at risk of developing conduct disorder later in life. In this example, perhaps a fundamental problem in inhibiting or regulating behavior shows different manifestations at different stages of development. In other cases, such as the comorbidity between reading difficulties and motor impairments, it seems unlikely that there is any direct causal link at the cognitive level between these two disorders; both problems may simply reflect the fact that brain development has gone awry with diverse effects on cognitive development. So, in this case, we would argue that problems with balance and motor coordination are unlikely to tap a cause of problems in learning to read. We will say much more about comorbidities between different disorders in the chapters that follow and return to the issue in Chapter 9.

Summary and Conclusions

In this book we will review what we know about a range of developmental disorders. We will consider a wide range of disorders including reading disorders, language disorders, arithmetic disorders, motor disorders, and autism spectrum disorders. This chapter has outlined a number of key conceptual issues that lie at the heart of studies of developmental cognitive disorders. We have argued that such disorders can only be understood in the context of a developmental theory of how the cognitive processes concerned typically operate, and by inference how those developmental processes are delayed or disordered in some children. As we shall see, most developmental disorders seem best characterized in terms of delays to typical developmental processes. This leads us to see such disorders as dimensional: The children identified are simply at the bottom end of a continuum of normal variation in the population. Nevertheless, diagnostic labels can be useful in communicating the form of difficulties experienced by different groups of children. Finally, the process of trying to understand the causes of developmental disorders is highly complex and depends critically upon having explicit theories of the nature of each disorder and the causal processes operating at different levels to generate the behavioral profile seen. Such causal theories can be tested in a variety of ways, but two of the most powerful forms of evidence come from longitudinal and intervention studies. We have introduced the idea of path diagrams as ways of representing causal theories, and we will use such diagrams in different chapters to represent different theories about the origins of the disorders we discuss.

2

Reading Disorders I: Developmental Dyslexia

Of all the cognitive deficits that occur in children, reading disorders are the most studied and best understood. Studies in this area serve as a model for the approaches that we outlined in Chapter 1, and illustrate nearly all the methodological and theoretical points that were made in that chapter.

When we consider reading skills it is important to distinguish between reading accuracy and reading comprehension. We typically assess reading accuracy by asking children to read words aloud. Tests of reading accuracy usually consist of lists of unrelated words that are graded in difficulty from easy to hard. In contrast, reading comprehension is usually measured by giving children passages to read (either aloud or silently) and then asking them questions to assess what they have understood.

In this chapter we will focus on dyslexia, which is probably the best understood of all specific cognitive impairments that occur in childhood. Dyslexia is a disorder in which children find it very difficult to read accurately and with fluency. Chapter 3 will deal with reading comprehension impairment, which can be thought of as the "mirror image" of dyslexia. Children with reading comprehension impairment can decode words adequately but have great trouble in understanding the meaning of what they read.

Reading Disorders in Children: Definitions and Prevalence

The *Diagnostic and Statistical Manual of Mental Disorders* (DSM-IV; American Psychiatric Association, 2004) classifies a person as having reading disorder when their "reading achievement, as measured by individually administered standardized tests of reading accuracy or comprehension, is substantially below that expected given the person's chronological age, measured intelligence, and age-appropriate education." A number of points are raised by this definition. First, note that the definition refers to both reading accuracy and comprehension, but as we have already hinted reading comprehension impairment is quite distinct from dyslexia. Second, the definition is explicitly a developmental definition, and states that reading needs to be below the level expected for a person's age and education. Learning to read takes many years of practice and instruction, so we do not expect a 6-year-old to be a proficient reader, and we expect the average 10-year-old to be a much better reader than the average 6-year-old. Third, the definition also acknowledges the importance of education. Children are taught to read at school and if a child has not been given adequate teaching then this may be a sufficient explanation for poor reading skills. Finally, the last point made by the definition, that reading should be below the level expected in relation to a child's intelligence, has proved a matter of considerable controversy. This idea is referred to as a discrepancy definition (the reading level is discrepant from the level expected for a child's IQ and age).

At first blush the idea that reading depends on intelligence (IQ) seems eminently reasonable. Surely, bright children will learn to read more easily than less bright children, just as they learn other things more easily? This idea, however, depends on a strong theoretical assumption that often has not been made explicit (that variations in IQ are a cause of variations in the ease with which children learn to read) and this assumption is, at best, unproven (Stanovich & Siegel, 1994). The correlation between IQ and reading accuracy ranges from about .3 to .6, which, although far from massive, does suggest that somewhere between 10 and 30% of the differences in reading ability amongst children might be explicable in terms of IQ. This correlation between reading ability and IQ guided studies of large representative samples of children (epidemiological studies) that had the aim of describing the nature and prevalence of reading problems in the child population. One of the first and most influential epidemiological studies of reading ability was carried out on the Isle of Wight (Rutter & Yule, 1975). In this study, measures of reading ability, IQ, and a number of other variables were taken from all children on the island between the ages of 9 and 11 years. Rutter and Yule distinguished between specific reading retardation (children whose reading ability was below the level predicted for their age and IQ – dyslexia) and reading backwardness (children whose reading was below the level predicted for their age, ignoring IQ).

Of course, the prevalence of dyslexia using a definition such as that of specific reading retardation depends on how far below expectation a child needs to be before being labeled as dyslexic. If we simply assume that all scores (reading, age, and IQ) are distributed normally then 2.28% of children should score more than 2 standard errors of measurement below their "predicted" reading score (the statistics behind this claim need not detain us). Using this cut-off Yule, Rutter, Berger, and Thompson (1974) reported rates of specific reading retardation (using a test of reading accuracy) ranging from 3.1% among children in the Isle of Wight to 6.3% in an Inner London Borough. Other, more recent studies have suggested rather lower rates of reading problems and a recent American study (S. Shaywitz, Escobar, Shaywitz, Fletcher, & Makugh, 1992) using a less stringent cut-off point of 1.5 standard errors of measurement reported prevalence rates of 5.6% in first grade, 7% in third grade, and 5.4% in fifth grade.

In all these studies, reading problems are defined in terms of a discrepancy between a child's reading score and that expected for their age and IQ. But what evidence is there that IQ is important? This question really revolves around whether children with specific reading difficulties (poor reading in relation to age and IQ) are different to children with general reading problems associated with low general cognitive ability.

Current evidence suggests that these two groups of children differ much less than many experts would have expected. Perhaps the most critical question to ask is whether classifying children as having *specific* reading difficulties / dyslexia rather than as having more general reading difficulties has implications for how they will make progress in learning to read.

In one of the first studies to address this question, Rutter and Yule (1975) reported that over a 4- to 5-year period children diagnosed as having specific reading difficulties actually made less progress in learning to read than those with general reading problems (and perhaps most interestingly there was the opposite pattern for arithmetic, with the children with specific difficulties making more progress). However, the prospects for children with dyslexia may have improved since then and more recent studies have failed to show an effect of IQ differences at least as far as gains in reading accuracy are concerned (Hatcher & Hulme, 1999; Share, McGee, McKenzie, Williams, & Silva, 1987; B. Shaywitz, Fletcher, Holahan, & Shaywitz, 1992).

In summary, IQ certainly correlates with children's reading accuracy. However, IQ does not explain well the problems some 3–6% of children have in learning to read. From an educational perspective there is no evidence that children who have word-level (decoding) reading problems will vary in their responsiveness to teaching according to their IQ level, and theoretically there is no reason to believe that the causes of word recognition difficulties in reading are different in children with low, rather than high, IQ.

In terms of giving a useful definition of dyslexia, the definition of reading disorder offered by DSM-IV is not very helpful because it conflates problems of reading accuracy (dyslexia) with problems of reading comprehension. A more useful definition, and one that anticipates much of the evidence we will cover in this chapter, is given by Lyon, Shaywitz, and Shaywitz (2003): "Dyslexia is a specific learning disability that is of neurobiological origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling...These difficulties typically result from a deficit of the phonological component of language..." (adapted from *http://www.interdys.org/FAQWhatIs.htm*).

This definition retains an emphasis on a discrepancy between reading and IQ (hence the term specific learning disability). Although the usefulness of a reading/IQ discrepancy for diagnosis has been hotly debated, in terms of research practice the use of IQ discrepancy-defined groups has been, and remains, the usual approach when studying dyslexia. This is a cautious research strategy; by selecting groups of poor readers with at least average IQ, the hope is to exclude more general learning problems and so maximize the chances of establishing the cognitive deficits that are the causes of reading problems. We shall see shortly that this research agenda has been pursued with considerable success.

Summary

Dyslexia can be operationally defined as a problem in learning to recognize printed words at a level appropriate for a child's age. It is in fact quite a common disorder affecting around 3–6% of children, with more boys than girls affected (Rutter et al., 2004). As we shall see, in most cases dyslexia appears to depend on problems of phonology (skills in dealing with speech sounds). However, in addition, social factors play a key role in determining the risk for reading disability (Rutter & Maughan, 2005; Yule et al., 1974).

The persistence of dyslexia

There are now several studies that have examined the profile of difficulties shown by children with dyslexia when they reach adulthood. Although many such children who have received appropriate help develop reasonable levels of reading accuracy, reading speed (or fluency) appears more difficult to remediate, and spelling skills typically remain impaired (Bruck, 1990; Maughan & Hagell, 1996). Indeed, in a follow-up of children with specific reading difficulties from the Isle of Wight study when they were in their mid-40s, it was reported that 80% of these people had spelling scores at least two standard deviations below the population average (Rutter, Kim-Cohen, & Maughan, 2006). Thus, like many developmental disorders considered in this book, it appears that dyslexia persists into adulthood, though it appears to have a range of different manifestations in adult life that are, as yet, poorly understood.

Comorbidities between dyslexia and other disorders

Comorbidity is a term used to refer to the co-occurrence of different disorders. Dyslexia has been reported to occur together with language impairment, attention deficit hyperactivity disorder, and developmental coordination disorder (Catts, Adlof, Hogan, & Ellis Weismer 2005; Kadesjo & Gillberg, 2001; Kaplan, Wilson, Dewey, & Crawford, 1998; Willcutt & Pennington, 2000) as well as with difficulties in mathematical cognition. Moreover it is not unusual for more than two of these disorders to co-occur, especially in referred samples. As yet, the frequency of such comorbidities is not established and their causes and consequences is the subject of ongoing research (see Chapter 9 for discussion).

The Normal Development of Literacy: A Theoretical Framework

Studies of normal development and studies of developmental disorders can inform each other. A central claim of this book is that any proper understanding of a developmental disorder must be couched in terms of a model of normal development. To understand dyslexia is to be able to say how reading development in dyslexia goes awry in comparison to normal development. A better understanding of dyslexia will in turn help to refine and constrain theories of normal development because individuals who show striking failures of development help to sharpen our appreciation of the processes underlying normal development. With this in mind, we will consider the normal development of reading, to inform our later explanations of dyslexia.

Proponents	Gough & Hillinger (1980)	Mason (1980)	Marsh et al. (1980)	Chall (1983)	Frith (1985)	Ehri (1998)	Stuart & Coltheart (1988)	Seymour & Duncan (2001)
Number of developmental periods	*2*	*3*	*4*	*5*	*3*	*4*	*2*	*4*
1. Pre-reading	Cue reading	Contextual dependency	Rote, linguistic guessing	Stage 0: Letters/ book exposure	Logographic	Pre-alphabetic	Partial orthographic	Pre-literacy
2. Early reading		Visual recognition	Discrimination, net guessing	Memory & contextual guessing		Partial alphabetic		Dual foundation
3. Decoding	Cipher reading	Letter sound analysis	Sequential decoding	Stage 1: Decoding attending to letters/ sounds	Alphabetic	Full alphabetic	Complete orthographic	Logographic Alphabetic
4. Fluent reading			Hierarchical decoding	Stage 2: Fluency, consolidation	Orthographic	Consolidated alphabetic, automaticity		Orthographic Morphographic

Figure 2.1 Stage models of reading development. (From Ehri, L. C. (2005). Development of sight word reading: Phrases and findings. In Snowling, M. J. and Hulme, C. (Eds) *The Science of Reading: A Handbook* (pp. 135–154). Oxford, Blackwell.)

How do children learn to read?

A number of theories propose that reading development proceeds in a series of stages or phases (Ehri, 2005, for a review). Although there are differences between different models (see Figure 2.1 by way of illustration), we describe here in outline the sequence of development culled from stage models.

Children begin the process of learning to read by making quite arbitrary associations between printed words and pronunciations. This visual approach to reading is limited and children soon show evidence of coming to understand the systematic relationships between the letter sequences in printed words and the sounds that the letters represent. As reading skill develops, reading becomes more rapid and less effortful and appears to depend upon sophisticated representations of the relationships between print, sound, and meaning, at a number of different levels.

At the earliest point in development, referred to as the logographic stage (Frith, 1985), the child appears to be attaching a label (the word's name) to a string of letters, without any proper appreciation of how the letters in a word map on to its pronunciation. At this stage, reading errors come predominantly from the set of words the child has been taught, with a tendency for them to preserve word length. For example, Seymour and Elder (1986) reported a child reading policeman as "children" saying, "I know it's that one because it is a long one." They also noted confusion between words with salient features in common. One child read smaller as "yellow" (both share a double l) and another read stop as "lost" (both share the cluster st though not in the same position).

One important difference between stage theories concerns how early, and in what way, children come to start using phonological information in learning to recognize words. (see Box 2.1). According to Ehri (1992), as soon as the young child has some

Box 2.1 The nature of phonological skills

"Phonological skills" is a blanket term used by psychologists to refer to skills that involve dealing with speech sounds. An important distinction in relation to reading development is between implicit and explicit phonological processing. Implicit phonological processing skills are those that are automatically engaged, for example in verbal short-term memory tasks. Such implicit phonological tasks can be contrasted with explicit phonological tasks, usually referred to as phonological awareness or phonological sensitivity tasks. These explicit tasks require the child to reflect upon and manipulate the speech sounds in words.

The most common tasks used to tap implicit phonological processing in studies of reading development are verbal short-term memory and rapid automatized naming (RAN) tasks. In verbal short-term memory tasks, participants usually listen to a string of numbers (digit span) or words (word span) and then repeat these items in the order of presentation. Two short-term memory phenomena provide evidence that the task engages phonological codes. The first is the "phonological confusability" effect, the finding that the recall of word lists is better when the items in the list are phonologically distinct than when there is overlap, and the second is the word length effect, the finding that more short than long words can be recalled in order. In the RAN task the participant is presented with a matrix of objects, colors, letters, or digits and is required to name the items as quickly as possible. This task requires rapid retrieval of the phonological forms (the names) of the items in the matrix.

There are robust correlations between performance on implicit phonological processing task and reading skills. However there are generally stronger relationships between reading and explicit phonological awareness. It is widely held that the development of phonological awareness proceeds from large to small units. Thus, children first become sensitive to the syllable structure of words and only later become aware of intrasyllabic units. English has a complex syllable structure. All syllables contain a vowel; simple CVC syllables comprise an onset (the consonant before the vowel) and a rime (the technical term used to describe the unit comprising the vowel and the final consonant or coda). In turn, rime units can be segmented into phoneme units, namely the vowel and the coda. In more complex syllables (see below), both the onset and the coda may include consonant clusters. The difficulty of a phonological awareness task will depend on a number of factors including the size of the phonological unit and the nature of the manipulation that is required. Generally tasks involving the manipulation of larger units (e.g., syllables or rime units) are easier than tasks involving smaller units (phonemes). Tasks involving the deletion or transposition of sounds within words are typically harder than tasks requiring judgments about the similarity between sounds in words.

Box 2.1 *(cont'd)*

Syllable	CRUST
Onset – rime	CR UST
Onset – vowel – coda	CR U ST
Phoneme	C R U S T

basic letter–sound and letter–name knowledge (at the age of 5 years or so), this starts to influence the process of learning associations between letter strings in words and their pronunciations. The use of letter–sound relationships in reading gradually becomes more and more explicit and systematic and children enter an alphabetic stage where they read using phonological strategies. Simple alphabetic strategies involve using letter–sound correspondences (sometimes described as "phonic strategies") to decipher print and, depending on how they have been taught, children can sometimes be heard to sound out and blend unknown words (CAT, > /k/, /ae/, /t/ > "cat"). As children consolidate this alphabetic stage, the application of letter–sound knowledge becomes progressively more automated and less effortful and the orthographic representations that underpin word recognition become more fully specified (the orthographic stage of reading development).

