Learning to Read

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A child of 6 knows the meanings of many spoken words—10,000 by one estimate (Anglin, 1993). He or she can understand oral questions, commands, and stories. Yet if this same information is presented in written form the child is hard pressed to decipher it. How do children learn to read, and how do they reach a point at which reading seems as easy and natural as listening? In this chapter, we consider the development of reading ability, focusing on the development of single-word reading in alphabetic writing systems. We ask how children grasp the idea that writing is related to language and how they learn about the links between the letters in printed words and the sounds in the corresponding spoken words. As we will see, addressing these developmental questions requires an understanding of the nature of alphabetic writing systems and a grasp of theories of skilled reading.

1.0 Written Language and Spoken Language

A child needs to learn many things in order to become a good reader. Written language is often more formal than spoken language, and it may use different words and different constructions. Consider the sentence, "He, John Jones, is the person to whom George placed the call." We would not be surprised to come across this sentence in a book, but we would be surprised to hear it, rather than "George called John," when talking to a friend. To become a highly skilled reader, one must become familiar with the written language register and its conventions. For example, words like *whom* and constructions like appositional phrases are more common in written English than spoken English. The gap between written language and spoken language is greater in languages such as Arabic than it is in English, and it can be compounded for readers of any language who speak a nonstandard dialect.

Our interest here is in how children master the basics of reading in the first place. In the United States and many other countries, reading materials designed for beginners typically use words and constructions that are familiar to children in their spoken forms. What is critical, then, is that children are able to translate the printed words on the page into a speech-based representation. This may be overt speech, as when children read aloud, or an inner code that preserves certain characteristics of speech—the interior voice that children (and adults) often claim to hear when reading silently. Children who are able to translate printed language into spoken language can usually, given their extensive spoken vocabularies and their syntactic knowledge, comprehend the meaning of the print. This process of translating printed material into a speech-based form is commonly called *decoding*.

Decoding is made possible by the fact that writing represents language; it is *glottographic* (Sampson, 1985). Whether the unit of language that writing symbolizes is the phoneme (an *alphabetic* writing system), the syllable (a *syllabic* writing system), or the morpheme (a *logographic* writing system), writing systems assign symbols to linguistic units and present them in a conventional arrangement. Reading, then, involves recovering the linguistic units (see also Frost & Ziegler, this volume). For alphabetic writing systems, which have featured in the majority of the research on reading and reading development and which are the focus of this chapter, spellings lead readers toward the phonemic representations of words. (See Hanley, 2005 for a discussion of learning to read in Chinese, a nonalphabetic writing system.) Spellings may not provide full information about words' spoken forms, however. Readers of English must fill in stress (is *present* a noun with first-syllable stress or a verb with second-syllable stress?), and readers of Swedish must fill in tone (does *anden* have a simple tone and mean 'the duck' or does it have a double tone and mean 'the spirit'?).

The central problem in learning to read, then, is learning to decode. Before children can begin to do this, they must understand that writing represents language and that there exists a code to be broken. We consider these early developments in the section that follows. In later sections, we go on to consider theoretical perspectives on the nature and development of decoding itself.

2.0 Early Learning About Relations Between Writing and Language

Researchers have called the initial period of reading development—the time before children begin to decode themselves—the *prealphabetic* (Ehri, 1998) or *logographic* (Frith, 1985) period. The first label stresses what young children cannot do: They cannot decode alphabetic writing phoneme by phoneme. The second label implicitly proposes a hypothesis about what children do: They treat an alphabet as if it were a logography, a glottographic system in which each word or morpheme of the language is represented with its own graphic symbol. In this view, for example, young children may recognize their own name as a special, unique symbol. They do not divide the written name into components and link each component to a smaller unit of sound, but they do know that the written word represents a specific linguistic form.

The idea that writing is glottographic—that it does not record concepts directly but rather represents language, which in turn represents concepts—is an idea that needs to be learned, however. Some children who are commonly described as logographic readers do not appear to understand the basic nature of writing. Instead, they may believe that writing is *semasiographic*, directly encoding meaning. Anecdotal evidence for this point comes from a 3 ½ year old of our acquaintance who pointed to a stop sign and told an adult that the writing on it said "Don't cross the street." When the adult questioned her again a few minutes later about the word on the sign, the child reported that it said "Don't go." To this child, the symbol STOP represented a general meaning, one that could be expressed equally well using different words. The child did not yet seem to know that writing represents specific linguistic forms.

