The Role of Working Memory in Reading Disability*

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Other presentations have focussed on the importance of phonological awareness in reading acquisition and on the central role Isabelle Liberman has played in theoretical and empirical advances in this area. It was noted that she led the way in recognizing the cognitive demands of reading: that reading, in contrast to speaking and listening, requires explicit awareness of phonological segments and that this awareness is difficult to achieve given the embedded nature of phonemes in syllables. In this paper I will show that Dr. Liberman also led the way in investigating how metaphonological abilities relate to underlying phonological processes. She was among the first to identify the need to understand the organization and functioning of the language system in order to explain sources of difficulty for poor readers. Together with Donald Shankweiler and several students, Isabelle Liberman conducted insightful and elegant research on the working memory deficits of poor readers, discovering that phonological processes are implicated here, as well as in the deficits in phonological awareness.

In my presentation I would like to accomplish three things: First, I will take note of the large body of evidence that deficits in a specifically verbal form of working memory are associated with reading problems, and to point out Dr. Liberman's enormous contribution to our understanding of the source of these limitations in language processing.

Second, I will consider evidence (both old and new) that the efficiency of phonological processes is an important limiting factor in working memory capacity and that poor readers often have inefficient phonological processes. Third, I will discuss current evidence pertaining to possible causal links between the phonological processes underlying phonological awareness, verbal working memory, and lexical access.

The association of verbal working memory deficits with reading disability

While deficiency in metaphonological awareness is certainly the language factor most strongly implicated in reading disability, there is reason to believe that difficulties in awareness betoken more basic problems in language use. At the level of underlying language processes, perhaps the most striking characteristic of poor readers is the common occurrence of verbal memory problems. Teachers often comment on the difficulties poor readers have retaining information for even brief periods of time, and there now exists a massive number of research studies reporting an association between reading disability and short-term memory limitations. When given a short list of digits, or letters, or words, or even nameable pictures to recall, poor readers recall fewer items than do good readers. The generality of the relationship between reading difficulty and working memory is highlighted by the finding that it holds both for readers of alphabetic writing systems and for people in Eastern Asia learning syllabic and logographic scripts (Mann, 1985; Ren & Mattingly, 1990). Evidence also emerges from the unusual condition of hyperlexia: Healy, Aram, and Horowitz (1982) presented findings on 12 hyperlexic children who despite very low cognitive functioning in almost every area were good decoders. Performance on working memory tasks stood out as one of the few cognitive strengths of these children.

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Evidence for a causal role of memory in reading performance comes from a small number of prediction studies that found memory capacity in kindergarten to be significantly related to later success at learning to read. For example, Share, Jorm, Maclean, and Matthews (1984) reported on a longitudinal study of 543 children and found a correlation of about .4 between kindergarten performance on sentence memory tasks and reading level at the end of first grade. In a subsequent analysis of these children, Jorm, Share, Maclean, and Matthews (1986) subdivided the children who became poor readers (now followed to the end of third grade) into those with a specific reading problem and those who had reading problems and also had low IQs. For both groups language deficits, including poor memory performance, were apparent at the kindergarten phase prior to reading acquisition. The low IQ children, in addition to their language impairments, had other problems such as poor performance on perceptual-motor tasks and on a nonverbal auditory task.

The consequences of a reduced capacity in working memory may be extensive. Some have suggested that limited capacity may make it more difficult to discover and master metaphonological skills. Evidence compatible with this is presented by Wagner, Balthazor, Hurley, Morgan, Rashotte, Shaner, Simmons, and Stage (1987). In this study with 111 kindergarten nonreaders, the results best fit a model specifying a single latent factor for phonological awareness and for verbal working memory. Others, such as Perfetti and Lesgol (1977; 1979), have noted that deficits in memory may make it more difficult to learn how to decode. A recent study by Dreyer, 1989, reports a correlation of .65 between performance on a recall task and decoding skill. A further impact of limited memory resources on reading has been suggested by Perfetti (1985) who hypothesized that for the slow, beginning decoder limits in working memory may be used up getting to the words of the text. Once the words have been decoded, insufficient resources are left for other higher language processes. This is consistent with the observation that children may fail to comprehend a sentence in text even when they manage to decode all the words it contains. Similarly, Liberman and her colleagues have stressed the integrative function of working memory and considered that its chief contribution would be to facilitate syntactic and other sentence-level processes (Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977; Mann, Liberman, & Shankweiler, 1980; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). In keeping with this, Mann, Shankweiler, and Smith (1984), Smith, Macaruso, Shankweiler, and Crain (1989), and Fowler (1988) have found evidence that poor reader's difficulties with sentence level tasks stem in part from deficits in working memory.

