Review

Form–meaning links in the development of visual word recognition

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Learning to read takes time and it requires explicit instruction. Three decades of research has taught us a good deal about how children learn about the links between orthography and phonology during word reading development. However, we have learned less about the links that children build between orthographic form and meaning. This is surprising given that the goal of reading development must be for children to develop an orthographic system that allows meanings to be accessed quickly, reliably and efficiently from orthography. This review considers whether meaning-related information is used when children read words aloud, and asks what we know about how and when children make connections between form and meaning during the course of reading development.

Keywords: word reading; children's reading; orthography; word learning

Learning to read takes time and it requires explicit instruction. Nevertheless, what young children learning to read accomplish over their first few years of reading experience is truly remarkable. Armed with a relatively small amount of code (in English, the 26 letters of our alphabet), children begin to develop the skills they need to recognize words. By middle childhood, they will have seen many thousands of printed words. From this, they are able to extract principles that generalize, allowing them to read words that they have never seen before, words such as *Hogwarts*, *Voldemort* and *Quidditch*. Alongside this impressive power to generalize, they are able to learn and to remember words that seem to disobey all of the rules, words such as *friend*, *meringue* and *shove*. They are also flexible in their learning, disambiguating words that look the same but sound different (*tear* in her eye versus *tear* in her dress) or sound the same but look different (*where* and *wear*, *there* and *their*). There can be no doubt that the goal of successful reading is for the reader to understand and interpret the content of the text they have read, nor that this is a highly complex skill (e.g. Kintsch & Rawson 2005; Perfetti *et al.* 2005). Equally though, there is no doubt that at the foundation of reading is our ability to process words: if a child fails to read words, if they are slow to read words or if they are unable to appreciate the meanings of words, reading comprehension will be seriously hampered. Thus, it is important to understand how children learn to read words as

without this skill, text comprehension simply cannot happen.

At the very heart of learning to read words is the need for children to learn about form—that is, orthography (letters), phonology (sound) and the links between orthography and phonology. Appropriately, therefore, this has been the focus of research into how children learn to read words, and over the last three decades, the field has learned an enormous amount about how children learn to process form. I begin by reviewing some of this work. Arguably, however, we have learned less about the links that children build between form and meaning. This is surprising given that the goal of reading development must be for children to develop an orthographic system that allows meanings to be accessed quickly, reliably and efficiently from orthography. The second part of our review considers what we know about how and when children make connections between form and meaning during the course of reading development. Two topics are addressed. First, is there any evidence that children's knowledge about the meanings of words contributes to reading development, specifically to the process of reading single words out loud? Second, how and when do children begin to access meaning from orthography? Both of these topics have attracted discussion and debate in the adult literature but have received much less attention in the developmental literature.

1. LEARNING FORM: MAKING LINKS BETWEEN ORTHOGRAPHY AND PHONOLOGY

As skilled adults, most of our reading is silent. In contrast, reading in young children is characterized by reading out loud and much of what we know about

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One contribution of 11 to a Theme Issue 'Word learning and lexical development across the lifespan'.

children's reading development has been learned from experiments that ask children to read aloud letter strings.¹ This demands that children make explicit links between spellings and their sounds—between orthography and phonology. Before considering how this process develops, it is worth noting that in adults, orthography and phonology are tightly linked. This is clearly illustrated by the striking finding that orthographic knowledge interferes with phonological processing in literate adults: even when a task is presented entirely within the auditory domain, orthographic information exerts an influence. For example, skilled readers are faster to decide that pairs of (aurally presented) words rhyme if they also share a spelling (e.g. *rope–hope*), compared with pairs of words that do not share a spelling (e.g. *rope–soap*; Seidenberg & Tanenhaus 1979). People are also sensitive to spelling and orthography when processing speech, for example when asked to decide whether a heard item is a word or a non-word in an auditory lexical decision task (e.g. Chereau *et al.* 2007; Ziegler *et al.* 2008). Interference continues to be seen in tasks designed to minimize strategic factors influencing performance (Taft *et al.* 2008). In illiterate people (and in young children who are pre-readers), orthographic interference is not observed (De Santos Loureiro *et al.* 2004; Serniclaes *et al.* 2005). One way to interpret these observations is to suggest that in literate people, phonology and orthography become tightly linked such that one code activates the other very quickly and automatically, consistent with the language processing system being highly interactive. Alternatively, learning to read may cause orthography to become amalgamated with phonology, such that orthographic information is coded into the phonological representations of literate people (Ehri & Wilce 1980; Ziegler & Goswami 2005). Either way, it is clear that once people acquire an orthographic code, its effects are powerful, exerting an influence in the absence of any visual stimuli or visual task demands. But how it is that children develop such a system?

The first task facing the novice reader is to become familiar with the alphabet and with the alphabetic principle—the revelation that letters code phonological information and that there is a systematic relationship between printed words and their pronunciations (Byrne 1998). As soon as children begin to grasp this principle, we see evidence that their reading attempts are underpinned by phonological knowledge. Building on earlier work by Ehri & Wilce (1985), Rack *et al.* (1994) taught 5-year-old children to associate printed abbreviations (cues) with phonological forms. For example, children learned to associate the letter cue *dbl* with the word 'table'. Rack *et al.* compared two types of visual cue: phonetic and control. Phonetic cues, like *dbl* for table, embodied something of the sound of the base word, but one letter was replaced by a letter representing a sound that differed only in voice, not in place or manner of articulation (in this example, the letter *t* was replaced by the letter *d*; 't' and 'd' sound similar, differing only in whether the vocal cords are vibrating when the sound is released). Control cues were identical to phonetic cues except that replaced letters were phonetically more distant

(for example, *kbl* for table). Even though the children had extremely limited reading skills (they were completely unable to read even a very simple nonsense word), they found it easier to learn to associate phonetic cues than control cues.

This phonetic cue effect shows that beginning readers are sensitive to the relationship between the phonological features of spoken words and letters, and that this sensitivity assists learning. This is considered to form the basis of the alphabetic principle, playing a crucial role in the development of decoding. Decoding is the term used to describe the active process by which children map from orthography to phonology, usually in a letter-by-letter (or grapheme-by-grapheme) manner, 'sounding-out' words to decipher their pronunciation. Decoding is effortful, particularly for longer words (e.g. Samuels *et al.* 1978). It is also error prone, especially in a language such as English where the relationship between orthography and phonology is not transparent. For example, a child may read *island* as 'izland'. Notwithstanding these limitations, decoding has been hypothesized as the *sine qua non* of reading acquisition and learning about orthography (Share 1995) as it provides children with a means to translate a printed word into an oral language code; in turn, this offers opportunities to acquire word-specific orthographic knowledge that is gradually learned and refined over time.

