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Reprint

Annals of Dyslexia, Vol. 45
1995

THE REPRINT SERIES
The Orton Dyslexia Society
Chester Building/Suite 382
8600 LaSalle Road
Baltimore, MD 21286-2044

Evidence for Phonological Processing Deficits in Less-Skilled Readers

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Although weaknesses in metaphonological skills are well-documented in poor readers, prior studies have yielded inconsistent findings as to whether less-skilled readers also have deficits in the more primary phonological processes entailed in verbal working memory and speech production tasks. The present study was designed to examine this issue by comparing less-skilled third-graders readers (n = 30) with younger children at the same reading level (n = 30) and with more-skilled agemates (n = 30) on a variety of tasks that require phonological processing (i.e., three "verbal memory" tasks [word span, span with concurrent processing, pseudoword imitation] and three "speech production" tasks [word-pair repetition, tongue twisters, rapid naming]). The results were striking: the less-skilled third-grade readers had significantly lower accuracy scores than both their agemates and the younger normal readers on the word span, pseudoword imitation, word-pair repetition, and tongue twister tasks. Measures of accuracy were more related to reading ability than were measures of speed. Per-

formance on a pseudoword imitation task was the variable most strongly linked to reading achievement.

INTRODUCTION

Numerous studies over the past two decades have documented the role of phonological awareness in reading development: becoming consciously aware of the sound structure of words has proven to be a necessary requirement for learning to read. Whether underlying phonological processes also may be important for reading success has been considered for at least two reasons. First, metaphonological difficulties may reflect more basic difficulties in phonological processes (e.g., Brady and Shankweiler 1991; Liberman, Shankweiler, and Liberman 1989; Wagner and Torgesen 1987). For example, the nature or quality of a word's phonological representation, both in the lexicon and in working memory, may affect the ease of discovering or analyzing the phonological structure (Fowler 1991). Second, because reading entails phonological recoding of print, difficulties in phonological coding, storage, and/or output might make a contribution, independent of phonological awareness, to reading disability (e.g., Perfetti 1985).

Yet efforts to demonstrate that underlying phonological processes play a causal role in reading disability have produced results that are both inconsistent and challenging to interpret (Pennington et al. 1991; Torgesen in press). Although a large number of studies have reported intriguing correlations between reading skill and performance on phonological tasks involving memory and production (e.g., Brady 1991), the size of the correlation varies widely across studies. Even where the correlations are significant, memory and production explain considerably less variance than does phonological awareness. The goals of the present study were to identify a basic phonological measure that could explain a substantial portion of the variance in reading skill, and to begin to gather evidence that it plays a causal role. In addition, we wished to explore whether the phonological weakness of poor readers is more directly linked to the speed or to the quality of phonological processing.

BACKGROUND

Much of the research in this area has focussed on whether reading group differences are evident on measures of short-term

memory span. Span procedures require the participant to repeat a short sequence of items in the order they were presented. Performance (i.e., number correctly reported) is generally taken to reflect the capacity and/or efficiency of a hypothetical short-term memory system. Two papers in particular fostered interest in research on whether poor readers had deficits in short-term memory: Torgesen (1978-1979) noted the frequent pattern by disabled readers of poor memory span performance on IQ test batteries. Second, in a landmark paper, Shankweiler and Liberman and their colleagues (1979) concluded that the span deficits of less-skilled readers occur not only with visual stimuli presentation, as most prior studies had used, but with auditorily presented sequences as well (Shankweiler et al. 1979).[1] Further experiments confirmed that poor readers often perform less well than age-matched good readers on a variety of span measures, provided the stimuli can be coded phonologically (i.e., the input can be represented in a speech code [e.g., sequences of words, pseudowords, letters, digits, and nameable pictures]). In contrast, if the stimuli were difficult to label phonologically, such as nonsense squiggles or symbols from an unfamiliar writing system, groups of poor readers did as well as their better-reading peers: within each reading group, variation in ability was observed, but this variability was not linked with reading skill (see Brady (1991) for a review). Thus, poor readers appear to have neither a general short-term memory deficit nor a difference in motivation. Rather, a specific problem in phonological coding in memory was identified as the basis of poor readers' limited span performance (for reviews see Brady 1991; Jorm 1983; Wagner and Torgesen 1987). Subsequent work examining the nature of errors produced on verbal span tasks confirmed that poor readers use the same coding strategy as better readers, but are less accurate or efficient at doing so (Brady, Mann, and Schmidt 1987).

Complementing these studies with disparate reading groups, experiments with special populations have further

[1]Their study also documented a reduced "rhyme effect" or "phonological similarity effect" for less-skilled readers (i.e., good readers were significantly better at recalling non-rhyming strings of letter names than at rhyming sequences; the difference in conditions was negligible for poor readers). This set of results was interpreted as evidence of a phonological memory problem not restricted to reading tasks. Though some questions were raised about the role of task and subject factors in the rhyme effect (e.g., Hall et al. 1983), later studies revealed a developmental pattern; a sufficient span is necessary to show the rhyme effect (Logie et al. 1991) and poor readers attain this at a later age than do good readers (Olson et al. 1984).

strengthened the case for the role of phonological memory in reading acquisition. A series of studies with deaf readers by Hanson (see Hanson 1991 for a review) provides strong evidence for the necessity of phonological coding in memory for skilled reading. She documented that congenitally deaf individuals who had become fluent readers had somehow acquired a phonological coding strategy despite never having heard speech (see also Hanson, Goodell, and Perfetti 1991). Two findings emerged from this line of research: use of a phonological coding strategy is associated with better memory span, and better verbal memory span (or phonological coding) is linked with superior reading performance.

Recent research with young adults with Down syndrome also points to a contribution of phonological memory to reading acquisition. For these subjects, who varied both in reading skill and in IQ, performance in phonological memory accounted for a substantial portion of the within-group variability in reading achievement, over and above that explained by general cognition (Fowler, Doherty, and Boynton 1995).

A third special population, hyperlexic children, have low intelligence yet strong word recognition ability (with poor comprehension) (e.g., Healy et al. 1982). Scrutiny of the IQ profiles of these children reveals that memory is a cognitive strength, in contrast to numerous areas of weakness.

