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Reading Science: Progress and Prospects

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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 process implied that 9 words were read. This is the rapid current of reading observable by the tools of reading science and the basis of much 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, and observations on learning to read and reading problems.

We begin by replacing our metaphor of dynamic currents with a more static representation of what reading science seeks to understand, drawing on the Reading Systems Framework (RSF, Perfetti & Stafura, 2014). Although a dynamic model may capture the reality of reading, a component-based model allows us to describe this reality more clearly. The RSF, illustrated in Figure 1, organizes cognitive components of reading, representing the distinct knowledge sources (collectively, the knowledge systems) that drive the word identification and comprehension systems. The lexicon—knowledge about word forms and meanings—is central in connecting these two systems. We apply the framework to examine research progress through a sparse, selective use of the research, which receives more detailed treatment in other chapters of this Handbook.

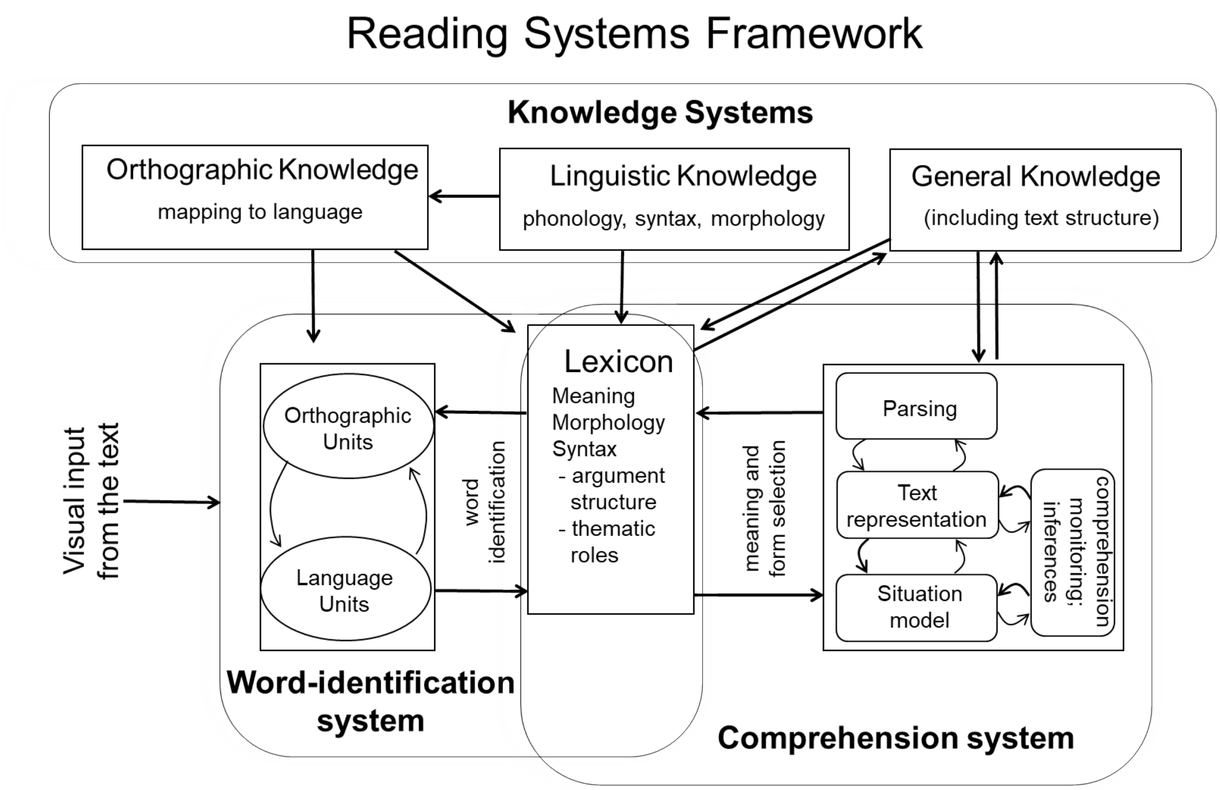

Figure 1. The Reading Systems Framework (modified from Perfetti & Stafura, 2014) consisting of word-identification, comprehension, and knowledge systems, with a central role for the lexicon.

Reading and Reading Science in historical context

Humans have been reading for around 3500 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 results published by E.B. Huey (1908), who acknowledged contemporary research by Erdmann and Dodge, add up to 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 reading, the evolution of writing and the alphabetic principle, meaning and "interpretation", and teaching children to read. That covers a lot, notably omitting only dyslexia, a slight that was repaid by Orton (1925) when he ignored Huey's book and its research in his classic on "word blindness".

