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Processing the Written Word

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Reading and writing are among the towering achievements of human cognition and are the hallmarks of modern civilization. Connections between these two abilities have been demonstrated (see Shanahan 2006 for a review). For example, writing behaviours in kindergarten children predict their subsequent reading achievement in first grade (Shatil, Share and Levin 2000) and the ability to read words correctly predicts spelling accuracy in typically developing young writers (Berninger, Abbott, Abbott, Graham and Richards 2002).

In the present chapter, we consider the processes that support the recognition of visually presented words, a critical component of skilled reading. Readers are able to rapidly and relatively effortlessly map printed strings of letters onto the corresponding representations of words in their mental lexicon. How do they do this? While visual word recognition might appear to be a deceptively simple task involving pattern recognition, the mechanisms and processes that allow readers to access the orthography, phonology, meaning and morphology of a word remain contentious, even in English (see Balota, Yap and Cortese 2006 for a review).

We will first provide a brief historical overview of the work on English, along with a description of the tasks psycholinguists rely on to investigate word processing. This will be followed by a selective review of some of the key findings in the literature and a discussion of the major theoretical models. Finally, although the word recognition literature has been largely informed by work in English, it is clear that English is in some respects an 'outlier' writing system (Share 2008) and we conclude by discussing how and why the teasing apart of language-specific and language-universal reading processes needs to be guided by the study of a wide range of orthographies.

Visual word recognition: a historical overview

In languages which are based on the alphabetic writing system, words can be recognized via their constituent letters but the reverse is also true. Cattell (1886) was the first to study the influence of the word context on letter identification and he observed that letters (e.g., <n>) were easier to recognize when they were embedded in words than in nonwords (e.g., *born* vs. *jorn*). That is, when letters are presented very briefly, participants are more accurate in reporting the identity of letters presented in the context of words, compared to letters presented in isolation or in the context of non-words (Reicher 1969; Wheeler 1970). This so-called *word superiority effect* is a theoretically profound puzzle. Specifically, if letters are a necessary prerequisite for recognizing a word, how is it that word-level information is able to influence the perception of the word's constituent letters?

In order to explain this intriguing context effect, McClelland and Rumelhart (1981) developed the highly influential interactive activation model of letter perception (see Figure 26.1). This computational model (i.e., implemented as a computer program) comprises simple processing nodes that are organized in three levels (features, letters, words), with nodes connected to one another via facilitatory (represented by arrows) and inhibitory (represented by filled circles) connections. When a word is presented to the model, the feature-, letter- and word-level nodes consistent with that word are activated. Importantly, as word-level nodes receive activation, they provide feedback to position-specific letters. Thus, the top-down influence of word-level on letter-level representations is responsible for the word superiority effect reported by Cattell (1886) and subsequent researchers.

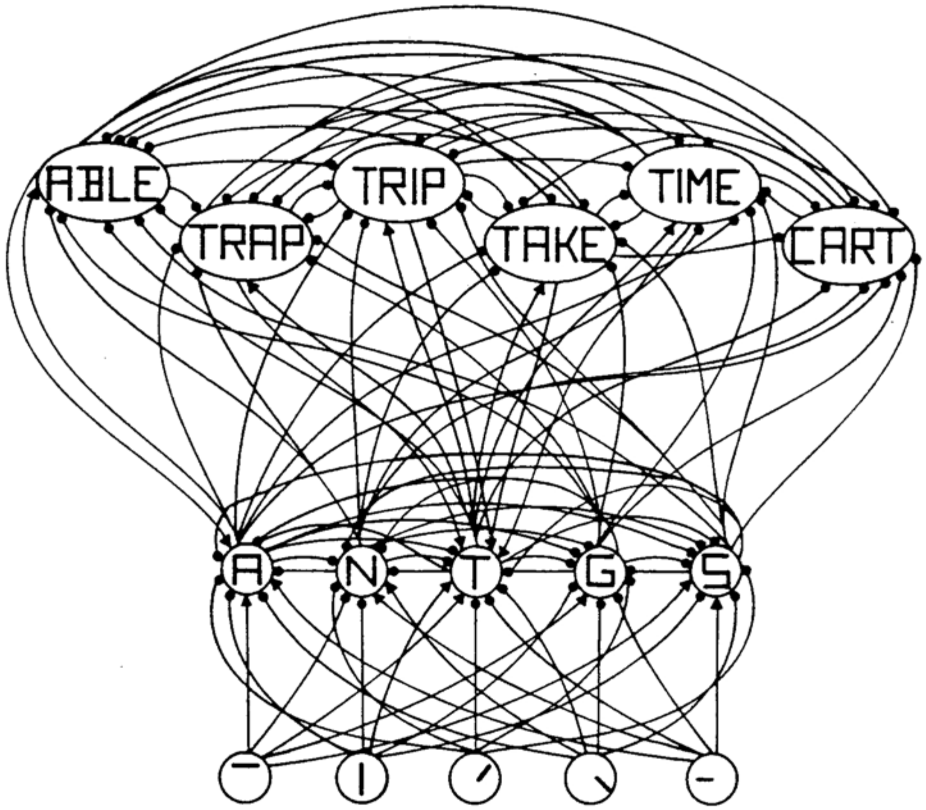

Figure 26.1 McClelland and Rumelhart's (1981) interactive activation model of letter recognition. From 'An interactive activation model of context effects in letter perception: Part 1. an account of basic findings' by J.L. McClelland and D.E. Rumelhart, *Psychological Review,* 88, p. 380. Copyright 1981 by the American Psychological Association. Reprinted with permission.

