ON THE BASES OF TWO SUBTYPES OF DEVELOPMENTAL DYSLEXIA*

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Abstract

This study examined whether there are different subtypes of developmental dyslexia. The subjects were 51 dyslexic children (reading below the 30th percentile in isolated word recognition), 51 age-matched normal readers, and 27 younger normal readers who scored in the same range as the dyslexics on word recognition. Using methods developed by Castles and Coltheart (1993), we identified two subgroups who fit the profiles commonly termed "surface" and "phonological" dyslexia. Surface subjects were relatively poorer in reading exception words compared to nonwords; phonological dyslexics showed the opposite pattern. However, most dyslexics were impaired on reading both exception words and nonwords compared to same-aged normal readers. Whereas the surface dyslexics' performance was very similar to that of younger normal readers, the phonological dyslexics' was not. The two dyslexic groups also exhibited a double dissociation on two validation tasks: surface subjects were impaired on a task involving orthographic knowledge but not one involving phonology; phonological dyslexics showed the opposite pattern. The data support the conclusion that there at least two distinct subtypes of developmental dyslexia. Although these patterns have been taken as evidence for the dual-route model, we provide an alternative account of them within the Seidenberg and McClelland (1989) connectionist model. The connectionist model accounts for why dyslexics tend to be impaired on both exception words and nonwords; it also suggests that the subtypes may arise from multiple underlying deficits. Performance on exception words and nonwords is not sufficient to identify the underlying basis of dyslexic behavior; rather, information about children's performance on other tasks and their remediation experiences must be taken into account as well.

On the Bases of Two Subtypes of Developmental Dyslexia

Developmental dyslexia is observed in children who fail to achieve normal reading skills, in contrast to the acquired forms of dyslexia that occur in premorbidly literate individuals as a consequence of brain disease or injury. This article describes a study of developmental dyslexia that addresses three main questions:

- Are there different subtypes of dyslexia, associated with distinct deficit profiles?

- Are these deficits associated with specific components of reading or do they reflect general delays in reading acquisition?

- What are the theoretical implications of these deficit patterns concerning models of visual word recognition?

The literature on acquired dyslexia contains a number of detailed case studies reporting various profiles of partial reading impairment (e.g., Beauvois & Derousne, 1981; Bub, Cancelliere, & Kertesz, 1985; Marshall & Newcombe, 1973; Shallice, Warrington, & McCarthy, 1983; Patterson, 1981). Most analyses of the acquired dyslexias assume some form of the dual-route model of reading (Marshall & Newcombe, 1973; Coltheart, 1978; Coltheart, Curtis, Atkins, & Haller, 1993; Morton & Patterson, 1980; Saffran, 1985); in fact, data concerning acquired dyslexia have played an important role in the development of the dual-route approach. This model proposes that skilled readers utilize two procedures in computing phonological codes from orthography, the so-called "lexical" and "sublexical" procedures for reading aloud. The lexical procedure involves using the orthographic representation of a word to retrieve an associated phonological representation stored in the mental lexicon. Because the lexicon only contains known words, this lookup procedure cannot be used in pronouncing nonwords. The sublexical procedure uses knowledge of the correspondences between orthographic and phonological units that occur in alphabetic writing systems to generate phonological representations. These correspondences are typically assumed to be represented in terms of grapheme-phoneme correspondence rules. The sublexical procedure produces correct output for words whose phonological codes are correctly specified by the rules (so-called "regular" words) and it is also used in pronouncing nonwords. The rules produce incorrect output for irregular ("exception") words such as HAVE and COLONEL, which must be pronounced by means of the lexical procedure.

One of the significant achievements of the dual-route approach is its account of the patterns of acquired dyslexia termed *surface* and *phonological* dyslexia. Surface dyslexic patients have relatively preserved regular word and nonword reading but are impaired in reading exception words (Bub et al., 1985; Coltheart et al., 1983; Marshall & Newcombe, 1973). Errors on exception words often take the form of regularizations, such as /izland/ for *island*. In the dual-route model, surface dyslexia results from damage to the lexical procedure. Reliance on the sublexical procedure results in a disproportionate number of errors on exception words. In contrast, patients with phonological dyslexia (Beauvois & Derouesne, 1979; Patterson, 1982; Shallice & Warrington, 1980) have relatively preserved word reading, with specific difficulty in pronouncing nonwords, which in the dual-route model is attributed to a damaged sublexical procedure. However, these patterns of impairment can also be explained within the connectionist modeling framework developed by Seidenberg and McClelland (1989) and recently extended by Plaut, McClelland, Seidenberg, and Patterson (in press). This model (see Figure1) has a single mechanism mapping from orthography to phonology which utilizes weighted connectionst between units encoding distributed representations, rather than pronunciation rules or lexical lookup. The model provides a natural account of so-called "fluent" and "dysfluent" forms of acquired surface dyslexia, as well as phonological dyslexia (Patterson et al., 1989; Plaut et al., in press). The same computational principles have also been used to explain the behaviors associated with deep dyslexia (Plaut & Shallice, 1993; see Plaut et al., in press, and Seidenberg, in press, for further discussion).

Insert Figure 1 About Here

The attempt to use a single theoretical framework (such as the dual-route model or the Seidenberg and McClelland connectionist model) to explain both normal and disordered processing represents a powerful approach to understanding cognitive phenomena. A natural question is whether such models can also account for patterns of developmental impairments. Several taxonomies of developmental dyslexic subtypes have been proposed over the years (e.g., Boder, 1973; Doehring, Trites, Patel & Fiedorowicz, 1981; Frith, 1985; Lovett, 1987; Mitterer, 1982; Seymour & MacGregor, 1984; Seymour, 1986). These taxonomies are often proposed on the basis of descriptions of individual differences in reading subskills among dyslexics (e.g., Boder, 1973; Doehring, et al., 1981; Lovett, 1987) rather than models of normal performance. Attempts to apply the dual-route model in the developmental domain represent a notable exception. Several studies have described dyslexic children with differing degrees of deficiency in reading nonwords and exception words, leading to the conclusion that there are developmental analogues of the acquired forms of dyslexia (Baddeley, Ellis, Miles, & Lewis, 1982; Castles and Coltheart, 1993; Coltheart, Masterson, Byng, Pryor, & Riddoch, 1983; Frith, 1985; Holmes, 1973; Marshall, 1984; Seymour & MacGregor, 1984; Temple & Marshall, 1983).

Temple and Marshall (1983), for example, described a 17-year old girl reading at about the 10-year-old level who could read simple, high frequency regular and exception words aloud well, but was very poor at reading nonwords and low frequency words. Her erroneous responses often contained actual words or components of words, suggesting that she was attempting to find a visual analogy to the target word or nonword, and she made very few regularization errors. Thus, she seemed to fit the "phonological dyslexic" pattern. Other case studies in which word reading was considerably more developed than nonword reading have been described by Campbell and Butterworth (1985), Sartori and Job (1982), Seymour and MacGregor (1984), Snowling, Stackhouse and Rack (1986), and Snowling and Hulme (1989).

With regard to developmental analogues of surface dyslexia, Coltheart et al. (1983) described a 17 year old who also read at about the 10-year-old level, but was much better at reading regular words aloud than exception words. This individual made frequent regularization errors. Other developmental surface dyslexic cases were described by Holmes (1973), Job, Sartori, Masterson, and Coltheart (1984), and Seymour (Seymour, 1986; Seymour & Evans, 1993; Seymour & and MacGregor, 1984). In one study (Goulandris & Snowling, 1991) an individual with both surface dyslexia and visual memory deficits was described. These studies suggest that two of the main patterns of acquired dyslexia can be observed in children without known histories of neuropathology. The cases provide further support for the dual-route model's assumptions about separate lexical and sublexical naming mechanisms (Coltheart, 1987).

In a recent group study, Castles and Coltheart (1993) presented additional evidence concerning the existence of developmental forms of surface and phonological dyslexia. They gave lists of regular and exception words and nonwords to 53 dyslexics (ages 7 to 14) and a group of 56 normal readers (ages 7 to 14). Ten cases were found in which exception word reading was low, but nonword reading was within the normal range for age (based on 90% confidence intervals), a "surface dyslexic" profile. In eight cases nonword reading was low whereas exception word reading was within the normal range, a "phonological dyslexic pattern". Three cases were noted in which both skills were within the normal range for age, and the remaining 32 cases were low on both exception words and nonwords, a "mixed" deficit pattern, relative to age. Castles and Coltheart used a regression methodology to identify individuals in this latter group who were relatively more impaired on one stimulus type. Six of the 32 cases with deficits on both nonwords and exception words showed a discrepancy in favor of nonwords (surface dyslexic profile), 21 showed a discrepancy in favor of exception words (phonological dyslexic profile), and 5 cases were equally low on both tasks. Castles and Coltheart concluded that the phonological and surface dyslexic profiles were actually quite common among the developmental dyslexic population, and that these profiles represented differences in the efficiency of the two processing routes.

Methodological, Empirical, and Theoretical Issues

Castles and Coltheart's (1993) findings complement earlier case studies and provide the strongest evidence to date for the conclusion that there are developmental forms of the types of impairments predicted by the dual-route model. However, this research raises several important methodological, empirical, and theoretical questions.

Are there distinct "surface" and "phonological" subtypes of developmental dyslexia? A large body of research supports the conclusion that dyslexia is commonly associated with deficits in the representation and processing of phonological information (see Wagner & Torgesen, 1987; and Rack, Snowling & Olson, 1992 for reviews). Among the tasks that these children perform poorly is nonword pronunciation, the task thought to be criterial for this type of deficit within the dual-route approach. Such children typically also show impairments on other tasks utilizing phonological information, such as phoneme deletion and rhyme judgment. Whether the pattern termed "surface" dyslexia constitutes a distinct subtype is less clear. Bryant and his colleagues (Bryant & Impey, 1986; Snowling, Bryant & Hulme, in press) have questioned the evidence that has been taken to support a distinct surface dyslexic subtype. Their argument hinges on the additional information provided by what are called "reading level control" subjects (Backman, Mamen, & Ferguson, 1984; Bryant & Goswami, 1984). These are younger normal subjects whose reading abilities are similar to the dyslexics'. Bryant and Impey (1986) compared Temple and Marshall's (1983) phonological dyslexic and Coltheart et al.'s (1983) surface dyslexic to 10-year-old normally progressing readers who scored at about the same level as the dyslexic cases on a word recognition test. Most of the characteristics of surface and phonological dyslexia were found to an even greater degree in one or more normal readers. For example, some of the normal readers made even more regularization errors than the surface dyslexic case and some made as many word substitution errors as the phonological dyslexic. The younger normal readers differed from the dyslexics in one important respect: none of them was as poor at nonword reading as either of the two dyslexic cases. Bryant and Impey's (1986) results suggest that the surface dyslexic case represented either a delayed but normal pattern, or a mild phonological deficit, whereas the phonological dyslexic case represented a specific phonological decoding deficiency that is rarely seen among normal readers.

Coltheart (1987) took issue with these conclusions by questioning some of the assumptions underlying the use of reading level controls. As he correctly points out, matching groups on reading level is not like matching them on chronological age or eye color. The choice as to how to assess reading ability for the purpose of equating two groups may influence the theoretical conclusions that can be drawn. For example, reading level controls are typically matched with dyslexics on single word decoding ability. Insofar as the dyslexics are similar to these control subjects in terms of word reading but not necessarily with respect to nonword pronunciation, this approach is biased toward identifying phonological dyslexics. The debate between these parties has continued over a several year period with little movement toward resolution (see Bryant & Goswami, 1988; Stanovich, Nathan, & Vala-Rossi, 1986).

