Reading, complexity and the brain

Usha Goswami

Abstract

Brain imaging offers a new technology for understanding the acquisition of reading by children. It can contribute novel evidence concerning the key mechanisms supporting reading, and the brain systems that are involved. The extensive neural architecture that develops to support efficient reading testifies to the complex developmental processes that underpin the acquisition of literacy. Here, I provide a brief overview of recent studies, analysed within a cognitive framework of reading development.

Key words: reading, phonology, brain

Introduction

"Reading is a highly complex task involving the rapid co-ordination of visual, phonological, semantic and linguistic processes" (Plaut, 2005, p. 24). This statement, made by one of the foremost connectionist modellers working on reading, must be taken seriously. Connectionist models are computational models built from networks of simple processing units, intended to model the neural networks that support learning by the brain. Brain imaging shows that the neural networks that develop to support skilled reading are multi-modal. Although centred in the language systems of the brain, as reading develops oral language networks which link phonology and semantics become linked to visual and cross-modal networks, enabling the developing reader to read aloud both familiar and novel words. There are also multiple levels of feedback within the system, with even apparently 'bottom-up' processes such as the visual identification of letters affected by whether the letters occur within words that are familiar or unfamiliar (Lupker, 2005). Similarly, when a literate person performs purely auditory tasks, spelling knowledge affects performance (e.g., participants are slower to decide that 'sign' is a real word than 'wine', because the spelling pattern '-ign' is less frequent (Ziegler et al., 2004)). It was once believed that skilled readers could go 'directly' from print to meaning, without involving phonology at all (the original 'dual route' model (Coltheart, 1978)). We now know that phonology is always involved when written words are recognised, even when very skilled readers are comprehending text (e.g., Ziegler and Ferrand, 1998). Reading is a linguistic process.

Recent experiments in skilled reading show the mutual interdependency of spelling and sound in the skilled system: "relations between a word's spelling and its phonology, its body and its rime, and its graphemes and phonemes become mutually reinforcing relations with neither being causally prior to the other" (Van Orden and Kloos, 2005, p. 77; bodies are letter patterns corresponding to rimes as in 'eak' and 'eek' for the rime/Ik/, graphemes are letters or letter clusters that correspond to phonemes as in 'f' or 'ph' for the phoneme/f/). During development, however, the data suggest that phonology is primary, at least in the earliest phases of learning to read. Children come to the task of reading with an oral language system that has already been developing for 4 or more years. To learn to read, they need to learn to comprehend language when it is written down using a visual code, rather than communicated orally. According to the 'simple view' of reading (Rose, 2006), reading comprehension can be separated from teaching children efficient procedures for translating visual codes (such as letters) into sounds. Hence decoding can be taught independently of comprehension. Yet there are many experiments with adults showing semantic effects on visual word recognition (e.g., participants are faster at recognising the printed word 'cat' when they have just seen the printed word 'dog' (Lupker, 2005)). So comprehension can help decoding.

Reading single words aloud: the background

Historically, theories of reading aloud assumed two logically distinct processes, which were thought to be alternative 'routes' to the acquisition of reading. For example, in the 1970s there was much discussion of 'Phonecian' versus 'Chinese' reading acquisition strategies (e.g., Baron, 1977). Children who were learning to read character-based orthographies like Chinese were assumed to need visual reading strategies, in which visual information alone could be used to retrieve meaning. Children who were learning to read alphabetic languages were assumed to require code-breaking skills. It was assumed that once the brain had learned the symbol–sound code operating in a particular orthography, then reading was a simple process of phonological assembly. Children learning transparent alphabetic languages like Greek or Italian were thought to translate letters into phonemes and assemble word pronunciations by blending the phonemes together (a 'Phonecian' reading strategy). Many experiments were conducted with children learning to read in English, to compare the contribution of 'Chinese' versus 'Phonecian' acquisition strategies (e.g., Baron, 1979). It was assumed that, developmentally, children could choose to learn to read by either Chinese or Phonecian strategies.

The 'dual route' model of reading acquisition is still given prominence by some authors (Stuart, 2006), and is accepted as plausible in the simple view of reading proposed in the appendix to the Rose Review (Rose, 2006). However, the 'dual route' view of reading development has not been supported by brain imaging. For example, we can use neuroimaging to explore the processes underpinning the development of reading in deaf children. It was once assumed that deaf children could only learn to read via the 'direct' or 'visual' route (e.g., Conrad, 1979), because their deafness was assumed to preclude a reliance on phonology. However, neuroscience is showing that, despite the apparently different demands on the brain made by learning to read if you are deaf, the same language-based neural networks are involved. Deaf readers rely on the same phonological system as everyone else (MacSweeney et al., 2008). Similarly, cross-language brain imaging studies reveal that Chinese and English chinese develop essentially the same neural networks to support reading (Ziegler, 2005). The Chinese brain does not develop a different neural architecture for recognising written words, despite the complex visual characters that constitute the Chinese orthography. Although there is some additional recruitment of visuo-spatial networks to support character recognition (Siok et al., 2004), the core neural systems for Chinese reading are linguistic: phonological, syntactic and semantic. Before discussing in detail some neuroimaging studies of reading acquisition that are currently available, I will provide a brief overview of recent cognitive studies of reading and its acquisition by young children.