The progress since 1908 has occurred despite a 60-year slow-down that preceded a surge of research in the 1970s/80s. Much of this progress is enabled through the development of tools that allow closer looks at the intricate, interleaved processes and knowledge interactions that occur rapidly in reading. Eye tracking, Event Related Potentials (ERPs) and some behavioral measures can detect the rapid stream processes of reading. The slower stream products of reading processes 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 both experimental control and modeling of reading processes.

Reading itself is changing too, at least in its forms, also enabled by technology. We have been in the midst of digital literacy for some time, asking what is different about it and whether the differences matter for the processes and strategies of reading. (They clearly matter for the concept of literacy.) Although we omit these issues because of space limitations, the reading systems we discuss remain part of digital reading.

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 identifying typical written forms (excluding low spatial frequency pictorials) depends on high-resolution vision, which is delivered by the densely packed retinal cells in the fovea. This means that the acuity needed to identify a specific letter within a word is limited to one-two degrees of horizontal visual angle at normal viewing distance. Although less precise visual information is available beyond this area, the result is that only a single word or two (with the help of parafoveal viewing) is viewed in an eye fixation.

Readers adapt to this limitation by making frequent eye fixations, 60% of content words with some studies finding more than 80% (Rayner et al., 2005). They also adjust their fixation rates (and the number of regressions) in response to text difficulty and their reading goals, one of the key regulatory strategies in reading. Word fixations are of a sufficiently short duration that 3-5 words can be fixated on within a second of reading (Rayner et al., 2004; 2005). With assists from context and parafoveal viewing, a reader may approximate the 9 words in Gough's (1972) one second.

Especially important, eye tracking measures show effects of linguistic and cognitive variables. The familiarity of a word, its predictability from context (Rayner et al., 2004), and the structure of the sentence (Clifton & Staub, 2011) influence one or more of these measures. Thus, eye-tracking measures reflect reading processes that identify words in context and the linguistic properties that affect these processes. Further, some measures reflect the more passive, automatized aspects of reading (e.g. fixation durations) and some reflect regulatory processes the reader engages in response to difficulties (e.g. regressions).

Readers' eye movement control must accommodate the perceptual constraints while also producing rapid reading rates. Serial processing models assume that only a single word is in visual attention, e.g. the EZ Reader model (Reichle et al., 1998; 2003). To accommodate rapid reading rates with serial processing, the brain must signal an eye movement before the word has been identified completely, because the actual launch moment 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 that is relatively predictable from context than for a word of lower frequency or predictability. The alternative solution to perceptual constraints is to allow parallel processing on adjacent words (SWIFT model, Engbert et al., 2005). A recent model allows for parallel processing of words and provides specific word identification mechanisms (Snell et al., 2018). The question of parallel vs serial processing of words remains a point of contention.

Orthographic Processing and Models of Word identification

The word-identification system codes the 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)—allowing words to be recognized.

Word Superiority

One of the most intriguing problems in reading science is how the reader's knowledge of orthographic units pays off in skilled reading. The long-standing intuitive 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 (1896; 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.

Because it seems so intuitively reasonable and perhaps because experimental research shifted from the mental to the behavioral, Cattell's explanation (and Huey's) stood unchallenged until the independent publications of experiments by Reicher (1969) and Wheeler (1970). Cattell's conclusion that words are perceived as wholes might be correct, but his experiments could not support this conclusion. They 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.

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 3rd position would not favor a word response because either letter completes a word. The publication of these experiments stimulated a new 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.

Interactive Activation

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—graphic features of letters, letters, and words—with bidirectional activation between adjacent levels of the hierarchy. Activation from letters to words that contain those letters accumulates evidence for some words more than others; and activation from a highly activated word to the letter level accumulates evidence for the letters in that word. The result is that letters are perceived better in pseudowords than letter strings because they benefit from feedback to the letter level from real words that contain these letters (e.g. *loke* with *lake, like, poke*, etc). Similarly, bi-directional activation causes <k> to be better perceived in *lake* than *loke,* producing the real-word superiority effect.

Despite the interactive activation model's restricted application to a small set of 4-letter English words, it 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 having them built in (Plaut et al., 1996; Seidenberg & McClelland, 1989). 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 been 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 contrast between the models is between a model that learns—without necessarily showing either the time course or the pattern of learning outcomes by 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).