Several factors likely contribute to children's early belief that writing is semasiographic. Some of the symbols that are most familiar to young children, such as drawings and photographs, represent meaning in a direct way, and children may believe that writing does the same. Children can think about a cat or a table as something that can be represented symbolically, as in a picture, but it is hard for them to conceive of language, which fades quickly, as an object that can be represented. It is particularly difficult for children to conceive of phonemes as objects that can be represented, for they are difficult to access as separate units in the speech stream (see Ehri, Nunes, Willows, Schuster, Yaghoub-Zadeh, & Shanahan, 2001).

If young children believe that writing represents concepts directly, how does it do this? According to some researchers, children initially believe that writing is *iconic*; that it represents concepts by virtue of its physical resemblance to instances of those concepts. Supporting this view are the results of studies in which children are shown printed words such as *ballerina* and *ball* and are told that one of the words goes with a picture of a ballerina and the other goes with a picture of ball. English-speaking prereaders tend to use the relative sizes of the objects to solve the task. As a result, they do relatively well on pairs such as *ballerina–ball*, where the word for the bigger object is spelled with more letters, and relatively poorly on pairs such as *caterpillar–cat*, where the word for the bigger object is spelled with fewer letters (Bialystok, 1991). Similar results have been reported for Swedish-speaking (Lundberg & Tornéus, 1978) and Hebrew-speaking preschoolers (Levin & Landsmann, 1989). Children's search for iconicity, however, is usually fruitless. Only very occasionally do words look at all like what they represent. The word dog can be imagined as looking like a dog, with erect ears on the d and a tail on the g, and camel may have two humps in the middle. But even in Chinese, where certain of the characters started off as pictures of the thing they represent, this sort of iconicity does not go very far, and the great majority of words in any language do not even represent physical objects. Children are bound to become discouraged with iconic reading strategies.

If writing does not represent meaning by virtue of iconicity, perhaps it does so by virtue of physical adjacency. This hypothesis works well for a number of the printed words that children see. For example, a child may take the word *Cheerios* on a cereal box to refer to the cereal because of the word's proximity to a photograph of a bowl of cereal and to the pieces of cereal themselves. In this case, the child's guess is correct. Experimental evidence for young children's use of adjacency comes from the *moving word task*. In this task, a printed word such as *girl* is placed under a picture of a girl but then is moved under a picture of a tree. Young children often report that the word now says *tree* (e.g., Bialystok, 1991).

How do children learn that writing is not necessarily related to its object by virtue of physical resemblance or adjacency? How do they learn that writing represents specific spoken words as opposed to general meanings? Children's experiences with the spellings of their names may play an important role in this learning. A child's first name is usually the first printed word that he or she can recognize and reproduce; names of family members, pets, and friends are also learned early. A child named Jane has the opportunity to observe that neither the graphic form of her name as a whole nor its individual components look at all like she does. Whether the word is near to her or her depiction or not, its interpretation is the same. That interpretation is a specific linguistic form, *Jane*. The word cannot be read as *little girl* or as *four year old*. Children's experiences with names may thus help them learn that printed words represent specific linguistic forms and that physical similarity and contiguity do not govern interpretation. Consistent with this view, children perform better in the moving word task with proper names than with other kinds of words (Bialystok, 2000).

Young children' experiences with their names and other common words they learn by rote may cause them to believe, however, that interpretation is purely conventional; that they must memorize each word anew. Anecdotal evidence for this idea comes from Valentina, an Italian 5 year old, who wrote her name correctly. When asked to write the corresponding male name, Valentino, which differs in only the last vowel, she strung together letters that she knew in what appeared to be a random sequence (Stella & Biancardi, 1990). Apparently, Valentina did not link the letters in her name to their sounds and so was unable to write a name that differed from hers in just one sound.

