. Within-age correlations between span and rapid-speaking durations were significant only in first graders; correlations between span and interword pauses, only in fifth graders. When subsamples were selected to match spans across age groups, both types of duration also were matched between Grades 1 and 3. However, fifth graders had considerably shorter interword pauses than their third-grade counterparts. Thus, a particular memory span is accompanied by different profiles of processing rates in children of different ages. © 1999 Academic Press

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In digit span tasks, each participant listens to lists of digits and tries to repeat each list in the correct serial order. List lengths increase until the participant no longer can succeed, and the span typically estimates the list length repeated correctly on 50% of the trials. Span is used in intelligence tests and predicts performance in a variety of comprehension and problem-solving situations (Dempster, 1985).

Even though span tasks are procedurally simple, the underlying processes are not well understood. Influential approaches to span differences between age groups, and between individuals within an age group, have attempted to explain these differences on the basis of a single speed-of-processing difference. In perhaps the first such study, Baddeley, Thomson, and Buchanan (1975) found a

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linear relation between the rate at which an individual adult could read or pronounce a small group of words when asked to do so rapidly and the number of such words that the individual could remember in a serial recall task. Similar findings have since been obtained in many studies, including studies of increases in span with development during childhood (e.g., Hulme & Tordoff, 1989) and decreases in span with adult aging (e.g., Kynette, Kemper, Norman, & Cheung, 1990). In the usual interpretation of these individual differences and age effects, it is assumed that rapid-speaking speed is an indication of covert verbal rehearsal speed, which is thought to be important in short-term serial recall tasks (Baddeley, 1986). Other studies have made the argument that the individual and age differences in rehearsal speed serve as just one type of indication of a more global speed of processing that differs among individuals, changes with age, and is related to the performance of almost any cognitive task (Fry & Hale, 1996; Kail & Park, 1994; Salthouse, 1996).

Cowan et al. (1998) challenged the global processing-rate assumption by showing that there are at least *two* separate processing rates that are both related to memory span but are unrelated to each other. In addition to the rapid-speaking rate that proved to be important in past studies, painstaking computer-based measurements were made of aspects of the timing of recall of correctly repeated, subspan lists within the memory span task itself. Two previous studies had shown that the duration of words in the response remained fairly constant across list lengths and individuals, but that the duration of *silent pauses* between words in the responses increased as a function of the length of the list; that, for a particular list length, the silent pauses were shorter for individuals with higher spans; and that these pauses decreased with development in childhood (Cowan, 1992; Cowan et al., 1994). These articles suggested that the interword pause times reflected the time it took the participant to retrieve the correct word to be recalled from a short-term memory representation of the list during the span task. Cowan et al. (1998) showed that interword pause durations in the memory span responses and rapid-speaking durations in a separate, speeded task both correlated with memory span but nevertheless did not correlate with one another. They picked up different portions of the span variance, together accounting for 60% of the span variance and 87% of the age-related span variance in a structural equation model.

The importance of this result is that it rules out an overly simple view of cognitive development, a view that otherwise would be attractive because of its extreme parsimony. However, it leaves open the question of exactly what modification is needed in the global processing-rate theory of development. One possibility is that all processing rates develop in parallel and reach maturity at the same time within an individual, but with a large amount of individual variation in the relative speeds of particular processes, depending on the individual's profile of abilities. In contrast to this parallel-development view, another possibility is that different processing rates not only are uncorrelated with one another, but also mature at different ages. A related possibility is that at least some processing rates do not directly determine memory span, in which case one could find two groups of individuals with the same span but different processing rates. The present article distinguishes among these possibilities through a reanalysis of the data from Cowan et al. (1998) that could be carried out only on the basis of the full, original data set, not from the published report.

First, memory retrieval rate and articulation rate measures will be discussed in greater detail as background. Then the data reanalysis will be reported, including (1) the course of development of span and processing rates, (2) the pattern of within-age correlations between span and rates, and (3) the procedures in which children of different ages were matched for span. These analyses indicate that separate retrieval and articulation rates are not related to memory span in the same way within different age groups.

THE SHORT-TERM MEMORY RETRIEVAL MEASURES AND THEIR MEANING

To obtain the retrieval measures we have used, the stimulus on each trial has been a spoken list of words or digits and the response has been spoken also. After the experimental session, a speech waveform editor has been used to measure, for all correctly repeated lists, the duration of each speech segment within the responses. For a particular word set, the durations of words in the response have been found to remain more or less fixed across age groups and list lengths. However, silent periods between words in the response change as a function of these variables. First, as the list length increases, the mean silent periods grow longer. One can further distinguish between the *preparatory interval,* which comes between the end of the stimulus list and the beginning of the participant's response, and the *interword pauses,* which come between words in the response. The preparatory intervals in response to lists of a particular length decrease with increasing age, but they are nevertheless uncorrelated with span. In contrast, the interword pause durations are inversely related to span as well as to age (Cowan, 1992; Cowan et al., 1994, 1998).