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.

The issue in word identification is more specific: whether the phonology of a word is "pre-lexical"—the phonemes activated by letters and letter strings lead to word identification—or "post-lexical"—word phonology follows access to the orthographic form of the word. Opinion generally favored a direct-to-meaning identification procedure (no pre-lexical 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 some 30 years ago. One approach was to expose a word briefly (35-45ms) 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 semantic category mistakes on the word "rows", suggesting that the word's phonology was activated automatically, creating confusion with "rose". Experiments by 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 provides stabilization for the word's identity including its meaning features (van Orden et al., 1990).

Table 1 summarizes the properties and functions of the phonology that, on our account, are integral with word identification and highly general. In alphabetic reading, this involves automatic, recurring interactions between letter strings and phoneme strings, including the whole word level. These ortho-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 processing of the sentence that contains it.

Table 1. Properties and Functions of Phonology During Word Identification

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

Beyond the mere activation of lexical phonology is characterizing its content. The fact that silent reading is so rapid could suggest that, rather than a fully specified pronunciation, a phonological skeleton of consonants is quickly activated, followed by vowels (Berent & Perfetti, 1995). Other research implicates a fuller, multi-level phonology including even 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 in word identification has been confirmed in research on 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 the word-identification system with a few brief highlights of what substantial neuroimaging research has added to the study on word reading.

The 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 conclusion regarding the visual role of left posterior areas while modifying the conclusion about phonology. The identification of brain networks connecting 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 (VWFA) (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 sub-circuits that make up the larger reading network, as synthesized by Dehaene (2009).

An important question is how this reading network develops. The basic areas—the posterior visual areas and the left hemisphere language areas—get connected through experience in reading. Somehow the VWFA tunes basic vision resources to respond more specifically to visual word forms. Certainly, this tuning is stimulated by reading experience (McCandliss et al., 2003). However, there appear to be built-in potentials to 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.

An interesting question is why the VWFA locates in the left posterior area. This may be due to the availability of nonspecialized neural tissue or of some property that makes it suitable for graphic input. Another possibility—that this location allows word form information to be near to left hemisphere language areas—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 VWFA. 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 specific to models of word identification and the behavioral data supporting them? Although there must be a neural substrate for reading, any particular neural implementation of reading processes cannot be assumed. Additionally, results from imaging do not automatically calibrate with behavioral results. For example, finding a brain area that responds more to real words than pseudowords is a measure across time intervals that greatly exceed that of word identification. (MEG results do expose these short intervals.) However, brain-behavior model comparison and theoretical syntheses are helpful, as Taylor et al. (2013) demonstrated. They concluded that 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.

Problems in the Word-identification system: Dyslexia

Reading problems involve disruptions in the ortho-phonological knowledge sources and/or the processes of the word-identification system (Figure 2). Some disruptions have been linked to sensory-neural or perceptual neural problems, e.g., the visual system (Lovegrove et al., 1986) and the temporal coding of the auditory system (Tallal, 1980). Although identifying "ultimate" causes is important for a biological explanation, it is less-so for applying the functional levels of the reading systems framework to reading problems. Visual input to the word-identification system is the beginning of the functional cognitive level of explanation and its disruption has been a continuous candidate for a causal role since the early case-studies of acquired dyslexia in English emphasized (Pringle-

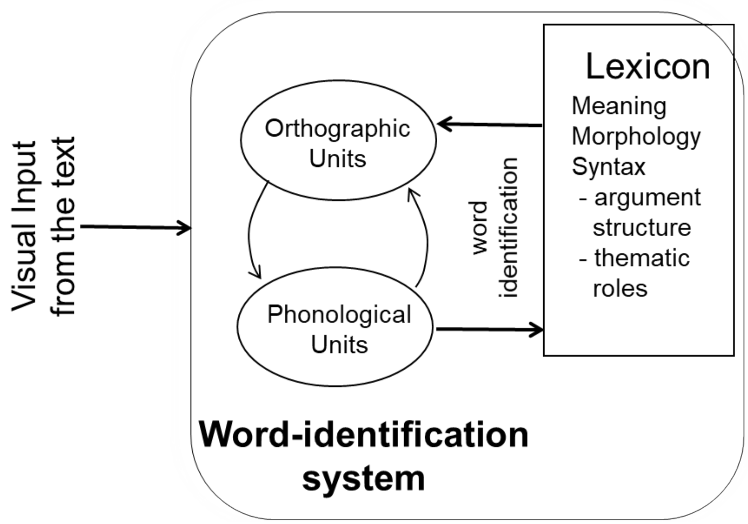

Figure 1. The word identification system. Phonological units rather than language units are highlighted to reflect their special role in dyslexia

Morgan, 1896). Orton's (1925) theory emphasized hemispheric specialization (Orton, 1925), but was widely interpreted as postulating a vision disruption.