This developing orthographic system soon begins to show its sophistication. For example, young children are sensitive to the frequency and legality of different orthographic patterns, and even kindergarten children are able to decide that a written string such as *pass* is more likely to be a word than a string such as *ppes* (Cassar & Treiman 1997; Pacton *et al.* 2001). These results suggest that over time and following even quite limited exposure to written language, children become sensitive to orthographic constraints, based on the frequency of occurrence of letters in words that they have been exposed to. By 7 years of age, orthographic knowledge interferes with phonological processing such that auditory lexical decision times are slowed for items that contain inconsistent spelling–sound patterns, as they are in literate adults (Ventura *et al.* 2006). Interestingly, Ventura *et al.* found that interference from orthography was more pervasive in young children than in adults, with interference being seen for words as well as non-words (in adults, orthographic interference on phonological processing is only seen for lexical items), indicative of a highly interactive system, emphasizing mappings between orthography and phonology. By 10 years of age, children begin to show a more adult-like pattern of orthographic interference, with orthography influencing lexical (word), but not sublexical (non-word), phonological processing (Ventura *et al.* 2008).

As children encounter words in print, they continually expand and refine their orthographic knowledge. Ziegler & Goswami (2005) provide an eloquent description of how reading experience allows children to identify and extract units of correspondence between sound and spelling that are relevant for their language. These units operate at multiple and flexible

'grain sizes', determined by the constraints of the language and, importantly, the nature of the print vocabulary encountered by the child. Grain sizes may be small, corresponding to a single grapheme–phoneme correspondence (e.g. T pronounced as 't' or CK pronounced as 'k') or may be large, corresponding to a larger unit of spelling–sound correspondence (e.g. ING pronounced 'ing' or STR pronounced 'string'). Print experience, in interaction with the phonological and orthographic characteristics of the language, provides the database from which statistical regularities are abstracted. These ideas are consistent with the lexical tuning hypothesis offered by Castles *et al.* (2008). Castles *et al.* (2008) used a technique known as masked priming. Here, participants make lexical decisions, that is, they are asked to decide whether a written string (the target) is a word or a non-word. Before the string appears, another string (the prime) is displayed very briefly, usually for less than 50 ms. Despite participants being unable to report the prime stimulus, it influences processing of the target. When the prime is identical to the target, the target is processed faster, an effect known as identity priming. Using data from a series of masked priming experiments, Castles *et al.* argued that early in development, the orthographic system can afford to be fairly broadly tuned: if a child's reading vocabulary contains relatively few words, competition from other items will not be high. With reading experience, however, written vocabulary grows and lexical competition increases, demanding that the orthographic system adapts. Castles *et al.* (2008) demonstrated that early in development, the orthographic system is quite lax, with young readers showing 'identity' priming even when the target and prime differed by a letter (e.g. *julk* primed *JUNK*). Two years later, the same children, like adults, did not show priming in this condition, suggesting that their orthographic systems had become more precise. This demonstrates how reading development is a continuous process. Even in adulthood, new words are regularly learned, and indeed, the learning of new forms may have an effect on the processing of those that are already in existence (e.g. Bowers *et al.* 2005a). This view of reading development emphasizes continuous learning, characterized by interactivity and restructuring as new items enter an individual's lexicon via reading experience.

2. FORM–MEANING CONNECTIONS I: IS THERE A ROLE FOR MEANING IN READING ALOUD?

So far, our discussion has focused on the links that children form between orthography and phonology during the course of reading development, a process that provides the foundation of learning to read words. Over the last three decades, a large body of research has been concerned with examining the skills and abilities that underpin this development. This has provided clear evidence that learning to read is promoted by changes and growth in children's spoken language, particularly within the phonological domain (for review, see Goswami & Bryant 1990). Put simply, there is an intimate relationship between

the children's appreciation of the sound structure of speech and their ability to learn letter correspondences that map onto units of speech (e.g. Hulme *et al.* 2002). Without wishing to challenge the central role of phonological skills in learning to read, we can ask what other factors also contribute to its development. For example, we know relatively little about how beginning readers code orthographic representations—this is an important question for future research (for review, see Castles & Nation 2006, 2008). In this paper, however, we ask whether there is a role to be played by other aspects of oral language, beyond phonology. The rationale here is simple: integral to a word being a lexical item is the fact that it has meaning. Thus, in addition to familiar words comprising phonological and orthographic representations, they also have semantic representations. Do these make any contribution to the development of word reading?

Before addressing this question, it is important to clarify what is meant by word reading in this context. Most of us think of reading in terms of the silent reading of text. Clearly, this demands a complex set of processes that culminate in meaning being extracted from text. However, a large body of research has centred on the much more narrowly focused question of how adults read single words out loud. The extent to which the same processes are engaged when we read continuous text remains an open question.

In adults, the question of whether semantic representations contribute to the process of reading aloud has generated some debate over recent years. While contemporary models of reading aloud (in adults) emphasize procedures that translate from orthography to phonology (e.g. via both direct lexical and non-lexical routes of the dual-route cascade (DRC) model (Coltheart *et al.* 2001) and via the orthography–phonology pathway in the triangle model (Plaut *et al.* 1996)), they also propose a role for semantics. In the DRC model, semantic factors contribute via the lexical semantic route, whereas in the triangle model, semantic representations feed into the orthography–phonology–semantics pathway. Discussion here will focus on the triangle model for two reasons. First, the orthography–phonology–semantics pathway has been partly implemented in this model—this is not the case for the lexical semantic route of the DRC. Second, the triangle model has attempted to model development as well as skilled processing, and therefore is more relevant when we consider how children learn to read words.

In brief, the triangle model sees semantic factors contributing directly to reading aloud and its development (Plaut *et al.* 1996). Reading aloud follows from the activation of codes from visual input, and it is accomplished via two pathways working in parallel: a phonological pathway comprising connections between orthography and phonology and a semantic pathway comprising mappings between semantic, phonological and orthographic representations. Implementations of the model involve both pathways and all types of representation for the computation of all items, regardless of their lexicality, familiarity or frequency. However, as the phonological pathway is more direct, it is thought to be faster and therefore

to contribute more to reading aloud than the semantic pathway. Importantly, although the semantic pathway is always active, contributing some information to the reading process, its contribution becomes more important when the phonological pathway is compromised (for example, when reading words that have inconsistent mappings between orthography and phonology).