However, although the association between verbal memory and reading ability has repeatedly been noted, a number of concerns have been raised about whether performance differences on underlying phonological variables are centrally related to levels of reading attainment. In an article targeting several of these issues, Pennington et al (1991) point out that groups of poor readers typically have been compared to chronological-age matched controls, raising questions about whether their poor performance stems from limited reading experience, rather than serving as a causal factor in reading attainment.[2] Such a concern would apply, for example, to a recent large cross-sectional study reporting consistent correlations between reading ability and short-term memory in subjects ranging from 6 to 49 years of age (Siegel 1994). Because uncontrolled variance in reading experience and in general intellectual ability may have contributed to the magnitude of these effects, the specific locus of difficulty remains unclear. Similar uncertainty

[2]However, see Shankweiler et al. (1992) for discussion of the utility of the chronological-age match design for theory evaluation.

applies to a longitudinal study of children identified as reading disabled at 9 or 10 years of age (Torgesen 1991). When retested nearly a decade later, some of the children had become better readers, while others remained reading impaired. Interestingly, verbal memory span paralleled reading level; those who had improved in reading also showed gains in memory capacity. Thus, one could argue either that phonological memory abilities influenced reading development (e.g., limits in phonological memory impeded reading acquisition for those who had not improved), or, alternatively, that increased reading ability in the better reading subjects had facilitated memory performance.

Further concerns have also been raised about the low predictive value of kindergarten memory measures for subsequent reading development, especially in comparison to phonemic awareness. For example, Wagner, Torgesen, and Rashotte (1994) report a longitudinal study in which verbal memory performance was significantly associated with early literacy skills in kindergarten (though less strongly than other measures), but not with reading achievement in first or second grades. Further analyses indicated that the variance accounted for by phonological memory in kindergarten was redundant with phonological awareness measures. On the other hand, at least one study (Hansen and Bowey 1994) now suggests that phonological memory may explain a significant portion of the variance in reading achievement (5 to 7%) not explained by IQ or phonological awareness.

Some of the difficulty pinpointing the role of phonological memory in reading development may be compounded by variations in the memory tasks used in different studies (e.g., digit span vs. nonword repetition), as well as in the component of reading skill assessed (e.g., decoding skill vs. comprehension). Hansen and Bowey (1994) discuss the potential limitations of span measures, which may be influenced by both attention factors and by use of rehearsal strategies, and recommend nonword repetition as a more direct measure of ability to create and briefly maintain phonological representations. In nonword repetition, sometimes termed pseudoword repetition or pseudoword imitation, the subject is asked to repeat individual items (e.g., contramponist) that conform with the phonological patterns in English, but that do not have an established lexical entry. Though familiarity with phonologically similar real words (e.g., contortionist for contramponist) has been demonstrated to influence performance (e.g., Dollaghan, Biber, and Campbell 1995; Gathercole 1995), long-term memory effects are thought to be less for this task than for other verbal memory

measures. On the other hand, the necessity to encode and store the novel item accurately taps fundamental properties of short-term phonological memory.

Others (Daneman and Carpenter 1980 ; Siegel 1994; Turner and Engle 1989) report strong links between memory and reading in older subjects, when the memory measure requires both storage and active decision making. The standard task, referred to in the present study as a concurrent span measure, involves listening to a set of sentences, judging whether each is true or false, and then repeating the last word from each sentence. Considered a measure of working memory, this concurrent processing task requires "executive functioning" in that a limited capacity work space must not only maintain the input, but also must monitor and carry out further processing (see Baddeley [1986] and Pennington [in press] for further elaboration).

THE NATURE OF THE PHONOLOGICAL MEMORY DEFICIT: SPEED VERSUS ACCURACY

A further concern is whether to characterize the presumed phonological deficit as arising from reduced speed of phonological processing or from less accurate phonological representations. Potential parallels with development of memory capabilities have fueled this issue.

Memory span is known to increase steadily from early childhood to adult years (e.g., Dempster 1981). Current accounts of this phenomenon emphasize the role of articulatory speed in the development of memory recall capacity. For example, in the working memory model proposed by Baddeley and Hitch (1974), a subsystem referred to as the phonological loop (i.e., the verbal short-term store) briefly maintains verbally coded information by a process of articulatory rehearsal (i.e., the decaying representations in the phonological store are refreshed by a process of repeated articulation). Accordingly, "as children become older, their articulatory skills improve, either as a result of practice, maturation of the central nervous system or both. This allows them to rehearse subvocally at a faster rate, and hence maintain more items in the phonological store." (Baddeley 1986, p. 201). Central to this and other explanations[3] has

[3]The association between speed of articulation and memory span also has been cast as an indirect result of overall processing speed (e.g., Kail and Park 1994) and as a component of operational efficiency in a limited resource model (e.g., Case, Kurland, and Goldberg [1982] suggest that speed of articulation reflects the automaticity of encoding operations which, in turn, impacts on the functional memory capacity).

been the repeated finding of strong associations between speed of articulation and memory span in developmental studies (e.g., Case, Kurland, and Goldberg 1982; Hitch, Halliday, and Littler 1989; Hulme et al. 1984; Rapala and Brady 1990) and in studies of adults (e.g., Baddeley, Thomson, and Buchanan 1975; Hoosain 1982). For example, Hulme et al. (1984) found a linear relationship between speaking rate and recall performance for subjects ranging in age from 4 to adult.

Given how closely tied development of memory and speed of articulation appear to be, one might expect that speech rate will also be related to reading skill. The evidence supporting a link is equivocal, however. On the positive side, dyslexic college students were reported to be slower at repeating phrases than were their normal-reading peers (Catts 1989). Further support was provided by McDougall et al. (1994). In their study, articulatory speed, calculated as the words per second produced in a word-triad repetition task, was significantly associated with word recognition performance. Further, in predicting reading ability, speech rate both shared variance with short-term memory span and accounted for significant additional variance. McDougall et al. argue that "the efficiency of the speech-based component of short-term memory span" (i.e., speech rate) (p. 127) is what distinguishes good and poor readers.