At the orthographic level, dual-route conceptualizations of English reading inspired partly by observations of patients (Patterson & Marcel, 1977; Shallice et al., 1983) became applied to developmental dyslexia. Whether acquired or developmental, reading problems could be characterized by selective disruption of the direct (lexical) route or the indirect (sublexical route) to word identity. Castles and Coltheart (1993) established the apparent existence of each disruption type among children with reading problems. Testing performance on both irregular, exception words (requiring the lexical route) and pseudowords (requiring the sublexical route), they identified patterns of relative weakness as surface and phonological dyslexia. Most children who had problems showed difficulties with both exception words and pseudowords. However, disassociations between exception word and pseudoword performance appeared for 45 children, 29 with a phonological dyslexia profile and 16 with a dominant surface dyslexia pattern. In the RSF, the surface dyslexic would be impaired in visual-orthographic memory, whereas the phonological dyslexic would be impaired in the linkage between sublexical orthographic strings and pronunciations and/or in phonological knowledge. A signal finding from Castles & Coltheart (1993) was that phonological problems are more frequent that lexical problems.

This period witnessed the ascendance of phonology as the main cause of dyslexia. Problems with exception words could be recast from surface dyslexia to developmental delay (Manis et al., 1996)—reading experience insufficient to acquire high quality word representations of exceptionally spelled words. A connectionist model by Seidenberg & McClelland (1989) showed the plausibility of a key assumption: a serious problem in phonological representations can lead to a "deficit" in reading exception words. Many other studies, including a review by Rack et al (1992), an earlier 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, such problems early, preliterate language skills are important and predict the phonological skills for children at risk for dyslexia (Snowling et al., 2003). Promising is the possibility that interventions can improve children's oral language skills and their prospects for reading (Hulme et al., 2020).

The primacy of a phonological deficit does not rule out other factors in dyslexia. Hypotheses of visual problems continued throughout this period (e.g., Livingstone et al., 1991; Stein & Walsh, 1997) to the present day (Facoetti et al., 2019). In addition, a deficit in automatized naming gained prominence (e.g., Norton & Wolf, 2011) and, when added to a phonological deficit, produces a "double deficit" (Wolf & Bowers, 1999). Ziegler and colleagues (Ziegler et al., 2019) capture some of the causal complexity, concluding that most children show phonological deficits while also showing weaknesses in nonphonological tasks, especially letter detection. Although these other factors must be considered, the phonological deficit hypothesis has accumulated sufficient evidence and advocacy that it is now the standard theory. Indeed, the 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), which expresses this assumption, continues to accumulate evidence (Catts, 2018; 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, reading comprehension is a distinctive part of reading, even if partly subsumed by 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 parsing—comes from reading research.

Whereas word identification operates with a restricted set of knowledge sources, 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 3.

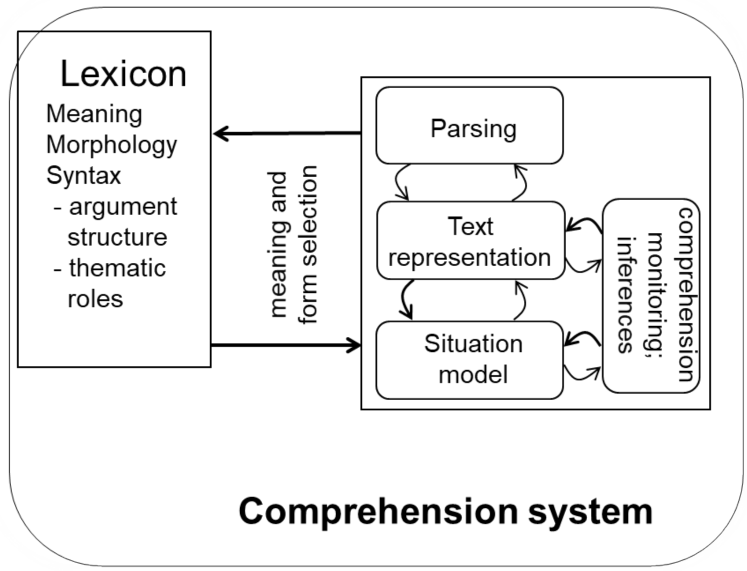

Figure 3. The comprehension system

The lexicon plays a pivotal role. The output of the word-identification system, the word's meaning and pronunciation, is the input to the comprehension system. The role of word meaning in comprehension is obvious enough; however, a word's identity includes its pronunciation and this too is input to the initial comprehension processes, where it supports rapid processes of structure building, integration, and, when needed, repair. Readers have access to the exact form of a word during the reading of a sentence before a less precise memory for meaning only ("gist" memory) emerges.