Although memory difficulties in poor readers are commonplace, they are not universal. In an important study by Torgesen and Houck (1980), two groups of learning disabled children were identified, only one of which had memory impairments. Further, the proportion of variance between good and poor readers accounted for by working memory performance is generally markedly lower (approximately 10%) than the proportion accounted for by phonological awareness abilities (approximately 40-70%). Wagner (1988) reported on a meta-analysis of longitudinal correlational studies and training studies that finds relatively independent causal roles for metaphonological processes and for working memory. Thus the exact role of working memory deficits in reading disability remains unclear. On the one hand, the occurrence of these difficulties in poor readers is widespread, having been found across language and writing systems, in diverse populations, and to be present in those destined to be poor readers prior to reading acquisition. On the other hand, it must be acknowledged that memory limitations are not as consistently or as strongly associated with reading disability as are deficits in metaphonological skills.

These facts warrant a searching examination of working memory processes and their role in reading. Ultimately, we will need to understand the interplay between metaphonological processes and memory processes to fully comprehend the requirements of reading acquisition and the bases of reading failure.

A group of investigators from Haskins Laboratories began this enterprise by exploring the basis and extent of memory deficits for poor readers (Liberman et al., 1977; Shankweiler et al., 1979). Drawing on the evidence that information in verbal working memory is retained in a phonological or speech code, they hypothesized that poor readers have a specific difficulty with the use of phonological representations in working memory, and went on to demonstrate that good readers, like adults (Baddeley, 1966; Conrad, 1972), find lists of nonrhyming words easier to recall correctly than rhyming lists. Presumably, because in the nonrhyming case the internal phonological or speech representations for the words are very distinct, whereas for the rhyming
words they are so similar to each other that it is easier for them to be confused. Unlike the good readers, poor readers didn't show this pattern. They were not adversely affected by rhyme; performance on rhyming lists was not appreciably different from performance on nonrhyming lists. These results were interpreted to suggest that poor readers are not as adept as good readers at forming phonological representations.

In subsequent work the Haskins researchers and others have found the rhyme effect in good and poor readers to be affected by both subject and task factors (Brady, Mann, & Schmidt, 1987; Ellis, 1980; Hall, Wilson, Humphreys, Tinzmann, & Bowyer, 1983; Watkins, Watkins, & Crowder, 1974). Nonetheless, the line of research on the rhyme effect, or phonological similarity effect, paved the way in pointing to the role of phonological processes in the memory and reading difficulties of poor readers.

Using this paradigm, Shankweiler et al. (1979), made a further noteworthy observation that the memory differences between good readers and poor readers were apparent whether visual presentation was used, or auditory presentation. They suggested that poor readers have a general problem with the use of a phonological code, independent of how the material is presented, not a difficulty that is restricted to the reading process itself. In contrast, they, and others (Katz, Shankweiler, & Liberman, 1981; Liberman, Mann, Shankweiler, & Werfelman, 1982; Vellutino, Pruzek, Steger, & Meshoulam, 1973), found that poor readers do not perform less well than good readers on short-term memory tasks with nonspeech stimuli such as doodle drawings or photographs of strangers. With these stimuli, not easily given a phonological label, no significant differences in performance between good and poor readers were observed. These findings supported the conclusion that poor readers do not suffer from a general memory impairment. Rather they are often deficient in the ability to remember linguistic material, however it is presented, and the problem appears to be related to phonological processes involved in encoding or storing verbal information.

Explanations of developmental and reading-group differences in memory span

At this point it wasn't apparent whether poor readers were employing some other coding strategy to retain items in STM, such as a visual or semantic strategy, or whether they were using phonological codes, but doing so inefficiently. Long before, Conrad (1971) had suggested that children younger than six did not use phonological coding in memory. However, more recent research by Alegria and Pignot (1979) found the rhyme effect to be present in children as young as four, and, indeed, phonological coding in working memory would seem to be essential for a child to learn to speak a language. Yet, for some reason, poor readers show the rhyme effect at a later age than do children who are better readers. For example, using a cross-sectional design, Olson, Davidson, Kliegl, and Davies (1984) reported that by adolescence poor readers demonstrated the phonological similarity effect, though they still showed lower levels of recall than good readers (see also Johnston, 1982, and Siegel & Linder, 1984).

These findings suggest that factors which contribute to developmental differences in verbal STM performance may also account for reading group differences in linguistic memory. I should note that Dempster (1981), reviewing numerous studies, estimated that span approximately triples from an average of slightly more than two items at age two to an average of nearly seven items at adulthood. Children who are poor readers systematically lag behind their age mates in recall level. Three kinds of explanations have been offered to account for developmental and reading group differences in verbal STM performance. I would like to describe all three, but I'll be brief about the first two, which seem inadequate, and I'll elaborate more on the third position; an operational efficiency view that emphasizes the role of phonological processes.

Mnemonic strategies. First, the differential use of mnemonic strategies has been offered as an explanation for developmental increments in STM span. According to this view, children become increasingly aware that certain strategies will enhance recall, and are thus increasingly able to employ an appropriate technique. It is clear that mnemonic strategy use does advance as children become older. These advances include more frequent spontaneous use of rehearsal strategies, such as the way we repeat a phone number to remember it briefly, and better use of imposed or subjective organization.