Some children may learn of the existence of systematic links between printed and spoken words only when teachers or parents start showing them how to sound out words. Other children begin to understand this on their own when they learn the names of letters and encounter words whose pronunciations are linked in an obvious way to certain of their component letters. For example, Jane can hear the full names of the letters *J* and *A* in the pronunciation of her name, and part of the name of the letter *N*. This may help her realize that the letters in her name's spelling are motivated by the word's sounds; they are not arbitrary. Experimental support for the idea that young children can use their knowledge of letter names to make sense of the relations between certain printed words and their pronunciations comes from studies in which children are taught print–speech pairs that are partly motivated by letter names (e.g., *BT* is pronounced as *beet*) and pairs that are not so motivated (e.g., *BT* is pronounced *bait*). U.S. preschoolers learn the former kinds of pairs more easily than the latter, supporting the idea that they benefit from links between print and speech that are based on letter names (e.g., Treiman & Rodriguez, 1999). Studies of children exposed to Hebrew have led to similar conclusions (Levin, Patel, Margalit, & Barad, 2002). Letter names may thus give children a start in understanding that the spellings of printed words are systematically related to the words' pronunciations, helping children enter what has been called the *partial alphabetic* phase of reading development (Ehri, 1998). However, children who are limited to letter names are quite some distance from full decoding.

Once children enter school, reading instruction begins in earnest. Children are exposed to printed words and sentences and to the spoken forms to which they correspond, and they are expected to generate spoken forms on their own. Children now enter what is called the *alphabetic* period of reading development (Ehri, 1998; Frith, 1985), a period during which they learn about the system that links writing to speech. In the sections that follow, we consider two different theoretical perspectives on the nature of alphabetic writing systems and the nature of learning that have influenced researchers' thinking about how children learn to decode. These are the *dual-route cascaded* perspective and the *single-route parallel connectionist* perspective; or, to be brief, the dual-route and single-route perspectives.

3.0 Dual-route Perspective

The dual-route perspective (see also Rastle, this volume) has guided much research on reading and reading development in alphabetic writing systems. Its best known instantiation is in the work of Coltheart and colleagues. Computer simulations of skilled readers that embody dual-route hypotheses exist for English (Coltheart, Rastle, Perry, Langdon, Ziegler, 2001), German (Ziegler, Perry, & Coltheart, 2000), and French (e.g., Ziegler, Perry, & Coltheart, 2003). Equally explicit dual-route models of reading development do not yet exist, but dual-route thinking has been influential in shaping research and theory on reading development.

The dual-route perspective states that skilled readers read words via both *lexical* and *nonlexical* routes. In the lexical route, the reader looks up a word in a mental lexicon or dictionary and, if the information has been stored there, accesses the word's pronunciation. In the nonlexical route, the reader assembles a pronunciation using rules that relate units of spelling to units of sound. Typically, both the lexical and nonlexical routes are involved in word reading. For example a reader might retrieve the full pronunciation of *fun* from his or her mental lexicon while simultaneously gaining information about the word's pronunciation by combining the pronunciations for *f*, *u*, and *n*. The nonlexical route is particularly important in allowing readers to decode words that they see for the first time.

To understand how the development of decoding is viewed from a dual-route perspective, we must consider the nature of the nonlexical route. This route, as described in current models, embodies a number of assumptions about the nature of alphabetic writing systems and the nature of learning. One set of assumptions concerns the units that are involved in spelling-to-sound translation. The dual-route view assumes that the role of letters in alphabetic writing systems is to symbolize phonemes. For example, the *b* in the English word *bit* stands for the phoneme /b/. (For an explanation of the phonetic symbols used in this chapter, see International Phonetic Association, 1999.) Any letter which does not directly symbolize a phoneme must be part of a multiletter unit which itself stands for a phoneme. For example, the *h* of *phone* forms a unit with the *p*, and together these two letters symbolize /f/. The final *e* of *phone* forms a unit with the *o*, and these two letters symbolize /o/. Researchers who have been influenced by the dual-route view use the term *grapheme* to refer to the graphic symbol or group of symbols that represents a single phoneme. The assumption is that graphemes are the basic functional units of writing and that their pronunciations are not predictable from those of their components.