Learning to read: a cognitive framework

The role of phonological awareness

Hundreds of studies of the factors underpinning reading development have shown that the phonological knowledge that develops as a normal part of language acquisition is the key to the child's acquisition of reading. The critical construct is 'phonological awareness', or the child's ability to recognise and manipulate elements of sound within words (Ziegler and Goswami, 2005, for a recent review). These elements can be at a relatively large 'grain size', like the syllable, or at a smaller 'grain size', such as the phoneme. Young children's brains have accurate mental representations for thousands of spoken word forms. At 16 months of age, median spoken vocabulary size is 55 words (Fenson et al., 1994). By 23 months, it is 225 words. By age 6, the average child has a spoken vocabulary of around 6,000 words and a comprehension vocabulary of around 14,000 words (Dollaghan, 1994). In order for the brain to represent each word as a distinct and unique sequence of sounds, each word in the mental lexicon must incorporate phonological information along with information about meaning. The brain must represent the sound elements that comprise a particular word, the order in which these elements occur, the semantic referent matched by the sounds and articulatory information about how to produce these sounds itself. Articulation, or learning to produce sounds, appears to be a very important part of developing a phonological system.

The primary phonological processing unit across the world's languages is actually the syllable, not the phoneme (Port, 2006). Developmental research reveals an apparently language-universal sequence in the development of phonological awareness, from syllable awareness, through 'onset-rime' awareness, to 'phoneme' awareness. Syllables ('oasis' has three syllables, 'toffee' has two syllables) can be segmented into subparts called onsets and rimes. The onset is the sound or sounds before the vowel, such as the 'spr' sound in 'spread' and the 'st' sound in 'stop'. The rime is the vowel and any subsequent sounds in the syllable, such as the 'ed' sound in 'spread' and the 'op' sound in 'stop'. The phoneme is the smallest unit of sound that changes meaning. 'Stop' and 'step' differ in meaning because the vowel sound is different in each word. In many of the world's languages, onsets and rimes are the same as phonemes. This is because the dominant syllable structure across the world's languages is consonant–vowel (CV). Relatively few words in English are CV syllables (5% of English monosyllables follow a CV structure, see De Cara and Goswami, 2002). Examples of English words comprised of CV syllables are 'go', 'do' and 'yoyo'.

Cross-language research shows that while syllable and onset-rime awareness emerge developmentally as language is acquired, phoneme awareness is not a maturational phenomenon but requires direct teaching. This is because the sound elements that we call 'phonemes' are not natural acoustic units in the speech stream, but are abstractions from the speech stream. Young infants can recognise the acoustic cues that differentiate a phoneme like 'p' from a phoneme like 'b' (indeed, so can other mammals), but these acoustic cues are not the same as phoneme awareness. For example, the sound represented by the letter P in 'pit' is not the same acoustically as the sound represented by the letter P in 'spoon'. Acoustically, the sounds at the beginning of 'chair' and 'train' are more similar than the sounds at the beginning of 'train' and 'tip' (and pre-reading children perceive this (Read, 1986)). Nevertheless, in the English spelling system it is the latter sounds that are represented by the same letter (T). To develop the kind of phoneme awareness required for reading, therefore, children must learn to treat sounds as the same when they are symbolised by the same letter. Hence the development of phonemic awareness depends in part on letter learning and accordingly on the consistency with which letters symbolise phonemes in different spelling systems. Unsurprisingly, therefore, there is cross-language divergence in the rate of development of phonemic awareness.

Two key factors appear to explain cross-language differences in the emergence of phonemic awareness. One is the phonological complexity of the spoken language. The other is the orthographic consistency of the written language. Phonemic awareness usually emerges fairly rapidly in languages with consistent orthographies, and in languages that have a simple syllable structure (languages based on CV syllables are considered to have a simple structure). Most of the world's languages use a simple syllable structure. In these languages, the child learning about phonemes has an advantage, because onset-rime units (which depend on dividing the syllable at the vowel, yielding C–V) and phonemes (which for these languages are also the C and the V) are phonologically equivalent. Consider Italian and Spanish as an example. Here, the onset-rime segmentation for words like 'casa' [house] is/c//A//s//A/. This onset-rime segmentation is equivalent to segmenting the word 'casa' into phonemes. For CVCV words, onset-rime segmentation and phonemic segmentation are equivalent.

Now consider the fact that in both Spanish and Italian there is a 1:1 mapping between print and sound. One letter consistently maps to one phoneme. Many of these phonemes are already represented in the child's spoken lexicon of word forms, because they are also onsets and rimes (as in the example of 'casa'). The extra advantage is obvious. Children who are learning to read consistent alphabetic orthographies like Italian and Spanish can solve the 'mapping problem' of mapping units of print (letters) to units of sound (phonemes) with relatively little effort. Most of the sounds that they need are already represented in the spoken lexicon via onset-rime segmentation. All of the letters that they meet will map onto only one of these sounds. The learning problem is relatively simple.

