CHAPTER ONE

Progress in Reading Science: Word Identification, Comprehension, and Universal Perspectives

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Like the flow of a stream, skilled reading is a mix of fast and slow currents. The rapid identification of words and their meanings co-occur with almost-as-rapid meaning integration processes. Moving along simultaneously is a current of deeper, more contextualized comprehension and interpretation. Understanding how these overlapping currents work to produce skilled reading is one goal of a systems approach to reading.

In 1972, Philip Gough published a paper titled "One Second of Reading" (Gough, 1972). During this second, Gough's estimations of various visual and coding processes implied that 9 words were read. This is the rapid current of 'online' reading observable by the tools of reading science, which have supported much of its progress. In what follows, we highlight advances in the study of skilled reading, from word identification to comprehension, emphasizing language and writing system influences, the convergence of brain and behavior data, with brief links to reading difficulties and learning to read.

We begin by replacing our metaphor of stream currents with a static representation of what reading science seeks to explain, drawing on the Reading Systems Framework (RSF) (Perfetti & Stafura, 2014). Although a dynamic model may capture the reality of reading as it happens, a component systems model allows us to describe this reality more clearly. The RSF, illustrated in Figure 1.1, organizes the knowledge sources (collectively, the

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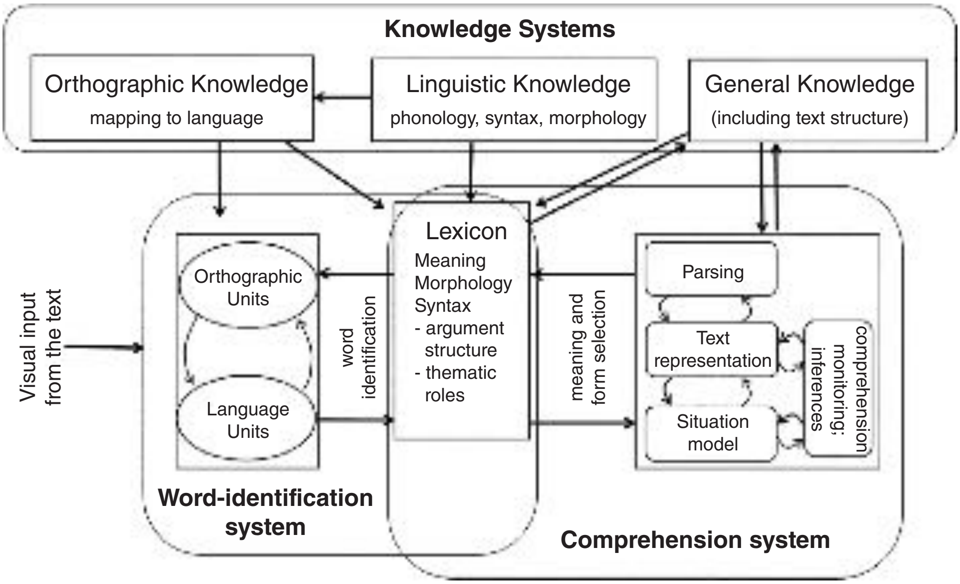

Figure 1.1 The Reading Systems Framework (modified from Perfetti & Stafura, 2014) consisting of word-identification, comprehension, and knowledge systems, with a central role for the lexicon.

knowledge systems) that drive both word identification and comprehension. The lexicon – knowledge about word forms and their meanings – is central in connecting these two systems. We apply the framework to examine research progress, describing three significant advances.

Reading and Reading Science in Historical Context

Humans have been reading for around 3,500 years. Or at least writing has been around for about that long, which is all we have to go on. Reading science is much younger. Although reports of patients with acquired reading disorders appeared earlier (Berlin, 1887; Kussmaul, 1878), Cattell's (1886) experiments on the time it takes to read words and letter strings mark the beginning of experimental reading research. The broader research findings published by E. B. Huey (1908), who acknowledged contemporary research by Erdmann and Dodge, are the most substantial landmark for a beginning of reading science. Indeed, most of Huey's observations in the *Psychology and Pedagogy of Reading* remain foundational for reading science: word perception, the "inner voice" in silent reading, meaning, and "interpretation," the evolution of writing and the alphabetic principle. Notably omitted was dyslexia, a slight that was repaid by Orton (1925) when he ignored Huey's book and its research in his classic work "Word Blindness."

Much of the progress since has been enabled by tools that reveal the intricate and interleaved processes and knowledge interactions that occur rapidly in reading: Eye tracking, Event Related Potentials (ERPs) and chronometric behavioral measures can detect the processes that constitute the rapid stream of reading. The products of these processes – the slower stream of reading – are exposed by behavioral output measures, and by imaging tools that identify brain areas associated with these processes. Beyond laboratory tools, the development of computational modeling has added precision to theoretical accounts and large language corpora provide statistical tools for the modeling of reading processes.

Advance 1: The Word-identification System in Skilled Alphabetic Reading

Visual processing and models of eye movements

We begin with the lower left portion of the Reading Systems Framework, the visual input that initiates the identification of a printed word. Pre-dating modern-day observations that the brain was not designed for reading (e.g., Dehaene, 2009), Huey (1908) pointed out that reading is "intensely artificial." "The human eye and the human mind, the most delicate products of evolution, were evolved in adaptation to conditions quite other than those of reading" (p. 8).

The core visual constraint is that the acuity needed to identify a specific letter within a word is limited to one to two degrees of visual angle at normal viewing distance. Within this narrow window, only a single word or two (with the help of parafoveal viewing) can be identified during an eye fixation, although less precise visual information is available peripherally.

As detailed by Liversedge et al. (this volume), readers adapt to this limitation by making frequent eye-fixations, directly fixating on between 60% and 80% of content words (Rayner et al., 2005). They also adjust their fixation rates (and the number of regressions) in response to text difficulty and reading goals, one of the key regulatory strategies in reading. Word fixations vary in duration, generally allowing three to five words to be fixated within a second of reading (Rayner et al., 2004, 2005). With assistance from word properties, context, and parafoveal viewing, a reader may approximate the reading rate implied by Gough's (1972) one second of reading. The familiarity of a word, its predictability from context (Rayner et al., 2004), and the structure of the sentence (Clifton & Staub, 2011) all exert an effect on eye movement measures. Some measures reflect the more passive, automatized aspects of word identification (e.g., fixation durations), whereas others also reflect regulatory processes that help the reader make sense of the text (e.g., regressions). Together, eye-tracking measures reflect how context and the linguistic properties of words affect how easily they are read and understood.