The rules of the nonlexical route (see Rastle & Coltheart, 1999; Ziegler et al., 2000; and http://www.maccs.mq.edu.au/~max/DRC/FrenchDRC.doc for a list of the rules that are currently postulated for English, German, and French, respectively) link graphemes to phonemes. They capture those spelling-to-sound relations that are relatively simple and of wide utility. Each rule translates a grapheme to a phoneme. In English, for example, *oo* is pronounced as /u/, allowing *boot* to be decoded correctly. According to the dual-route perspective, then, *boot* is a *regular* word, one for which the nonlexical route produces the right pronunciation. *Brook* is an *exception* word, one that requires input from the lexical route in order to be pronounced correctly. The nonlexical route includes some rules that depend on a grapheme's position in a word. For example, English *e* is translated to /i/ at the ends of words (*he*) but as /ɛ/ in other positions (*hem*). In other cases, grapheme-to-phoneme translation depends on the surrounding letters. For example, English *c* is translated as /s/ when before *e* , *i*, or *y*, but as /k/ otherwise.

According to the dual-route view, then, skilled readers can deal with single-syllable words on two levels.[1] One level is that of whole words. Readers' knowledge of print-to-sound links at this level is captured by the lexical route. With few exceptions, each printed word corresponds to a unique spoken word and each printed word is translated to speech in the same manner. A second level is that of graphemes and phonemes. Readers' knowledge of these links is captured by the nonlexical route, which incorporates those mappings that are most regular and predictable, closest to the one-to-one ideal.

The dual-route perspective sees learning as occurring at both the whole-word level and the level of graphemes and phonemes. Evidence for children's use of the whole-word level comes from the *lexicality effect*—the fact that familiar words (e.g., *home*) are pronounced more easily than otherwise similar nonwords (e.g., *bome*). Evidence for use of the grapheme–phoneme level comes from the *regularity effect*—the fact that regular words (e.g., *road*) are pronounced more easily than exception words (e.g., *broad*). These effects have been found from an early age in children learning such languages as English (e.g., Coltheart & Leahy, 1996) and French (e.g., Sprenger-Charolles, Siegel, & Bonnet, 1998). The dual-route model has been influential in thinking about individual differences among typically developing children—some children may rely more heavily on the nonlexical route and others more highly on the lexical route (e.g., Eme & Golder, 2005)—and in thinking about the problems experienced by dyslexic children (e.g., Castles & Coltheart, 1993; see Snowling & Caravolas, this volume, for discussion of developmental dyslexia).

Although the dual-route model has played an important role in guiding studies of reading development, we believe that it is founded on some questionable assumptions about the nature of alphabetic writing systems and the nature of learning. Alphabetic writing systems link spellings and sounds at the level of whole words and at the level of individual letters and letter groups, but these are not the only levels at which links exist. Graphic units that symbolize single phonemes—the graphemes of the dual-route view—can sometimes be broken down into smaller units. For example, application of the dual-route view to Italian would force us to treat the *ch* of *chiaroscuro* and the *gh* of *ghetto* as unitary graphemes. However, this treatment may be misleading. Italian *c* is normally pronounced as /k/ (e.g., *credenza*, *coloratura*) but as /tʃ/ before *e* or *i* (*cicerone*). The letter *h* is used after *c* in words such as *chiaroscuro* to show that the *c* has its normal /k/ pronunciation rather than the /tʃ/ that would otherwise occur before *i*. The same thing occurs in the case of *g*, as in *ghetto* (cf. *gondola*, *granita* with /g/, *gelato* with /dʒ/). If we follow the dual-route view that a letter that does not symbolize its own phoneme must form part of a grapheme with another letter, it follows that the *ch* of *chiaroscuro* and the *gh* of *ghetto* are unanalyzable entities. This is probably not the best or most psychologically realistic solution. Similar issues arise for Russian, where soft (palatalized) consonants may be spelled with a two-letter sequence, such that the first letter spells the corresponding hard consonant and the second letter is known as the soft sign. Additional evidence that digraphs can be analyzed comes from German. In this language *ah* is long /ɑː/ (*Bahn* /bɑːn/ 'path') and *a* is the corresponding short vowel /a/ (*Bann* /ban/ 'excommunication'); *h* has the same lengthening effect for other vowels as in *Mehl* /meːl/ 'flour', *Bohne* /boːnə/ 'bean', and *Führer* /fyːrɐ/ 'leader'. That the pronunciations of two-letter sequences or digraphs like *ah* and *eh* are predictable from their components would be lost by treating the digraphs as wholes. Letters with diacritical marks may be analyzable as well, as when an acute accent appears over any Irish vowel to indicate that the vowel is long. Even English shows some degree of predictability with digraphs. The various spellings of the sound /o/ in the words ***roll***, ***bone***, ***boat***, ***bow***, ***soul***, and ***though*** all begin with an *o*, for example. We are not aware of any research on the degree to which learners of these and other languages benefit from the internal structure of digraphs and letters with diacritics, but we suspect that learners do benefit to some extent.