The learning problem becomes more difficult if the spoken language has a more complex syllable structure. An example is German. German has some CV syllables, but it also has CVC syllables, CCVC syllables and CVCC syllables (it even allows CCC clusters, as in 'Pflaume' and 'Strasse'). For most syllables in German, onset-rime segmentation will not be equivalent to phonemic segmentation. However, although the phonology is complex, the orthography is consistent. One letter maps to one and only one phoneme. This helps the German child to acquire phonemic awareness. Letters are a reliable clue to phonemes, and so despite the multiple consonant clusters, the German child is still at an advantage.

The child who is faced with the most difficult mapping problem is the child learning to read an orthographically inconsistent language which also has a complex syllable structure. Examples include English, French, Danish and Portuguese. Like German, English allows CCC clusters ('string', 'sprain', 'split'). Some English syllables are CV (about 5%), but most are either CVC, CCVC or CVCC (see De Cara and Goswami, 2002). Hence, onset-rime segmentation is rarely equivalent to phonemic segmentation. English also has a relatively large number of monosyllables (around 4,000, German has about 1,400). In English, one letter may map to as many as five or more phonemes (e.g., the letter A maps to different vowel sounds in 'cat', 'car', 'cake', 'care' and 'call'). Given this analysis, it is unsurprising to find that phonemic awareness develops relatively slowly in English-speaking children. The rate at which children learning to read different languages develop phonemic awareness can be measured by phoneme counting studies. A selection of studies carried out in different languages is summarised in Table 1.

Despite these marked differences in the emergence of phonemic awareness across languages, cross-language studies of reading acquisition have shown that phonological sensitivity at all three linguistic levels (syllable, onset-rime, phoneme) predicts the acquisition of reading (see Ziegler and Goswami, 2005, for a review). It has also been shown that training phonological awareness has positive effects on reading acquisition across languages, particularly when it is combined with training about how visual symbols (e.g., letters or letter sequences) correspond to sounds in that language (e.g., Bradley and Bryant, 1983). Helping children who are at risk of reading difficulties to develop well-specified phonological codes can be very beneficial to their progress, particularly if such interventions occur early (e.g., Schneider et al., 2000). Deaf children also develop phonological codes, for

Table 1: Data (% correct) from studies comparing phoneme counting in different languages in Kindergarten or early Grade 1

Language	*% phonemes counted correctly*
Greek[1]	98
Turkish[2]	94
Italian[3]	97
Norwegian[4]	83
German[5]	81
French[6]	73
English[7]	70
English[8]	71
English[9]	65

1, Harris and Giannoulis (1999); 2, Durgunoglu and Oney (1999); 3, Cossu et al. (1988); 4, Hoien et al. (1995); 5, Wimmer et al. (1991); 6, Demont and Gombert (1996); 7, Liberman et al. (1974); 8, Tunmer and Nesdale (1985); 9, Perfetti et al. (1987) and Grade 2 children.

example via lip reading ('speech reading') and vibrational cues. This is the case even if signing is their native language. For deaf children too, individual differences in phonological awareness are related to reading acquisition (e.g., Harris and Beech, 1998).

The role of orthographic consistency

Grapheme–phoneme recoding skills develop in tandem with phonemic awareness. As might be expected, therefore, children learning to read languages with varying degrees of orthographic consistency also develop grapheme–phoneme recoding skills at different rates. A comprehensive cross-language comparison of grapheme–phoneme recoding skills during the first year of acquisition was conducted by the *European Concerted Action on Learning Disorders as a Barrier to Human Development*. As part of this Action, participating scientists from 14 European Community (EC) countries developed a matched set of items of simple real words and nonwords suitable for first grade readers. The real and nonword items were then given to children from each country during their first year of reading instruction (see Seymour et al., 2003). As children in different EC countries begin school at different ages, the children varied in age at the time of testing. However, they were equated for degree of reading instruction across orthography, as they were all tested at the same time point midway through their first year at school. The methods of reading instruction used by participating schools in the different countries could not be equated exactly, however the schools were chosen so that all children were experiencing phoneme-level 'phonics' teaching (including those children who were learning to read the more inconsistent orthographies). The data from this study for monosyllables are shown in Table 2.

Table 2: Data (% correct) from the COST A8 study of grapheme–phoneme recoding skills for monosyllables in 14 European languages (adapted from Seymour et al., 2003)

Language	*Familiar real words*	*Nonwords*
Greek	98	97
Finnish	98	98
German	98	98
Austrian German	97	97
Italian	95	92
Spanish	95	93
Swedish	95	91
Dutch	95	90
Icelandic	94	91
Norwegian	92	93
French	79	88
Portuguese	73	76
Danish	71	63
Scottish English	34	41

The table is arranged so that the languages are listed in terms of decreasing orthographic consistency. This makes it easy to see that the children who were acquiring reading in the orthographically consistent EC languages (Greek, Finnish, German, Italian, Spanish) were those performing close to ceiling. This was true for both word and nonword reading. The children doing less well were those learning to read Danish (71% correct), Portuguese (73% correct) and French (79% correct). However, although grapheme–phoneme recoding skills were less accurate in these orthographies, the reduced levels of accuracy are in line with the reduced orthographic consistency of these languages. Danish is relatively inconsistent for reading (Elbro and Pallesen, 2002), whereas Portuguese and French are relatively inconsistent for spelling (Defior et al., 2002; Ventura et al., 2004; Ziegler et al., 1996). The children who were performing most poorly were those learning to read in English (34% correct). These children were retested a year later, following an extra year of phonics-based literacy instruction, and were still performing below children reading the other languages. However, this relatively poor performance would be predicted by the bidirectional inconsistency of English spelling (severe inconsistency in *both* reading and spelling, see Ziegler et al., 1997). The English children face the most difficult learning problem. They are trying to learn correspondences for phonemes embedded in complex syllables, and the correspondences are not predictable (English does not follow a system of 1:1 letter–sound mappings). On this analysis, it is not so surprising that the English children were lagging behind their European peers.