Some important factors, however, render the interpretations of these two studies ambiguous. In the Catts' study, the trials on which poor readers were slower were those with greater phonological complexity (e.g., blue plaid pants), leaving open the possibilty that phonological difficulty was the source of the problem rather than speed per se. In the McDougall et al. study, if the subjects produced an error, the trial was started over, perhaps inducing a tendency to slow down. Thus, it remains uncertain whether the slower times for the poor readers stem from their difficulties with the phonological requirements of the task, rather than from slower phonological processing per se.

Other studies have failed to obtain results consistent with a speed explanation. In a project using third-, fifth-, and seventh-grade children matched for reading comprehension level (Stanovich, Nathan, and Zolman 1988), speed of articulation was found to be strongly age dependent, but not related to reading ability. Two other studies exploring whether a relationship exists between speed of speech production and reading ability have failed to obtain significant results. Brady, Poggie, and Rapala (1989) measured onset time by good and poor readers for repetition of multisyllabic real words and for single-syllable

pseudowords. No reading group differences in speed were found. Similarly, Rapala and Brady (1990), with a pseudoword task more like the McDougall et al. procedure, failed to observe deficits in speed of speech production for the less-skilled readers.

Although the case for reading group differences in speed of phonological processing is mixed, evidence that poor readers have difficulty with other aspects of articulation is accumulating. Both Brady, Poggie, and Rapala (1989) and Rapala and Brady (1990), mentioned above, reported significant reading-related differences in the accuracy of their speech measures: poor readers were more likely to mispronounce the stimuli (e.g., ajiculture for agriculture; sheeshee for seeshee). Likewise, a number of studies now document less accurate word and pseudoword repetition by less-skilled readers (Apthorp 1995; Brady, Shankweiler, and Mann 1983; Catts 1986; Kamhi et al. 1988; Hansen and Bowey 1994; Snowling 1981; Snowling et al. 1986; Taylor, Lean, and Schwartz 1989). These findings have led several researchers to propose that the accuracy or quality of phonological representations may be the critical dimension linking phonological processes with reading ability (Brady 1991; Elbro, Nielsen, and Petersen 1994; Fowler 1991; Gathercole and Baddeley 1989; Shankweiler and Crain 1986; Snowling et al. 1986; Vellutino and Scanlon 1989).

Goals of the Present Study

Important questions remain about the nature of the hypothesized phonological deficit of less-skilled readers and about the robustness of its association with reading failure. Prior research has failed to yield consistent results on either issue, possibly due to variations in the memory measures employed, in the reading skills assessed, and in the control groups used. In the present study, we wanted to conduct a careful comparison of the basic phonological abilities of less-skilled readers with both chronological-age matched subjects and with younger, reading-age controls. Participants were assessed on a set of memory measures that require phonological processing including word span, pseudoword imitation, and a working memory task. In addition, to explore speech production performance, a set of measures was administered that would allow us to evaluate both speed and accuracy of responses (i.e., word pair repetition, tongue twister repetition, and rapid naming of objects). Our main goals were to address three questions: (1) To determine whether poor readers would perform worse than both age mates and younger reading-age controls; (2) To identify which

of the above measures was most clearly associated with reading ability and whether this varied depending on the reading outcome measure; and (3) To investigate whether reduced speed or accuracy characterized the performance of the poor readers.

METHOD

SUBJECTS

From the 266 second- and third-grade children whose parents provided a signed consent form, 90 children (47 girls and 43 boys) from two school districts in Rhode Island were selected to participate in the study. The districts were urban/suburban in nature, and the population of each of the districts represented a mix of socioeconomic and educational backgrounds. Initial criteria for inclusion included:

a) Normal cognitive function: standard scores between 80 and 125 on a receptive vocabulary test (the Peabody Picture Vocabulary Test-Revised [PPVT-R] [Dunn and Dunn 1981]) and on a nonverbal measure of visual-spatial ability, the Block Design subtest of the Wechsler Intelligence Scale for Children-Revised (WISC-R) (Wechsler 1974).[4]
b) Typical age for grade: second graders had to be between 7;0 and 8;1 years of age and third graders between 8;2 and 9;4 years at the time of testing.
c) Nonnative speakers of English were excluded from the study, as were children identified as having hearing or speech impairments.

The 90 children were assigned to one of three groups on the basis of reading skill and grade level; efforts were made to match for general cognition across groups. Reading level was determined by scores on the Word Attack and Word Identification subtests of the Woodcock Reading Mastery Tests Revised (WRMT-R), Form G (Woodcock 1987). The Passage Comprehension subtest was also administered, but was not used for selection purposes. Third graders whose scores were consistently below grade level formed the less-skilled group; those whose scores were consistently above grade level formed the

[4]Subtests of the WISC-R are reported as scaled scores. These were converted to standard scores so we could compare them more easily with the PPVT-R scores.

more-skilled group.[5] The reading-level comparison group included second graders matched for decoding ability, as well as for IQ, with the less-skilled third graders; they were reading close to their own grade level.

Descriptive statistics for age, cognitive ability, and reading level are summarized in table I. Consistent with the design, there were no significant age differences between the two third-grade groups (t (58) = 1.46, p = .15), and no significant differences between any of the groups in either verbal ($F(2,87)$ = .58, p = .56) or nonverbal ($F(2,87)$ = .97, p = .38) cognitive functioning. Also in keeping with the design, significant differences were evident between less-skilled and more-skilled third-grade readers on the three reading measures ($F(2, 58)$ = 49.38, $p<$ .001). Follow-up t-tests indicated that the difference was significant for each of the subtests: Word Attack , $t(58)$ = -9.70, $p<$ .001; Word Identification, $t(58)$ = -11.01, $p<$ .001; and Reading Comprehension, $t(58)$ = -3.77, $p<$ .001.[6] Finally, the third-grade less-skilled readers did not differ significantly from the second-grade readers in either Word Attack, $t(58)$ = .20, p = .85, or in Word Identification performance, $t(58)$ = 1.32, p = .19. On the Passage Comprehension measure, the study group did slightly better (a three month advantage) than the reading level comparison group, $t(58)$ = 2.30, p = .025.

