Speaking Up for Vocabulary:

Reading Skill Differences in Young Adults

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Abstract

This study is part of a broader project aimed at developing cognitive and neurocognitive profiles of adolescent and young adult readers whose educational and occupational prospects are constrained by their limited literacy skills. We explore the relationships among reading-related abilities in participants ages 16 to 24 years spanning a wide range of reading ability. Two specific questions are addressed: (a) Does the simple view of reading capture all nonrandom variation in reading comprehension? (b) Does orally assessed vocabulary knowledge account for variance in reading comprehension, as predicted by the lexical quality hypothesis? A comprehensive battery of cognitive and educational tests was employed to assess phonological awareness, decoding, verbal working memory, listening comprehension, reading comprehension, word knowledge, and experience with print. In this heterogeneous sample, decoding ability clearly played an important role in reading comprehension. The simple view of reading gave a reasonable fit to the data, although it did not capture all of the reliable variance in reading comprehension as predicted. Orally assessed vocabulary knowledge captured unique variance in reading comprehension even after listening comprehension and decoding skill were accounted for. We explore how a specific connectionist model of lexical representation and lexical access can account for these findings.

Surprisingly, the cognitive basis of reading differences has not been nearly as well studied in young adults as in learners during the primary school years (Curtis, 2002). This is especially true for individuals who are not college bound. Our study was motivated by a desire to better understand the reading-related abilities of young people who, for whatever reason, have failed to attain a level of reading proficiency adequate to the demands of the modern workplace. Consequently, we recruited young people, ages 16 to 24 years, representing a wide spectrum of abilities and educational backgrounds. Although our approach was to sample broadly, we focused on settings (i.e., adult schools, community colleges) that experience has suggested include a significant number of students whose reading skills are poorly developed, so that their future educational and occupational prospects are limited (Dietrich & Brady, 2001; Shankweiler, Lundquist, Dreyer, & Dickinson, 1996). The reading abilities of the participants ranged from fifth grade to post–high school. Their educational environments at the time of participation ranged from high school and adult school through community college. Reading research and language comprehension research alike have neglected unskilled readers who may not meet legally established criteria for learning disabilities (LD). An adequate understanding of the reading-related limitations of the many young people outside the university track of the traditional postsecondary educational system is badly needed to plan effective adult education and remedial programs.

We took two proposals about reading skill as our point of departure. The *simple view of reading* proposes that reading comprehension is literally the product of decoding skill and general language comprehension capacity (Gough & Tunmer, 1986), when each are measured appropriately. A tenet of the simple view of reading is that decoding—the ability to identify words by way of orthographic–phonological mapping—is the one new skill that an individual must acquire to learn to read. A second proposal, the *lexical quality hypothesis*, focuses on the role of word knowledge in the reading process, positing that skilled reading depends on high-quality lexical representations (Perfetti & Hart, 2002). Specifically, this hypothesis holds that robust word knowledge, including knowledge of syntactic–semantic relationships among words, facilitates printed word recognition when decoding cues are weak. In evaluating these proposals, we adopted an analytic approach based on regression modeling to take advantage of the fact that people vary continuously in their reading skill and in the underlying capacities that support it. Our theoretical perspective is grounded in connectionist views of word knowledge (e.g., Seidenberg & McClelland, 1989).

Reading is among the most highly complex skills that school children are called upon to master, and it is influenced by a variety of perceptual, linguistic, and cognitive abilities. Gough and Tunmer (1986) found it useful to cope with this complexity by framing the simple view of reading (SVR). The SVR separates the variables pertaining to reading success into two groups. One group consists of those skills related to printed word recognition as such. It comprises the visual and visual–phonological (and –morphological) mapping skills that are needed to productively derive word meanings from print representations. We may call this group of abilities D, for *decoding*. The other group of abilities includes the many factors that reading shares with spoken language, such as vocabulary, syntax, semantics, and pragmatics. Call them L, for *language*. Each group of variables is, obviously, complex. Gough and Tunmer proposed that R, or *reading comprehension*, is the product of D and L and that when these are properly measured, they account for all of the variance in R.

The choice of indices for each group of D and L is an important consideration for any investigation of reading ability. D is typically assessed by skill in reading nonwords, and L is ordinarily identified with comprehension of spoken sentences or narrative passages. Hoover and Gough (1990) defined D (decoding) as "the ability to rapidly derive a representation from the printed input that allows access to the appropriate entry in the mental lexicon, and thus, the retrieval of semantic information at the word level" (p. 130). This definition of decoding is general enough to cover several plausible specific mechanisms:

1. Decoding could be a purely visual pattern recognition skill, in which visual patterns are directly associated with semantic and syntactic information in the lexicon.
2. Decoding could activate the lexical entries indirectly, via a phonological channel.

Hypothesis 2 itself can take a range of forms: (a) the mapping from orthographic words to phonological words could be accomplished purely by rote; (b) it could be a systematic map, a rule-based system that takes advantage of the regularities in the relationships between letters and sounds, or (c) it could be some combination of the two. Hoover and Gough (1990) clearly favored possibility (b). In their study, they measured readers' ability to correctly pronounce orthographically legitimate nonwords and used that score as an index of decoding skill. Our test battery includes the Word Attack task from the *Woodcock-Johnson–III Tests of Achievement* (WJ-III; Woodcock, McGrew, & Mather, 2001), a nonword reading task that closely corresponds to Hypothesis 2(b). In our initial implementation of the SVR, this nonword reading measure is used as the index of decoding ability (D).

For beginning readers, it is clear that a lack of decoding ability is the primary obstacle to fluent reading (Adams, 1990; Snow, Burns, & Griffin, 1998). The primary locus of reading difficulty seems to be different for older students and adults. For them, it is thought that the demands of text reading more often reflect challenging content and vocabulary, which heavily involve the L side of reading. Indeed, it has been claimed that among adult readers, differences in listening comprehension (L) alone account for most of the variance in reading comprehension (Palmer, MacLeod, Hunt, & Davidson, 1985). However, there is considerable evidence to suggest that even among more mature readers, decoding skill continues to account for unique variance in reading comprehension (Bell & Perfetti, 1994; Cunningham, Stanovich, & Wilson, 1990; Lundquist, 2004; Shankweiler et al., 1996).

To fairly assess the relationship of listening comprehension to reading comprehension, it is necessary to have measures of each that are well calibrated to one another. In the present study, we accomplished this by splitting materials from the *Peabody Individual Achievement Test–Revised* (PIAT-R; Markwardt, 1998) Reading Comprehension subtest into parallel sets to assess print comprehension and speech comprehension. We also assessed participants' ability to comprehend short narrative passages in print. However, where the comparability of reading comprehension and listening comprehension tasks was critical, we made use of the PIAT-R–based comprehension measures.

A corollary of the SVR is that *potential* reading comprehension capacity will be limited by the capacity to comprehend equivalent material in spoken form. Given this proviso, reading disability is best characterized as a discrepancy between achieved reading skill and speech comprehension rather than as a discrepancy between reading comprehension and general cognitive capacity (Aaron, 1997; Gough & Hillinger, 1980; Perfetti, 1985; Stanovich, 1991).

Although the SVR explains a lot about reading skill, there have been suggestions that it can be improved on. For example, reading fluency is known to be well correlated with overall reading skill (Fuchs, Fuchs, Hosp, & Jenkins, 2001). Furthermore, nearly all individuals who meet accepted criteria for reading disability have deficits in word reading speed or accuracy (Fletcher et al., 1994; Stanovich & Siegel, 1994). Joshi and Aaron (2000) proposed that "the rate at which the written word is processed should be considered as a factor to be reckoned with in reading" (p. 87) independent of general comprehension and decoding skill. Their proposal calls for supplementing the model of reading based on the two-factor SVR with an additional component of *processing speed*. In another connection, Shankweiler et al. (1996) suggested that as readers mature, their fine-grained knowledge of relationships among words, including derivational morphology and orthographic conventions, gained through experience with both spoken and written language, is an increasingly important component of reading skill. In the following section, we turn to the lexical quality hypothesis put forward by Perfetti and

Hart (2002)—a proposal that we believe has the potential to account for interrelationships among word knowledge, lexical processing speed, and reading skill.

Role of Word Knowledge

A link between word knowledge and reading comprehension is plausible at face value, and empirical support is well established (e.g., Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Cunningham et al., 1990; McKeown, Beck, Omanson, & Pople, 1985). Perfetti and Hart (2002; see also Perfetti & Lesgold, 1979) maintained that the *quality* of lexical representations influences the ease with which those representations can be accessed. In this context, *quality* refers to the extent that a lexical representation includes all staple components of a word (orthographic, phonological, and syntactic–semantic), the richness of the specification of each component, and the degree to which the components are integrated with each other.