Reading strategies for inconsistent orthographies

As consistent orthographies (almost) only have regular words, children learning to read these orthographies can learn to read rapidly when taught grapheme–phoneme recoding strategies. Children who are learning to read languages like Italian, Turkish and German develop very successful grapheme–phoneme recoding strategies within the first months of learning to read (e.g., Cossu et al., 1995; Durgunoglu and Oney, 1999; Wimmer, 1996). It is also easy to teach reading in these languages, because teaching methods such as 'synthetic phonics' will work for almost any word in the language. There are various experimental 'hallmarks' that are suggestive of a reliance on grapheme–phoneme recoding in children's reading. One is a *length* effect. Children who are reading by applying grapheme–phoneme correspondences should take longer to read words with more letters/phonemes. Children learning to read consistent orthographies like Greek show reliable length effects compared with children learning to read English (e.g., Goswami et al., 1997).

Another hallmark of grapheme–phoneme recoding is skilled nonword reading. Children who are applying grapheme–phoneme correspondences should be as efficient at reading letter strings that do not correspond to real words (e.g., *tix*, *tegwump*) as they are at reading letter strings that do correspond to real words (*ball*, *wigwam*). Numerous experiments show that young readers of consistent orthographies like German are much better at reading matched nonwords than English children (e.g., Frith et al., 1998). However, there is more than one way of reading a nonword. A nonword like 'tix' can either be read by applying grapheme–phoneme correspondences, or can be read by analogy to a familiar real word like *six*. German children show no difference in reading accuracy for nonwords that can be read by analogy compared with nonwords that cannot be read by analogy. English children do show a difference. For example, Goswami et al. (2003) contrasted nonwords that could be read by analogy to real English words (e.g., *dake* [cake], *murn* [burn]) to phonologically matched nonwords that required grapheme–phoneme recoding (e.g., *daik*, *mirn*). The English children found the analogy nonwords (48% correct) easier than the grapheme–phoneme nonwords (38% correct) when presentation was blocked by nonword type. The German children read the two types of nonwords (analogy, GPC) very efficiently, even when the nonwords were mixed together into one list. This was interpreted as evidence that the German children were applying grapheme–phoneme recoding strategies to both types of nonwords. The English children showed a strategy switching cost with the mixed list, making almost 20% more errors on the same items when the nonwords representing different grain sizes were mixed together.

Another way of comparing the use of rhyme analogy versus grapheme–phoneme recoding strategies across orthographies is to use matched nonwords of more than one syllable. Recoding these items to sound should give identical phonology, but the graphemes comprising the nonwords can be manipulated so that they either comprise familiar spelling patterns for rhymes or comprise rhyme spellings that do not exist in the orthography. For example, 'loffee' can be compared with 'loffi'. Whereas 'loffee' can be read by analogy to 'toffee' and 'coffee', there is no written English word with the spelling pattern 'offi'. Similarly, 'taffodil' can be read by analogy to 'daffodil', but 'tafoddyl' has no analogy. Goswami et al. (1997) gave these kinds of nonwords to English and Greek children who were matched for reading age and for their knowledge of the real word analogues that formed the basis for the nonwords. They found that English 7-year-olds were significantly better at decoding the analogous nonwords. The children read 51% of the analogous bisyllables correctly, and 27% of the analogous trisyllables. For the non-analagous nonwords, accuracy levels were 39% correct and 7% correct, respectively. The Greek children did not show more accurate decoding for the analogous nonwords, and in addition showed accuracy levels of over 80% for all nonword types. When the Greek 7-year-olds were compared with English 9-year-olds in order to equate overall nonword reading ability (above 80% correct), there was still a 10% advantage for the analogous nonwords for the English readers, compared with a 0% advantage for the Greek readers.

These comparisons of nonword reading across orthography suggest that the neural system developed by the English children to support reading reflects the material that is being learned. These data are easily explained by connectionist approaches. Connectionism tries to model the brain, by explaining cognitive development in terms of simple neural networks that learn complex structure from 'input'. For reading development, the primary input that is modelled is the spelling system. Spelling patterns in English can be more consistent at the large 'grain size' of the rhyme than at the 'small' grain size of the phoneme (Treiman et al., 1995). Accordingly, this is reflected in orthographic learning and is revealed by experimental studies. However, as noted by Ziegler and Goswami (2005), a satisfactory connectionist model of reading development across languages does not yet exist. One reason is that modellers tend to begin from the learning problem of mapping letters to sounds, omitting to model the structured phonological system that has developed before the child's exposure to print.