Delay or deviance? A related question is whether the "surface" and "phonological" subtypes represent deviations from normal developmental patterns (Bryant & Impey, 1986; Ellis, 1985). The acquired forms of surface and phonological dyslexia are thought to be deviant both because they result from damage to the normal reading system and because they produce patterns that are not seen in skilled adult readers. The developmental cases are thought to derive from congenital anomalies that produce nonstandard patterns of acquisition. However, several outcomes can be imagined. One is that, as in the case of the acquired forms of dyslexia, the developmental forms result in patterns that are not observed in normal readers at any age or level of reading acquisition--a *deviant* developmental pattern. A second, less extreme, alternative is that a given subgroup might fail to acquire a particular subset of reading skills, a *specific deficit* pattern. A third possibility is that a subgroup might lag in a broad spectrum of reading skills and hence resemble younger normal readers, a *developmental delay* pattern. Again the issue turns on who the dyslexics are compared to and with respect to which aspects of reading. Coltheart and colleagues consider the use of reading level controls to be fraught with difficulties; however, comparing dyslexics only to age-matched controls (as in Coltheart & Castles, 1993) provides no information at all concerning the relationship between their behavior and that of younger normal readers.

Reliability. The next issue concerns the reliability of dyslexic subtypes, an issue that has been raised repeatedly in the developmental dyslexia literature (Bryant & Impey, 1986; Manis, et al., 1990; Seymour & MacGregor, 1986; Wilding, 1989). The surface and phonological dyslexics in studies such as Castles and Coltheart's were identified on the basis of statistical criteria applied to their performance on diagnostic tasks such as naming exception words and nonwords aloud. There is normal variation associated with performance of these tasks as well as measurement error. It is important, then, to establish the reliability of differences between individuals or subgroups. One approach is to use validation measures that are related to the hypothesized reading deficits but independent of the tasks used to classify the subjects. For example, children with a phonological deficit revealed by poor nonword reading can be tested on nonreading tasks involving phonological representations (e.g., rhyming, phoneme segmentation, etc.).

Incidence rate. There is also a question about the frequencies with which the putative dyslexic subtypes occur. There is considerable support for the view that nonword reading deficits, as well as deficits in non-reading tasks that utilize phonological skills, are quite common among developmental dyslexics (Bruck, 1990; 1992; Rack, et al., 1992; Seymour, 1986; Stanovich, 1988). In a review of the literature comparing groups of dyslexic children to reading-level-matched normal readers, Rack et al. (1992) concluded that most dyslexic children have phonological decoding skills that fall below the level one would expect based on their overall word recognition ability. Analyses of 432 subjects from their own data set indicated that dyslexics varied on a continuum from low to moderately high nonword reading skill relative to word reading skill. Their data suggest that extreme cases of both phonological and surface dyslexia may be found at the ends of the continuum, but that the modal pattern is a moderate nonword deficit. Castles and Coltheart (1993) also observed that phonological dyslexia was quite common in their sample (57% of their cases had phonological impairments when predicted from exception word reading scores). Although several case studies of developmental surface dyslexia have been described, the relative frequency of this pattern is difficult to estimate. Castles and Coltheart (1993) provided the clearest evidence. In their sample of 53 dyslexics, 20% had nonword reading within the normal range and exception word reading below the normal range, and an additional 12% had low scores on both tasks with a discrepancy suggestive of a surface pattern.

Theoretical implications. Finally, there are questions about the kinds of theories that can explain the patterns of acquired and developmental dyslexia. Castles and Coltheart's analysis of developmental dyslexia is part of the dual-route account of normal processing, acquisition, and the breakdowns associated with brain injury. According to this view, the two main subtypes of developmental dyslexia result from a failure to acquire a fully functioning lexical or sub-lexical mechanism. However, two additional issues need to be addressed. First, it is necessary to consider how other theories might account for the same data. Seidenberg and McClelland (1989), for example, have developed a connectionist model of lexical processing that aspires to account for facts about acquisition, skilled performance, and dyslexia. Patterson et al. (1989), Seidenberg (in press) and Plaut et al. (in press) describe applications of this model to acquired forms of dyslexia. Seidenberg and McClelland (1989) and Seidenberg (1993) discuss some implications of the model concerning developmental dyslexia. According to Seidenberg (1993), the model illustrates how a specific reading deficit can derive from more than one underlying cause. For example, nonword reading deficits are commonly observed in developmental dyslexia and are taken in the dual-route model as evidence for an impairment in using GPCs. However, the Seidenberg and McClelland model's performance in reading nonwords can be impaired by several very different types of anomalies; moreover, none of these involve GPCs. Such models have not as yet been applied to the specific "surface" and "phonological" patterns identified in developmental studies such as Castles and Coltheart's (1993), however.

It is also necessary to consider how these models account for other facts about dyslexia. The dual-route approach focuses on the comparison between levels of exception word and nonword naming. Identifying differences between the theories will require examining other aspects of dyslexic performance, however. For example, one important finding in the Castles and Coltheart study was that most children exhibited a mixed pattern in which they were poor on both nonword and exception word reading. The dual-route model can only explain this by assuming that most children actually have partial damage to both routes. Another model might provide a more complete account of dyslexia by explaining why this pattern predominates.

Overview of the Study

The study described below provides new data bearing on these issues. First, we used Castles and Coltheart's methods to determine relationships between word and nonword reading in dyslexia, with an eye towards observing the "surface" and "phonological" subtypes. Second, we administered the dyslexic subgroups that emerged from this analysis converging measures of phonological and orthographic processing to assess the reliability of the subgroups that had been identified. Third, we considered how the phenomena could be explained within both the dual-route model and the connectionist framework developed by Seidenberg and McClelland (1989).

We used the regression method of identifying subtypes developed by Castles and Coltheart (1993) in order to allow close comparisons with their study. Their procedure worked as follows. Normal and dyslexic groups were obtained that were matched approximately in age (the normal readers were slightly younger). First, they regressed nonword and exception word reading on age for the normal readers and found a strong linear relationship. Dyslexics were identified as having a deficit in nonword or exception word reading if they fell outside the 90% confidence interval for the regression line constructed for the normal reader group. Second, they assessed the extent to which subjects exhibited discrepancies between exception word and nonword reading. Here they regressed nonword reading on exception word reading, again found a significant linear relationship for the normal readers, and constructed 90% confidence intervals. Dyslexics who fell below the 90% confidence interval for nonword reading, given their level of exception word reading, were termed phonological dyslexics. Dyslexics who fell below the 90% confidence interval for exception word reading, given their level of nonword reading, were termed surface dyslexics. We used the same methods in the study reported below, with some minor modifications.

In order to address the external validity of the subtypes, we gave tasks that tapped orthographic skill and phonological awareness. Orthographic skill refers to knowledge of specific word spellings. While it is likely that readers and spellers integrate orthographic and phonological knowledge, a partially independent measure of orthographic knowledge can be obtained by requiring subjects to select the correct spelling of a word among pseudohomophones or homonyms (Olson, et. al, 1985). We adapted Olson et al's (1985) orthographic knowledge task for the present study. Phonological awareness refers to the ability to identify and manipulate the phonemic level of representation in speech. A minimal level of phonological awareness is thought to be necessary to begin learning spelling to sound relationships, and indeed skill in phonological awareness has been shown to be one of the strongest predictors of later reading skill (Bradley & Bryant, 1985; Goswami & Bryant, 1990) as well as one of the most consistent deficits in dyslexic children and adults (Bruck, 1992; 1994; Manis, Custodio, & Szeszulski, 1993; Rack, et al., 1992).

Our hypothesis was that if the subgroupings are valid, phonological dyslexics should perform relatively poorly on a phonological awareness task, perhaps reflecting a specific deficit in phonological processing, whereas surface dyslexics should be relatively poor on the orthographic task, reflecting possible deficits in knowledge of specific word spellings.

We also analyzed subjects' exception word reading errors in order to determine whether phonological and surface dyslexics showed the characteristic pattern of errors reported in previous case studies (e.g., Coltheart et al., 1983; Temple and Marshall, 1983). Phonological dyslexics would be expected to produce fewer regularization errors (such as *tongue* read as /tungu/ and*bureau* read as "burrow") than either surface dyslexics or same-aged normal readers, reflecting their poor command of spelling-sound correspondences.

Finally, we compared dyslexics to two groups of normal readers. The practical and conceptual limitations involved in using "reading level" and "chronological age" control groups have been thoroughly aired in the literature (Bryant & Goswami, 1988; Coltheart, 1987). From our perspective, the primary motivation for including comparisons to both same-aged and younger normal readers is simply that the question as to how dyslexics' performance compares to that of children learning to read normally is an important one to address. The two groups of normal readers do not function as "control" groups for the dyslexics in the usual sense but rather provide different points of comparison. We will therefore refer to comparisons to "younger normal" (YN) and "same-aged normal" (SN) subjects instead of reading level and chronological age "controls."

Coltheart's (1987) further objection to the use of reading level control groups is that reading involves multiple component skills and therefore the choice as to which aspects of reading ability to assess for the purpose of equating two groups may influence the theoretical conclusions that can be drawn. This observation is correct, but it does not follow that no comparisons between dyslexics and younger readers could be informative. Our assumption is that it is reasonable to compare dyslexics to younger readers whose word reading abilities are similar because word reading is a major determinant of reading ability and people are considered dyslexic if their word reading is impaired. Moreover, we are not restricted to global comparisons between groups; individual subject data will be presented and analyzed.

In summary, our study involves dyslexics, age-matched normal readers ("same-aged normal readers") and younger normal readers similar to the dyslexics in terms of word recognition skill. Unlike Bryant, our comparisons between groups do not assume that the younger normal and dyslexic readers are "equated" in terms of reading ability; unlike Coltheart, we assume the comparison between the younger normal and dyslexic readers is informative.

Experiment

Method

Subjects

The subjects were 51 dyslexic children, 51 same-age normal readers (SN comparison group), and 27 younger normal readers (YN comparison group). The dyslexic sample consisted of 14 females and 37 males. Twenty-one dyslexics were recruited from Special Education classes at public schools in the Los Angeles area, and 30 from a private school serving a learning disabled population. All of the dyslexics were receiving some degree of remedial instruction through their schools in reading, spelling or language arts, ranging from less than an hour a day of small-group instruction to several hours a day in the case of many of the private school children. The methods of reading instruction in use varied from phonics-based to sight-word-based, with most children receiving a mixture of the two approaches. Within the private school population, the children with the lowest reading grade levels (e.g., below the 4th grade level) tended to receive more of both types of instruction per day than the children with higher reading grade levels. To qualify for the study, the children had to fall within the age range 9 to 15, attain an IQ score of 85 or above on the Wechsler Intelligence Scale for Children-III (WISC-III; Wechsler, 1991), and score at or below the 30th percentile on the Word Identification subtest of the Woodcock Reading Mastery Test-Revised (Woodcock, 1987). In about half the cases, IQ scores were prorated from a short form of the WISC-III (Vocabulary, Block Design, Similarities and Picture Completion). Descriptive information on age, IQ, reading grade level and reading percentile are shown in Table 1. Dyslexics subjects had an average percentile score of 14.1 on the Woodcock Word Identification test. Their mean grade level score of 4.4 in Word Identification put them about 2.5 grades below their assigned grade level in reading.