The interactive activation model is historically and theoretically significant for a number of other reasons. First, it emphasizes the highly interactive nature of lexical processing and the importance of top-down information. Second, the model relies on *cascaded processing*. That is, as soon as a level is activated, it passes activation to the next level immediately. This is different from *thresholded processing* wherein processing in a later stage is initiated only after processing in the previous stage is complete. Third, because of the way the model is structured, the activation dynamics of each word unit are constrained by the activity of other similarly spelled words (see discussion of *orthographic neighbours* later). Although the interaction activation model was intended to explain letter processing, rather than word perception, this framework, together with its processing assumptions, has become a key component of a number of computational models of visual word recognition (e.g., the dual-route cascaded model; Coltheart, Rastle, Perry, Langdon and Ziegler 2001). We will now describe the tools psycholinguists use and review some basic findings, before returning to these models.

How is word recognition studied?

A number of procedures have been developed to study word recognition, including *perceptual identification* of a visually degraded word (e.g., TABLE; see Dufau, Stevens and Grainger 2008), *semantic classification* ('Is *dog* living or non-living?'; see Taikh, Hargreaves, Yap and Pexman, 2015) and *eye tracking* (participants' eye movements are recorded as they read text; see Reichle, Rayner and Pollatsek 2003). In this chapter, we focus on the two simpler tasks that have been the gold standards for research on isolated word recognition: *lexical decision* and *speeded (i.e., timed) pronunciation*. In the lexical decision task, participants are presented with a string of letters and are asked to response via yes/no buttons if the letter string forms a word or non-word (e.g., *flirt* elicits a 'yes' response while *flirp* elicits a 'no' response). In the speeded pronunciation (or speeded naming) task, participants are required to read aloud a visually presented word as quickly and accurately as possible and response times are recorded. For both tasks, researchers are primarily interested in how quickly people make lexical decisions (i.e., decision latencies for correct 'yes' responses to words), or how quickly they initiate the correct pronunciation of words. The underlying assumption here is that lexical decision and pronunciation response times reflect the cognitive processes involved in accessing stored representations.

That said, no single task or method can faithfully capture the dynamics of word recognition. Any word recognition task measures both the underlying construct of interest (i.e., word recognition) as well as operations that are specific to that task. For example, lexical decision performance is sensitive to binary decision-making processes that are independent of word identification (e.g., response organization and motor planning; see Balota and Chumbley 1984) while pronunciation times are heavily influenced by a word's initial phonemes (e.g., a response beginning with /s/ might be systematically detected later than a response beginning with /m/; Kessler, Treiman and Mullennix 2002). In order to be more confident that an effect reflects word-recognition processes, rather than idiosyncratic task demands, it is important to look for converging evidence across multiple experimental paradigms (Jacobs, Rey, Ziegler and Grainger 1998).

Benchmark findings in word recognition

A great deal of research has focused on how the various statistical properties associated with a word (e.g., number of letters, number of syllables, frequency of occurrence) might influence word recognition. In this section, we will focus on the impact of the most important lexical-level and semantic-level variables, which have been quantified at the level of the whole word. There is, however, a rich literature examining how *sublexical* representations (i.e., the units below the word level such as letters, morphemes and syllables) mediate word recognition (see Carreiras and Grainger 2004 for a review) but this is beyond the scope of the present chapter. We also do not discuss variables such as age-of-acquisition (AoA; i.e., the age at which a word is learned) because it is unclear if AoA effects reflect lexical-level or semantic-level processing (see Juhasz 2005 for more discussion).

Effects of variables on isolated word recognition

Word frequency

The most important predictor of word recognition performance is the frequency with which a word appears in print. In virtually every lexical processing task, participants recognize high-frequency words (e.g., *house,* printed frequency = 514 / million words) faster and more accurately than low-frequency words (e.g., *louse,* printed frequency = 1.69 / million words) (see English Lexicon Project, Balota *et al*. 2007, for more examples; http://elexicon.wustl.edu). Despite its deceptive simplicity, the *word-frequency effect* is a fundamental constraint that any word recognition model has to accommodate. For example, according to serial search models (Forster 1976; Paap, McDonald, Schvaneveldt and Noel 1987), the presented letter string is serially compared against entries in the mental lexicon, in descending order of frequency. In contrast, activation-based models (e.g., McClelland and Rumelhart 1981) assume that each word representation has a resting activation level or activation threshold that varies with frequency of exposure. Frequent words are recognized faster because they have higher resting activation levels or lower activation thresholds and therefore less stimulus information is required for word identification.