This cognitive analysis suggests that children learning to read in English need to be taught phonological recoding strategies at more than one 'grain size' in order to become competent readers. Of course they need to develop efficient grapheme–phoneme recoding strategies, but they also need to develop 'rhyme analogy' strategies to take advantage of spelling–sound consistency at the larger 'grain size' of the rhyme. Children learning to read English do develop orthographic representations that reflect rhymes, even in the absence of direct teaching, and this has been shown by a variety of experimental techniques including making analogies during story reading (Goswami, 1988), reading pseudohomophones (Goswami et al., 2001) and comparing the decoding of 'analogy' versus 'GPC' nonwords (Goswami et al., 1997, 2003). Brown and Deavers (1999) have suggested that children learning to read in English adopt 'flexible unit size' strategies. This cognitive analysis suggests that English children might also benefit from 'flexible unit size' teaching. Recommendations concerning direct instruction of phonics need to recognise that English phonology is complex, that the English orthography is complex (with varying levels of consistency) and that hence teaching might also have to be complex. The complexity inherent in learning to read in English is certainly supported by data from brain imaging.

Learning to read: brain imaging data

Brain imaging studies are consistent with behavioural work in demonstrating that reading begins primarily as a phonological process. When the brain activity in novice readers is measured during the early phases of learning to read, it is the neural structures for spoken language that are particularly active (Turkeltaub et al., 2003). As reading expertise develops, an area in the visual cortex originally named the 'visual word form area' (VWFA) becomes increasingly active (Cohen and Dehaene, 2004). However, as well as being active when participants process real words, the VWFA is also active during 'nonword' reading. This demonstrates experience-dependent tuning of this orthographic system via reading experience. When participants are asked to 'read' word forms that lack meaning, such as 'BRATE' and 'TEGWOP', the VWFA becomes active. This means that the VWFA is not a logographic system, and is not the brain correlate of the 'direct' route to reading hypothesised by the dual route model. Rather, the VWFA is thought to store orthography–phonology connections at different grain sizes (Goswami and Ziegler, 2006a) – that is, words and chunks of words.

The most popular method for studying brain activity during word recognition by children is functional magnetic resonance imaging (fMRI). The fMRI technique measures changes in blood flow in the brain, and hence summates changes in brain activity over time. In fMRI, maximum activity will be measurable 6–8 seconds after reading a particular word. fMRI works by measuring the magnetic resonance signal generated by the protons of water molecules in brain cells, generating a blood oxygenation level dependent (BOLD) response. Usually, the data from fMRI studies are interpreted in terms of peaks of BOLD response in different neural networks. This does not mean that the other areas of the brain are silent during reading, rather that they are significantly less active than the peak areas.

However, 6–8 seconds is a long time in the brain. Neurons communicate on a millisecond scale, with the earliest stages of cognitive information processing beginning between 100 and 200 ms (a fifth of a second) after stimulus presentation. The speed of cognitive information processing has led to more studies using the electroencephalogram (EEG) methodology for studying reading. EEG measures the extremely low-voltage changes caused by the electro-chemical activity of brain cells, thereby reflecting the direct electrical activity of neurons at the time of stimulation (e.g., at the time of seeing a word). Data from EEG studies suggest that the brain has decided whether it is reading a real word or a nonword within 160–180 ms of presentation, for children and adults across languages (e.g., Csepe and Szucs, 2003; Sauseng et al., 2004). This demonstrates contact with semantics within a fifth of a second. While the EEG methodology is very sensitive to timing in the brain, it is difficult to localise function using this technique.

The types of tasks used to study reading while collecting data about brain activity are currently rather limited. The most commonly used tasks are: asking participants to read single words and then comparing brain activation to a resting condition with the eyes closed; asking participants to pick out target visual features while reading print or 'false font' (false font is made up of meaningless symbols matched to letters for visual features like the 'ascenders' in the letters b, d, k); making phonological judgements while reading words or nonwords (e.g., "do these items rhyme?": leat, jete) and making lexical decisions (e.g., pressing a button when a word is presented, and a different button when a nonword is presented). Adult experiments show a high degree of consistency concerning the neural networks that underpin skilled reading (e.g., Price et al., 2003; Rumsey et al., 1997; see Price and McCrory, 2005, for a recent overview). Word recognition in skilled readers appears to depend on a left-lateralised network of frontal, temporoparietal and occipitotemporal regions. The frontal, temporoparietal and occipitotemporal regions essentially comprise the language, auditory, cross-modal and visual areas of the brain. At a very simple level, semantic and memory processing is thought to occur in temporal and frontal areas, auditory and phonological processing in temporal areas, articulation in frontal areas, visual processing in occipital areas and cross-modal processing in parietal areas.

There are still rather few neuroimaging studies of children reading, particularly of younger children. However, the studies that have been done show a high degree of consistency in the neural networks recruited by novice and expert readers. I will discuss one example here. Work by Turkeltaub and colleagues has used fMRI and the false font task to compare neural activation in English-speaking children and college students aged from 7 to 22 years (Turkeltaub et al., 2003). Because 7-year-olds can perform the 'false font' task as well as adults, changes in reading-related neural activity are more likely to reflect developmental differences than differences in expertise. Turkeltaub et al. found that adults performing their task activated the usual left hemisphere sites. When they restricted the analyses to children below 9 years of age, the main area engaged was left posterior superior temporal cortex. This region is traditionally considered to be active during phonological tasks, and is the putative locus of grapheme–phoneme translation. As reading developed, activity in left temporal and frontal areas increased, while activity previously observed in right posterior areas declined. Reading-related activity in the brain thus becomes more left-lateralised with development.