Insert Table 1 about here

The 51 SN comparison subjects consisted of 16 females and 35 males recruited from the same public schools as the dyslexic children. Controls were obtained by sending permission letters to a random sample of students who were not currently enrolled in Special Education classes. To qualify for the study, the subjects had to fall within the age range 9 to 15, attain a prorated IQ score between 85 and 140 on the WISC-III, and score at or above the 40th percentile on the Word Identification subtest of the Woodcock. Descriptive information on age, IQ, word recognition grade level and reading percentile are also shown in Table 1. It can be seen that dyslexics were similar to the SN group in IQ and age.

The 27 children in the YN comparison group consisted of 9 females and 18 males selected in the same manner as the SN comparison group and from the same public schools. These subjects were all in either the 2nd or 3rd grade. Qualifying criteria for IQ and reading percentile scores were the same as those for the SN group. The subjects were selected on the basis of a score on the Woodcock Word Identification test (single word reading) that fell within the same range as the dyslexic children's scores. Descriptive information is given in Table 1. It can be seen that dyslexic children as a group did not differ from the YN comparison group in IQ or in Woodcock Word Identification grade level.

Materials and Procedure

Woodcock Word Identification test. This is a standardized test of isolated word reading. The composition of the test reflects the distribution of regular and exception words in the English language; it is about 80% regular words.

Nonword reading task. The nonwords were adapted from the list of 48 single-syllable stimuli used by Treiman, Goswami, & Bruck (1990), and included 16 additional single-syllable stimuli created for this experiment. The nonwords utilized a variety of spelling-sound correspondences (e.g., *baich, feap, lum, soag, peef, choub*), and included some items with no close word neighbors (e.g., *cleesh, phuve, skresp, stieb*). The items were printed in lowercase letters (Geneva font, 24 point). Children were asked to read the nonwords aloud as they were presented on cards one item at a time. All 64 items were administered to all subjects. The complete set of items is provided in the Appendix.

Exception word reading task. The 45 exception words were selected from a frequency-graduated list designed by Adams and Huggins (1985) to assess sight word vocabulary skills. Sample items on this list are: *ocean, busy, sword, island, rhythm, anchor, colonel, drought, bouquet, sergeant and heirloom.* The words were printed in list format on a single sheet of paper (lower case, Geneva, 24 point). Subjects read the words aloud as they moved through the list from top to bottom. Errors were recorded but responses were not timed. All 45 items were administered to all subjects. The complete set of items is provided in the Appendix.

Position analysis task. This task required subjects to listen to a nonword, repeat it aloud to ensure that they had encoded the nonword correctly, and then pronounce the sound that came immediately before or after a target sound pronounced by the experimenter. The experimenter always repeated the entire nonword before the subject responded. For example, the subject might hear /skwupt/ and repeat it, followed by the question: which sound comes before the /t/ in /skwupt/? There were four practice and 24 experimental items altogether. Half the items involved identifying the sound before and half after the target phoneme. The target phoneme was in the initial consonant cluster for six items (e.g., which sound comes before /r/ in /bremps/?) and in the final consonant cluster for 18 items (e.g., which sound comes after /n/ in /spland/?). Phonemes were always pronounced by the experimenter in phonemic form, rather than by means of a letter name, and subjects were encouraged to respond with phonemes rather than letter names. In some cases, it was easier for the subject to say the letter name and this was allowed. The experimenter did not acknowledge whether the response was correct or not on experimental trials. The position analysis task was thought to be a relatively direct test of phoneme segmentation and sequencing, as it minimized memory demands, reduced the contribution of articulation problems, and controlled for errors in phoneme perception. Because the stimuli were nonwords consisting of from four to six phonemes, it was considered unlikely that the subjects would adopt a mental spelling strategy. Evidence that many subjects adopt such a strategy has been reported for phoneme deletion tasks when the items are short, familiar words. The strategy was less common when the items were nonwords (Stuart, 1990).

Orthographic choice task. This task was adapted from a similar procedure used by Olson et al. (1985). Subjects viewed two printed letter strings arranged horizontally on the screen of an Apple Macintosh computer and decided which letter string was a correctly spelled word (e.g., *streat/street, blame/blaim, certain/surten*). The letters were printed in lowercase, Geneva font, 24 point. Subjects responded by pressing the left or right button on a response console with two 3/4 inch buttons located about 3 inches apart. Errors and reaction time were recorded for each item. There were 6 practice and 52 experimental items. No feedback was given on the experimental trials. Olson et al. (1985) originally intended this task to measure word-specific orthographic knowledge. However, the task cannot be considered an unconfounded measure of the ability to use this information, because it is possible that subjects' ability to decode the stimuli phonologically affects their responses. However, studies subsequent to Olson et al. (1985) have shown that the task of discriminating between pseudohomophones appears to be measuring something distinct from phonological decoding skill, as indicated by patterns of correlation with measures of word identification and print exposure (Cunningham & Stanovich, 1990; McBride, Manis, Seidenberg, Doi, & Custodio, 1993). The complete set of items is provided in the Appendix. Using a liberal definition of spelling-sound regularity (items are regular if there is more than one other word in the language with similar spelling and pronunciation), 18 of the items were exception words.

Children were tested individually in a single session that lasted from 35 to 55 minutes. The test session included the Woodcock Word Identification test, the nonword reading task, the exception word reading task, the position analysis task, the orthographic choice task, and if necessary the WISC-III subtests (Vocabulary, Similarities, Block Design and Picture Completion). The position analysis task was given to all of the subjects, with the exception of one person in the YN comparison group, due to experimenter error. The orthographic choice task was given to 36 dyslexics, 45 SN comparison subjects and all 27 YN comparison subjects. The discrepancy in numbers of subjects on this task was due to the fact that one group of subjects was tested in 1992 and another smaller group in 1993. The latter group was given many additional tasks not included in the present study, but was not given the orthographic choice task. The exception word reading error data were phonetically transcribed by the experimenters for 31 of the dyslexics and all 27 YN controls, again owing to changes in the procedures for the studies conducted in 1992 and 1993. Hence, error data could only be analyzed for this subset of the original sample. Errors were too infrequent to analyze for SN comparison.

Results

Means and standard deviations for the dyslexics as a group and the two comparison groups are shown in Table 1. As expected, differences between dyslexics and the SN group were highly significant for both nonword reading, t (100) = 10.53, and exception word reading, t (100) = 10.71. Dyslexics performed more poorly than the SN group on the position analysis task, t (100)= 5.00, and were less accurate, t (79) = 5.01, and slower, t (79) = 4.72, than the SN group on the orthographic choice task (all $p < .0001$). Differences between dyslexics and the YN comparison group were significant only for nonword reading, t (100) = 3.85, $p < .001$, although differences on position analysis approached significance ($p < .07$).

These results indicate that the dyslexic sample was impaired as a group relative to age-matched normal subjects on all the experimental tasks. In addition, as in many previous studies (e.g., Rack et al., 1992), the dyslexics were impaired in nonword reading relative to the YN comparison group.

Identification of "Pure" Surface and Phonological Dyslexics

A simple method for identifying relatively "pure" cases of surface and phonological dyslexia is to use cutoff scores based on the SN comparison group's mean and standard deviation. Using a cutoff score of one standard deviation below the SN group mean, 44 (86.3%) of the 51 dyslexics were low in nonword reading, 44 (86.3%) were low in exception word reading, and 39 (76.5%) were low in both nonword and exception word reading. Using the same cut-off, 5 subjects were low in nonword reading only and 5 subjects were low in exception word reading only. These subgroups are too small for meaningful statistical analyses.

These data indicate that the dyslexic group was made up primarily of individuals who were low in both nonword and exception word reading, relative to good readers of the same approximate age. However, using a stringent criterion (normal performance on one task and abnormal performance on the other) 10 subjects appeared to have a selective deficit on one task. This provides a conservative estimate (20% of the sample) of how many dyslexics might be considered to be "pure" phonological or surface dyslexic cases.

Identification of Dyslexics Subgroups Using the Regression Method

We used the Castles and Coltheart regression technique to identify dyslexics with larger than expected discrepancies between nonword and exception word reading, based on the linear relationship between nonword and exception word reading in the SN group. The method will be used to identify both "pure" cases and additional subjects who are below normal on both tasks, but exhibit a more extreme deficit on one task than the other.

There was a statistically reliable relationship between nonword and exception word reading for the SN group, $F(1, 49) = 14.72$, $p < .001$, with 23.1% of the variance in one task accounted for by variation in the other. Predicted values based on this linear relationship were used to identify those dyslexic subjects who were performing below expectations on one task relative to the other task. Ninety-five percent confidence intervals were established using the SN groups' scores for the regression of exception word reading on nonword reading scores (Figure 2) and the regression of nonword reading on exception word reading scores (Figure 3). The regression lines and confidence limits for the normal readers as well as plots of the dyslexics' scores are shown on these figures. This procedure was identical to that used by Castles and Coltheart except that they used a 90% confidence interval.

Insert Figures 2-3 About Here

The results indicate that 17 out of 51 cases were below the confidence limit in nonword reading based on the confidence intervals established for the SN group for the prediction of nonword reading by exception word reading (see Figure 2). These subjects can be said to have markedly lower nonword reading than would be expected among normally developing readers, given their level of exception word performance. These cases are represented by the filled circles in Figure 2. This was termed the phonological dyslexic profile by Castles and Coltheart.

Fifteen out of 51 cases were below the confidence limit in exception word reading relative to nonword reading using the confidence interval for the SN group (see Figure 3). These cases are represented as filled circles in Figure 3. This was termed the surface dyslexic profile by Castles and Coltheart. An additional five cases, represented by unfilled circles below the confidence limits in both Figures 2 and 3, could not be classified as either phonological or surface dyslexics because they met the criteria for both subgroups, using the SN reference group. In other words, they had equally severe deficits on both tasks, and hence did not fit unambiguously into one subgroup or the other.

Mean values for age, IQ, word identification grade level and all experimental tasks are shown in Table 2 for the phonological and surface dyslexic subgroups that emerged from these analyses. Mean scores for SN and YN comparison groups are also shown. The phonological and surface dyslexic subgroups were comparable in age, IQ, and word recognition grade level, and differed, as expected, on the defining measures (nonword and exception word reading). Both subgroups were statistically equivalent to the SN group in age and IQ, and performed at a lower level in both nonword and exception word reading (all p -values $< .001$). The phonological dyslexics did not differ statistically from the YN comparison group in IQ, word reading grade level or exception word reading, but read fewer nonwords correctly, $t(42) = 5.74$, $p < .0001$ (all t-tests are two-tailed). The surface dyslexics did not differ from the YN comparison group in IQ, word reading grade level or nonword reading, but read fewer exception words correctly, $t(42) = 2.34$, $p < .05$.

Insert Table 2 about here

Position Analysis And Orthographic Choice Tasks

Given that the subgroups were identified on the basis of extreme scores on one task relative to another, it is possible that some of these discrepancies resulted from error variance. Regression of these extreme scores back toward the means of both tasks would be expected with repeated measurement. Hence, it is important to determine whether the subgroups can be validated using different but conceptually related measures of the same skills.