[5]Of the 139 third-grade children tested in Session 1, 75 were not continued in the study for the following reasons: 11 were too old; 3 were too young; 14 had PPVT-R or Block Design Scores that were higher than permissible (i.e., >125); 14 had PPVT-R or Block Design Scores that were lower than permissible (i.e.,< 80); 2 had inconsistent Word Attack and Word Identification scores; 7 had identified speech problems; and 24 fit the criteria, but were not used because their age or IQ scores would have lessened the comparability of the groups (i.e., their scores were too far above or below the mean of the less-skilled readers). Sixteen of the 24 third graders who met the criteria, along with a corresponding group of fourteen second graders, participated in a pilot study conducted prior to Session 2. (In the pilot study, the Concurrent processing task was presented to evaluate whether the directions were easily understood and whether the material in the sentences was appropriate for this age group. The 30 children in the pilot group had no difficulty with the task and it was included as originally constructed in the study.)

[6]Although the less-skilled readers in this monolingual Northeast sample were reading close to what national norms suggest is "grade level," and the more-skilled readers were reading well above that national "average," our goal in this study was to look at factors bearing on variation in reading skill within a well-matched sample, independent of whether children met criteria as "reading disabled." This approach is consistent with recent evidence indicating that reading is normally distributed (e.g., Shaywitz et al. 1994) with no qualitative differences between those who are simply less-skilled and those who meet criteria as "reading disabled."

TABLE I. MEANS, STANDARD DEVIATIONS, AND RANGES FOR AGE, COGNITIVE ABILITY, AND READING FOR THE THIRD-GRADE LESS-SKILLED, THIRD-GRADE SKILLED, AND GRADE 2 READERS

	Third-grade Less-skilled Readers (Study Group) ($N = 30$)	Third-grade Skilled Readers (Age-level Comparison) ($N = 30$)	Grade 2 Readers (Reading-level Comparison) ($N = 30$)
Age			
Mean (*SD*)	8.8 (3.9)	8.7 (3.1)	7.7 (4.1)
Range	8.2 - 9.3	8.3 - 9.0	7.0 - 8.1
PPVT-R			
Mean (*SD*)	100.5 (10.8)	103.1 (10.5)	102.8 (9.8)
Range	80 - 123	83 - 123	86 - 122
Block Design			
Mean (*SD*)	102.2 (10.7)	105.7 (9.0)	102.7 (11.7)
Range	80 -125	80 -120	80 - 125
Word Attack			
Mean (*SD*)	2.1 (.48)	11.1 (5.1)	2.1 (.45)
Range	1.2 - 2.9	4.2 - 16.9	1.2 - 2.9
Word Identification			
Mean (*SD*)	3.0 (.50)	5.0 (.89)	2.8 (.46)
Range	2.1 - 4.0	3.6 - 7.1	2.0 - 4.1
Comprehension			
Mean (*SD*)	3.3 (.80)	4.5 (1.5)	3.0 (.41)
Range	2.0 - 6.4	3.0 - 7.3	1.9 - 3.5

EXPERIMENTAL MEMORY MEASURES (UNSPEEDED)

In order to determine each child's ability to remember verbally encoded information, three tasks were administered. These tasks were not standardized tests, but were research measures designed to emphasize specific components of verbal memory (i.e., storage, processing). Tape recordings of subjects' responses were used to rescore the protocols for the three measures and to obtain inter-rater reliability scores. The first author and a trained research assistant rescored all the responses after each testing session. Inter-rater reliability scores were based on at least 50

percent of the data from each group of subjects. Data used to assess inter-rater reliability were randomly selected.

Word Span. Each subject's ability to recall and sequence sets of unrelated but meaningful words was assessed with a memory task adapted from Rapala and Brady (1990). This task was included to provide a measure of storage capacity. The task consisted of 13 lists of monosyllabic concrete nouns (e.g., rose, plate) that subjects were asked to recall in the order presented. Three three-word lists were presented first, followed by five four-word lists and five five-word lists. The word lists were recorded on audio tape and were presented to the children through headphones. The children were instructed to recall the words in the order they were heard as soon as presentation of the list was completed. They were also instructed to say "blank" for any word that could not be recalled. Each subject's score on this task was the number of words recalled in correct serial position. The maximum possible score on this task was 54. The internal reliability estimate on this measure for this sample was $r = .73$ (Cronbach's alpha) ($N = 90$). It should be noted that the reliability may be attenuated because the word-span memory measure gradually increased in difficulty and was therefore not consistent throughout. That is, earlier task items were easier to remember than later items. Inter-rater reliability for this measure was $r = .99$.

Concurrent Processing. In order to evaluate each subject's ability to remember a series of words while engaged in another processing task, an adaptation of Daneman and Carpenter's (1980) Reading Span Test was administered. Subjects used headphones to listen to a series of unrelated sentences that had been recorded on audio tape. There were 12 sets of sentences, arranged as follows: (a) four sets of two sentences, (b) four sets of three sentences, and (c) four sets of four sentences. As soon as each sentence was read, the participants decided whether the sentence was true or false. After the complete series of sentences had been read, subjects recalled the last word of each sentence in the series. The words did not need to be recalled in the order presented. An example of a two-sentence series was: (1) "People drink out of forks" and (2) "We see colors in a rainbow." The correct response was either "forks, rainbow" or "rainbow, forks." The child's score was the total number of words correctly recalled. The maximum possible score on this task was 36. The internal reliability estimate on this measure for this sample was $r = .74$ (Cronbach's alpha) ($N = 90$). As noted with the word-span memory measure, the reliability for this

measure also may be reduced because the task gradually increased in difficulty, with earlier items being easier to recall than later items. Inter-rater reliability for the memory span with concurrent processing measure was $r = .99$.

Pseudoword Imitation. This measure was given to assess the ability to establish, maintain, and output phonological representations. The Pseudoword Imitation task consisted of 28 pseudowords, each of which was derived from a polysyllabic real word by means of phoneme substitutions (Taylor, Lean, and Schwartz 1989). Although Taylor, Lean, and Schwartz referred to the measure as Pseudoword Repetition, it is called Pseudoword Imitation in this study to avoid confusing it with the tasks described below that require multiple repetitions of each item. In the Taylor, Lean, and Schwartz study, the inter-item reliability was .87, and the test-retest reliability was .89.