We propose that the lexical quality hypothesis (LQH) implies a differential effect of modality, so that the comprehension of print depends on high-quality lexical representations to a greater extent than does the comprehension of speech. We will expand on this idea in the discussion section. Here, we anticipate that discussion with a set of observations. First, we note that in general, linguistic comprehension depends both on information from the sensory input systems *and* on listener/reader knowledge of linguistic structure and contextual constraints. As the linguistic signal becomes less informative (noisier or weaker), top-down constraints become more important to the process of comprehension (Elliott, 1979; Kalikow, Stevens, & Elliott, 1977). Moreover, print is in many ways an impoverished linguistic signal relative to speech. Not only is print, for many, a less practiced modality, it also lacks information found in speech, as from co-articulation and prosody. Furthermore, print often has less contextual support than speech. Thus, individual variation in the availability of top-down constraints (specifically, word knowledge), or in the ability to exploit them, may explain some differences in comprehension, particularly where the linguistic signal is weak. The LQH focuses on top-down influences on lexical access stemming from the organization of lexical knowledge internal to the reader. We are specifically interested in the effect of lexical quality on lexical access when bottom-up cues (visual or acoustic) to word identity are relatively weak. We leave aside the issue, albeit important, of readers' capacity to exploit contextual constraints in support of word identification, as discussed in Stanovich (1980) and much subsequent work.

To assess word knowledge, our battery includes measures of both expressive and receptive vocabulary. We chose orally administered tasks to avoid confounds with reading comprehension. Given the importance of vocabulary to comprehension, a deeper understanding of its precursors is desirable. Two measures included in our battery have, in other studies, predicted significant variance in word knowledge: experience with print and verbal working memory. We examined the relative contributions of these two factors to word knowledge in our study population.

Stanovich, West, and Harrison (1995; see also Stanovich & Cunningham, 1992; West & Stanovich, 1991; West, Stanovich, & Mitchell, 1993), in a study of college students and older adults, found that *experience with print* was a reliable predictor of vocabulary even after differences in working memory, IQ, and education were taken into account. Indeed, Perfetti and Hart (2002) also acknowledged the importance of reading experience to developing high-quality lexical representations. Two closely related measures of print experience are included in our battery: magazine and author recognition checklists (Cunningham & Stanovich, 1990; Stanovich & Cunningham, 1992). In these tasks, participants have to distinguish actual magazine titles or author names from foils consisting of fictional titles or names. The checklists are scored using a signal detection logic, in which participants are penalized for false positive responses. Participants' age and years of education were also collected as indicators of more general experience.

A number of studies have observed a relationship between *verbal working memory* and children's word knowledge (Avons, Wragg, Cupples, & Lovegrove, 1998; Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1990; but see Aguiar & Brady, 1991) and also of adults' ability to acquire new words in a second language (Atkins & Baddeley, 1998). We incorporated an auditory version of the Daneman and Carpenter (1980) sentence span task as an index of verbal working memory. This type of task is designed to tap both processing and short-term storage, thereby mirroring the challenge of reading texts or apprehending spoken discourse. In a departure from most work using sentence span measures in adults, we used an auditory presentation of sentence materials to avoid confounding differences in verbal working memory, as such, with differences in reading ability. In one common view, verbal working memory includes an inherently phonological component (Baddeley, 1986; Shankweiler & Crain, 1986), which is a possible locus for the phonological constraints on both print and speech comprehension. There is evidence, however, that the variance in reading comprehension captured by measures of verbal working memory may be mediated by other factors; as noted, working memory has been shown to account for variance in word knowledge. To assess how closely the working memory exploited in reading is specific to language, our test battery also included a nonverbal test of memory for visual patterns, which can be viewed as a nonverbal analog of sentence span.

Questions to Be Addressed

Our concern with the nature of reader differences and reading-related skills of young adults led us to ask the following questions:

1. Does the two-factor SVR give a satisfactory account of reading comprehension differences in this population, as it does for learners in the elementary grades?
2. What are the relative contributions to reading comprehension of decoding and listening comprehension?
3. What factors, if any, pick up variance in reading comprehension after decoding and listening comprehension have been accounted for?
4. What is the relative contribution of word knowledge to comprehension of print and comprehension of speech?

Preview of Findings

The central finding we will report is that Gough and Tunmer's (1986) simple view of reading accounts for most of the variance in reading comprehension among the adolescent and young adults we studied. Moreover, decoding ability uniquely accounts for a significant proportion of the variance even among these 16- to 24-year-olds. But we also found an additional, somewhat unexpected, result: Significant unique variance is captured by vocabulary knowledge, as assessed via oral vocabulary tests. This outcome is surprising from the perspective of the SVR, which holds that the effects of oral vocabulary knowledge should be entirely subsumed by general language comprehension. Perfetti and Hart's (2002) lexical quality hypothesis provides insight into this result: High-quality lexical representations compensate for the relative weakness of the print signal, as contrasted with the speech signal. To make this concrete, we will describe in the discussion section an activation-based model that predicts such modality differences.

Method

Participants

Our participants were young people, ages 16 to 24 years. In keeping with our interest in those who struggled with reading in primary and secondary school, we specifically targeted adult education centers serving urban neighborhoods. There, we found individuals whose secondary schooling had been interrupted for one reason or another, but who were now seeking either a high school equivalency certificate or resuming a regular high school program at the center. Furthermore, we recruited through advertisements in a local newspaper and posters placed on adult school and community college campuses, which brought in individuals with a wider range of backgrounds, but with abilities continuous with those of the other participants. Nearly all participants were enrolled in some kind of educational program, whether high school, adult school, or community college. A few were recent graduates and were not enrolled in school at the time they participated in our study.

Those selected for participation had to be capable of reading simple material with sufficient understanding to perform our reading tasks. To determine this, we used the Fast Reading subtest of the *Stanford Diagnostic Reading Test* (SDRT; Karlson & Gardner, 1995). This 3-min test consists of a short expository passage containing 30 choice points at which the participant is required to select the appropriate word from among three alternatives. In previous work with this population, we determined that the proportion of correct responses was a better indicator of their ability to perform our tasks than the absolute score. Thus, we set no minimum score, but we required an accuracy of at least 70% correct on items attempted. This cutoff would exclude some individuals with severe reading disabilities, while admitting others whose reading was accurate but slow. We also screened to ensure that participants had acquired English as their first language. Finally, participants were required to have an estimated Full Scale IQ of 80 or more. All participants gave informed consent.

Data were collected from a total of 47 participants. Two of them failed to meet the minimum IQ requirement and were excluded from subsequent analyses. Data from one participant were identified as problematic and so were excluded from all subsequent analyses. Thus, the analyses presented here are based on a sample size of 44 (18 males).

Participants were paid for completing the protocols described hereafter as well as eye-tracking and functional magnetic resonance imaging protocols that are reported elsewhere (manuscript in preparation). Altogether, testing time averaged about 5 hours over two sessions. All protocols were approved by the Yale University human investigation committee.

Assessment of Reading-Related Skills

The measures assessing reading-related skills were organized into the following groups:

- Group A: print mapping and reading skills (reading isolated words, reading nonwords, pseudohomophone detection, reading comprehension, and oral reading speed).
- Group B: oral language measures (phonological awareness, vocabulary, auditory verbal working memory, and listening comprehension.
- Group C: nonlinguistic mental facility and speed (memory for visual sequences, analogical reasoning).

In addition to the foregoing measures, we assessed experience with print using author and title checklists. In summarizing these measures, we report the published reliabilities for published tests when these were administered in the standard way. Otherwise, we report reliabilities derived from our own data. We also report age and years of education completed at time of testing.

Group A: Print Mapping and Reading Skills

Nonword reading. The *Woodcock-Johnson–III Tests of Achievement* (WJ-III; Woodcock et al., 2001) Word Attack subtest, Form A, served as a measure of rule-based decoding skill. Participants read aloud individual pseudowords presented in list form. This test is a relatively pure measure of skill in orthographic–phonological decoding. Average reliability of this task across the age range of our study participants has been reported as .82 (McGrew & Woodcock, 2001).

Word reading. The WJ-III Word Identification subtest, Form A, provided a measure of memory-based decoding capacity (Woodcock et al., 2001). Participants read aloud a list of individual words graded in difficulty. Because no contextual support is available, this test primarily taps decoding skill, but it involves the decoding of known word forms rather than novel ones. Average reliability of this task across the age range of our study participants has been reported as .90 (McGrew & Woodcock, 2001).