Notwithstanding their centrality, there is substantial evidence that word-frequency effects do not unequivocally reflect lexical processing. As discussed earlier, performance on any given word-recognition task taps both lexical access and mechanisms specific to the task's demands. In line with this, Balota and Chumbley (1984) reported that frequency effects were larger in lexical decision, compared to speeded pronunciation or semantic classification. They argued that frequency effects are exaggerated in the lexical decision task because of post-access processes that serve to discriminate between familiar words (e.g., *dinner*) and unfamiliar pronounceable non-words (e.g., *pansol*). Specifically, low-frequency words (e.g., *louse*), compared to high-frequency words (e.g., *house*), overlap more with non-words on familiarity and it is therefore more difficult to discriminate low-frequency words from nonwords. This delays responses to low-frequency words, thereby increasing the size of the word-frequency effect. The take-home message here is that frequency effects (and very likely many other psycholinguistic effects) reflect both lexical access and task-specific demands.

Length

Across tasks, words with more letters, such as *caterpillar,* generally take longer to recognize than words with fewer letters, such as *cat* (see New, Ferrand, Pallier and Brysbaert 2006 for a review); this is known as the *length effect*. Although it is likely that length effects are partly driven by visual or articulatory processes that are beyond the purview of word recognition models, they are more compatible with models that incorporate some sort of serial processing (e.g., dual route cascaded model; Coltheart *et al*. 2001) than models that rely exclusively on parallel processing (e.g., connectionist models; e.g., Plaut, McClelland, Seidenberg and Patterson 1996).

Orthographic and phonological similarity

Words vary in the extent to which they look like or sound like other words. For example, *yacht* is visually distinct, whereas *cat* resembles many other words in English (e.g., *hat*, *cot*, *cap*). In a classic study, Coltheart, Davelaar, Jonasson and Besner (1977) proposed a new orthographic similarity metric that they termed *orthographic neighbourhood size* (or *N*). This measure is defined by the number of orthographic neighbours a word possesses, where neighbour is defined as any word that can be obtained by substituting a single letter of a target word (e.g., the neighbours of *cat* include *hat*, *cot* and *cap*). Across a number of languages, researchers have observed that lexical decision and pronunciation response times are faster for words with many, compared to few, neighbours (see Andrews 1997 for a comprehensive review). This is a surprising trend and is difficult to reconcile with the notion of a competitive lexical retrieval procedure, which predicts that neighbours should inhibit, rather than facilitate, word recognition (Andrews 1997).

The phonological similarity of a word can be captured by an analogous metric called *phonological neighbourhood size*. This reflects a target word's number of phonological neighbours (i.e., words created by substituting a single phoneme) so the neighbours of *gate* include *hate*, *get* and *bait*. Yates (2005) has observed that across multiple lexical processing tasks, words with many phonological neighbours are processed more rapidly, attesting to the importance of phonology in visual word recognition. Although neighbourhood size effects have been very well studied in the literature, the *N* definition of a neighbour (Coltheart *et al*. 1977) seems too inflexible. Neighbours are necessarily of the same length as the target word and are derived through the substitution of a single letter or phoneme. Longer words tend to have few or no neighbours, implying that the *N* metric is optimized for shorter words. More recently, less restrictive metrics of orthographic and phonological similarity have been proposed and tested for words of all lengths (e.g., Levenshtein Distance 20; Yarkoni, Balota and Yap 2008; see also Davis 2006).

Semantic richness

Thus far, we have considered the influence of lexical-level characteristics. There is mounting empirical evidence that the meaning-level characteristics of a word also matter. Specifically, word recognition is facilitated for semantically *richer* words, i.e., words which are associated with relatively more semantic information (see Pexman 2012 for a review). Indeed, researchers have identified a number of dimensions that tap a word's semantic representation, which include *number of semantic features*, *imageability*, *body-object interaction*, *sensory experience ratings*, *number of associates*, *number of senses* and *semantic neighborhood density*. The number of semantic features for a word is obtained by asking participants to produce the features they think are important for a particular concept (McRae, Cree, Seidenberg and McNorgan 2005); for example, the features associated with *cucumber* include 'is a vegetable', 'has green skin' and 'used for making pickles'.

The imageability of a word is indexed by subjective ratings of the extent to which a word evokes mental imagery (Cortese and Fugett 2004); for example, *snake* is a high imageability word (rating = 6.5) while *sieve* is not (rating = 1.9). Body–object interaction (BOI) is based on subjective ratings of the extent to which a human body can physically interact with a word's referent (Siakaluk, Pexman, Aguilera, Owen and Sears 2008); *rainbow* is a low-BOI word (rating = 1) while *ball* is a high-BOI word (rating = 6.66). Similarly, sensory experience ratings (SERs) tap the extent to which a word evokes a sensory and/or perceptual experience; *price* has a low SER (rating = 1.4) while *music* has a high SER (rating = 5.7) (Juhasz and Yap 2013). A word's number of associates (Nelson, McEvoy and Schreiber 1998) reflects the number of distinct first associates elicited by a word in a free-association task (Nelson, McEvoy and Schreiber 1988); *lace*'s associates include *shoe*, *dress*, *frill*, *pretty*. Other dimensions include number of senses (Miller 1990) and semantic neighbourhood density, i.e., the extent to which a word co-occurs with other words in the language (Shaoul and Westbury 2010). Generally speaking, words with more features, associates and number of senses are recognized faster, as are words which are high on imageability, semantic neighbourhood density, body-object interaction and sensory experience ratings.