Turning to behavioural data, although there is some evidence consistent with semantic factors contributing to reading aloud in adults, the data are not unequivocal, making interpretation difficult. First, semantic properties such as ambiguity and imageability influence lexical processing in adults (e.g. Hino & Lupker 1996; Woollams 2005), even after lexical variables such as frequency are controlled (e.g. Balota *et al.* 2004). However, imageability correlates highly with other important variables known to influence lexical processing, especially age-of-acquisition (AoA; e.g. Ellis & Monaghan 2002; Monaghan & Ellis 2002). Some theorists have argued that early acquired words have different phonological structures to words that are acquired at a later age (e.g. Brown & Watson 1987), meaning that apparent differences in semantic factors (as indexed by imageability effects) might in fact be a consequence of differences in phonological factors (as indexed by AoA). A second source of evidence for semantic influences on reading aloud comes from patients with semantic dementia who show declines in reading aloud that parallel their loss of semantic knowledge (e.g. McKay *et al.* 2007; Woollams *et al.* 2007). Note however that not all patients with semantic dementia show deficits in reading aloud (e.g. Blazey *et al.* 2005). Finally, when adults are taught to read novel words, pre-training the meanings of the words leads to more successful orthographic learning of the same items (McKay *et al.* 2008). Consistent with the triangle model, semantic involvement in reading aloud was demonstrated most clearly when the words to be learned contained inconsistent or irregular mappings between spelling and sound. However, a recent experiment suggests that the semantic effect in this experiment might be a consequence of learners paying greater attention to words in the semantic pre-exposure condition (Taylor *et al.* submitted), rather than the meaning content contributing directly. Clearly, more work is needed to confirm the extent to which semantic factors influence the processes involved in word naming.

Relatively few studies have examined semantic influences on children's reading of words. There is however an association between meaning-related factors and word reading development. Beginning readers find high imageability words easier to learn (Laing & Hulme 1999), suggesting that an item's 'semantic richness' influences its readability. Younger children, like poorer readers, rely more on context when attempting to read words than do older children or more skilled readers (e.g. Stanovich *et al.* 1985). More generally, children who have weak semantic skills show relative weaknesses when reading aloud inconsistent or irregular words (Nation & Snowling 1998, 2004; Ouellette 2006; Bowey & Rutherford

2007; Ricketts *et al.* 2007), reminiscent of the relationship between word reading and semantic knowledge reported in semantic dementia.

Given this evidence supporting a general association between meaning-related factors and learning to read, what does the triangle model predict about the potential role of semantics as children learn to read words? At a basic level, if semantic factors contribute to the computation of sound from print, there ought to be a relationship between children's semantic skills and the progress they make in learning to read words. A more specific prediction stemming from the triangle model is that the contribution of semantics should be strongest when children are asked to read words that have inconsistent mappings between orthography and phonology. Nation & Cocksey (2009a) tested these predictions. They asked 7-year-old children to read aloud two lists of words. One comprised regular words, all containing consistent mappings between orthography and phonology, whereas the other list was composed of irregular words, all containing atypical mappings between orthography and phonology. The two lists were matched for frequency and various other factors known to influence lexical processing. Knowledge of the meaning of the words was also assessed by asking the same children to define the same words orally. This allowed Nation and Cocksey to explore the relationship between word knowledge in the oral domain and reading aloud. If, as predicted by the triangle model, semantic factors contribute to reading aloud, there ought to be a close relationship between definition knowledge and reading success, especially for the irregular words—words that depend more on semantic support because of their atypical mappings between orthography and phonology.

To some extent, the results provided evidence for this relationship. Not surprisingly, children were better able to read the regular words than the irregular ones, but consistent with the two lists being well matched for frequency, definition knowledge was equivalent for the two types of word. Across items, there was a correlation between definition knowledge and reading success, and this was closer for the irregular words. This shows that children were more likely to read correctly those words that were familiar in their oral vocabulary, consistent with semantic factors playing a role. Importantly, however, other data reported by Nation & Cocksey (2009a) suggest that this conclusion may be premature. The same children also heard the same words embedded in an auditory lexical decision task, requiring them to discriminate words from non-words. Across items, reading performance was associated with auditory lexical decision performance; further analyses revealed that lexical decision success was at least as closely associated with reading as was semantic knowledge, measured by the definitions task.

Nation and Cocksey's data support the view that there is an association between knowledge in the oral domain and reading aloud, particularly for irregular words, thus supporting the general principles of the triangle model. However, their data are less clear about whether the association between knowledge

and reading is most appropriately construed as a *semantic* contribution to word reading. Definition knowledge—clearly a semantic variable—was no better a predictor of reading success than auditory lexical decision performance. Arguably, when young children decide whether an auditory token is a word or not, they are accessing a form of semantic knowledge. Clearly, however, it is possible to know that an item is a word without knowing much, if anything, about its meaning. Thus, we can conclude from Nation and Cocksey's data that knowledge of lexical phonology—familiarity with the phonological form of a word—shows an association with children's ability to read that word. However, it is not yet clear whether semantic knowledge contributes anything over and above the contribution made by lexical phonology. An important caveat here is that Nation and Cocksey assessed semantic knowledge using a definitions task. This is a demanding task and, arguably, the narrow scoring system may fail to capture the subtleties of semantic knowledge. Future investigations may benefit from using a semantic categorization-type task rather than definitions; as well as revealing whether the children know a word, decision latencies would provide an index of processing cost, perhaps revealing gradations in semantic knowledge that do relate to reading proficiency.