Skilled readers control their eye movements to accommodate the perceptual constraints on word identification while maintaining reading efficiency. How this is accomplished is the target of eye-movement control models. Serial processing models assume that only a single word is in visual attention, for example, the EZ Reader model (Reichle et al., 1998, 2003). To accomplish rapid reading rates with serial processing, the brain must signal an eye movement before the word has been identified completely because the movement lags behind the brain's launch signal. Thus, EZ Reader assumes a signal that word identification is imminent (not complete) is what prompts an eye movement. This signal comes earlier for a familiar word or one predictable from context. An alternative solution to perceptual constraints is to allow parallel processing on adjacent words (SWIFT model, Engbert et al., 2005). A more recent model allows for parallel processing of words and provides specific word identification mechanisms (Snell et al., 2018). The question of parallel versus serial processing of words remains a point of contention (see Grainger, and Liversedge et al., this volume).

Orthographic processing and models of word identification

The word-identification system codes visual input as familiar orthographic units. The skilled reader has acquired an inventory of orthographic units – graphs, to use a neutral term – and connected them to language units (the word-identification system in Figure 1.1)—allowing words to be identified.

From word superiority to interactive activation. One of the most intriguing problems in reading science is how the reader's knowledge of orthographic units is used in skilled reading (Grainger, this volume). The long-standing answer is that readers come to recognize a word as a whole unit rather than a string of letters. J.M. Cattell's famous experiments (1886; reviewed in Huey 1908) were intended to demonstrate this. After viewing a briefly exposed string of letters, Cattell attempted to report all the letters in the string. When the letters spelled a word, he could report more letters than when he viewed a random letter string.

In fact, Cattell's experiments could not distinguish perception of the whole word from memory for some of its letters. Remembering enough letters would prompt retrieval of a word that contains them, making the report of the letter string a mix of perception, memory, and a bias to respond with words. Nevertheless, Cattell's explanation (and Huey's) stood unchallenged until the independent publications of experiments by Reicher (1969) and Wheeler (1970).

Reicher (1969) and Wheeler (1970) controlled for response bias by asking participants which of two letters had been briefly presented (and masked) in a particular position. For example, given the string *lake*, probing whether *k* or *t* had appeared in the third position would not produce a word bias, because either letter completes a word. The publication of these experiments stimulated a generation of research on the "word superiority effect," eventually leading to a modified conclusion: Letters within nonword pronounceable strings (pseudowords) are also perceived better than random strings of letters. Letters in real words are perceived a little better than letters in these pseudowords, but the largest difference seems to concern the internal structure of the letter string, its word-like orthography and phonology.

McClelland and Rumelhart (1981) explained both the word superiority effect and the pseudoword superiority effect in a new approach, a model that connected three hierarchical levels – words, letters, and letter segments – with bi-directional activation between adjacent levels of the hierarchy. Activation spreading from letters up to words accumulates recognition evidence for specific words; and activation from a word down to the letter level accumulates evidence for the letters in that word. Thus, letters are perceived better in pseudowords than letter strings because they receive feedback from words that contain these letters (e.g., the *k* in *loke* receives feedback from *lake* and *like*). Similarly, bi-directional activation causes *k* to be better perceived in *lake* than *loke,* producing word superiority effect.

This approach became a model for how to conceptualize "interaction" in a precise way. The explicit representation of letters and words in a lexical memory system later gave way to Parallel Distributed Processing (PDP) models that learned connections rather than having them built in (Plaut et al., 1996; Seidenberg & McClelland, 1989; Seidenberg et al., this volume). However, the principles of the original interactive model with "localized" lexical representations were retained in other models of alphabetic reading (e.g., Grainger & Jacobs, 1996). Many computational models have been developed since these earlier models, which were restricted by small lexicons and limited generality across word reading tasks (Norris, 2013). These problems, and the focus on alphabetic writing, continue to challenge the generality of reading models.

The lexicon and how to get there from an orthographic string. The distinction between computing and retrieving word pronunciations has had an enduring influence on models of reading. Early expressions of dual route ideas (Baron & Strawson, 1976; Forster & Chambers, 1973) became formalized by Coltheart et al. (2001) in the Dual Route Cascaded (DRC) model: A reader can arrive at a word's pronunciation in two ways: 1) Decoding its letters to phonemes and producing the aggregated results – the computed route (also called sublexical, assembled, indirect). 2) Retrieving the pronunciation stored with its orthographic word-form – the retrieved route (also called lexical, addressed, direct).

For a skilled reader, the difference between the two routes escapes notice because reading experience has established familiar lexical representations for many words. Thus, with appropriate experience, a reader may pronounce *choir* as easily as *chore*, unaware that the first resulted from the retrieval of a stored pronunciation associated with its spelling, while the second might have resulted from either route depending on familiarity with the word.

Both the DRC and PDP models can simulate word reading performance. For PDP models, the structure of mental representations emerges from many cycles of pattern association and error-reduction learning. The DRC model, in the tradition of classic models with fixed assumptions, predicts experimental data based on a fixed architecture. Coltheart et al. (2001) showed that dual route models provide many specific, correct predictions of experimental results. The fundamental difference between the two models is between a model that learns – without necessarily showing either the time course or the pattern of learning outcomes of an actual learner – and a model that has already learned and is now ready to read any word or letter string one can throw at it. Narrowing the gap between these models are approaches that add a learning component to the DRC model (Pritchard et al., 2016) and combine elements of connectionist and DRC modeling (Perry et al., 2007; see Seidenberg et al., this volume for discussion).

Phonology in skilled word identification. Concerning readers' self-reports, Huey wrote, "Of nearly thirty adults who were thus tested, the large majority found inner speech in some form to be a part of their ordinary reading. Purely visual reading was not established by any of the readers,.. . ." (1908, p. 119). This conclusion about phonology during silent reading continues to seem correct (see Brysbaert, this volume).

The issue in word identification is more specific: whether the phonology of a word is "prelexical" – the phonemes activated by letters and letter strings lead to word identification – or "postlexical" – word phonology follows after access to the orthographic form of the word. Opinion generally favored a direct-to-meaning identification procedure with no prelexical phonology in skilled reading, rationalized partly by questionable assumptions about the consequences of English spellings: Because English spelling-to-pronunciation mappings have inconsistencies, readers learn to read English without using these unreliable mappings.

However, various experimental approaches provided evidence to the contrary. One was to expose a word briefly (35–45 ms) followed by a backward mask consisting of letter strings. When the letter mask reinstated the word's phonemes, identification of the word improved, even when the letters were changed (*choir* – #### – *kwire*) (Perfetti et al., 1988). This effect implies that, prior to the word's identification, some of its phonology had been activated. Lukatela and Turvey (1994a, b), using a similar logic with primed lexical decision, found that homophone primes (e.g., *towed* – *toad*) produced strong facilitation relative to spelling controls. These conclusions were supported by a meta-analysis by Rastle and Brysbaert (2006).