Good and poor reader differences have also been explained in this way. Tarver, Hallahan, Kauffman, & Ball, 1976, and Torgesen, 1977, reported that good readers are more likely to use self-initiated rehearsal than children with reading problems. And Torgesen (1978-79) reported that good readers are more likely to use a chunking
strategy or to consciously impose an organizational plan on materials to be recalled. But additional findings, as well as interpretative difficulties, suggest that differences in mnemonic strategy use is not the sole basis for individual differences in memory function. Lange (1978) confirmed that adults and adolescents were more likely than younger children to make use of organizational principles, but differences in this strategy were not discerned in children from 5 to 12 years of age. Yet this is a period during which short-term memory span has been found to increase dramatically (Dempster, 1981).

A second conflicting piece of evidence for the role of mnemonic strategies in developmental increases in span comes from a series of experiments which have equated children's use of certain control processes during STM tasks. For example, Samuel (1978) grouped items in internal patterns in recall lists. Children ranging in age from six to nineteen all benefited equally from that grouping technique, so the age differences were maintained (see also Huttenlocher & Burke, 1976, and Engle & Marshall, 1983).

Similar results have been obtained when the subjects were good readers and poor readers. That is, when reading groups are equated on the use of strategies, differences in recall span still occur. Thus while the use of mnemonic strategies improves as individuals get older, it does not appear to be the central factor either in developmental or in reading-group differences.

Capacity. A second approach to developmental changes in memory span has postulated an actual difference in capacity of short-term memory. Proponents of capacity explanations hold that a certain number of memory slots are available prior to the presentation of any stimuli. Developmental differences in span are attributed to the presence of a greater number of these slots as a function of age: so a two-year-old might have 2 slots, and adults might have 7 slots (Pascual-Leone, 1970, and Halford & Wilson, 1980). This position is consistent with the observation of developmental increases in recall, and also fits the observed differences in STM span among good and poor readers.

However, a series of experiments conducted by Baddeley, Thomson, and Buchanan (1975) demonstrated that the number of items that can be recalled is not fixed for a given individual. The number varies with the length of the stimulus (in number of syllables). Thus, temporal duration of the item list proved to be a strong determinant of span. Similarly, Ellis and Hennelley (1980) did experiments with bilingual Welsh students and showed that these subjects had a longer digit span when the digits were given in English than in Welsh, maintaining that the differences were attributable to the fact that Welsh numbers take a longer time to say. In addition, as will be discussed below, increases in memory span with age can be offset if unfamiliar stimuli are used for recall. Thus it seems than an explanation in terms of a fixed number of slots cannot account for important individual differences in STM performance.

Operational efficiency. The third position I wish to present, which I find a more promising explanation, is an operational efficiency view that proposes that memory is served by a limited capacity system and that memory operations such as encoding and retrieval become more efficient with relevant experience. As a result, the amount of operating resources needed to complete short-term memory tasks decreases with age and there is a functional increase in storage capacity. I find it useful to view the working memory system as a pie: if perception or encoding requires one quarter of the pie, three-quarters will be left over for recall. If one gets better at encoding, more resources will be available for memory. My version of this hypothesis is that the difficulty observed in encoding phonological information is not restricted to memory tasks but occurs at a more abstract level, whenever it is necessary to create and maintain a phonological representation. To evaluate this hypothesis one can look for parallels between performance on tasks involving speech perception, speech production, and verbal short-term memory.

I will begin with some observations from the developmental literature and I will review here some studies with single age groups that seem relevant.

First, with adult subjects it has been observed that if the encoding requirements on a memory task are made more difficult by changing the perceptual demands, then short-term recall suffers. For example, Rabbitt (1968) had adults listening to digits in white noise. In one condition they were asked to repeat individual items, in another condition they had to recall lists of digits. Noise levels that caused no effect on perception of the individual items, significantly impaired recall of the same stimuli. Recall of the lists not in noise was greater than recall of the lists with noise. Adding noise and increasing the perceptual difficulty adversely affected memory. Likewise, Luce, Feustel and Pisoni (1983) demonstrated that adults have poorer recall of lists of synthetically spoken items than of lists of natural speech, and
Mattingly, Studdert-Kennedy, and Magen (1983) reported poorer recall if the words were spoken in different dialects. These three studies illustrate different ways of making the encoding demands more difficult, but all are compatible with the view that when more resources are used up for encoding, less are available for storage or recall, hence there is a trade off.

A second line of evidence for the relevance of underlying phonological processes to working memory functioning comes from a report by Locke and Scott (1979) that children with articulation disorders also have impaired short-term memory performance. Similarly, Ellis (1979) reviews findings of concordant error patterns by adults in spontaneous speech production and in short-term memory tasks.

The third source of evidence comes from investigations that for both adults and children, the intrinsic efficiency of phonological processes correlates positively with memory span. Thus significant correlations are obtained between how fast one can speak and how much is recalled on a short-term memory task. This has been found both in adult studies (Baddeley, et al., 1975; Hoosian, 1982; Naveh-Benjamin & Ayres, 1986; Nicolson, 1981) and in developmental studies. Hulme, Thomson, Muir, and Lawrence (1984) tested individuals from four years of age to adulthood and obtained a linear relationship between maximal speaking rate and recall performance. A particularly compelling set of findings comes from a study by Case, Kurland, and Goldberg in 1982. Testing three-to-six year old children, all of whom are unlikely to use mnemonic strategies, these authors observed a strong correlation between how rapidly the children could repeat the test words and the size of their memory span. The older children, who could articulate faster, recalled more of the words. 