Similar conclusions were reached by McKague *et al.* (2001). They taught young children either the phonological forms of new words or their phonological forms plus semantic information, before introducing their orthographic forms. Both types of pre-exposure facilitated orthographic learning, but there was no advantage for the semantic condition. Importantly, however, all items were regular in terms of orthography–phonology mappings. Evidence for a semantic contribution may be evident for items that contain less consistent spelling patterns. This pattern has been observed when adults learn to read aloud new words (McKay *et al.* 2008, but see Taylor *et al.* (submitted) for an alternative perspective), but is yet to be tested in developing readers. It is also important to note that in both Nation & Cocksey's (2009a) experiment and McKague *et al.*'s study, the children were young, averaging about 7 years of age. Simulations in the triangle model revealed that the relative contribution of the phonological pathway and the semantic pathway changed with reading experience (Plaut *et al.* 1996). Early in development, resources were devoted to establishing direct connections between orthography and phonology (the phonological pathway), akin to the early stages of learning to read. Later in training, however, the model came to depend increasingly on the semantic pathway, and this was most apparent for the computation of words with inconsistent mappings between orthography and phonology—words that are most challenging for the phonological pathway working in isolation. In keeping with the triangle model, it could be that semantic factors (beyond lexical phonology) only begin to exert an influence on children's reading aloud later in development, as the range and difficulty of words children are expected to be able to read increases. If correct, the item-by-item relationship between semantic factors

and word reading should strengthen as reading skill increases.

In summary, evidence to date concerning whether semantic factors contribute to the process of children reading aloud remains equivocal. Although there is evidence consistent with there being a general association between meaning-related factors and learning to read words (e.g. Laing & Hulme 1999; Nation & Snowling 2004), attempts to specify the exact nature of this association have failed to find evidence that semantic knowledge about words influences children's reading aloud of those same words (McKague *et al.* 2001; Nation & Cocksey 2009a). It does seem to be the case, however, that lexical phonology—defined as familiarity with the word-level phonological form—is associated with word reading success.

Why might this be? Share's (1995, 2008b) self-teaching hypothesis offers a straightforward explanation whereby familiarity with the oral form of a word provides a strategy that can be used to support partial decoding attempts. For example, a child who reads *iron* as 'i-ron' may reason that this is not a word and so search for a familiar phonological form that is similar to the partial decoding attempt. An alternative view sees whole-word phonology playing a more active or implicit role, contributing to the reading-aloud response. Such interactivity is consistent with the general principles of the triangle model, although it is important to note that lexical phonology is not in itself represented in the model; instead, lexical knowledge emerges from distributed patterns of activation across phonological, orthographic and semantic units. From this perspective, lexical phonology, as indexed by performance on auditory lexical decision, may incorporate semantic influences (Plaut 1997). Taylor *et al.* (submitted) offer an alternative characterization of lexical phonology within a triangle model framework. They suggest that the semantic pathway is supported not by semantics, but by a mechanism that binds together the phonemes in known words in a qualitatively different way from common sublexical combinations of phonemes. They note that this is how semantic support operated in Plaut *et al.*'s (1996) implementation of the triangle model, with the so-called semantic support being provided by 'additional input to the phonological units, pushing them towards their correct activations' (Plaut *et al.* 1996, p. 95). This resonates with the implemented lexical route of the CDP+ model, a connectionist model that combines components of the triangle model with components of the DRC model and approximates aspects of skilled word reading well (Perry *et al.* 2007). In contrast to the triangle model, it does not aim to incorporate semantic representations. Although more recent versions of the triangle model have incorporated richer and arguably more plausible semantic representations (Harm & Seidenberg 1999, 2004), there has been no detailed discussion of how and indeed whether this influences reading aloud. Clearly, more empirical and modelling work is needed to understand the role that these levels of representation play in children's word reading development, as well as to clarify the distinction between lexical phonology and semantics more generally.

3. FORM–MEANING CONNECTIONS II: DIRECT LINKS FROM ORTHOGRAPHY TO SEMANTICS?

So far, we have considered reading aloud—how children generate a pronunciation from a printed letter string. We now turn to consider the question of how young readers access meaning from orthography. This question has generated considerable debate in the adult literature and is considered a classic issue in reading research. Central to this debate has been whether lexical access (defined here as accessing meaning from print) is direct from orthography (e.g. Forster 1976; Coltheart 1978) or indirect. Indirect lexical access is phonologically mediated, with orthography activating meaning via phonological recoding (e.g. Van Orden *et al.* 1990). Over recent years, evidence from empirical studies and computational modelling has led to a model of lexical access that incorporates both a direct orthography-to-semantics (O→S) route and an indirect orthography-to-phonology-to-semantics (O→P→S) route working in balance in skilled readers (Harm & Seidenberg 2004). Thus, rather than debate whether lexical access is direct or indirect, it is more appropriate to view lexical access as flexible in skilled readers.

Turning to developmental issues, Harm and Seidenberg noted three facts about the relationship between orthography, phonology and semantics that are important when thinking about reading development: orthography and phonology are correlated in alphabetic languages, phonology and semantics are known to young children (via oral language) and mappings between orthography and semantics are difficult to learn (although ultimately faster) to compute meaning as they are less well correlated. Harm & Seidenberg's (2004) connectionist model of lexical access behaved in a way consistent with these observations. Early in training, the model relied more on O→P→S to compute meaning from print. Despite the early predominance of the phonologically mediated pathway, mappings between O→S began to develop over time, and in the fully trained model, both pathways worked together in parallel and both contributed to lexical access.

How well do Harm and Seidenberg's simulations account for behavioural evidence from children? Very few studies have addressed this issue directly, although the clear evidence that phonological decoding is at the core of reading development has led to the assumption that lexical access in children is achieved via phonological recoding, O→P→S (e.g. Wagner & Torgesen 1987). Some evidence for this is provided by Doctor & Coltheart's (1980) observation that 6–10-year-old children are heavily reliant on phonological mediation when reading for meaning. They found that younger children were far more likely to accept a sentence such as 'she bloo up the balloon' as meaningful than older children, leading them to argue that lexical access in children is initially mediated by phonology, but that this strategy is gradually replaced by direct links emerging between orthography and semantics over time.

More recent evidence, however, suggests that children might be making direct links between orthography and semantics from the early stages of

reading development. Nation & Cocksey (2009b) asked 7-year-old children to make semantic decisions about words, using the semantic competition paradigm devised by Bowers *et al.* (2005b). Items contained embedded words, for example, the word *hip* is embedded in the word *ship*. In the congruent condition, neither the carrier word nor the embedded word was related to the category judgement (e.g. is *ship* an animal?), whereas in the incongruent condition, embedded words were related in meaning to the category (e.g. Is *ship* a body part: although *ship* is not a body part, the embedded word *hip* is a body part). Children were significantly slower and less accurate at making category judgements in the incongruent condition, demonstrating that semantic information is activated very rapidly from subword orthography.

