CHAPTER 5

Visual word recognition

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5.1 Introduction

> Because the emissary, his mouth (being) heavy,
> was not able to repeat (it),
> The lord of Kulaba patted clay and wrote the
> message like (on a present-day) tablet—
> Formerly, the writing of messages on clay was not
> established—
> Now, with Utu's bringing forth the day, verily this
> was so,
>
> (from *Enmerkar and the Lord of Arrata*, cited in Schmandt-Besserat, 1996: 2)

This Sumerian epic provides the oldest known account of the development of a system for writing language (Schmandt-Besserat, 1996). It tells the story of an emissary sent by Enmerkar, lord of Kulaba, to negotiate the purchase of timber, metals, and precious stones from the lord of a distant land. Following many rounds of difficult negotiations, a day came that the emissary was unable to commit Enmerkar's full instructions to memory. Enmerkar dealt remarkably effectively with this problem: He invented a system for writing language, which he used to inscribe his instructions onto a clay tablet. On that day, Enmerkar perhaps unwittingly also provided the foundation for what was to become a cognitive skill central to life in modern society: reading.

Though the contribution of Enmerkar himself is dubious, the Sumerians of Mesopotamia are generally credited with the invention of writing, and by implication reading, at the end of the 4th millennium BC. Thus, unlike our inborn capacity to use spoken language, reading must be seen as a cultural phenomenon that constitutes an astonishing form of expertise. Understanding the mechanisms underlying skilled reading is at the centre of modern psycholinguistics, and has been a topic of considerable interest since the beginnings of psychology as a scientific discipline (e.g. Cattell, 1886; Huey, 1908). This brief chapter considers some of the theoretical and empirical issues that have shaped our understanding of one specific aspect of skilled reading—the recognition of single printed word— focusing in particular on aspects of this problem that are the subject of significant recent inquiry.

5.2 Orthographic representations

Our discussion begins with a term used in early psycholinguistic theories to denote a mental dictionary thought to package together all of the orthographic (spelling), semantic (meaning), and phonological (pronunciation) information about known words: the mental lexicon. This term still surfaces in the literature on the recognition of printed words, and it is not particularly out of the ordinary to see references to "lexical access" or "access to the mental lexicon" from the visual stimulus. These types of references are ambiguous, however, because it has been thought for many years that information about the orthographic forms of words is stored separately from information about the phonological forms of words and from information about the meanings of words (see e.g. Allport and Funnell, 1981; Baron, 1977; Borowsky and Besner, forthcoming; Coltheart, 2004; Coltheart et al., 2001; Forster and Davis, 1984; Grainger and Jacobs, 1996; Morton, 1979; Morton and Patterson, 1980). Implemented models of skilled reading such as the interactive-activation model (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982), the DRC model (Coltheart et al., 2001), the SOLAR model (Davis, 1999), the MROM model (Grainger and Jacobs, 1996), and the distributed-connectionist models (Harm and Seidenberg, 2004; Plaut, 1997; Plaut et al., 1996;

Seidenberg and McClelland, 1989; see Seidenberg, Chapter 14 this volume) thus postulate bodies of orthographic knowledge, which are distinct from bodies of semantic knowledge and bodies of phonological knowledge. Visual word recognition begins with these orthographic representations; and so too, this chapter begins by considering three key issues about their nature.

5.2.1 Orthographic input coding: letters and letter positions

The earliest theories of visual word recognition (Cattell, 1886) posited that words are recognized not in terms of their component letters but as wholes, on the basis of their shapes. Though this hypothesis continues to engender fascination (e.g. Pelli et al., 2003; Perea and Rosa, 2002; Saenger, 1997), most modern theories suggest that word recognition is based on the analysis of letters. There is a broad consensus, based on evidence from behavioral (see e.g. Bowers, 2000) and neuropsychological (Coltheart, 1981; see also Rapp et al., 2001) studies, that these representations are *abstract letter identities*. They are abstract in the sense that they are independent of surface properties such as case, position, font, colour, retinal location, or size. Thus, for example, the stimuli in Figure 5.1 all map onto the same abstract letter identity.[1]

Figure 5.1 Example visual stimuli thought to map onto a single abstract letter identity.

Mapping the visual stimulus onto abstract letter representations enables skilled readers to recognize words rapidly, even though they may appear in surface contexts (e.g. handwriting, typeface) of which the reader has no experience.

Representations of orthographic form need to encode more than abstract letter identities, however. They also need to encode information about the position of the letters in the stimulus. Otherwise, readers would not be able to detect the difference between anagram stimuli like *top*, *pot*, and *opt*, which share all the same letters. The interactive-activation model (McClelland and Rumelhart, 1981; Rumelhart and McClelland 1982), along with its subsequent variants including the DRC model (Coltheart et al., 2001) and the MROM model (Grainger and Jacobs, 1996), solves this problem through the use of slot-based coding. In this scheme, there are slots for each letter position in a stimulus, and each of these slots is filled with a separate set of letter units (one unit for each letter of the alphabet). For example, the word CLAM would be represented by selecting C in the first slot, L in the second slot, A in the third slot, and M in the fourth slot ($C_1L_2A_3M_4$). The distributed-connectionist models, by contrast, have solved the letter position problem in a variety of ways. These include slot-based coding schemes (e.g. Harm and Seidenberg, 2004) and Wickelcoding (Seidenberg and McClelland, 1989)—a scheme in which a word is represented by triplets of letters (e.g. CLAM would be represented as #CL, CLA, LAM, AM#).

Recent research has begun to highlight the inadequacies of these types of schemes for coding letter order, however. The general problem is that stimuli that are perceptually very similar may be represented by very different slot-based codes or Wickelcodes (see Davis, 1999; Davis, 2005; Plaut et al., 1996). Consider the text presented below, which was taken from an email message circulated globally that purported to address the mechanisms underlying letter position coding.

> Aoccdrnig to rseearch at Cmabrigde Uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht the frist and lsat ltteer be at the rghit pclae.