In a convincing test of this relationship, Case et al. found that when adults' speaking rate was slowed to the rate for six-year-old children by giving the adults more difficult items, memory span with these stimuli also dropped to the six-year-old level. Although the encoding processes involved in memory were only evaluated by word-repetition speed, these results indicate that developmental increases in memory span may be linked to the efficiency of related phonological processes.

Let us consider the reading-group literature to examine whether the verbal memory differences of good and poor readers might also be accounted for by the efficiency of underlying phonological processes. This remains to be fully addressed: speech perception, verbal memory, and speech production abilities in good and poor readers have generally been looked at in isolation, and so relations among these processes have not been examined in depth. I'll discuss current findings addressing the operational efficiency hypothesis and will then present findings from a study with Michele Rapala (Rapala & Brady, 1990).

First, I have noted investigations which found a correspondence in poor readers between less effective use of phonological coding in short-term memory (indicated by a lack or reduction of the phonological similarity effect) and reduced memory span (Mann et al., 1980; Mark, Shankweiler, Liberman, & Fowler, 1977; Olson et al., 1984; Shankweiler, et al., 1979; Siegel & Linder, 1984). Related to this, error analyses have indicated that while both reading groups use phonological coding strategies, poor readers are less accurate. In 1983 Donald Shankweiler, Virginia Mann and I first noted this, looking at the errors made by third-grade good and poor readers on lists of nonrhyming words (Brady, Shankweiler, & Mann, 1983). The response sequences included items, for both good readers and poor readers, that had not occurred in the original strings. In the vast majority of cases, these errors were recombinations of phonological components that were present in the initial sequence (for example, for the target items train and plate, several subjects reported "trait" and "plane"). These transposition errors occurred for both reading groups, but more frequently for the poor readers. Thus, the poor readers were clearly using a phonological coding strategy, but having more difficulty than the good readers in retaining the correct combination of phonological segments. In a follow-up study, Brady et al. (1987) used lists of nonsense syllables to assess the incidence and circumstances of such errors with greater precision. We constructed lists in which the items shared zero, one, or two phonological features. Across lists of syllables, the order of the stimuli also varied systematically so we could ask whether adjacent items were more likely to be transposed than were nonadjacent ones, and whether the effect of shared features is greatest for immediately adjacent segments. As expected, poor readers made more errors than good readers, but for both groups transposition errors accounted for the majority of errors. For both reading groups, these more often involved swaps from adjacent syllables and there was a significant effect of phonological feature similarity, with a greater number of transpositions occurring between syllables that had features in common. (The effects of
feature similarity and of adjacency seemed to be independent.) These kinds of errors suggest that the inferior performance of poor readers is not the consequence of a different coding strategy, but relates to differences in the formation or storage of phonological representations. Thus, we again have a correspondence between less effective coding in STM and poorer recall.

A second area of investigation has demonstrated speech perception deficits for poor readers, possibly reflecting a general difficulty in encoding language. Different paradigms have been used such as word repetition tasks and categorical perception tasks, but the common finding is that poor readers are less accurate (Apthorp, 1988; Brady et al., 1983; Brady, Poggie, & Rapala, 1989; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Goetzinger, Dirks, & Baer, 1981; Palley, 1986; Read, personal communication; Snowling, 1981; Snowling, Goulandris, Bowlby, & Howell, 1986; Werker & Tees, 1987.

The task has to be somewhat demanding in order to detect lower performance by poor readers. For example, Brady et al. (1983) found poor readers to be worse at identifying monosyllabic words in noise, but not monosyllabic words presented without noise. In subsequent studies we and others have also found poor readers to do less well on clearly presented words if the phonological demands are increased either by lengthening the stimuli by using multisyllabic words or by decreasing item familiarity by using pseudowords. The evidence with multisyllabic real words, as well as earlier findings that word frequency of stimuli has a comparable effect on both reading groups (Brady et al., 1983), argues against an explanation that poor readers’ difficulties in phonological processing are confined to nonwords (cf., Snowling et al., 1986). It is unclear, however, whether the problem repeating words arises during the perception or production components of such tasks, or to the common requirement of formulating a phonological representation. Indeed, with respect to speech production, there are reports in the clinical literature that individuals with reading difficulty often display misarticulations in their speech (Blalock, 1982; Chastay, 1986; Johnson & Mylebust, 1967; Klein, 1986), as well as empirical demonstrations that dyslexics are slower and less accurate at repeating phrases (Catts, 1986; Catts, submitted: though for this task memory requirements may be a factor.) Finally, additional evidence of a link between phonological processes and memory capabilities with respect to reading level has been tentatively supported by positive correlations between how fast children can name lists of digits and their memory span (Spring & Capps, 1974; Spring & Perry, 1983; Torgesen & Houck, 1980.) The naming task involves speech production but also requires retrieving the names of the digits. Thus, more than one factor may be contributing to the correlation with memory.