Pseudohomophone identification. For each item, participants must choose the one pseudoword that would be pronounced like a real word, from among three alternatives (Olson, Forsberg, Wise, & Rack, 1994). Sixty triads of pseudoword stimuli were presented by computer using Psyscope software (Cohen, MacWhinney, Flatt, & Provost, 1993). Accuracy and response times were recorded. This test taps decoding ability because it necessitates the generation of a phonological representation for each item, but it also requires the participant to compare the generated phonological form with representations stored in the mental lexicon; thus, vocabulary knowledge is exercised as well. Reliability was $\alpha = .84$.

Print sentence comprehension. Our first of two reading comprehension measures was an abridged version of the Reading Comprehension subtest from the *Peabody Individual Achievement Test–Revised* (PIAT-R; Markwardt, 1998). Participants read a list of increasingly difficult sentences and then choose a picture, from an array of four, that best matches the meaning of the sentence. Odd-numbered items from the subtest were administered in the standard way to assess reading comprehension, whereas even-numbered items were used to assess listening comprehension, as described hereafter (Spring & French, 1990). The standard stop condition of 5 errors in 7 consecutive items was used for the abridged form. For the abridged form, we found a reliability of $\alpha = .90$; Leach, Scarborough, and Rescorla (2003) reported a reliability of $\alpha = .89$ for a similarly abridged form of the task administered to fourth- and fifth-grade students.

Print passage comprehension. Participants read aloud and answered questions about Passages 5, 7, and 9 from the *Gray Oral Reading Test*, fourth edition, Form A (GORT; Wiederholt & Bryant, 2001). Each of the passages was followed by five comprehension questions. The passage comprehension score is the total number of correct responses for the three passages. Reliability for the GORT subset used here was $\alpha = .67$.

Reading speed. We collected and summed oral reading times for the three GORT passages. Reading speed was then calculated as the combined word count of the three passages (N = 361; Passage 5, n = 106; Passage 7, n = 107; Passage 9, n = 148) divided by total reading time.

Spelling. Items consisted of 36 of the 72 words from the experimental spelling test of Shankweiler et al. (1996). Items were such that they could not generally be spelled simply by reference to letter–phoneme correspondence rules, but neither were their spellings highly idiosyncratic; the ability to spell items correctly depended on familiarity with a range of orthographic conventions as well as with some common exceptions. Reliability was $\alpha = .87$.

Group B: Oral Language Measures

Phonological awareness. A *Spoonerism Production Test* was used to measure phonological awareness. This required participants to exchange the initial consonant for pairs of spoken names (Perin, 1983). For example, *John Lennon* is transformed into *Lon Jennon*. To carry out this task, participants must hold the pair of stimulus names in memory, separate the initial phoneme from each, attach each severed phoneme to the alternate remainder, and pronounce the newly synthesized items. Reliability was $\alpha = .94$. Response times were recorded in addition to accuracy (Paulesu et al., 1996).

Receptive vocabulary. The *Peabody Picture Vocabulary Test–Revised* (PPVT-R; Dunn & Dunn, 1997) required the participants to select a picture from a group of four alternatives that best depicted a spoken target word. The average reliability across the age range of our population was .95 (Dunn & Dunn, 1997).

Expressive vocabulary. The vocabulary subtest from the *Wechsler Abbreviated Scales of Intelligence* (WASI; Psychological Corp., 1999) tests individuals' abilities to verbalize what they know of a word's meaning. The average reliability coefficient for adults (age $\geq$ 17) has been reported as .94.

Verbal working memory. We used an auditory version of the *Sentence Span* task (Daneman & Carpenter, 1980) to assess working memory. Participants were required to judge increasingly long series of sentences (containing 2 to 5 items) as *true* or *false* and then, at the end of each series, to verbally recall the final words of every sentence in the series; words did not have to be recalled in the order presented. Scores corresponded to the total number of items correctly recalled. Reliability was $\alpha = .85$. This type of task taps both processing and short-term storage, thereby mirroring a challenge presented by following discourse or reading texts. We administered the test in the auditory mode rather than the printed mode to avoid confounding differences in verbal working memory, as such, with differences in reading ability. Daneman and Carpenter referred to this variant as *Listening Span*.

Speech sentence comprehension. We used the even-numbered items from the PIAT-R Reading Comprehension subtest (Markwardt, 1998) to assess listening comprehension, whereas the odd-numbered items were used to assess reading comprehension (Spring & French, 1990; Leach et al., 2003). This maneuver allowed us to assess reading and listening comprehension with well-matched tasks. Parallel to the printed form, participants attend to increasingly difficult tape-recorded sentences and, for each one, choose a picture from an array of four that best matches the meaning of that sentence. The standard stop condition of 5 errors in 7 consecutive items was used. For the subset of items used for listening comprehension, we found a reliability of $\alpha = .87$. Leach et al. (2003) reported a reliability of $\alpha = .87$ for listening comprehension assessed in this way with fourth- and fifth-grade students.

Group C: Nonlinguistic Mental Facility and Speed

Visual memory. We used a computerized version of the *Corsi Blocks* task (Corkin, 1974) implemented in Psyscope (Cohen et al., 1993). The participant has to reproduce increasingly long visuospatial patterns by tapping successively on an irregular arrangement of nine circles displayed on a touch-sensitive computer screen. The patterns occur in blocks of five at each of the lengths from three through ten. The participant's score is the longest sequence that he or she can successfully reproduce three out of five times. This is a purely nonverbal memory test; there is no obvious way to code the patterns verbally.

Matrix reasoning. This is a test of visual analogical reasoning from the WASI (Psychological Corp., 1999). The average reliability coefficient for adults (age ≥ 17) is .94 (Psychological Corp., 1999).

Other Measures

Print Experience. We used magazine and author checklists based on the work of Cunningham and Stanovich (1990; Stanovich & Cunningham, 1992) to assess experience with printed materials. In the magazine checklist, the participant had to distinguish actual magazine titles from foils consisting of fictional titles ($\alpha = .74$). True positive and false negative responses were used to compute accuracy scores penalized for guessing, so that the reported scores are equal to the number of real titles checked minus the number of false titles checked. The author checklist was similarly structured and scored ($\alpha = .86$).

Composite Measures. Our test battery contained content-overlapping measures for reading comprehension, vocabulary, and print experience. For data reduction purposes and to increase reliability, the following composite scores were generated:

Reading Comprehension composite, derived from PIAT-R Print Sentence Comprehension and GORT Passage Comprehension

Vocabulary composite, derived from PPVT-R and WASI Vocabulary measures

Print Experience composite, derived from author and title recognition checklists

Data Preparation

Prior to analysis, the distributions of variables were examined for deviations from normality and for outliers through the inspection of quantile–quantile plots and histograms. Several variables showed evidence of nonnormality. For each such case, we used the method of maximum likelihood to estimate an unconditional Box-Cox power transformation to minimize deviations from normality (Atkinson, 1985). Primary analyses targeted composite measures of reading comprehension and vocabulary; these composites showed good distributional properties. We applied the Box-Cox power transformation to variables suffering from potentially problematic distributional properties wherever these occurred as criterion measures. No obvious outliers were observed in the univariate distributions.

We checked for multivariate outliers in the most critical portions of the variable space by examining quantile–quantile plots of Mahalanobis distances against a chi-square distribution with *df* equal to the dimensionality of the variable space. We examined two subsets of our variable space in this way. The first was defined by 5 variables: the composite measures of reading comprehension and vocabulary, as well as speech sentence comprehension and the decoding measures of word and nonword reading. In the second case, we examined a 7-dimensional space defined by the component measures of each of the two aforementioned composites as well as the speech comprehension measure and the two decoding measures. In neither case did we observe any outliers.

We took the additional step of screening for data points that were likely to exert excessive influence on the fit of models of interest. As our primary focus is on reading comprehension, we fit all simple regressions targeting our composite measure of reading comprehension as well as all simple regressions targeting the PIAT-R–derived measure of Print Sentence Comprehension. We then checked for the presence of influential observations on the fit of each model by examining Cook's distance statistic for each data point (Cook, 1977). Data from one participant were discovered to be problematic. This data point was observed to inflate correlations with reading comprehension, whether composite or simple, and each other variable under consideration. Thus, this participant was excluded from the summaries and analyses reported hereafter. Recursive application of this procedure revealed no other problematic observations (see Note 1).