Turkeltaub et al. then conducted further analyses focusing just on the younger children. Here, they investigated the relationships between three core phonological skills and word processing. The three core phonological skills were phonological awareness, phonological memory and rapid automatised naming (RAN). Turkeltaub et al. calculated partial correlations between activated brain regions and each of these three measures while controlling for the effects of the other two measures. They found that the three different measures correlated with three distinct patterns of brain activity. Brain activity during phonological awareness tasks appeared to depend on a network of areas in left posterior superior temporal cortex (phonology) and inferior frontal gyrus (articulation). Children with better phonological skills showed more activity in this network. As noted earlier, this network is the primary area recruited by young children at the beginning of reading development. Hence the brain uses phonological recoding to sound rather than logographic recognition as the key early reading strategy. Activity in the inferior frontal gyrus increased with reading ability. This area is also important for phonology (Broca's area), as it underpins the motor production of speech. Left inferior frontal gyrus is also activated when deaf participants perform phonological awareness tasks silently in fMRI studies (MacSweeney et al., 2008), and is more active in dyslexic readers (Simos et al., 2002). This suggests that articulation is important in supporting phonology for less-skilled readers.

Current brain imaging data therefore support a 'single route' model of reading development, based on a process of developing connections between spelling and sound at different grain sizes (Ziegler and Goswami, 2006). Reading is founded in phonology from the beginning (Goswami and Ziegler, 2006b). The VWFA becomes more active as reading develops, reflecting the experience-dependent development of an orthographic lexicon. This lexicon contains both whole words and fragments of familiar words such as orthographic rimes (Pugh, 2006). The VWFA is not a logographic lexicon, able to support 'Chinese' processing or a 'direct route' from printed word to meaning. Brain imaging studies of typically developing children show that the neural networks for spoken language play an important developmental role in reading from the outset. These language networks necessarily include semantic networks, as spoken language networks represent phonology–semantic connections.

Conclusions

Ziegler and Goswami (2005) noted that behavioural researchers have designed their experiments as though visual word recognition was unaffected by auditory word recognition, as though reading development was unaffected by language development and as though skilled reading was unaffected by phonological development. However, they argued that developmental processes cannot be captured if these simple assumptions are maintained. Development depends on complex interactions between these component skills. Similarly, it can be argued that the Rose Report has made recommendations about the teaching of reading as though learning to read was unaffected by the child's pre-existing language development, was unaffected by the structuring of their pre-existing phonological knowledge and was unaffected by their understanding of word meanings and their ability to comprehend language. Brain imaging is revealing the immense complexity of the human brain and of the neural networks that develop to support human skills. Reading is one of the most complex cognitive skills that humans can learn. It is supported by multi-modal networks uniting motor systems, language systems, semantic systems and reasoning systems. It seems inherently unlikely that a 'simple view' of reading can provide a framework for teaching that is sufficiently rich to capture this complexity.

References

BARON, J. (1977) 'Mechanisms for pronouncing printed words: use and acquisition', in D. LaBerge and S. J. Samuels (Eds.) *Basic Processes in Reading: Perception and Comprehension*. Hillsdale, NJ: Erlbaum, pp. 175–216.

BARON, J. (1979) Orthographic and word-specific mechanisms in children's reading of words. *Child Development*, 50, pp. 60–72.

BRADLEY, L. and BRYANT, P. E. (1983) Categorising sounds and learning to read: a causal connection. *Nature*, 310, pp. 419–421.

BROWN, G. D. A. and DEAVERS, R. P. (1999) Units of analysis in nonword reading: evidence from children and adults. *Journal of Experimental Child Psychology*, 73, pp. 208–242.

COHEN, L. and DEHAENE, S. (2004) Specialization within the ventral stream: the case for the visual word form area. *NeuroImage*, 22, pp. 466–476.

COLTHEART, M. (1978) 'Lexical access in simple reading tasks', in G. Underwood (Ed.) *Strategies of Information Processing*. London: Academic, pp. 151–216.

CONRAD, R. (1979) *The Deaf School Child*. London: Harper & Row.

COSSU, G., GUGLIOTTA, M. and MARSHALL, J. (1995) Acquisition of reading and written spelling in a transparent orthography: two non parallel processes? *Reading and Writing*, 7.1, pp. 9–22.

COSSU, G., SHANKWEILER, D., LIBERMAN, I. Y., KATZ, L. and TOLA, G. (1988) Awareness of phonological segments and reading ability in Italian children. *Applied Psycholinguistics*, 9, pp. 1–16.

CSEPE, V. and SZUCS, D. (2003) Number word reading as a challenging task in dyslexia? An ERP study. *International Journal of Psychophysiology*, 51, pp. 69–83.

DE CARA, B. and GOSWAMI, U. (2002) Statistical analysis of similarity relations among spoken words: evidence for the special status of rimes in English. *Behavioural Research Methods and Instrumentation*, 34.3, pp. 416–423.

DEFIOR, S., MARTOS, S. and CARY, L. (2002) Differences in reading acquisition development in two shallow orthographies: Portuguese and Spanish. *Applied Psycholinguistics*, 23, pp. 135–148.