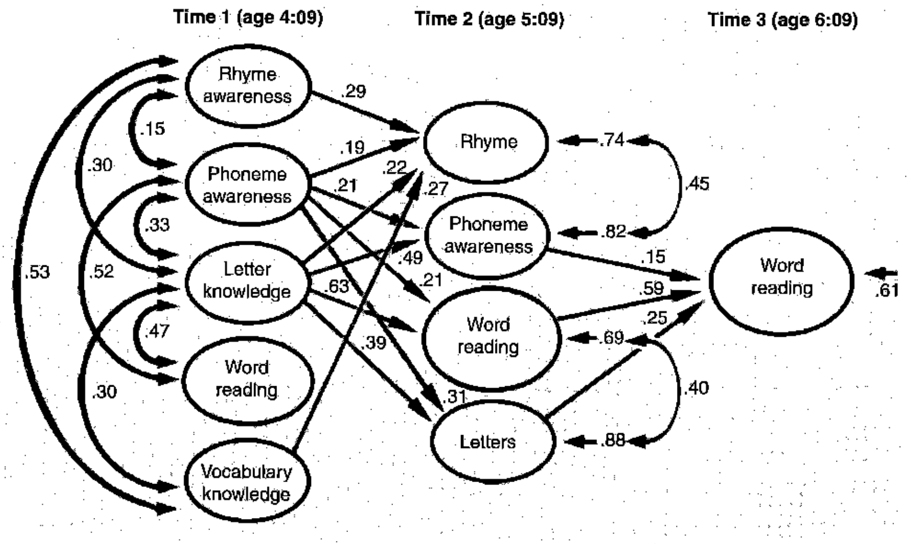
Stage models of reading provide descriptions of the way in which children's reading changes with age but they do not provide a mechanistic account of how these developmental changes come about; nor do they permit consideration of individual differences in the rate or course of development. A powerful way to investigate the role of different cognitive skills in learning to read is to conduct longitudinal studies (see Box 2.2). In these studies children are studied over a number of years, preferably beginning before they have started reading. If we can find measures of cognitive skills in prereaders that predict children's progress in learning to read, this may give us clues to the causes of variations in reading development.

Bradley and Bryant (1983) conducted a highly influential study that examined the relationship between early phonological skills and later reading achievement. The study involved some 400 children who were followed between the ages of 4 and 8 years. There was a strong relationship between the children's phonological awareness assessed on tasks tapping rhyme and alliteration skills at 4 years and their reading and spelling skills at 8, even when the effects of IQ, memory, and social class were controlled. Similar findings were reported by Lundberg, Olofsson, and Wall (1980) from a study conducted in Denmark where, at the time, reading instruction did not begin until the age of 7 years. These two studies were the starting point for a now voluminous literature showing the strong relationship between phonological awareness prior to reading instruction and later reading achievement (see Bowey, 2005, for a review).

If we accept that phonological skills and learning to read are intimately related, a more specific question is whether different levels of phonological representation are particularly crucial. Words consist of syllables (*Butterfly* has three syllables). Spoken syllables in turn can be segmented at different levels. A monosyllabic word such as *Spring* consists

Box 2.2 A longitudinal study of normal reading development

Muter, Hulme, Snowling, and Stevenson (2004) conducted a study in which 90 children were given a wide range of measures just after they entered school and then they were retested 1 and 2 years later (at the start of their second and third year in school). At school entry the children were assessed on a range of measures of rhyme and phoneme manipulation skills as well as on measures of vocabulary, reading, and letter knowledge. Rhyme skills were assessed by three tasks: rhyme detection (this is a CAT, which of these three words "fish, gun, hat" rhymes with cat) rhyme production (the word is "day," tell me as many words as you can that rhyme with "day"), and rhyme oddity (the words are "sand, hand, bank," which word does not rhyme with the others?). Phoneme skills were assessed with two tests: phoneme deletion (the word is "tin," "tin without the /t/ says....[in]") and phoneme completion (here the examiner said the beginning of a word and the child had to complete it by giving the final (missing) sound; given a picture of a gate the examiner would say "the word is /geɪ/" and the child would respond with a sound to complete the word "/t/"). In all these tests, pictures of the words were shown to the child. Children's letter knowledge (how many letters could the children give the name or sound for), reading skills (reading aloud lists of simple words), and vocabulary knowledge (selecting the correct picture from one of four pictures that represented a spoken word) were also assessed.



Longitudinal predictors of word recognition from age 4 to 6 years. (Muter, V., Hulme, C., Snowling, M. J., Stevenson, J. Phonemes, rimes, vocabulary and grammatical skills as foundations of early reading development, *Developmental Psychology*, 40, p. 674, 2004, published by American Psychological Association and adapted with permission.)

Box 2.2 (*cont'd*)

The main results from this study are shown in the path diagram. Following the conventions for path diagrams, the arrows from the measures at Time 1 to the measures at Time 2 represent the statistically significant relationships between these measures, and the numbers above the arrows indicate the relative strength of these relationships. As can be seen there were only two predictors of reading skills at Time 2; these were children's ability to manipulate phonemes in spoken words and their letter knowledge (and these same variables then continue to predict variations in reading skills at Time 3). This study gives strong support to the idea that phoneme manipulation ability and letter knowledge are two critical foundations for children learning to recognize words in reading.

of an onset /spr/ and a rime /ɪŋ/. At a finer level syllables can be divided into individual phonemes /s/p/r/ɪ/ŋ/. Goswami and Bryant (1990) proposed that rhyming skills were the precursors of reading development (in children learning English) and argued that the first links that children make in learning to read are between large units (onsets and rimes) and groups of letters, with the development of links between phonemes and graphemes being a second step. A number of studies have now tested this idea but have come down in favor of an alternative view, notably that rhyme and phoneme segmentation skills are relatively independent of each other and that initial phoneme segmentation ability is a far better predictor of children's subsequent progress in learning to read than is rime (Hulme, et al., 2002; Muter, Hulme, Snowling, & Stevenson, 2004).

Together, these studies converge with others in the literature (Byrne, 1998) in demonstrating that phoneme awareness and letter knowledge are critical foundations for the development of reading skills in children just entering school. Children who have some ability to manipulate phonemes in spoken words when they enter school and who have good knowledge of the sounds of letters make much better progress in learning to read than children for whom either of these skills is weak.

But to what extent do the findings we have discussed regarding learning to read apply to languages other than English? For children learning to read English, a major problem is the irregular relationship between letters and sounds. English is referred to as an irregular, opaque, or deep orthography (the relationships between spelling (orthography) and sound are not straightforward, as illustrated by words such as *colonel* and *yacht*). Many other European languages such as Czech, German, and Italian have much more transparent orthographies with letters generally corresponding to single phonemes. We therefore need to consider whether learning to read in English draws on rather different underlying cognitive skills to learning to read in other languages.

Learning to read in different alphabetic languages

Although rather few studies have made direct comparisons between readers of different orthographies using the same stimuli, there is now substantial evidence that children learn to read and spell more quickly in transparent writing systems than in opaque systems such as English (Seymour, 2005).

One of the first studies to demonstrate differences between children learning to read in opaque and transparent orthographies was conducted by Oney and Goldman (1984), who compared the reading skills of children learning to read in English (American) and Turkish. Turkish is a transparent orthography containing consistent letter–sound correspondences and therefore provides an interesting comparison with the opaque orthography of English. These researchers investigated nonword as well as word reading. While words can be read from memory by directly accessing orthographic representations (memorized spelling patterns), nonword reading provides a relatively pure test of decoding ability. Oney and Goldman (1984) reported that both decoding accuracy and speed were better among children learning to read in Turkish than English.

Wimmer and Goswami (1994) used a similar technique to investigate the influence of orthographic consistency on reading development in English- and German-speaking children. In this study, children were asked to read numerals (1, 3, 5), number words (ten, seven) and nonwords derived from the number words by changing the onset of the syllable (e.g. sen, feven). There were no group differences in the speed or accuracy with which numerals and number words could be read, but there was a group difference in nonword reading: German children, who had learned the transparent language, made fewer errors and read the nonwords faster (see also Frith, Wimmer, & Landerl, 1998, who noted that English children have particular difficulty reading vowels that are represented inconsistently in the English orthography).

Caravolas, Volin, and Hulme (2005) made a direct comparison between the predictors of reading development in Czech (a highly transparent orthography) and English using carefully equated measures in the two languages. Reading in both languages was assessed by a test of reading fluency (the rate of reading aloud a list of unrelated words) since in the regular Czech orthography all children would be able to read aloud with near perfect accuracy. Spelling accuracy was also assessed. In both languages the predictors of variations in reading fluency were identical (phoneme awareness and coding – a speeded copying test), indicating that even in a transparent orthography variation in a child's ability to isolate phonemes in speech is a critical determinant of individual differences in reading ability (see Patel, Snowling, & De Jong, 2004, for a Dutch–English comparison). Phoneme awareness (along with reading ability and vocabulary) was also a predictor of spelling in both languages.

Thus it seems that the ease with which children learn to read in different languages varies according to the transparency of the mappings between letters and sounds in the orthography. In transparent orthographies, where these mappings are straightforward, children learn to read more easily. However, variations in the rate of learning to read are predicted by variations in children's ability to manipulate phonemes in speech in transparent orthographies just as in an opaque orthography such as English. Moreover, there is a reciprocal relationship between phonological awareness and the development of literacy in alphabetic writing systems. Morais, Cary, Alegria, and Bertelson (1979) showed that illiterate adults performed less well on phoneme awareness tasks than people who had been taught to read, suggesting that people's awareness of phonemes improves as a result of learning to read and spell. In line with this view, phoneme awareness appears to develop more quickly in readers of transparent languages, along with their reading skills, than in readers of English and other less transparent languages (notably Chinese, a nonalphabetic language; Read, Zhang, Nie, & Ding 1986).

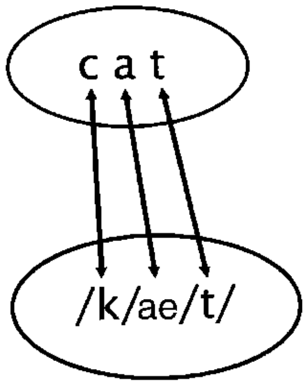


Figure 2.2 A simple diagram of the letter string CAT with arrows from the letters to the phonemes in the spoken word /k/ /æ/ /t/.

In summary, children need to be able to make connections between strings of letters in printed words and the sounds (phonemes) for which those letters stand in the spoken word (Figure 2.2).

This process of learning mappings between letters and sounds has interactive effects: Developing reading skills may depend upon incomplete, nascent phoneme-level representations of speech, but learning to recognize words in reading in turn facilitates the further refinement of the phonemic representations of speech.

Connectionist models of learning to read

As we have seen, there are specific cognitive requisites for learning to read but quintessentially it can be thought of as a process of learning. In recent years, the process of learning to read has been simulated in connectionist models that provide explicit theories of how children learn to map speech onto orthographic strings during reading development. Connectionist models are mechanistic models, implemented as computer programs. Their essential feature is that representations of words are not holistic (global representations) but are distributed across many simple processing elements in input and output systems. The input system can be thought of as representing words in their orthographic or printed form and is implemented as a set of orthographic units coding the letters and their position in printed words. Correspondingly, the output system represents words in their phonological or spoken form as a set of phonological units coding the phonological features of word pronunciations. Patterns of activation across these input and output units gradually

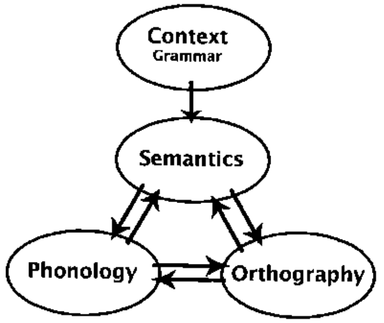


Figure 2.3 The Triangle model of Seidenberg and McClelland (1989). (Seidenberg, M. S. and McClelland, J., A distributed, developmental model of word recognition, *Psychological Review*, 96, p. 526, 1989, published by American Psychological Association and adapted with permission.)

become associated with each other as a function of learning, just as during reading acquisition children gradually learn the associations between letter strings in written words and their pronunciations.

The most influential connectionist model of reading development was proposed by Seidenberg and McClelland (1989; see Figure 2.3), referred to here as SM89. This "Triangle" model contains sets of representations dealing with orthographic (print), phonological (speech sound), and semantic (meaning) information, interconnected by sets of hidden units. The sets of hidden units give the model flexibility and allow it to learn complex sets of interdependencies between inputs and outputs.

The part of the model first implemented was a network with orthographic input and phonological output units connected by a set of hidden units (the so-called phonological pathway). Before "training" the model had essentially weak and random connections between the orthographic and phonological units, via the hidden units. Arguably, this beginning state is like that of the child when first approaching the task of reading. Training the model involved so-called supervised learning using a mathematical procedure (the generalized delta rule); the details need not bother us here. Essentially, on each training trial the computer presents the network with an input (a set of letters) and the network sends what can be thought of as feedback–activation from the activated input units to the hidden units and then on to the output units (this pattern of activity on the output units corresponds to the model's "pronunciation" of the printed word presented). At the start of training this output pattern will be random, and bear no systematic relationship to the correct pattern. The output pattern is then compared to the desired, or ideal, output pattern and the strengths of the connections between the output and input units (via the hidden units) are adjusted over many learning trials to bring them closer to the desired pattern. At the end of the training the model will "pronounce" nearly all the words on which it has been trained correctly (though there will likely be some small degree of error); the model has abstracted the relationships that exist between input and output representations in the set of words on which it is trained.

After training on a large corpus of nearly all English single-syllable words the SM89 model simulated several aspects of human word recognition. Perhaps the most important observation for present purposes was that after training the model could generalize (from knowledge embodied in the connections between input and output units) to words it had not been explicitly taught to read. That is, when presented with a novel string of letters, the model will generate a plausible pronunciation for that string. This can be likened to the developing reader's growing capacity to read new words that they have not seen before (though it has to be said that the ability of the SM89 model to read nonwords was not as good as that of a typical skilled adult reader of English; Besner, Twilley, McCann, & Seergobin, 1990).

A development of the SM89 model implemented to improve its generalization was proposed by Plaut, McClelland, Seidenberg, and Patterson (1996). Essentially, Plaut et al. (1996) adopted forms of representation in their new model corresponding to phonemes and graphemes and this allowed them to overcome the earlier model's problems with generalization (i.e. reading nonwords). When tested on nonword reading, the Plaut et al. (1996) model outperformed SM89, with performance approximating that of adult readers. Just as children learn to read most effectively when they come to the task with well-specified phonological representations (Snowling & Hulme, 1994), generalization within the connectionist architecture was better when training began with well-structured input and output representations (see also Harm & Seidenberg, 1999; Hulme, Quinlan, Bolt, & Snowling, 1995).

Another limitation of the SM89 model was that it did not deal with meaning. Plaut, et al. (1996) attempted to improve their model of reading by implementing a semantic pathway. In addition to the phonological pathway of connections between orthography and phonology, the Plaut et al. model contained a semantic pathway mapping orthography to phonology via semantic representations. Plaut et al.'s semantic units did not attempt to encode word meanings. Rather, the simulation involved training a network in which a semantic pathway provided additional activation to the phoneme units. An effect of combining semantic and phonological influences in the model was to increase the rate of learning, particularly for exception words (words like *yacht* that do not conform to the rules of pronunciation in English). In the later stages of training, Plaut et al. (1996) showed that the two pathways became highly specialized, so that the semantic pathway began to deal primarily with the pronunciation of exception words while the phonological pathway continued to be involved in the pronunciation of words (and nonwords) with consistent pronunciations.

The Triangle model (Plaut et al., 1996) provides a good framework for considering both the interaction of phonological and semantic skills during the course of reading development and individual differences in reading and its disorders (Plaut, 1997; Snowling & Hulme, 2006). According to this model the process of learning to read consists of creating mappings between orthography and phonology (the phonological pathway), and between orthography and phonology via semantics (the semantic pathway). Within each representational system in the triangle (orthography, phonology, semantics) we can think of words as being represented in terms of patterns of activation present on primitive features (these might be, for example, primitive line segments of letters, or features of how sounds in words are articulated, such as place or voicing). From a connectionist perspective, the child learning to read creates patterns of association (or mappings) that embody the relationships between spelling and sound, and spelling and meaning. In this view there is no need to postulate distinct phases or stages of development, but different stage-like behaviors may emerge as a consequence of different levels of training of such a "network". Moreover, such a system may display "rule-like" behavior without having any explicit representation of rules. It appears, as we will see later, that for children with dyslexia this phonological pathway does not develop as it should because of an underlying weakness in the phonological system.