Because each interword pause increases with the list length, Cowan (1992) suggested that, during the pauses, participants must do more than just process the next word to be spoken. Instead, the entire list or some proportion of it apparently has to be processed in order for the next word to be retrieved. This may be a sort of short-term memory search or scanning process, analogous to what has been proposed by Sternberg and his colleagues to explain the rate of pronunciation of lists by adults in a speeded response situation (Sternberg, Monsell, Knoll, & Wright, 1978; Sternberg, Wright, Knoll, & Monsell, 1980). Within this context it makes sense that the interword pauses are markedly shorter for more capable participants (e.g., older children) than for less capable ones if the pauses are measured at a fixed list length, but not if pauses are measured for each participant's span-length lists. At span, the level of difficulty, and apparently the time taken up by retrieval processes, appears to be more similar across individuals (Cowan, 1992; Cowan et al., 1994, 1998).

Considerable work has been done to characterize further the processes taking place during interword pauses. Some of this work illustrates the similarity of interword pause times to memory search times. Memory search most typically has been measured using tasks in which the participant must make a rapid decision about whether an item was part of a recently presented list (Sternberg, 1966). Cowan et al. (1998, Experiment 2) found that one such memory search measure was correlated with memory span but not with a covert rehearsal rate measure, making it analogous to interword pauses as anticipated. Hulme, Newton, Cowan, Stuart, and Brown (in press) further found that interword pause times and memory search times in a Sternberg-type task were correlated.

The processes taking place during interword pauses do not appear to be mainly articulatory in nature, inasmuch as the pauses do not differ in duration as a function of word length (Cowan et al., 1994; Hulme et al., in press). They do appear to involve lexical retrieval from long-term memory, inasmuch as the pauses are much shorter in the recall of English word lists than they are in the recall of recently experienced nonsense-word lists (Hulme et al., in press). On the basis of all of this evidence, Hulme et al. suggested that interword pauses involve both (1) short-term *memory search* processes to determine what portion of the phonological short-term memory record corresponds to the word to be recalled next and (2) *redintegration* processes involving a search through lexical representations in long-term memory, which can be carried out to decide what item best matches the phonological short-term memory record of what was presented (a record that often has become degraded by that time). Presumably, the difficulty of memory search depends on the length of the list, the difficulty of redintegration depends on the strength of memory for the underlying lexical item (greater for words than for nonsense words), and both processes affect the durations of interword pauses within spoken responses in the span task.

THE ARTICULATION MEASURES AND THEIR MEANING

Baddeley et al. (1975) were the first to show that the maximal rates at which adult participants could pronounce small sets of items used in the memory span task were correlated with their memory spans. The correlation was such that each participant could remember about as many items as he or she could pronounce in about 2 s. The interpretation (developed further by Baddeley, 1986) was that short-term memory depends on a phonological memory buffer that contains representations that fade within about 2 s unless they are refreshed, and that the rate of rehearsal determines how many items can be refreshed in a repeating loop before they fade. The maximal rate of overt articulation was assumed to estimate the rate of covert rehearsal, an assumption that fits the available data fairly well (Landauer, 1962). Many subsequent studies have shown that a linear relation between speech rate and memory span occurs across age group means in various conditions (for a review see Cowan, 1995, chap. 3). For example, Hulme and Tordoff (1989) found this linear relation across 12 means: 4-, 7-, and 10-year-olds' means for two different monosyllabic word sets, a bisyllabic word set, and a set of longer multisyllabic words, all acoustically dissimilar within a set. (The same regression line did not fit sets of acoustically similar words, which have a lower intercept than dissimilar words; this pattern was observed also by Schweickert, Guentert, & Hersberger, 1990.)

When the data are viewed in more detail, however, the rehearsal idea is not so neatly supported. Correlations between speech rate and memory span are found for individuals within a particular age group in the older children, but not in 4-year-olds. At that young age, the correlation is nonsignificant or is reversed (Cowan et al., 1994; Gathercole, Adams, & Hitch, 1994). This finding is consistent with the previous assumption that young children do not rehearse (Flavell, Beach, & Chinsky, 1966). Some have even questioned whether rehearsal is needed at all to explain effects in the short-term memory literature, such as the word length effect, that had been attributed to rehearsal (e.g., Brown & Hulme, 1995). However, it is not difficult to imagine that there are other processes needed for short-term memory that would be related to the rapid production of articulatory elements, such as the ability to maintain and use representations of relatively complex phonological sequences (e.g., Caplan, Rochon, & Waters, 1992).