The robust and wide-ranging effects of semantics on visual word recognition is difficult to reconcile with the intuitive view that there is a discrete (or magic) moment in time when a word is identified and it is only after this magic moment that meaning is accessed (Balota 1990). Instead, research findings are more consistent with an early influence of semantics that emerges through cascaded processing and feedback from semantic-level to lexical-level representations. In general, there is also little evidence that the disparate semantic effects described above reflect a unitary theoretical framework. Instead, any model that attempts to explain how semantics are derived from print will have to incorporate multiple dimensions and frameworks (Pexman, Siakaluk and Yap 2013).

Context/priming effects

Up to this point, our review has focused on recognition of isolated words. Researchers have also explored how presenting a context or priming word before the target word modulates word recognition performance. In typical priming experiments, two letter strings are presented consecutively and the experimenter is able to manipulate the relationship between the two letter strings. *Prime*-TARGET pairs can be orthographically (*couch – TOUCH*), phonologically (*much – TOUCH*), semantically (*feel – TOUCH*), or morphologically (*touching – TOUCH*) related to the target word. Primes may also be either *unmasked* (i.e., they are visible) or *masked* (i.e., they are presented too briefly to be consciously processed). Masked priming is useful because participants are unaware of the relationship between the target and prime and results are therefore less likely to be contaminated by participants' strategies (Forster 1998).

Orthographic priming

The orthographic priming literature, in which researchers generally use masked primes, has greatly informed our understanding of the 'front-end ' of visual word recognition and the nature of the orthographic code (Grainger 2008). In order to correctly identify a word, an orthographic input code (which encodes the identity and position of letters) needs to be created. How the perceptual system codes letters in relative space is less clear. The most common method for coding letter position in early computational models, such as the interactive activation model (McClelland and Rumelhart 1981), is *slot-based coding*, where each letter is tagged to its specific position in the string. For example, for *dog*, the letter <d> is coded by a unit that specifically represents <d> in position one.

Despite the pervasiveness of position-specific coding, data from the masked orthographic priming literature provide important evidence against rigid slot-based explanations (see Davis 2012 for a review). For example, Forster, Davis, Schoknecht and Carter (1987), using masked orthographic priming, compared the facilitatory influence of a substitution neighbour non-word prime (e.g., *ansmer – ANSWER*) to that of a transposition neighbour nonword prime (e.g., *anwser – ANSWER*). Interestingly, they found that transposition neighbour non-word primes facilitated target recognition better than substitution neighbour non-word primes. This finding is problematic for position-specific coding schemes, which are insensitive to shared letters in other letter positions. Specifically, such schemes treat *ansmer* (overlap for 5/6 letters) as more similar than *anwser* (overlap for 4/6 letters). Generally, these data are more consistent with coding schemes which propose that letter strings (e.g., *judge*) are represented by the following set of *open bigrams* (<ju>, <jd>, <jg>, <ud>, <ug>, <ue>, <dg>, <de>, <ge>) (Grainger and van Heuven 2003; Whitney 2001) or by models that use spatial patterns to represent the relative activity of different letter nodes (Davis 2010).

Researchers have also used masked priming to investigate whether syllables serve as functional units in lexical processing. For example, if words are automatically parsed into syllables when a word is being identified, one might expect recognition for *BALCONY* (which begins with the syllable *BAL*) to be facilitated when *bal*, compared to *ba*, is presented as a prime. Syllable priming effects have generally been unreliable in English (Brand, Rey and Peereman 2003), suggesting that syllables are not a relevant functional unit in English, where syllabic boundaries are not always clear (but see Yap and Balota 2009).

Phonological priming

The priming procedure has been useful for exploring the role of phonology in visual word recognition. More specifically, researchers have been interested in whether phonology is generated only after lexical access, or if automatically generated phonological codes precede and constrain word identification. To answer this question, experimenters have relied on masked phonological priming. For example, Lukatela and Turvey (2000) reported that compared to control primes (e.g., *clep*), phonologically related primes (e.g., *klip*) sped up the process of word recognition to a target like CLIP, despite primes being presented for only 14 ms. This finding is consistent with an extensive meta-analysis by Rastle and Brysbaert (2006), which revealed small but reliable effects of masked phonological priming across multiple studies. These results, along with others (see Halderman, Ashby and Perfetti 2012 for a review) provide strong evidence for the idea that phonology, like semantics, plays a very early role in word recognition and helps to stabilize the identity of the presented word.