In our own work we’ve found poor readers to be as fast as good readers at single word repetition, but not as accurate (Brady et al., 1983; Brady, Poggie, & Rapala, 1989). A recent study by Stanovich, Nathan, and Zolman (1988) using a reading-age match design makes the point that speech of articulation is strongly age-dependent. Children matched on reading ability who were in the third, fifth, and seventh grades differed markedly in speed of repetition of simple words though their memory spans were comparable. This would seem to undercut the importance of the link between reading ability and articulation, and by extension, the role of speed of formulating phonological representations in memory span. Yet the studies with adults cited earlier that report a continuing association between speed of articulating, memory span and reading ability raise doubts that developmental factors artifactually account for the correspondence between memory span and articulation found by Hulme et al. (1984). Likewise, the experimental design of Case et al. (1982) also presents convincing evidence of a significant relation between encoding processes and memory span. In sum, phonological difficulties in memory, in speech perception, and in speech production have been observed in children with reading difficulties and there have been occasional reports of correlations between these measures. Relations among the underlying phonological processes need to be more closely investigated, both in developmental studies and in reading-group comparisons. In addition, we need to disentangle the factors of speed and accuracy of articulation as they relate to memory span and reading ability.

To review, in seeking an explanation of the short-term memory deficits characteristic of poor readers, I have considered the explanations proposed for developmental changes in memory performance. The explanation in terms of mnemonic strategy use did not seem adequate. The use of mnemonic strategies does increase developmentally and is sometimes observed to be superior in good readers as compared to poor readers, but noteworthy changes in memory span occur during years in which changes in mnemonic strategies are not evident. Further, when different age
groups or reading groups are induced to use the same strategy, differences in span are still present. The capacity view, maintaining that the actual number of slots in memory increases, is contradicted by evidence that the length and familiarity of items are important determinants of recall. The third position maintains that verbal working memory is a limited capacity system and that the efficiency of encoding and retrieving limit the resources available for retaining information. Both the developmental research and the reading-group research point toward a role of the efficiency of phonological processing in memory capacity. However, in each field the questions have been incompletely addressed, and some of the findings appear to be in conflict. The developmental studies have focussed on the correspondence between speaking rate and memory, emphasizing the importance of speed of articulation. The reading studies have more extensively investigated phonological processes in speech perception and speech production that may relate to memory performance, but have generally examined each area in isolation.

A study by Michele Rapala and me (Rapala & Brady, 1990) was designed to investigate more thoroughly whether developmental and reading group differences in verbal STM can be accounted for by differences in the efficiency of related phonological processes. Using an extensive battery of tests, a cross-sectional developmental study was carried out with 4 1/2 year olds, 6 1/2 year olds and 8 1/2 year olds to examine the association between verbal STM and phonological processes in speech perception and speech production. Complementing the developmental study, a comparison of 8 1/2 year old good readers and poor readers was conducted using the same test battery to assess directly whether poor readers' difficulties in STM are associated with deficits in other phonological processes.

The measures included a verbal short-term memory task using lists of words and a non-verbal memory task known as the Corsi Blocks test (Corsi, 1972). In that task, nine identical black blocks are scattered on a platform and the experimenter points to a number of blocks, in turn. The subject then must reproduce this sequential pattern. We also included a number of phonological tasks. There were two speech repetition tasks; repetition of monosyllabic and multisyllabic words. The children were told to say each word carefully but as quickly as possible. To control for the role of perception in the first task, we also included tasks in which the child would hear a tone and was asked to respond with a particular word (in one condition the monosyllable "cat"; in another condition the multisyllable "banana"). Here no speech signal has to be encoded, so we eliminated the speech perception requirement. In the word repetition and control tasks, responses were scored for speed of onset and for accuracy. Lastly, we had a production measure in which the child was told to repeat six times in succession a two-syllable tongue twister such as "sishi" or "bublu." On this task, the time to produce the six repetitions was measured and the accuracy of each syllable was recorded.

We obtained significant correlations between all the measures in our developmental study, but of course everything improves with age. To check that the variable of age, or some general cognitive factor that improves with age, wasn't the actual basis for the significant relations, we conducted a series of correlational analyses with the effects of age controlled. When age is controlled (see Table 1) a significant relationship continues to exist between VSTM and the other phonological processes. The negative direction of the coefficients indicates that as the time to produce stimuli decreases, and as the number of errors decreases, verbal short-term memory span increases. The control measures which tested speed of articulation without a perceptual component did not correlate significantly after age was partially out. Perhaps these tasks weren't sufficiently sensitive; alternatively, the processes tapped by these measures are less closely related to memory.