Building on this finding, two additional factors were manipulated. First, given children's reliance on phonological decoding and the assumption that lexical access is heavily dependent on O→P→S mappings (Doctor & Coltheart 1980; Wagner & Torgesen 1987), Nation & Cocksey (2009b) predicted that semantic interference would be seen only when the embedded word shared its pronunciation with the carrier word (e.g. the *plum* in *PLUMP* versus the *bus* in *BUSH*). Second—and following the same logic—more semantic interference was anticipated when embedded words overlapped at the beginning of carriers (e.g. the *cat* in *CATCH*) rather than at the end of carriers (e.g. the *rice* in *PRICE*). Rather surprisingly, however, neither the stability of pronunciation between embed and carrier nor the relative position of embeds influenced the magnitude of semantic interference in 7-year-old children: just as in adults, interference occurred in all conditions, as revealed by processing costs in the reaction time analyses and differences in accuracy.

These findings permit us to draw two notable conclusions about visual word recognition in young children. First, the fact that semantic interference operated at a subword level suggests that the semantic activation from orthography is not dependent on the identification of the whole word. Second, the finding that semantic interference was equivalent regardless of whether or not embedded words shared their pronunciation with the carrier word demonstrates that semantic activation is not dependent on phonological mediation. In turn, this shows that access to meaning from print can be direct, consistent with children using O→S connections much earlier in development than traditionally assumed. Thus, in addition to making connections between orthography and phonology, these findings suggest that beginning readers also forge links between orthography and semantics during the course of reading development.

4. FORM–MEANING CONNECTIONS AND LEARNING TO READ

Children learn a huge amount about words and orthography as their reading skills develop. Armed with basic decoding skills and an appreciation that letters code for phonological information, children have a means to begin to learn from their print experiences,

accumulating knowledge about letters and their sounds. Two different perspectives concerning the nature of form–meaning links in children’s reading development have been reviewed. First, we asked whether children’s knowledge about the meanings of words contributes to the process of reading aloud. This remains a contentious issue in the adult literature, with a recent comprehensive study concluding that semantic involvement contributes a small but significant role in reading aloud (McKay *et al.* 2008). Although there is clear evidence of a general relationship between vocabulary knowledge and word reading (e.g. Nation & Snowling 2004; Ouellette 2006; Bowey & Rutherford 2007; Ricketts *et al.* 2007), it is not clear whether semantic factors play a specific role in reading aloud. Evidence to date fails to find support for a semantic involvement (McKague *et al.* 2001; Nation & Cocksey 2009a). More work is needed to clarify these findings in children of different ages and different levels of reading experience. The second perspective considered when and how children begin to access meaning from orthography. Although few data speak on this issue, Nation & Cocksey’s (2009b) experiment provides clear evidence that 7-year-old children access meaning-level information from subword orthography, without phonological mediation. This shows that despite a relatively limited amount of reading experience, direct links have been made between orthographic and semantic representations.

One way to characterize reading development is as a process of constant learning, with experience leading to a continuous re-shaping of lexical knowledge over time, as new words are encountered and old words re-encountered. This characterization fits well with attempts to model reading development using connectionist models in which orthographic knowledge emerges gradually from the processing of input, without the specification of in-built changes in representational constraint. Various versions of the triangle model (Plaut *et al.* 1996; Harm & Seidenberg 2004) have been used to illustrate this approach in this review. It is important, however, to note its limitations and, in particular, to reflect upon its developmental plausibility. As its limitations are discussed at length elsewhere (e.g. Coltheart 2005), we consider here its developmental plausibility.

Three issues seem particularly problematic at the present time, although as Harm & Seidenberg (2004) point out, these are issues that can be addressed in future modelling attempts. First concerns the nature of orthographic representation. The model was not pre-trained on orthography, unlike semantics and phonology, which were both trained heavily before the onset of reading. Given the importance of letter knowledge during the early stages of word learning (e.g. Byrne & Fielding-Barnsley 1989; Muter *et al.* 2004), an elementary introduction to letters early in training is important if psychologically valid orthographic representations are to develop. This point is nicely demonstrated by Powell *et al.* (2006) who made a direct comparison between kindergarten children learning to read and the triangle model (the version reported by Plaut *et al.* (1996)). They noted

that early in development, the original model did not generalize its knowledge to novel words very well and levels of non-word reading accuracy were much lower than they observed in beginning readers. In a revised model, they mimicked letter–sound knowledge by pre-exposing the model on grapheme–phoneme correspondences, before the introduction of words. This led to faster learning and greater generalization, bringing the model more in line with data from children. An issue for the model, more generally, is that the slot-coding scheme to represent orthography is not compatible with some behavioural data (for discussion, see Bowers *et al.* (2005b)).

A second issue concerns the nature of training and the training set of words the network is exposed to. In the triangle model, learning is achieved by a variant of a back-propagation algorithm. This means that learning is supervised, in the sense that the output of the network is monitored by an external ‘teacher’, and differences between the actual output and the correct output trigger changes in the network’s connections. Although children learn through explicit instruction, they rarely receive feedback on each reading attempt. Instead, training is much more variable, sometimes comprising direct modelling of appropriate response, sometimes explicit training in phonological awareness or letter–sound knowledge and often no feedback at all. Harm & Seidenberg (2004) suggest that this rich and varied learning environment may be more advantageous than providing correct feedback on each trial as it ‘may discourage the development of overly word-specific representations in favour of representations that capture structure that is shared across words, improving generalisation’ (p. 673). This is an interesting issue for future research, but at present, it is important to note that the nature of feedback provided to a network differs substantially from the experiences of children learning to read.

A third and related issue concerns the learning algorithm used by Harm and Seidenberg. Very slow learning rates were employed so as to prevent the network’s weights from oscillating wildly. The consequence of this is that many trials were required to learn each word, with the very large training set being presented thousands of times. This contrasts sharply with observations from children’s learning where initial reading experiences tend to comprise exposure to a small vocabulary of written words that increases in size as proficiency develops (Powell *et al.* 2006). Despite this incremental and relatively limited training environment, very few exposures may be sufficient for a child to learn a new word (Share 2004; Nation *et al.* 2007).