The words were tape recorded and presented to the children through headphones. The children were told they would hear a list of nonsense words presented one at a time. They were asked to repeat each word as soon as it was heard. Scoring was based on that of the Taylor, Lean, and Schwartz study. A response was scored as correct if all the phonetic components of the word were in the correct sequence. Errors included phonetic omissions, additions, substitutions, and transpositions. The maximum possible score on this task was 28. For this sample of subjects, the internal reliability estimate was $r = .82$ (Cronbach's alpha). Inter-rater reliability was $r = .99$.

EXPERIMENTAL SPEECH PRODUCTION TASKS (SPEEDED)

Three speeded repetition tasks were administered to assess specific components of speech production (i.e., accuracy, speed). Following the procedures noted above, tape recordings of subjects' responses were used to rescore the protocols for the three measures and to obtain inter-rater reliability scores.

Word-pair Repetition. A task adapted from Hulme et al. (1984) was given to assess each child's ability to produce familiar words rapidly. The stimuli were 10 word pairs that were combinations of either monosyllabic or multisyllabic concrete nouns (e.g., car/hat; banana/elephant). The word pairs were presented orally by the examiner to the children one at a time. The children were asked to repeat each word pair once to ensure that it had been perceived correctly. If a child mispronounced a word pair, corrective feedback was given, and the child was asked to say the word pair again. This procedure was followed until the child correctly repeated the word pair. The

children were then told to repeat the word pair as rapidly as possible without making mistakes until told to stop. The examiner started the stopwatch at the beginning of the first repetition and stopped the watch after the 10th repetition. To ensure a continuous production of speech and to minimize the potential effect of subjects anticipating the number of repetitions being counted, the children were told to stop at some point between the 11th and 13th repetitions. This point varied randomly with each word pair; that is, either the 11th, 12th, or 13th repetition was chosen as the stopping point. This task was scored for both accuracy and speed. Responses were written on the protocol by the examiner and also were tape recorded. The accuracy score was the total number of errors for the 10 word pairs. The speed score was the average length of time it took to repeat the word pairs. Only word pairs that were repeated without errors were included in the speed score calculation. This technique resulted in a varying number of scores from subject to subject. For the 90 subjects, an average of seven word pairs were repeated without error. The average number of word pairs accurately repeated by each group were as follows: less-skilled study group = 7.1; age-level comparison group = 7.9; reading-level comparison group = 6.1. To determine the speed score, the tape recorded responses were analyzed on a Macintosh computer using a MacRecorder and Sound-Edit software. The subjects' recorded responses were played into the MacRecorder and were displayed on the computer screen. With this procedure, the beginning and end of each response could be precisely determined and timed. The internal reliability estimate for accuracy on this measure for this sample was $r = .47$ (Cronbach's alpha) ($N = 90$). Inter-rater reliability for the Word-pair Repetition measure was $r = .99$. A reliability coefficient for time on this task could not be calculated because only word-pairs that were repeated without errors were used.

Tongue Twisters. The Tongue Twister task was used to evaluate each child's ability to produce nonsense words rapidly (Rapala and Brady 1990). The task consisted of 10 disyllabic pseudowords that had a tongue-twister-like quality (e.g., seeshee). The two-syllable length was used because the age groups included in this study typically are able to recall easily word strings of this length (Dempster 1981; Rapala and Brady 1990). In the Rapala and Brady study, the split-half reliability for speed was .95 and for accuracy, .71. The pseudowords were presented orally by the examiner to the children one at a time. The children were asked to repeat each pseudoword once to

ensure that it had been encoded correctly. If a child mispronounced a stimulus, corrective feedback was given, and the child was asked to say the item again. This procedure was followed until the child correctly repeated the pseudoword. The children were told to repeat the pseudoword as rapidly as possible without making mistakes until told to stop. The stopwatch was started at the beginning of the first repetition and stopped after the 10th repetition. For the same reasons noted with the word-pair repetition task, the children were told to stop at some point between the 11th and 13th repetitions. This point varied from trial to trial. This task was scored for both accuracy and speed. The accuracy score was the total number of errors produced during repetition of the 10 tongue twisters. The speed score was the average length of time it took to repeat the tongue twisters. Only tongue twisters that were repeated without errors were included in the speed score calculation. For all 90 subjects, an average of seven tongue twisters were repeated correctly; however, the less-skilled third-grade readers produced on average only 6.1 correct responses, whereas both the age-level and the reading-level comparison groups produced an average of 7.5 correct responses. Responses were written on the protocol by the examiner and were also tape recorded. A Macintosh computer was used to determine the speed score, using the same procedure described for the Word-pair Repetition task. The equal length Spearman-Brown reliability coefficient for accuracy for this sample was $r = .65$ ($n = 90$). Inter-rater reliability for accuracy on the Tongue Twister Task was $r = .99$. A reliability coefficient for time on this task could not be calculated for the same reason that was noted for the word-pair repetition task.

Rapid Naming. This measure was given to determine each child's ability to rapidly name pictured objects. The pictures were 45 black and white line drawings of familiar objects arranged in five rows of nine pictures each. Five different drawings were used with each drawing being presented nine times. To ensure the use of a specific label for each item, the drawings were named by the examiner, and the children were asked to repeat the names. Then the children were instructed to name all the drawings on the page as rapidly as possible without making mistakes. This task was scored for speed using the same procedure as that used for the Word-pair Repetition and Tongue Twister tasks. Accuracy scores for this measure were not used because very few children made errors when naming the drawings.

PROCEDURE

The PPVT-R, the Block Design subtest of the WISC-R, and the Word Attack and Word Identification subtests of the WRMT-R were individually administered to each of the 266 children who returned a signed permission form. Each test was administered in the standardized manner recommended in the manuals. The testing session lasted approximately 30 minutes.

The 90 children selected for the study participated in two additional testing sessions. The memory and speech production tasks, as well as the Passage Comprehension measure, were individually administered during these two sessions. The tasks were divided into two sets. Set A included the following tasks: (a) Word Span, (b) Pseudoword Imitation, and (c) Word-pair Repetition. Set B included: (a) memory span with Concurrent Processing, (b) Tongue Twisters, (c) Passage Comprehension, and (d) Rapid Naming. The order of tasks within each set was chosen to avoid presenting difficult tasks last and to provide variation in task demands. To control for order effects, presentation of the sets was counterbalanced. Approximately half the subjects in each reading group were tested on Set A in the second session and on Set B in the third session. For the other half of the subjects, the sets were reversed. All the measures were administered in a standardized manner. Each session lasted 30-40 minutes. The first author tested approximately two-thirds of each group; a trained research assistant tested the remaining one-third of each group.