The most well-known evidence came from the semantic category judgment experiments of van Orden (1987). Presented with the category "flowers," readers sometimes made category mistakes on the word *rows*, suggesting that the word's phonology was activated automatically, creating confusion with *rose*. Jared and Seidenberg (1991) found this effect was limited to low frequency words when only shallow meaning (animate/inanimate) decisions were required. For a familiar word, some general meaning features may be accessible prior to full phonology. More generally, both phonological and semantic activations are triggered by a familiar word form in an interdependent way. The rapid activation of a word's phonology can stabilize the word's identity including its meaning features (van Orden et al., 1990).

Table 1.1 summarizes the properties and functions of the phonology that, on our account, are part of word identification. In alphabetic reading, this involves automatic, recurring interactions between letter strings and phoneme strings, including the whole word level. These orthographic-phonological interactions occur in the most rapid swirls of the fast current of skilled reading, resulting in a stable word identity that remains accessible during the reading of the sentence that contains it.

Beyond the mere activation of lexical phonology is its content. The speed of silent reading could suggest that, rather than a fully specified pronunciation, a phonological skeleton of (more reliable) consonants is quickly activated, followed by (less reliable) vowels (Berent & Perfetti, 1995). Other research implicates a fuller, multilevel phonology including stress patterns (Ashby & Clifton, 2005). Some uncertainty remains concerning the phonological content and the time course of segmental (consonants and vowels) and supra-segmental (lexical stress) phonology. However, a rapidly activated phonological component of word identification has been confirmed in research on

Table 1.1 Properties and functions of phonology during word identification

Properties		*Functions*	
Automatic or Routine	Not easily suppressed		
Universal or Highly General	Observed in all writing systems	Helps stabilize word identity	Stable identity supports memory and comprehension
Sublexical as well as Lexical	Sublexical processes depend on writing system		
Rich Content	From low level (articulatory features) to supra-segmental (syllabic stress)		

sentences as well as isolated words across multiple methods, including eye-tracking, ERP, and MEG studies (Halderman et al., 2012).

What have we learned about word reading from neuroimaging? We conclude our review of word reading with a few highlights of what neuroimaging research has added to understanding in this area (see Yeatman, this volume, for comprehensive review).

Two landmark papers in 1988 reported positron emission tomographic (PET) studies in *Science* (Posner et al., 1988) and *Nature* (Petersen et al., 1988). From a vantage point years later, the results seem modest. Petersen et al. (1988) concluded the results "favor the idea of separate brain areas. . .(for) separate visual and auditory coding of words, each with independent access to supramodal articulatory and semantic systems" (p. 585). More interesting for models of word identification was their conclusion that the results argued against "obligatory visual-to-auditory recoding." If we understand "auditory" as phonological, this conclusion was at odds with the behavioral data just starting to emerge around that time.

Later research with fMRI confirmed the role of visual left posterior areas while modifying the earlier conclusion about phonology. The identification of brain networks that connect visual areas to phonological and meaning areas has been a major achievement of cognitive neuroscience. Studies found that increases in reading skill are associated with increased activation in left-hemisphere areas in both temporal and frontal brain areas (Turkeltaub et al., 2003) and identified the left posterior (occipital-temporal) region as the site of orthographic processing or the visual word form area (Cohen et al., 2000; McCandliss et al., 2003). Additional areas in the temporal, parietal, and frontal lobes support meaning, memory, and attentional functions. It is the interconnections among specific areas that comprise the multiple subcircuits that make up the larger reading network, as synthesized by Dehaene (2009).

An important question is how this reading network develops. A general answer is that the basic areas – the posterior visual areas and the left hemisphere language areas – get connected through experience in reading. Additionally, built-in potentials may support this development. Saygin et al. (2016) found that the connectivity pattern within left hemisphere visual areas observed in individual children at age 8 could be predicted by connectivity "fingerprints" that were observed, but not functional at age 5, prior to reading instruction.

A more specific question is the development of the visual word form area, which becomes tuned through experience to respond to word forms (McCandliss et al., 2003). On the neuronal recycling hypothesis (Dehaene, 2009), this adaptation reflects a general principle, that neural circuits originally functioning for one purpose (recognizing objects) are redeployed for another (recognizing words). As to its location in the left hemisphere, a functional perspective suggests an additional consideration – that this allows word form perception to be near to left hemisphere language areas. This possibility was explored by Fiez and colleagues (Moore et al., 2014), who trained adults to associate phonemes with faces, a “face font” that was then used in text reading. Following training, reading the face font produced significant activation in a left hemisphere region close to the visual word form area. This suggests that the left-hemisphere location of orthographic processing may serve the interconnections between the visual system and left-lateralized language areas.

Does identifying the brain’s reading network add something to models of word identification and the behavioral data supporting them? Other than required connections between visual and language areas, there is little to constrain the neural implementation of reading processes. Additionally, results from imaging do not automatically align with behavioral results. For example, finding a brain area in an fMRI study that responds more to words than pseudowords reflects the cumulative effects of processing that extends over time intervals that greatly exceed the time course of the processes involved in word identification (though note that MEG can expose these short intervals). However, brain-behavior model comparisons and theoretical syntheses are helpful, as Taylor et al. (2013) demonstrated. They concluded that both the DRC (Coltheart et al., 2001) and the Triangle PDP model (Plaut et al., 1996) could predict activation patterns during word and pseudoword reading. In fact, all components of the finer-grain DRC model could be observed in brain data.

Disruptions in the word-identification system. Disruptions to the development and operation of visual word identification arise from inadequate orthographic-phonological knowledge sources and/or the processes that use these knowledge sources, as shown in Figure 1.2. Because visual input initiates word identification, hypotheses about its

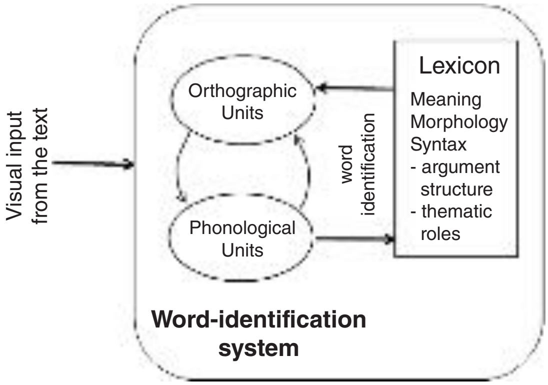

Figure 1.2 The word-identification system of the Reading Systems Framework. “Phonological units” rather than “language units” are highlighted to reflect their specific importance in dyslexia.

disruption (in visual processes) emerged in the earliest observations of acquired dyslexia (Pringle-Morgan, 1896; see Woollams et al., this volume), then developmental dyslexia (Orton, 1925; see Wagner et al., this volume) and in later work inspired by visual neuroscience (Lovegrove et al. 1986; Facoetti et al, 2019). However, it is now well established that the primary causes of disruption lie in the orthographic-phonological phases of identification.