Though the specific idea expressed in this passage does not entirely stand up to research (see M. H. Davis, 2003; Grainger and Whitney, 2004 for discussion), the text does illustrate one major problem with these coding schemes. To be specific, one reason that we can read this passage so easily is that stimuli with letter transpositions (e.g. WAHT) are perceived as being very similar to their base words. Forster et al. (1987) used a masked form priming technique (see below) to explore this issue. They found that identity primes (e.g. what-WHAT) and transposition primes (e.g. waht-WHAT) produced equivalent levels of facilitation on lexical decision

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[1] Some may wonder how information from the printed stimulus maps onto these abstract letter identities. The received view is that letter identification is based on the detection of feature primitives (e.g. horizontal bar, curve that opens to the right) stored in memory. Even despite variations in letter presentation, it turns out that many orthographies can be described with relatively few features and are thus amenable to an approach based on feature analysis (see e.g. Neisser, 1967 for a discussion).

latency; and further, that both of these prime types produced more facilitation than substitution primes (e.g. whut-WHAT; see also Perea and Lupker, 2003 for an extension of this finding to associative priming, e.g. jugde-COURT versus judge-COURT and judpe-COURT). Despite the perceptual similarity of WAHT to WHAT demonstrated by these experiments, the slot codes for WAHT and WHAT overlap by only 50 per cent (W_1T_4). The situation is even worse with Wickelcoding, because on that scheme the codes for WAHT (#WA, WAH, AHT, HT#) are entirely different from the codes for WHAT (#WH, WHA, HAT, AT#; Davis,1999). Thus, neither of these letter coding schemes appears to provide an adequate explanation for these findings.

Further difficulties for slot-based coding schemes arise when "deletion neighbors" are considered (Davis, 2005). Deletion neighbors are words that can be derived from other words by removing one or two letters (e.g. PLUCK-LUCK; REPLAY-PLAY). On a left-aligned slot-based coding scheme, the words PLUCK ($P_1L_2U_3C_4K_5$) and LUCK ($L_1U_2C_3K_4$) share no overlap whatsoever, and should thus be perceived as highly dissimilar. Research using masked form priming (De Moor and Brysbaert, 2000; Drews and Zwitserlood, 1995; Schoonbaert and Grainger, 2004) and simple lexical decision (Davis and Taft, forthcoming) has, however, indicated that these types of letter strings are instead perceived as being highly similar. These and related findings (e.g. Davis and Bowers, 2004) have laid bare the inadequacies of existing schemes for coding letter position, and have made the search for a letter position coding scheme that better captures perceptual similarity among words one of the most interesting problems in visual word recognition research today (see also Dehaene et al., 2005, for a discussion of this problem from a neurobiological angle). Leading theories of position encoding include the open bigram coding scheme (Grainger and Van Heuven, 2003; Schoonbaert and Grainger, 2004; Whitney and Berndt, 1999; Whitney, 2001) and the spatial coding scheme as used in the SOLAR model (Davis, 1999). Unlike slot-based coding, which codes the absolute position of letters in the stimulus (e.g. the H in WHAT is in position 2), both of these coding schemes capture the *relative* position of letters in the stimulus (e.g. the H comes after the W in WHAT). Research is currently under way to adjudicate between these alternatives (see Davis, 2005 for a review).

5.2.2 Local and distributed word representations

Though all implemented models of visual word recognition postulate an orthographic body of knowledge that encodes letters and letter order, the form of this knowledge differs across models. Classical models of visual word recognition based on the interactive-activation model (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982), such as the DRC model (Coltheart et al., 2001) and the MROM model (Grainger and Jacobs, 1996), postulate multiple levels of orthographic representation, one of which is an *orthographic lexicon* within which known words are represented locally (i.e. one unit stands for one word). The more spellings that are in someone's vocabulary, the more individual units that person will have in their orthographic lexicon. Distributed-connectionist theories, in contrast, deny the existence of an orthographic lexicon—or indeed, any lexicon (e.g. Harm and Seidenberg, 2004; Plaut, 1997; Plaut and Booth, 2000; Plaut et al., 1996; Seidenberg and McClelland, 1989; see Seidenberg, Chapter 14 this volume). These theories propose instead that the orthographic information about known words is coded in a distributed manner as learned patterns of activation over a large body of units. There are no individual units for known words in these models. This distinction between local and distributed lexical representations is a fundamental one for modelling skilled reading, and has been an issue of considerable debate over the last fifteen years of research.

The primary manner in which researchers have explored this distinction is in terms of the lexical decision task. Lexical decision is one of the most elementary abilities of the skilled reader. *Given sufficient time*, skilled readers can decide with a remarkable degree of accuracy (perhaps 100 per cent) whether a visually presented letter string (e.g. BALSE, FALSE) is a known word or a non-word. Classical models of visual word recognition provide a natural account of lexical decision by virtue of their local representations of known words: if the visually-presented stimulus is represented in the orthographic lexicon, then it is a word. Further, both the DRC and MROM models have been able to simulate a wide range of human lexical decision data (Coltheart et al., 2001; Grainger and Jacobs, 1996). One may wonder, however, how the distributed-connectionist models are able to perform the lexical decision task, given that there are no local representations of known orthographic forms in these models. Indeed, this has been an issue of significant concern to distributed-connectionist modellers for some time (see Plaut, 1997; Seidenberg and McClelland, 1989), and has been discussed at length in the literature on visual word recognition (see e.g. Borowsky and Besner, forthcoming; Besner et al., 1990; Coltheart et al., 1993; Coltheart, 2004; Coltheart et al., 2001; Rastle and Coltheart, 2005).