Current dual-route models, with their lists of separate rules, do not provide a way to capture generalizations that hold across a series of rules, such as that German *h* makes the preceding vowel long. The German model does not represent what is common to the digraphs *ah*, *eh*, *oh*, *uh*, *äh*, *öh*, and *üh* (they all end in *h*), and it does not represent what is common to their sounds (they are all long vowels). As Ziegler et al. (2000) noted, the number of rules that the German dual-route model must postulate would decrease considerably if such higher-level generalizations could be incorporated. Many languages have such generalizations, often more prolifically than in this German example. The dual-route model's failure to account for them is a real problem, for users of such systems may pick up these generalizations.

Another problem is that, by stressing those links between letters and sounds that are most regular and most predictable, the dual-route view downgrades patterns that are useful for relatively small subsets of words or that are less predictable. For example the nonlexical route of the current English dual-route model translates *oo* to /u/, ignoring the fact that *oo* corresponds to /ʊ/ in some words and that it corresponds to /ʊ/ in most words where it precedes *k* (e.g., *book*, *cook*, *nook*). Another context-conditioned pattern involves the effect of a following *d* on *ea*. The likelihood of /ɛ/ pronunciations increases in this context (e.g., *head*, *dread*), although /i/ pronunciations still occur before *d* (e.g., *bead*, *mead*), as in other contexts. These kinds of patterns are fairly common in English, and they increase the degree to which pronunciation can be predicted from spelling (Kessler & Treiman, 2001). Although the English dual-route model currently includes several context-conditioned rules, it does not include the ones just mentioned or indeed most of the other ones that Kessler and Treiman documented. Research has shown that children begin to use certain context-conditioned patterns rather early in the course of learning to read, starting as early as first grade for some of the patterns described above (Treiman, Kessler, Zevin, Bick, & Davis, 2006). That is, children may learn not only about broad patterns like that linking *b* to /b/ but also about more specific patterns like that linking *oo* to /ʊ/ before *k*.

These observations call into question the dual-route assumption that the only links between spelling and sound that children need to learn are those highly predictive links that are found at the level of whole words and at the level of graphemes and phonemes. Patterns exist at other levels as well, not only in English but in other languages, and learning these patterns is an important part of learning to decode. Given how often children see most reasonably common words over the course of their reading experience, they need not pick up the patterns on the first or second or even hundredth exposure to a word in order for the patterns to be useful over the long run. For example, an English-speaking child who tries to read *there* for the first time may well mispronounce it as /θɪr/ because *th* is pronounced /θ/ in many words such as *think* and *ere* is often pronounced as in *here*. Indeed, the dual-route model considers *th* and *ere* as graphemes and translates them in these ways. Over time, however, the child likely notices certain regularities. *Th* spells /ð/ in other words like *this*, and *ere* spells /ɛr/ in words like *where*. The cognitive burden of learning to read *there* is not as heavy as if it had some totally unique spelling like *qgpyi*. The dual-route view sees the whole word *there* and the graphemes *th* and *ere*; it does not acknowledge these additional levels and patterns. Even if this additional information does not suffice to correctly decode a word on the first encounter, it makes the link between the printed form and the pronunciation less arbitrary and easier to remember.

Written words, in summary, are like Russian nesting dolls. Just as a smaller doll fits inside a larger one, which itself fits inside a larger one, so a spelling is a nested series of graphic units embedded in other graphic units. Each level typically adds information not explicitly present at the lower, embedded level, but at the same time that lower level is not devoid of information. Becoming a skilled user of an alphabetic writing system involves learning about all of the levels and types of information. The dual-route view of decoding, with its focus on only some of the levels, is incomplete. We turn now to the connectionist perspective, which has the potential to provide a fuller explanation.