RELATION OF THE RATE MEASURES TO MEMORY SPAN

Cowan et al. (1998, Experiment 1) examined digit span using four spoken lists at each list length (from two items on, until span was reached) in a group of children in first, third, and fifth grade ($n = 24$ per group). They examined interword pauses within correctly repeated lists comprising two, three, and four items, given that those were the list lengths at which all participants had at least one correctly repeated list. The durations of these pauses were assumed to reflect short-term memory retrieval rates. Correlations between measures were examined using all 72 individuals' scores together, and it was found that the correlations between interword pauses and memory span estimates were moderate, in the range of about .4. (These pauses exclude preparatory intervals, which do not correlate with span.) Cowan et al. also used several measures of what we may term rapid articulatory rates. Cowan et al. did not use the measures that are most common in the field, in which a small set of items is to be repeated several (e.g., 10) times in rapid succession until the experimenter gives the signal to stop. Instead, Cowan et al. used a measure in which the numbers 1–10 were to be pronounced only once per trial and measures in which random lists of one to four items were presented and were to be pronounced, following a start cue, only once per trial (with six successive trials using each particular list). This method was intended to eliminate the time participants presumably needed in the more widely used procedures to mentally prepare the speech sequence at the beginning of every repetition cycle. In the correlations that included all 72 children, the rapid articulatory measures were found to be correlated with span at about a .4 level.

Despite the moderate correlations of each of the two types of processing rates with memory span, these two types of rate (retrieval rates in the span task, indexed by interword pauses, and articulation rates in the speeded task) were found to be uncorrelated with one another. As mentioned earlier, they reflected different portions of the variance in memory span and accounted for most of the age-related variance in span. Moreover, Cowan et al. (1998, Experiment 2) carried out a conceptual replication with 180 adults using very different measures of short-term memory retrieval and speeded articulatory processing, and the basic finding was replicated (i.e., retrieval and articulation measures correlating with span but not with each other).

Based on the Cowan et al. (1998, Experiment 1) report, it is not possible to determine the ages at which a particular type of processing rate may have become critical for recall. It was found that the mean retrieval rates and speeded articulation rates both speeded up across ages and that digit span also speeded up. However, this does not tell us when the processing rates mature relative to memory span. Do both rates mature at the same time, commensurate with memory span development, or does one rate or the other surge ahead at a particular age?

One way to approach that question is to examine a simplified set of combined means for each type of measure (based on standardized scores) so that the locus of age effects overall can be determined. A second way is to examine correlations between memory span and various timing measures for children within each age group. For ages at which there is a rapid pace of development in a timing measure and a related development in span, the within-age correlation between that timing measure and span should be relatively large. The within-age correlation should be smaller when span and that timing measure do not develop together at a particular age. Here I report within-age correlations in the data of Cowan et al. (1998), which were not reported in that article.

A third manner of examining the data offers further insights into the ages at which particular processes mature. In particular, here I have reanalyzed the data from Cowan et al. (1998) by using subsamples matched for span across age groups to see if different age groups perform on the basis of different profiles of ability.

METHOD

The results reported here are based on data from the sample of 72 children (Grades 1, 3, and 5, with 24 children per age group) studied by Cowan et al. (1998, Experiment 1). Span and timing measures were used to generate standardized scores (*z* scores) so that these could be averaged across measures of a particular type for the sake of simplicity within some of the analyses. One mean *z* score was calculated for digit span across two runs (i.e., for each child, the two *z* scores were averaged); another was calculated for the duration of interword pauses across correctly repeated lists of length 2, 3, and 4, the lengths at which all children had data (three *z* scores were averaged); and still another was calculated for rapid-speaking durations in the task of counting from 1 to 10 and in rapid repetition of random lists of one, two, three, and four digits (five *z* scores were averaged).

Additionally, by randomly eliminating data from participants with the most extreme spans, a matched sample was created to compare children in Grade 1 versus those in Grade 3. Data from the Grade 1 child with the lowest span and the Grade 3 child with the highest span were eliminated, and this process was repeated until the mean span was higher in the younger group than in the older group. In case of tied spans within a group, the participant to eliminate was chosen randomly. The resulting matched sample comprised 18 children per age group, with mean ages of 89.87 months ($SD = 4.39$) and 111.96 months ($SD = 5.14$), respectively, and mean spans of 4.76 ($SD = 0.50$) and 4.67 ($SD = 0.45$), respectively. (Of the selected first graders, 8 were male, and of the selected third graders, 9 were male).