The Pattern of Reading Impairment in Dyslexia

According to the models of reading development outlined above, phonological skills are critical for learning to read. In the Triangle model, learning to read is a process of creating mappings between orthography and phonology (the phonological pathway) and from orthography to phonology via semantics (the semantic pathway). If children with dyslexia have problems in the representation of phonology this would clearly be expected to impair the phonological pathway and, less obviously, might also delay the development of the semantic pathway (because learning the associations between semantic and phonological representations may be hindered by the phonological problems in dyslexia).

Clinically, the pattern of reading problems seen in English-speaking children with dyslexia is consistent with this idea. One of the first signs of dyslexia is a problem learning letter names and sounds. The ability to learn letters can be thought of as a form of paired-associate learning that depends upon creating associations between visual forms (of the letter) and new phonological forms (names or sounds). The bulk of evidence from studies of paired-associate learning suggests it is the verbal aspect of the process that creates problems for children with dyslexia, that is, a deficit in phonological learning (Vellutino, 1979).

Beyond letter learning, children with dyslexia typically have marked problems in reading isolated single words, where context and meaning can be of little help, and rather less severe problems in reading prose. Surprisingly it is often the case that the child with dyslexia may struggle with reading a passage aloud but show reasonable understanding by relying on well-developed language comprehension skills. Typically children with dyslexia will find learning to spell even more difficult than learning to read. Whereas reading can proceed on the basis of partial cues, spelling requires full information.

One of the most direct ways of investigating the development of decoding skills is to look at how well a child can read nonwords. A typically developing 7-year-old child will have no difficulty pronouncing nonwords such as pim or zot that they have never seen before. Children with dyslexia have problems in reading nonwords in comparison to younger children matched for reading age (Rack, Snowling, & Olson, 1992). Van Ijzendoorn and Bus (1994) conducted a meta-analysis and showed that the nonword reading deficit was moderate in size (Cohen's d =0.48; based on a total sample size of 1183 children). (See Box 2.3 for an explanation of effect size as used in this meta-analysis.)

Are there Different Types of Dyslexia in Childhood?

So far we have not referred to individual differences among children with dyslexia. Are all children with dyslexia the same, or are there different types of dyslexia? There have been many attempts to find so-called subtypes of dyslexia and many of these have been based upon the patterns of reading difficulties the children show. It has been suggested that children with dyslexia may be classified as phonological or surface dyslexics.

Phonological dyslexia is the pattern we have described above in which children experience severe nonword reading difficulties. Children with phonological dyslexia appear to have marked problems in using "phonic" reading strategies (sounding out unfamiliar words), while their use of lexical strategies (recognizing familiar words) is comparatively normal. Surface dyslexia is a term used to describe a different reading pattern. These children may read nonwords relatively accurately (but often slowly) and they find regular words (words like *camel* that can be sounded out using spelling–sound rules) easier to read than exception words (words like *yacht* that violate spelling–sound rules). Children with surface dyslexia have been described as often making regularization errors with exception words, that is, pronouncing them incorrectly as if they do follow spelling–sound rules (Coltheart, Masterson, Byng, Prior, & Riddoch, 1983). In other words, surface dyslexia is a pattern of reading that suggests overreliance on a phonological strategy; it is as if these children are locked in to using a letter–sound strategy slavishly and inflexibly. To identify how common these putative subtypes of dyslexia are, studies have been conducted with groups of children with dyslexia. Castles and Coltheart (1993) came up with an ingenious way of performing this classification. They suggested that nonword reading could be used as a measure of a child's phonological reading skills, and that exception word reading could be used as a measure of lexical reading skills (by lexical reading skills we mean the stored knowledge of words that a child has acquired; exception words are used for this because, arguably, they cannot be decoded using knowledge of spelling–sound correspondences; if you do not recognize the word *yacht* it will be difficult to work out how it is pronounced).

Castles and Coltheart (1993) then went on to use regression to predict nonword reading from exception word reading in a sample of normal children, and conversely to predict exception word reading from nonword reading in these same children. They then superimposed the scores for the children with dyslexia on these two plots. In such plots, children with dyslexia whose nonword reading fell below the level expected from their exception word reading ability, but whose exception word reading predicted from nonword reading was within normal limits, were classified as showing phonological dyslexia. Conversely, children with dyslexia whose exception word reading fell below the level expected for their nonword reading ability, but

Box 2.3 Effect sizes and meta-analysis

When we are considering findings from quantitative studies an important issue concerns the relative size of different effects. This is referred to as effect size in statistics and the basic idea is simple. Suppose we wanted to compare the differences in height and weight between samples of men drawn from the populations of two cities. We find the following figures for the two cities (City A: average height 175 cm, average weight 91 kg; City B: average height 173 cm, average weight 71 kg).

The men in City A are taller and heavier than the men in City B. The question, however, is how to compare these figures for height and weight in terms that make them comparable. Is the 2 cm difference in height smaller, bigger, or about the same as the 20 kg difference in weight? To make this comparison we need to express these differences in relation to the degree of variability in each of the measures. The measure of variability that we will use is the standard deviation of each measure. We can divide the difference in height by the standard deviation for height (this measure then gives us Cohen's d, the size of an effect in standard deviation or z-score units) and the same can be done for weight.

Let us suppose that the standard deviation of height in this population is 11 cm and the standard deviation of weight is 19 kg (these figures have been chosen to be roughly correct for 18-year-old males in Britain). So the difference in height relative to the variability of height is $2/11 = 0.18$ (Cohen's $d = 0.18$) ; and for weight the corresponding figure is $20/19 = 1.05$ (Cohen's $d = 1.05$). These figures show that the difference in weight for men in the two cities (1.05 standard deviation units) is much larger than the difference in height (0.18 standard deviation units).

Cohen (1988) suggested that in studies that are typical of psychology, effect sizes of 0.2 or less were small, effect sizes around 0.5 were medium, and effect sizes of 0.8 or above were large. As psychologists we are probably most familiar with IQ as a measure. IQ is measured on a scale where the population average is 100 with a standard deviation of 15. This means that in terms of Cohen's d a difference in IQ of 3 points would be a small effect ($d = 3/15 = 0.20$), a difference of 8 points would be a medium effect ($d = 8/15 = 0.53$), and a difference of 12 points would be a large effect ($d = 12/15 = 0.8$).

There are other measures of effect size that can be used, but in this book, where we are typically interested in the difference in means between two groups, Cohen's d is the most obvious one to use, and one that is very easy to understand. When we discuss differences in the average level of performance between clinical and control groups of children we will often use this measure of effect size to convey the magnitude of a given effect.

One other important feature of effect sizes is that they give a way of combining information from many different studies, using a technique called meta-analysis. So for example, van Ijzendoorn and Bus (1994) found many studies that had

Box 2.3 (*cont'd*)

examined how well children with dyslexia could read nonwords but the different studies had used many different tests of nonword reading ability. However, given that each study reports the mean and the standard deviation for the nonword reading scores for the dyslexic and control children, they could calculate an effect size for each study and then average the effect sizes from the different studies to get an average effect size. Combining effect sizes in this way (usually giving a greater weight to the estimates of effect size from studies with large samples) gives us a powerful way of combining the results from different studies.

whose nonword reading predicted from exception word reading was within normal limits, were classified as showing surface dyslexia. Thus, in this scheme, children with phonological dyslexia have problems in nonword reading in the presence of adequate exception word reading, while children with surface dyslexia have problems with exception word reading but adequate nonword reading.

One important problem with this study, however, was that the data for normally developing children came from children whose reading skills were much better than those of the children with dyslexia (Snowling, Bryant, & Hulme, 1996). This research strategy has been criticized on the grounds that it creates problems for the interpretation of group effects. Essentially, by comparing children who differ in levels of reading achievement, it is not possible to judge whether apparent group differences between good and poor readers are a cause of their reading problem or a consequence of different amounts of reading experience. To get around this problem, a common strategy is to compare children with dyslexia, not only with children of the same age who are normal readers but also with younger children matched for reading age (RA controls).

Two studies following on from Castles and Coltheart (1993) used this technique to compare children with dyslexia with younger RA controls (Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Stanovich, Siegel, & Gottardo, 1997). These studies produced much weaker evidence for subtypes of dyslexia: Stanovich et al. showed that 17/68 children with dyslexia showed the phonological pattern but only 1/68 showed the surface pattern. Similar results were also obtained in the study by Manis et al. Most interestingly, in both studies it was the children classified as having phonological dyslexia who tended to show significant deficits on tests of phonological ability.

In our view it is better to move away from using the phonological and surface subtype labels since these are just behavioral descriptions of patterns of reading impairment that are not in fact stable over time (Manis & Bailey, 2001). The results described above might be better thought of in terms of continuous variations in the skills that underlie reading development. As Griffiths and Snowling (2002) showed, children with the most severe phonological difficulties will tend to show the most severe nonword reading difficulties. The surface dyslexic pattern seems in contrast to be associated with much milder phonological difficulties. Mild phonological difficulties, possibly coupled with being taught with an emphasis on "phonics" and low levels of print experience, may lead to a surface dyslexic pattern in which the child laboriously tries to sound out every unknown word. It is important to emphasize that the reading patterns that are used to "diagnose" surface and phonological dyslexia are concerned with children's attempts to read aloud words (or nonwords) they do not know. However, all these children with dyslexia show poor word recognition skills in relation to their age, and these problems are manifested in problems in reading both irregular and regular words. Testing nonword reading gives us a tool to examine how well a child's phonological reading system is working and it is clear that a significant proportion of children with dyslexia show nonword reading problems that are even more severe than expected for their overall level of reading skill. These children appear to be those with the most severe phonological difficulties.

Dyslexia in Different Languages

As we saw earlier there is evidence that children find it easier to learn to read in languages such as Czech and German with regular sound–spelling correspondences than in English, which has somewhat irregular sound–spelling correspondences. We might expect that the problem of dyslexia would be less severe in regular writing systems than in an irregular writing system such as English. There is some evidence in support of this idea. It has been claimed that among German-speaking children with dyslexia early difficulties with phoneme awareness are overcome by the second year in school (Wimmer, 1996) and that in terms of reading accuracy they may be no worse than CA controls, although they do appear to read more slowly and many have spelling difficulties (Landerl & Wimmer, 2000; Wimmer, 1996). However, Caravolas et al. (2005) compared the cognitive deficits found in groups of English and Czech children with dyslexia using more sensitive (and more difficult) measures of phoneme awareness than those used by Wimmer and his colleagues in studies of German. Caravolas et al. found that in both Czech and English the children with dyslexia showed severe problems in manipulating phonemes in spoken words. These findings suggest that problems in phoneme manipulation skills are a core deficit in children with dyslexia in both regular and irregular orthographies (see Caravolas, 2005, for a review). In Chinese, where phoneme level skills are less important, the picture is somewhat different. However it is worth noting that poor rapid naming skills characterize children with dyslexia in Chinese who have difficulty in establishing character–sound connections, which depend on phonological learning.

Cognitive Explanations of Developmental Dyslexia

With these ideas about normal reading development, and the pattern of reading difficulties shown by children with dyslexia as background, we are now ready to consider some of the possible cognitive causes of dyslexia. If we accept the triangle model as a metaphor for learning to read single words, then problems with the creation of any of the three classes of representation embodied in the model might be involved: problems with phonological (sound), orthographic (print) or semantic (meaning) representations, or problems in creating appropriate linkages between these classes of representation. These three representational systems (or modules to use Fodor's term) all develop quite gradually. The phonological and semantic systems are both components of oral language and typically these systems, and the linkages between them, are quite well developed by the time a child goes to school (see Chapter 4). The phonological system allows a child to perceive the sound structure of spoken words, and to produce those sound structures when speaking. The semantic system allows a child to access the meanings of words they hear and to express the meanings they want to convey using appropriate words in speech. Both systems therefore participate in language comprehension and production. According to some models, the phonological system used in speech perception may be separable from the phonological system required for speech production.

In contrast to the phonological and semantic systems, the orthographic system is something that only develops as a result of learning to read. The development of this system depends critically upon the ability to map the speech sounds of spoken words onto the visual representations of printed words. Satisfactory development of orthographic representations therefore depends not only on language skills but also upon sensitivity to the graphic features of letters and the ability to parse letter strings, together referred to as graphemic parsing skills.

By far the best developed theory of dyslexia is that it arises from a phonological deficit. This dominant phonological deficit theory of dyslexia attributes the child's reading difficulties to an inability to establish the phonological pathway in the triangle model. Here we will present this theory in some detail, and we will only consider alternative theories (for which the evidence is much weaker) very briefly.

Dyslexia as a phonological deficit

It may be useful to start by drawing the phonological deficit theory of dyslexia in a path diagram (see Figure 2.4). This is a very simple causal theory stating that problems with phonology that pre-date reading are a cause of later reading problems. Though this theory could be refined and developed in various ways, representing the

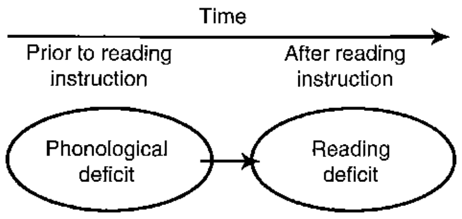


Figure 2.4 Path model showing the primary cause of dyslexia.

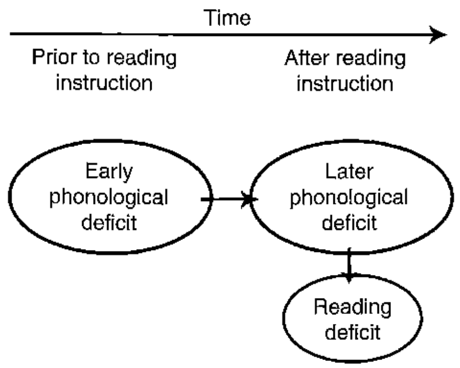


Figure 2.5 Elaborated path model showing causes of dyslexia.

bare-bones of this theory is a useful place to start. Such a theory makes at least two strong claims:

1 Children who become dyslexic will show a phonological deficit before they begin to learn to read.
2 The severity of the phonological deficit will predict variations in the severity of the reading deficit.

We should note that the version of this theory we are advocating sees the phonological deficit persisting through time. It is the phonological deficit present at the time the child is learning to read that is the proximal cause of reading difficulties. The important point, however, is that the cause (a phonological deficit) pre-dates the consequence (a reading problem). We can represent this slightly elaborated theory as in Figure 2.5.

In this slightly elaborated theory, the later phonological deficit is shown as persisting at the time that reading emerges (the underlying phonological deficit is acting forward in time to cause problems in learning to read). This theory makes an additional and highly specific prediction which is that the early phonological deficit affects later reading ability through a mediated relationship. That is, the effects of the early phonological deficit are entirely mediated by (operate through) its effects on the later phonological deficit. It is the later phonological deficit that is the immediate cause of the reading problem. (We can test such mediated relationships statistically, but that is not important in the current context.) What this means is really very simple: If a child had a phonological deficit early in life that was remedied before they started reading, this would not matter and reading would develop normally (as seems to be the case for some children whose developmental speech difficulties resolve by school entry; see Chapter 4). However, a child who has a persisting phonological deficit that is present when they start to learn to read will develop a reading problem that, on average, will be more severe the more severe the phonological deficit. There is evidence for both late (after reading has begun) and early (before reading has begun) phonological deficits in dyslexia, but there is much more evidence concerning the late deficits. We will consider this evidence first.

Phonological deficits in school-age children with dyslexia

Before considering evidence for phonological deficits in children with dyslexia, a couple of methodological points are worth reiterating. First, the studies we will summarize typically involve groups of children with moderate to severe reading problems but normal IQ. This is a conservative strategy; if we find cognitive deficits in people with reading problems who have average IQ, then the deficit cannot simply be due to some general intellectual impairment and might therefore be a possible cause of the reading problem. Second, these studies often compare children with dyslexia to normally developing children of the same age and IQ (a chronological-age (CA)-matched design), and sometimes also to younger normally developing children whose reading skills are at the same absolute level (the reading-age (RA)-matched design). The logic here is that if children with dyslexia perform more poorly on a task than younger children who have the same level of reading skill, then the difference cannot be explained in terms of reading ability or experience. This is particularly important with tasks where it could be the case that learning to read improves the skill in question, which is the case for almost all measures of phonological ability given the evidence we have considered earlier that there is a reciprocal relationship between phonological and reading skills. It is useful to consider evidence for phonological deficits in dyslexia under two broad headings: phonological awareness and phonological processing. In the literature, this difference has also been referred to as explicit versus implicit phonology.