The answer appears to be that these models can't perform this task—at least not in the manner that human readers can perform it. Rastle and Coltheart (2005) explained that the only way in which these models have been able to simulate the word/non-word discrimination with any degree of accuracy is on the basis of *semantic information* (Plaut, 1997; Plaut and Booth, 2000; see also Bullinaria, 1995). Seidenberg and McClelland (1989) claimed that their model could make this discrimination without consulting a semantic system; but closer inspection (Besner et al., 1990; Fera and Besner, 1992) revealed significant problems with the model's performance of the lexical decision task, "[calling] into question the … claim that words can be distinguished from non-words by a distributed system lacking word-specific representations" (Plaut, 1997: 787). The problem with making lexical decisions on the basis of semantic information is that it renders these models incapable of explaining how patients with severe acquired semantic damage can perform the lexical decision task at levels of accuracy comparable to those of skilled readers without brain damage. Coltheart (2004) described several such neuropsychological cases. Irrespective of how unimpaired readers perform the lexical decision task (i.e. whether they use semantic information in making their decisions), the cases described by Coltheart (2004) demonstrate that readers *can* perform the lexical decision task without the use of semantic information. This is exactly what models without local representations of words have difficulty doing (see also Rastle and Coltheart, 2005).[2]

The most recent work on lexical decision in distributed-connectionist models was undertaken by Harm and Seidenberg (2004), who explored the use of two sources of *orthographic* information—orthographic stress and orthographic distance—for simulating the word/-non-word discrimination. Understanding exactly how these measures were computed is not important for the purposes of this chapter; what is important is that each of these measures reflects information about the state of orthographic units in a distributed-connectionist network following presentation of a visual stimulus. Harm and Seidenberg (2004) demonstrated that average orthographic distance and orthographic stress measures computed during stimulus processing differed for groups of words and non-words, and claimed that "these variables produce results that provide a basis on which lexical decisions could be made." One problem with this conclusion, however, is that Harm and Seidenberg (2004) did not report the *accuracy* with which their network could make the word/-non-word discrimination (Rastle and Coltheart, 2005). Even though the *groups* of words and non-words produced different *average* stress and distance values, it is not apparent from Harm and Seidenberg (2004) whether there is a value of stress and/or distance that reliably discriminates words from non-words to the level of accuracy achieved by skilled readers under non-speeded conditions.[3] Perhaps an even larger problem is that the orthographic information consulted in these simulations was computed on the basis of an orthographic representation regenerated from a semantic representation.[4] Thus, Rastle and Coltheart (2005) argued that this approach to lexical decision is still not immune to the neuropsychological evidence presented by Coltheart (2004), since any damage to semantic representations would impair the regenerated orthographic representations.

None of these are "in principle" arguments against the position that orthographic lexical

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[2] I am grateful to Ken Forster for observing that another piece of evidence that skilled readers *can* make lexical decisions without the use of semantic information is the experience of knowing that a particular letter string is a word without having any idea of what it means. I have this experience with the word *aver*, for example.

[3] These words and non-words would, of course, have to be matched on orthographic structure. Plaut and Booth (2000) attempted a simulation of lexical decision based on semantic information in which they compared trained letter strings with a CVC structure against untrained letter strings with a VCV structure. The VCV structure had not been encountered previously by the network. Borowsky and Besner (forthcoming) highlight the folly of simulating the task in this manner: in an equivalent experiment with human readers, the decision could be made with 100% accuracy simply by classifying the initial letter as a vowel or consonant.

[4] In this simulation, orthographic units activated semantic units, and the activated semantic pattern was used to compute a secondary orthographic representation. It was this secondary orthographic representation (reconstructed from the activated semantic pattern) that was used to calculate the orthographic stress and orthographic distance values.

knowledge is represented in a distributed manner. However, in fifteen years of study, models with distributed representations have yet to produce an acceptable account of one of the most basic abilities of skilled readers: deciding under non-speeded conditions whether a visually presented letter string is a known word. One must take a cautious approach in drawing inductive inferences about the reading system from this failure; indeed, these models may yet produce an acceptable account of this most elementary ability. However, at least at present, it appears that a great irony of distributed-connectionist modelling is that it has helped to demonstrate the importance of local orthographic representations in the visual word recognition system.

5.2.3 Frequency, cumulative frequency, and age of acquisition

The most powerful determinant of the time taken to recognize a word is the frequency with which it occurs (see e.g. Monsell, 1991; Murray and Forster, 2004 for reviews). Effects of word frequency have been reported in lexical decision (e.g. Forster and Chambers, 1973; Balota et al., 2004) along with every other task thought to contact the orthographic representations involved in visual word recognition. These include, for example, perceptual identification (e.g. Broadbent, 1967), reading aloud (e.g. Balota and Chumbley, 1984), and eye fixation times in reading (e.g. Inhoff and Rayner, 1986; Schilling et al., 1998). Though some have questioned whether frequency effects might be exaggerated in the lexical decision task (Balota and Chumbley, 1984), there is widespread agreement that one's experience with words is somehow encoded in (local) orthographic representations of known words and thus influences the ease with which those words are recognized. The interactive-activation model (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982) and its subsequent variants (Coltheart et al., 2001; Grainger and Jacobs, 1996), for example, conceptualize frequency effects in terms of the resting activation of local orthographic representations of words: Units representing words that occur frequently in print have higher resting levels of activation than units representing words that occur only rarely in print, and thus reach a criterion for recognition more quickly.

Recently, an interesting debate has emerged in the literature, which questions exactly how our experience with words is encoded into the orthographic representations supporting visual word recognition. Previous research has always suggested that the frequency with which a particular printed word occurs in the language provides a good estimate of our experience with words, and thus influences recognition time (e.g. Forster and Chambers, 1973). These frequency estimates are normally gathered through the analysis of large corpora of adult text, in which the occurrences of individual words are counted (e.g. Baayen et al., 1993; Kucera and Francis, 1967; Zeno et al., 1995). However, more recent research has suggested that the age at which we acquire a word may also be an important determinant of our experience with words (e.g. Brysbaert et al., 2000; Morrison and Ellis, 1995; Gerhand and Barry, 1999). Might this information also be encoded in representations of orthographic form? Research attempting to manipulate these factors orthogonally seems to suggest that there may indeed be independent effects of printed frequency and age of acquisition (Morrison and Ellis, 1995; Gerhand and Barry, 1999) on visual word recognition: the time taken to recognize a word is reduced both when that word has a high printed frequency and when that word was acquired early in life.