Performance on the two validating tasks, position analysis and orthographic choice, is summarized in Table 2. The phonological dyslexic subgroup performed more poorly than the SN group on the position analysis task t (19)=4.88, $p < .001$, and on the orthographic choice task (for accuracy: t (56) = 2.24, $p < .05$; for latency: t (56) = 3.00, $p < .005$). The surface dyslexics performed more poorly on the orthographic choice task (for accuracy:t (53) = 5.31, $p < .001$; and for latency: t (9.5) = 2.64, $p < .05$) but did not differ reliably from the SN subjects on the position analysis task. The phonological dyslexics scored reliably lower than the YN comparison group on the position analysis task, t (41)= 3.27, $p < .01$., but better on the orthographic choice task, with fewer errors,t (38) = 2.37, $p < .05$ and faster responses, t (38) = 2.48, $p < .025$. Compared to the surface dyslexics, the phonological dyslexics made more errors on the position analysis task, t (30) = 2.49, $p < .025$, and fewer errors on the orthographic choice task, t (30) = 3.65, $p < .01$. The two subgroups did not differ in orthographic choice latency. The surface dyslexics did not differ significantly from the YN comparison group on position analysis or orthographic choice error rate or latency.

Exception Word Naming Errors

Further exploration of the validity and reliability of the subgroup assignments was conducted by examining exception word naming errors. Naming errors were divided into four mutually exclusive categories: (a) phonologically appropriate word responses (e.g., *bureau* read as "burrow" and*whom* read as "womb"); (b) phonologically appropriate nonword responses (e.g., *tongue* read as /tungu/ and *whom* read as /wam/); (c) phonologically inappropriate word responses (*tongue* read as "tug" and *anchor* read as "ancient"); and phonologically inappropriate nonword responses (e.g., *echo* read as / etho/ and *encore* read as /ekor/). To be classified as phonologically appropriate, the response had to contain pronunciations of each spelling unit that were present in at least one English word, excluding proper names. For example, /foren/, /foran/ and /forin/ were all scored as appropriate responses to *foreign*, given the different pronunciations *ei* receives in English (e.g., *receive, ceiling, reign ,weight*, and*height*.). This is a liberal scoring criterion, as it allows some pronunciations that would seem inappropriate to most fluent readers given the orthographic context of the word. However, these pronunciations are systematic and might be less inappropriate for children still learning to read.

Phonological dyslexics, surface dyslexics and the YN comparison group made numerous pronunciation errors. The number of errors ranged from a low of 10 to a high of 38 per subject out of a total of 45 items. Word naming error data were available for all of the YN group (n=27) but for only a subset of the dyslexics (13 phonological and 9 surface dyslexics). SN controls made too few errors for analysis. The proportion of errors in each category is shown for each group in Table 3.

Insert Table 3 about here

Phonological dyslexics made fewer phonologically appropriate nonword responses than surface dyslexics, t (20) = 2.69, $p < .05$, but did not differ from the YN comparison group. In addition, phonological dyslexics made more phonologically inappropriate word responses than both surface dyslexics, t (20) = 1.95, $p < .05$, and the YN group, t (38) = 2.19, $p < .05$. Surface dyslexics and the YN comparison group did not differ reliably on any of the error dimensions.

In summary, the results for both the validating tasks and the error analyses indicate that phonological dyslexics have phonological difficulties that are greater than would be expected based on their level of word reading ability, whereas surface dyslexics do not differ in any fundamental way from younger normal readers with the same overall word reading ability.

Comparison of Dyslexic Subgroups to YN Comparison Group

The above analyses used the same-aged normal readers' performance to identify subtypes of dyslexics. This analysis tells us something about how the dyslexics' performance differed from good readers of the same age. The following analyses consider how the dyslexics' performance compared to that of the younger normal readers. The basic question to be addressed is the extent to which the dyslexics' performance resembled that of younger children learning to read at the normal rate. The regression analyses described above for the SN group and the dyslexics were repeated using regression equations for the YN comparison group. As was the case with the SN group, exception word and nonword reading showed a strong linear relationship, F (1, 25) = 23.18, $p < .0001$, with 48.1% of the variance in one task accounted for by the other (see Figures 4 and 5). Compared to the SN group, the YN group showed relatively low exception word reading at a given level of nonword reading skill. The regression lines 95% confidence intervals for nonword reading predicted from exception word reading and for exception word reading predicted from nonword reading are shown in Figures 4 and 5, along with the dyslexics' actual scores. Cases who were identified as surface or phonological dyslexics in the SN group analysis are darkened in.

Insert Figures 4-5 About Here

It is apparent from these figures that there was far more overlap between the surface dyslexic subjects and the YN comparison group than was the case for phonological dyslexics. Twelve of the 17 phonological cases identified in the regression analysis for the SN group (represented by the filled circles in Figure 8) fell below the confidence limit for the YN group. In contrast, only one of the 15 surface dyslexic cases identified in the SN group regression analyses (represented by the filled circles in Figure 9) fell below the confidence limit for the YN group. Put another way, most dyslexics with the surface dyslexic profile scored within the range of the YN comparison group on both nonword and exception word reading, whereas most dyslexics with the phonological deficit profile fell below the YN comparison group in nonword reading. Note that all five of the "mixed" cases identified in the SN group analysis (see Figure 3) fell within the confidence limits for the YN comparison group in both Figures 4 and 5.

DISCUSSION

The results of this study replicate Castles and Coltheart's (1993) finding that some developmental dyslexics exhibit significant discrepancies between nonword and exception word reading. We found 10 cases out of 51 (19.6%) with a relatively "pure" form of dyslexia, i..e., a deficit on one task and performance within the normal range on the other. At the same time, it is important to point out that the dyslexic sample as a whole tended to be impaired on both exception words and nonwords. Using the one standard deviation cutoff, we found that 76.5% of our sample was impaired on both tasks relative to the SN group and only 3.9% were within the normal range on both tasks. Reanalyzing Castles and Coltheart's (1993) data using the same criteria used in our study, we found that 75.6% of their dyslexics were low in nonword reading, 77.4% were low in exception word reading, 60.4% were low on both tasks and 7.5% were within the normal range on both tasks. Eight subjects were specifically low in nonword reading, and nine were specifically low in exception word reading. These figures indicate that the two samples were roughly comparable in terms of the distribution of reading subtypes, although the proportion of individuals with relatively "pure" deficits was somewhat higher in Castles and Coltheart's (1993) sample (32% vs. 20% for our sample).

In our sample, an additional 32 cases, out of the total of 51, were found to have larger than expected discrepancies between exception and nonword reading using the regression procedure. This analysis includes subjects who were impaired on both tasks compared to the SN subjects. Because our study used a 95% confidence interval and Castles and Coltheart used a 90% confidence interval, we reanalyzed their data using the 95% confidence interval. Using the appropriate SN comparison group regression equations generated from their data, the number of dyslexics showing low nonword reading relative to exception word reading was higher in their sample (54.7%) than in ours (33.3%). The number showing low exception word reading relative to nonword reading was similar (26.4% for Castles and Coltheart's data, 29.4% for our data). Taken together, the two studies indicate that the majority of the dyslexic sample shows larger than expected discrepancies between nonword and exception word reading, based on the regression method, although a sizeable number in both samples had the opposite (surface dyslexic) pattern or relatively equal deficits on both tasks.

The minor differences between the results of the two studies may be attributable to differences between subject samples Castle and Coltheart's dyslexics showed a lower correlation between exception word and nonword reading (*r* = .11) than observed in our dyslexic sample (*r* = .36) and in the normal reader samples in both studies (*r* = .56 for Castles and Coltheart's SN group; *r* = .48 for our SN group and *r*= .69 for our YN group). The lower correlation fits with the observation that Castles and Coltheart's sample contained more individuals with extreme discrepancies between nonword and exception word reading than were present in our sample. Whether such a low correlation between exception word and nonword reading is typical of dyslexic samples in general remains to be seen. We know of no published data that would help decide this issue at present.

The results also bear on the question of whether the dissociations between nonword and exception word reading found in some dyslexics represent deviations from the norm, specific developmental delays in particular subskills, or general developmental delays in word reading. Our results revealed that the phonological dyslexic profile overlapped far less than did the surface dyslexic profile with the YN group. Twelve of the 17 phonological dyslexics showed lower nonword reading than the YN group, when predicted from exception word scores. Only one of the 15 surface dyslexics showed lower exception word reading than the YN group, predicting from nonword scores. These data suggest that the phonological dyslexic profile represents a specific deficit in phonological processing, whereas the surface dyslexic profile represents a more general delay in word recognition. Bruck's (1990, 1992) data on adults with childhood diagnoses of dyslexia are consistent with this hypothesis. She found several cases in which the individual eventually developed near normal levels of word reading but remained below the fourth grade level in nonword reading and phonological awareness. This finding suggests that individuals with severe phonological deficits in childhood may never develop normal levels of phonological skill. In the same vein, Manis, et al. (1993) found that dyslexic children made greater advances over a two-year period on a standardized word reading measure than they did on measures of nonword reading and phonological awareness, suggesting that the phonological deficit pattern is harder to compensate for or harder to remediate than the surface dyslexic pattern.

We cannot argue that all cases of surface dyslexia represent a general delay in word recognition, as one of our subjects and two of Castles and Coltheart's (based on inspection of percent correct scores) showed discrepancies in favor of nonword reading that were greater than any found in our YN comparison group. Such rare cases need to be examined in more detail in order to determine whether they differ reliably from other subjects.

The results of the phonological awareness and orthographic choice tasks, and the exception word reading errors, validate the division of the dyslexic sample into these subgroups. Phonological dyslexics had more difficulty analyzing the phonemic structure of spoken nonwords than either surface dyslexics or the YN group, yet they were better at discriminating between sound-alike words and nonwords based on their orthography than either of the other groups. In the analyses of the exception word naming errors, phonological dyslexics were less likely than surface dyslexics to produce phonologically appropriate nonword responses and more likely to produce phonologically inappropriate word responses (visual approximations). Phonological dyslexics produced more visual approximation responses than the YN group as well. Most striking was the finding that the surface dyslexics' performance did not differ in any important ways from the YN comparison group.

The pattern of results points to a double dissociation between the phonological and surface dyslexic subgroups identified in this study. Phonological dyslexics have low levels of phonological skill, given their level of word recognition and orthographic knowledge, whereas surface dyslexics have low levels of orthographic knowledge relative to their level of phonological skill. This finding is consistent with a hypothesis that phonological and surface dyslexia derive from different underlying deficits. Phonological dyslexics are relatively more impaired at the phonological processing skills necessary for reading development and surface dyslexics are relatively more impaired at using orthographic information. Surface dyslexics appear to be more generally impaired in component word reading skills (including use of both orthographic and phonological knowledge); as a result their performance is on par with younger normal readers matched in overall word recognition skill.

In summary, these data suggest that the surface-phonological distinction has descriptive utility as a way of differentiating two categories of dyslexic children. The methods introduced by Castles and Coltheart provide useful tools for exploring important individual differences among dyslexic readers when supplemented with other measures of cognitive processes in reading and comparisons to younger normal readers. We now turn to the implications of these findings concerning models of word recognition.