4.0 Single-Route Perspective

Single-route connectionist models attempt to explain cognition in terms of networks of simple units. For single-word reading, these include units that represent the input (the letters in a printed word and their ordering) and those that represent the output (the sounds), as well as *hidden units* that mediate between these two sets of units. Learning involves modifying the connections between the units in response to exposure to a substantial number of examples. Computer programs that are meant to simulate human learners are exposed to print–speech pairs in a way that is thought to capture important aspects of a child's experience, including the fact that more common words are seen more often. The program generates a pronunciation for each presented letter string, compares it to the correct pronunciation, and adjusts the weights on its connections so as to bring the generated pronunciation closer to the correct one. Over the course of numerous exposures to words, the weights on the model's connections begin to approximate the statistical structure of the training vocabulary. For example, if a model is taught the pairs *bit*–/bɪt/, *boot*–/but/, *book*–/bʊk/, *boost*–/bust/, and *brook*–/brʊk/, the learned weights come to capture the fact that words beginning with *b* have pronunciations beginning with /b/ and that words with medial *oo* have pronunciations that contain either /u/ or /ʊ/, with the latter occurring before final *k* /k/. A model of this type was first proposed by Seidenberg and McClelland (1989) for English, and more recent models are described by Plaut, McClelland, Seidenberg, and Patterson (1996) and Harm and Seidenberg (2004). Similar models have been implemented for other languages, such as German (Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004). These models are explicitly developmental in the sense that current dual-route models are not. The weights on the connections are initially random, to simulate a child who cannot decode, and the fully trained model is meant to simulate a skilled reader. Connectionist models of these kinds may be considered single-route models in that the same set of connections, operating in parallel, can handle both familiar words and novel words.

Our brief description of the single-route perspective helps highlight its assumptions about the nature of written language and the nature of learning. The system to be learned, an alphabetic writing system in the present case, is assumed to be structured. That structure need not be limited to one-to-one relations between letters or letter groups and phonemes, however. Indeed, connectionist models are well suited for picking up subtle patterns in a system—patterns that apply in many instances but not all. This is the kind of structure that, we have argued, characterizes

English and certain other alphabetic writing systems. The models see knowledge of statistical structure as emerging gradually. A model might incorrectly translate *brook* to /bruk/ on its first exposure to this word, but with repeated exposure to this and other words the model begins to learn that *oo* is often pronounced as /ʊ/ before *k*. In our view, the assumptions made by the single-route perspective about the nature of alphabetic writing systems and the nature of learning give such models the potential to provide more realistic explanations of the development of alphabetic decoding skill than do dual-route models.

At a broad level, what is known about the development of decoding skill in children fits with the single-route connectionist perspective. These models are consistent with the lexicality effect and the regularity effect that have been observed in children and that were discussed earlier in this chapter. The models are expected to perform better on trained words than on untrained items and better on words that conform to widespread patterns than on words that do not. However, not all words that are classified as exceptional by the dual-route view behave alike according to single-route models. For example, the vowel pronunciations of *brook* and *broad* deviate from the /u/ and /o/ that are generated by the nonlexical route of the dual-route model, and so both are exception words by that view. However, *brook* fits the pattern that *oo* is often /ʊ/ before *k*, and *broad* does not fit a broader pattern. As mentioned earlier, Treiman et al. (2006) found evidence that children, from an early age, begin to adjust their pronunciations of vowels depending on the surrounding consonants in such cases as that of *oo* before *k*. This outcome is consistent with the single-route perspective. Indeed, the nonword pronunciations produced by children at different levels of reading skill in the Treiman et al. study corresponded fairly closely to those produced by a connectionist model with different amounts of training.