In addition to these outstanding issues for the triangle model, more behavioural data from children are also needed. Despite a large body of work documenting the nature of orthographic representations and orthographic processing in adults (for recent review, see special issue edited by Grainger (2007)), very few studies have considered the *development* of these representations and processes. Similarly, the adult literature has attended to the role of morphology in word reading, providing evidence that sensitivity to morphological structure influences the early stages of

visual word recognition (e.g. Rastle *et al.* 2004; McCormick *et al.* 2008). We know that children are sensitive to morphological structure in metacognitive awareness tasks and that this becomes reflected in their spelling attempts as literacy develops (e.g. Nunes *et al.* 1997, 2006; Kemp 2006; however, studies are only just beginning to examine in detail how morphology maps to orthography in the development of orthographic representations. For example, Burani *et al.* (2008) found that children were faster to read pseudowords that were made up of root and suffix morphemes (for example, *womanist* is a pseudoword but is made from two morphemes, namely *woman* + *ist*) than pseudowords that did not contain embedded morphemes. Interestingly, younger children (and poorer readers) also showed a processing advantage for words that contained morphological structure, suggesting that they were relying on morphological parsing to a greater extent than more skilled readers (see Reichle & Perfetti (2003) and Verhoeven & Perfetti (2003) for further preliminary work in this area).

Another area where additional data are needed concerns silent reading. As noted earlier, much of what we have learned about how children learn to read comes from studies of reading aloud rather than silently. Certainly, as children get older, reading aloud becomes less common, meaning that a thorough understanding of reading development requires researchers to explore silent reading. Indeed, recent studies following this approach suggest that word recognition is surprisingly parallel and interactive, even in very young readers (e.g. Alario *et al.* 2007; Nation & Cocksey 2009b).

Studies that marry an experimental methodology with a developmental perspective are likely to be fruitful, either via a longitudinal design, or via a cross-sectional design that considers carefully participants' reading experience. In combination with the wealth of information already known about children's reading development, data of this kind have the potential to enhance our understanding of how and when children begin to forge links between form and meaning during the course of reading development.

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ENDNOTE

¹This review will focus on research in English. Important insights have been learned from studying reading development in other languages. For recent reviews, see Ziegler & Goswami (2005) and Share (2008a).

REFERENCES

- Alario, F. X., De Cara, B. & Ziegler, J. C. 2007 Automatic activation of phonology in silent reading is parallel: evidence from beginning and skilled readers. *J. Exp. Child Psychol.* **97**, 205–219. (doi:10.1016/j.jecp.2007.02.001)
- Balota, D. A., Cortese, M. J., Sergent-Marshall, S. D., Spieler, D. H. & Yap, M. J. 2004 Visual word recognition of single-syllable words. *J. Exp. Psychol. Gen.* **133**, 283–316. (doi:10.1037/0096-3445.133.2.283)
- Blazey, A. M., Coltheart, M. & Cassey, B. J. 2005 Semantic impairment with and without surface dyslexia: implications for models of reading. *Cogn. Neuropsychol.* **22**, 695–717. (doi:10.1080/02643290442000257)
- Bowers, J. S., Davis, C. J. & Hanley, D. A. 2005a Inferring neighbours: the impact of novel word learning on the identification of visually similar words. *Cognition* **97**, B45–B54. (doi:10.1016/j.cognition.2005.02.002)
- Bowers, J. S., Davis, C. J. & Hanley, D. A. 2005b Automatic semantic activation of embedded words: is there a 'hat' in 'that'? *J. Mem. Lang.* **52**, 131–143. (doi:10.1016/j.jml.2004.09.003)
- Bowey, J. A. & Rutherford, J. 2007 Imbalanced word-reading profiles in eighth-graders. *J. Exp. Child Psychol.* **96**, 169–196. (doi:10.1016/j.jecp.2006.11.001)
- Brown, G. D. A. & Watson, F. L. 1987 1st in, 1st out—word learning age and spoken word frequency as predictors of word familiarity and word naming latency. *Mem. Cogn.* **15**, 208–216.
- Burani, C., Marcolini, S., De Luca, M. & Zoccolotti, P. 2008 Morpheme-based reading aloud: evidence from dyslexic and skilled Italian readers. *Cognition* **108**, 243–262. (doi:10.1016/j.cognition.2007.12.010)
- Byrne, B. 1998 *The foundation of literacy: the child's acquisition of the alphabetic principle*. Hove, UK: Psychology Press.
- Byrne, B. & Fielding-Barnsley, R. 1989 Phonemic awareness and letter knowledge in the child's acquisition of the alphabetic principle. *J. Educ. Psychol.* **81**, 313–321. (doi:10.1037/0022-0663.81.3.313)
- Cassar, M. & Treiman, R. 1997 The beginnings of orthographic knowledge: children's knowledge of double letters in words. *J. Educ. Psychol.* **89**, 631–644. (doi:10.1037/0022-0663.89.4.631)
- Castles, A. & Nation, K. 2006 How does orthographic learning happen? In *From inkmarks to ideas: challenges and controversies about word recognition and reading* (ed. S. Andrews). Hove, UK: Psychology Press.
- Castles, A. & Nation, K. 2008 Learning to be a good orthographic reader. *J. Res. Reading* **31**, 1–7. (doi:10.1111/j.1467-9817.2007.00367.x)
- Castles, A., Davis, C., Cavalot, P. & Forster, K. 2008 Tracking the acquisition of orthographic skills in developing readers: masked priming effects. *J. Exp. Child Psychol.* **97**, 165–182. (doi:10.1016/j.jecp.2007.01.006)
- Chereau, C., Gaskell, M. G. & Dumay, N. 2007 Reading spoken words: orthographic effects in auditory priming. *Cognition* **102**, 341–360. (doi:10.1016/j.cognition.2006.01.001)
- Coltheart, M. 1978 Lexical access in simple reading tasks. In *Strategies of information processing* (ed. G. Underwood). London, UK: Academic Press.
- Coltheart, M. 2005 Modelling reading: the dual route approach. In *The science of reading: a handbook* (eds M. J. Snowling & C. Hulme), pp. 6–23. Oxford, UK: Blackwell.
- Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. 2001 DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychol. Rev.* **108**, 204–256. (doi:10.1037/0033-295X.108.1.204)
- De Santos Loureiro, C., Willadino Braga, L., Souza, L. N., Filho, G. N., Queiroz, E. & Dellatolas, G. 2004 Degree of illiteracy and phonological and metaphonological skills in unschooled adults. *Brain Lang.* **89**, 499–502.
- Doctor, E. A. & Coltheart, M. 1980 Children's use of phonological encoding when reading for meaning. *Mem. Cogn.* **8**, 195–209.
- Ehri, L. C. & Wilce, L. S. 1980 The influence orthography on readers conceptualisation of the phonemic structure