From Global Top-Down structures to Actual Comprehension

Understanding comprehension as a word-by-word, phrase-by-phrase, and sentence-by sentence process is a challenge. It is not surprising that research on comprehension started at the other end—where global structures could be seen as shaping local processes. Thus, early AI systems designed for comprehension started with global organizers, conceptual scripts for restricted situational comprehension (Schank & Abelson, 1977). Similarly, approaches within psychology and education emphasized schemata, situated conceptual structures (Anderson & Pearson, 1984). Demonstrations of global guidance came from studies showing that a nearly incomprehensible text could be understood readily 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 depended on whether the reader was a music student (Anderson et al., 1977).

Other approaches focused on more generalized mental structures (e.g., story grammars, Mandler & Johnson, 1977; Stein & Glenn, 1979) that guide the comprehension of narratives. More universally, Trabasso and colleagues (Trabasso et al., 1984) argued that people seek causality in reading stories, demonstrating that causal expectations predict how readers understand sentences in relation to causal structures they infer from the text (Trabasso & Suh, 1993). In RSF terms, these approaches focused on the general knowledge component, largely ignoring the comprehension processes that use it. They demonstrated global influences without dealing with the nuts and bolts of comprehension.

Text comprehension from the bottom up

With their *Psychological Review* paper, Kintsch and Van Dijk (1978) approached text comprehension as a cyclical process, with every text element activating meaning to produce a coherent representation of the text as a whole. This approach was further developed as the Construction Integration (CI) Model (Kintsch, 1988), which proposed two phases of comprehension: An initial construction phase, prompted by word meaning, spreads activation across memory of text elements and general knowledge—a passive, automatic process.[1] An 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 CI-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 the complementary processes of memory-based meaning mapping and structure building. Other models also explain text reading through bottom-up, memory-based processes, including the Resonance Model (Myers & O'Brien, 1998) and the more recent Resonance, Integration and Validation Model (RI-Val, 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).

[1] As applied in the CI 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).

Top-down influences became more elaborated in theories that postulate mental structures to guide the reader's construction of coherence, e.g. dimensions of time, space, and causality in the event-indexing model (Zwaan et al., 1995). In an integrative approach, the Landscape Model combines 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 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 strategic processes initiated by the reader , and these processes are determined by the reader's standard for coherence in a particular reading situation (van den Broek et al., 1995; van den Broek & Helder, 2017).

The situation model: Knowledge and Inferences

Text comprehension results in mental representations at multiple levels, two at minimum: the surface text form and the mental-model (Johnson-Laird, 1983). Text comprehension research has generally adopted the three-way distinction of van Dijk & Kintsch (1983): surface level, text-base, and situation model. The difference between the two and three level models is the assumption that there is a level of language-based text meanings (propositions) intermediate between clauses/sentences and situated meanings.

Critical in the situation-model, as illustrated in the RSF, is the role of inferences that make use of multiple knowledge sources from both general knowledge and the text itself. Much research has examined the role of inferences beyond those bridging inferences needed to make a text coherent (See O'Brien et al., 2015). For example, when reading "The bright sun lit the field. Alfred's snowman melted", coherence is maintained by inferring that the heat of the sun caused the snow to melt (Singer et al. 1992). With the activation of relevant knowledge to trigger inferences, comprehension becomes referentially richer and, potentially, more deeply coherent, although error-prone. Successful comprehension attains a situation model that is enriched by inferences and referentially specific but also well aligned with the text meaning.

Sentences

Processing at the word and sentence level in text comprehension research is assumed more than studied. In fact, an important component in the RSF is missing from most models, the processes that configure words into phrases and link them into interpretable structures. These parsing processes build structures with associated meanings. Research on sentence comprehension has sought to identify the multiple influences on the structure building and repair processes. These processes are driven by implicit knowledge of grammatical structures combined with computational pressures on simplicity (Frazier & Rayner, 1982), statistical tendencies 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).