A closer look, however, reveals the methodological difficulties inherent in conducting these studies (Zevin and Seidenberg, 2002). For one thing, the age of acquisition measures typically used in these studies is based on subjective estimates from adults of the age at which certain words were acquired (Gilhooly and Logie, 1980). Though these measures correlate with objective measures of the age at which children acquire object names (Morrison et al., 1997), they are estimates nonetheless. Measures of printed word frequency are also estimates, and these estimates differ depending on the size and nature of the corpus used (Zevin and Seidenberg, 2002). Pairing these measurement issues with the fact that printed word frequency and age of acquisition are so highly related (high-frequency words are those most likely to be learned early; $r = -.68$, Carroll and White, 1973) can render it very difficult to design experiments that examine independent effects of these variables. Indeed, Zevin and Seidenberg (2002) demonstrated that recent studies of age of acquisition have typically confounded the age of acquisition variable with at least one of the available counts of printed word frequency.

Further—and this is also a critical point—it might be the case that printed frequency and age of acquisition are actually two dimensions of a single variable: cumulative frequency (i.e. the frequency with which an individual is exposed to a particular word over their lifetime; e.g.

Lewis et al., 2001; Zevin and Seidenberg, 2002). It is certainly not unlikely that our experience with words (and the representation of this experience in the recognition system) accrues over our lifetimes; indeed, the view that cumulative frequency provides a better description of our experience with words than printed word frequency is now fairly uncontroversial (see Brysbaert and Ghyselinck, forthcoming). The difficult question of interest and debate at present is whether cumulative frequency can account fully for the age of acquisition effect observed on visual word recognition. Recent research using experimental (Stadthagen-Gonzales et al., 2004) and regression (Brysbaert and Ghyselinck, forthcoming; Ghyselinck et al., 2004) approaches suggests that the answer is probably "no": the age at which a word was acquired also seems to play a role in its recognition. Clearly, however, further empirical and computational research is necessary in this important area, which promises to give us insight into the mechanisms by which we acquire experience with printed words and represent this experience in the recognition system.

5.3 Processing dynamics and sechanisms for selection

Thus far, our discussion has homed in on a theory of visual word recognition that consists of multiple levels of orthographic representation. The visual stimulus is analyzed in terms of its features; these features map onto a level of representation that codes abstract letter identity as well as letter position; and these letters map onto a level of representation at which the orthographic forms of known words are represented locally and somehow coded for our experience with them. However, this theory so far consists only of the architecture. How is information transmitted through these levels of representation? Further, what is the mechanism by which a single local word unit corresponding to the target is selected? These are the questions that are considered in this section.

5.3.1 The interactive-activation model

Two empirical findings, the word superiority effect (Reicher, 1969; Wheeler, 1970) and the pseudo-word superiority effect (Carr et al., 1978; McClelland and Johnston, 1977) were crucially important in constraining early accounts of visual word recognition. In the Reicher-Wheeler experiments, a word (e.g. WORK) or a non-word (e.g. OWRK) was flashed very briefly and then replaced by a pattern mask. Participants were then forced to decide which of two letters (e.g. D or K), presented adjacent to the position of the previous target letter, was in the stimulus. Results showed that letter identification was more accurate when letters had been presented within word stimuli than within non-word stimuli. Further experiments (Carr et al., 1978; McClelland and Johnston, 1977) demonstrated that the letter-identification benefit seen with words extends to pronounceable non-words (e.g. K is identified with greater accuracy in TARK than in ATRK). These findings provided benchmark phenomena for the development of the interactive-activation model (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982), which many still consider to be the cornerstone of our understanding of processing and selection in visual word recognition (see e.g. Coltheart et al., 2001; Davis, 2003; Grainger and Jacobs, 1996; but see Forster, 2005; Murray and Forster, 2004 for important criticisms). The model is depicted in Figure 5.2.

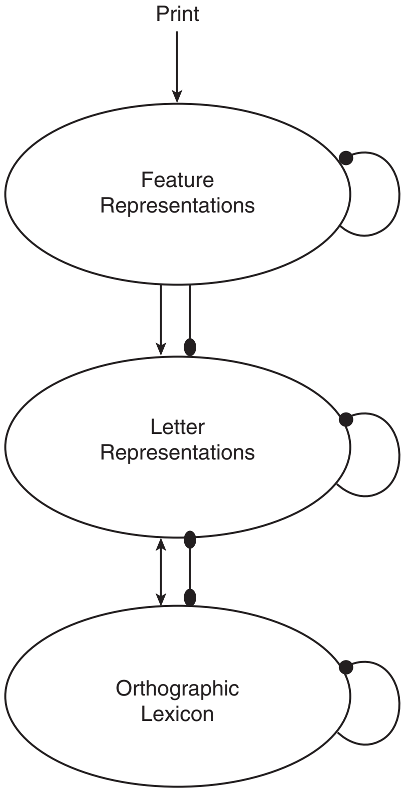

Figure 5.2 The interactive-activation model of visual word recognition (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982).

In the model, information from the visual stimulus flows through feature, letter, and word levels of representation. Each of these levels of representation consists of individual units called nodes. The connections between these adjacent levels of representation are both excitatory and inhibitory: nodes at every level excite nodes at adjacent levels with which they are consistent and inhibit nodes at adjacent levels with which they are inconsistent. For example, the initial letter T in a stimulus will activate word nodes for TAKE, TALL, and TREE while inhibiting word nodes for CAKE, MALL, and FREE. Information flows continuously (i.e. in "cascade"; McClelland, 1979) through these levels of representation. Unlike the logogen models that preceded it (e.g. Morton, 1969; 1979), information at one level of representation does not have to reach a threshold before being passed on to another level of representation (see Coltheart et al., 2001 for a discussion).

Information flows between adjacent layers of the model in a bidirectional manner (e.g. information travels from letters to words and also from words to letters). It is through these bidirectional connections that the model explains how knowledge of a higher-level unit (e.g. a word) can influence the processing of a lower-level unit (e.g. a letter). Letters embedded in words are particularly easy to recognize (i.e. the word superiority effect) because they enjoy top-down support from nodes activated by the stimulus at the word level. Letters embedded in pronounceable pseudo-words (i.e. the pseudo-word superiority effect) may also enjoy top-down support through these bidirectional connections. Even though pseudo-words are not represented by nodes at the word level, they too can activate (and derive support from) nodes at this level that represent visually-similar words (e.g. TARK activates and derives support from nodes for PARK, DARK, TURK, etc.).