The link between skilled and disrupted word identification processes is made explicit in dual-route models, which postulate selective disruption to either the direct (lexical) route or the indirect (sublexical) route to word identity. Castles and Coltheart (1993) established the existence of each type of disruption by testing children's performance on both irregular, exception words (requiring the lexical route) and pseudowords (requiring the sublexical route). Although a problem with both kinds of words was most common, disassociations between exception word and pseudoword performance appeared for some children. Most showed a phonological dyslexia profile (more difficulty with pseudowords), while others showed a surface dyslexia pattern (more difficulty with exception words). In the Reading Systems Framework, the surface dyslexic is impaired in visual-orthographic memory, whereas the phonological dyslexic is impaired in the linkage between sublexical orthographic strings and pronunciations.

These two different manifestations of disruption to the word reading system might, however, arise from a single problem in the phonological system. Difficulty reading exception words might be recast not as surface dyslexia but as due to a developmental delay (Manis et al., 1996) – that is, reading experience that is insufficient to acquire high-quality word representations of exceptionally spelled words. A connectionist model by Seidenberg and McClelland (1989) showed the plausibility of a key assumption: A serious problem in phonological representations can lead to a "deficit" in reading exception words. Other studies – a review by Rack et al. (1992), a critique of visual deficit hypotheses (Vellutino, 1981), demonstrations of phonological processing and memory deficits (Brady & Shankweiler, 1991; Snowling et al., 1986) and a review of acquired dyslexia cases (Ramus, 2003) – added to the persuasiveness of the phonological deficit hypothesis. Imaging results converged to show associations between reading problems and failures to engage left hemisphere language areas (Shaywitz et al., 2004; Simos et al., 2007; Turkeltaub et al., 2003). Although the cause of phonological problems is uncertain, there is evidence that they originate prior to literacy: Among children at risk for dyslexia, preliterate language skills predict their phonological skills and subsequent reading skills (Hulme et al., 2015; Snowling et al., 2003). Moreover, interventions can improve children's oral language skills and their prospects for reading (Hulme et al., 2020).

Other work has suggested that phonological problems may reflect lower level deficits in, for example, temporal coding in the auditory system (Tallal, 1980) or the perception of speech (Noordenbos & Serniclaes, 2015; although others have questioned these ideas (e.g., Strong et al., 2011; Snowling et al., 2019). Further, it has been proposed that automatized naming problems (e.g., & Wolf, 2011), when added to a phonological deficit, produce a "double deficit" (Wolf & Bowers, 1999) and Ziegler et al. (2019) concluded that most children show phonological deficits while also showing weaknesses in nonphonological tasks, especially letter detection. Although there are potentially multiple causes of disruption to the word-identification system, the phonological deficit hypothesis is supported by extensive evidence and is now the standard theory. Indeed, a phonological deficit is part of the definition of dyslexia provided by the International Dyslexia Association (https://dyslexiaida.org/definition-of-dyslexia/).

Advance 2. Comprehending while Reading

It should be contentious to consider a subsystem of reading called "reading comprehension." If learning to read words unlocks the resources of spoken language comprehension, then anything special about reading ends at word identification. "The Simple View of Reading" (Gough & Tunmer, 1986; Hoover & Gough, 1990) expresses this assumption and continues to accumulate evidence (Catts, 2018; Hjetland et al., 2020; Lonigan et al., 2018; Nation, 2019). Moreover, reading comprehension builds on spoken language experience. Preschool measures of oral language predict school-entry indicators of word level skills that predict later comprehension skills (Hulme et al., 2015).

Nevertheless, comprehension is a distinctive subsystem of reading, even if it derives from general language comprehension. Moreover, excluding reading comprehension as part of reading would ignore the largest body of research on skilled comprehension. Much of what is known about *language* comprehension – including such basic aspects as sentence comprehension – comes from reading research (see Liversedge et al., this volume).

Whereas word identification operates with a restricted set of knowledge sources (graph forms (e.g., letters), phonology, and morphology), comprehension operates with every knowledge source one can imagine. To simplify the resulting complexity, we refer to the RSF comprehension subsystem, extracted here as Figure 1.3.

The lexicon plays a pivotal role. The output of the word-identification system, the word's pronunciation and meaning features, is the input to the comprehension system.

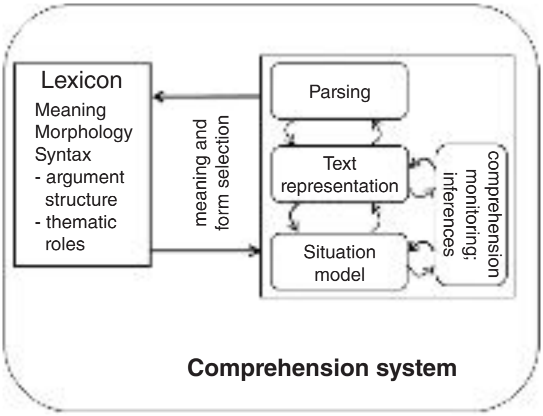

Figure 1.3 The comprehension system of the Reading Systems Framework.

A word's meaning is directly integrated into ongoing comprehension and its pronunciation helps secure the word's identity, thus supporting processes of structure building, integration, and, when needed, repair.

From global top-down structures to actual comprehension

Text comprehension results from word-by-word, phrase-by-phrase, and sentence-by-sentence processes that are challenging to study. So, research started at the other end – where global structures could be seen as shaping local word and sentence processes. Early artificial intelligence (AI) systems started with global organizers for restricted situational comprehension (Schank & Abelson, 1977). Similarly, approaches within psychology and education also emphasized situated conceptual structures or schemata (Anderson & Pearson, 1984). Evidence for global top-down guidance came from studies showing that a nearly incomprehensible text could be understood with a helpful title (Bransford & Johnson, 1972) and that a text lacking referential specificity could be understood as being about either music or card playing depending on whether the reader was a student in music education or physical education (Anderson et al., 1977).

Other approaches focused on more generalized mental structures (e.g., story grammars, Mandler & Johnson, 1977; Stein & Glenn, 1979) that guide narrative comprehension. Trabasso and colleagues (1984) argued that people seek causality in reading stories and showed that causal expectations predict how readers understand sentences (Trabasso & Suh, 1993). In Reading Systems Framework terms, these approaches focus on the general knowledge component and largely ignore comprehension processes. They provide demonstrations of global influence without dealing with the nuts and bolts of comprehension.