Morphological priming

Do morphemes, the smallest units of meaning in English, serve as access units in word recognition? Specifically, are morphologically complex words such as *painter* automatically decomposed into *paint* and *er*? Studies based on the masked morphological priming paradigm reveal that recognition of a target word (e.g., *SAD*) is facilitated by the masked presentation of morphologically related words (i.e., *sadness*) (Rastle, Davis, Marslen-Wilson and Tyler 2000). Masked morphological priming effects indicate that there is early and obligatory decomposition of words into morphemes and that this process is relatively blind to the meaning of the word (Rastle, Davis and New 2004). For a review of this interesting literature, readers are encouraged to consult Diependaele, Grainger and Sandra (2012).

Semantic priming

The *semantic priming effect* refers to the finding that words are recognized faster when preceded by a semantically related prime (e.g., *cat – DOG*) than by an unrelated prime (e.g., *mat – DOG*). This robust finding is one of the most important effects in the lexical processing literature and helps shed light on the architecture of the mental lexicon and the sematic network (see McNamara 2005 for a review). Related primes are able to facilitate target recognition even when primes are heavily masked (Balota 1983), suggesting that the meaning of a word is processed in the absence of conscious awareness. A number of theoretical mechanisms have been argued to underlie semantic priming, including *automatic spreading activation* (i.e., a word preactivates other related words via semantic or associative pathways; Collins and Loftus 1975) and *expectancy* (i.e., there is strategic generation of possible candidates for the upcoming target; Becker 1980).

Models of visual word recognition

Earlier in this chapter, we described the classic interactive activation model (McClelland and Rumelhart 1981), which subsequently became a critical component of modern computational models of word recognition. These computational models have focused mainly on speeded (i.e., timed) pronunciation performance, i.e., the processes that convert the printed word to speech. One contentious debate in this area has to do with whether word pronunciation is mediated by one or two mechanisms.

According to the dual-route cascaded (DRC) model (Coltheart *et al*. 2001), two distinct pathways support word pronunciation (see Figure 26.2). In the *lexical* route (on the left), the presented letter string (e.g., *dog*) activates its corresponding entries in the orthographic and phonological lexicons and the entry in the phonological lexicon then activates the word's phonemes (i.e. /dɔg/). In contrast, the *sublexical* route (on the right) serially assembles the pronunciation of a letter string by mapping graphemes onto phonemes via abstract grapheme–phoneme correspondence (GPC) rules. These rules (e.g., <k> ® /k/) are based on statistical criteria, i.e., /k/ is the phoneme most commonly associated with <k> in English monosyllables. The DRC model thus explains how people are able to pronounce novel letter strings (e.g., *flirp*), while accounting for other empirical findings in the literature. In English, the *regularity effect* has stimulated a large body of work: *regular* words (e.g., *hint* /hɪnt/) which conform to GPC rules, are pronounced faster than *irregular* (or exception) words (e.g., *pint* /paɪnt/) which violate the rules. There is also a well-known interaction between regularity and frequency, wherein the regularity effect is larger for low-frequency, compared to high-frequency, words (Andrews 1982).

The foregoing interaction is neatly accommodated by the DRC model's assumption that the lexical route is influenced by word frequency, but the sublexical route is not. Specifically, low-frequency irregular words (e.g., *pint*) are pronounced more slowly than low-frequency regular words (e.g., *hint*), because the two routes produce conflicting pronunciations for

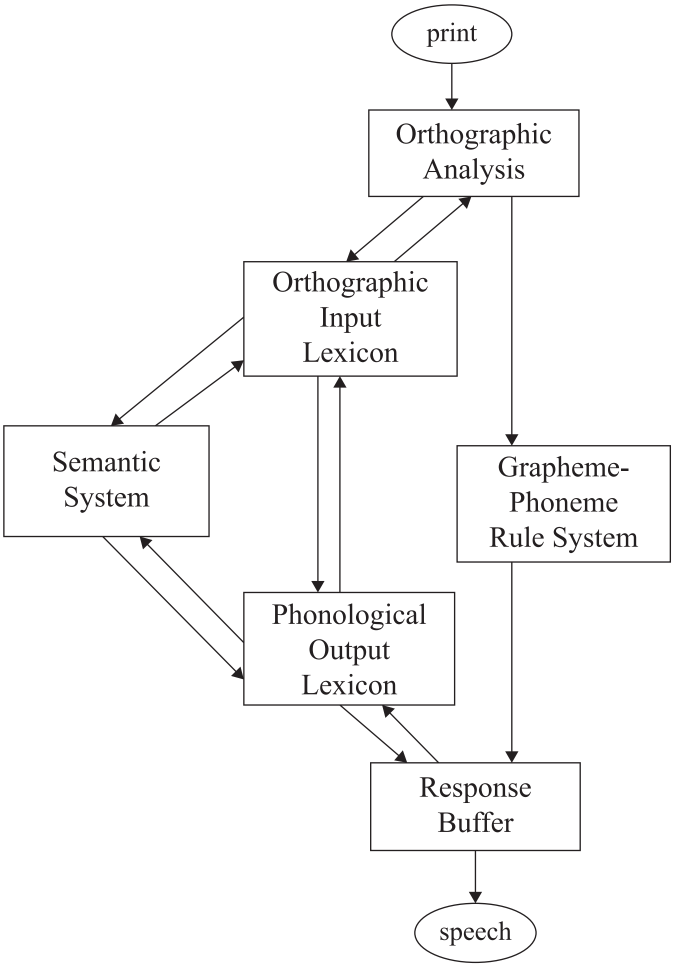

Figure 26.2 Coltheart *et al.*'s (2001) DRC model of visual word recognition and reading aloud. From 'DRC: a dual route cascaded model of visual word recognition and reading aloud' by M. Coltheart, K. Rastle, C. Perry, R. Langdon and J. Ziegler (2001), *Psychological Review* 108, p. 214. Copyright 2001 by the American Psychological Association. Reprinted with permission.