RESULTS

DESCRIPTIVE STATISTICS

Descriptive statistics for the memory and speech production variables were examined for violations of assumptions. The data were slightly non-normal for four of the variables (Tongue Twister [Accuracy]; Tongue Twister [Time]; Word-pair Repetition [Accuracy]; Word-pair Repetition [Time]). Normality was achieved with transformations,[7] and the transformed scores for these variables were used in all further analyses. Descriptive statistics for the three groups are summarized in table II.

[7]Square root transformations were calculated for Tongue Twister (Accuracy) scores, for Word-pair Repetition (Accuracy), and for Word-pair Repetition (Time). Log 10 transformation was used to correct the Tongue Twister (Time) scores.

TABLE II. MEANS, STANDARD DEVIATIONS, AND RANGES FOR VERBAL MEMORY AND SPEECH PRODUCTION SCORES FOR THE THIRD-GRADE LESS-SKILLED, THIRD-GRADE SKILLED, AND GRADE 2 READERS

	Third-grade Less-skilled Readers (Study Group)	Third-grade Skilled Readers (Age-level Comparison)	Grade 2 Readers (Reading-level (Comparison)
Word Span[a]			
Mean (SD)	29.8 (9.7)	36.5 (8.0)	33.8 (8.9)
Range	17 - 53	23 - 51	21 -50
Concurrent Processing[b]			
Mean (SD)	18.2 (4.2)	21.9 (3.6)	17.53 (4.4)
Range	8 - 26	11 - 28	7 - 26
Pseudoword Imitation[a]			
Mean (SD)	17.5 (4.4)	23.3 (3.0)	21.9 (3.3)
Range	7 - 26	15 - 27	12 - 26
Word-pair Repetition (Accuracy)[a] (Errors)			
Mean (SD)	9.5 (5.7)	3.5 (3.3)	5.0 (4.4)
Range	2 -26	0 - 15	0 - 17
Tongue Twister (Accuracy)[a] (Errors)			
Mean (SD)	11.6 (6.9)	4.3 (3.4)	6.3 (4.3)
Range	1 - 25	0 - 14	1 - 15
Word-pair Repetition (Time)[c]			
Mean (SD)	12.3 (2.0)	11.5 (1.5)	12.1 (1.8)
Range	9.03 - 16.56	9.60 - 14.61	9.46 - 18.57
Tongue Twister (Time)[c]			
Mean (SD)	7.7 (1.8)	7.6 (1.3)	7.8 (1.4)
Range	5.13 - 11.46	5.61 - 12.18	5.68 - 11.26
Rapid Naming (Time)[b]			
Mean (SD)	53.9 (11.76)	48.1 (9.2)	58.4 (10.3)
Range	34.23 - 81.53	33.41 - 73.71	40.68 - 85.21

Student-Newman-Keuls Results:
[a]Less-skilled third-grade readers < Skilled third-grade readers = Grade 2 readers
[b]Skilled third-grade readers > Less-skilled third-grade readers = Grade 2 readers
[c]No significant group differences

PRINCIPAL COMPONENTS ANALYSIS

In order to obtain a parsimonious summary of the memory and speech production variables for all 90 subjects, a Principal Components Analysis was performed (see table III for results). Three factors, accounting for 68% of the variance among the variables, were extracted. The first two factors alone accounted for 56% of the variance. Factor one included the three unspeeded memory variables and the two speeded speech production accuracy variables ("Memory/Accuracy" factor). Factor two consisted of two of the three speech production time variables (i.e., Tongue Twisters and Word-pair Repetition) ("Speed" factor). The Rapid Naming variable loaded most strongly on Factor three; however, this variable also loaded on the "Memory/Accuracy" factor.

TABLE III. FACTOR LOADINGS FOR EACH FACTOR'S PREDICTOR VARIABLES

	Factor 1	Factor 2	Factor 3
Word Span	−.765		
Concurrent Processing	−.730		
Pseudoword Imitation	−.650		
Tongue Twister (Accuracy)	.614		
Word-pair (Accuracy)	.559		
Rapid Naming (Time)	.527		.661
Tongue Twister (Time)		.848	
Word-pair (Time)		.699	

Note: Only loadings >.50 are given

MULTIVARIATE ANALYSIS OF VARIANCE (MANOVA)

A MANOVA procedure was used to determine whether the reading groups differed significantly on the memory and speech production measures. Based on the results of the Principal Components Analysis, three factors were examined. The first factor ("Memory/Accuracy") was a composite of the Word Span, Concurrent Processing, Pseudoword Imitation, Word-pair Repetition (Accuracy), and Tongue Twister (Accuracy) scores. The second factor ("Speed") consisted of the Word-pair Repetition (Time) and Tongue Twister (Time) scores. The third factor was the Rapid Naming (Time) score.

The results of the MANOVA indicated that there was a significant group effect on the three factors, $F(6, 168) = 5.90$, $p<.001$. Univariate comparisons revealed that two of the three factors were affected by group: the "Memory/Accuracy" factor, $F(2, 87) = 12.69$, $p< .001$, and the Rapid Naming variable, $F(2,87) = 7.34$, $p< .001$. No group effect was obtained for the "Speed" factor.

ANALYSES OF VARIANCE AND STUDENT-NEWMAN KEULS

In order to determine which variables were significantly affected by group, follow-up Analyses of Variance (ANOVAs) were conducted on the factors showing a significant group effect in the MANOVA procedure. ANOVAs on the three memory and two speech production accuracy variables indicated that there was a significant group effect for each of the five variables: Word Span ($F(2, 87) = 5.79$, $p = .004$); Concurrent Processing ($F(2, 87) = 10.09$, $p< .001$); Pseudoword Imitation ($F(2, 87) = 24.88$, $p< .001$); Word-pair (Accuracy) ($F(2, 87) = 15.26$, $p< .001$); Tongue Twister (Accuracy) ($F(2, 87) = 13.75$, $p< .001$). As noted, the MANOVA procedure revealed a significant group effect for the Rapid Naming variable.