DEMONT, E. and GOMBERT, J. E. (1996) Phonological awareness as a predictor of recoding skills and syntactic awareness as a predictor of comprehension skills. *British Journal of Educational Psychology*, 66, pp. 315–332.

DOLLAGHAN, C. A. (1994) Children's phonological neighbourhoods: half empty or half full? *Journal of Child Language*, 21, pp. 257–271.

DURGUNOGLU, A. Y. and ONEY, B. (1999) A cross-linguistic comparison of phonological awareness and word recognition. *Reading and Writing*, 11, pp. 281–299.

ELBRO, C. and PALLESEN, B. R. (2002) 'The quality of phonological representations: a causal link?', in L. Verhoeven, C. Elbro and P. Reitsma (Eds.) *Precursors of Functional Literacy*. Vol. 11. Amsterdam: John Benjamins Publishing Company, pp. 17–32.

FENSON, L., DALE, P. S., REZNICK, J. S., BATES, E., THAL, D. and PETHICK, S. (1994) Variability in early communicative development. *Monographs of the Society for Research in Child Development*, 59.5, Serial no. 242.

FRITH, U., WIMMER, H. and LANDERL, K. (1998) Differences in phonological recording in German- and English-speaking children. *Scientific Studies of Reading*, 2, pp. 31–54.

GOSWAMI, U. (1988) Orthographic analogies and reading development. *Quarterly Journal of Experimental Psychology*, 40A, pp. 239–268.

GOSWAMI, U., PORPODAS, C. and WEELWRIGHT, S. (1997) Children's orthographic representations in English and Greek. *European Journal of Psychology of Education*, 3, pp. 273–292.

GOSWAMI, U., ZIEGLER, J., DALTON, L. and SCHNEIDER, W. (2001) Pseudohomophone effects and phonological recoding procedures in reading development in English and German. *Journal of Memory and Language*, 45, pp. 648–664.

GOSWAMI, U., ZIEGLER, J., DALTON, L. and SCHNEIDER, W. (2003) Nonword reading across orthographies: how flexible is the choice of reading units? *Journal of Applied Psycholinguistics*, 24, pp. 235–247.

GOSWAMI, U. and ZIEGLER, J. C. (2006a) Fluency, phonology and morphology: a response to the commentaries on becoming literate in different languages. *Developmental Science*, 9.5, pp. 451–453.

GOSWAMI, U. and ZIEGLER, J. C. (2006b) A developmental perspective on the neural code for written words. *Trends in Cognitive Sciences*, 10.4, pp. 142–143.

HARRIS, M. and BEECH, J. R. (1998) Implicit phonological awareness and early reading development in prelingually deaf children. *Journal of Deaf Studies and Deaf Education*, 3.3, pp. 205–216.

HARRIS, M. and GIANNOULIS, V. (1999) 'Learning to read and spell in Greek: the importance of letter knowledge and morphological awareness', in M. Harris and G. Hatano (Eds.) *Learning to Read and Write: A Cross-Linguistic Perspective*. Cambridge: Cambridge University Press, pp. 51–70.

HOIEN, T., LUNDBERG, L., STANOVICH, K. E. and BJAALID, I. K. (1995) Components of phonological awareness. *Reading and Writing*, 7, pp. 171–188.

LIBERMAN, I. Y., SHANKWEILER, D., FISCHER, F. W. and CARTER, B. (1974) Explicit syllable and phoneme segmentation in the young child. *Journal of Experimental Child Psychology*, 18, pp. 201–212.

LUPKER, S. J. (2005) 'Visual word recognition: theories and findings', in M. J. Snowling and C. Hulme (Eds.) *The Science of Reading: A Handbook*. Oxford: Blackwell, pp. 39–60.

MACSWEENEY, M., WATERS, D., BRAMMER, M., WOLL, B. and GOSWAMI, U. (2008) Phonological processing in deaf signers and the impact of age of first language acquisition. *Neuroimage*, 40, pp. 1369–1379.

PERFETTI, C. A., BECK, I., BELL, L. and HUGHES, C. (1987) Phonemic knowledge and learning to read are reciprocal: a longitudinal study of first grade children. *Merrill-Palmer Quarterly*, 33, pp. 283–319.

PLAUT, D. C. (2005) 'Connectionist approaches to reading', in M. J. Snowling and C. Hulme (Eds.) *The Science of Reading: A Handbook*. Oxford: Blackwell, pp. 24–38.

PORT, R. (2006) 'The graphical basis of phones and phonemes', in M. Munro and O. Schwen-Bohn (Eds.) *Second Language Speech Learning: The Role of Language Experience in Speech Perception and Production*. Amsterdam: John Benjamins, pp. 349–365.

PRICE, C. J., GORNO-TEMPINI, M-L. D., GRAHAM, K. S., BIGGIO, N., MECHELLI, A., PATTERSON, K. and NOPPENEY, U. (2003) Normal and pathological reading: converging data from lesion and imaging studies. *NeuroImage*, 20.Suppl. 1, pp. S30–S41.

PRICE, C. J. and MCCRORY, E. (2005) 'Functional brain imaging studies of skilled reading and developmental dyslexia', in M.J. Snowling and C. Hulme (Eds.) *The Science of Reading: A Handbook*. Oxford: Blackwell Publishing, pp. 473–496.