Phonological awareness in dyslexia

Phonological awareness tasks measure children's ability to make explicit judgments about the sound structure of spoken words. One of the first studies to show that children with dyslexia are poor at these sorts of task was that of Bradley and Bryant (1978), who compared a group of 12-year-old children with dyslexia with a group of younger RA-matched children. In this study, children heard a sequence of four words and simply had to select the word that did not rhyme, or did not begin with the same sound, as the other three words. The children with dyslexia were worse at this task than the RA controls, and were also worse at generating words to rhyme with a target word. Subsequent studies have confirmed this pattern of impairments in phonological awareness tasks in children and adults with dyslexia compared to RA controls (Bruck, 1990; Manis, Custodio, & Szeszulski, 1993).

There is evidence, as we saw earlier, that for normally developing children awareness of phonemes seems to be much more strongly related to reading than is awareness of larger phonological units such as rimes. We might expect, therefore, that children with dyslexia would show even greater deficits on measures of phoneme awareness than on measures of rime awareness. This turns out to be the case. Swan and Goswami (1997a) compared children with dyslexia with a group of CA and younger RA controls. The children with dyslexia were worse than the CA control group, but comparable to RA controls, on tests of syllable segmentation and onset–rime similarity. However, they were actually significantly worse than the RA controls on a phonemic awareness task. The same pattern was found by Windfuhr and Snowling

(2001). Thus in children with dyslexia, as in normally developing children, the ability to analyze speech at the phonemic level appears to be particularly closely related to the ability to learn to read.

Phonological processing in dyslexia

Phonological processing tasks require the child to use speech, without necessarily reflecting upon the structure of spoken words. Typical examples of tasks that psychologists have used to investigate phonological processing include repeating a word or nonword, naming a picture, or remembering a list of words. Children with dyslexia show difficulties on all these simple tasks.

Nonword repetition One of the simplest procedures we can use to assess a child's phonological abilities is to ask them to repeat a spoken word or nonword. Snowling (1981) compared the ability of children with dyslexia with a group of RA controls, some 4 years younger, to repeat polysyllabic words (e.g., pedestrian, magnificent) and nonwords derived from the same words (kebestrian, bagmivishent). The children with dyslexia had no difficulty repeating the words but were worse than the RA controls at repeating the nonwords.

In a further study Snowling, Goulandris, Bowlby, and Howell (1986) examined the repetition of nonwords, low-frequency words, and high-frequency words by children with dyslexia and CA and RA controls. To examine the possible importance of perceptual factors, the words and nonwords were presented in varying degrees of noise (noise masking). Both the children with dyslexia and the controls were affected by the noise masking, to a similar degree, suggesting that any difficulty in repetition could not be attributed to problems in perception. Most importantly, however, the children with dyslexia repeated fewer nonwords correctly than both the CA and RA controls. With low-frequency words the children with dyslexia showed milder difficulties, being worse than the CA controls, but similar to the RA controls.

A parsimonious account of these findings is that children with dyslexia have particular difficulties in setting up the speech motor programs that are necessary to articulate a novel item (see also Hulme & Snowling, 1992). Furthermore, it is plausible that the speech production problems revealed in nonword repetition tasks are fundamental to explaining a wide range of difficulties in children with dyslexia. In fact nonword repetition ability in normally developing children has been shown to be a good predictor of vocabulary acquisition (Baddeley, Gathercole, & Papagno, 1998) and of foreign language learning (Service, 1992). Clinically, there is a strong association between dyslexia and subtle speech problems, including mispronouncing unusual words, word-finding problems, and malapropisms (interchanging a word with a similar sound for the intended word). People with dyslexia also often complain of difficulties in learning foreign languages. The speech production problems underlying nonword repetition problems may well delay the learning of spoken vocabulary and one of the consistent findings from population surveys is that children with reading difficulties are slow to learn to speak. These problems of learning may also compromise the quality of representations for spoken words that are stored in memory, and this in turn may result in difficulties in tasks such as naming, to which we will now turn.

Naming difficulties Confrontation naming, which involves asking someone to name a picture, provides a simple way of assessing a child's language skills. Snowling, van Wagtendonk, and Stafford (1988) gave 11-year-old children with dyslexia a picture naming test and compared their performance with that of an age-matched and a younger comparison group. The children with dyslexia named fewer pictures than CA controls but were comparable to the younger children of roughly similar reading skill. In a second study each child with dyslexia was individually matched with a normal reader for their ability to define spoken words. This arguably gives a measure of the size of a child's vocabulary. The children were then given two other tasks: a confrontation-naming test (as before) and a test requiring the child to choose a picture that corresponded to a spoken word. These two tests give measures of closely related but different aspects of vocabulary knowledge. Confrontation naming gives a measure of expressive vocabulary (how many words can a child successfully produce) while matching a spoken word to a picture gives a measure of receptive vocabulary. The results were very clear; the children with dyslexia showed deficits on confrontation naming (expressive vocabulary) but were normal on the word/picture-matching task (receptive vocabulary).

These naming difficulties in dyslexia are consistent with the idea that semantic information (word meanings) is adequately represented in memory but that phonological information (word sounds) is poorly represented. Further evidence that is consistent with this idea comes from a study by Swan and Goswami (1997b). Here a group of children with dyslexia together with RA and CA controls were given a difficult naming task. The children with dyslexia performed even more poorly on this task than the RA controls and only did as well as generally poor readers of low IQ. Importantly, however, the children with dyslexia were able to define many of the words they had been unable to produce as names to the pictures, indicating that they had effective semantic representations of the words.

A different way of assessing naming problems is by using tests of rapid automatized naming (RAN; Denckla & Rudel, 1976). Denckla and Rudel gave children cards with 50 (10 rows of 5) common items (letters, digits, color patches) to name as quickly as possible. This study, together with many subsequent ones, showed that on average children with dyslexia are slower on such tests than typically developing readers of the same age (Wolf & Bowers, 1999), and that these problems persist into adulthood (Pennington, van Orden, Smith, Green, & Haith, 1990). The precise nature and best theoretical explanation for these RAN deficits in children with dyslexia is currently the subject of much research.

One simple view would be that slow naming on the RAN task is just another indicator, along with failures to name objects with long low-frequency names correctly, of an underlying deficit in phonological representations (Snowling & Hulme, 1994; Wagner, Torgesen, & Rashotte, 1994). If the phonological forms of words are stored inefficiently in memory, it may take longer to retrieve them when they are needed. Another view is that RAN deficits may be part of a difficulty with a timing mechanism (Wolf & Bowers, 1999). There are certainly other possibilities as well: The

RAN task demands rapid articulation and sustained concentration, and both of these might be weaker in children with reading problems. For present purposes we simply note that studies of RAN provide evidence, from another very simple task, suggestive of underlying phonological problems in dyslexia.

Short-term memory Although children with dyslexia have been reported to show normal visual memory, verbal short-term memory tasks are an area of difficulty for them (Hulme, 1981; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). In a typical verbal short-term memory task, the person hears a spoken list of words and simply has to repeat these words in the same order as they are presented. This task will obviously tap the adequacy of speech perception and production mechanisms (amongst other processes) and we know that people place very heavy reliance on a phonological code for the completion of such tasks (Crowder, 1978). Evidence for the importance of phonological coding comes from the observation that it is much harder to remember sequences of items that sound similar to each other than sequences that sound dissimilar (the phonological similarity effect; Conrad, 1964) and it is harder to remember sequences of long words than short words (the word length effect; Baddeley, Thomson, & Buchanan, 1975). It appears that children with dyslexia, like normal readers, place heavy reliance on the same phonological code in these tasks but that this code operates less efficiently (Hall, Ewing, Tinzmann, & Wilson, 1981; Johnston, Rugg, & Scott, 1987).

The effects of word length on short-term memory take a highly specific form. Longer words take longer to articulate and there is a strong relationship between the rate at which people can articulate words of different lengths and their memory for these words (Baddeley et al., 1975). It also appears that, developmentally, differences in short-term memory performance are closely paralleled by changes in maximal articulation. Figure 2.6 shows the results of an experiment with children ranging in age from 4 to 11 years as well as adults (Hulme, Thomson, Muir, & Lawrence, 1984). In this study, participants were given lists of one-, two- and three- syllable words to remember that were selected from pictures in young children's books; they were also asked to repeat aloud these same words as quickly as they could. It is clear that both the differences in memory between words of different lengths and the differences in memory performance with age are closely paralleled by differences in articulation rate. These results show that there is a close association between speech production processes and short-term memory processes.

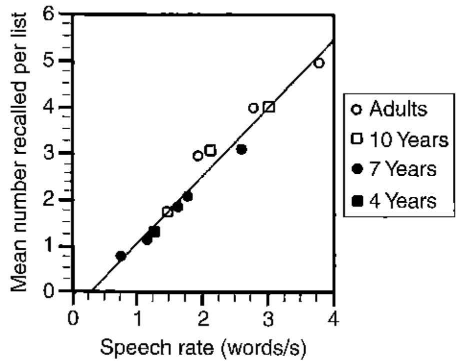


Figure 2.6 The relationship between speech rate and memory span across development. For each age group, three symbols are shown representing the results from one-, two- and three- syllable words. (Reprinted from *Journal of Experimental Child Psychology*, 38, Hulme, C., Thomson, N., Muir, C., and Lawrence, A. L. Speech rate and the development of short term memory span, pp. 241–253, copyright (1984), with permission from Elsevier.)

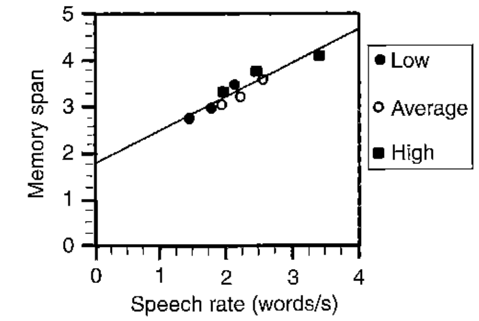


Figure 2.7 The relationship between speech rate and memory span in children of low, average, and high reading ability. (Reprinted from *Journal of Experimental Child Psychology*, 58, McDougall, S., Hulme, C., Ellis, A. W., and Monk, A. Learning to read: The role of short-term memory and phonological skills, p. 120, copyright (1994), with permission from Elsevier.)

McDougall, Hulme, Ellis, and Monk (1994) used the relationship between word length and articulation rate to explore the origins of memory differences in children who differed in reading ability. This study did not involve children with dyslexia, but a fairly large sample (90) of children who differed widely in reading ability. The children were simply divided into three groups according to reading ability, and the poor readers were selected in such a way that they had similar, though less severe, reading problems to those seen in dyslexia. The results of this study (shown in Figure 2.7) are remarkably clear. The poor readers have substantially lower memory spans (memory span is the longest list a subject can recall correctly) than the average and good readers, but the differences between groups in memory span are exactly paralleled by differences in speech rate. In fact if differences in speech rate between the groups are controlled for statistically, differences in recall are eliminated.

The best theoretical account of the relationship between word length, speech rate, and memory performance is currently the subject of debate. For present purposes it is worth considering that it might be that those individuals who can articulate words more quickly also have better developed phonological representations of those words. The findings of McDougall et al. (1994) demonstrate clearly that the short-term memory difficulties of poor readers are intimately related to problems in speech processing mechanisms (as indexed by slow rates of articulation). In short, there seems to be a basic inefficiency in the operation of this phonological code in children with dyslexia that might tentatively be related to an underlying problem with speech production mechanisms that also results in impaired speech rate.

Phonological paired-associate learning We have already seen that children with dyslexia find naming difficult. Naming is a memory retrieval task in which we use the visual stimulus (the object we see) as a cue to retrieve the name of that object from memory. Difficulties in naming provide evidence that this retrieval process is inefficient in children with dyslexia.

We can look at these problems in a different way, by examining the process of learning new names. Learning the names of objects is an example of visual–verbal paired-associate learning. In paired-associate learning we have to learn that a particular stimulus (the picture) is associated with a particular response (the name). We know from many experiments that children with dyslexia find paired-associate learning difficult when a verbal response is required, but that they perform normally if they have to learn to associate two visual nonverbal forms (Vellutino, Scanlon, & Spearing, 1995). Children with dyslexia also find it difficult to learn to associate nonsense names with unusual animals (Wimmer, Mayringer, & Landerl, 1998) or with abstract shapes (Windfuhr, 1998). It is plausible to see these difficulties in verbal paired-associate learning as another reflection of problems with the representation of phonological information in children with dyslexia. However, Hulme, Goetz, Gooch, Adams, and Snowling (2007) showed, in a large sample of normally developing children, that visual–phonological paired-associate learning and phoneme awareness were statistically independent predictors of variations in reading skill. This suggests that there may be something tapped by measures of phonological learning that is not simply reducible to phonological skills per se.

Are phonological deficits present before reading development begins?

The phonological deficit found in children with dyslexia is present before reading begins (and hence cannot be a consequence of the reading impairment). Evidence for this comes from longitudinal studies of children selected for being at risk of dyslexia (because of a family history of the disorder). In the first study of this type, Scarborough (1990) reported data from 34 at-risk children. The analyses compared the performance of 20/32 of the at-risk children who went on to develop reading problems with the 12/32 at-risk children who became normal readers. The at-risk children who became dyslexic showed problems with pronunciation in spontaneous speech at 2.5 years, had problems with receptive vocabulary and object naming at 3 years, and at 5 years (before they started school) had weaknesses in letter knowledge, phoneme awareness, and object naming. This study shows that, as well as having phonological difficulties well before they learn to read, children with dyslexia show signs of some broader language weaknesses (such as shorter utterances and lower syntactic complexity) in the preschool years.

Convergent findings have since been observed in a number of other studies. Pennington and Lefly (2001) followed the progress of 67 children at high risk of dyslexia and 57 controls considered to be at low risk, from before entry to kindergarten when the children were 5 years old to the summer after second grade. They found an increased risk of dyslexia in affected families: 34% of the high-risk group were diagnosed as "reading disabled" in second grade, compared to only 6% of the low-risk (control) group. Children who became reading disabled showed deficits on tests of speech perception, verbal short-term memory, rapid serial naming, and phonological awareness at all testing points relative to controls and to high-risk unimpaired children.

Similar results were reported by Snowling, Gallagher, and Frith (2003), who followed 56 children at high risk of reading difficulties from just before their fourth birthday until 8 years of age. The children who went on to become dyslexic experienced delayed early language development at 3 years 9 months (Gallagher, Frith, & Snowling, 2000), with weaknesses in object naming, letter knowledge, and nonword repetition; at 6 years they had persisting oral language impairments and phonological awareness was poorly developed. In contrast, the high-risk unimpaired group was not distinguishable from controls on oral language tests. In similar vein, Hindson et al. (2005) compared the cognitive, language, and preliteracy skills of preschool children who were either at family risk of dyslexia or not. The at-risk group showed lower scores on a wide range of phonological and language measures, including phoneme awareness, rhyme awareness, letter knowledge, verbal memory, articulation rate, and vocabulary knowledge.

It seems safe to conclude that children with dyslexia display a phonological deficit before they have begun to learn to read. In contrast to findings from laboratory studies, children from family samples also appear to show some broader (nonphonological) language weaknesses in the preschool years. Arguably in family samples, oral language difficulties affect reading development via delayed phonological skills. Within this model, phonological deficits are mediators of poor reading (Figure 2.8).

Is the phonological deficit the product of a speech perception deficit?

The evidence so far shows that children with dyslexia perform poorly on a variety of tasks that tap phonological (speech processing) skills. We have argued that these

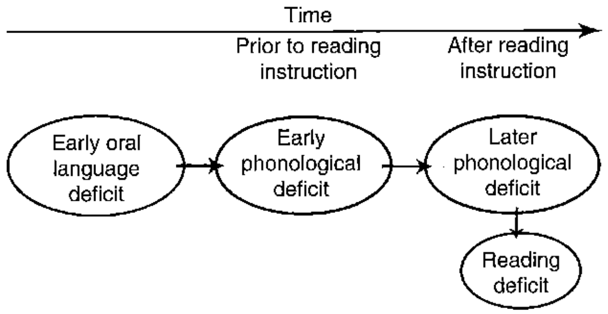


Figure 2.8 Path diagram showing phonological deficits as mediators of poor reading.