The method that was used to match children across Grades 1 and 3 was used also to match children across Grades 3 and 5. The resulting matched sample once more turned out to comprise 18 children per group (a fortunate coincidence), with mean ages of 112.32 months ($SD = 4.54$) and 137.19 months ($SD = 5.52$), respectively, and mean spans of 5.10 ($SD = 0.33$) and 5.06 ($SD = 0.40$), respectively. (Of the selected third graders, 8 were male, and of the selected fifth graders, 6 were male.)

It was not feasible to match samples in Grades 1 and 5 directly because there was not enough overlap in the span distributions to provide a sufficient sample. The matched samples were compared on interword pauses (the retrieval measures) and on speeded speech rates (the articulatory measures), which are reported in turn below.

RESULTS

Course of Development of the Measures

Inspection of the means shown in Cowan et al. (1998, Table 1) suggests that span, interword pauses in the memory span task, and rapid-speaking durations in separate, speeded tasks have different maturational courses. Whereas span improves steadily across age groups, the largest developmental changes occur relatively early for the rapid-speaking measures and late for the interword pause measures. The mean *z* scores for span and the timing measures, shown in Table 1, tend to confirm this description. A one-factor ANOVA of the span scores produced an age effect $F(2, 69) = 10.63$, $MSE = 0.67$, $p < .001$. Post hoc Newman–Keuls tests between adjacent age groups showed that the difference was significant in a comparison of Grade 1 with Grade 3, $p = .04$, and also in a comparison of Grade 3 with Grade 5, $p = .02$. An ANOVA of interword pauses

TABLE 1
Mean *z* Scores for Three Types of Variables in Three Age Groups in the Data Set Used by Cowan et al. (1998, Experiment 1)

	Age group		
Measure	Grade 1	Grade 3	Grade 5
Memory span	−.53 (.19)	−.03 (.15)	.56 (.16)
Interword pause duration	.42 (.15)	.07 (.16)	−.49 (.19)
Rapid-speaking duration	.36 (.19)	−.13 (.13)	−.22 (.12)

Note. Standard error of the mean is in parentheses. Each reported mean is an average of mean *z* scores for each individual, with each individual's means based on two span *z* scores (for two span runs), three mean interword pause duration *z* scores (for list lengths 2, 3, and 4), and five rapid-speaking duration *z* scores (for counting from 1–10 and repetition of random lists of one to four digits).

also produced an effect of age, $F(2, 69) = 7.38$, $MSE = 0.67$, $p = .001$. However, the Newman–Keuls comparison between Grade 1 and Grade 3 was nonsignificant, $p = .15$, although it was significant in the comparison between Grade 3 and Grade 5, $p = .02$. Finally, an ANOVA of rapid-speaking durations also produced an effect of age, $F(2, 69) = 4.41$, $MSE = 0.53$, $p = .02$. However, for this measure it was the Grade 1 versus Grade 3 comparison that reached significance, $p = .02$, but not the Grade 3 versus Grade 5 comparison, $p = .66$. Notice that the significant post hoc comparisons occurred at different ages for the two timing measures. This finding does not prove that either timing measure completely stops developing by Grade 5, but it does suggest that the two timing measures have different developmental courses.

Correlations within Each Age Group

Correlations within each age group between memory span and each timing measure are reported in Table 2. Although the samples are small, the table clearly indicates that the correlations differed at different ages. Within Grade 1, correlations between speaking rates and memory span were largest; within Grade 3, none of the correlations were particularly large, and none were significant; and within Grade 5, correlations between interword pauses and memory span were largest.

Correlations using the simplified pattern obtained with mean *z* scores were consistent with the more detailed pattern shown in Table 2. Within the first-grade children, the mean *z* scores for rapid-speaking durations were significantly related to those for span, $r(22) = -.63$. However, the pause durations were not significantly related to span, $r(22) = -.18$, or to rapid-speaking durations, $r(22) = .21$. Within third-grade children, none of the correlations reached significance. Within the fifth-grade children, it was the interword pauses that were related to

TABLE 2
Within-Age-Group Correlations between Memory Span and Various Timing Measures, Calculated from the Data Set Used by Cowan et al. (1998, Experiment 1)

Timing measure	Age group: Grade 1	Grade 3	Grade 5
Rapid-speaking durations			
Count 1–10	−.44*	−.08	.06
1-Digit lists	−.32	−.16	.15
2-Digit lists	−.57*	−.27	−.38
3-Digit lists	−.46*	−.18	−.26
4-Digit lists	−.60*	−.25	−.23
Interword pauses in span responses			
2-Digit lists	.05	−.04	−.48*
3-Digit lists	−.19	−.25	−.41*
4-Digit lists	−.28	−.36	−.39
5-Digit lists	−.28	−.17	−.40

Note. $N = 24$ for every correlation except pauses within five-digit lists, for which $n = 21$, 24, and 23 in Grades 1, 3, and 5, respectively.