If we look at the results between these measures and non-verbal memory (see Table 2), again with age partialled out, the overall patterns is very different. One variable produced a significant correlation, but with this many comparisons that could be a chance result. The lack of a general relationship between nonverbal memory and phonological processes contrasts sharply with the consistent association found between verbal recall and the other phonological measures. This indicates that while there are age-related improvements in a variety of cognitive skills, the observed relationship between verbal STM and the other phonological measures expressly reflects shared linguistic processing factors. Indeed, the results of a discriminant function analysis, conducted with the nine language measures indicated that one significant discriminant function accounted for 83.4 percent of the total variance. This result suggests the tests of speech perception, speech production, and verbal memory tap a single underlying dimension.
Table 1. Developmental study: First order correlations (age partialled) between verbal short-term memory and each of eight phonological variables (N=74).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Partial r</th>
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<tbody>
<tr>
<td><strong>Accuracy measures</strong></td>
<td></td>
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<tr>
<td>Speech Perception: Errors on Monosyllabic Words</td>
<td>-.25*</td>
</tr>
<tr>
<td>Speech Perception: Errors on Multisyllabic Words</td>
<td>-.43*</td>
</tr>
<tr>
<td>Tongue Twister Errors</td>
<td>-.42*</td>
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<tr>
<td><strong>Speed measures</strong></td>
<td></td>
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<tr>
<td>Speech Perception: RT on Monosyllabic Words</td>
<td>-.25*</td>
</tr>
<tr>
<td>Speech Perception: RT on Multisyllabic Words</td>
<td>-.32*</td>
</tr>
<tr>
<td>Tongue Twister Speed</td>
<td>-.35*</td>
</tr>
<tr>
<td>Control: Monosyllabic</td>
<td>-.21</td>
</tr>
<tr>
<td>Control: Multisyllabic</td>
<td>-.17</td>
</tr>
</tbody>
</table>

*p < .05

Table 2. Developmental study: First order correlations (age partialled) between verbal short-term memory span and nine language measures (N=74).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Partial r</th>
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<tbody>
<tr>
<td><strong>Verbal STM</strong></td>
<td>.20</td>
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<tr>
<td><strong>Accuracy Measures</strong></td>
<td></td>
</tr>
<tr>
<td>Speech Perception: Errors on Monosyllabic Words</td>
<td>-.09</td>
</tr>
<tr>
<td>Speech Perception: Errors on Multisyllabic Words</td>
<td>-.12</td>
</tr>
<tr>
<td>Tongue Twister Errors</td>
<td>-.07</td>
</tr>
<tr>
<td><strong>Speed measures</strong></td>
<td></td>
</tr>
<tr>
<td>Speech Perception: Reaction Time (RT) on Monosyllabic Words</td>
<td>-.24*</td>
</tr>
<tr>
<td>Speech Perception: RT on Multisyllabic Words</td>
<td>-.18</td>
</tr>
<tr>
<td>Tongue Twister RT</td>
<td>-.08</td>
</tr>
<tr>
<td>Control: Monosyllabic</td>
<td>-.01</td>
</tr>
<tr>
<td>Control: Multisyllabic</td>
<td>-.02</td>
</tr>
</tbody>
</table>

*p < .05

On comparing the 8 1/2 year old good and poor readers, we found, as have others, that the groups differed on verbal memory but not on nonverbal memory. We also found that memory performance correlated significantly with the error scores for multisyllabic words and for tongue twisters, and that a substantial proportion of the variance in VSTM span could be accounted for by the accuracy of phonological processing (VSTM, multisyllabic errors: \( r^2 = .25 \); VSTM, tongue twister errors: \( r^2 = .15 \)).

In sum, it is likely that verbal working memory plays a major role in reading, whether memory deficits, per se, emerge as a primary factor or as a contributing factor of reading disability. Therefore, it is essential to understand the functioning of the phonological system serving verbal working memory. The present findings are com-
patible with the view that: a) poor readers are
deficient in phonological processing; b) that phonological limitations lead, in turn, to limitations in the efficient use of working memory; and, c) that nonverbal memory processes are served by separate cognitive functions. However, this is a very minimal conceptual framework, and much work remains to be done on the nature of the working memory system and on the factors accounting for differences in capacity. For example, as noted earlier, the role of both speed and accuracy in phonological processing needs to be further studied to determine how these processing variables relate to the functioning of the phonological system and to the construct of efficiency. In addition, it is important to study further the basis and extent of the commonalities across speech perception, speech production and verbal memory. Our findings fit the hypothesis that the need to encode the stimulus phonologically is shared across all the tasks, and that this may be the basis of the correlations we obtained. Yet we appreciate that other factors such as rehearsal and retrieval need to be studied in this light to evaluate alternative explanations.

In addition, the present findings suggest it would also be worthwhile to explore further whether the deficits of poor readers on verbal memory tasks are to be explained in terms of lower efficiency on a continuum of normal phonological processing. Lastly, it will be important to relate the deficits of poor readers on these more basic phonological processes to the robust evidence that poor readers also have deficits in metaphonological awareness. In the next section we turn to this question, reviewing current findings on the relations among various phonological processes.

What are the relations among phonological processes?