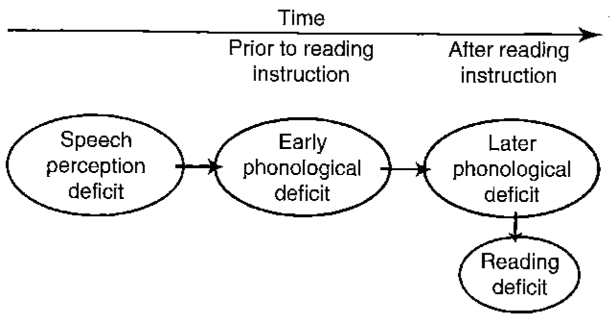


Figure 2.9 Path diagram showing a possible causal role of speech perception deficits in the development of reading problems.

phonological problems seem to reflect a problem with speech production rather than speech perception. It remains the case, however, that problems of perception and production are hard to separate, and it is always possible that subtle problems in the perception of speech, could lead to problems with speech production. In fact it is possible that problems with the perception of speech might lead to problems in creating adequate phonological representations. We might represent that theory as in Figure 2.9. Within this theory, again phonological deficits mediate the impact of speech perception on reading. Evidence directly relevant to this causal theory is limited, though a number of studies have examined speech perception in school-age children with dyslexia.

Speech can be analyzed as units of different sizes. A fundamental unit is the phoneme. A phoneme is defined as the smallest unit of sound that signals a difference in meaning. So, for example, *pin* and *bin* are two words that differ only in the first phoneme, and the initial sounds in these two words are represented as /p / and /b/. In fact phonemes themselves can be considered to be composed of even smaller parts, perhaps analogously to the way atoms can be considered to consist of subatomic particles. In the case of the initial phonemes (or obstruents) in *pin* and *bin* the sounds /p / and /b/ differ by only one phonetic feature; this feature is voice onset time (VOT), the time between lip closure and the onset of vocal cord vibration. (Intuitively, the similarity between these sounds is probably obvious when you say the words *pin* and *bin*; the sounds /b/ and /p/ seem more similar to each other than each is to the /s/ sound in *sin*, which comes from a different class of sounds called fricatives.) Phonetic features are defined in terms of the articulatory movements or gestures that are involved in their production, but the differences in articulation of course correspond (often in complex ways) to differences in the acoustic form of words.

Natural speech is complex and it is difficult to control its properties in experiments. For this reason much research on speech perception uses synthetic or computer-generated speech. Computer-generated speech makes it possible to manipulate the features of speech in precise and replicable ways. Differences between the sounds /p/ and /b/ reflect differences in VOT. In speech the timing of this cue shows more or less continuous variation. Consonant phonemes cannot be produced or perceived in the absence of a vowel and therefore consonants are placed in a syllable with a vowel when we ask people to make judgments. So, for example, we might present to people two synthesized syllables /ba/ and /pa/ (these sound like *bah* and *pah*). However, if the cue of VOT is continuously varied in such a pair of syllables we do not perceive a continuously varying signal that gradually sounds less like /pa/ and more like /ba/. Instead we perceive either the syllable /pa/ or /ba/ (see Figure 2.10). This is referred to as categorical perception (we perceive sounds as belonging to one or other category, while being relatively insensitive to differences between sounds within a category; this is clearly adaptive, because we want our speech perception module to recognize the spoken words we hear in an unambiguous way).

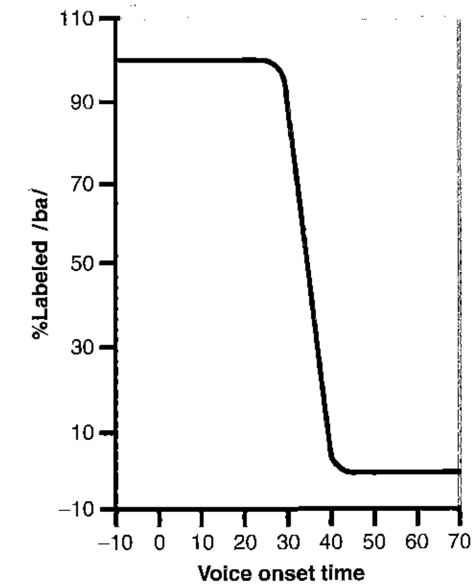


Figure 2.10 Graph showing categorical perception for [ba] versus [pa].

Several studies have now investigated the perception of synthetic and natural speech stimuli in children with dyslexia. Evidence from several studies shows that children with dyslexia on average have mild difficulties on speech perception tasks (Chiappe, Chiappe, & Siegel, 2001; de Weirdt, 1988; Reed, 1989). However, there is accumulating evidence that these group differences might be attributable to a subgroup of children in the sample who show speech perception deficits. Manis et al. (1997) examined the perception of synthetic stop consonants (/b/ and /p/) in 12-year-old children with dyslexia. Overall, the performance of children with dyslexia was more error prone and they were more likely to identify clear instances of /p/ as /b/ and vice versa; this particular difficulty might plausibly be related to a difficulty in attaching the appropriate "labels" to the different stimuli rather than to a problem with speech perception per se. Manis et al. went on to show that among the children with dyslexia only 7/25 had difficulties on the speech perception task, and these children also showed severe phoneme awareness difficulties.

Adlard and Hazan (1998) reported that 4/13 children with dyslexia had quite severe problems on natural speech discrimination tasks and with a difficult synthetic speech identification task (sue – zoo) when compared to younger RA controls. It appears that these children with dyslexia probably had the most severe phonological difficulties – they were amongst the worst on a test of nonword reading and two of the group had severe nonword repetition difficulties. A similar pattern to this was also found by Masterson, Hazan, and Wijayatilake (1995).

However, a subtly different conclusion emerges from a study by Joanisse, Manis, Keating, and Seidenberg (2000). In this study a large group of 137 children with reading difficulties were given phoneme identification tests involving voice onset time (dug – tug) and place of articulation (spy – sky). Somwhat surprisingly, the poor readers as a group did not differ from the CA controls on these speech perception measures and, furthermore, poor readers with the most severe phonological difficulties were not the most impaired on the phoneme identification measures. However, a small subgroup of nine poor readers performed at a lower level than younger RA controls on the phoneme identification tasks. These children were referred to as "language impaired" dyslexics and were characterized by poor vocabulary knowledge and low scores on a test of word structure tapping grammatical skill. Regression analyses showed that, among the children with dyslexia, performance on a word structure test (tapping morphology) was a strong predictor of speech perception ability (phoneme identification) while tests of phonological skills (phoneme deletion and nonword reading) were not. The findings from this study suggest that the speech perception problems that are sometimes, but not always, found in children with dyslexia may relate to broader oral language difficulties that occur in a minority of these children, rather than being tied specifically to phonological difficulties.

It is perhaps important to emphasize that experiments such as these, with difficult discriminations and many trials, are very demanding of attention in young children. Children may do badly on such tasks because they find it difficult to maintain attention even though their perceptual abilities are actually fine. A different, and perhaps better, way of investigating speech perception comes from the gating task (Grosjean, 1980). Here children hear progressively longer snippets of recordings of single words and the task is simply to say what the word is. Typically, people can identify a word before they have heard all of it, and more familiar (high-frequency) words are identified more easily. Some studies have found that children with dyslexia typically recognize words in gating tasks as well as age-matched controls (Elliott, Scholl, Grant, & Hammer, 1990; Griffiths, & Snowling, 2001). However, a slightly more complex pattern of results was reported by Bruno et al. (2007), who performed a gating task with a group of children with dyslexia and age-matched controls. As in previous studies these authors found no difference in the accuracy of performance on the gating task between the children with dyslexia and controls. However, they also scored responses in the gating task for whether the child responded with an item from the correct category (defined as a word that ended in the same category of consonant (nasal, lateral, or oral stop consonant) as the target word). On this score, the children with dyslexia performed less well than the age-matched control children. These responses, it was argued, reflected how well children could use information from coarticulation to identify the likely terminal consonant in the word (coarticulation refers to the fact that the way a vowel is articulated will differ depending upon the consonant that follows it). In regression analyses, it was shown that a measure of phoneme and syllable deletion was related to the category gating scores, but that gating was not a predictor of reading ability once the effect of phoneme and syllable deletion was accounted for. It was argued that these results support the theory that children with dyslexia have poor representations of the phonological forms of words (and that these difficulties with phonological representations account for their difficulty in arriving at the best "category" of response in the gating task).

It seems from the studies considered so far that any problems in speech perception in children with dyslexia are certainly less marked than the problems shown on phonological output tasks such as nonword repetition and confrontation naming. Recently, a variant of the hypothesis that speech perception difficulties might be a cause of dyslexia has been proposed by Serniclaes, Van Heghe, Mousty, Carré, and Sprenger-Charolles (2004). They propose that children with dyslexia display an "allophonic mode of speech perception." Allophones are variants of the same phoneme that normal listeners would categorize as belonging to the same phoneme category. Normal listeners are relatively insensitive to differences between allophones but are correspondingly highly sensitive to differences between different phonemes. Serniclaes et al. suggested that children with dyslexia show greater sensitivity to allophones and a reduced sensitivity to differences between speech sounds that cross a phoneme boundary.

To test this idea they compared a group of 18 9-year-old children with dyslexia to a group of normally developing children of the same age. The task involved children listening to pairs of syllables that differed in voice onset time (VOT) and deciding if each pair was the same or different; different pairs of syllables varied in the degree of difference in VOT. The expectation for normal listeners is that people should show increased sensitivity to pairs of syllables that cross the phoneme boundary, and this was found for the control children. The children with dyslexia, in contrast, showed a flatter function, with the suggestion of reduced sensitivity at the phoneme boundary and slightly enhanced sensitivity at another point within a phoneme category. Levels of performance on the speech discrimination task were very low, however, suggesting that the task may have been too difficult for all the participants (including some adults who were tested).

In summary, it appears that problems on speech perception tasks in children with dyslexia are relatively mild in comparison to the problems shown on other phonological tasks, and some studies report that only a small minority of children with dyslexia show such impairments. Most studies in this area say little about what differentiates those children with dyslexia who have speech perception impairments from the majority whose speech perception appears normal. However, the study by Joanisse et al. makes quite a convincing case that the speech perception problems found in children with reading difficulties might actually be a manifestation of broader oral language problems that are found in only a minority of children with reading difficulties. (In this view speech perception problems are not a cause of the phonological and reading problems seen in most children with dyslexia, though they may contribute to the phonological difficulties in a subgroup of children with dyslexia who also have broader (nonphonological) language difficulties.) We badly need more studies that explore this issue, using broader and more inclusive assessments of different oral language skills and preferably following children longitudinally to explore whether the patterns of association between different impairments change with age.

An important study that moves us some way toward this goal was reported by Boada and Pennington (2006), who set out to test the segmental hypothesis of dyslexia. According to the segmental hypothesis (Fowler, 1991), the cause of reading problems can be traced to poorly specified phonological representations that, in turn, compromise reading development, a view with which we have sympathy (Snowling, 2000; Snowling & Hulme, 1994). In order to test this hypothesis, Boada and Pennington (2006) used three tasks designed to assess implicit phonological processing in dyslexia and also measured speech perception, explicit phonological awareness, nonword repetition, and rapid automatized naming (RAN) for colors and objects. In addition, to assess the hypothesis that language-impaired children with dyslexia might show more severe impairments, particularly speech perception deficits, they included groups of children with dyslexia only (RD) and children with dyslexia who also had a history of speech-language difficulty (RD+LD) according to parental report (it should be noted at the outset that this way of differentiating the two groups was not validated in terms of concurrent language performance and therefore could be regarded as less than ideal).

These two groups of poor readers were compared with an age-matched (CA control) and a younger typically developing (RA control) group of readers, matched on performance IQ, gender, and socio-economic status. ADHD symptoms were also measured by parent report.

There were three tasks measuring implicit phonology. Perhaps the one to yield the clearest results was the syllable similarity task, in which children heard triads of words, two sharing the first phoneme (e.g., bis, bun) and two sharing syllable structure (e.g., bis, dis). Each word in each triad was associated with a small toy animal and the child's task was to learn the names of the animals. On each training trial the child repeated the word as the toy was shown and on each learning trial the child responded by pointing to indicate the toy that went with the name (e.g., which one is "dis"?). These trials were alternated up to six times. For children who learned the names to the criterion there was a delay of 2 min in which the child named letters or numbers and then they were asked to name the animals again and once more after 30 s.

There was no difference between the RD and RD + LD groups on this or on any of the implicit phonology tasks, therefore the data were pooled. The main variable of interest was the proportion of confusion errors on the learning trials that shared the first phoneme with the target name, compared with the proportion that shared its syllable structure. The assumption was that children who make relatively more phonemic errors have more mature segmental memory representations (Treiman & Breaux, 1982). In fact, the RD groups made more syllabic structure confusions than phonemic errors when compared to the CA controls. The RA controls showed less mature performance than the CA controls and made similar numbers of both types of error during learning; however, after the delay they made more phoneme errors than the RD group.

These findings (together with others reported) show that children with dyslexia have problems on implicit phonological tasks, which in turn suggest that they have poorly specified or nonsegmental (not phonemically organized) phonological representations. Perhaps most importantly, it was found that the measures of implicit phonology correlated with measures of phoneme awareness but that the measures of implicit phonology accounted for additional variance in reading ability after controlling for phoneme awareness and a range of other cognitive skills.

Phonological impairments in children with dyslexia: A summary

The evidence reviewed shows that children with dyslexia have problems on a variety of phonological tasks and that some of these problems are present before they have started learning to read. Phonological deficits appear to be more clearly in evidence on tasks tapping phonological output (e.g., memory or naming) than phonological input (speech perception) processes. The dominant theory at the present time is that the core deficit in dyslexia is a deficit in the way spoken words are represented in the brain (the phonological representations hypothesis). Recent evidence, particularly regarding individual differences in the phonological processes that are affected, makes it likely that this deficit in phonological representations may be the outcome of a number of different developmental trajectories. For example, the speech perception deficits found in some children with dyslexia, possibly associated with oral language deficits, are a plausible cause of phonological deficits. For other children, the cause may be related to a difficulty in establishing articulatory motor programs for new words. Furthermore, the systems responsible for speech perception and speech production are likely to have a highly interactive relationship during development. Deficits in speech perception early in development might have knock-on effects on the development of speech output systems, and vice versa. In this view, although speech perception difficulties may be largely resolved by the age when they are typically investigated in children with dyslexia, it is still possible that these problems are important in explaining the development of some of the other phonological deficits found in people with dyslexia through adult life. Longitudinal studies are badly needed to test alternative causal models of the relationships among different speech processing (phonological) skills and reading attainments.

Are phonological impairments in dyslexia caused by auditory perceptual problems?

Another theory regarding the cause of the phonological difficulties seen in children with dyslexia is that these are the consequence of a problem with basic auditory perceptual mechanisms (Tallal, 1980). The same hypothesis has also been proposed as an explanation for the language-learning problems of children with specific language impairment (SLI) and we will consider this in Chapter 4. The hypothesis

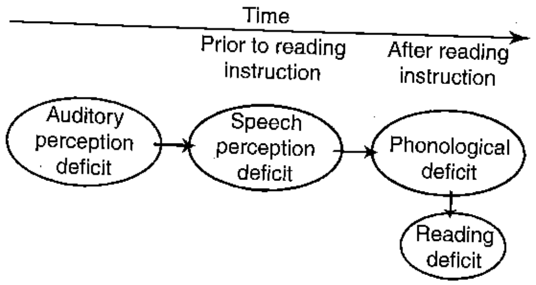


Figure 2.11 Path diagram showing a possible causal role of an auditory perceptual deficit in the development of reading problems.

originally proposed by Tallal (Tallal 1980; Tallal & Piercy 1973) was that the language-learning difficulties found in dyslexia and SLI arose from a slow rate of auditory processing, which in turn led to problems in perceiving rapid auditory changes that are critical for identifying consonant sounds in speech.

This hypothesis, that dyslexia is caused by a problem in rapid auditory temporal processing, is shown in path diagram form in Figure 2.11. As can be seen, the hypothesis clearly predicts that variations in auditory perception should predict variations in both speech perception and phonological skills.