* $p < .05$, two-tailed.

span, $r(22) = -.45$. In this group, rapid-speaking durations were not related to span, $r(22) = -.16$, or to pauses, $r(22) = -.16$.

Figure 1 yields insight into why these different patterns of correlations were obtained. It is a scatterplot of individual *z*-score averages for span as a function of rapid-speaking duration, in Grade 1 (top panel) and Grade 5 (bottom panel). These two groups were used to illustrate extremes of the developmental continuum in the data. Different interword pause duration mean *z*-score ranges are represented in the figure with different symbols. The two panels of the figure suggest that there was a certain range of each duration variable that was critical for performance in the span task. For the children in Grade 1, there was an orderly, though somewhat curvilinear, relation between rapid-speaking duration (on the *x* axis) and memory span (on the *y* axis). Not much relation between pause times and span can be observed, but that may be because few children in this age group had the very short pause times represented by the solid circles. For children in Grade 5, on the other hand, not much relation between rapid-speaking durations (on the *x* axis) and span (on the *y* axis) can be observed, but that may be because most children in this age group had relatively brief speaking durations. In this age group, however, there were many children with very brief pause times (solid circles), and they tended to recall more than children with longer pause times (open squares).

To summarize, very long rapid-speaking durations were associated with especially poor span in some younger children, whereas very short interword pause times in the span task responses were associated with especially good span in

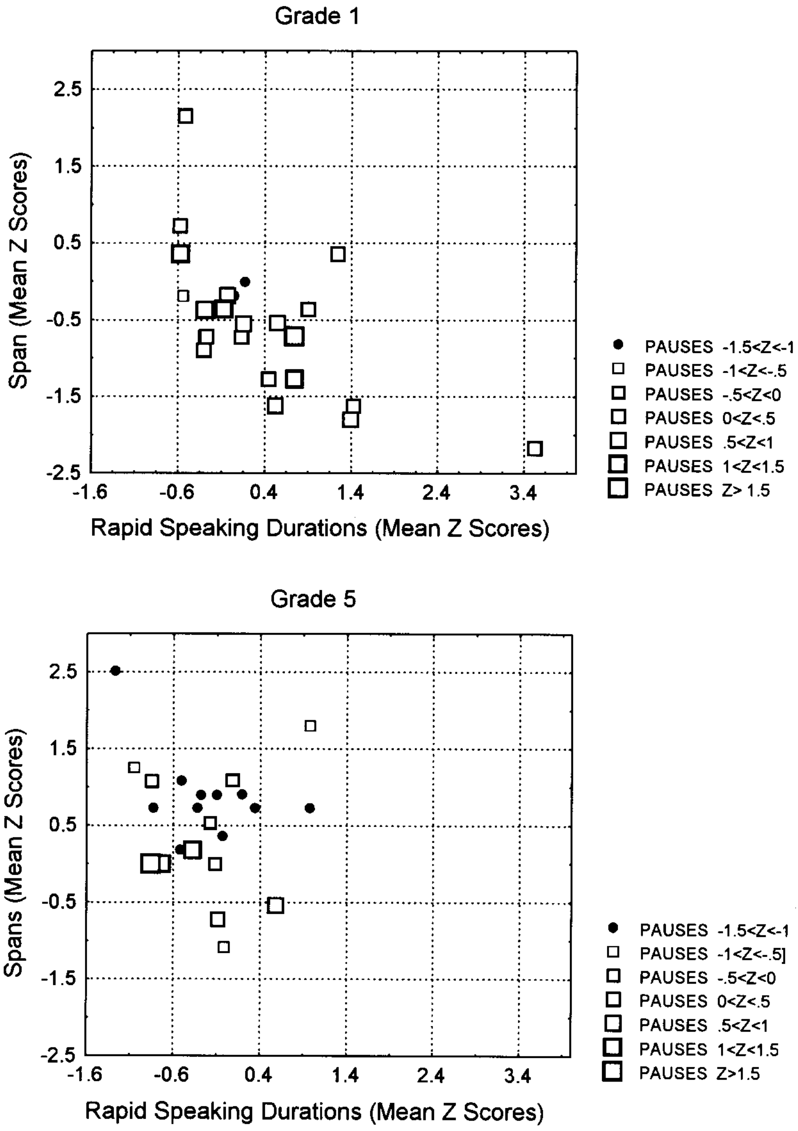

FIG. 1. Scatterplot of individuals' mean *z* score averaged across two *span* runs as a function of mean *z* score averaged across five measures of *rapid-speaking duration* (count 1–10 and random lists of lengths 1, 2, 3, and 4), separately for children in Grade 1 (top panel) and Grade 5 (bottom panel). Solid circles represent individuals with the shortest *interword pauses* (*z* scores averaged across list lengths 2, 3, 4, and 5); open squares represent those with longer pauses, the size of the square covarying with the mean duration of the pause. Notice that rapid-speaking durations above $z = 0.4$ (right side of graphs) were much more prevalent in Grade 1 children and corresponded to low spans, whereas interword pauses below $z = -1.0$ (solid circles) were much more prevalent in Grade 5 children and corresponded to relatively high spans.