The discussion so far has indicated that printed letter strings (whether words or non-words) can activate multiple nodes at the word level. For example, the stimulus CAKE activates the node for CAKE at the word level, but also activates nodes for visually similar alternatives like CARE, FAKE, CAPE, RAKE, and COKE. When the printed stimulus corresponds to a word, nodes for alternative candidates will be activated more weakly than the node for the target, but will be activated nonetheless. How, then, does the recognition system select the node corresponding to the target from these multiple candidates? One possible mechanism is search. Both the search model (Forster, 1976; Murray and Forster, 2004) and the activation-verification model (Paap et al., 1982; Paap and Johansen, 1994) posit that target selection is achieved through a frequency-ordered serial search or verification process that seeks to establish which candidate provides the best fit to the stimulus.[5] The interactive-activation model solves this target selection problem in a different manner, however: through competition. In the model, inhibitory connections between word nodes enable the most active node (typically that of the target) to drive down the activation of multiple alternative candidates. Of course, the presence of many competing candidates will also make it difficult for the target to reach a critical recognition threshold, since inhibition emanating from those competing candidates will act to drive down activation of the target (see e.g. Andrews, 1997; Davis, 2003; Davis and Lupker, forthcoming; Grainger and Jacobs, 1993; Grainger et al., 1989 for a discussion of competitive mechanisms in target selection).

5.3.2 Neighborhood (N) effects

The general problem of selecting a representation of the target stimulus from multiple candidates has provided the impetus for a significant body of research on lexical similarity effects in word recognition. Coltheart et al. (1977) defined the neighborhood size of a stimulus (N) as the number of words that can be created by changing one letter of that stimulus. Using this metric of lexical similarity, the word CAKE, for example, has a very large neighborhood (e.g. BAKE, LAKE, CARE, COKE, CAVE, etc). Coltheart et al. (1977) reported that high-N non-words (e.g. PAKE) were rejected more slowly in lexical decision than low-N non-words (e.g. PLUB), an effect now replicated by a number of investigators (e.g. Davis and Taft, forthcoming; Forster and Shen, 1996; McCann et al., 1988). It is not hard to see why high-N non-words should be difficult to reject in lexical decision. Such non-words activate many nodes at the word level (i.e. they look like many actual words), and this total activation makes it difficult to decide that the stimulus is not a word. However, Coltheart et al. (1977) also reported no effect of N on the YES response in lexical decision: high-N and low-N words were recognized with similar latencies. This result is interesting, since it is inconsistent with both of the mechanisms for target selection

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[5] Both of these models have played a very important part in the development of our understanding of visual word recognition over the past 30 years. However, they are described only briefly in this chapter because they play a far more limited role than the interactive-activation model in driving research at present.

described above (i.e., search and competition). These mechanisms would seem to predict that a large N should be detrimental to the recognition of words, since a large N implies the activation of many competing candidates.

This issue surfaced again ten years later, when Andrews (1989) observed that high-N words are *easier* to recognize in lexical decision than are low-N words, especially when these words are of a low printed frequency. Simultaneously, however, Grainger et al. (1989) reported inhibitory effects of neighborhood frequency on lexical decision. They found that words with at least one higher-frequency neighbor are recognized more slowly than are words with no higher-frequency neighbors, an effect seemingly in line with the predictions of competitive network models like the interactive-activation model. These findings would appear to be contradictory, since words with many neighbors usually have at least one higher-frequency neighbor—presumably all that it takes to delay lexical decision (Sears et al., 1995). Thus, the first three examinations of the effect of N on the recognition of words seem to have produced the three logically possible results: no effect (Coltheart et al., 1977); facilitation (Andrews, 1989); and inhibition (Grainger et al., 1989). Empirical findings over the next fifteen years have not especially clarified this matter (see Andrews, 1997 for a review). Several investigators have continued to report facilitatory effects of N on the YES response in lexical decision (Andrews, 1992; Balota et al., 2004; Forster and Shen, 1996; Sears et al., 1995), while several others have continued to report inhibitory effects of neighborhood frequency in this task (Carreiras et al., 1997; Grainger, 1990; Grainger et al., 1992; Grainger and Jacobs, 1996; Grainger and Segui, 1990; Huntsman and Lima, 1996; Perea and Pollatsek, 1998). This issue is central to our understanding of mechanisms for target selection in visual word recognition, and so these inconsistencies must be resolved.

Three types of explanation have been offered for these inconsistent effects. The first explanation relates to the fact that while most of the facilitatory neighborhood findings have been reported using English stimuli (but see Davis and Taft, forthcoming), most of the inhibitory findings have been reported using French, Spanish, or Dutch stimuli (Andrews, 1997). One possibility (Ziegler and Perry, 1998) is that the direction of the neighborhood effect is determined by the relative balance of two opposing effects: inhibition due to competition from neighbors and facilitation due to overlap with larger sublexical units (e.g. bodies, rimes[6]). N is positively correlated with these larger sublexical units, such that a word with many neighbors will usually also consist of highly frequent sublexical units (Andrews, 1997). Because larger units play a more important role in English than in other languages (see Ziegler and Goswami, 2005 for discussion), one would expect to find facilitatory N effects in English and inhibitory N effects in other languages—precisely the pattern normally observed.