Text comprehension from the bottom up

Kintsch and van Dijk (1978) approached text comprehension as a cyclical process, with every text element activating meanings on the way to a coherent representation of the text as a whole. The Construction Integration model (Kintsch, 1988, Kintsch & Rawson, 2005) proposed two phases of comprehension: An initial construction phase, prompted by word meaning, spreads activation across memory of both text elements and general knowledge in a passive, automatic process.[1] A companion integration phase uses the overlap of meaning among the activated elements to constrain what information remains for the next cycle. Multiple integration phases lead to a coherent representation of the text.

The Construction Integration model moved text comprehension research toward a processing approach, incorporating memory-based, word-meaning, and sentence level components. The structure building framework (Gernsbacher, 1990, 1997) emphasized

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[1] As applied in the Construction Integration model, "construction" contrasts sharply with its use in other comprehension accounts, where it entails an active role for the reader in constructing understanding (e.g., Graesser et al., 1994).

the complementary processes of memory-based meaning mapping and structure building. Later models retained this focus on bottom-up, memory-based processes, including the Resonance Model (Myers & O'Brien, 1998) and the more recent Resonance, Integration, and Validation Model (Cook & O'Brien, 2014).

Global influences continued to be emphasized in constructivist theories that assume readers are driven to construct coherence and search for meaning (Graesser et al., 1994). Top-down influences were elaborated more specifically as mental structures to guide the reader's construction of coherence, for example, dimensions of time, space, and causality in the Event-Indexing Model (Zwaan et al., 1995). The Landscape model combined the automatic bottom-up processes of memory-based models with the top-down influences of constructionist theories (van den Broek et al., 2005; van den Broek et al., 1999). In this model, a coherent mental representation emerges from both text and external knowledge activation patterns that increase and diminish over the course of reading a text. Comprehension results from the mixing of automatic passive processes with reader-initiated strategic processes determined by the reader's standard for coherence and goals in a particular reading situation (van den Broek et al., 1995; van den Broek & Helder, 2017; see van den Broek & Kendeou, this volume).

The situation model: Knowledge and inferences

Text comprehension results in memories at multiple levels, two at minimum: the text surface and the mental-model (Johnson-Laird, 1983). Research generally has followed the three-way distinction of van Dijk and Kintsch (1983): surface level, text-base, and situation model. This three-way distinction adds a level of language-based text meanings (propositions) intermediate between clauses/sentences and situated meanings.

Critical in the situation model are inferences that require knowledge from both the text and the reader's general knowledge. Bridging inferences are often required to make a text coherent (see O'Brien et al., 2015). For example, in reading "The bright sun lit the field. Alfred's snowman melted," one maintains coherence by inferring that the sun's heat caused the snow to melt (Singer et al. 1992). When related knowledge triggers elaborative inferences, which are not required for coherence, comprehension becomes referentially richer and more interpretative, although unwarranted inferences can lead to inaccuracies. Successful comprehension attains a situation model that is enriched by inferences and referentially specific, but also well aligned with the text meaning.

Sentences. In most text comprehension research, processing at the word- and sentence-levels is assumed more than studied or specified. In fact, an important component of the Reading Systems Framework is missing from most models of text comprehension: the parsing processes that configure words into phrases into syntactic structures with associated meanings (see Liversedge et al., this volume). Research on sentence comprehension has sought to identify the multiple influences on these structure building and repair processes: implicit knowledge of grammatical structures, computational pressures on simplicity (Frazier & Rayner, 1982), statistical patterns of language use, and various lexical and contextual influences (Gibson & Pearlmutter, 1998). A major enduring issue is the relative influence of linguistic knowledge and knowledge of the world, two factors that are difficult (but possible) to separate (Warren & Dickey, 2021).

There is an intimate connection between building syntactic structure and building a situation model. To build a situation model from "The spy saw the cop with binoculars," the reader must decide whether to attach "with binoculars" to "saw" or to "the cop" There is no information within the sentence to favor one structure over the other. In the absence of other information, the choice is influenced by a simplicity strategy (e.g., assume "the" begins a minimal noun phrase, which favors attaching "with binoculars" to "saw"). However, when the preceding text has established that there were two cops, one of whom has binoculars, then this preference is readily reversed (Britt et al., 1992). Readers generally wind up with the structure needed for the intended meaning, but this often follows an initial incorrect parse whose repair is revealed in reading measures (Frazier & Rayner, 1982).

These structure-building processes are in the fast current of reading supported by multiple knowledge sources and co-occurring with semantic integration processes. The result is the continuous updating of the reader's situation model.

Incremental comprehension: Integration and prediction. To the extent possible, readers integrate the meaning of each word into their ongoing representation of the text. These incremental processes use information momentarily accessible from different knowledge sources (linguistic knowledge, prior text knowledge, general knowledge). The integration of word meaning with text meaning – word-to-text integration – is the connection point of the word-identification and comprehension systems, supported by knowledge systems with the lexicon playing a special role (Perfetti & Stafura, 2014). The fast currents of reading benefit from the force of these inputs, which ordinarily combine for smooth comprehension.

Methods with high temporal resolution are needed to observe these rapid integration processes. Event-Related Potentials (ERPs) can reflect the temporal unfolding of multiple processes during the reading of a single word in a text. Reading a word produces ERP indicators of visual attention (P1), orthographical processing (N170), text-related word meaning processes (N400), and memory-related text processes (P600 or Late Positivity component (LPC)) (Luck & Kappenman, 2011). Meaning-retrieval and early integration processes are observed in the 300–500 ms time window spanning the N400 and additional integration and updating processes are observed in the 500–700 ms window of the P600. The N400 has been considered an indicator of semantic fit between a word and its context since the benchmark study of Kutas and Hillyard (1980). They found that in sentence contrasts such as "He spread the warm bread with butter/socks," a more negative N400 occurred on the contextually inappropriate "socks." Countless studies since confirmed the N400 as an indicator of word meaning processing in relation to context (Kutas & Federmeier, 2011). A specific interpretation is that it is an early indicator of meaning-based word-to-text integration (e.g., Nieuwland & Van Berkum, 2006; Stafura & Perfetti, 2014). An alternative proposal is that the N400 indicates only word meaning retrieval, while the word's integration with text meaning occurs later, indexed by the P600 or Late Positivity component (Brouwer et al., 2012; Delogu et al., 2019).

Most ERP results in text comprehension include within-sentence effects, with measures on words at the end of sentences, sometimes the middle. Examining words at the beginning of a sentence provides a clearer focus on text effects beyond within-sentence effects. At the beginning of a sentence, the reader must open a new structure (e.g., a sentence, a noun phrase) where the only integration possible is with prior text. The general conclusion from sentence-beginning studies is that integration occurs only when the word being read prompts retrieval of a text memory (Perfetti & Helder, 2020). When they occur, these integration effects result from co-referential binding with meanings from the preceding sentence (Stafura & Perfetti, 2014), with an additional boost possible from global text meaning (Helder et al., 2020). Finally, although prediction effects are often found on words within sentences, Calloway and Perfetti (2017) found no role for word prediction at sentence beginnings when the (rated) integrability of a word into the text was controlled.