In other chapters in Brady and Shankweiler (in press), we have focussed on phonological awareness and on verbal working memory as potential factors in reading disability. Before we consider how these may be related, I must remind you that a third area of language function, lexical access, is often also associated with reading ability. Naming, as a test of lexical access, requires the subject to retrieve a phonological label in response to visual stimuli such as colors, numbers, letters, or pictured objects. Poor readers tend to be slower on tasks requiring the rapid naming of visual stimuli and they also have been reported to make more errors in retrieving phonologically complex labels (i.e., words such as thermometer or stethoscope (Catts, 1986; Katz, 1985). The strength of the association between reading ability and measures of lexical access has been found to depend on the particular measures taken and other factors such as word frequency, age, and task variables. The correspondence is strongest when tested in kindergarten, and when the task is to scan and label an array of high frequency items selected from a finite pool (e.g., Wolf, 1986). With older children, reading-group differences are consistently found only when the items to be labeled are orthographic symbols (e.g., Blachman, 1983; Katz & Shankweiler, 1985; Wolf et al., 1986). (See Stanovich, 1985, and Wagner & Torgesen, 1987, for reviews.)

Although each of these abilities draws on phonological representation, we are not yet in a position to explicate the nature of the underlying relations among phonological awareness, verbal working memory, and lexical access. Research addressing this question has been limited, piecemeal, and contradictory. If one considers how the phonological processes may be related, there are five logical possibilities, as Wagner and his colleagues indicate (Wagner et al., 1987): 1) There may be a unitary deficit common to metaphonological processes, phonological coding in working memory, and phonological coding in lexical access; 2) Though all are phonological, each may be a separate ability, with three independent processes implicated; 3) The metaphonological processes may be independent of the other two. Wagner et al., 1987, term this pattern of organization “an awareness versus use” classification. The remaining two combinations represent the other possible permutations of two latent abilities; 4) Phonological awareness and verbal working memory may be tied to a common factor. In this view, phonological awareness tasks rely heavily on the efficiency of coding in working memory, but use of phonological information to access stored items in the lexicon taps separate processes; 5) Phonological awareness and lexical access may be linked, perhaps by some relation between awareness of phonological structure and organization or utilization of phonological information in the lexicon. Phonological coding to maintain information in working memory would then constitute a separate aspect of processing.

The unitary deficit view is attractive in light of the compelling evidence that poor readers have deficits largely confined to the phonological domain of language. It is appealing to propose
that the three classes of phonological abilities have some underlying common factor that accounts for the individual deficits. All draw on the same underlying knowledge base: the phonological component of the language apparatus. In this way, there would be unique requirements for metaphonological, working memory, and lexical processes, but the underlying phonological representation might be inadequate and yield difficulties in each of the other areas (Liberman & Shankweiler, 1985).

So far, the studies that have attempted to examine abilities in all three phonological areas have not supported a unitary deficit, but there has not otherwise been much agreement between them. One study, a meta-analysis of the results of longitudinal correlational studies and training studies, indicated relatively independent causal roles in the acquisition of reading skills for the three phonological abilities we have identified (Wagner, 1988). The second study, conducted with 51 adults (including familial dyslexics, clinic identified dyslexics, and normally reading adults), also supported a multiple factors model (Pennington, Van Orden, Kirson, & Haith, in press), though individual tasks loaded somewhat differently on the three factors. The third, a study of preschoolers' phonological processing abilities (Wager et al., 1987) reported that at this prereading stage two coherent phonological abilities were evident: 1) memory and awareness having a common factor and 2) lexical processes as a separate component.

Other investigations have examined the relations between only two of the three phonological abilities; here too the results have been inconsistent. One line of research has attempted to examine whether the deficits in phonological awareness and memory relate to a common factor. In one view, phonological awareness tasks may rely heavily on the efficiency of coding in working memory. And indeed, those awareness measures that most strongly relate to reading ability (Stanovich, Cunningham & Cramer, 1984; Yopp, 1988) generally involve comparing a number of stimuli, manipulating segments, or deleting segments. All of these tasks require greater working memory involvement than less discriminating phonological awareness measures such as rhyme generation. Conversely, the development of phonological awareness may facilitate the ability to use phonological segments in working memory, as opposed to larger articulatory units such as syllables (see Fowler, this volume). Thus, one research goal has been to investigate whether there is a common deficit and to contrast metacognitive processes from more basic language processes. It is known, for instance, that in the absence of reading instruction, abilities to isolate and manipulate phonological segments are limited (Morais, Cary, Alegria, & Bertelson, 1979; Read, Zhang, Nie, & Ding, 1986). And yet it is presumed that the underlying phonological processes involved in ordinary speaking and listening have developed normally. Further, in studies of adults who failed to develop skill in reading, phonological awareness deficits are present, while difficulties in the other phonological abilities are not as apparent as in young poor readers (see Pennington et al., in press). These age-specific differences among poor readers lead to the hypothesis that perhaps metaphonological processes are distinct from the underlying phonological domain and that the associations between awareness and memory in young children merely reflect simultaneous increases in development. An alternative may be that the emergence of phonological awareness and subsequent reading acquisition depend on a certain minimum of working memory efficiency, beyond which individual differences in memory capacity are less crucial. In fact, research in children designed to evaluate the correspondence has yielded mixed results. Thus, Mann and Liberman (1984), Fowler (1988) and Goldstein (1976) reported significant correlations between awareness and memory tasks. On the other hand, several studies failed to find significant correlations between awareness and memory measures (Alegria, Pignot, & Morais, 1982; Blachman, 1983; Mann, 1984), or evidence (from factor analysis) that they load on a single factor (Mann & Ditunno, in press).