The second explanation for the inconsistent neighborhood findings was proposed by Grainger and Jacobs (1996), who argued that the inhibitory pattern might be the "true" pattern and that the facilitatory pattern may result from strategic processes involved in the decision component of the lexical decision task. They postulated a "fast guess" decision mechanism whereby the "YES" response in the lexical decision task can be made on the basis of the total activity of units in the orthographic lexicon (see also Coltheart et al., 2001). It is through this fast guess mechanism that the facilitatory effects of neighborhood size are deemed to arise. This theory has received support from observations that the direction of the neighborhood effect can be shifted from inhibition to facilitation by stressing accuracy or speed in task instructions (De Moor et al., forthcoming; Grainger and Jacobs, 1996). Situations in which participants are instructed to be very accurate typically produce inhibitory neighborhood effects, presumably because participants in these situations have to access a specific lexical node undergoing competition from other nodes. Conversely, situations in which participants are instructed to be very fast typically produce facilitatory neighborhood effects, presumably because participants in these situations can make their decision on the basis of the strategic fast guess mechanism, and do not have to access a specific lexical node undergoing competition.

The third explanation for the inconsistent neighborhood findings is due to Davis and Taft (forthcoming). These authors have recently suggested that these inconsistencies may be a consequence of the fact that the N-metric as defined by Coltheart et al. (1977) is overly restrictive. This metric is based on a slot-based scheme for coding letter position, and therefore excludes transposed-letter neighbors and deletion neighbors

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[6] The body or rime of a syllable consists of its vowel plus its final consonants, where the body refers to the syllable's orthography and the rime refers to its phonology. For example, the body of MOOT is -OOT and the rime of /mut/ is /ut/.

of target words—neighbors that are perceptually similar to target words (see discussion above). Thus, items like ACRE (which have no higher-frequency neighbors, as defined on Coltheart's N-metric) may have been used inappropriately as experimental controls in many of the studies of neighborhood frequency, even despite the fact that they have higher-frequency transposed-letter neighbors (e.g. CARE) and higher-frequency deletion neighbors (e.g. ARE). Davis and Taft (forthcoming) speculate that if the neighborhoods of such target words had been properly defined in previous studies, the true inhibitory pattern might have emerged. It is not difficult to see that each of these three explanations for the inconsistent neighborhood findings provides exciting possibilities for future research on a problem that is fundamental to our understanding of selection mechanisms in visual word recognition.

5.3.3 Masked form priming effects

Masked form priming effects are another important source of evidence concerning selection mechanisms in visual word recognition. Masked form priming is a technique in which a briefly presented lower-case prime (e.g. 50 ms) is sandwiched between a forward pattern mask and an upper-case target presented for some type of lexical processing task (including lexical decision, reading aloud, semantic categorization, perceptual identification; e.g. Evett and Humphreys, 1981; Forster and Davis, 1984; Forster et al., 1987; Forster and Davis, 1991). Because participants in these experiments do not have conscious experience of the prime (they normally report seeing a flash or nothing at all prior to the target), it is normally argued that masked priming provides a highly- esirable situation in which neither strategic nor episodic factors can be invoked to explain the priming effects observed (but see Bodner and Masson, 2001). Researchers using this technique over the past twenty years have normally sought to determine how the recognition of a target word is influenced by the prior presentation of a visually similar word or non-word prime.

Priming in the interactive-activation model is conceptualized as a balance between facilitation and inhibition (Davis, 2003; Ziegler et al., 2000). Primes activate visually similar targets, thus producing savings in the time it takes for those targets to reach a critical recognition threshold of activation. However, primes can also activate word nodes that compete with targets for recognition. Davis (2003) therefore suggested that prime lexicality (i.e. the word/non-word status of a prime) should be a particularly influential factor in determining the magnitude of form priming effects. Non-word primes (e.g. azle–AXLE) should typically produce robust facilitation, because these primes activate nodes for their corresponding targets without also activating any strongly competitive nodes. In contrast, word primes (e.g. able–AXLE) activate nodes for their corresponding targets but also activate their own nodes, which compete with the target nodes for recognition. The interactive-activation model therefore predicts that word primes should facilitate target recognition to a much lesser degree than non-word primes (Davis, 2003). Search models (e.g. Forster et al., 1987; Forster and Veres, 1998), on the other hand, predict facilitation of visually similar masked primes on target recognition because these models propose that visually similar primes (whether words or non-words) constrain the area of the orthographic lexicon that is searched.

Broadly speaking, data from masked form priming seem to show support for the interactive-activation model. First of all, masked non-word primes facilitate lexical decisions to target words (e.g. bontrast–CONTRAST). This result was first obtained by Forster and Davis (1984), and has since been replicated numerous times (e.g. Davis and Lupker, forthcoming; Forster et al., 1987; Forster et al., 2003; Forster and Veres, 1998; Perea and Lupker, 2003). In contrast, most of the experiments that have examined the effects of masked word primes on target recognition have revealed inhibitory effects or null effects (e.g. de Moor and Brysbaert, 2000; Davis, and Lupker, forthcoming; Drews and Zwitserlood, 1995; Forster and Veres, 1998; Grainger et al., 1991; Grainger and Ferrand, 1994; Segui and Grainger, 1990). That said, for reasons not yet totally clear (Davis and Lupker, forthcoming), facilitatory effects in this situation are sometimes obtained (Forster et al., 1987; Forster and Veres, 1998). Further research is needed if these findings are to be reconciled with the interactive-activation model.

There is also one special case in which masked word primes *always facilitate* the recognition of visually similar targets: the case in which primes comprise a *morphological surface structure*. Stimuli that have a morphological surface structure are those that can be parsed into known morphemes (i.e. stems and affixes) on the basis of their orthography (Rastle and Davis, 2003). For example, the stimuli DARKNESS and CORNER both have a morphological surface structure (even despite the fact that only one of the stimuli, DARKNESS, is genuinely morphologically complex) because they can both be parsed into stems and suffixes (DARK+NESS; CORN+ER). Now, previous research (De Moor and Brysbaert, 2000) has demonstrated that the recognition of a target word is normally inhibited when that target word is preceded by a masked word prime that constitutes an "addition neighbor" (e.g. brothel-BROTH). These inhibitory effects are not observed, however, if that addition neighbor has a morphological surface structure (e.g. brother-BROTH; Rastle et al. 2004). In these circumstances, robust facilitation of the magnitude typically obtained by identity primes is instead observed (Longtin et al., 2003; Rastle and Davis, 2003; Rastle et al., 2004). Furthermore, there is no effect of the lexicality of the prime on the magnitude of priming (Longtin and Meunier, 2005). Primes with a morphological surface structure facilitate recognition of their embedded targets, irrespective of whether those primes are words or non-words. One explanation for this set of results is that morphological surface structure enables a rapid perceptual segmentation of a prime, which disables that prime's ability to activate a word node that would normally compete against the target for recognition. For example, the prime BROTHER may be rapidly segmented into {BROTH} + {ER}, thus enabling activation of the word node for the target (BROTH) without activating the competing word node for the prime (BROTHER). Primes such as BROTHEL cannot be segmented because they do not constitute a morphological surface structure (i.e. -EL never functions as an English suffix), and thus end up competing with the target for recognition (see also Marslen-Wilson, Chapter 11 this volume).