Prediction has become a central idea in explanations of comprehension. At first pass, prediction and integration seem to be opposite mechanisms: prediction, an anticipatory forward process and integration, a memory-based process. However, in theoretical treatments, *prediction* has lost its meaning connection to everyday usage and given a much broader scope than predicting specific words. Kuperberg and Jaeger (2016) argued that predictive processes operate continuously while reading, influenced by multiple levels of linguistic units that pre-activate meaning features at these different levels, rather than specific words. If we understand prediction in this broad sense, we can capture the complementary contributions of prediction and integration: The basic process is memory-based integration occurring in overlapping phases. Reading a word can retrieve a text memory, initiating the integration processes that support coherence. This memory process is facilitated by the accessibility of meaning features that have been pre-activated ("predicted") by prior text meanings (Perfetti & Helder, 2020). This account removes prediction as a special process and appears consistent with a large-scale replication study that suggests incremental processing can be interpreted as a "cascade of processes" comprising activation and integration of word meanings in their context (Nieuwland et al., 2020) and with other attempts to reframe "prediction" (Ferreira & Chantavarin, 2019; for reviews see Hauk, 2016; Nieuwland, 2019).

What neuroimaging studies add to comprehension research. Our conclusion on the contribution of neuroimaging results is brief: Their contribution so far to comprehension theory is limited, especially in the context of comprehension of texts longer than one or two sentences. Early neuroimaging studies identified brain regions associated with reading narrative texts (e.g., Xu et al., 2005; Yarkoni et al., 2008) and correlated brain activation with behavioral measures of comprehension – for example, detection of coherence breaks (e.g., Ferstl et al., 2005; Hasson et al., 2007) and inference generation (Kuperberg et al., 2006; Virtue et al., 2006). A general conclusion is that text comprehension, beyond sentence comprehension, involves an extension of the language network (Ferstl et al., 2008). This network includes the left lateralized language areas in the frontal and temporal lobes identified in sentence comprehension, plus extension to the anterior temporal pole, prefrontal area, and the right hemisphere. These additional areas are broadly associated with semantic processing, executive functioning and inferencing, and coherence building and non-literal meaning, respectively (Ferstl et al., 2008).

More recently, research has sought to connect imaging results with other important issues in comprehension research – reading narrative versus expository texts (Aboud et al., 2019), local versus global comprehension (Egidi & Caramazza, 2013), and responses to differences in text coherence (Helder et al., 2017). Beyond identifying brain regions are proposals for how other brain networks interact with language areas during comprehension (Hagoort, 2019).

One reason for the limited contribution of imaging studies to cognitive explanations of comprehension is the low temporal resolution of the fMRI BOLD signal. In our streams metaphor, this signal shows the slower currents (and down-stream results of the fast currents). Because it reflects the flow of oxygenated blood to brain areas, the BOLD signal develops slowly, over seconds, whereas incremental comprehension processes occur over milliseconds. Further, fMRI images provide only the strength of the correlation between the expected and observed ratios of oxygenated blood during a reading task. These factors limit the interpretations of the underlying processes of comprehension. Although this is also true for imaging studies of word identification, the results there show enough convergence to be connected to theory and behavioral results. A promising approach for comprehension is to connect the brain areas identified in fMRI to the interpretation of ERP components that reflect meaning and integration processes (Brouwer & Hoeks, 2013)

Disruptions in the reading comprehension system. Text comprehension sometimes fails. Disruptions in comprehension can arise from processes within the comprehension system (see Figure 1.3) and the linguistic and conceptual knowledge systems (Figure 1.1) they depend on. Pressure points within the comprehension system emerge with specific demands. For example, syntactic complexity and ambiguity threaten sentence comprehension; a failure to make a required inference threatens sentence comprehension and text coherence; and a text requiring conceptual knowledge not accessible to the reader threatens global text comprehension. However, the disruptions are not so conveniently localized as these observations imply. Disruptions to word-identification processes do not end there, but can spread to result in disruptions to sentence and global text comprehension. The lexicon is a particularly important pressure point in the system, sending its output – multiple levels of information about the word being read (context-relevant meaning and form class, potential for argument role filling and for referential specification, and more) – to the comprehension system. A disruption at this point has consequences "downstream." This much is a description of what can go wrong for any reader for a specific text. A skilled reader can repair comprehension failures.

The research field, however, has been concerned with individual differences in comprehension failures – "poor comprehenders" (e.g., Cain & Oakhill, 2007; Hulme & Snowling, 2011; Oakhill & Yuill, 1996). Rather than address them here, we instead emphasize that, aside from language impairments – which can affect multiple linguistic knowledge sources and processes – the ordinary range of reading skill does not include individuals who have dysfunctional processing subsystems of comprehension. Rather than faulty processes such as inference making or a lack of comprehension monitoring, activating relevant knowledge may be the main issue. Knowledge of word forms (orthography), word meanings (vocabulary knowledge), knowledge of language machinery (syntax, morphology), and conceptual knowledge combine to support successful comprehension.

Readers for whom the word-identification system works efficiently, but nevertheless consistently fail in comprehension may lack sufficient critical knowledge or fail to have the knowledge activated strongly or quickly enough to engage in inference making and comprehension monitoring when reading the text (Nation, 2005). One of the points of progress in the study of individual differences has been an increased recognition of the need to assess reading components (fluent word identification, vocabulary, relevant knowledge) in order to identify some other targeted components of the reading comprehension system (see Cain, this volume).

Advance 3. Toward a More Universal Science of Reading

The advances discussed so far come largely from research on reading in alphabetic writing systems, mainly English. Indeed, the two routes of the DRC model were intended to capture an orthographic property of English – its inconsistent mappings between letters and phonemes.[2] Reading science needed to address reading more broadly and a step in that direction came from the comparative analysis of orthographies by Katz and Frost (1992). "Orthographic depth" orders orthographies according to the tradeoff they make between coding speech components and meaning. Thus, among alphabetic writing systems, Welsh and Finnish are shallow (consistent mappings to phonemes), Czech and Italian only slightly less so, with English at the deep end. Moving beyond alphabetic writing toward a more universal perspective, orthographic depth was extended to nonalphabetic writing, for example, the consonant-based Abjad system and morpho-syllabic Chinese.

The single scale of orthographic depth, however, fails to reflect the design principles that separate other systems from alphabets. Explicit attention to these principles was the basis of the Universal Phonological Principle (Perfetti et al., 1992; Perfetti, 2003) that reading words universally involved phonology at the lowest level allowed by the writing system and the psycholinguistic grain size hypothesis (Ziegler & Goswami, 2005), which focused on where the writing system makes its connection within the phonological hierarchy. Where this connection is made – phoneme, syllable, word – has consequences for reading development. Despite increasing recognition of writing system differences, Share (2008) correctly argued that the dominant role of English in reading research had resulted in research questions and models of reading that might not apply to other systems.