Tallal and Piercy (1973) developed a task called the Auditory Repetition Task (ART) to test their theory. In the ART, the child listens to two complex tones that differ in pitch, separated by a gap that varied in duration (the interstimulus interval or ISI). The child has to copy the order of the tones by pressing one of two response keys in turn (the child is first trained to associate each of the two complex tones with a response key). Tallal and Piercy reported that SLI children found this task more difficult than typically developing children of the same age, but only when there was a relatively short gap between the two successive tones (ISI < 150 ms).

Tallal (1980) reported that ART performance was poor relative to that of controls for 9 of the 20 reading-impaired children in her study, and that ART scores were correlated with nonword reading ability ($r = .81$). Tallal speculated that the problems on ART shown by some of the children with dyslexia may have been related to problems in oral language skills rather than reading problems. In a subsequent study Tallal and Stark (1982) studied a group of children with dyslexia selected for normal oral language abilities. In this group they found no problems on the ART in relation to normal control children. This finding suggests strongly that the problems with the ART sometimes found in samples of children with dyslexia are actually associated with oral language difficulties, rather than being a specific correlate of reading problems (this is the same pattern as described for measures of speech perception earlier).

In line with this suggestion three other studies have failed to find evidence for problems on rapid auditory temporal processing difficulties in children with dyslexia. Nittrouer (1999) found that good and poor readers did not differ in performance on an ART-like task, nor did the poor readers show impairments in a speech perception task requiring the use of brief formant transitions to cue a phonemic contrast involving manner of articulation. Marshall, Snowling, and Bailey (2001) found no differences between children with dyslexia and RA controls in mean ART performance, although there was a small subgroup of children with dyslexia (24%) whose ART performance was outside the normal range. These children also tended to take longer to reach the criterion in a tone identification and response mapping pretest, suggesting that verbal labeling skill rather than simply efficiency in rapid auditory processing is important for ART performance. Finally, Bretherton and Holmes (2003) examined performance on the ART in a group of dyslexic children and a group of age-matched control children (aged 10–12 years old). There was no evidence of selective problems on the ART at rapid rates in the dyslexic group (as postulated by Tallal's theory) and performance on the ART was not predictive of variations in phonological awareness or reading skills in these groups of children. Overall these studies fail to provide support for the idea that the phonological deficits seen in dyslexic children can be traced to a basic problem with rapid auditory temporal processing.

Heath, Hogben, and Clark (1999) performed a direct test of whether problems on the ART are linked to reading problems or oral language problems. They selected a group of children with dyslexia with normal oral language skills, a group of children with dyslexia with poor oral language skills, and group of control children of the same age. The experiment involved extensive practice followed by a procedure whereby the ISI between pairs of tones was systematically varied across a large number of trials to obtain a reliable estimate of a child's threshold on the ART (i.e., the smallest ISI at which the child could reliably judge the order of the two tones). There was no statistically reliable difference on the ART between the control children and the children with dyslexia and normal language skills. However, the controls were reliably better on this task than the children with dyslexia and language impairments. The children with dyslexia and normal language skills showed a very wide range of performance on the ART. Further exploration of this group showed that those children with the weakest language skills were the worst on the ART (there was a correlation of –.62 between language scores (on the Clinical Evaluation of Language Fundamentals, CELF) and the ART in this group). A subgroup of children with dyslexia with better oral language skills (9/16) was identical to the controls on the ART. This study shows clearly that problems on the ART are associated with oral language difficulties in children, but not with dyslexia. There were only weak correlations between ART thresholds and a measure of nonword reading in the whole sample, suggesting that this measure is only weakly associated with children's phonological skills.

In summary, it seems that a deficit in rapid auditory perceptual skills cannot account for the phonological impairments found in children with dyslexia. When problems on these tasks do occur in samples of children with dyslexia they appear to be restricted to a subgroup of children who show oral language difficulties. This pattern is the same as for measures of speech perception. Problems on speech perception and rapid auditory perceptual tasks both seem to be associated with language difficulties rather than reading difficulties, though in the absence of longitudinal data it is difficult to rule out the possibility that they are a distal cause of reading impairments for a subset of children.

There remain other variants of the theory that phonological deficits in dyslexia may arise from a basic auditory perceptual impairment. Witton et al. (1998) suggested that problems in detecting dynamically changing auditory stimuli may be critical. They reported that adults with a history of dyslexia were impaired on both visual and auditory tasks requiring dynamic processing. Similarly, Witton, Stein, Stoodley, Rosner, and Talcott (2002) found that adults with a history of dyslexia had problems in detecting frequency modulation (variations in pitch) but not amplitude modulation (variations in loudness). However, in a study with a large sample of children, some of whom were dyslexic and some of whom had attentional problems, Hulslander et al. (2004) showed that these same tasks did not account for variations in reading ability, once the effects of IQ had been controlled (whereas conventional measures of phonological abilty, including phoneme awareness, RAN, and nonword repetition, did account for substantial amounts of variance in reading ability). This finding raises strong doubt about the theory that reading problems have any specific relationship with problems in perceiving dynamic auditory stimuli. A similar conclusion with even larger samples comes from Heath, Bishop, Hogben, and Roach (2006).

One final variant of the theory is that the phonological impairments seen in children with dyslexia may be caused by a deficit in the perception of rhythm (or amplitude envelope onsets; Goswami et al., 2002). This is measured in tasks requiring children to detect discrete beats in signals that vary in loudness. Goswami et al. (2002) reported data from 24 children with dyslexia, 25 CA controls and 24 younger RA controls. The task involved children detecting beats in stimuli that varied in how suddenly a tone changed in loudness. The stimulus that changed in loudness most suddenly could be perceived easily as containing beats; the question was how much more slowly the change in loudness could be made while still being judged to contain beats (rather than being judged to be slowly varying). The children with dyslexia were significantly worse at detecting the beats than children of the same age (d = 1.42, a very large effect) but not significantly different from RA controls (d = 0.66, a medium effect). It is reported that beat detection thresholds correlated with reading and spelling ability (and also mathematics ability) but unfortunately these correlations are only reported for the sample of children as a whole, which will tend to inflate their magnitude.

A concern about this study is that the main comparison is actually between children who are markedly superior in reading ability (the CA controls had an average reading standard score of 142) and a group of children who, though described as dyslexic, appear to have average levels of single word reading for their age (an average reading standard score of 101). The theory advocated is that the deficit in rhythm (beat) perception is the origin of a difficulty in syllable segmentation, which in turn leads to the phonological deficit seen in children with dyslexia. It remains to be seen whether further studies will demonstrate the predicted longitudinal relationship between specific problems of rhythm perception and the phonological difficulties seen in children with dyslexia.

Possible alternative causal theories of dyslexia

There is strong evidence that a phonological deficit is one cause of the reading difficulties seen in many children with dyslexia. It remains possible, or even likely, that other factors also may play a causal role in the disorder. It is important to distinguish two ways in which additional causes might operate. An additional cause might operate via its effect on phonological skills (we have already considered two such additional causes of this sort (auditory perceptual or speech perceptual deficits), which some have suggested might be the ultimate cause of a phonological impairment). Other causes might, however, operate separately from the phonological deficit. In a path diagram the arrows from these causes would lead directly to reading, or at least would not lead to reading via the phonological deficit (Figure 2.12).

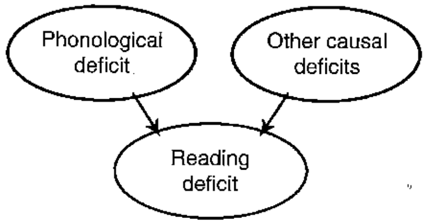


Figure 2.12 Path diagram showing putative causes of dyslexia.

The most widely studied alternative causal theories of dyslexia have been the Automatization/Cerebellar Deficit Theory (Nicolson & Fawcett, 1990; Nicolson, Fawcett, & Dean, 2001) and the Visual Perceptual (e.g., Lovegrove, Martin, & Slaghuis, 1986) or Visual Attentional Deficit (e.g., Facoetti & Molteni, 2001) theories. Unfortunately, space in this chapter precludes giving a full review of the many studies that have assessed these alternative theories.

While it may seem plausible that problems in visual perceptual or attentional processes could contribute to causing problems in learning to read, attempts to establish this have so far met with very limited success. The two dominant approaches to this idea have produced a complex and sometimes contradictory pattern of findings. A recent methodologically thorough study by Heath, Bishop, Hogben, and Roach (2006) concludes that "deficient perceptual processing in dyslexia may be an associated (and inconsistent) marker of neurological abnormality rather than being causally implicated in reading difficulties" (p. 905). This is essentially the same conclusion that Hulme (1988) and Ramus (2004) reached earlier. While a few individuals with dyslexia have been described who show good phonology coupled with visual processing impairments (Goulandris & Snowling, 1991; Romani, Ward, & Olson, 1999; Valdois, Bosse, & Tainturier, 2004), it seems unlikely that such visual impairments are widespread in dyslexia and their causal status is unknown.

The Automatization/Cerebellar Deficit Theory arose from studies showing that children with dyslexia had difficulties on dual tasks involving motor skills (e.g., balancing and counting at the same time; Nicolson & Fawcett, 1990). However, a study by Raberger and Wimmer (2003) and a meta-analysis by Rochelle and Talcott (2006) suggest that these difficulties may reflect the presence of comorbid ADHD in the children with dyslexia who were included in the research samples. In our view neither this theory nor the visual perceptual/attentional theories are well supported by current evidence.

Etiology of Dyslexia

We have painted a picture of dyslexia as a disorder in which children's progress in learning to read is hampered by deficient phonological skills. We now need to consider why these phonological deficits arise. It appears that dyslexia is heavily influenced by genetic risk factors that operate to affect the development of some of the language systems in the left hemisphere of the brain. However, genes act through environments (Rutter, 2005a) and the environment in which children learn to read also has a marked impact on reading disorders.

The genetics of dyslexia

It has been known for many years that dyslexia runs in families (DeFries Vogler, & LaBuda, 1986) and this suggests that genetic factors play a role. One way of looking at this is in terms of familial risk: 40% of boys and 18% of girls with a dyslexic parent are also dyslexic (Pennington & Smith, 1988). More definite evidence for genetic factors comes from twin studies. Early studies showed that, as expected for a genetically influenced trait, concordance rates for dyslexia were higher in MZ than DZ pairs (e.g., Bakwin, 1973). In the largest twin study of dyslexia to date (The Colorado Twin Study; DeFries, Fulker, & LaBuda, 1987) the concordance rates were 68% for MZ and 38% for DZ twins, which suggests that genetic influences are moderately important (DeFries & Alarcon, 1996).

One drawback to looking at concordance rates is that the method is only really suited to discrete categories that are more typical of physical characteristics such as eye color. However, it is clear that dyslexia is not well described in this way; children have reading problems that vary in degree. To overcome this problem, as described in Chapter 1, DeFries and Fulker (1985) developed a method of genetic analysis for twin data dealing with continuous traits such as reading ability. In these analyses the reading test scores for twins are compared. In the Colorado study a child with dyslexia, who was also a twin, was first selected for the study. These children, selected for having a disorder, are referred to as probands. The DeFries and Fulker method examines the extent to which the MZ and DZ co-twins' reading scores resemble their probands' scores. If genetic similarity influences the extent to which a child has a reading disorder, the MZ co-twins should be more similar to their probands than are the DZ co-twins. This is exactly what was found. In fact, the calculations resulted in an estimated group heritability of around 50% for dyslexia. This can be interpreted as meaning that 50% of the difference in reading scores between the probands and the general population is accounted for by genetic differences. However, heritability appears to be higher (and therefore the role of environmental factors lower) among children with more severe reading disorders (Bishop, 2001) and among those with higher IQs (Olson, Datta, & DeFries, 1999). So, genetic factors may be more important contributory causes of dyslexia in some subgroups of children than others.

An important extension of the behavior-genetic method allows examination of whether two heritable deficits are caused by the same or different genes. Using such an approach, Gayan and Olson (2001) estimated the degree of common genetic influence across literacy and phonological awareness skills in twins selected for poor reading ability. Although phonological decoding (assessed by nonword reading) and orthographic skills (assessed by judging which of two plausible spellings for a word was the correct one) were both significantly heritable, there was only partial overlap between the genetic influences on these variables. Deficits in phonological decoding and poor phonological awareness had shared genetic origins, whereas the genetic influences on orthographic deficits appeared to be somewhat independent of those on phonological awareness. Arguably, this is what might be expected given the role that exposure to print plays in the development of mature orthographic representations.

It is generally accepted that the risk of inheriting dyslexia will depend upon the combined influence of many genes of small effect, as well as environmental influences. In a complex trait such as reading ability there is likely to be a large set of gene loci (quantitative trait loci, QTLs) that are implicated. Various strategies have been used in molecular genetic studies of dyslexia (Fisher & DeFries, 2002). In linkage analysis, DNA from pairs of affected siblings is compared to find regions of the genome that show linkage. Linkage refers to the fact that genes that are close together on a chromosome tend to travel together across generations. Thus, sequences of DNA that are similar across affected relatives can throw light on gene variations that may play a role in determining dyslexia. However, it is important to be aware that finding linkage to a marker only narrows down the search for genes to particular regions of DNA and it is not the same as finding a specific gene.

At the time of writing, the strongest evidence for linkage with dyslexia is a site on the short arm of chromosome 6. The first study to identify this QTL for dyslexia was that of Cardon et al. (1994) using a sample of siblings and fraternal twins. When one sibling had dyslexia, the other sibling was more likely to also have dyslexia if both shared the same form of certain marker genes on the short arm of chromosome 6. Other linkages that have replicated in at least some samples are on the short arms of chromosomes 2, 3 and 18 and the long arm of chromosome 15 (see Fisher et al., 2002; Fisher & Francks, 2006; Parachini, Scerri, & Monaco, 2007, for reviews) and a whole genome scan also identified potential gene loci on chromosomes 13, 21 and the X chromosome.

Most recently, evidence has been presented for a single gene on chromosome 6p (KIAA0319) being a susceptibility locus for developmental dyslexia (Cope et al., 2005). It is known that this gene is expressed in brain tissue though its precise form of action remains unknown. A follow-up study (Harold et al., 2006) has provided a confirmation of this gene locus along with additional evidence pointing specifically to single nucleotide polymorphisms (variations in single base pairs), which it is speculated may be involved in regulating the action of the gene. These results are both complicated and exciting and show that considerable progress is being made towards identifying some of the many specific genes that appear to be implicated in the development of dyslexia.

Environmental influences on dyslexia

In addition to genetic influences, environmental factors, sometimes in combination, also contribute to a child's risk of developing reading problems. It has been known since the epidemiological studies of the 1970s that dyslexia is more common in children from poorer socio-economic circumstances. Direct literacy-related activities in the home are also important and mother's educational level affects the literacy environment they provide for their children (Whitehurst & Lonigan, 1998); however, this may have more of an impact on reading comprehension than on decoding skills (Stevenson & Fredman, 1990).

Importantly, from very early in development, children differ in their interest in books, and where parents themselves have literacy problems there may be limited reading-related experiences on offer in the home (Petrill, Deater-Deckard, Schatsneider, & Davis, 2005). Outside of the home, there is also evidence that schooling can make a substantial difference to reading attainments (Rutter & Maughan, 2002). Over time, the cumulative impact of such processes leads to massive variations in children's exposure to print, a factor known to have an independent effect on reading progress (Cunningham & Stanovich 1990).

Another potent environmental influence that we discussed earlier is the language of learning. Dyslexia is associated with poor decoding and poor phoneme awareness in opaque orthographies such as English, but manifests itself primarily as a problem with reading fluency and spelling in transparent orthographies. In turn, reading instruction practices tend to be different in different languages and these too can be expected to have an effect, though at present this is confounded with language and therefore is not well researched.

Brain processes in dyslexia

Considerable progress has been made over the last decade or so in identifying the brain structures responsible for dyslexia. The evidence reviewed earlier showed that language processes (particularly phonological processes) are impaired in dyslexia. We would therefore expect that the brain regions responsible for language processing will be impaired in dyslexia (see Figure 2.13). In the majority of people, language is lateralized in the left hemisphere of the brain. Clear evidence for this comes from studies of adults who have suffered brain damage. Damage to Broca's area (in the left frontal lobe) typically results in problems in speech production, while damage to Wernicke's area (in the left temporal lobe, behind Broca's area) typically results in problems with understanding speech. We might therefore expect to find abnormalities in the structure and function of these and other left hemisphere language systems in dyslexia.