- of words. *Appl. Psycholinguist.* **1**, 371–385. (doi:10.1017/S0142716400009802)
- Ehri, L. C. & Wilce, L. S. 1985 Movement into reading—is the 1st stage of printed word learning visual or phonetic? *Reading Res. Q.* **20**, 163–179. (doi:10.2307/747753)
- Ellis, A. W. & Monaghan, J. 2002 Reply to Strain, Patterson and Seidenberg (2002). *J. Exp. Psychol. Learn. Mem. Cogn.* **28**, 212–220. (doi:10.1037/0278-7393.28.1.215)
- Forster, K. I. 1976 Accessing the mental lexicon. In *New approaches to language mechanisms* (eds R. J. Wales & E. Walker). Amsterdam, The Netherlands: North Holland.
- Goswami, U. & Bryant, P. 1990 *Phonological skills and learning to read*. London, UK: Erlbaum.
- Grainger, J. 2007 Cracking the orthographic code: an introduction. *Lang. Cogn. Process.* **23**, 1–35. (doi:10.1080/01690960701578013)
- Harm, M. W. & Seidenberg, M. S. 1999 Phonology, reading acquisition, and dyslexia: insights from connectionist models. *Psychol. Rev.* **106**, 491–528. (doi:10.1037/0033-295X.106.3.491)
- Harm, M. W. & Seidenberg, M. S. 2004 Computing the meanings of words in reading: cooperative division of labor between visual and phonological processes. *Psychol. Rev.* **111**, 662–720. (doi:10.1037/0033-295X.111.3.662)
- Hino, Y. & Lupker, S. J. 1996 Effects of polysemy in lexical decision and naming: an alternative to lexical access accounts. *J. Exp. Psychol. Hum. Percept. Perform.* **22**, 1331–1356. (doi:10.1037/0096-1523.22.6.1331)
- Hulme, C., Hatcher, P. J., Nation, K., Brown, A., Adams, J. & Stuart, G. 2002 Phoneme awareness is a better predictor of early reading skill than onset-rime awareness. *J. Exp. Child Psychol.* **82**, 2–28. (doi:10.1006/jecp.2002.2670)
- Kemp, N. 2006 Children's spelling of base, inflected, and derived words: links with morphological awareness. *Reading and Writing* **19**, 737–765. (doi:10.1007/s11145-006-9001-6)
- Kintsch, W. & Rawson, K. A. 2005 Comprehension. In *The science of reading: a handbook* (eds M. J. Snowling & C. Hulme), pp. 248–265. Oxford, UK: Blackwell.
- Laing, E. & Hulme, C. 1999 Phonological and semantic processes influence beginning readers' ability to learn to read words. *J. Exp. Child Psychol.* **73**, 183–207. (doi:10.1006/jecp.1999.2500)
- McCormick, S. F., Rastle, K. & Davis, M. H. 2008 Is there a 'fete' in fetish? Effects of orthographic opacity on morpho-orthographic segmentation in visual word recognition. *J. Mem. Lang.* **58**, 307–326. (doi:10.1016/j.jml.2007.05.006)
- McKague, M., Pratt, C. & Johnston, M. B. 2001 The effect of oral vocabulary on reading visually novel words. *Cognition* **80**, 231–262. (doi:10.1016/S0010-0277(00)00150-5)
- McKay, A., Castles, A., Davis, C. & Savage, G. 2007 The impact of progressive semantic loss on reading aloud. *Cogn. Neuropsychol.* **24**, 162–186. (doi:10.1080/02643290601025576)
- McKay, A., Davis, C., Savage, G. & Castles, A. 2008 Semantic involvement in reading aloud: evidence from a nonword training study. *J. Exp. Psychol. Learn. Mem. Cogn.* **34**, 1495–1517. (doi:10.1037/a0013357)
- Monaghan, J. & Ellis, A. W. 2002 What exactly interacts with spelling-sound consistency in word naming? *J. Exp. Psychol. Learn. Mem. Cogn.* **28**, 183–206. (doi:10.1037/0278-7393.28.1.183)
- Muter, V., Hulme, C., Snowling, M. J. & Stevenson, J. 2004 Phonemes, rimes, vocabulary, and grammatical skills as foundations of early reading development: evidence from a longitudinal study. *Dev. Psychol.* **40**, 665–681. (doi:10.1037/0012-1649.40.5.665)
- Nation, K. & Cocksey, J. 2009a The relationship between knowing a word and reading it aloud in children's word reading development. *J. Exp. Child Psychol.* **103**, 296–308. (doi:10.1016/j.jecp.2009.03.004)
- Nation, K. & Cocksey, J. 2009b Beginning readers activate semantics from sub-word orthography. *Cognition* **110**, 273–278. (doi:10.1016/j.cognition.2008.11.004)
- Nation, K. & Snowling, M. J. 1998 Semantic processing and the development of word-recognition skills: evidence from children with reading comprehension difficulties. *J. Mem. Lang.* **39**, 85–101. (doi:10.1006/jmla.1998.2564)
- Nation, K. & Snowling, M. J. 2004 Beyond phonological skills: broader language skills contribute to the development of reading. *J. Res. Reading* **27**, 342–356. (doi:10.1111/j.1467-9817.2004.00238.x)
- Nation, K., Angell, P. & Castles, A. 2007 Orthographic learning via self-teaching: effects of exposure, durability, and context. *J. Exp. Psychol.* **96**, 71–84.
- Nunes, T., Bryant, P. & Bindman, M. 1997 Morphological spelling strategies: developmental stages and processes. *Dev. Psychol.* **33**, 637–649. (doi:10.1037/0012-1649.33.4.637)
- Nunes, T., Bryant, P. & Bindman, M. 2006 The effects of learning to spell on children's awareness of morphology. *Reading and Writing* **19**, 767–787. (doi:10.1007/s11145-006-9025-y)
- Ouellette, G. P. 2006 What's meaning got to do with it: the role of vocabulary in word reading and reading comprehension. *J. Educ. Psychol.* **98**, 554–566. (doi:10.1037/0022-0663.98.3.554)
- Pacton, S., Perruchet, P., Fayol, M. & Cleeremans, A. 2001 Implicit learning in real world context: the case of orthographic regularities. *J. Exp. Psychol. Gen.* **130**, 401–426. (doi:10.1037/0096-3445.130.3.401)
- Perfetti, C. A., Landi, N. & Oakhill, J. 2005 The acquisition of reading comprehension skill. In *The science of reading: a handbook* (eds M. J. Snowling & C. Hulme), pp. 227–247. Oxford, UK: Blackwell.
- Perry, C., Ziegler, J. C. & Zorzi, M. 2007 Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. *Psychol. Rev.* **114**, 273–315. (doi:10.1037/0033-295X.114.2.273)
- Plaut, D. C. 1997 Structure and function in the lexical system: insights from distributed models of word reading and lexical decision. *Lang. Cogn. Process.* **21**, 116–133.
- Plaut, D. C., McClelland, J. L., Seidenberg, M. S. & Patterson, K. 1996 Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychol. Rev.* **103**, 56–115. (doi:10.1037/0033-295X.103.1.56)
- Powell, D., Plaut, D. C. & Funnell, E. 2006 Does the PMSP connectionist model of single word reading learn to read in the same way as a child? *J. Res. Reading* **29**, 299–250.
- Rack, J., Hulme, C., Snowling, M. J. & Wightman, J. 1994 The role of phonology in young children learning to read words—the direct-mapping hypothesis. *J. Exp. Child Psychol.* **57**, 42–71. (doi:10.1006/jecp.1994.1003)
- Rastle, K., Davis, M. H. & New, B. 2004 The broth in my brother's brothel: morpho-ortho segmentation in visual word recognition. *Psychon. Bull. Rev.* **11**, 1090–1098.
- Reichle, E. D. & Perfetti, C. A. 2003 Morphology in word identification: a word-experience model that accounts for morpheme frequency effects. *Sci. Stud. Reading* **7**, 219–237. (doi:10.1207/S1532799XSSR0703_2)
- Ricketts, J., Nation, K. & Bishop, D. V. 2007 Vocabulary is important for some, but not all reading skills. *Sci. Stud. Reading* **11**, 235–257.
- Samuels, S. J., LaBerge, D. & Bremer, C. D. 1978 Units of word recognition: evidence for developmental changes. *J. Verbal Learn. Verbal Behav.* **17**, 157–720.