Implications Concerning Models of Word Recognition and Reading Acquisition

Insofar as our study replicated the basic results reported by Castles and Coltheart, it can also be taken as supporting their basic conclusions. As they suggested, the two dyslexic subtypes can be understood in terms of damage to the two main routes in the dual route model. According to this view, learning the sublexical pronunciation rules is a separate process from learning word-specific pronunciations; hence a dyslexic could be better or worse than normal readers in using one pronunciation mechanism compared to the other. A particularly unfortunate child might be impaired in using both mechanisms, resulting in poorer performance on both exception words and nonwords compared to controls. Our data are compatible with this view as long as attention focuses only on the dissociations between exception word and nonword reading. However, the study provides considerable additional information that requires explanation. Two aspects of the data stand out: the fact that most subjects were impaired on both exceptions and nonwords, and the finding that whereas the surface dyslexic subjects looked like younger normal readers, the phonological dyslexic subjects did not. Thus, the two subtypes appeared to be associated with different developmental sequences.

As we have noted, most of the dyslexics did not exhibit the clean dissociations between exception word and nonword naming that would be expected from developmental anomalies that cause individual routes to develop abnormally. The dual-route model does not provide any basis for predicting that most dyslexics will be impaired on both types of stimuli, but it could be made compatible with this fact by introducing additional assumptions. For example, there could be a neurophysiological explanation for why both routes tend to be partially impaired, or it could be that the full development of each route is somehow dependent on the other. Similarly, the dual-route model would not predict that the surface dyslexic subgroup would be more similar to younger normal readers than the phonological dyslexic subgroup. Again, however, nothing precludes introducing additional assumptions in order to accommodate these results. For example, one could compare the dyslexics to different younger normal readers. We compared them to younger subjects who performed at a similar level on a word recognition test; this may tend to increase the similarity between the younger normal subjects and the surface dyslexics. As we have noted, the reason for comparing groups that perform similarly on word recognition is simply the relevance of this task to reading. Other comparisons could be considered, however.[1]

An alternative approach is to attempt to explain this range of facts in terms of existing principles concerning knowledge representation, learning, and processing. With that in mind we turn to the model developed by Seidenberg and McClelland (1989; hereafter SM89; Plaut, McClelland, Seidenberg, & Patterson, in press, describe more recent versions of this model). In their "connectionist" or "parallel distributed processing" model (see Figure 1), lexical information is represented by patterns of activation over units encoding distributed representations of orthography, phonology, and semantics. Processing involves computing one code (e.g., phonology) from another (e.g., orthography or semantics). The characteristics of these computations are determined by the settings of the weights on connections between units. Learning involves adjusting the weights. In the simulation model, this is accomplished by using a learning algorithm such as simple backpropagation (as in SM89) or backpropagation through time (as in Plaut et al.'s, in press, more recent simulations).

The dual-route model requires two procedures for computing from orthography to phonology (lexical and sublexical) because of the assumption that spelling-sound knowledge is represented in terms of pronunciation rules. These mechanisms are then invoked in explaining the patterns of dyslexic impairment. The Seidenberg and McClelland model uses a different form of representing this knowledge, allowing a single mechanism mapping from orthography to phonology to generate correct output for all types of letter strings--"rule-governed" words such as GAVE, exceptions such as HAVE, and nonwords such as MAVE. The learning algorithm picks up on the systematic aspects of the correspondences between spelling and pronunciation but is also able to encode the exceptions to these patterns. The model uses a single set of weights to generate pronunciations, rather than pronunciation rules for regular words and lexical lookup for exceptions.

One of the features of the SM89 approach is that it correctly accounts for data concerning the effects of frequency and consistency of spelling-sound correspondences. Whereas the dual-route model is based on the dichotomy between rule-governed words and exceptions, in the connectionist model there is a continuum of spelling-sound consistency. The rule-governed items and exceptions are at opposites ends of this continuum; however, the model also correctly predicts the effects associated with words that exhibit intermediate degrees of consistency (e.g, Glushko, 1979; Jared & Seidenberg, 1991). These effects are a direct consequence of using a single set of weights to encode both "rule-governed" items and exceptions. Although the weights are set on the basis of exposure to a set of words, they can also be used in pronouncing nonwords. The Seidenberg and McClelland (1989) model generated correct pronunciations for simple nonwords such as MAVE and NUST, but mispronounced difficult nonwords such as FAIJE and JINJE. The Plaut et al. (in press) model achieved much more accurate nonword pronunciation by using an improved phonological representation.

Given that the model accounts for a broad range of phenomena concerning the performance of normal adult readers, it is reasonable to consider whether it can account for facts about developmental dyslexia. However, another consequence of using the same set of weights to pronounce both regular and exception words and nonwords is that the model cannot account for the "surface" and "phonological" patterns in terms of damage to independent lexical and sublexical naming mechanisms. The question then is whether the model can provide alternative explanations for them. One way to view developmental dyslexia is in terms of the kinds of anomalies that could cause the system illustrated in Figure 1 to fail to develop normally. Seidenberg and McClelland (1989) and Seidenberg (1992, 1993) discussed several factors that could affect the orthographic-phonological computation in particular.

First, there could be an impairment in the ability to learn, i.e., in the procedure used to set the weights. There is evidence that reading impairment is sometimes secondary to a learning impairment (Morrison, 1984). However, the forms of dyslexia under consideration here are thought to derive from more specific impairments in the reading process or in the use of spoken language. Second, there could be impairments in visual perception resulting in impaired input to the reading system. The idea that visual perceptual impairments underlie at least some cases of dyslexia has a long history (Orton, 1937; Vellutino, 1979) and recently has undergone a revival because of new evidence concerning possible deficits in the magnocellular visual channel (Livingstone, Rosen, Drislane & Galaburda, 1991). The effects of a visual perceptual deficit can be simulated within the SM89 model; see Seidenberg (1992) who described the effects of degrading the orthographic representations on the acquisition of spelling-sound knowledge. However, the extent to which dyslexia is associated with visual perceptual deficits remains unclear, and most recent accounts of dyslexia have implicated linguistic factors such as phonological processing and lexical retrieval as causes of the reading problems (Bruck, 1992; Goswami & Bryant, 1990; Rack, et al., 1992; Stanovich, 1988; Wagner & Torgesen, 1987).

Third, impairments in the representation or use of phonological knowledge would also limit the model's capacity to master orthographic-phonological correspondences. Phonological impairments could be realized in several ways. For example, the model might be configured with phonological units that allow only a relatively coarse representation of phonemic segments; or it might be provided with intact phonological representations but trained using phonological patterns that are degraded, as a way of capturing effects of auditory perceptual deficits. Finally, there could be what Seidenberg and McClelland (1989) termed a "resource" limitation. The hidden layer of units in the model plays a critical role in its ability to encode the quasi-regular pronunciation rules of English. Performance of the model depends on having enough of these units. Seidenberg and McClelland (1989) discussed the results of a simulation in which the model was configured with half as many hidden units as normal. The model was still able to learn, but showed poor nonword reading, exaggerated frequency effects, and was unable to master many of the exception words. These last two impairments are potentially relevant to understanding phonological and surface dyslexia.

Phonological Dyslexia In A Model Without Pronunciation Rules

Anomalies in the representation of phonological information are one aspect of the phonological deficits hypothesized by Liberman and Shankweiler (1985) and others (Bruck, 1992; Stanovich, 1988; Wagner & Torgesen, 1987) to be a major cause of dyslexia. This account suggests that as a consequence of impairments in speech perception, speech production, or some other aspect of phonological processing, the child fails to develop complete and precise phonemic representations during the acquisition of spoken language. Learning to read involves learning how the written and spoken forms of language relate to each other, among other tasks. In an alphabetic orthography, such as the one used for English, graphemic symbols largely correspond to phonemic segments. Learning the mappings between these codes is thought to be difficult when the phonemic segments are not clearly represented.

Using degraded phonological representations in the SM89 model to simulate phonological processing problems has specific effects on learning: it impairs performance on nonwords more than on words. One reason for this is because nonword generalization is a more difficult task than merely producing the pronunciations of words in the training set. The model has not been exposed to the nonwords before and must piece together their pronunciations on the basis of exposure to other items. In a sense, the model provides a computational realization of the concept of pronouncing nonwords "by analogy" to known words (Glushko, 1979). With moderately impaired phonological representations, the model will still be able to learn the pronunciations of the words on which it is trained, but nonword performance will suffer. One way of viewing the system that Seidenberg and McClelland (1989) actually implemented is that it illustrates these effects. The model employed a phonological representation (Wickelphones) that was only able to represent some general aspects of the structure of spoken words. In particular, the Wickelphonology employed articulatory features associated with phonemes but not an explicit phonemic level of representation. This phonological representation was rich enough to allow the model to learn the pronunciations of the words in the training corpus and generate plausible pronunciations for simple nonwords. However, the limitations of this representation became apparent from the model's performance on difficult nonwords such as FAIJE. Thus, the model inadvertently illustrated that a "deficit" in phonological representation has a disproportionate effect on nonwords. Plaut and McClelland (1993), Plaut et al. (in press), and Harm, Altmann, and Seidenberg

(1994) describe SM89-type models that utilize improved phonological representations. The principal change in the representations used in these simulations involved introducing an explicit phonemic level. These models again learn the training set with a high degree of accuracy; however, they also exhibit much improved performance on nonword generalization.

These simulations suggest a connection between impaired phonological representations and the deficits in nonword pronunciation that are the signature feature of the phonological dyslexic subtype. In this way the Figure 1 model provides an account of phonological dyslexia that does not involve the spelling-sound correspondence rules that are the source of this impairment in the dual-route model. On our view, the pattern derives from an impairment in phonological representation, which affects the single orthography to phonology conversion mechanism that underlies both words and nonwords. The computational properties of this mechanism explain why the impairment tends to have a greater impact on nonwords than on words.[2]

Aside from providing an alternative hypothesis concerning phonological dyslexia, does this analysis add anything to understanding the phenomenon? Both the dual route and the SM89 model can explain why nonword naming is impaired. As we have suggested, it is necessary to look at more detailed aspects of the dyslexics' performance in order to distinguish between the theories. Consider first the fact that developmental phonological dyslexics tend to be impaired in reading exception words as well as nonwords. We have posited an impairment in phonological representation that affects the acquisition of orthographic-phonological correspondences. In the SM89 model, this mechanism is not specific to nonwords; it is also used in reading regular and exception words. Hence the model predicts that with a sufficiently severe impairment these items will be affected as well. The extent to which different types of items are vulnerable to this type of impairment is predicted by the model's performance on them in the normal simulation. Like subjects, the normal model had the most difficulty with nonword pronunciation, some difficulty with exception words, and little difficulty with regular words. A relatively mild phonological deficit will have the biggest impact on nonwords, with little effect on regular or exception words (as in SM89). More severe phonological impairments will also affect exceptions and finally regular words. Thus, it follows quite naturally from this account that both exceptions and nonwords might be simultaneously impaired. The dual-route account completely misses the fact that exception words can be affected by the same deficit that impairs nonword naming. It must instead assume that when both nonwords and exceptions are impaired both routes happen to be impaired simultaneously, an assumption for which there is no independent evidence.