Results

Descriptive Summary

Means and standard deviations for each measure are shown in Table 1. Summaries of cognitive measures are based on raw scores. Where available, we also include grade-equivalent or age-equivalent scores (see Note 2). Furthermore, estimated Full Scale IQ, based on the Vocabulary and Matrix Reasoning subtests from the WASI, is included (Psychological Corp., 1999). For the poor readers in our study, as defined by a median split on the reading comprehension screening measure, it is worth noting that scores on the PIAT-R–based reading comprehension task (print sentence comprehension) were appreciably lower than scores for the corresponding listening comprehension task (speech sentence comprehension), which is based on the same set of materials (Wilcoxon signed rank test for paired samples, $n = 22$, $T^{+} = 197$, $p < .05$). This indicates that the sample includes many individuals whose ability to comprehend material in printed form is weak in relation to their capacity for comprehension of the same kinds of material in speech. The better readers in our sample showed no such discrepancy.

TABLE 1
Means and Standard Deviations of All Cognitive, Educational, and Demographic Measures

Measure	*M*	*SD*	Max. possible
Word Reading (WJ-III)			
Raw score	67.68	5.39	76
Grade equivalent score	13.27	4.82	
Pseudohomophone Identification			
Accuracy	47.82	7.09	60
Response time	3.59	0.71	
Nonword Reading (WJ-III)			
Raw score	27.16	3.03	32
Grade equivalent score	10.68	4.62	
Print Sentence Comprehension			
Raw score	33.89	5.81	41
Grade equivalent score	9.87	3.14	
Print Passage Comprehension	11.95	2.17	15
Reading Speed (wpm)	176.50	39.01	
Spelling	25.93	6.41	36
Spoonerism			
Accuracy	15.32	4.02	18
Response time	5.75	3.29	
Expressive Vocabulary (WASI)	57.48	8.30	84
Receptive Vocabulary (PPVT-R)			
Raw score	172.77	17.56	204
Age equivalent score	19.37	4.44	
Speech Sentence Comprehension			
Raw score	34.98	4.53	41
Grade equivalent score	10.23	2.55	
Verbal Working Memory	31.91	5.75	42
Matrix Reasoning (WASI)	27.16	3.18	35
Visual Memory	4.98	1.41	9
Magazine Recognition	10.50	5.97	40
Author Recognition	7.30	6.33	40
IQ	104.89	12.81	—
Age	20.60	2.28	—
Years of Education	12.52	2.35	—

Note. $N = 44$ except for Spoonerism response time ($n = 41$): Three participants were unable to complete that task at all. All time measures are reported in seconds. WJ-III = *Woodcock-Johnson–III Tests of Achievement* (Woodcock, McGrew, & Mather, 2001); WASI = *Wechsler Abbreviated Scales of Intelligence* (Psychological Corp., 1999); PPVT-R = *Peabody Picture Vocabulary Test–Revised* (Dunn & Dunn, 1997).

Intercorrelations among the measures from Table 1, including the composites derived from those scores, are presented in Table 2, below the diagonal; above the diagonal are the intercorrelations among age-partialed scores. Unless otherwise noted, further discussion will refer to correlations among non–age-adjusted variables.

We identified some of the correlations that will be salient in the regression analyses to follow, designating correlations of .60 or higher as *strong* and correlations higher than .30 but less than .60 as *modest*. Our chief criterion measure, the reading comprehension composite, correlated strongly with word reading (r = .76) and modestly with the pseudoword measures of pseudohomophone identification accuracy (r = .46) and nonword reading (r = .49). Furthermore, there were strong correlations between reading comprehension and the spoken language measures of speech sentence comprehension (r = .74), vocabulary composite (r = .84), and verbal working memory (r = .62). The reading comprehension composite also correlates strongly with the estimated print experience composite (r = .75). Finally, it

TABLE 2
Simple Correlations Among Measures and Composite Scores With and Without Adjustment for Age

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Word reading	—	.47	–.42	.66	.69	.55	.69	.53	.63	–.42	.66	.74	.73	.43	.52	.42	.33	.57	.73	.71	.60	.00	.33
2. PHID accuracy	.54	—	–.39	.73	.24	.42	.38	.25	.50	–.52	.27	.28	.29	.00	.31	.12	.00	.18	.41	.33	.26	.00	.00
3. PHID response time	–.45	–.42	—	–.29	–.21	–.19	–.22	–.53	–.51	.24	–.28	–.26	–.28	.00	–.25	–.23	–.20	–.24	–.39	–.35	–.25	.00	.00
4. Nonword reading	.62	.72	–.30	—	.47	.44	.51	.35	.57	–.52	.36	.40	.40	.00	.41	.14	.00	.27	.47	.41	.33	.00	.14
5. Print sentence comprehension	.77	.36	–.27	.44	—	.59	.88	.44	.26	–.52	.75	.73	.78	.59	.57	.49	.30	.60	.65	.69	.70	.00	.30
6. Print passage comprehension	.62	.48	–.24	.45	.66	—	.91	.30	.18	–.34	.57	.63	.63	.58	.45	.46	.12	.52	.46	.54	.56	.00	.27
7. Reading comprehension composite	.76	.46	–.28	.49	.91	.91	—	.41	.24	–.48	.73	.76	.79	.66	.56	.53	.23	.62	.62	.68	.70	.00	.31
8. Reading speed	.61	.34	–.55	.36	.55	.39	.52	—	.50	–.31	.52	.47	.52	.17	.42	.34	.18	.53	.48	.55	.53	.00	.31
9. Spelling	.71	.56	–.53	.55	.46	.32	.43	.58	—	–.42	.15	.25	.21	.00	.29	.21	.33	.34	.46	.44	.20	.00	.16
10. Spoonerism response time	–.48	–.56	.27	–.53	–.56	–.40	–.53	–.38	–.47	—	–.45	–.43	–.46	–.23	–.50	–.39	–.25	–.23	–.48	–.39	–.49	.00	.00
11. Expressive vocabulary	.72	.35	–.33	.37	.78	.63	.77	.58	.30	–.50	—	.80	.96	.55	.61	.51	.25	.55	.76	.72	.84	.00	.30
12. Receptive vocabulary	.81	.39	–.31	.38	.82	.69	.83	.57	.46	–.48	.82	—	.94	.62	.53	.62	.28	.58	.62	.66	.77	.00	.31
13. Vocabulary composite	.80	.39	–.34	.39	.84	.69	.84	.61	.40	–.51	.95	.95	—	.61	.60	.59	.28	.60	.73	.73	.85	.00	.32
14. Speech sentence comprehension	.56	.15	.00	.00	.70	.64	.74	.32	.25	-.32	.62	.72	.70	—	.30	.59	.18	.43	.40	.45	.59	.00	.18
15. Verbal working memory	.59	.38	–.29	.42	.63	.51	.62	.49	.40	–.54	.66	.60	.66	.41	—	.49	.34	.38	.47	.47	.61	.00	.29
16. WASI matrices	.50	.21	–.28	.16	.57	.52	.60	.42	.33	–.44	.57	.67	.65	.65	.54	—	.58	.36	.45	.45	.72	.00	.27
17. Visual memory	.49	.16	–.26	.00	.49	.27	.42	.33	.49	–.34	.38	.48	.45	.37	.44	.64	—	.36	.36	.40	.39	.00	.19
18. Magazine recognition	.66	.29	–.30	.29	.70	.60	.72	.61	.48	–.32	.63	.69	.69	.55	.47	.46	.51	—	.66	.90	.50	.00	.32
19. Author recognition	.77	.47	–.42	.48	.70	.53	.68	.55	.55	–.52	.79	.68	.77	.50	.53	.51	.47	.71	—	.92	.67	.00	.33
20. Print experience composite	.77	.41	–.39	.41	.76	.61	.75	.63	.56	–.45	.77	.74	.79	.57	.54	.53	.53	.92	.92	—	.65	.00	.36
21. IQ	.72	.36	–.32	.37	.80	.66	.80	.60	.36	–.58	.93	.85	.93	.71	.70	.81	.53	.62	.77	.75	—	.39	.61
22. Age	.48	.30	–.19	.10	.58	.36	.51	.38	.47	–.25	.38	.59	.51	.47	.33	.33	.49	.48	.36	.45	.39	—	.75
23. Years of education	.65	.29	–.16	.21	.67	.52	.65	.57	.49	–.27	.56	.69	.65	.51	.52	.50	.53	.64	.58	.66	.61	.75	—

Note. For correlations involving spoonerism response time, $N = 41$; for all others, $N = 44$. Correlations of composite measures with their component tasks are boxed. PHID = pseudohomophone identification (Olson et al., 1994); WASI = *Wechsler Abbreviated Scales of Intelligence* (Psychological Corp., 1999). Below the diagonal are simple correlations among measures without adjustment for age. Above the diagonal are simple correlations of age-partialed scores (Variables 1–20 only). $|r| \geq .31$, $p < .05$; $|r| \geq .40$, $p < .01$; $|r| \geq .49$, $p < .001$; $|r| \geq .57$, $p < .0001$; $|r| \geq .63$, $p < .00001$.

correlated with measures of nonlinguistic mental capacity: WASI matrices (*r* = .60) and visual memory (*r* = .42).