Nevertheless, as I've argued in the preceding section, a link appears to be justified among the more basic language tasks associated with reading disability. Verbal memory, phonological perception, speech production, and lexical access all require the creation of a phonological representation, whether this representation is initially generated internally or activated by incoming stimuli. As noted, we and others have obtained significant correlations between the accuracy of phonological processes in perception and production and the capacity of working memory; this relationship obtains developmentally as well as in comparisons of good readers and poor readers. In contrast, these processes are not related to nonverbal memory performance (cf. Rapala & Brady, 1990). Significant correlations
have also been reported between naming speed and memory span (Spring & Capps, 1974; Spring & Perry, 1983; Torgesen & Houck, 1980), although Stanovich (1985) notes inconsistencies in this outcome. Along similar lines, Elbro (1988) finds that poor performance in discriminating minimal pairs of words in noise is associated with slow lexical assess. Thus while we have evidence of correspondence between the underlying processes, these may or may not be separable from phonological awareness.

In sum, it seems premature to attempt to state how the various phonological processes are related to one another. At present, the field is characterized by lack of accord. Theoretical and empirical evidence can be gathered for a number of the potential patterns of relations among the phonological processes. Gains will no doubt be made, as they were in previous decades (e.g., Vellutino, 1979), by improving how we ask the important questions. Several methodological shortcomings are now recognized as detracting from the merit of many studies. For example, the lack of convergent results may stem from the frequent use of a single task for each construct, which may not provide an adequately valid, reliable, or sensitive measure. Thus in future work it will be important to include multiple measures of each construct to attain more robust information. In addition, it will be important to factor out general cognitive ability since this affects performance on almost all cognitive measures, and may inflate the association between any of the phonological processing tasks. Third, many of the studies have not had a sufficient number of subjects to warrant the statistical procedures used and to obtain reliable information on the questions addressed. In addition, we need conceptual advances so that we know better how to evaluate the processing requirements of various tasks. At present, in each area of phonological processing several measures are used and, for the most part, we know little about their comparability. For example, memory tasks may involve a continuous presentation task in which only the last few of a numerous and indeterminate number of stimuli are requested for recall, they may entail recall of entire strings, or of individual items. The stimuli may be digits, words, nonwords, or pictures. The task requirements are not constant, and performance on them may not vary uniformly with respect to reading ability.

Selection criteria for subjects also remains a thorny issue. We still have the concerns about how to assess reading ability and IQ, and about whether we should assess performance in other areas of achievement (e.g., math) or of cognitive functions (e.g., attention). The more recent vogue of reading-age matches only exacerbates these concerns. It has been very profitable to compare the particular reading skills of individuals who are at an equivalent reading level in order to address questions about deviant reading patterns, but I am concerned that when we extend the use of this paradigm to study underlying cognitive processes (e.g., verbal memory) that the dual diversity of age and cognitive ability makes it difficult to match subjects appropriately or to interpret the outcome (see Shankweiler, Crain, Macaruso, & Brady, in press, for further discussion).

All of these points bring me to the somewhat tiring conclusion that in the reading field we need to refine our knowledge of the individual constructs of speech perception, speech production, verbal working memory, and lexical access. In other chapters in the Brady and Shankweiler (in press) volume, we can see that the effort to fine-tune our understanding of the construct of phonological awareness is already underway. I don't want to imply that we shouldn't at the same time attempt to test hypotheses about how the whole picture fits together, but it will be important to be cautious about interpreting individual studies. As Stanovich (1985) discusses, we need to adhere to the principle of converging evidence. The power of this principle has been awesome concerning the evidence that reading problems are associated with language deficits and, in particular, with phonological awareness. When we ask, as we have been here, how the different phonological processes relate, convergence is lacking and we need to ask why.

In closing, in this paper I have attempted to accomplish three goals. In the first section, the widespread association of verbal short-term memory deficits with reading disability was briefly reviewed. The prevalence of this association underscores the need to examine the factors that contribute to working memory performance. In the second section of the paper I argued that studies of memory development and of memory deficits in poor readers provide tantalizing indications that efficiency of phonological coding may be an important factor in memory performance. In the third section I raised the question of how working memory processes are related to other phonological processes, phonological awareness and lexical access that
have also been associated with reading deficits. At present, attempts to delineate the connections between them have yielded contradictory indications. Conceptual and methodological advances, which hinge on the continued cooperation of disciplines involved in the study of language, will be needed to advance our grasp of these issues.

REFERENCES


**FOOTNOTES**


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