The Student-Newman-Keuls procedure was used to determine which groups differed significantly on the Word Span, Concurrent Processing, Pseudoword Imitation, Word-pair (Accuracy), Tongue Twister (Accuracy), and Rapid Naming (Time) variables. The results of these analyses indicated that the age-level comparison group performed significantly better than both the study group of less-skilled readers and the reading-level comparison group on the Concurrent Processing and Rapid Naming measures ($p < .05$). The less-skilled third-grade readers and the reading-level comparison group did not differ significantly on these two measures.

Of particular importance to this study was the fact that the Student-Newman-Keuls procedure also indicated that the study group performed significantly worse than either of the comparison groups on the Word Span, Pseudoword Imitation, Word-pair (Accuracy), and Tongue Twister (Accuracy) measures ($p < .05$). The age-level comparison and the reading-level comparison groups did not differ significantly on these four measures.

MULTIPLE REGRESSION ANALYSES

A series of multiple regression analyses were conducted to determine whether the memory and articulation variables used

in this study would significantly improve the prediction of reading skill beyond what could be explained by age and verbal ability. (See table IV.) When Word Attack was the criterion variable, the eight phonological variables combined explained a further 31% of the variance in nonword reading not predicted by age or verbal ability ($F(8, 79) = 4.81$, $p < .01$). One variable, Pseudoword Imitation, made a significant contribution on its own, accounting for 12% of the variability in reading among the 90 subjects over that accounted for by age and cognition ($F(1,79) = 14.58$, $p < .01$).

When Word Identification was used as the criterion variable, the phonological processing variables together explained 34% of the proportion of variance in real word reading not predicted by age and verbal cognition ($F(8,79) = 6.68$, $p < .01$); on its own, Pseudoword Imitation accounted for 14% of the variance ($F(1, 79) = 21.44$, $p < .01$). When Passage Comprehension was the criterion variable, the phonological processing variables explained 12% of the variance in comprehension, over and above that explained by age and cognition; this failed to reach significance.

TABLE IV. HIERARCHICAL MULTIPLE REGRESSION ANALYSES WITH WORD ATTACK, WORD IDENTIFICATION, AND PASSAGE COMPREHENSION PERFORMANCE AS THE CRITERION VARIABLES (n= 90)

Variables entered in three steps	Beta	T	Sig. of T	Adj. R^2	Change in R^2
(A) Word Attack					
1. Age	.36	3.79	.01	.056	
2. PPVT-R	-.07	-0.71	.48	.064	.008
3. 8 Phono. Process. Var.[a]				.371	.307
(B) Word Identification					
1. Age	.42	4.83	.01	.074	
2. PPVT-R	.09	1.07	.29	.148	.074
3. 8 Phono. Process. Var.[a]				.492	.344
(C) Passage Comprehension					
1. Age	.33	3.23	.01	.056	
2. PPVT-R	.25	2.59	.01	.179	.123
3. 8 Phono. Process. Var.[a]				.298	.119

[a]The eight phonological processing variables were: Word Span, Concurrent Processing, Pseudoword Imitation, Word-pair (Accuracy), Word-pair (Time), Tongue Twister (Accuracy), Tongue Twister (Time), and Rapid Naming (Time).

DISCUSSION

One of the primary goals of the present study was to investigate the association between reading ability and performance on measures of underlying phonological processes. Although poor readers often do not do as well as good readers on tasks measuring verbal short-term memory span, verbal working memory, and speech production, the prior research findings have been neither consistent nor compelling. Thus, the question persists as to whether less-skilled readers have noteworthy deficits in the phonological processes entailed in listening and speaking. The results obtained in the current study provide strong affirmative evidence.

In this study, less-skilled third-grade readers had significantly lower scores on two verbal memory measures (i.e., Pseudoword Imitation and Word Span) and on two speech production accuracy measures (Tongue Twisters and Word-pair Repetition) both when compared with their age-mates and when compared with younger readers. That is, although less-skilled third graders had achieved reading skills equivalent to those of normal-reading second graders, their performance on several phonological measures was significantly below even the second grade level. These results argue against an interpretation that poor readers are simply progressing at a slower rate than their better-reading peers: if so, one would expect a cognitive profile comparable to that found in younger normal readers at the same level of reading skill. Likewise, the outcome goes against a strict account that phonological skill delimits extent of reading development. In that case, parallel patterns with the younger subjects would again be expected. Whereas failure to differ from reading-age matched subjects would have left more than one explanation to be considered, the present findings less ambiguously point to weaknesses in underlying phonological processes.

The results also suggest that the domain of difficulty for less-skilled readers pertains to the quality of phonological processing. All of the tasks tapping accuracy and recall of phonological representations loaded on a single factor, separate from the speed measures. Moreover, performance on the untimed accuracy measures, most notably Pseudoword Imitation, accounted for a significant proportion of the variance in reading (i.e., Word Attack and Word Identification performance). Although our results differ from those of McDougal et al. (1994) which pointed to reading group differences in speed of

articulation, it may be that the slow, careful performance of the poor readers in their study was a deliberate attempt to avoid the very errors found in our study; both sets of results would appear to reflect a weakly established representation, prone to errors under speeded conditions. More curious is the lack of age effects for the speed measures, such as were observed by Stanovich, Nathan, and Zolman (1988) and others noted in the introduction. The absence of an age-speed relationship in the present study may be due to the narrower age range and/or use of older subjects than were used in those studies reporting a developmental trend.

In the present study, scores on the Rapid Naming task loaded both with the memory/accuracy factor and more strongly on an independent factor. This suggests that the task demands of the memory span and repetition tasks are not identical to those for rapid naming. In a Discriminant Function Analysis, not reported in the results section because of redundancy with the multiple regression analyses, the Rapid Naming task comprised a discriminant function together with Concurrent Processing. This function maximally discriminated skilled third-grade readers from second-grade readers, with the less-skilled third-grade readers falling between these two groups. Hence it is plausible that performance on these measures corresponds, at least in part, with reading experience and development. This seems quite reasonable in the case of working memory, which requires complex processing. Thus differences in reading experience may contribute to the reported association between working memory and reading comprehension in older subjects (e.g., Daneman and Carpenter 1980; Pennington et al. 1990). On the other hand, the outcome with Rapid Naming was not fully anticipated: it was included to provide an additional assessment of articulatory output. Though parallels of the task demands of rapid serial naming with the complex requirements of reading have been pointed out (e.g., Wolf 1991), the predictive value of naming speed in kindergarten for subsequent reading performance has tended to reduce the focus on the role of experience for this measure.