pint. In contrast, for high-frequency words, the difference in pronunciation times for regular (e.g., *save*) and irregular (e.g., *have*) words is attenuated or absent, because the lexical route produces an output before there is competition from the slower sublexical route. The DRC model is also able to handle an important neuropsychological *double dissociation* between *surface dyslexia* and *phonological dyslexia,* acquired as a result of brain damage. Individuals with surface dyslexia (Patterson, Marshall and Coltheart 1985) can read aloud non-words and regular words, but they regularize irregular and exception words (e.g., *pint* would be pronounced as /pɪnt/ in keeping with the rules). Conversely, individuals with phonological dyslexia (Coltheart 1996) have difficulty even with simple pronounceable non-words (e.g., *mup*), but can read aloud both regular and irregular words. Thus, surface dyslexia appears to reflect an impairment in the lexical route while phonological dyslexia reflects an impairment in the sublexical route (see Pollak and Masterson, this volume, for further discussion).

The major theoretical alternative to the dual-route model is represented by the parallel distributed connectionist model (see Figure 26.3) developed by Seidenberg and McClelland (1989) (see also Plaut *et al*. 1996). In this computational model, input units code the word's spelling, while output units code the word's pronunciation; input and output units are connected via hidden units. The model is based on distributed representations, in the sense that specific words are not associated with specific units. Instead, the orthography and phonology of words are coded by a pattern of activation over multiple units. Each unit has some activation level and connections between units can either be facilitatory or inhibitory. An important aspect of connectionist models is that these connections are not 'hand-wired' by the modeller. Instead, there is a learning phase in which the model learns to associate a phonological output with an orthographic input (e.g., *dog* ® /dɔg/) using an algorithm called *back-propagation*, which adjusts the weights of the connections so as to minimize the discrepancy between the actual and desired output.

After the training period, Seidenberg and McClelland (1989) demonstrated that the model could successfully simulate many of the benchmarks effects observed in speeded pronunciation performance of skilled readers. Moreover, it could account for the frequency × regularity interaction described above using a single mechanism rather than different routes. This mechanism was able to abstract the statistical spelling-to-sound regularities in English and to use the same mechanism to correctly generate the pronunciations of words and non-words. In contrast, the DRC model (Coltheart *et al*. 2001) requires the sublexical route to pronounce non-words. The connectionist perspective is also attractive because it includes a learning mechanism and is able to handle the *quasi-regular* (i.e., mostly systematic but with many exceptions) nature of English spelling–sound mappings without relying on explicit formal rules.

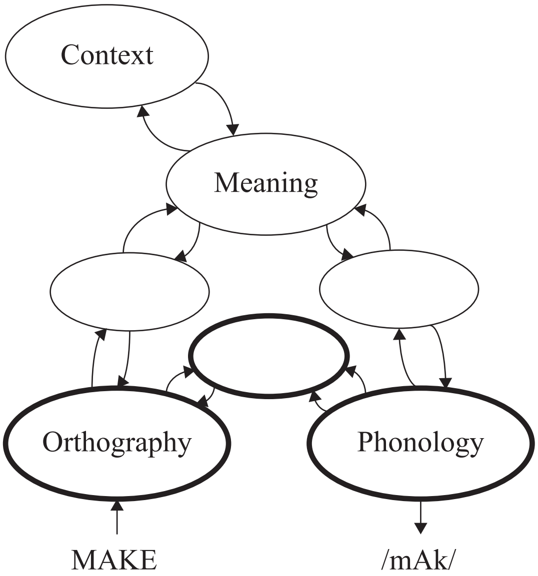

Figure 26.3 Seidenberg and McClelland's (1989) parallel distributed processing model. From 'A distributed, developmental model of word recognition and naming' by M.S. Seidenberg and J. L. McClelland (1989), *Psychological Review, 96*, p. 527. Copyright 1989 by the American Psychological Association. Reprinted with permission.

Although the regularity effect (i.e., faster pronunciations for regular words) can be easily accommodated by both classes of models, the *consistency effect* is particularly vexing for the DRC model. *Consistency* reflects the extent to which a word is pronounced like similarly spelled words. For example, *cave* is consistent because most similarly spelled words (e.g., *gave*, *pave*, *save*, *wave*) are pronounced the same way, whereas *have* is inconsistent because its pronunciation is different than most similarly spelled words. Consistent words are generally pronounced faster than inconsistent words (Jared 2002) and this effect is of critical importance because the connectionist model predicts and produces consistency effects, whereas the DRC model does not predict these effects and has difficulty simulating them (Zevin and Seidenberg 2006).