Single-route models see development as occurring in a continuous rather than a stage-like manner. This contrasts with theories of reading development that divide the alphabetic phase of development into one or more earlier periods, characterized by learning of basic connections between print and speech, and a later period, characterized by learning of more complex patterns and use of larger units such as syllables and morphemes. Frith (1985), for example, refers to the alphabetic stage and the orthographic stage, and Marsh, Friedman, Welch, and Desberg (1981) distinguish between sequential decoding and hierarchical decoding. Ehri (1998) proposes the partial alphabetic phase, the full alphabetic phase, and the consolidated alphabetic phase, although she sees the distinctions among these phases as less clear-cut than do the preceding theorists. According to single-route models, children may not gain the ability to use complex context-conditioned patterns in an adult-like way until relatively late in the course of decoding development. However, this does not mean that they use qualitatively different learning mechanisms or processing procedures for complex patterns than for simpler patterns.

Although single-route models have promise, the existing models suffer from certain weaknesses that hinder their ability to account for the development of decoding skill in children. Some of these weaknesses concern the models' coding of spellings. The first connectionist model of single-word reading, that of Seidenberg and McClelland (1989), coded spellings as an unordered collection of three-letter substrings (trigrams) found in the word. Thus *rogue* would be coded as the set {*-ro*, *gue*, *ogu*, *rog*, *ue-*}. With this type of coding, if the model hadn't been trained with the word *rogue*, it would be unlikely to know that the vowel is an /o/ as opposed to an /ɑ/, because the trigrams in the word are either unique to *rogue* (*ogu*) and thus couldn't have been learned previously, or they don't occur in /o/ words more than in /ɑ/ words. A human reader, however, might immediately surmise that the *o* is /o/ because of the final *e*. The model of Plaut et al. (1996) includes a coding of printed words in terms of position-dependent graphemes, so that *chip* contains initial *ch*, medial *i*, and final *p*. This raises the question of how children know that certain letters in printed words are more likely to be treated as units than others; the graphemes are not built into children in the way that they are built into the model. Harm and Seidenberg (2004) used a somewhat different procedure, coding letters in terms of the position they occupy with regard to the vowel. For example, the *p* of *chip* belongs to the slot "vowel + 1" and the *p* of *chimp* belongs to the slot "vowel + 2". All three of these coding schemes represent a given letter differently in different positions of a word; the first scheme additionally represents a letter as different when it is in the same position but surrounded by different letters. Thus initial *b* is coded as different from final *b* in all three schemes. The *p* of *chip* is coded differently from the *p* of *chimp* in the schemes of Seidenberg and McClelland and Harm and Seidenberg, although not in that of Plaut et al. The result is that what the models learn about the pronunciation of a letter in one position will often not transfer to other positions. This lack of transfer does not fit with the nature of alphabetic writing systems. Although some letters in some writing systems are translated differently depending on their position (e.g., *e* before a single consonant vs. at the end of a word in English *hem* vs. *he*), most are not. In other words, the writing systems show a degree of generalization that is greater than expected by current single-route models. Children may show more generalization than the models too, although this issue has been little investigated. The results of Thompson, Cottrell, and Fletcher-Flinn (1996) suggest that beginning readers learn correspondences that are to some extent tied to specific word positions but that some generalization occurs as well.

Similar issues of generalization arise with regard to the coding of spellings by single-route models. Syllable-initial and syllable-final phonemes are coded as different, and this causes problems for the phonological dimension like those discussed above for the spelling dimension. Also, if a model does not represent phonemes in terms of features, it will not show a preference for patterns that involve natural classes of phonemes such as hard and soft consonants (as in Russian and Irish) or short and long vowels (as in German and Irish). The model of Seidenberg and McClelland (1989) has a featural representation of phonemes, as does that of Harm and Seidenberg (2004), but Plaut et al. (1996) represent phonemes as unitary.

The hidden units of connectionist models allow them to generalize over spellings and phonemes that they code as different. In this way the models can account for higher-level generalizations in a way that dual-route models cannot. However, a model that does not account for the similarities among different spellings or the similarities among different phonemes may show less generalization than human learners. An Irish child, having seen a dozen cases in which *i* makes the preceding consonant soft, may immediately generalize to the thirteenth consonant. A model that does not capture the similarities among soft consonants would not generalize in this way. The powerful learning mechanisms that allow connectionist models to form categories and pick up patterns on the basis of exposure make it possible for them to learn generalizations that do not occur in natural writing systems and those that would be difficult for people to learn, as well as more natural generalizations.