- Seidenberg, M. S. & Tanenhaus, M. K. 1979 Orthographic effects on rhyme monitoring. *J. Exp. Psychol. Hum. Learn. Mem.* **5**, 546–554. (doi:10.1037/0278-7393.5.6.546)
- Serniclaes, W., Ventura, P., Morais, J. & Kolinsky, R. 2005 Categorical perception of speech sounds in illiterate adults. *Cognition* **98**, B35–B44. (doi:10.1016/j.cognition.2005.03.002)
- Share, D. L. 1995 Phonological recoding and self-teaching: sine qua non of reading acquisition. *Cognition* **55**, 151–218. (doi:10.1016/0010-0277(94)00645-2)
- Share, D. L. 2004 Orthographic learning at a glance: on the time course and developmental onset of self-teaching. *J. Exp. Child Psychol.* **87**, 267–298. (doi:10.1016/j.jecp.2004.01.001)
- Share, D. L. 2008a On the Anglocentricities of current reading research and practice: the perils of overreliance on an 'outlier' orthography. *Psychol. Bull.* **134**, 584–615. (doi:10.1037/0033-2909.134.4.584)
- Share, D. L. 2008b Orthographic learning, phonological recoding, and self-teaching. *Adv. Child Dev. Behav.* **36**, 31–82. (doi:10.1016/S0065-2407(08)00002-5)
- Stanovich, K. E., Nathan, R. G., West, R. F. & Vala-Rossi, M. 1985 Children's word recognition in context: spreading activation, expectancy, and modularity. *Child Dev.* **56**, 1418–1428. (doi:10.2307/1130461)
- Taft, M., Castles, A., Davis, C., Lazendic, G. & Nguyen-Hoan, M. 2008 Automatic activation of orthography in spoken word recognition: pseudohomograph priming. *J. Mem. Lang.* **58**, 366–379. (doi:10.1016/j.jml.2007.11.002)
- Taylor, J. H. S., Nation, K. & Plunkett, K. Submitted. The influence of consistency, frequency and semantics on learning to read: an artificial orthography paradigm.
- Van Orden, G. C., Stone, G. O. & Pennington, B. F. 1990 Word identification in reading and the promise of sub-symbolic psycholinguistics. *Psychol. Rev.* **97**, 488–522.
- Ventura, P., Morais, J. & Kolinsky, R. 2006 The development of orthographic consistency effect in speech recognition: from sub-lexical to lexical involvement. *Cognition* **105**, 547–576. (doi:10.1016/j.cognition.2006.12.005)
- Ventura, P., Kolinsky, R., Pattamadilok, C. & Morais, J. 2008 The developmental turnpoint of orthographic consistency effects in speech recognition. *J. Exp. Child Psychol.* **100**, 135–145. (doi:10.1016/j.jecp.2008.01.003)
- Verhoeven, L. & Perfetti, C. 2003 Introduction to this special issue: the role of morphology in learning to read. *Sci. Stud. Reading* **7**, 209–217. (doi:10.1207/S1532799XSSR0703_1)
- Wagner, R. K. & Torgesen, J. K. 1987 The nature of phonological processing and the acquisition of reading skills. *Psychol. Bull.* **101**, 192–212. (doi:10.1037/0033-2909.101.2.192)
- Woollams, A. 2005 Imageability and ambiguity effects in speeded naming: convergence and divergence. *J. Exp. Psychol. Learn. Mem. Cogn.* **31**, 878–890. (doi:10.1037/0278-7393.31.5.878)
- Woollams, A. M., Lambon Ralph, M. A., Plaut, D. C. & Patterson, K. 2007 SD-squared: on the association between semantic dementia and surface dyslexia. *Psychol. Rev.* **114**, 316–339. (doi:10.1037/0033-295X.114.2.316)
- Ziegler, J. C. & Goswami, U. 2005 Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. *Psychol. Bull.* **131**, 3–29. (doi:10.1037/0033-2909.131.1.3)
- Ziegler, J. C., Petrova, A. & Ferrand, L. 2008 Feedback consistency effects in visual and auditory word recognition: where do we stand after more than a decade? *J. Exp. Psychol. Learn. Mem. Cogn.* **34**, 643–661. (doi:10.1037/0278-7393.34.3.643)