There is another important respect in which this theory differs from the dual-route account. In the dual-route theory, phonological dyslexia derives from an impairment in grapheme-phoneme correspondence rules that are used in pronouncing nonwords and regular words, but does not affect exceptions. In fact there are no children who can only read exceptions. In the dual-route theory this is explained by assuming that the lexical route can be used to read both regular and exception words. This account therefore predicts that phonological dyslexics should tend to be impaired in reading nonwords and approximately equally proficient in reading the two types of words. Whether a word has a regular or irregular pronunciation is irrelevant if the lexical route is fully functioning. According to our theory, in contrast, the phonological impairment has a primary affect on nonwords and and a secondary effect on exceptions. Two implications follow. First, children with phonological impairments will tend to be impaired on both exceptions and nonwords, with only a very mild impairment producing the "pure" pattern in which only nonword naming is affected. Second, where the impairment is severe enough to affect words, exceptions should be more impaired than regular words. (The one exception would be if the phonological deficit were so severe as to produce ceiling effects on errors.)

Our account of the phonological dyslexic pattern is also consistent with the observation that it deviates from the pattern observed in younger normal readers. The model illustrates how learning proceeds when constrained by a specific type of representational deficit. This deficit has specific effects on word and nonword naming. The effects of this deficit over the course of acquisition result in atypical developmental patterns. The degree to which behavior deviates from normal depends on the degree of impairment. In most of our subjects, the phonological impairment is severe enough to affect both exception word and nonword naming.

Surface Dyslexia As A Resource Deficit

The SM89 model suggests a very different etiology for the surface dyslexic pattern. The basic surface dyslexic pattern is that simple spelling-sound correspondences can be mastered, but not the pronunciations of exception words. As Seidenberg and McClelland (1989) suggested, the capacity of their model to learn the pronunciations of exception words depended on the computational resources that were available to it, specifically the number of interlevel hidden units. Seidenberg and McClelland described simulations comparing the normal 200 hidden unit model with a model configured with 100 hidden units. The model with fewer hidden units was able to learn many "rule-governed" spelling-sound correspondences, but not the exceptions. The model allocated the limited resources that were available for solving the problem to the patterns that occurred most frequently and consistently. With sufficient training, such a model could become very proficient at using a relatively small number of spelling-sound "rules" but at a cost: poor performance on the larger proportion of words that must be treated as exceptions.

This account of surface dyslexia is interesting because it does not involve the impairment to the lexical route implicated in the the dual-route account. Again, however, having shown that the model is consistent with the basic behavioral facts, it must be asked whether it adds anything in explaining them. Here again, the model explains the additional features of the subtype described previously. First, our account suggests why the impairment does not tend to be specific to exception words. The basis of the deficit is a set of units which, by hypothesis, mediate all orthographic to phonological conversion. Too few hidden units results in slower acquisition of the regular spelling-sound correspondences and thus poorer than normal performance on regular words and nonwords. However, as SM89 showed, the exceptions are also handled very poorly by a resource-deficient model. Our surface dyslexics exhibited this pattern: they were impaired on both nonwords and exceptions, though relatively more so on exceptions. Thus, just as our account of phonological dyslexia explains why exceptions tend to be impaired along with nonwords, the account of surface dyslexia explains why regular words tend to be impaired along with exceptions. Hence absence of "pure" forms of the developmental impairments presents no problem.

Second, insofar as this deficit pattern involves poorer performance on both exceptions and nonwords, it represents a kind of developmental delay. The resource-limited model's performance is like that of the normal model at an earlier stage in training. Similarly, the surface dyslexics were similar to younger normal readers, who had not yet mastered very many of the exception words. We therefore have a simple account of why the surface dyslexics' performance was like that of younger normal readers whereas the phonological dyslexics' was not. One impairment derives from a resource limitation that results in slower mastery of all types of stimuli. The other derives from a specific representational deficit that results in performance that deviates from normal at any age.

Impact Of Remedial Reading On Underlying Deficits

Children learning to read are exposed to several widely varying curricula, including phonics and whole word (or "whole language") approaches (Adams, 1990). In addition, children who encounter difficulty in reading receive various types and amounts of remediation. It is important to consider the potential impact of different remediation experiences on the patterns of reading deficits that are observed. An individual with an underlying phonological deficit might conceivably be made "purer" by receiving remediation that emphasizes sight word vocabulary and provides very little training in phonological awareness or decoding. Conversely, extensive phonics training might yield an even more mixed profile, with impairment on both nonwords and exceptions.

Still more interesting are the possible outcomes for a resource-limited surface dyslexic exposed to remediation regimes that differed in degree of emphasis on phonological decoding. One possibility is that the individual would receive extensive phonics training, resulting in a profile that resembles many of the surface dyslexics in our study (relatively good phonological awareness and decoding, poor knowledge of specific word spellings). Another possibility is that a whole-word emphasis might result in greater reliance on a direct visual-to-semantic route. Pronunciation would then be achieved by computing the meaning of a word and then using the meaning to generate a pronunciation. Under this scenario, the effect of remediation would be to cause a transition from the surface dyslexic pattern to the phonological dyslexic pattern. This implication is especially important, insofar as it suggests that there may be two pathways to becoming a "phonological dyslexic." One involves a phonologically-based deficit that has particular impact on nonword reading. This individual presents the classic picture of a phonological impairment: poor performance on "phonological awareness" and other speech-related tasks, both prior to and after the onset of reading education. The other derives from a resource limitation combined with remediation emphasizing visual or whole-word processing. The latter individual will not exhibit the independent speech-related processing deficit and will only fit the phonological dyslexic pattern after considerable instruction.

The possibility that there are at least two distinct pathways into phonological dyslexia might account in part for why the pattern is so common. However, it raises a cautionary note insofar as only some children with nonword reading deficits should be found to be phonologically impaired if assessed more closely. Longitudinal studies of normal and disabled readers exposed to different types of reading curricula are necessary to explore the implications of this account.

Conclusions

We have proposed accounts of the phonological and surface subtypes within the framework of the Seidenberg and McClelland (1989) model. The model can account for the classic surface and phonological profiles that were developed within the dual-route framework, but also accounts for aspects of the data that are unexplained by the dual-route approach. Phonological dyslexia primarily results from an impairment in phonological representation that affects the course of reading by impeding the acquisition of the ability to map from orthography to phonology. The effects of this impairment depend on its severity: a relatively severe deficit causes poor performance on both words and nonwords; with a relatively milder impairment, better performance can be achieved on words (including exceptions) but nonword performance is still impaired. These behavioral patterns are not observed in younger normal readers with the same level of word recognition ability as the dyslexics. It is possible these pattern might be seen in even younger normal readers, particularly children who learn to read in a curriculum that de-emphasizes phonics. However, our prediction would be that since these children have normal phonological skills, they will eventually surpass the dyslexic children in nonword reading. Developmental surface dyslexia derives from a resource limitation, which yields a general delay in all aspects of word reading skill.

We have also explored how remediation may modify the behaviors associated with these underlying deficits. In the case of phonological dyslexia, there may be a constitutional problem that interferes with mastering spelling-sound correspondences, as evidenced by behavior genetic analyses suggesting high heritability for phonological decoding and phonological awareness deficits in poor readers (Olson, Wise, Conners, Rack, & Fulker, 1989). Visual or "whole word" processing may provide a work-around; however, it may be difficult to achieve efficient word processing by this method. Phonology plays a central role in learning to read and in skilled reading. Recognizing words on a visual, nonphonological basis may be something that is only accomplished for words that have become very familiar through high frequency of exposure (Seidenberg, 1985; 1992). Bruck's (1992) study of adults with childhood histories of dyslexia provides important clues in this regard. Her subjects exhibited a broad range of reading abilities. Although many were still impaired in reading words, there were some who were not. However, even these relatively skilled subjects were still impaired in nonword reading and on phonological awareness tasks. Thus, Bruck's best subjects managed to develop a relatively large sight-word vocabulary over a long period of time, but their phonological deficits persisted.

With regard to surface dyslexia, there is now evidence from twin studies that orthographic processing deficits are heritable (Olson, Forsberg, & Wise, 1994), adding to previous evidence that phonological processing deficits are heritable (Olson et al., 1989). Hence, it is possible that these problems are also constitutional in origin. While previously it has been hypothesized that this rarer subgroup of dyslexics might have a visual memory deficit, and at least one clearcut case study has been reported (Goulandris & Snowling, 1991), other studies have failed to find visual deficits in children who have poor orthographic knowledge (Hanley, Hastie, & Kay, 1992; Seymour & Evans, 1993). The hypothesis that the heritable deficit in cases of surface dyslexia involves resource deficits that affect a broad range of word recognition skills is worth pursuing further.

We have hypothesized that the type of remediation affects how the limited computational resources that are available to such individuals are allocated. A "phonics" approach will tend to reinforce the surface dyslexic pattern, insofar as regular word and nonword naming improve at the expense of exception words. A "whole word" approach may tend to cause a transition to the "phonological dyslexic" pattern. Of course, other treatments and effects can be imagined, and all of them will be further modulated by the degree of resource impairment. The model suggests that it will be important to look very closely at how the effects of different types of remediation interact with different types of dyslexia, especially in studies of subjects over long periods of time.

FOOTNOTES

1. Stanovich, et al. (1986) point out that matching on a reading comprehension test would tend to widen differences between dyslexics and younger normals on word decoding and phonological processing tests. Dyslexics could also be matched to (much) younger normal readers on nonword reading skill. In this case, dyslexics would most likely be better than the normal readers at both word recognition and orthographic processing tasks, possibly reflecting big discrepancies in amount of print exposure.

2. There is a second reason why a phonological impairment will have a greater effect on nonwords than on words. Both the dual-route model and the Seidenberg and McClelland model incorporate a visual-semantic pronunciation mechanism. This involves computing the meaning of a word from orthographic information, and then using the meaning to generate a pronunciation, as in speech production. This process represents a third "route" in the dual-route model. In both models, then, there is a semantically-based work-around for a deficit in the orthographic to phonological computation that is available for words (which have meanings stored in memory) but not for nonwords (which do not).

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Appendices

Exception Words (in the order given)

ocean, iron, island, busy, sugar, truth, whom, tongue, rhythm, stomach, wounded, sword, anchor, echo, chorus, dough, ache, ninth, react, tomb, vague, colonel, drought, trough, depot, aisle, bouquet, foreign, yacht, chauffeur, sergeant, suede, fiance, gauge, bureau, circuit, schedule, encore, heirloom, champagne, distraught, sovereign, righteous, benign, baroque

Nonwords (in alphabetic order)

baich, baim, chail, cheed, chob, chol, choub, chud, fep, feap, fesh, fip fiss, fod, foop, foud, goach, goam, jeeb, jirn, joal, jub, juck, juf, jul, leck, leem, lef, loash, losh, lum, meep, meesh, naig, neach, nog, nooch, paf, peef, soag, sug, vag, veed, veeg, vep, vess, vud, yoal, yol

NONWORDS WITH NO CLOSE WORD NEIGHBORS: cleesh, gheab, glaje, glouze, jirn, kelce, phuve, shrofe, skoce, skresp, smaip, sprenk, stieb, whuld, wreeb, zoag

Stimuli used in the Orthographic Choice task (in alphabetic order)

t**arget (foil)** : bark (barc), bean (bene), biscuit (biscut), blame (blaim), blink (blinc), bloom (blume), brawl (braul), built (bilt), by (bie), chair (cheir), cologne (calogne), column (collum), court (cort), debt (det), detour (detoor), doubt (dout), face (fais), feud (fude), fly (fligh), freight (frate), geyser (guyser), goat (gote), granite (grannit), guard (gaurd), hoop (hupe), journey (jurney), l;amb (lam), leap (leep), meant (ment), menace (mennis), mine (mign), mischief (mischef), monk (munk), more (more), odd (od), pageant (padgeant), poultry (poltrey), pursuit (pursute), rich (ritch), seize (seeze), shriek (shreek), ski (skee), soap (sope), soon (sune), source (sorce), sponge (spunge), style (stile), thumb (thum), tire (tyre), tortoise (tortace), vacuum (vacume), watt (wot)

	SUBJECT GROUP		
Variable	**Dyslexics**	**Same-Age Normal Readers**	**Younger Normal Readers**
Est. WISC-III IQ[1]	106.3 (14.9)	108.2 (12.5)	109.6 (12.1)
Age (in years)[1]	12.43 (1.78)	11.7 (1.4)	8.5 (.64)
Word Ident. Grade[1]	4.4 (1.05)	9.3 (3.0)	4.4 (1.17)
Word Identification. Percentile[1]	14.1 (10.7)	74.4 (14.9)	74.4 (16.2)
Exception Word %[1]	43.5 (17.7)	75.9 (12.4)	41.4 (13.0)
Nonword %[1]	61.9 (15.7)	88.9 (9.3)	76.9 (17.5)
Pos. Analysis %[2]	73.3 (19.1)	88.6 (10.5)	81.4 (15.6)
Ortho. Choice %[3]	76.0 (13.7)	90.0 (11.5)	74.6 (10.3)
Ortho Choice RT[3]	2148 (866)	1468 (387)	2468 (813)

Table 1

Mean Scores for Dyslexics and Comparison Group

(Standard Deviations in Parentheses)

[1] The N's for these tasks were dyslexics (51), same-age normal readers (SN group) (51) and younger normal readers (YN group) (27).