5.4 Word recognition and the reading system

Our discussion so far has centred on the architecture and mechanics of the recognition components of the reading system. However, the reading system also comprises pathways for the computation of meaning and for the computation of phonology (i.e., reading aloud). These latter pathways in particular have been studied in great detail from behavioral, neuropsychological, and computational perspectives (see Coltheart et al., 2001 for a review), and it is well beyond the scope of this chapter to review this literature. However, this final section of the chapter does consider the effects that these pathways to meaning and phonology may have on the recognition of printed words. Indeed, though visual word recognition is normally conceptualized as being driven primarily by the analysis of orthography, it is now indisputable that semantic and phonological information *can* contribute to this process. My discussion of these issues is necessarily brief. Further more detailed discussion can be found in several of the chapters in this volume including those of Frost and Ziegler (7), Lupker (10), Moss, Tyler, and Taylor (13), and Seidenberg (14).

5.4.1 The DRC model

One theory of skilled reading that may help us to understand phonological and semantic influences on visual word recognition is the DRC model (Coltheart et al., 2001). DRC is the most comprehensive theory of visual word recognition *and* reading aloud described to date, and it has been studied extensively (see Coltheart et al., 2001 for a review). The model takes its architecture, depicted in Figure 5.3, from many years of theoretical development on the nature of the skilled reading system dating back to Morton (1979), Morton and Patterson (1980), Harris and Coltheart (1986), and Patterson and Shewell (1987). Further, the model retains the processing and selection mechanisms of the interactive-activation model, which have been so successful in helping us to understand visual word recognition. Lexical decisions in the model are based on an analysis of activation of nodes in the orthographic lexicon.

This model, along with its capabilities for simulating phenomena concerning visual word recognition reading aloud, have been described extensively elsewhere (e.g. Coltheart et al., 2001; Rastle and Coltheart, 1999). Briefly, there are three processing pathways in the model: (a) a non-lexical pathway through which a printed letter string is translated to sound by rule (e.g. VIB → /v ⋂ b/); (b) a lexical pathway through which the phonological form of a word is retrieved directly following its activation in the orthographic lexicon; and (c) a second lexical pathway through which the phonological form of a word is retrieved via its meaning representation. Information about the printed stimulus flows through all of these pathways in cascade. Thus, semantic and phonological representations for a printed stimulus can be activated well before the activation of a node in the orthographic lexicon has reached a critical recognition threshold.

The crucial feature of this model for our discussion of visual word recognition is that it postulates

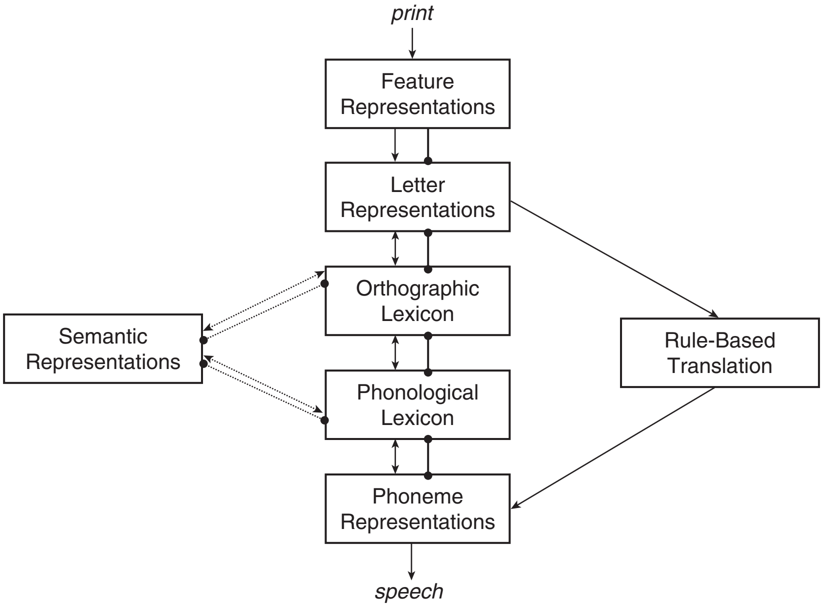

Figure 5.3 The DRC model of visual word recognition and reading aloud (Coltheart et al., 2001) Dashed lines indicate components of the model that have not yet been implemented.

bidirectional connections between semantic, phonological, and orthographic bodies of knowledge. These bidirectional connections provide an opportunity for phonological and semantic information to influence the rise of activation of nodes in the orthographic lexicon (the source of information monitored in the recognition of printed words; see above). For example, the stimulus COAT will activate its own node in the orthographic lexicon through feedforward activation from the letter nodes. However, the orthographic node for COAT will also receive supporting activation from semantic nodes (activated via phonological nodes and/or via orthographic nodes) and from phonological nodes (activated via orthographic nodes, semantic nodes, and/or phoneme nodes). Though semantic and phonological information can influence the rise of activation in orthographic nodes, an important claim of this model is that neither semantic nor phonological information is a *necessary* condition for the recognition of a printed word. This postulate of the theory is based on considerable data from neuropsychological patients demonstrating that the recognition of printed words remains possible even in the face of severe semantic and/or phonological damage (see e.g. Coltheart, 2004; Coltheart and Coltheart, 1997; Coltheart et al., 1980/1987; Coltheart et al., 2001 for discussion). If there are bidirectional connections between orthography, semantics, and phonology, then what types of semantic and/or phonological influences might we observe on the recognition of printed words?