Predicting Variation in Reading Comprehension: Testing the SVR

Gough and Tunmer's (1986) SVR states that reading comprehension is the sole product of listening comprehension and decoding skill. The most direct implementation possible of the SVR, given the tasks in our battery, predicts the reading comprehension composite from listening comprehension (speech sentence comprehension) and nonword reading (WJ-III Word Attack subtest, Form A; see Note 3). We use simultaneous regression to assess how well the SVR fits our data. Age is included as a covariate in each model.

Table 2 (below the diagonal) shows that listening comprehension (speech sentence comprehension) alone captures 55% of the variance in our reading comprehension composite measure. Even if age is first partialed from each measure, there remains 44% shared variance (see Table 2, above the diagonal). In Table 3, Model A shows the result of predicting the reading comprehension composite score from listening comprehension and nonword reading, with age included as a covariate. This model captures 76% of the variance in reading comprehension. Thus, the SVR provides a good account of the variation in reading comprehension in our data. As can be seen from the unique variance captured by each factor, listening comprehension and decoding ability make largely orthogonal contributions to reading comprehension (note the complete lack of correlation between the two predictors; see Table 2). The addition of word reading or pseudohomophone identification measures to Model A in Table 3 fails to improve prediction significantly, whereas nonword reading remains a significant predictor in either case.

The SVR ascribes all reading-specific variation to decoding skill alone. We wanted to know if any factors in addition to decoding played a significant role in predicting reading comprehension ability after listening comprehension ability was accounted for. Thus, we conducted an exhaustive search of linear models targeting the reading comprehension composite under the constraint that listening comprehension had to be included. We looked for models that captured as much variance as our implementation of the SVR. Only one model improved reliably on that of Table 3, Model A. As predicted by the LQH (Perfetti & Hart, 2002), vocabulary knowledge accounted for a substantial portion of unique variance in reading comprehension.

TABLE 3
Simultaneous Regression Models Assessing Prediction of the Reading Comprehension Composite

Predictor	Std. β	*t*	*p*	Unique R^2
Model A				
Speech sentence comprehension	.62	7.07	< .00001	.30
Nonword reading	.42	5.41	< .00001	.18
Age	.18	2.02	.05062	.02
Model B				
Speech sentence comprehension	.38	3.75	.00058	.07
Nonword reading	.29	3.68	.00071	.06
Vocabulary composite	.41	3.59	.00092	.06
Age	.10	1.21	.23220	.01

Note. Unique R^2 is the proportion of variance captured by a given variable after taking into account all other predictors in the model. Model A, multiple R^2 = .76. Model B, multiple R^2 = .82.

Role of Vocabulary Knowledge

As Table 2 indicates, our vocabulary composite (a combination of WASI Vocabulary and PPVT-R Vocabulary, both of which are administered orally) captured a large amount of the variance in our reading comprehension composite (71%). This is hardly a surprising result; not knowing the meanings of the words in a text is a major impediment to understanding it. Under the SVR, the contribution of word knowledge to reading comprehension should be entirely subsumed under our measure of general language comprehension capacity (speech sentence comprehension).

However, when the vocabulary composite is added to the SVR-based model of Table 3, Model A (76% of the variance captured), it adds another 6%, accounting for a total of 82% of the variance (see Table 3, Model B). Table 3 shows that the contribution of word knowledge to reading comprehension overlaps considerably with the contributions of decoding and listening comprehension, but, contrary to the predictions of the SVR, it is not wholly contained within them. Of exploratory models targeting reading comprehension with three or fewer factors, none captured as much variance as Model B of Table 3. Moreover, no skill-based model with more than three factors improved significantly on Model B. As for experience-based measures, neither print experience nor years of education added to the predictive power of Model B, $F(1, 38) = 1.44$, *ns*, and $F(1, 38) = 2.12$, *ns*, respectively.

Of course, it is to be expected that the vocabulary composite is well correlated with reading comprehension, but the SVR would not lead us to expect that it would capture significant unique variance beyond the contributions of listening comprehension and nonword reading. Note that the vocabulary composite was based on two purely oral tests of word knowledge, so its contribution to reading comprehension is unlikely to stem from the existence of words known to some participants only in written form or from a mismatch in the general linguistic knowledge needed to succeed on our reading comprehension and listening comprehension measures. However, to explore the latter possibility, we targeted our PIAT-R–derived measure of reading comprehension (print sentence comprehension), which is well matched to our listening comprehension measure (speech sentence comprehension), with a model parallel to that in Table 3, Model B. A Box-Cox power transformation was applied to the print sentence comprehension criterion to ameliorate skewness. This model captures an essentially identical portion of variance to Table 3, Model B (82%). Listening comprehension, nonword reading, and vocabulary composite measures are all reliable contributors, capturing 4%, 3%, and 7% of unique variance, respectively.

The lexical quality hypothesis (LQH), in conjunction with our conception of lexical representation and lexical access, led us to investigate the relative contribution of vocabulary knowledge to the comprehension of print and of speech. Based on those concerns, we predicted that vocabulary knowledge would be more strongly predictive of reading comprehension than of speech comprehension. We tested this prediction by examining the relative contribution of vocabulary to the prediction of each comprehension measure while taking the other into account. In each model, a Box-Cox power transformation was applied to both PIAT-R–derived comprehension measures.

Unsurprisingly, given Model B of Table 3, vocabulary predicts a large portion of unique variance in the print sentence comprehension measure of reading comprehension, as shown in Table 4, Model A. The complementary model in Table 4 (Model B) shows that vocabulary is not similarly predictive of speech comprehension. Of course, vocabulary and listening comprehension (speech sentence comprehension) are highly correlated (see Table 2), but the point of Table 4, Model B is that vocabulary makes no *unique* contribution to the prediction of listening comprehension, after taking into account the contribution of reading comprehension (and of age). The addition of nonword reading to either of the models in Table 4 improves prediction slightly in both cases, $F(1, 39) = 5.97$, $p < .05$, and $F(1, 39) = 7.72$, $p < .01$, respectively. Moreover, vocabulary remains a significant predictor in the model targeting reading comprehension, while accounting for a nonsignificant portion of variance in the model targeting listening comprehension.

The asymmetry in the predictive power of vocabulary with respect to comprehension in each modality is also relevant to another matter. It is possible that the strong unique contribution of vocabulary to the prediction of reading comprehension shown in Table 3, Model B is due to our vocabulary measure picking up on residual unexplained variance due to the reduced precision of the PIAT-R–derived comprehension measures (see Note 4). Recall that our print sentence comprehension and speech sentence comprehension measures are each based on one half of the materials in the 82-item PIAT-R sentence comprehension task. As the Sentence Comprehension subtest of the PIAT-R (Markwardt, 1998), from which our comprehension measures are derived, includes a carefully titrated range of vocabulary, from very familiar to very obscure, it is not unreasonable to suppose that the vocabulary tests tap word knowledge on which the two PIAT-R–derived measures differ. Based on our own data, the reliabilities of the two PIAT-R–derived measures are .90 and .87, respectively. On the other hand, the published reliabilities of the PPVT and WASI vocabulary measures are reported as .95 (Dunn & Dunn, 1997) and .94 (Psychological Corp., 1999), respectively. If the structure of measurement error were the explanation for the predictive power of vocabulary with respect to reading comprehension, as seen in Table 3, then we would expect approximate symmetry in the predictive power of vocabulary with respect to comprehension in each modality. As Table 4 shows, that prediction is clearly not supported.

Predicting Word Knowledge

Finally, we examined potential precursors to word knowledge. Two factors have some currency in the literature: print experience (e.g., Stanovich et al., 1995) and verbal working memory (e.g., Baddeley et al., 1998). Table 5, Model A shows that the joint contribution of these two factors to vocabulary was substantial, accounting for 72% of

TABLE 4
Simultaneous Regression Models Assessing Contribution of Vocabulary to Print and Speech Comprehension

Predictor	Std. β	*t*	*p*	Unique R^2
Model A				
Speech sentence comprehension	.26	2.25	.03032	.03
Vocabulary composite	.60	5.67	< .00001	.16
Age	.15	1.83	.07547	.02
Model B				
Print sentence comprehension	.52	2.48	.01755	.06
Vocabulary composite	.25	1.27	.20969	.02
Age	.05	0.38	.70778	.00

Note. In both models, a Box-Cox power transformation was applied to each comprehension measure. Model A predicts print sentence comprehension from vocabulary, while controlling the contributions of age and speech sentence comprehension, multiple $R^2 = .80$. Model B predicts speech sentence comprehension from vocabulary, while controlling the contributions of age and print sentence comprehension, multiple $R^2 = .60$.

the variance. Table 5, Model B shows that verbal working memory and print experience remained reliable predictors of vocabulary even when other measures of memory and experience (i.e., visual memory and years of education completed) were included in the model. Moreover, the additional measures in Model B failed to improve prediction beyond Model A, $F(1, 38) < 1$.