some of the older children. The absence of correlations within the third-grade group can be explained on the grounds that they no longer had many of the very long rapid-speaking durations that were injurious to span in first graders, and did not yet have many of the very short interword pauses that were helpful to span in fifth graders. Inspection of individual-subject means in that group, not shown because of space considerations, supported that explanation.

Although this analysis indicates that the critical development in rapid-speaking duration tends to occur earlier than the critical development in interword pause duration, it cannot determine if these developments closely determine span. The purpose of the next analysis was to begin to answer that basic question, and therefore to understand better what causal mechanisms may or may not link individual differences in processing rates to span. Different age groups were matched for span to determine if that would result in a match also in the two types of timing measures.

Span-Matched Samples

Retrieval measures. In the matched samples, the mean duration of interword pauses in the span task were available for all children for list lengths 2, 3, and 4. They were available for list length 5 for all children except one fifth grader, who did not repeat any five-digit lists correctly; that list length was included, and the one child was omitted from the analysis of pause durations. These durations were examined in an Age Group (2) × List Length (4) ANOVA comparing the span-matched samples in Grades 1 versus 3, and another such ANOVA comparing the span-matched samples in Grades 3 versus 5.

The pause durations did not differ significantly for matched samples in Grades 1 versus 3, as shown in Fig. 2 (top panel). No effect involving age group approached significance. In contrast, in the Grade 3 versus 5 comparison, the duration of the interword pauses increased across list lengths much more quickly in the third graders, as shown in Fig. 2 (bottom panel), producing an interaction of Age Group × List length, $F(3, 99) = 2.96$, $MSE = 6000$, $p < .04$.

One possible interpretation of the age difference in interword pauses is that the fifth graders used in this comparison processed material to be recalled in a manner different from other children, such that these fifth graders might never show a relation between memory span and interword pauses. Arguing against this interpretation, though, correlations between span and interword pauses within the sample of 17 fifth-grade children who contributed to Fig. 2 were all significant, $r(15) = -.57, -.64, -.66$, and $-.55$ for list lengths 2–5, respectively.

Speeded articulatory rate measures. Articulation rate measures were available for the task of counting from 1 to 10 and for random digit lists of lengths 1, 2, 3, and 4. In each span-matched comparison, an Age Group (2) × Rate Measure (5) comparison was carried out. Neither age-group comparison produced any effect with age group as a factor. Indeed, the span-matched groups were closely matched on rapid-speaking rates, as shown in Fig. 3 (top panel, Grade 1 versus 3; bottom panel, Grade 3 versus 5). This was not the case in the original,

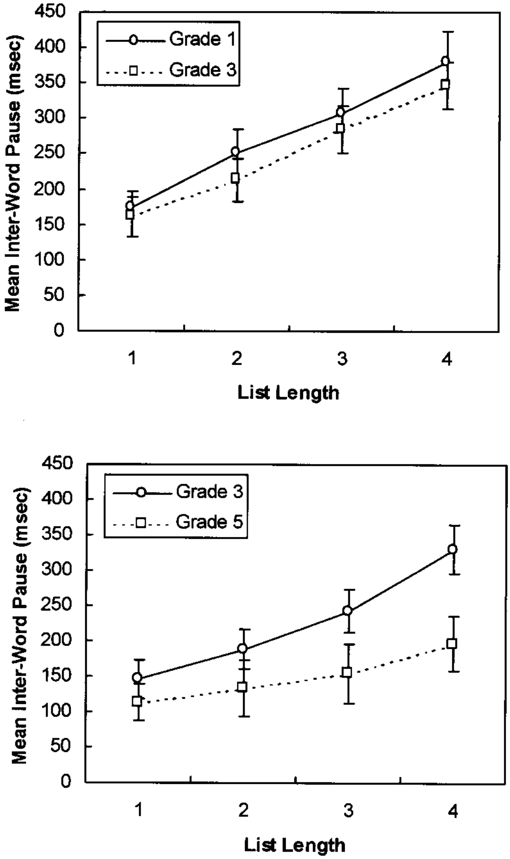

FIG. 2. Mean interword pause durations in correct repetitions of lists of four lengths, averaged across serial positions in the response, for span-matched samples of children in Grades 1 versus 3 (top panel) and Grades 3 versus 5 (bottom panel). Error bars reflect standard errors of the mean.

nonmatched samples of Cowan et al. (1998, Experiment 1), which produced some significant effects of age on rapid-speaking durations.