PUGH, K. (2006) A neurocognitive overview of reading acquisition and dyslexia across languages. *Developmental Science*, 9, pp. 448–450.

READ, C. (1986) *Children's Creative Spelling*. London: Routledge.

ROSE, J. (2006) *Independent Review of the Teaching of Early Reading*. Nottingham: DfES Publications.

RUMSEY, J. M., HORWITZ, B., DONOHUE, B. C., NACE, K., MAISOG, J. M. and ANDREASON, P. (1997) Phonological and orthographic components of word recognition: a PET rCBF study. *Brain*, 120, pp. 739–759.

SAUSENG, P., BERGMANN, J. and WIMMER, H. (2004) When does the brain register deviances from standard word spellings? An ERP study. *Cognitive Brain Research*, 20, pp. 529–532.

SCHNEIDER, W., ROTH, E. and ENNEMOSER, M. (2000) Training phonological skills and letter knowledge in children at-risk for dyslexia: a comparison of three kindergarten intervention programs. *Journal of Educational Psychology*, 92, pp. 284–295.

SEYMOUR, P. H., ARO, M. and ERKINE, J. M. (2003) Foundation literacy acquisition in European orthographies. *British Journal of Psychology*, 94, pp. 143–174.

SIMOS, P. G., FLETCHER, J. M., BERGMAN, E., BREIER, J. I., FOORMAN, B. R., CASTILLO, E. M., DAVIS, R. N., FITZGERALD, M. and PAPANICOLAOU, A. C. (2002) Dyslexia-specific brain activation profile becomes normal following successful remedial training. *Neurology*, 58, pp. 1203–1213.

SIOK, W. T., PERFETTI, C. A., JIN, Z. and TAN, L. H. (2004) Biological abnormality of impaired reading is constrained by culture. *Nature*, 431, pp. 71–76.

STUART, M. (2006) Teaching reading: why start with systematic phonics teaching? *Psychology of Education Review*, 30.2, pp. 6–17.

TREIMAN, R., MULLENNIX, J., BIJELJAC-BABIC, R. and RICHMOND-WELTY, E. D. (1995) The special role of rimes in the description, use, and acquisition of English orthography. *Journal of Experimental Psychology: General*, 124, pp. 107–136.

TURKELTAUB, P. E., GAREAU, L., FLOWERS, D. L., ZEFFIRO, T. A. and EDEN, G. F. (2003) Development of neural mechanisms for reading. *Nature Neuroscience*, 6.6, pp. 767–773.

TUNMER, W. E. and NESDALE, A. R. (1985) Phonemic segmentation skill and beginning reading. *Journal of Educational Psychology*, 77, pp. 417–527.

VAN ORDEN, G. C. and KLOOS, H. (2005) 'The question of phonology and reading', in M. J. Snowling and C. Hulme (Eds.) *The Science of Reading: A Handbook*. Oxford: Blackwell, pp. 61–78.

VENTURA, P., MORAIS, J., PATTAMADILOK, C. and KOLINSKY, R. (2004) The locus of the orthographic consistency effect in auditory word recognition. *Language and Cognitive Processes*, 19.1, pp. 57–95.

WIMMER, H. (1996) The nonword reading deficit in developmental dyslexia: evidence from children learning to read German. *Journal of Experimental Child Psychology*, 61, pp. 80–90.

WIMMER, H., LANDERL, K., LINORTNER, R. and HUMMER, P. (1991) The relationship of phonemic awareness to reading acquisition: more consequence than precondition but still important. *Cognition*, 40, pp. 219–249.

ZIEGLER, J. C. (2005) Do differences in brain activation challenge universal theories of dyslexia? *Brain and Language*, 98, pp. 341–343.

ZIEGLER, J. C. and FERRAND, L. (1998) Orthography shapes the perception of speech: the consistency effect in auditory word recognition. *Psychonomic Bulletin and Review*, 5, pp. 683–689.

ZIEGLER, J. C., FERRAND, L. and MONTANT, M. (2004) Visual phonology: the effects of orthographic consistency on different auditory word recognition tasks. *Memory and Cognition*, 32, pp. 732–741.

ZIEGLER, J. C. and GOSWAMI, U. (2005) Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. *Psychological Bulletin*, 131.1, pp. 3–29.

ZIEGLER, J. C. and GOSWAMI, U. (2006) Becoming literate in different languages: similar problems, different solutions. *Developmental Science*, 9.5, pp. 429–453.

ZIEGLER, J. C., JACOBS, A. M. and STONE, G. O. (1996) Statistical analysis of the bidirectional inconsistency of spelling and sound in French. *Behavior Research Methods, Instruments, and Computers*, 28, pp. 504–515.

ZIEGLER, J. C., STONE, G. O. and JACOBS, A. M. (1997) What's the pronunciation for _OUGH and the spelling for/u/? A database for computing feedforward and feedback inconsistency in English. *Behavior Research Methods, Instruments, and Computers*, 29, pp. 600–618.

CONTACT THE AUTHOR:
Usha Goswami, Faculty of Education,
University of Cambridge, 184 Hills Road,
Cambridge CB2 8PQ, UK.
e-mail: ucg10@hermes.cam.ac.uk