5.4.2 Semantic influences on recognition

The specific influences of semantic variables on the recognition of single printed words have been challenging to pin down because of the need to exercise control over numerous highly related variables (see e.g. Balota et al., 1991; Balota, 1994; Gernsbacher, 1984 for discussion). However, it now seems reasonably clear that printed words with particularly rich semantic representations are recognized more quickly than words with more impoverished semantic representations—though it is not yet known exactly how semantic richness is best conceptualized. Potential candidates include, for example, imageability (Balota et al., 2004), number of semantic features (Pexman et al., 2002), semantic neighborhood density (Buchanan et al., 2001; Locker et al., 2003), number of meanings (Hino and Lupker, 1996), number of related meanings (Azuma and Van Orden, 1997), and number of related senses (Rodd et al., 2002; see Lupker, Chapter 10 this volume for a full review). Irrespective of the exact nature of the semantic effect on recognition, researchers in this area have typically explained their findings in terms of interactivity between semantic and orthographic bodies of knowledge.

Priming studies also reveal semantic influences on visual word recognition. Meyer and Schvaneveldt (1971) were the first to demonstrate that lexical decisions to words (e.g. DOCTOR) are significantly shorter when they are preceded by semantically related words (e.g. NURSE) than when they are preceded by unrelated words (e.g. BREAD). This finding, which has been replicated numerous times, has motivated a literature of its own that is much too great to treat in this chapter (see e.g. Balota, 1994; Hutchison, 2003; Lucas, 2000; Neely, 1991 for reviews). The dominant metaphor for explaining semantic priming is spreading activation (e.g. Collins and Loftus, 1975; Neely, 1977). The idea is that the orthographic representation of the prime activates a semantic node, which then sends positive activation to related nodes (including the target) at the semantic level of representation. If the semantic node for the target is activated by the prime through spreading activation, then that semantic node may send activation back to its corresponding node in the orthographic lexicon— influencing the time it takes for that target orthographic node to reach a recognition threshold. Here again, we see the importance of bidirectional connections between orthography and semantics for explaining core phenomena in visual word recognition.

5.4.3 Phonological influences on recognition

Rubenstein et al. (1971) presented homophonic words (e.g. MAID, SALE), non-homophonic words (e.g. PAID, RAIL), pseudo-homophones (e.g. BURD, KOAT), and non-pseudo-homophonic non-words (e.g. GURD, WOAT) to participants for lexical decision. They observed that Yes responses were slower for homophones than they were for non-homophonic words, and that No responses were slower for pseudo-homophones than they were for non-pseudo-homophonic non-words. Both of these effects on lexical decision—the homophone effect and the pseudo-homophone effect—have been replicated (homophone effect: Ferrand and Grainger, 2003; Pexman et al., 2001; pseudo-homophone effect: Besner and Davelaar, 1983; Coltheart et al., 1977; McCann et al., 1988; McQuade, 1981; Vanhoy and Van Orden, 2001; Ziegler et al., 2001). On the theory pictured in Figure 5.3, the homophone effect could be understood in terms of an effect of feedback from nodes in the phonological lexicon to nodes in the orthographic lexicon (Pexman et al., 2001). For example, the stimulus MAID activates the phonological node for /me∩d/ in the phonological lexicon; and this node subsequently sends activation back not only to the orthographic node for MAID but also to the competitor orthographic node for MADE. The pseudo-homophone effect can also be understood in terms of feedback from phonological levels of representation to nodes in the orthographic lexicon. For example, on the theory in Figure 5.3, the stimulus KOAT will be translated by rule to /k$_{\mathrm{L}}$∪t/; this phonemic representation will then activate the phonological node for /k$_{\mathrm{L}}$∪t/ and subsequently the orthographic node for COAT. Rejecting this stimulus in lexical decision will be particularly difficult because of the activation of the orthographic node COAT.

Priming studies also reveal an influence of phonology on the recognition of printed words. Some of the most interesting work in this domain comes from the use of the masked form priming technique (see above). Numerous studies have now revealed that target recognition is speeded by the prior brief presentation of a masked pseudo-homophone prime (e.g. koat–COAT) relative to an orthographic control (e.g. poat–COAT). This benefit from phonology is observed in lexical decision (e.g. Drieghe and Brysbaert, 2002; Ferrand and Grainger, 1992; Lukatela et al., 1998; Rastle and Brysbaert, forthcoming) as well as a multitude of other tasks that tap recognition components of the reading system (e.g. Perfetti et al., 1988; Perfetti and Bell, 1991; see Rastle and Brysbaert, forthcoming, for a review). These findings indicate not only that phonology influences the recognition of printed words, but that phonological influences become apparent very early in processing. This evidence for “fast” phonology has led a number of researchers (e.g. Drieghe and Brysbaert, 2002; Frost, 1998; Lukatela and Turvey, 1994; Xu and Perfetti, 1999) to suggest that phonological recoding of a printed stimulus plays a leading role in its recognition, a role much more central to that allowed by theories such as the DRC model. Indeed, it remains to be seen whether these fast phonological effects can be explained by such a theory, in which the recognition of words is driven primarily by orthographic form and in which phonological effects on recognition are explained solely in terms of a feedback mechanism (Rastle and Brysbaert, forthcoming).

5.5 Conclusion

The printed word presents the skilled reader with a challenging problem. Letters often appear in surface contexts (e.g. fonts, sizes) with which we are unfamiliar. These letters form a limited array that renders distinct words highly confusable (e.g. SALT, SLAT). Information about the spellings, sounds, and meanings of these words must be stored; and one form of information must be accessed rapidly from the other. Further, these challenges present themselves to an organism that is not endowed with special hardware for reading. The skilled reader solves all these problems remarkably well. Skilled reading is not only highly accurate but also effortless; and we have seen evidence in this chapter that decoding a printed stimulus begins even before we are aware of its existence. Much has been learned over the past 125 years about the mechanisms that underlie this astonishing form of expertise, though it should be clear that there is still much, much more to learn.

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