More recent progress from research across languages and writing systems was the focus of two volumes on learning to read (Verhoeven & Perfetti, 2017a) and dyslexia (Verhoeven et al., 2019) The conclusions include universals across 17 languages in learning to read, along with specific features of languages, writing systems, and instruction (see chapters by Caravolas, McBride et al., and Nag, this volume).

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[2] English spellings are less irregular when additional factors are considered: the relative frequencies of different letter-phoneme mappings, the within-word positional constraints imposed by phonotactics and spelling conventions (Kessler, 2003), and the islands of regularity afforded by morphology (Rastle, this volume).

Table 1.2 Examples of adaptations of writing systems to language features

Language	*Adaptations of the writing system to features of the language*
Chinese	Small number of syllables with tones. Extensive syllable homophony makes alphabets and syllabaries less adaptive. Characters map onto syllable morphemes and can distinguish between homophones.
Japanese	Agglutinative language. Many multisyllabic words and small number of syllables with open structure. Japanese syllabaries (Kana) are adaptive to these factors, but historical borrowing of Chinese supports dominant Kanji character system.
Finnish	Relatively small number of phonemes and long words of several syllables. Complex inflectional morphology. Highly consistent alphabetic orthography supports decoding of multisyllabic, multimorpheme words
English	Phonological complexity and many syllables make an alphabet efficient. Simple inflectional morphology favors morphophonemes and morpheme spellings. A mismatched letter-to-phoneme ratio keeps phonological consistency low.

Cross-language comparisons suggest that writing systems show accommodation to the properties of the language they represent (Frost, 2012; Perfetti & Harris, 2013; Seidenberg, 2011). Illustrating this possibility, Table 1.2 summarizes four of the orthographies reviewed in Verhoeven and Perfetti (2017a). Two examples of alphabetic writing suggest accommodation to phoneme inventories, syllable structures, and morphology. The Chinese writing system suggests adaptation to its relatively few syllables, which create many meaning mappings for any given syllable. For example, it would be inefficient to simply represent the phonological properties of spoken Mandarin because it contains homophones with different meanings. Hence, the Chinese orthography uses semantic radicals to represent the meanings of words directly. Thus, whereas using an alphabetic writing system (there is such a system, Pinyin) would result in a huge number of homophones, the character system usually identifies a particular morpheme. In contrast, English seems a poor match to a syllabary because its phonological complexity would create large numbers of syllables, and thus less efficiency than an alphabet.

The variations across language and writing systems have important implications for reading science. Perfetti and Verhoeven (2017, Table 19.1) present an extended summary of reading development across languages. Some conclusions are specific to writing systems and languages (e.g., phoneme awareness is more important for learners of alphabetic than nonalphabetic writing); some are applicable broadly within a writing system (e.g., phoneme awareness in alphabetic orthographies is not dependent on mapping consistency); some apply across all writing systems (e.g., children's linguistic awareness emerges first at the syllable level).

One consequence of variation in mapping principles is variation in visual complexity. The number of graphs (the basic visual symbols of writing) depends on the number of linguistic units at the level where mapping occurs. In turn, the number of graphs determines their visual complexity: More graphs, more average complexity because the graphic features sufficient to distinguish among few graphs cannot distinguish among many graphs. The result is that abjads and alphabets, which typically have fewer than 40 graphs (letters), have less visual complexity than syllabaries and alpha-syllabaries, which typically have more than 400 graphs. All systems are visually simpler than the Chinese basic morpho-syllabary of more than 3 000 graphs (characters). In a study of graphs from different writing systems, Chang et al. (2017) reported that simple perceptual judgments of graphs vary with their complexity. Thus, visual complexity cannot be ignored in considering the challenges of learning to read. The long learning course required for Chinese and the many South Asian alpha-syllabaries (Nag, 2017) is partly a reflection of the number of graphs and the resulting visual complexity of these orthographies.

Comparative research has also stimulated the extension of models of alphabetic reading to nonalphabetic reading. Li and Pollatsek (2020) presented an integrated model of word reading and eye movement control for Chinese, applying the Interactive Activation model (McClelland & Rumelhart, 1981) for word identification while also implementing word segmentation. Segmentation is needed because spaces separate characters but not words. PDP models have also been extended to reading Chinese (Yang et al., 2009; Zevin, 2019) and to morphological effects in Hebrew (Plaut & Gonnerman, 2000).

The brain's reading network (revisited)

A universal brain reading network is strongly predicted by the fundamental principle of reading: that it converts systematic visual input (structured by writing systems) into language-mediated meaning. Early comparisons confirmed this prediction across alphabetic languages, while also showing variation of the reading network in relation to consistency of letter-phoneme mappings. English reading showed more use of a ventral pathway that includes the inferior temporal gyrus (IFG) compared with the more consistent Italian (Paulesu et al., 2000) and Spanish (Jamal et al., 2012). However, testing universality requires comparisons beyond alphabetic systems, and Chinese provides a high-contrast comparison with alphabetic reading.

Early neuroimaging studies of reading Chinese produced evidence for both a universal network and writing-system specific variations (Bolger et al., 2005; Tan et al., 2005), as does a more recent review (Xu et al., 2019). Universal areas include the left fusiform gyrus, highlighting its function in coding orthography regardless of the visual forms and mapping levels. However, Chinese shows more bilateral activation in posterior areas that support visual-orthographic processing and a less prominent role in some (but not all) studies for the inferior frontal gyrus. Another difference is the more prominent role of the left middle frontal gyrus (LMFG) in Chinese. The LMFG's location near a motor area involved in handwriting (Exner's area) suggests that its prominence in Chinese reading reflects an effect of character writing on character reading, consistent with the importance of writing practice in Chinese literacy instruction. Evidence for this comes from greater overlap of passive recognition and imagined writing in the LMFG for Chinese than for English (Cao & Perfetti, 2017). The greater writing practice in learning to read Chinese may help secure long-term orthographic memories for characters, consistent with conclusions from behavioral research (McBride-Chang, Chung et al., 2011). Although writing seems especially important in Chinese reading, a study by Nakamura et al. (2012) comparing French and Chinese on recognizing handwriting suggested the writing-reading role of the LMFG is shared across writing systems.

The significance and robustness of these Chinese-alphabetic differences across different word reading paradigms remains an issue. In comparing meaning judgments made to speech and print, Rueckl et al. (2015) found the shared areas of print-speech convergence across English, Spanish, Hebrew, and Chinese. These results affirm the universal connection of reading with spoken language. However, the brain networks for reading also reflect experience-based accommodations to the orthography-language connections required by the writing system (Cao et al., 2015).