DISCUSSION

Cowan et al. (1998) found that retrieval rates (measured by interword pauses in the responses to correctly recalled lists) and articulation rates (measured by speeded pronunciations of the digits 1–10 and of short, random digit lists) both correlated with memory span in a sample composed of first-, third-, and fifth-grade children, but that these rates did not correlate with each other. In the present article, several important additional analyses were provided, and they suggest that the two rates not only are independent, but also develop differen-

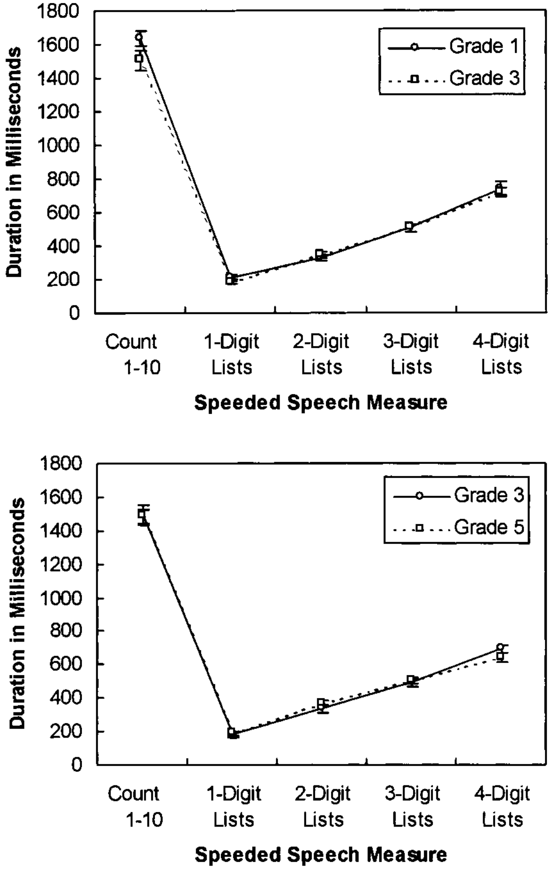

FIG. 3. Mean rapid-speaking durations in the counting task and in the rapid list repetition tasks with list lengths 1 through 4, for span-matched samples of children in Grades 1 versus 3 (top panel) and Grades 3 versus 5 (bottom panel). Error bars reflect standard errors of the mean, which in some cases are small enough to be difficult to see in the figure.

tially. First, post hoc comparisons of means based on composite measures showed that the largest developmental change in rapid-speaking durations occurred between Grade 1 and Grade 3, whereas the largest developmental change in interword pause durations occurred between Grade 3 and Grade 5.

Second, consistent with the pattern of changes in means, within-age-group correlations showed that rapid-speaking durations were correlated with span only in Grade 1, whereas interword pause durations were correlated with span only in Grade 5. An examination of the skill profiles at these ages (Fig. 1) suggested a reason for this pattern. The slowest region of rapid-speaking durations is associated with short spans, and it is found primarily in some of the first graders; the fastest region of interword pause durations is associated with long spans, and it is found primarily in some of the fifth graders. Another way to express this difference is to note that first graders were not highly differentiated in their interword pauses, with most of these children performing in an acceptable but less-than-ideal range; third graders were not highly differentiated in either timing measure; and fifth graders are not highly differentiated in their rapid-speaking durations, with most of these children performing in a good range on that variable.

Third, analyses with span-matched subsamples show that these two separate types of processing rates also operate differently across the age range. With spans matched, interword pauses were equivalent for children in Grade 1 versus Grade 3; but there was still a dramatic difference between interword pauses between Grade 3 and Grade 5 (see Fig. 2). No such pattern was obtained with rapid-speaking rates. When spans were matched either across Grades 1 and 3 or across Grades 3 and 5, the rapid-speaking rates were also well-matched (see Fig. 3). It is noteworthy that the variables that corresponded to each other best (span and speaking rate) were derived from different test procedures, whereas the variables that did not correspond to each another as consistently across ages (span and interword pauses) were derived from the same test procedure (the span procedure). It is apparently the similarity between the processes involved in span and a particular rate measure, rather than the similarity between the test situations from which they were derived, that determined the similarity between their results in span-matched samples.