Evidence from studies of brain structure and function broadly supports these predictions (for a review, see Grigorenko, 2001). At a gross level it appears that the brains of individuals with dyslexia may show less structural asymmetry (in the normal population there is a tendency for the left language-dominant hemisphere to be larger; Leonard et al., 1993). At a more specific level it has been suggested that there is less asymmetry in the planum temporale (e.g., Hynd et al., 1990) and the insula (Pennington et al., 2000) of dyslexic brains (both of these are temporal lobe structures implicated in language processing; cf. Eckert, 2004). It should be emphasized that these findings of average group differences conceal great variability among individuals in the relative sizes of these and other brain structures. There is always going to be at best an indirect relationship between assessments of the size of brain regions and how effectively these regions operate. Nevertheless, these findings from studying brain structure are broadly in line with what we would expect: Left hemisphere brain regions appear to show abnormalities of development in dyslexia.

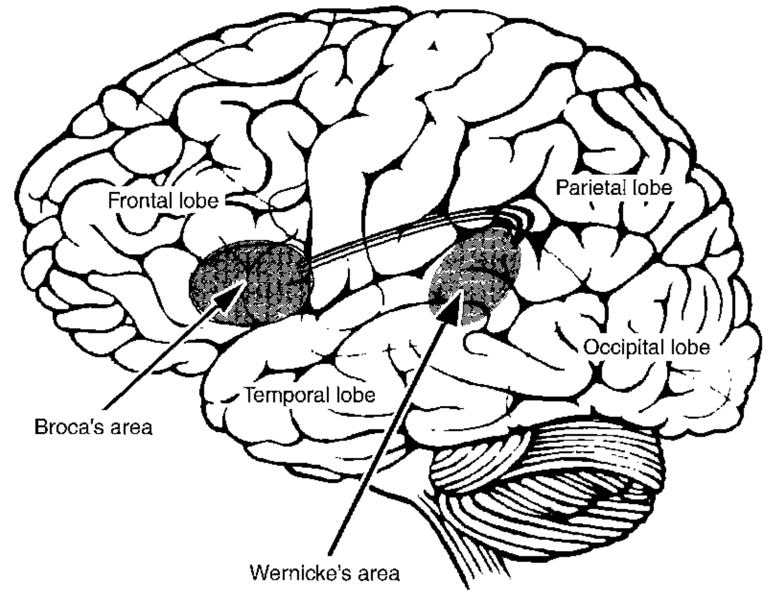


Figure 2.13 Schematic diagram showing the major lobes of the brain and Broca's and Wernicke's areas.

Arguably, more compelling evidence comes from studies of brain activity in children and adults with dyslexia (Demb, Poldrack, & Gabrieli, 1999; Grigorenko, 2001). It is useful to start by considering the brain regions activated in normal adult skilled reading. Thus, when normal adults read words it appears that a circuit of at least three left hemisphere regions is activated: the left mid-fusiform, left anterior fusiform, and left superior temporal cortex (see Plate 2). It appears that the left mid-fusiform is involved in processes associated with uniquely identifying objects and may also be involved in naming. The left anterior fusiform area appears to be involved in retrieving semantic information, while the left superior temporal region appears to be involved in processes related to articulation.

In light of these brain imaging studies of normal reading we can consider results from studies of people with developmental dyslexia. Brunswick, McCrory, Price, Frith, & Frith (1999) compared six adults who had been diagnosed with developmental dyslexia with six control participants while reading words or nonwords aloud, and also while performing an incidental reading task (judging the features present in letters in words or in falsefonts). They found that while the overall pattern of activation during reading was similar for both groups, the adults with dyslexia showed less activation in the left inferior and middle temporal lobe, left frontal operculum, and cerebellum. Increased activation in the adults with dyslexia was, however, observed in left hemisphere premotor cortex when reading aloud. It was argued that the reduced activation in the left temporal lobe reflected deficits in the ability of the adults with dyslexia to retrieve the pronunciations of printed words (lexical phonology) and that the increased activation in the premotor cortex reflected an effortful compensatory process involved in articulation.

Paulesu et al. (2001) performed an extension and replication of the study by Brunswick et al. including French, Italian, and English participants (each language group consisted of matched groups of controls and adults with developmental dyslexia). As in the Brunswick et al. (1999) study, they found reduced activation in posterior inferior temporal areas in their adults with dyslexia in both languages, which suggests that this area may represent a "universal" neural substrate for dyslexic reading difficulties. However the magnitude of these differences in brain activation between adults with dyslexia and controls was small. They also found some subtle differences, such that for English readers areas associated with naming were more strongly activated during reading, while in Italian readers brain areas associated with decoding were more strongly activated. These differences seem to parallel the differences between English and Italian orthography. Reading an irregular script such as English seems to call on areas associated with naming objects, which perhaps suggests a greater involvement of whole word phonology when reading English. Italian is a highly regular script and brain regions concerned with mapping letters onto sounds seem to be more highly activated. These differences though are a matter of degree, and there is extensive overlap in the brain regions involved in both languages. Nevertheless, such results are a tantalizing demonstration of how the learning environment affects the setting up of the neural circuitry of the brain.

Silani et al. (2005) went on to analyze structural MRI scans collected by Paulesu et al. from the same participants with dyslexia who had participated in the cross-language study. The technique used was voxel-by-voxel morphometry, which allows detailed analysis of the density of white matter (nerve fibers) and gray matter (nerve cell bodies) in different brain regions. An important finding of this study was that people with dyslexia showed increases as well as decreases in gray matter density compared to controls in brain regions that showed underactivity during reading (and also in naming). The increases in gray matter density were observed in regions slightly posterior to the left middle temporal gyrus where there was an area of apparent atrophy. Moreover, the increases in gray matter correlated negatively with reading performance such that individuals with more gray matter in these areas had slower reading speed (see Plate 3). A further finding was of less dense white matter in the connecting regions of the speech processing system, including Broca's area (frontal and parietal arcuate fasciculus). In contrast, examination of regions of the cerebellum and visual cortex, implicated by some in the etiology of dyslexia, did not reveal abnormalities. Together these findings point to reduced connectivity in the distributed temporoparietal and frontal networks that are involved in reading and, in particular, phonological and decoding processes. The findings converge with those reported by S. Shaywitz et al. (1998) from an fMRI study of young people with longstanding reading problems since childhood. This study shows that although the persistent poor readers activated posterior reading circuits to the same extent as controls, they did not show normal connectivity between these regions and frontal language areas.

Other brain imaging studies of adults with developmental dyslexia have explored the neural mechanisms underlying the phonological deficit that we have argued is the cognitive basis of dyslexia. In one of the first studies of this sort, Paulesu et al. (1996) compared rhyming and working memory tasks in a PET study with adults with dyslexia. In the rhyming task people had to judge if a pair of consonants rhymed (do P and B rhyme?) and this was compared to a test in which they had to make a judgment about the similarity in shape between a pair of Korean letters. In the memory task people had to detect when one of a pair of letters was presented again in a following sequence. In the rhyme judgment task the adults with dyslexia showed less activation in Wernicke's area and in the left insula amongst other regions, and in the verbal working memory task they showed less activation in several left hemisphere regions, including the insula (see Plate 4). It was suggested that the reduced activation of the insula in both tasks may reflect a "disconnection" between posterior language regions (Wernicke's area) and more frontal language areas (inferior frontal cortex) in dyslexia. S. Shaywitz et al. (1998) used fMRI to study phonological processing in children with dyslexia and found evidence of reduced left hemisphere activation in several left hemisphere regions, including Wernicke's area.

In summary, studies using brain imaging converge on the conclusion that left hemisphere language areas (temporo-parietal cortex) do not function normally in dyslexia (see Price & McCrory, 2005, for a more detailed review). However, the study of brain differences in dyslexia is still at a relatively early stage and although there is some consistency across studies it is difficult to evaluate the causal status of findings. It has to be remembered that reading experience (which may be reduced in people with dyslexia who have found learning to read very difficult) will potentially affect the structure and functional characteristics of brain circuits involved in reading. In this view some of the differences in brain activation patterns seen in people with dyslexia when reading, or performing phonological tasks, may be a consequence rather than a cause of their reading problems. However, evidence for the probable causal role of impairments of brain activation in the development of dyslexia comes from a recent longitudinal study by Hoeft et al. (2007). In this study some 64 children with reading difficulties (who were receiving a variety of reading interventions) were given a range of cognitive measures (including reading, IQ, and phonological processing abilities) as well as a reading task (judging whether pairs of written words rhymed) during which brain activation was measured with fMRI. Patterns of brain activation during the rhyme judgment task (particularly in the right fusiform, middle occipital, and left middle temporal gyri) were longitudinal predictors of increases in decoding ability (nonword reading skills) in these children, and combining these predictors with a range of relevant behavioral measures (including reading, IQ, and phonological skills) gave better predictions of the development of decoding than did the behavioral measures alone. Thus these results suggest that patterns of brain activation seen in a simple reading task can improve predictions of later reading skills better than purely behavioral measures. This in turn is consistent with the idea that such patterns of brain activation may tap into differences in brain function that are causally related to children's ability to learn to read.

With this in mind, another promising way forward is the investigation of the neural correlates of dyslexia in infancy, focusing on children born to families with a history of reading problems. It can be anticipated that some 50% of such children will develop dyslexia. The challenge then is to see if measures of brain response at this early stage in development are predictive of reading status later in childhood. As yet, only preliminary data speak to this issue (e.g., Richardson, Leppänen, Leiwo, & Lyytinen, 2003).

The etiology of dyslexia: A summary

It appears that dyslexia is a disorder strongly influenced by genetic risk factors (at least in many cases). Though the pattern of inheritance for dyslexia is not completely understood, a number of gene markers and one candidate gene have been identified that are associated with the disorder. However, it is likely that many genes in various combinations are involved (polygenic inheritance). These genetic mechanisms must act to influence the development of brain mechanisms that underlie our ability to learn to read. In dyslexia there is evidence for both structural and functional differences in various left hemisphere brain systems that are involved in spoken language and in reading, but the causes of these differences are poorly understood. The language of learning makes a difference to the manifestations of dyslexia and the problem is likely to be exacerbated when combined with social disadvantage.

A Cognitive Theory of Dyslexia

The evidence we have reviewed suggests that the predominant cognitive cause of dyslexia is a deficit in the phonological system (the part of the language system specialized for speech–sound processing). Although other causes have been mooted, the evidence suggests that many of these may reflect comorbidities between dyslexia and other developmental disorders (e.g., ADHD), or if they are causally implicated then this is likely to be to exacerbate the risk of dyslexia rather than as a primary risk factor.

The pervasive phonological deficits seen in dyslexia seem to depend upon problems in the left hemisphere brain systems that subserve speech and language processes (and the development of these systems presumably is under some degree of genetic influence). In this view, the phonological deficits in dyslexia (and presumably the neural correlates of these deficits) will be present during the preschool years and persist after reading develops. However, there are individual differences in dyslexia with respect to the precise pattern and severity of impairments across phonological domains, perhaps suggesting a diffuse pattern of brain difference. It is clear that there are different developmental trajectories that lead to dyslexia (Lyytinen et al., 2006) and it seems that dyslexia can occur in a pure form (as a specific deficit in speech processing mechanisms) or in the context of broader oral language difficulties (Snowling, 2008). In both cases, at the cognitive level this can be conceptualized as a delay or a difficulty in the development of segmental (phonemically structured) phonological representations.

When a child reaches the age of formal reading instruction with nonsegmental or coarse-grained phonological representations, this creates a significant obstacle to reading progress (at least in alphabetic writing systems). Within the triangle model (Plaut et al., 1996), the development of the phonological pathway (the foundation of reading) depends upon the creation of mappings between fine-grained phonological representations and orthographic patterns. In this view, if the normally developing child creates mappings between representations of individual graphemes and phonemes, the child with dyslexia may make connections at a cruder level, perhaps in extreme cases simply mapping between whole printed words and their pronunciations. This idea is illustrated in Box 2.4.

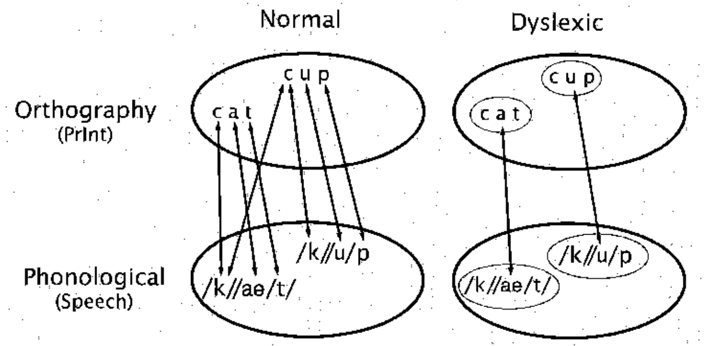
Learning in this way will be slow and inefficient and will not support generalization to new words that are encountered in reading. In prose reading, context provided by meaning and syntax can help the reader to guess the correct pronunciations of words based on partial information (such as the first and last letters in a word) and this may provide an explanation for why children with dyslexia find it easier to read prose than lists of isolated words. Nation and Snowling (1998b) showed that children with dyslexia benefit more from semantic context when reading single words than RA controls. In turn, such findings suggest that the semantic pathway in the triangle model may operate to bootstrap reading in children with dyslexia who have good oral language skills.

Together, research findings suggest that individual differences in the severity of the phonological deficit in dyslexia, together with individual differences in oral language skills, may well explain the wide range of behavioral outcomes that characterize the condition from compensated to persistently poor readers. An attempt to understand individual variation in developmental dyslexia in computational terms was proposed by Harm and Seidenberg (1999). Their formulation was cast with reference to a connectionist model containing a "phonological attractor" network (see Figure 2.14). An important function of this attractor network was to repair noisy phonological inputs using knowledge represented in the network by weights on connections between input and output units. To simulate phonological dyslexia, the network's capacity to represent phonological information was reduced, which can be likened to degrading phonological representations. Harm and Seidenberg's simulations showed that the more severe the impairment that they imposed on the phonological network, the greater the nonword reading deficit. In the case of the most severe impairments, exception word reading was also affected, constituting a severe and pervasive reading disorder.

Harm and Seidenberg's simulations suggest that the severity of a child's phonological deficit will affect their reading profile. It is likely that other cognitive factors

Box 2.4 Illustration of orthography–phonology mappings in normal and atypical reading development

The diagram below tries to represent, very simply, one way of thinking about the effects of learning to read in the absence of phonemically structured representations of speech, as is hypothesized to be the case in dyslexia and perhaps in young normally developing children. For a normally developing child illustrated on the left, their representations of spoken words consist of representations that contain phonemes. In this case when the child learns to read, connections may be established between the individual letters in printed words and the phonemes they correspond to in spoken words. However, for the child with dyslexia the representations of spoken words may be relatively holistic without information about the individual phonemes in the word. In such a case the connections will be at a relatively coarse-grained level. Here we have illustrated the idea that the connections are at the whole word level, which would be an extreme case. The more general point, however, is that in the absence of phonemic representations of speech the mappings created between print and speech will be coarse grained and will not support efficient generalization to unfamiliar words.



Fine-grained mappings between orthography and phonology in typical readers and coarse-grained mappings in dyslexia.

will also have a role to play in modifying reading (and spelling) performance and this is where, for example, visual difficulties may have a modifying influence. In this regard, Pennington (2006) has argued against the single deficit view of dyslexia as a phonological deficit and proposed that children with dyslexia also show speed of processing deficits. It can be argued that if speed of processing is less than optimal then this is likely to affect learning (Anderson, 1992). Within the Harm and Seidenberg model, a nonoptimal learning parameter affected the model's capacity to read exception words, with a lesser effect on nonword reading. The model predicts, therefore, that children with dyslexia who have speed of processing deficits will have poor exception word reading; to the extent that RAN measures speed of processing, then there is some evidence that this is the case (Manis, Seidenberg, & Doi, 1999).