Recently, researchers have also developed hybrid models which combine the best features of the DRC and connectionist models. The CDP+ (connectionist dual process) model (Perry, Ziegler and Zorzi 2007) is architecturally very similar to Coltheart *et al*.'s (2001) DRC model, except that the rule-based sublexical route is replaced by a two-layer connectionist network that abstracts the most statistically reliable spelling–sound relationships in the language. The CDP+ model is noteworthy because it is able to account for empirical phenomena far more successfully than its predecessors. For example, while the earlier models could only account for between 3 per cent and 7 per cent of the variance in human performance, the CDP+ model was able to account for over 17 per cent. Moreover, a disyllabic version of this model, the CDP++ model is now available (Perry, Ziegler and Zorzi 2010). This is an important advance because the visual word recognition literature has, to a large extent, been dominated by the study of monosyllabic words in experiments and computational models.

Finally, we should point out that the three models described in this section emphasize the processes that convert print to speech. There are also models that focus on how readers make lexical decisions, but space constraints preclude a description of these models (see Gomez 2012 for details).

The anglocentric nature of word recognition research

So far, we have described the major findings in the extensive English word recognition literature and have discussed how this body of work serves to motivate and constrain models of lexical processing. At this juncture, it is worth noting that most of the lexical processing literature has been based on how native English-speaking readers process English words. To what extent are the findings described in this chapter specific to the English writing system? This question is important because the English writing system is far from typical. Share (2008) described English as an outlier orthography with respect to the *inconsistency* of its spelling–sound correspondence (i.e., there is no one-to-one mapping of letters to sounds) and the complexity of its syllable structures. In light of the peculiarities of the English writing system, it could be argued that models informed by findings based on the English-language are unlikely to generalize to other languages, or even to other alphabetic writing systems (see Share 2008 for a discussion of the anglocentricities in research on reading).

Questions about the distinctions between language-specific versus language-general processing can be addressed by comparing experimental findings in English against findings based on languages which contrast with English. In an early effort to stimulate this sort of discussion, Frost, Katz and Bentin (1987) proposed the *orthographic depth hypothesis* (ODH), which itself is based on the dual-route model of reading (Coltheart *et al*. 2001). The ODH holds that shallow alphabetic orthographies (e.g., Finnish, Greek, Serbo-Croatian, Spanish) have relatively consistent mappings to phonology that facilitate rule-based sublexical decoding of the printed word, whereas the inconsistent mappings in deep alphabetic orthographies (Danish and French, as well as English) necessitate more reliance on the lexical pathway during reading. More recently, researchers have found *grain size theory* useful for describing why the optimal linguistic unit for processing differs across orthographies (Ziegler and Goswami 2005; Ziegler, Perry, Jacobs and Braun 2001). Psycholinguistic grain size theory encompasses orthographic syllable complexity as well as orthography–phonology mappings and appears to have pedagogical implications. Processing small unit sizes (e.g., phonemes) appears optimal for orthographies with consistent mappings and mostly simple syllable structures, such as consonant-vowel (CV) or consonant-vowel-consonant (CVC) structures. Processing larger unit sizes (e.g., rimes or syllables) appears optimal for orthographies with inconsistent mappings to phonology and/or complex syllable structures (CCVC; CVVCC).

As discussed in the previous section, the complex relationship between the letters and the sounds of English words has been a driving force in the debate on whether word pronunciation entails one or two mechanisms. From a pedagogical perspective, the inconsistencies of the English writing system have been a source of frustration for educators (e.g., Dewey 1971) and they present difficulties for beginner readers (Spencer 2009). Seymour, Aro and Erskine (2003) investigated the reading abilities of native-speaking children from 13 different countries and found that the rate of acquisition for 100 common words was up to two years slower for children learning English than those learning Finnish, a shallow orthography with simple syllables (see Leppanen, Niemi, Aunola and Nurmi 2006). Seymour *et al*. (2003) explained their results by suggesting that reading acquisition is more effortful for children learning to read in English and similarly deep orthographies with complex syllables. They need much more time to establish a *dual foundation* system. That is, there is a *logographic* process (which identifies and stores familiar words) for handling words with inconsistent orthography–phonology mappings (e.g., *yacht*) and a sublexical *alphabetic* process which decodes regular words using rules (e.g., *steamer).* Children who are learning a shallow orthography only have to establish the alphabetic foundation (see Table 1 of Seymour *et al*. 2003 for a guide to the classification of languages in terms of orthographic depth and syllabic complexity).