Another weakness of single-route connectionist models, as models of human reading behavior, may lie in their assumption that humans are perfect statistical learners. Comparisons of the vowel pronunciations produced by English-language single-route models and those produced by skilled readers suggest that the models make more use of context, in certain situations, than readers do (Treiman, Kessler, & Bick, 2003). Although college students adjust their pronunciation of vowels such as *oo* depending on the following consonants, they do not adjust as much as the models. Skilled readers may have some tendency to operate with simple rules and patterns—*oo* is pronounced as /u/—even when more complex patterns could yield better prediction. These tendencies appear to be stronger in children than adults, with children taking some time to reach adult levels of context sensitivity (Treiman et al., 2006). People's tendency to use simple rules may in part reflect teaching—children are sometimes explicitly taught to pronounce *oo* as /u/—but it may go deeper. For a person, a rule that takes context into account may be intrinsically harder to learn and use than a rule that does not. For a connectionist model, there may be little difference if other factors, such as number of exposures, are equal.

Despite the problems mentioned above, we believe that single-route models fit better with what we know about the nature of alphabetic writing systems and the nature of learning than dual-route models. Given the developmental nature of connectionist models, surprisingly little research has been carried out to generate and test specific predictions for reading development in normal children. Research has tended to focus, instead, on the models' implications for children with reading disorders (e.g., Harm & Seidenberg, 1999). In the future, we hope to see more empirical research on reading development inspired by single-route models as well as further development of the models themselves.

5.0 Teaching of Decoding

We have addressed the development of decoding in light of the dual-route and single-route perspectives, but we have said little as yet about how children are taught or should be taught to decode. Many children are explicitly taught about the relations between certain letters and sounds in *phonics* instruction. In other instructional approaches, often called *whole language*, children are expected to figure out unknown words on the basis of context rather than decoding and to deal with known words as wholes. We do not have the space in this chapter to say much about debates about methods of reading instruction (see Snow & Juel, 2005, for a review). However, we wish to point out that the rules taught to children in phonics instruction are in many ways like the rules of the nonlexical route of the dual-route theory. Children are taught simple patterns of wide utility, such as that *b* is pronounced as /b/ or that *oo* is pronounced as /u/. When children encounter words that do not conform to the taught rules, they are typically encouraged to memorize these exceptional items as sight words. The single-route perspective alerts us to the fact that lists of simple rules do not exhaust the regularities that exist in English and certain other alphabetic writing systems. Given the many patterns that exist, we cannot explicitly teach children every pattern that could help them. Children must learn many of the patterns themselves. Teachers can help by providing feedback on how individual words are pronounced, just as a single-route model receives feedback, so that children can adjust their spelling-to-sound knowledge. Teachers can also help by encouraging the idea that words' spellings are systematically related to their sounds. A word that does not fit a simple pattern a child knows may exemplify a more complex pattern; it does not necessarily need to be memorized by rote. For example, the pronunciation of *book* does not fit with the idea that *oo* is always pronounced as /u/ but it does fit with the idea that the pronunciation of this and other vowels may change in a systematic way with the consonantal context. Although teachers cannot teach every pattern, they can help provide the conditions under which children can learn the patterns most effectively.

6.0 Conclusions

Learning to read involves grasping the idea that writing represents language and that there are systematic links between the components of printed words and the components of spoken words. In alphabetic writing systems, which have been the focus of interest in this chapter, these links are at the level of phonemes. Children need to learn these links in order to decode words and remember their spellings. Once children have this knowledge, they are in a good position to understand what they read and to learn about the special characteristics of the written language register. The development of decoding skill can be viewed from the perspective of dual-route theories of skilled decoding or from the single-route connectionist perspective. Although both views can account for some aspects of decoding development, we have argued that the single-route perspective is more promising. However, further development of the single-route models is required to realize that promise. In general, research on reading development needs to be informed by an understanding of skilled reading and an understanding of the nature of writing systems. This has not always been the case in the past, and we hope that the present chapter is a step in that direction.

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Footnote

[1]Current dual-route are largely limited to single-syllable words, explaining why our discussion is limited to these types of words. Single-route models are similarly limited.