Discussion

The studies most nearly comparable to ours, in terms of the measures administered and the age of the participants, were carried out by Cunningham, Stanovich, and Wilson (1990), Lundquist (2004), and Ransby and Swanson (2003). The first two of these studies were based on college students, hence representing a narrower range of variation than that sampled in the present study. However, all of these studies attested to the continuing relevance of decoding differences among adult readers, finding a significant, though small contribution of decoding to reading comprehension and reading efficiency measures.

As to the role of vocabulary, Cunningham et al. (1990) reported that in a model targeting reading comprehension with measures of listening comprehension, decoding skill, and vocabulary, the last item accounted for a unique 6.5% of variance out of a total multiple R^2 of .58. Lundquist's (2004) findings also suggested that word knowledge plays a role in reading comprehension differences. He reported that a model predicting Nelson-Denny reading comprehension from Nelson-Denny vocabulary scores, verbal working memory (exactly the same listening span task that we used), and latencies to pronounce nonwords accounted for 28% of the variance in his sample of college students. However, the Lundquist study did not attempt to isolate the role of vocabulary from other measures of verbal ability and so cannot speak directly to the question whether vocabulary played an independent role over and above listening comprehension and decoding skill.

Ransby and Swanson (2003) focused on adult readers with childhood diagnoses of dyslexia, contrasting those individuals with age-matched and reading-level–matched controls. They reported that reader group alone predicted 36% of the variance in reading comprehension, but the contribution of the group contrast became nonsignificant when either decoding skill or (orally assessed) word knowledge were used as autoregressors. This would seem to indicate that both measures were possible contributors to variation in reading comprehension in their sample. Notably, a general test of language comprehension failed to fully obviate the contrast between individuals with reading disabilities and age-matched controls.

Finally, Baddeley, Logie, Nimmo-Smith, and Brereton (1985), in a study based on a sample of adults with much wider ranges of age and ability, reported that vocabulary was a reliable predictor of reading comprehension in a model that also included a verbal sentence span measure similar to ours, as well as a measure of nonverbal memory (counting span). They did not, however, take into account the contributions of listening comprehension or decoding skill to reading comprehension.

TABLE 5
Simultaneous Regression Models Assessing Prediction of the Vocabulary Composite

Predictor	Std. β	*t*	*p*	Unique R^2
Model A				
Verbal working memory	.31	3.07	.00379	.07
Print experience	.56	5.25	< .00001	.19
Age	.15	1.64	.10959	.02
Model B				
Verbal working memory	.31	2.94	.00552	.06
Print experience	.56	4.61	.00005	.15
Age	.15	1.14	.726152	.01
Education (years)	.05	0.32	.75118	.00
Visual memory	–.08	–0.77	.44445	.00

Note. Model A, multiple R^2 = .72. Model B, multiple R^2 = .73.

Decoding and the SVR

Our test battery included three measures of decoding skill. The nonword reading task is a relatively pure measure of rule-based decoding skill. The pseudohomophone identification task and the word reading task both have requirements that overlap significantly with nonword reading, but each also imposes unique task demands. Word reading allows the practiced reader to leverage memory-based mappings between print and meaning. Pseudohomophone identification, on the other hand, requires the reader to use rule-based decoding skills to arrive at a phonological representation and then map that representation to a known word. So, the *decoding* requirements of pseudohomophone identification and nonword reading are essentially the same, but word reading taps a different aspect of decoding skill.

As we noted in the Results section, the addition of either word reading or pseudohomophone identification measures to the model based on the SVR (Table 3, Model A) failed to improve the overall fit. However, several other studies have found that familiarity with specific orthographic–lexical (or –sublexical) mappings is an important component of decoding skill. In one such study, Waters, Seidenberg, and Bruck (1984) showed that beginning readers (primary school students) demonstrated a more robust orthographic regularity effect than did more experienced readers (college students). In other words, beginning readers are more affected than experienced readers by inconsistencies in orthography–phonology mappings. Presumably, younger readers rely more heavily on rule-based decoding principles and, consequently, suffer more when those principles fail them.

Furthermore, Greenberg, Ehri, and Perin (1997; see also Read & Ruyter, 1985) found that even adults whose reading skills were quite poor performed better than reading-level–matched children at reading atypically spelled words—a task that exercises memory-based decoding skill. Together, these findings suggest that adults rely more on memory-based mapping and less on analytic decoding routines than do younger readers. It is not clear whether the underpinnings of this trend lie in cognitive development or, perhaps, in differences in educational practices targeting younger versus older readers. Greenberg et al. also showed that adult poor readers showed deficits in nonword reading relative to reading-level–matched children. This is significant because rule-based decoding skill is particularly important for the acquisition of new vocabulary via print. Our data indicate that a nonword reading index of decoding skill accounts for variation in the reading comprehension of young adults, whereas word reading does not. Both the present findings and those of Greenberg et al. indicate that variation in rule-based decoding skill is an important antecedent of reading skill even among adults. Thus, less skilled adult readers are relatively deficient in precisely that aspect of decoding skill that should be most useful to them in supporting the acquisition of new words from print. Moreover, these facts help to substantiate Gough and Tunmer's (1986) choice of nonword reading as the preferred index of decoding skill.

Role of Vocabulary

The lexical quality hypothesis (LQH) states that comprehension depends on high-quality lexical representations (Perfetti & Hart, 2002). This leads to the prediction that vocabulary knowledge should play an important role in accounting for differences in reading comprehension. Our data indicate that vocabulary does make a contribution to reading comprehension over and above the variance captured by listening comprehension and decoding skill, as Table 3, Model B shows. This is consistent with the aforementioned findings of Cunningham et al. (1990) and Ransby and Swanson (2003). More important, the present work followed these previous studies in including well-matched listening comprehension and reading comprehension tasks.

Furthermore, our conception of the LQH, which we will expand upon in the next section, prompts us to surmise that top-down influences on comprehension (i.e., quality of lexical representations) are most important when bottom-up cues to meaning (provided by speech or print signals) are at their weakest. Hence, we predict an asymmetry in the contribution of word knowledge to the comprehension of print and speech as a consequence of two premises:

1. Mappings from print to lexicon are less practiced than those from speech to lexicon.
2. The print signal is inherently weaker than the speech signal, as it is devoid of such information as provided by co-articulation of speech sounds, prosody, nonlinguistic context, and speaker affect.

Our data support this prediction, as shown in Table 4.

Connectionist Model

What mechanism might be responsible for the observed asymmetrical influence of lexical quality? We adopt a connectionist perspective based on the framework first outlined by Seidenberg and McClelland (1989; see also Harm & Seidenberg, 1999, 2004; Joanisse & Seidenberg, 2003; Plaut & Shallice, 1993; Plaut, McClelland, Seidenberg, & Patterson, 1996). This model (summarized in Figure 1) treats spoken signals, written signals, and semantic representations as patterns of activation across banks of units. Each unit sends excitatory or inhibitory signals to the units it is connected to (as indicated by the arrows in the diagram). The strengths of these weighted connections are developed via a training process: The network is exposed to many examples of desirable behavior (e.g., activating an appropriate set of semantic features in conjunction with the phonological or orthographic features of a particular word), and small changes in the weights are made, which iteratively improve the model's ability to exhibit coherent behavior (Pearlmutter, 1989, 1995; Rumelhart, Hinton, & Williams, 1986; see Note 5). This training process is analogous to the individual's acquisition of linguistic knowledge through experience.

Two properties of this model are important for the issues at hand. First, the encoding of complex lexical properties is *distributed*: Many units are activated to encode the different properties a word has (orthographic, phonological, semantic, and syntactic). Second, some of the connections in the model are *recurrent*: The connections form loops, so that activation can cycle around repeatedly within as well as between some banks of units. These two properties, in conjunction with the training regimen, imply that features occurring together (in training or experience) will tend to reinforce each other. Therefore, when some features of a word become active (e.g., phonological features by way of speech input), then the network will tend to turn on other features associated with that word (e.g., its semantic features), ultimately leading to the activation of enough features for the word as a whole to be usefully accessible.