A second goal of this study was to identify a measure of phonological processing that was closely related to reading. Of the tasks administered, the individual variable most strongly associated with reading-group differences (i.e., Word Attack and Word Identification scores) was the pseudoword repetition task. As mentioned earlier, a growing body of studies have reported significant differences between reading groups on this

type of measure.[8] The ease of conducting a pseudoword imitation task may avoid some of the potential confounds of motivation, of use of strategies, or of attention which may affect performance on span measures. At the same time, the cognitive requirements of pseudoword imitation are complex, as indicated in debate about whether faulty performance reflects encoding, memory, or output difficulties (e.g., Gathercole 1995; Snowling, Chiat, and Hulme 1991).

An important insight to be drawn from research to date is that reading group differences on underlying phonological processes appear to be most evident on tasks that place demands on encoding phonological information (i.e., when there is minimal top-down information or when the input is difficult to analyze (e.g., because of noise). Hence, tasks that entail novel phonological patterns seem particularly taxing (though see Torgesen and Houck 1980). For example, in the present study, when pseudowords had to be repeated in the Tongue Twister task, the less-skilled readers were able to repeat fewer items correctly (i.e., a mean of 6.1 out of 10 trials) than were either of the comparison groups (both of which had an average of 7.5 trials fully correct). When, instead, real words had to be repeated, the number of trials repeated accurately by the less-skilled readers was between that of the two comparison groups (i.e., a mean of 7.1 correct versus 7.9 for the age-matched group and 6.1 for the reading-matched group). The conclusion that poor readers' difficulty is particularly acute for new phonological sequences also is compatible with the numerous anecdotal

[8]Choice of stimuli is important for this type of task. The items need to be sufficiently difficult for the age-group to be tested: the stimuli used by Gathercole and Baddeley (1989) appear to work well with young children, the stimuli presented by Taylor, Lean, and Schwartz (1989) seem to be satisfactory with early elementary children, and Apthorp (1995) had to use quite long pseudowords to discern reading-group effects in adults.

In addition, as noted earlier, because word-likeness of the stimuli has been demonstrated to be a factor in repetition performance (e.g., Dollaghan, Biber, and Campbell 1995; Gathercole 1995), and because poor readers often have weaker vocabulary knowledge than their better reading classmates (e.g., Kail and Leonard 1986; Vellutino and Scanlon 1987), skilled readers may be more able to draw on top-down information from existing vocabulary knowledge, in addition to having greater facility at processing novel phonological sequences. However, the selection procedure followed in the present study (i.e., the age-matched subjects were selected to have comparable vocabulary knowledge) handles potential concerns that the poor performance on the pseudoword imitation task by these less-skilled third graders stems from differences in vocabulary knowledge. Likewise, the younger reading-matched children had similar standard scores, but lower raw scores than the less-skilled readers, suggesting again that the deficits we observed for the less-skilled readers are not to be explained by differences in top-down processing.

reports by disabled readers of how difficult it is to retain new names or vocabulary items, as well as with empirical studies documenting that less-skilled readers require more exposure to be able to produce accurately the phonological sequences for newly-learned words (Aguiar and Brady 1991; Aguiar 1993; Kahmi, Catts, and Mauer 1990; Nelson and Warrington 1980).

Although our study strengthens the evidence that reading aptitude varies with basic phonological skill, it remains that memory is less consistently associated with reading than are other phonological tasks, generally accounting for less of the variance than do measures of phonemic awareness or rapid serial naming (e.g., Fletcher et al. 1994; Felton and Wood 1989).[9] The issue is further complicated by the fact that the association between memory and reading/prereading appears to vary with age. For example, the significant correlation between awareness and memory reported in early development (e.g., Wagner et al. 1987; Wagner et al. 1993) appears to have declined by the elementary years (Wagner, Torgesen, and Rashotte 1994). Conversely, the association between reading comprehension and working memory appears to increase with age (see Pennington et al. 1991 for a review). Interestingly, the association between pseudoword repetition and reading also appears to become stronger over the years between kindergarten and fifth grade (see Torgesen, in press, for discussion of an unpublished manuscript by Torgesen, Wagner, and Rashotte 1994). Given the complex assembly of skills to be mastered in learning to read (i.e., phonological awareness, decoding, word recognition, reading comprehension) and the possibility that phonological memory may relate to the component skills of reading differently at different ages, the need for further careful, analytic studies is essential.

In closing, the results of the present study confirm that less-skilled readers have underlying phonological weaknesses: in addition to the well-documented deficits in metaphonological skills, individuals with reading problems also have significant difficulty with more automatic phonological processes entailed in some aspect of verbal short-term memory. These findings underscore the importance of further investigation to better understand the source of difficulty in underlying phonological processes for poor readers, and they renew incentive for studying the interplay of metalinguistic and underlying phonological skills.

[9]However, the stronger associations of phonemic awareness and rapid naming tasks with reading performance may be inflated by greater reciprocal relationships with reading development than for memory tasks (see Torgesen, in press, for discussion).

ACKNOWLEDGMENTS

We would like to thank the East Providence and Bristol, Rhode Island, school systems for allowing us to work with their students. We are particularly grateful to the four principals and 21 teachers whose students were involved in this project. These dedicated professionals made many adjustments in their routines to accommodate the data collection schedule. Special thanks go to Jeanne O'Connor who provided invaluable assistance with the collection of data and to Anne Fowler and Hollis Scarborough for their very helpful recommendations on the manuscript. We are also grateful for the financial support provided by a National Institutes of Health grant (HD-01994) to Haskins Laboratories and by a National Center for Research Resources grant (NSS2-S07-RR07086-14) to the University of Rhode Island. This paper is based on the doctoral dissertation of the first author.

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