Thus, in the final section of this chapter, we will consider whether the findings for English are solely language-specific, or whether they can be used to inform a more universal model of alphabetic processing. Our starting point was to look for an archetypal alphabetic orthography that contrasts sharply with English and to examine how language processing demands are modulated by the properties of a particular writing system. We chose *Bahasa Melayu* (or Malay), an Austronesian language spoken by 250 million people living in Indonesia, Malaysia, Brunei and Singapore (Tadmor 2009), for three reasons. First, *Rumi*, the most common form of written Malay, has parallels with Finnish. It has a shallow alphabetic orthography (reformed in 1972; see Prentice 1987), with a similar range of Latin letters to English (20 consonants and 5 short vowels) and simple syllable structures. Second, characteristics such as these are known to influence literacy development in children (Caravolas 2004; Ellis and Hooper 2001; Seymour *et al*. 2003) and so they would be expected to leave developmental ‘footprints’ on the skilled processing of adults (Ziegler and Goswami 2005).

However, the main reason for the choice of contrasting language was the availability of a lexical database for 9,592 Malay words (see Yap, Rickard Liow, Jalil and Faizal 2010) with behavioural measures on a subset of words (N = 1,520) for both lexical decision and speeded pronunciation responses from the same group of skilled readers (N = 44). To our knowledge, the Malay Lexicon Project (MLP; Yap *et al*. 2010) is the only published database on a very shallow orthography with simple syllable structures, although resources for many European languages are now available (see Balota, Yap, Hutchison and Cortese 2012 for a list). Data extracted from the MLP enabled us to examine more directly whether some of the objective differences between orthographies, such as the ratio of letters to phonemes (proxy for consistency: English $M = 27/44$; Malay $M = 25/34$) and the number of letters per syllable (proxy for syllable complexity: English $M = 3.41$, $SD = .99$; Malay $M = 2.54$, $SD = .41$) exert an influence on underlying cognitive processes.

To examine cross-linguistic differences in processing demands between English (deep orthography) and Malay (shallow orthography), we used multiple regression analyses to compare the effects of word-frequency, word length and two measures of orthographic similarity on lexical decision and speeded pronunciation performance across the two languages. There were some noteworthy findings. First, in both languages, it was clear that word-frequency effects were larger in lexical decision, compared to speeded pronunciation; this is consistent with a greater reliance on familiarity-based information (such as word-frequency) for driving the word/non-word discrimination process in lexical decision (Balota and Chumbley 1984). Second, word length effects were much larger in Malay than in English in both tasks. Finally, the influence of orthographic neighbours was stronger in English than in Malay, particularly in lexical decision, the task that requires readers to make yes/no decisions about whether a string of letters forms a word (e.g., *fishing*) or non-word (e.g., *fisleng*).

In line with the ODH (Frost *et al*. 1987), the larger word length effects in Malay than in English indicate that skilled readers of a shallow orthography rely heavily on a rule-based sublexical mechanism which assembles pronunciations in a serial manner. With reference to grain size theory, word length effects serve as a marker for small unit processing (Ziegler and Goswami 2005) and our finding of larger length effects in Malay provides converging evidence for the idea that small grain sizes or units are optimal for readers of a shallow orthography. Along with the greater influence of orthographic neighbours in English, these language-specific findings provide intriguing evidence that readers of English are more obliged to depend on lexical processes, unlike readers of Malay. These data therefore also buttress Seymour *et al*.'s (2003) conclusion that children develop a dual (logographic and alphabetic) foundation to optimize reading acquisition in deep alphabetic orthographies such as English.

As interest in cross-linguistic research grows further, it is becoming clear that what we know about processing the written word in English is only one part of a rather complicated story. There is marked variation amongst alphabetic orthographies in the way they represent morphology as well as phonology. Researchers have also reported individual differences amongst readers both within typically developing native-English speakers (Yap, Tse and Balota 2009) and amongst subtypes of bilinguals who speak English as a second language (Lemhöfer, Dijkstra, Schriefers, Baayen, Grainger and Zwitserlood 2008). For theoretical and practical reasons, the need to develop language-specific, reader-specific models that diverge from those for English monolinguals may become as pressing as the search for universal accounts (see Frost 2012 for a detailed review of this debate).

Annotated guide to further reading

For in-depth surveys of visual word recognition research, readers are encouraged to consult *Visual Word Recognition Volumes 1 and 2*, edited by James S. Adelman (Adelman 2012a;

2012b) and *From Inkmarks to Ideas: Current Issues in Lexical Processing*, edited by Sally Andrews (Andrews 2006). These edited volumes contain state-of-the-art reviews of various domains of word recognition (models, methods, orthography, phonology, meaning, context, individual differences, development) by leading researchers and document the substantial work that has been done so far and the challenges ahead.

For readers with more focused interests, McNamara (2005) and Neely (1991) provide excellent reviews of the important semantic priming literature. The edited volume by Kinoshita and Lupker (2003) also sheds more light on the masked priming paradigm and how this tool has been useful for exploring the automaticity of the components that underlie visual word recognition. Finally, a relatively recent approach to studying lexical processing in English and other languages involves the development of freely accessible large-scale databases containing the lexical characteristics (e.g., word-frequency) and behavioural data (e.g., lexical decision and speeded pronunciation times) for very large sets of words. Balota, Yap, Hutchison and Cortese (2012) describe the various resources presently available, as well as how this *megastudy* approach can be exploited to better understand various aspects of word recognition.

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