An example illustrates the 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 cause a preference of one structure over the other; thus, 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 this sentence occurs in a text that has established that there were two cops, one of whom had 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 (essentially automatic) parse whose repair is revealed in reading measures (Frazier & Rayner, 1982).

These structure building processes are in the fast current of reading, co-occurring with semantic integration processes. These integrative processes are where the word-identification system, the comprehension system, and the knowledge systems meet in the RSF.

Incremental Comprehension

To the extent possible, readers integrate the meaning of each word into their representation of the text. These incremental processes use information momentarily accessible from different knowledge sources (linguistic knowledge, prior text knowledge, general knowledge), leading to a continuously updated understanding. 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 a special role for the lexicon (Perfetti & Stafura, 2014). The fast currents of reading benefit from the force of these inputs, which ordinarily combine for smooth comprehension.

Observing these rapid integration processes requires methods with high temporal resolution, especially eye-tracking and Event-Related Potentials (ERPs). ERPs are distinctively useful because they reflect the temporal unfolding of multiple processes during the reading of a single word. A 600 ms exposure of a word in a text produces indicators of visual attention (P1), orthographical processing (N170), word-based meaning processes (N400), and memory-related text processes (P600 or LPC) (Luck & Kappenman, 2011). Integration processes are observed in the 300-600 ms time window spanning the N400 and the P600. The N400, a negative going shift in amplitude that peaks around 400 ms after the onset of a critical word, 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 "socks". Countless studies since have confirmed the meaning-based interpretation of the N400 during text reading (Kutas & Federmeier, 2011). However, more specific interpretations of "meaning-related" are contested (Coopmans & Nieuwland, 2020; Delogu et al., 2020), as is the exact interpretation of the P600 in text processing. In its role in incremental comprehension, the N400 has been taken as an early indicator of meaning-based word-to-text integration (e.g., Nieuwland & van Berkum, 2006; Stafura & Perfetti, 2014).

Most studies measure ERP effects on words at the end of sentences, sometimes the middle, thus reflecting largely within-sentence effects. 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 for 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).

A focus on sentence beginnings brings a perspective on an issue that has become central in research on incremental comprehension: the role of prediction. At first pass, prediction and integration seem to be opposite mechanisms: prediction, an anticipatory forward process and integration, a memory-based process. Calloway and Perfetti (2017) found no role for word prediction at sentence beginnings when ratings of integrability of a word into the text was controlled. 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) argue that predictive processes operate continuously while reading, influenced by multiple levels of linguistic units that pre-activate meaning features more 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, establishing the critical integration that supports coherence. This memory process is facilitated by the accessibility of meaning features that have been pre-activated by prior text meanings (Perfetti & Helder, 2020). This account removes prediction as a special process and appears consistent with recent research (Nieuwland et al., 2020) and with other attempts to reframe “prediction” (Ferreira & Chantavarin, 2019). (For more on prediction, see the special issue in *Language, Cognition and Neuroscience* (Hauk, 2016) and a review by Nieuwland (2019).)

What neuroimaging studies add to comprehension research

We focus on imaging studies that are most relevant for theories of reading comprehension. Our conclusion on the contribution of neuroimaging results in refining text comprehension theory is brief: The contribution 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 during reading 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). The 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 with traditional issues arising from comprehension research—the identification of brain networks associated with reading narrative and expository texts (Aboud et al., 2019), local vs global comprehension (Egidi et al., 2013), and responses to differences in text coherence (Helder et al., 2017). Beyond identifying regions are proposals for how other brain networks interact with language areas during comprehension (Hagoort, 2019).

The contribution of imaging studies to cognitive explanations of comprehension processes remains limited, partly because the fMRI BOLD signal, the indicator of brain activation, has a low temporal resolution. It terms of our currents metaphor, it captures 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 some 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, as they do in the case of word identification, where imaging studies showed enough convergence to be connected to theory and behavioral results. It is possible that well targeted imaging research in reading comprehension also can lead to stronger connections with theory and behavior.

Advance 3. Toward a more universal science of reading

The advances discussed come largely from research in alphabetic reading, mainly English. Indeed, the two routes of the DRC model were intended to capture a specific property of English—its inconsistent mapping between letters and phonemes. Although such inconsistencies occur in other alphabetic orthographies, it is especially prominent in English. (Kessler 2003) pointed out problems with the standard measure of inconsistency, the number of context-free mappings for a grapheme, which ignores the frequencies of different mappings and within-word positional constraints imposed by phonotactics and spelling conventions. English spellings are less irregular when these factors are considered.)