In such a connectionist model, lexical access can be visualized as movement over dimpled landscapes, like those depicted in Figure 2 (Harm & Seidenberg, 2004). Points on the landscape correspond to states of the model (which, in turn, are analogs of mental

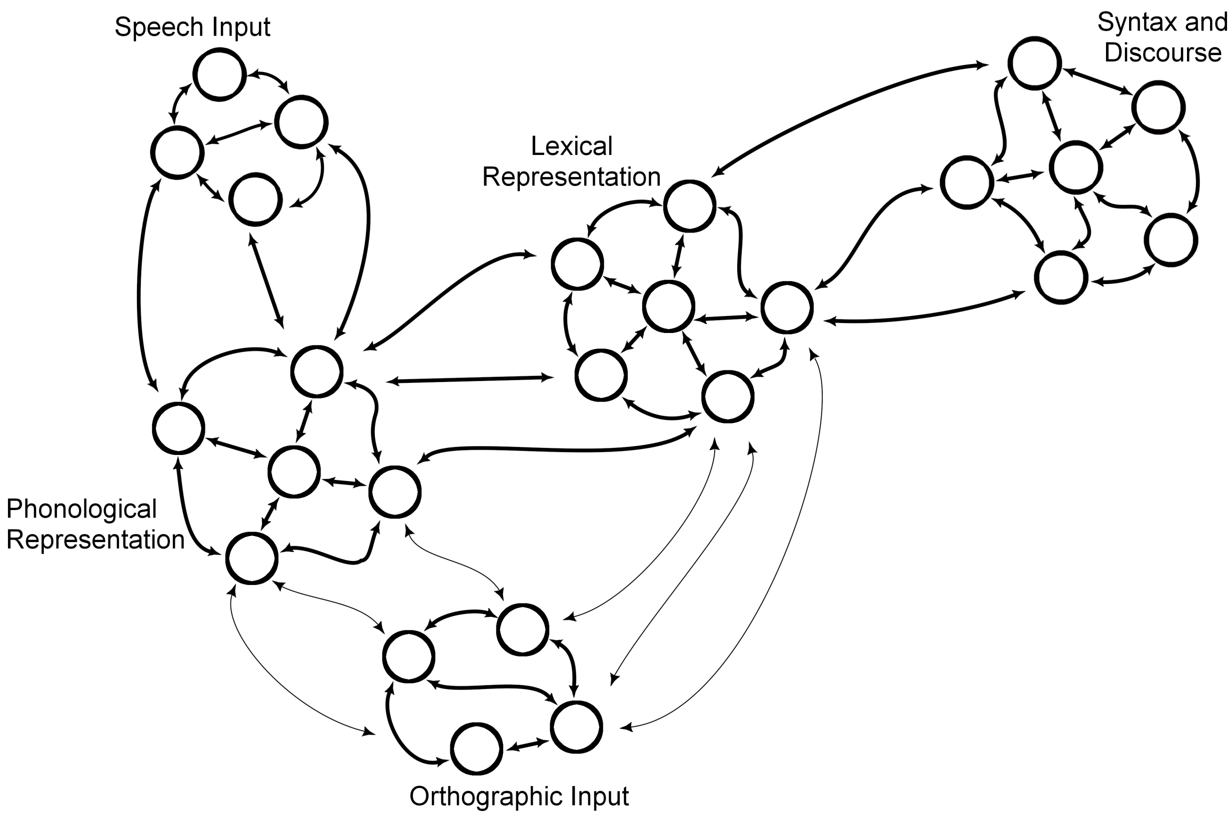

FIGURE 1. Activation-based model of orthographic, phonological, and lexical knowledge (see Seidenberg & McClelland, 1989).

states). The dimples, or basins, in the landscape correspond to word senses. Initially, when few of a word's features are active, the model is near the rim of a basin. Subsequently, when activation spreads from the initially activated features to other features of the word, we can think of the model state as sliding down the side of the basin and eventually coming to rest at the bottom. This bottom state corresponds to the network's interpretation of the word, given the representation at hand. We assume, as is standard in such models, that small-magnitude noise in the unit activations disturbs the process of gravitating into the basins, sometimes producing erroneous categorizations.

This type of system includes a straightforward mechanism for modeling both within- and between-subject variation in the quality of word knowledge. High-quality lexical representations are those with well-tuned connections among features, corresponding to deep basins with steep sides. So, within the lexicon of the individual depicted in Figure 2A, the right-hand basin corresponds to a better quality lexical representation than the left. Each individual has a landscape of basins, one for each of the word senses they know; thus, variation between individuals is modeled as contrast in the shapes of corresponding basins (e.g., the left-hand lexeme in reader 2A's lexicon is less well developed than the corresponding lexeme in reader 2B's lexicon). This model thus offers an explicit implementation of what Perfetti and Hart (2002) called the "functional identifiability" (p. 195) of words. Because people hear and use spoken language so extensively from an early age, the connections mediating the relationships between speech input, phonological representations, and semantic representations are well developed by adulthood. The speech modality thus strongly supports language interpretation. On the other hand, most young adults have less experience with print than with speech. There is also considerable variation in experience with print (Stanovich & Cunningham, 1992). Furthermore, print is a relatively impoverished signal vis-à-vis phonology and prosody. Stress, intonation, and co-articulation information are absent. Moreover, the phonological basis of an alphabetic writing system corresponds only approximately to the phonological representations formed on the basis of early experience with speech (Fowler, 1991), and there may be variation in how well an orthography maps to each individual's phonological representations due to dialectic variation (Charity, Scarborough, & Griffon, 2004).

These factors, we assume, are root causes of weak connections from orthographic input to phonology and from orthographic input to lexical representation. Because the activation of a word *form* is more tenuous via the print modality, the activation of that word's *meaning* will be weaker as well. Thus, top-down influences on lexical access—specifically, those aspects of word knowledge that encode syntactic and semantic information—will be more important to the comprehension of print than to the comprehension of speech (see Note 6).

Consider a reader with rich, well-tuned connections among the semantic and phonological features of words within the lexicon. Such a reader has an advantage in dealing with the weaker print signal compared to a reader whose lexical interconnections are impoverished. Strong mutually supporting connections between correlated features within the lexicon allow a word to be activated quickly, even given relatively poor cues from the orthographic channel. On the other hand, a reader whose connections among semantic and phonological features are not as rich or finely tuned will not be able to compensate as well for the weaker cues provided by the orthographic signal. Lexical access will be slower and more laborious. In the context of Figure 2, the system will gravitate more slowly toward the bottom of a basin (corresponding to longer reading times) and have a greater likelihood of being knocked out of the basin by noise (corresponding to arriving at an incorrect meaning, or failing to comprehend at all).

In contrast, differences in the quality of lexical representations will have less effect in the spoken modality, because the strength of the connections between speech and lexicon compensates for the weaknesses among semantic interconnections. Thus, the model provides an implementation of the notion that top-down cues (from lexical representation) are most important when bottom-up influences (linguistic perception derived from acoustic or visual signal) are at their weakest. We hasten to point out (as also observed by Perfetti & Hart, 2002) that even the lexicon of an individual with generally strong representations will certainly include many lexical representations that are *not* of high quality. The converse is also true. A person may have generally weak representations, but his or her lexicon will certainly include high-quality representations for many words. A marginally literate laborer may well have higher quality lexical representations for words that belong to the jargon of his trade than an attorney has for those same words.

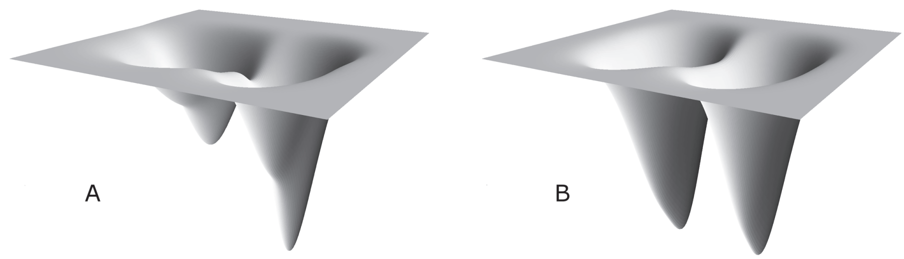

FIGURE 2. Energy landscapes depicting simplified, two-word lexicons. For Person A, the word sense on the left has a relatively low-quality encoding. Person B has better quality encoding for the left-hand word sense.