One possible reaction to the finding of different interword pause durations in relatively high-span third graders versus relatively low-span fifth graders is that this difference is tainted by other, unmeasured intellectual differences between the groups. Clearly, such differences are likely to exist, even though the samples were not extreme (given that they included 18 out of 24 children in each age group). Such unmeasured group differences do not disqualify the intended comparison, however. The point of that comparison was, after all, to determine whether speech timing predicts span in the same way in all age groups or not. The clear answer is that span timing is not fully predictive in the older age range. Speech timing variables provide an adequate account of span in the earlier grades, but nontiming variables must be taken into account to explain the finding that the less advanced fifth-grade children responded more quickly in the span task than the more advanced third-grade children despite having comparable mean spans and comparable mean speeds on rapid-speaking tasks.

The results have several important implications. First, they suggest that the single-speed theories of short-term memory (e.g., Baddeley, 1986; Kail & Park, 1994) must be modified to take into account multiple speeds. It was already clear that multiple independent speeds are correlated with span (Cowan et al., 1998). The present analyses show that these multiple speeds do not simply develop in parallel. Instead, it appears as if there are different periods for the importance of each timing variable (see Table 1). Within Grade 1, the development of articulatory speed is rapid and is related to memory span. The same is not true of interword pauses. Conversely, within Grade 5, it is the development of interword pauses that is rapid and is related to memory span, and the same is not true of articulatory speed (see Table 2 and Fig. 1).

Another issue is whether timing durations consistently help to determine spans. The relationship between processing speed and span theoretically could be a direct, consistent, causal one in the case of the rapid-speaking rates shown in Fig. 3, inasmuch as matching for spans results in a match in rapid-speaking rates also. However, it could not be consistent in the case of the interword pauses shown in Fig. 2. Those data show differences in pauses between third and fifth graders who were matched in spans. There must be some factor other than retrieval rate that allows these third graders to achieve spans as high as the fifth graders with whom they were matched.

One simple account would suggest that the retrieval rates indexed by interword pause durations in the span task are direct effects of maturation but indirect causes of span differences, at least between Grade 3 and Grade 5. For example, it may be that a faster retrieval rate allows a certain strategy for retaining and recalling the list items, but that a faster retrieval rate does not, in itself, ensure that the strategy will be used. Supporting this notion, current models of strategy usage and its development consider adequate speed and efficiency of processing to be necessary, but not sufficient, for the successful use of a mnemonic strategy. For example, within one general model (Bjorklund & Douglas, 1997) it is assumed that one must consider not only the speed and efficiency of processing, but also the person's knowledge, availability of mental resources, domain-specific and context-independent strategies, and metacognition. The concept would be that particular strategies can be used to maintain or strengthen items in memory but that a certain minimal processing speed is necessary in order for the strategies to be used effectively. Salthouse (1996) similarly has emphasized this point within a statistical analysis of cognitive aging.

We do not know what strategies are used but, in the immediate serial recall of digits, the available strategies would appear to be limited. One strategy might be to refresh the items in short-term memory by focusing attention on them or "scanning" them one at a time (Cowan, 1988, 1995), which would be a rapid, nonarticulatory analog to the rehearsal loop proposed by Baddeley (1986) and others. Another possible strategy would be to form mental associations between some adjacent digits in order to form larger "chunks" that could be memorized (Miller, 1956), and this, too, might depend on the ability to search through the items in short-term memory rapidly, perhaps to determine where the boundaries between chunks could occur. Between third and fifth grade, children may rather uniformly develop the adequate short-term memory retrieval speed to use such strategies, but only some of them may have learned how to take advantage of that added speed.

Pressing issues for future research include an understanding of how processing speed may contribute to strategy usage and how speed and capacity limits are related. The present paper provides a few clues that may be important for resolving these larger issues, by showing that a speedup of short-term memory retrieval with age does not uniformly and immediately lead to an improvement of memory span despite a general correlation between the two (see Fig. 2). By way of contrast, span and maximal articulatory speed, which is unrelated to retrieval speed, were exquisitely convergent within the age range tested (see Fig. 3). The reason for that convergence could be the mnemonic value of rapid covert rehearsal (Baddeley, 1986). Alternatively, given potential theoretical problems with that suggestion (e.g., Brown & Hulme, 1995), and given the fact that young children do not seem to engage in covert, cumulative verbal rehearsal (Cowan et al., 1994; Flavell et al., 1966; Gathercole et al., 1994), the reason for the convergence between span and articulatory speed could be the mnemonic value of some other skill that is only associated with rapid articulation ability. Such a skill could, for example, be the ability to read or extract information from phonological memory quickly (Gathercole & Hitch, 1993).

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