Disruptions in the word-identification system (revisited)

We should expect universal neural patterns associated with disruption in the word-identification system for two related reasons: 1) the apparent existence of brain reading networks that include universal components; and 2) the language constraint that all writing systems map graphs to language. However, manifestations of word-reading problems, including dyslexia, may vary with how the writing system makes demands on phonology. Such variation may depend on the level of phonological mapping – the grain size, phoneme or syllable (Wydell, 2019) – and the extent to which meaning encoded in morphology-preserving orthography can compensate for a phonological deficit.

Chinese provides both of these. It maps syllables rather than phonemes and it has meaning cues in its morphological orthography that may further reduce the demands of phonology. The abjads of Hebrew and Arabic and the alpha-syllabaries make additional demands on orthographic-morphological processing, seemingly without substantially reducing the demands of phonology. Indeed, Chinese seems to require a multiple-cause model that includes nonphonological sources. Phonological problems are found (Ho et al., 2000), but so too are associations of reading problems with rapid naming and orthographic knowledge (Ho et al., 2002) and morphology (Shu et al., 2006). Underactivation in the left middle frontal gyrus in Chinese readers with dyslexia appears more common than in alphabetic readers with dyslexia (Siok et al., 2004). If the LMFG supports neural-motor preparation for character writing as part of character recognition (Cao & Perfetti, 2017), this may suggest an orthographic factor in Chinese dyslexia.

Visual-orthographic processing challenges may be expected in Chinese, given the demands of learning around 3,000 characters in the first six years of school (see McBride-Chang et al., this volume). Visual attention and copying skills have been found to predict reading ability of children in Hong Kong (Liu et al., 2015). In the multicause analysis, Chinese reading has phonological dyslexia, but fewer cases compared with alphabetic reading and even fewer cases with phonology as the only factor. Both visual-orthographic processes and knowledge of Chinese compounding morphology may be important factors (McBride-Chang, Lam et al., 2011). Interestingly, modeling of Chinese dyslexia (Yang et al., 2009; Zevin, 2019) suggested that either a morpho-semantic or phonological disturbance produced wide-ranging character reading problems in Chinese; in contrast, a semantic disturbance in English affected only identification of exception words.

The conclusion across writing systems might be that Chinese requires explanations of reading problems based on multiple factors, more than other systems. Phonological, morphological, and visual-orthographic factors have been identified in behavioral research and inferred from brain imaging. However, these factors are likely to play a role in reading and reading problems across writing systems, including alphabetic. Perhaps, in the word-identification system, languages and writing systems affect only the relative prominence of the various knowledge sources and processes that act on them, providing a picture of core universality and systematic variation.

Concluding Reflections: Learning to Read and Reading Pedagogy

We have focused so far mostly on skilled reading, but we conclude with brief reflections on learning to read. The orthography-to-language mapping system – how graphs map onto units in spoken language, both phonological and morphological – is the foundation of learning to read. Beyond this foundation is the transition to the skilled reader of the Reading Systems Framework.

The experience-based shift in word reading

The progress to skilled reader requires establishing memories of visual word forms – orthographic memories. The ability to access a word memory rapidly is critical to fluent reading. The comprehension system depends on rapid and effortless input from the lexicon, and this, in turn, depends on rapid and effortless access to a word meaning from its form.

The importance of orthographic learning has been recognized in English reading research for some time (e.g., Ehri, 1992; Perfetti, 1992). As developed by Share (1995, 2004) in the self-teaching hypothesis, decoding a word supports the establishment of its orthographic memory (see Castles & Nation, this volume). Ehri (2005, 2014) describes overlapping phases of development that move toward a skilled phase characterized by orthographic mappings at morpheme and syllable levels.

This movement from decoding words to effortlessly identifying them can be expressed as a general operating principle (Verhoeven & Perfetti, 2017b): Word identification shifts from computation to memory-based retrieval for individual words as they become familiar, although sublexical procedures continue to be involved. Word reading speed becomes the distinguishing marker of skill once children reach a threshold level of word reading accuracy. The frequency effect in word reading is evidence that readers retrieve word identities (pronunciation, meaning) more quickly as word forms become more familiar. Developing readers, as they increase their skill at decoding, also increasingly use a rapid retrieval or "look-up" procedure when a word becomes sufficiently familiar. Moreover, the effect of experience is not merely on access to word forms. By encountering words in varying contexts, meaning aspects of lexical quality are refined and reading comes to reflect a rich experience-based lexical legacy (Nation, 2017).

How this development happens is simple: through practice. Experience in reading – *effective* experience in which children read words successfully and achieve comprehension – is the only certain path to establishing rapidly accessible orthographic representations. Beginning reading instruction supports this process only when it establishes the mapping foundations that allow this path to be used.

Teaching reading

The science of reading has established an ample basis for what needs to be learned and how to support this learning with systematic instruction. In teaching English, whether in the United Kingdom, the United States, Ireland, Australia, New Zealand, or other areas where children learn to read English as a first language, there is a continuous tension between competing instructional ideas. Science-based recommendations for teaching the foundations of the orthography-language mappings have been the subject of multiple national panels and reviews (Castles et al., 2018; Rayner et al., 2001). The strong knowledge base and the support of governments for science-based education have led to some improvements in English reading instruction (see Savage, this volume). However, these improvements are uneven. In the United States, recommended improvements have not penetrated teacher training as widely as is needed. Marilyn Adams (1998) pointed out that aspiring and practicing teachers in the late twentieth century were taught a "three-cueing system," syntactic, semantic, and grapho-phonic "cues" the child can use to identify a word. This practice seems to have continued in the United States (in contrast to the United Kingdom) well into the twenty-first century (Hanford, 2019). This strategy, rather than supporting the child's developing word-identification system, encourages guessing. In contrast, teaching in many other alphabetic languages generally provides direct support for decoding in beginning instruction (Verhoeven & Perfetti, 2017a). This direct support may be more important for the learner than the details of their orthography.

A final reflection

In skilled reading, the reading systems – the knowledge sources and the processes that use them – combine to present a smooth-surfaced stream of even-flow. Underneath the smooth surface are the mixed currents of processing that push the flow of reading so that, even in one second, processes of word identification, meaning retrieval, parsing, meaning integration, coherence building, and deeper understanding are present in overlapping, distributed phases. For learners to reach this level of skill, where only the smooth flow of the surface is visible, it is imperative to get foundational instruction right. This must be done in a way that supports the child's engagement in reading, thus enabling what Huey (1908, p. 197) called "willing effort" for further reading. The progress to skilled reading crucially depends on effective experience that can come only through reading itself.

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