Advancing a more universal perspective was 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, Welsh and Finnish are shallow (consistent mappings to phonemes), Czech and Italian only slightly less so, with English at the deep end. This analysis appeared to explain why learning to read English is a slower process than learning to read shallower orthographies (Aro & Wimmer, 2003; Wimmer & Goswami, 1994), although phonics-based teaching in English may reduce this difference (Landerl, 2000). The importance of phoneme awareness, however, is not dependent on the consistency of an alphabetic orthography (Caravolas et al., 2012).

Several approaches made comparisons beyond alphabets, including the application of orthographic depth to nonalphabetic writing, e.g. the consonant-based Abjad system and morphosyllabic Chinese. However, this single dimension scale fails to recognize basic design principles that separate these systems from alphabets. At a cognitive level, the Universal Phonological Principle (Perfetti et al., 1992; Perfetti, 2003) proposed that reading words universally involved phonology at the lowest level allowed by the writing system. Similarly, the psycholinguistic grain size hypothesis (Ziegler & Goswami, 2005) focused on where the writing system made its connection within the phonological hierarchy—phoneme, syllable, word—and the consequences of the connection point for reading development. However, despite the increased recognition of writing system differences, Share (2008) argued that the dominant role of English in reading research had resulted in research questions and models of reading that did not apply to other systems.

Some of the advances brought about by more recent comparative work are reflected in a two-volume series bringing together research and analyses across languages and writing systems in 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. Conclusions about dyslexia are based on 9 of these languages and again identify both universal and specific language and writing systems factors.

Cross-language comparisons also suggest that writing systems show accommodation to features of the language (Frost, 2012; Perfetti & Harris, 2013; Seidenberg, 2011). Illustrating this idea, Table 2 summarizes how four of the orthographies reviewed in Verhoeven and Perfetti (2017a) seem adaptive to properties of their language system.

Table 1. Examples of writing system adaptations 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 multi-syllabic, multi-morpheme 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.

Two examples of alphabetic writing suggest adaptations to phoneme inventories, syllable structures and morphology. Chinese writing suggests adaptation to its single-syllable morphemes, which create many meaning mappings for any given syllable. Thus, while alphabetic writing would create many homophones, the character system usually identifies a particular morpheme. In contrast, although one might think that English would be easier to read with a syllabary, its phonological complexity would create large numbers of syllables and thus less efficiency than an alphabet.

What is important for reading science are the consequences of language and writing system variation. Perfetti and Verhoeven (2017, Table 19.1) present an extended summary of reading skill development across 17 languages. Some conclusions are specific to writing systems and languages (e.g., phoneme awareness is more important in alphabetic than nonalphabetic writing systems); some are applicable broadly within a writing system (e.g., phoneme awareness is important in in all alphabetic orthographies, not dependent on mapping consistency); some apply across all writing systems (e.g., children's linguistic awareness emerges at the syllable level).

One consequence of variation in mapping principles is variation in visual complexity. The number of graphs 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 graph features sufficient to distinguish among few graphs must be expanded to distinguish among many graphs. The result is that abjads and alphabets, which typically have fewer than 40 graphs, have less visual complexity than syllabaries and alphasyllabaries, which typically have more than 400 graphs. All systems are visually simpler than the Chinese basic morpho-syllabary of more than 3,000 graphs. Importantly, in a study sampling graphs from different writing systems, Chang et al. (2017) report 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 alphasyllabaries (Nag, 2017) is partly a reflection of the number of graphs and their visual complexity.

Comparative research has also stimulated the extension of models developed for alphabetic reading to nonalphabetic reading. Li and Pollatsek (2020) present 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

The universality of the brain's 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 assumption across alphabetic languages, while also showing accommodations of the reading network to the less consistent letter-phoneme mappings of English—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 across writing systems and the testing ground is the high-contrast comparison between Chinese and alphabetic reading.