[2] The N's for this task were dyslexics (51), SN group (51) and YN group (26).

[3] The N's for this task were dyslexics (36), SN group (45) and YN group (27).

Table 2

Mean Scores for Dyslexic Subgroups and Comparison Groups

(Standard Deviations in Parentheses)

	SUBJECT GROUP			
Variable	**Phonological Dyslexics**	**Surface Dyslexics**	**SN Group**	**YN Group**
Est. WISC-III IQ[1]	104.0 (13.9)	113.5 (16.7)	108.2 (12.5)	109.6 (12.1)
Age (in years)[1]	12.68 (1.87)	12.27 (1.83)	11.7 (1.4)	8.5 (.64)
Word Ident. Grade[1]	4.43 (1.07)	4.07 (1.09)	9.3 (3.0)	4.40 (1.17)
Word Identification Percentile[1]	13.18 (10.2)	12.6 (10.8)	74.4 (14.9)	74.4 (16.2)
Exception Word %[1]	48.9 (15.7)	32.0 (11.6)	75.9 (12.4)	41.4 (13.0)
Nonword %[1]	49.6 (11.0)	72.7 (10.4)	88.9 (9.3)	76.9 (17.5)
Position Analysis %[2]	63.5 (20.4)	80.8 (18.8)	88.6 (10.5)	8.4 (15.6)
Orthographic Choice %[3]	82.4 (8.1)	69.4 (8.8)	90.0 (11.5)	74.6 (10.3)
Orthographic Choice RT[3]	1858 (495)	2385 (1085)	1468 (387)	2468 (813)

[1] The N's for these tasks were: phonological dyslexics (17), surface dyslexics (15), SN group (51), YN group (27).

[2] The N's for this task were: phonological dyslexics (17), surface dyslexics (15), SN group (51), YN group (26).

[3] The N's for this task were: phonological dyslexics (13), surface dyslexics (10), SN group (45), YN group (27).

Table 3

Word Naming Errors for the Dyslexic Subgroups and Younger Normal Readers

	Error Category			
	Phonologically Appropriate		**Phonologically Inappropriate**	
Subject Group	Word	Nonword	Word	Nonword
Phonological dys	5.1 (3.6)	19.9 (10.0)	38.3 (14.7)	36.7 (12.9)
Surface dyslexic	5.0 (2.2)	31.4 (9.8)	26.3 (13.4)	37.3 (7.5)
YN readers	6.1 (4.4)	27.1 (16.3)	26.2 (17.2)	40.6 (9.8)

Figure Captions

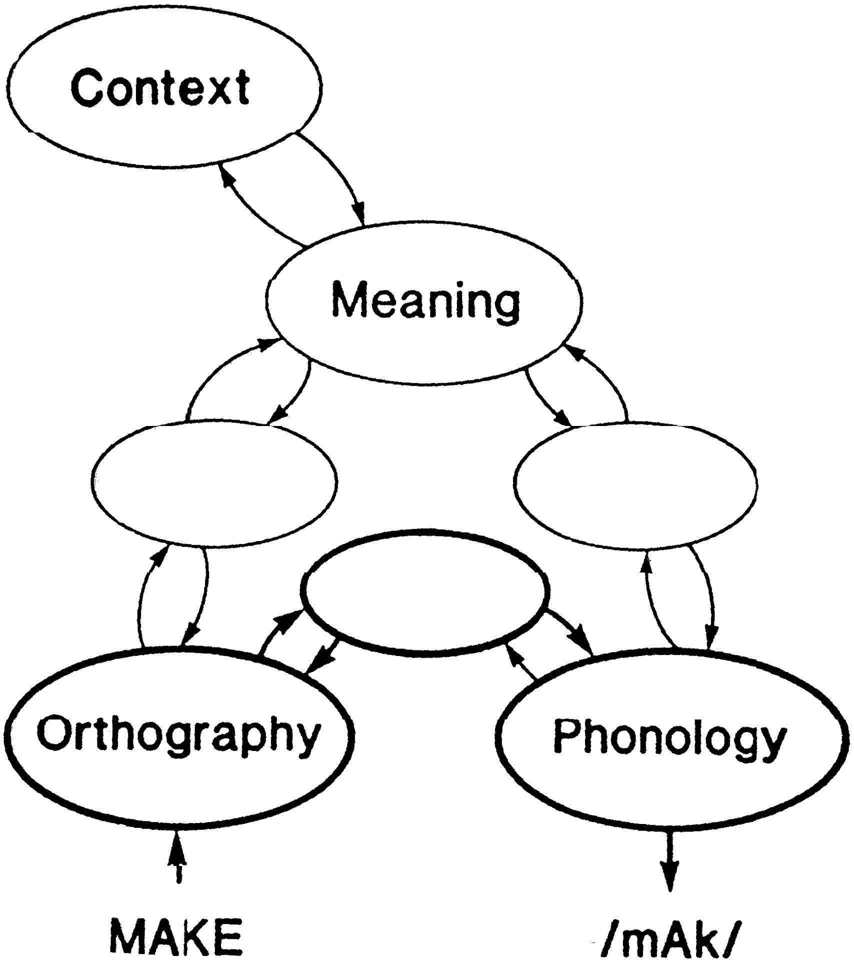
Figure 1. Seidenberg and McClelland (1989) model. Ellipses represent sets of units.

Figure 2. Nonword reading by exception word reading for SN and dyslexic subjects, with regression line and 95% confidence limits. Phonological dyslexic cases are represented by filled circles.

Figure 3. Exception word reading by nonword reading for SN and dyslexic subjects, with regression line and 95% confidence limits. Surface dyslexic cases are represented by filled circles.

Figure 4. Nonword reading by exception word reading for YN and dyslexic subjects, with regression line and 95% confidence limits. Phonological dyslexic cases are represented by filled circles.