Consider the word *bough*. As a close synonym of *branch*, its meaning is likely within the common experience of most individuals, even though the former word form may not be as familiar as the latter (based on frequency of occurrence). We maintain that access to a word that is stored in lexical memory—especially a moderately low-frequency word with irregular spelling like *bough*—may be modulated by the strength of its semantic representation. This is because, if a person has a word well represented in his or her internal lexicon, he or she will require a less robust external stimulus, whether in speech or print, to activate that representation to a useful level. In the case of speech perception, the benefit of a strong semantic representation may be superfluous due to the already well-oiled mapping from speech to lexicon. In the print mode, however, the relatively impoverished nature of the signal, exacerbated in the case of a word form that is both low frequency and orthographically irregular, may receive a boost due to robustly encoded semantics that is especially helpful.

Perfetti and Hart (2002) noted the existence of a number of "threats to lexical quality" (p. 193). For example, the word *bough* is confusable because its spelling could potentially trigger another word. One possibility is *buff*, which has the same rhyme as *rough* and *tough*—words that share an orthographic coda with *bough* and are more frequent. Alternatively, an encounter with *bough* might trigger the homophonous *bow* (as in "a bow to the audience") or even its homograph *bow* (as in "bow tie"). This web of ambiguities poses additional challenges, and an individual who has a weak lexical representation for *bough* will be at a disadvantage in apprehending that word (i.e., activating the extant representation) relative to someone who has a more robust representation, and especially so in print.

Additional Support for the LQH

Empirical support for the hypothesis that vocabulary strength supports reading comprehension comes, most critically, from a series of training studies by Beck, McKeown, and their colleagues. The upshot of these studies is that children who received a regimen of vocabulary training (which included a significant oral component) showed gains in reading comprehension relative to control groups who had been matched with the experimental groups on reading comprehension prior to training (Beck, Perfetti, & McKeown, 1982; McKeown, Beck, Omanson, & Perfetti, 1983). Although it is certain that experience with print is an important force behind vocabulary development (Cunningham & Stanovich, 1991; Stanovich & Cunningham, 1992; West & Stanovich, 1991; West et al., 1993), the causal connections between word knowledge and reading are not simple. Other studies of Beck and colleagues show that vocabulary training is especially helpful if a print-based regimen is supplemented with significant interactive and verbal components (Beck & McKeown, 1983; Beck, McKeown, & Omanson, 1987). Our model predicts this enhancement through its emphasis on the importance of coordinated behavior throughout the whole language processing system (not just the print interfaces).

Evidence for deficient lexical–semantic representations in poor readers comes from a study by Nation and Snowling (1999), who examined semantic priming in lexical decision to speech stimuli. They found that young poor comprehenders (average age about 10–11 years) showed a weaker semantic priming effect than did good comprehenders who were matched for age, nonverbal IQ, and decoding skill. Specifically, good comprehenders showed priming for semantically related items regardless of whether they tended to co-occur in the language. Poor comprehenders, on the other hand, only showed priming for semantically related words when they were also linked through co-occurrence. It seems that for poor comprehenders, the source of "semantic" priming effects may lie in mere word association rather than true semantic relatedness. If so, this suggests that in general, poor readers' lexical–semantic representations tend to be weaker than those of better readers. In another demonstration, Perfetti and Hart (2002) showed that more and less skilled adult readers differed in the speed at which semantic information becomes available. They required participants to judge semantic relatedness of word pairs. In cases where confusability was introduced through homophony (e.g., *knight/evening* vs. *night/evening*), more skilled readers showed the effect of confusability at shorter latencies than less skilled readers. Thus, these two studies provided converging evidence for the notion that less skilled readers have generally lower quality lexical–semantic representations than more skilled readers do.

The LQH allows us to explicate connections between reader skill and oral language use. One prediction is that the ability to use oral language to express semantic content should correlate with reading ability. It is well known that the object naming abilities of young poor readers are often slower and less accurate than those of unimpaired readers (e.g., Denckla & Rudel, 1976). We recognize that at least some of this difficulty is attributable to a phonological deficit (Katz, 1986). However, the claim that *all* semantic errors in naming can be explained by a phonological limitation is less convincing (e.g., Jared & Seidenberg, 1991; but see Cantwell & Rubin, 1992; Katz, 1996). Nation, Marshall, and Snowling (2001) provided evidence supporting a link between the quality of lexical representations and the facility of spoken language production. They showed that for many poor readers, underlying semantic weaknesses may be the source of difficulty in object naming.

Finally, it is appropriate to acknowledge the limitations of the present study. First, we chose to use a sentence–picture matching task based on a subset of the PIAT-R Sentence Reading Comprehension subtest (Leach, Scarborough, & Rescorla, 2003). This contrasts with listening measures based on narrative passages (e.g., Cunningham, Stanovich, & Wilson, 1990; Ransby & Swanson, 2003). The use of narrative passages rather than individual sentences may capture some aspects of comprehension that were missed by our measure. However, these tasks are not without limitations of their own. Chief among them is poor reliability. Second, there are signs that some of our measures may have suffered from partial ceiling effects, as indicated by mean scores within 1.5 *SD* of the maximum possible. It is obviously desirable to use indices with sufficient scope to capture variability at both ends of the distribution. However, ensuring this is a difficult objective to meet when the target population has a wide range of variability, as was the case, by design, with the present study. In our ongoing research program, we will address these measurement issues, while providing further tests of the hypotheses put forward here.

Summary

Perfetti and Hart's (2002) lexical quality hypothesis (LQH) provides a framework for illuminating specific links among reader skill, oral language use, and word knowledge. Although the connections between comprehension in each modality, and the capacities that support comprehension, remain to be fully clarified, our data and other research discussed here has supported the view that a searching examination of the decoding and language of Gough and Tunmer's (1986) simple view of reading (SVR) is necessary to arrive at a better understanding of the cognitive underpinnings of reader skill. In particular, this study supports a corollary of the LQH suggesting that the role of word knowledge in reading comprehension is not merely an extension of its role in speech comprehension. We believe that a close examination of the connections between the capacities that support general language comprehension and reading will prove a fruitful avenue for the further elucidation of reader skill differences and their cognitive foundation.

Nevertheless, there is appreciable evidence suggesting that both decoding skill and word knowledge are worthy targets of remediation efforts directed toward adult unskilled readers. Furthermore, the significant explanatory force contributed by both components of Gough and Tunmer's (1986)

SVR (listening comprehension and decoding) suggests that both improvement in decoding and improvement in spoken language skills are valuable goals. Vocabulary knowledge seems to be doubly important. Its significance for the understanding of spoken language is obvious. However, the present study indicates that weakness in word knowledge may compound weaknesses in decoding skill so that readers with poorly developed lexical representations have a disproportionately hard time with printed word identification. This, together with the fact that word identification skill figures prominently in reading comprehension, suggests that efforts directed at vocabulary development might be an especially helpful adjunct to reading instruction for adult poor readers.

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AUTHORS' NOTES

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2. *A summary report of these data was presented at the Twelfth Annual Meeting of the Society for the Scientific Study of Reading, June 24–26, 2005, Toronto, Canada. This research was supported by NIH grant HD-40353 to Haskins Laboratories.*

NOTES

1. *All statistical procedures were carried out with the R statistical system, version 2.1 (R Development Core Team, 2004).*
2. *The print sentence comprehension and speech sentence comprehension measures reported here are both derived from the PIAT-R Reading Comprehension subtest. However, due to the nonstandard method of administering these tasks, grade-equivalent scores for these measures were calculated in the following way: The raw score, s, for each task was scaled according to the following formula:* (s^2+18). *This value was then entered into the reading comprehension column of Table G1 in Markwardt (1998). Caution should be used in interpreting these derived scores.*
3. *Gough and Tunmer (1986) and Hoover and Gough (1990) actually proposed a multiplicative model (R = DL), but Dreyer and Katz (1992) argued that the multiplicative model lacks a clear advantage over the corresponding additive model (R = D + L). A possible exception to this generalization arises in cases that approach the lower bound of nil reading achievement (Joshi & Aaron, 2000), but the reading levels of our participants, though deficient, are far from this region. In keeping with Dreyer and Katz, we focus on the additive version. We are motivated here by a desire to consider the contributions of additional factors besides D and L, and it is straightforward to incorporate these into an additive model.*
4. *We are grateful to an anonymous JLD reviewer for pointing out this alternative hypothesis and suggesting a method of assessing it.*
5. *This model is a close relative of the "triangle model" of lexical representation introduced by Seidenberg and McClelland (1989) and developed in many subsequent articles. The "triangle" of these models corresponds to the orthographic bank, the phonological bank, and the lexical representation bank, and the connections between them, in our model.*
6. *To be clear, we are not suggesting that top-down influences on lexical access do not occur in speech—only that such influences are more important to the recovery of lexical information presented by eye. In fact, considerable experimental work has confirmed the importance of top-down influences on lexical access in the comprehension of speech (e.g. Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979).*

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