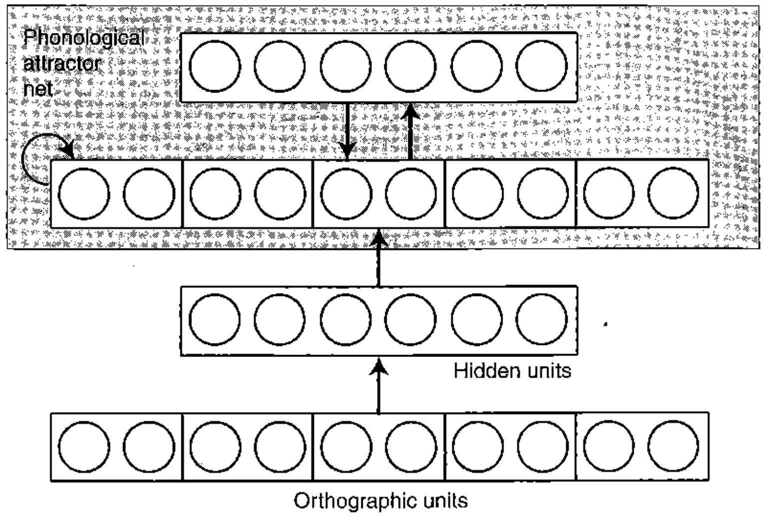


Figure 2.14 Neural network model of reading implemented by Harm and Seidenberg (1999). (Harm, M. W. and Seidenberg, M. S., Phonology, reading acquisition, and dyslexia: Insights from connectionist models, *Psychological Review* 106, p. 499, 1999, published by American Psychological Association and adapted with permission.)

The conceptualization of dyslexia afforded by connectionist models provides an important bridge between the cognitive and behavioral levels of explanation. Specifically these models allow us to understand how continuous variation in an underlying cognitive skill (phonology) can result in a variety of different behavioral outcomes, such as patterns of reading impairment, perhaps in interaction with other cognitive resources. Importantly, they highlight the fact that satisfactory reading development depends upon the status of phonological representations at the start of reading instruction. They also show explicitly how learning affects development and hence they embody environmental influences.

Figure 2.15 shows a path model of dyslexia, following the conventions used by Morton and Frith (1995). Bold arrows are used to indicate causal links for which there is evidence, and dotted arrows for testable hypotheses.

At the biological level, genes on chromosomes 6, 15, and 18 implicated in dyslexia are hypothesized to affect the development of left hemisphere brain networks and particularly temporoparietal cortex (these influences are depicted in Figure 2.15 as semicircles at the level of Biology). The brain differences are hypothesized to lead to problems with the development of phonological representations (either directly or mediated by delayed language development), which in turn affect reading development and related phonological processes. Within the model, a more severe phonological deficit should lead to more severe decoding problems and feedback to further reduce patterns of brain activity in regions subserving reading and phonology. However, the consequences may be less significant if the language of learning is

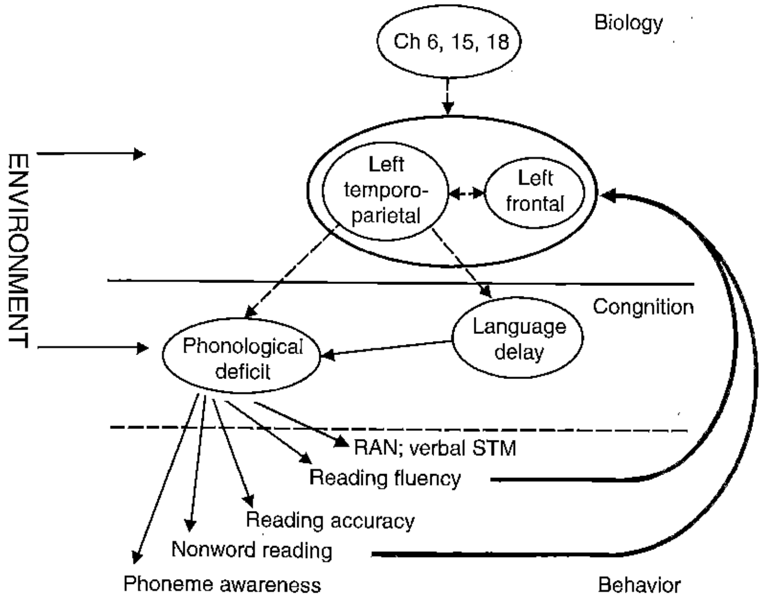


Figure 2.15 A path model of dyslexia showing a phonological deficit as the single proximal cause of a number of behavioral manifestations of dyslexia.

transparent and it is easier to establish grapheme–phoneme correspondences. Figure 2.16 includes a speed of processing impairment as an additional cognitive cause of reading difficulties (Pennington, 2006).

The prediction is that children with only speed of processing impairments will have problems with RAN, short-term memory tasks, and reading fluency, while children with double deficits in phonology and speed of processing will have more severe reading impairments. Potentially these models could be extended to include strengths as well as deficits at the cognitive level. A testable prediction is that the use of intact semantic skills, when present, might ameliorate the effects of poor reading (but not spelling) and lead to altered patterns of brain activity during reading.

Treating Dyslexia

Our understanding of dyslexia has obvious implications for treatment. Children with dyslexia have phonological difficulties that create severe problems in learning to map the letter sequences in printed words (graphemes: letters or letter combinations that stand for phonemes) onto the speech sounds that they represent (phonemes). We should expect, therefore, that teaching methods that help to overcome these phonological problems and that target the mastery of spelling–sound relationships should be particularly effective for children with dyslexia. There is a good deal of evidence that supports this prediction.

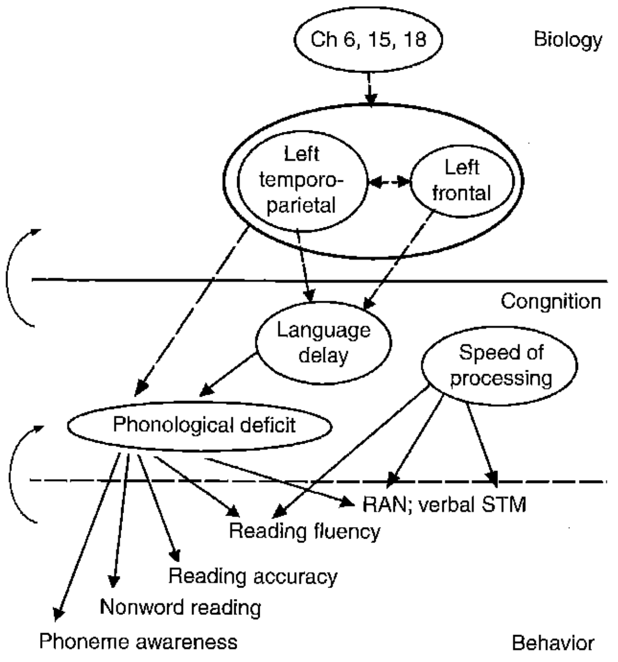


Figure 2.16 A path model of dyslexia showing separate deficits in phonology and speed of processing as causes of the behavioral manifestations of dyslexia.

The best evidence for how to treat dyslexia comes from well-controlled studies of the effectiveness of specific teaching methods. There are really two types of relevant studies: those dealing with older children with diagnosed reading problems, and those that try to prevent reading problems by intervening with young children considered to be at risk of reading problems. We will consider each of these in turn.

Teaching children with dyslexia to read

Hatcher, Hulme, and Ellis (1994) compared the effectiveness of three theoretically motivated interventions for 7-year-old poor readers. The children in this study were selected (based on a screening of all children in the county of Cumbria in the North of England) as being in roughly the bottom 15% for reading ability. Children were not excluded based on IQ, so that many, but certainly not all, of the children would be diagnosed as dyslexic.

The children were allocated to one of four matched groups at the beginning of the study. The method of intervention involved two individual half-hour lessons each week for 20 weeks. The teaching methods were based on the Reading Recovery methods developed by Clay (1985) in New Zealand, and the reading programs involved the children reading books carefully selected to be at an appropriate level of difficulty (the instructional level). There were three forms of intervention. The Reading Alone group received lessons involving reading books at the instructional level with an emphasis on the use of context and meaning, together with some exercises in reading and writing individual words. The Phonology Alone group received lessons involving intensive and explicit training in phonological skills, but no reading instruction. Finally, a Reading with Phonology group received a program of reading instruction based on that in the Reading Alone condition modified to emphasize explicit phonic training combined with the phonological training exercises used in the Phonology Alone condition. In addition these children received "sound-linkage" exercises that included practising letter–sound associations and relating spellings to sounds in words using plastic letters (such as swapping initial consonants in words to create new words).

All children were assessed on a wide range of reading and related measures before the intervention began and again after it was completed. The progress the three groups made in reading was compared with that in an unseen control group who did not receive any special treatment from the study (though many of these children were receiving a variety of forms of help from their schools and parents). The results were striking. At the end of the intervention the Reading with Phonology group had made more progress than either of the other two groups; they had in fact achieved an increase in their reading age of about 12 months over the 6-month period between their initial and final assessments. This picture was similar when considering spelling and reading comprehension. There was also evidence that at follow-up 9 months after teaching had finished the differences between groups remained, though the advantage of the Reading with Phonology group had diminished somewhat.

This study provides clear evidence that children with quite severe reading difficulties can make substantial progress if they are given highly structured individual teaching. The form of teaching that was most effective relates closely to the form of difficulty seen in dyslexia. The Reading with Phonology program directly tackled the children's phonological problems, while at the same time making explicit links between phonology and reading (by the use of sound-linkage exercises). This linkage seems critical to the success of the program because the Phonology Alone group (who actually received roughly twice as much training in phonological skills as the Reading with Phonology group) made substantial improvements in their phonological skills, but this did not translate into reliable improvements in their reading. The effectiveness of the Reading with Phonology teaching program might be related to the ideas presented earlier about how, in order to set up an efficient phonological pathway in the triangle model, the child needs to create links between the letters (or graphemes) in printed words and the phonemes in spoken words that the letters represent. It seems reasonable to suppose that the Reading with Phonology teaching program would be effective in developing the phonological pathway, because the program helps to improve the child's phonological (phonemic) representations of spoken words, while at the same time directly training connections between the phonological and orthographic representations of words through reading practice.

Further analyses of the data from this study (Hatcher & Hulme, 1999) showed that the best predictor of children's responsiveness to teaching (in terms of gains in reading accuracy) was their initial level of skill on a phoneme deletion test. However, children with higher verbal IQ made more progress in developing their reading comprehension skills.

A study by Torgesen and colleagues (Torgesen, 2001; Torgesen et al., 2001) is important in showing the size of gains that can be achieved for children with dyslexia when given sufficiently intensive instruction. In this study 60 8- to 10-year-old children with dyslexia were divided into two groups. One group was taught by the Lindamood Phoneme Sequencing (LIPS) program. In this program a particular emphasis was placed on developing children's awareness of phonemes by articulatory awareness training coupled with phonemic decoding of single words (85% of the time in the program), with just 15% of the time devoted to reading and writing practice with words and texts. The other group was given an Embedded Phonics (EP) program that involved a greater emphasis on reading text coupled with a smaller amount of direct phonic and phonemic awareness instruction. One unusual feature of the study was the intensity of the teaching involved: the children got two individual 50 min lessons each day for 8 weeks (67.5 h of teaching in 8 weeks, compared to 20 h of teaching in 20 weeks in the Hatcher et al. (1994) study).

The results of the study were very impressive. At the end of the intervention there was a small advantage for the LIPS group, but this was not statistically reliable. Both groups, however, had increased their reading accuracy scores to standard scores of around 90 (where the average for the population is 100) in comparison to standard scores in the 70–80 range at the beginning of the study. These figures mean that the children had made large strides in overcoming their reading difficulties, improving their reading scores from the severely impaired range to the lower end of the normal range. These gains were maintained at follow-up 1 and 2 years after the intervention had finished. However, it is worth noting that the children in this study remained very slow readers.

The Torgesen et al. (2001) study, together with some others (Hatcher et al., 1994; Lovett et al., 1994; Wise, Ring & Olson, 1999), indicates that systematic phonic teaching in combination with phonological awareness training is effective in helping to overcome the reading problems in dyslexia. It appears from the Torgesen et al. study that a range of different approaches that embody the basic principles of phonological awareness training and phonic reading instruction may have equivalent effects for many children with dyslexia.

Early interventions to prevent reading failure

An obvious implication of these studies is that early interventions to develop phonemic awareness and an understanding of the links between print and speech should help to prevent the development of reading difficulties in children with dyslexia. There is good evidence to support this idea.

In an early classic study Bradley and Bryant (1983) gave 4-year-old children a sound categorization test (a test assessing sensitivity to rhyme and alliteration). They selected a small subset of children with poor sound categorization skills and divided them into four groups. One group was given sound categorization training, a second group was given sound categorization combined with letter-sound training, while a third group was given semantic categorization training. The hypothesis for children who were poor at sound categorization at age 4 years was that training would improve their phonological skills and prevent the later development of reading difficulties. There was a trend for this to happen, but the greatest gains in reading were made by the children given sound categorization training in combination with letter-sound training.

More recent studies have produced impressive effects in the prevention of reading difficulties for children identified as being at risk of reading failure. Torgesen et al. (1999) gave 88 h of individual teaching to children identified as being the 12% most at risk of reading failure. The intervention started in kindergarten and carried on until second grade. The most effective intervention in this study was a version of the LIPS program described earlier. The children in this study achieved near average levels of reading accuracy and reading rate (standard scores of 99 and 97) that were maintained from second through to fourth grade. Again it is worth emphasizing the long duration and highly intensive nature of the teaching given in this study.

Hindson et al. (2005) provided an intervention involving phoneme awareness training coupled with book reading for children at family risk of dyslexia as well as for children deemed not at risk. A small group of the family at-risk children did not receive the intervention and served as a waiting list control group. The at-risk trained children improved in phoneme awareness and showed better scores on a test of print concepts after the intervention compared to the at-risk waiting list control group. However, the at-risk children were still behind the not-at-risk group in terms of letter-sound knowledge and early reading skills. When followed up 2 years later the at-risk children had weaker reading and spelling skills than the not-at-risk group. Thus the intervention probably helped the at-risk group improve their reading skills but they were not comparable to the not-at-risk group. It was found that a strong predictor of reading skills at the end of the study could be made from kindergarten phoneme awareness skills, and that children with better phoneme awareness responded better to the intervention than children with weaker initial skills.

Hatcher, Hulme, and Snowling (2004) compared four different methods of teaching delivered on a whole-class basis during the first 2 years of formal schooling. The basis of all methods was a highly structured phonically based teaching program (Reading Alone) and this program was supplemented either with rhyme-level phonological awareness training (Reading with Rhyme) or with phoneme awareness training (Reading with Phoneme) or both (Reading with Rhyme and Phoneme). For normally developing children there were no differences in reading skills at the end of the program between the four methods. However, for children deemed to be at risk of reading failure at the beginning of the study, the two conditions involving oral phoneme awareness training showed small but reliable improvements. These interventions, however, were not sufficient to prevent reading difficulties in the at-risk children, though they did result in less severe reading problems than in the other two methods of teaching. Early phoneme awareness skills were a powerful predictor of later reading skills in all of the groups of children (and a much more powerful predictor than rhyme-level skills). This study, like the Hindson et al. study, suggests that phoneme awareness training is a useful component of programs designed to help prevent early reading difficulties. Both studies, however, underline the fact that while interventions may help to ameliorate reading problems they do not eliminate reading problems in samples of at-risk children. It seems likely that to prevent the development of reading problems in such children would require very intensive interventions over extended periods of time.

Treating and preventing reading difficulties in dyslexia: A summary

Theoretically based interventions for dyslexia involving highly structured phonic reading instruction coupled with activities designed to improve phonemic awareness are effective in overcoming reading problems characteristic of dyslexia. Similarly, equivalent approaches applied to younger children deemed to be at risk of developing reading problems are effective in helping to reduce these children's reading problems. None of these approaches represent quick fixes however. Overcoming, or preventing, reading problems in dyslexia requires many hours of highly skilled and intensive teaching. Furthermore, it is likely that many children with dyslexic difficulties will need ongoing specialist teaching to support the development of their reading skills for extended periods of time: The miracle cure so far eludes us.

Chapter Summary

Developmental dyslexia is a common learning difficulty that occurs in around 3–4% of children. The disorder commonly co-occurs with a range of other problems, including attentional, language, and motor difficulties. The problems of children with dyslexia seem to reflect basic problems in the development of brain mechanisms concerned with processing speech sounds (phonological mechanisms). Though a range of other possible causes has been investigated extensively, so far the only well-supported causal hypothesis is that the majority of cases of dyslexia reflect this "phonological core deficit." It appears that genetic risk factors are a powerful causal influence on the development of dyslexia. Studies of the treatment of dyslexia are well advanced and we know a great deal about how to treat or to prevent the development of these children's reading problems. Interventions that involve a combination of highly structured reading instruction coupled with training in phoneme awareness are effective for both treating and helping to prevent the development of the disorder. It is a pity that many children who would benefit greatly from such specialist teaching programs still do not receive them.