Figure 5. Exception word by nonword reading for YN and dyslexic subjects, with regression line and 95% confidence limits. Surface dyslexic cases are represented by filled circles.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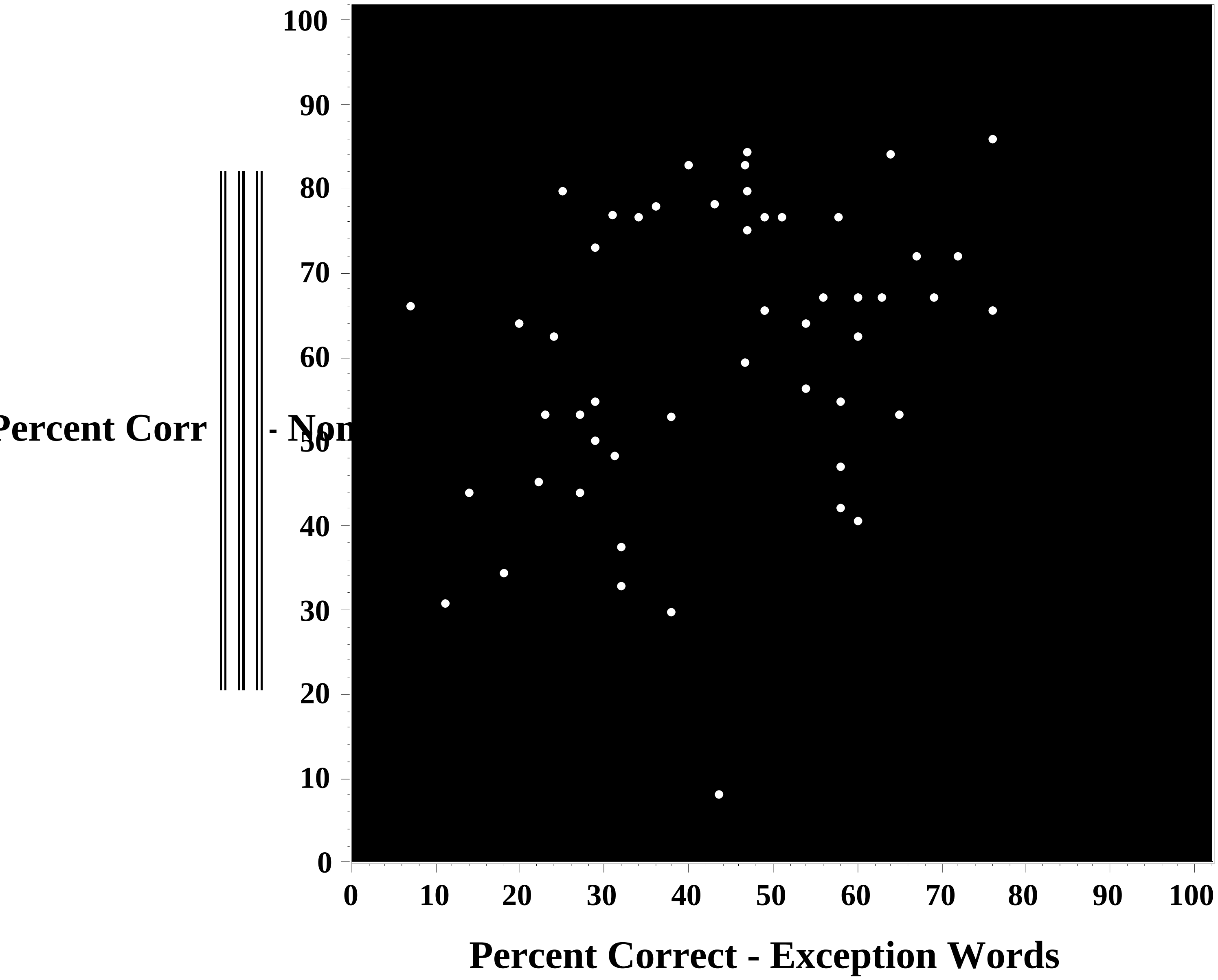
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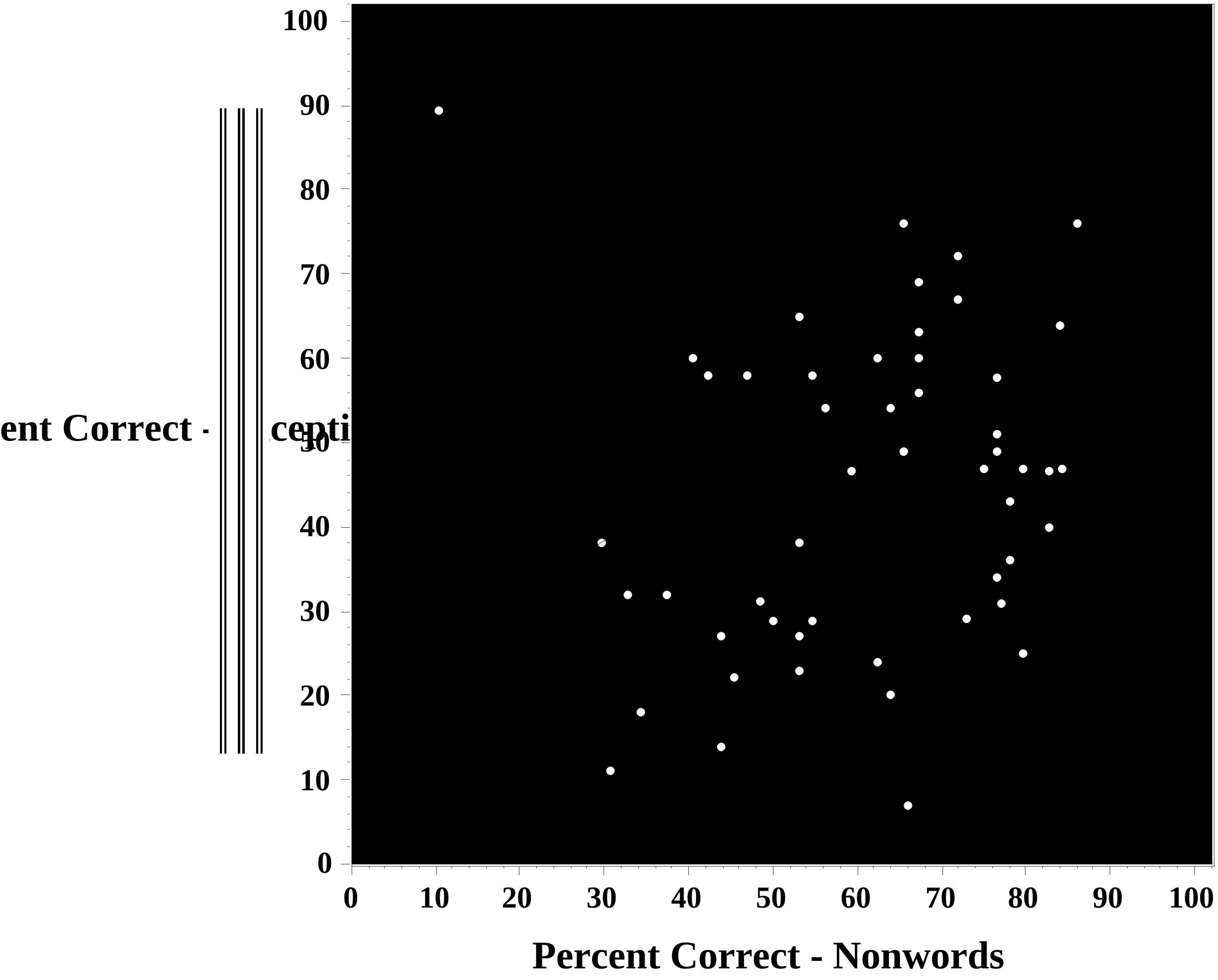
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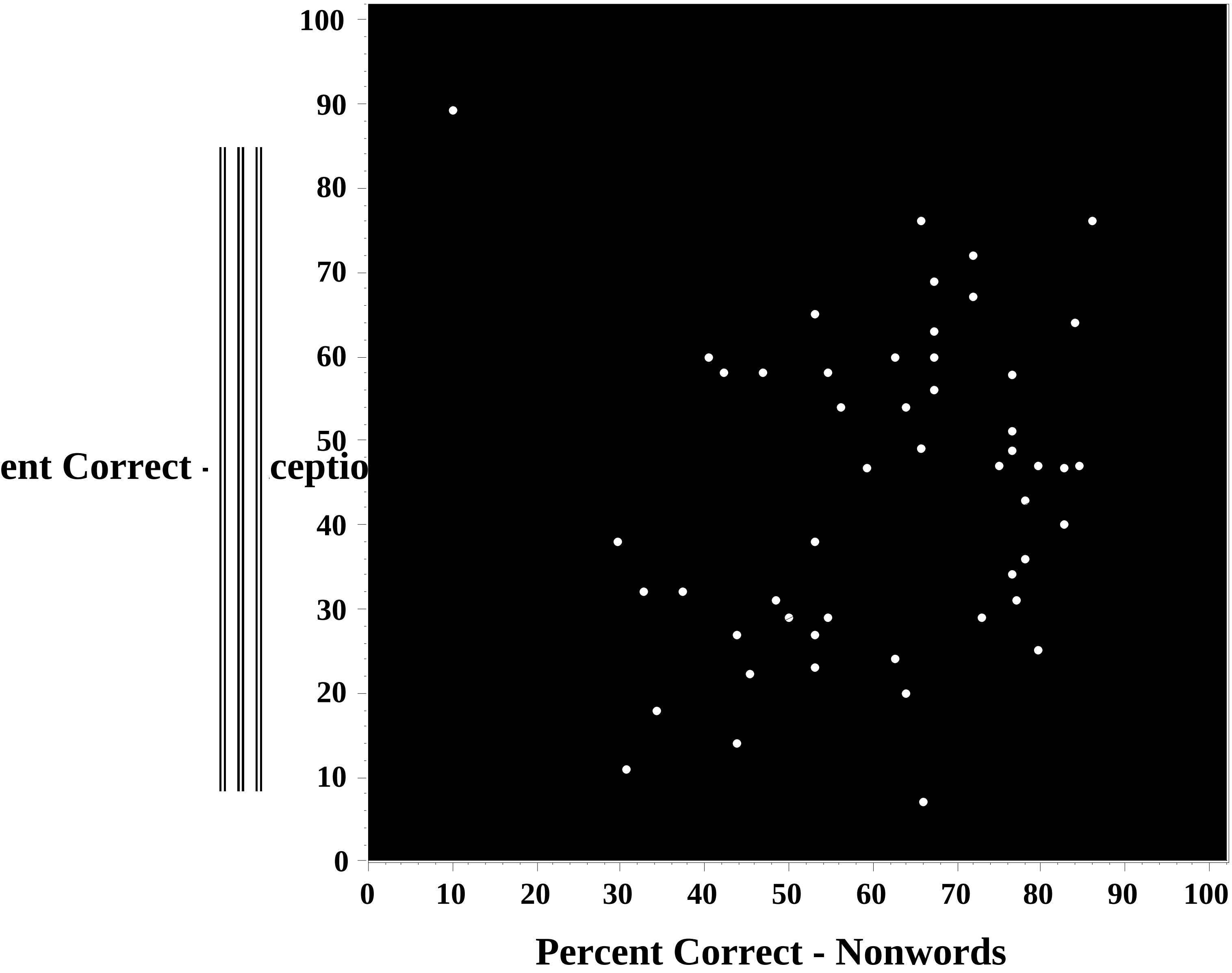
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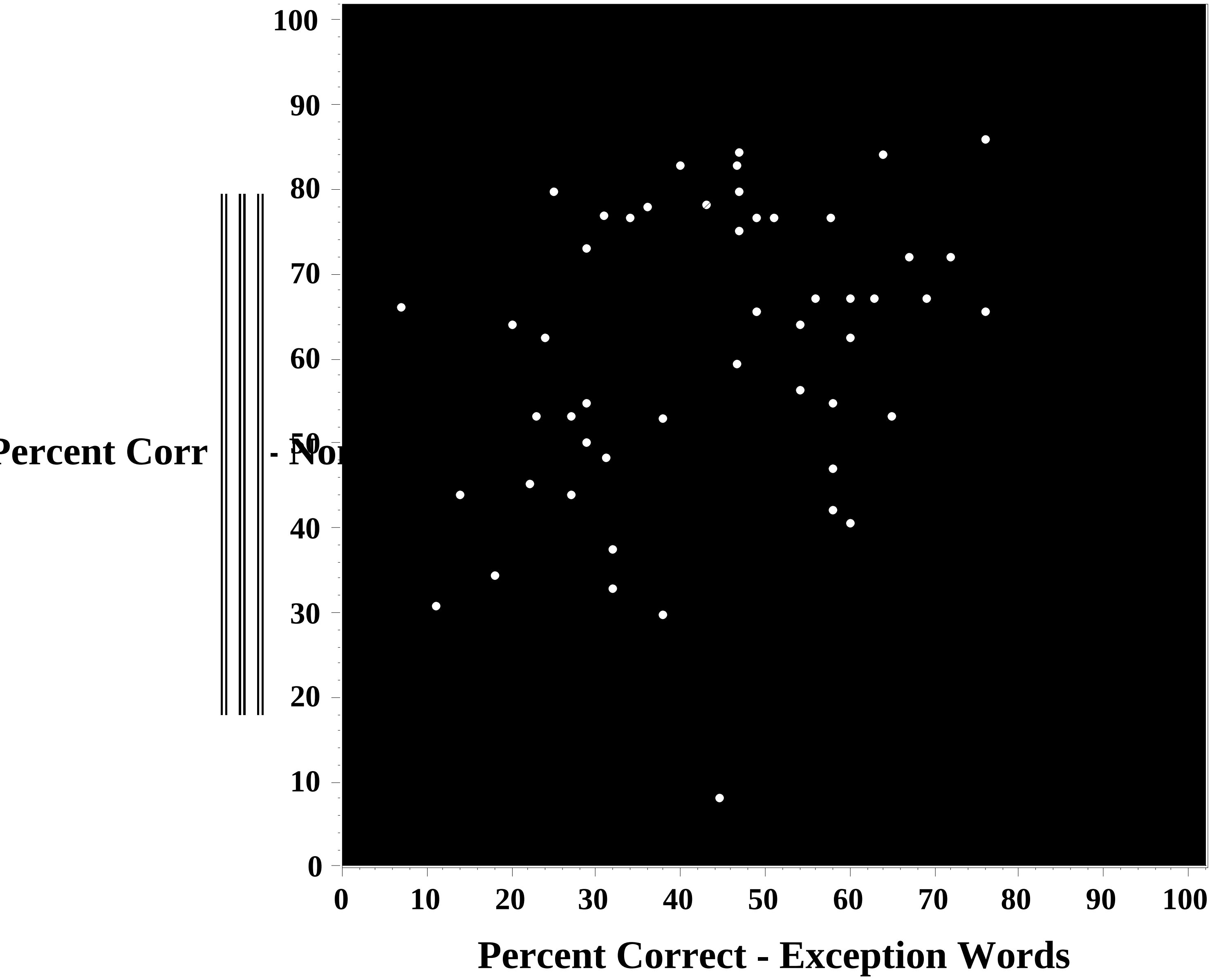
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Percent Correct - Exception Words