Reviews of early neuroimaging studies of Chinese studies presented 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. 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. One possible explanation is that the prominence of the LMFG, which is near a motor area involved in handwriting (Exner's area), reflects a role of character writing experience in character recognition, a consequence of the practice of writing in Chinese literacy instruction. Evidence for this is the greater overlap in the LMFG for passive recognition and imagined writing in Chinese than English (Cao & Perfetti, 2017). The greater writing practice in learning to read Chinese helps secure long-term orthographic memories for characters, consistent with conclusions from behavioral research (McBride-Chang, Chung et al., 2011). Although Chinese reading may have more support from writing, a study by Nakamura et al. (2012) comparing French and Chinese on recognizing handwriting suggests the writing-reading role of the LMFG is shared across writing systems.

The significance of these Chinese-alphabetic differences and their robustness across different word reading paradigms remain 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).

Dyslexia Revisited

The conclusion from alphabetic reading is that dyslexia is a disturbance of the ortho-phonological system caused by a phonological deficit. Does this picture hold for nonalphabetic reading as well? A hint may lie in results that suggest that, even for alphabetic reading, other factors are involved, including perceptual aspects of orthography (Ziegler et al., 2019) or even basic visual processes (Facoetti et al., 2019).

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

Chinese provides both of these. It maps syllables rather than phonemes and it has meaning cues in its ortho-morphology that may further reduce the demands of phonology. Thus, Chinese provides the high contrast test case of a universal dyslexia with a single cause. (The abjads of Hebrew and Arabic and the alphasyllabaries make additional demands on ortho-morphological processing, seemingly without substantially reducing the demands of phonology.) Indeed, dyslexia in Chinese seems to require a multiple cause model that includes nonphonological causes. Behavioral research does find phonological problems in Chinese dyslexia (Ho et al., 2000), but it also finds associations to rapid naming and orthographic knowledge (Ho et al., 2004), but also morphology (Shu et al., McBride-Chang, Wu, & Liu, 2006). Imaging studies report more under-activation in the left middle frontal gyrus in Chinese dyslexia than is reported in most alphabetic studies (Siok et al., 2004). Although this may reflect a phonological problem, the likelihood that the LMFG supports neural-motor preparation for character writing as part of character recognition suggests an orthographic factor (Cao & Perfetti, 2017).

Visual-orthographic processing challenges may be expected in Chinese, given the demands of learning around 3000 characters over 6 years. In fact, visual attention tasks and copying skills have been found to predict reading ability of children in Hong Kong children (Liu et al., 2015). In the multi-cause analysis, Chinese would have phonological dyslexia, but fewer cases compared with alphabetic reading and with even fewer cases with phonology as the only factor. Both visual-orthographic processes and knowledge of Chinese compounding morphology may play larger roles (McBride-Chang, Lam et al., 2011). Interestingly, as reviewed by Zevin (2019), modeling of Chinese dyslexia (Yang et al., 2009) demonstrates that either a morpho-semantic or phonological disturbance produces wide-ranging character reading problems in Chinese; in contrast a semantic disturbance in English affected only identification of exception words.

Reading problems in Chinese seem to require explanations based on multiple factors. Phonological, morphological, and visual-orthographic processes have been identified in behavioral research and inferred from brain imaging. Problems in the phonological system and its connections to orthography are a sufficient cause of dyslexia across languages, but not a necessary one.

Advance 4: Learning to Read and Reading Pedagogy

We conclude with brief observations about learning to read. The foundational learning is the orthography-to-language mapping system: how the graphs map onto units in the spoken language, both phonological and morphological. Writing systems vary in the relative weighting assigned to morphology and phonology. However, developmental generalities occur across languages in learning to read, as discussed in the preceding section. Here, we focus on a single important aspect of learning to read that provides the link to skilled reading.

The experience-based shift in word reading

Beyond the foundational learning of the mapping system is the progress from learner to the skilled reader of the Reading Systems Framework. This requires establishing memories of visual word forms—orthographic memories. The ability to rapidly access a word memory 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 (Ehri, 1992; Perfetti, 1992), exemplified in teaching by the idea of "sight" words. However, beyond the practice of sight word memorization for irregularly spelled words, the development of orthographic memories applies to all words. As developed by Share (1995; 2004) in the self-teaching hypothesis, decoding a word supports the establishment of its orthographic memory. 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. Word reading speed becomes the distinguishing marker of skill once children reach a threshold level of accuracy for word identification and decoding. In alphabetic and syllabic reading, sublexical procedures continue to be involved even as increased word familiarity provides access to an orthographic lexical memory. The frequency effect in word reading universally 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 some level of 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 is to be learned and how to support this learning with systematic instruction. In teaching English, whether in the U.S., the U.K., Ireland, Australia, New Zealand and the 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 orthographic-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 modest improvements in English reading instruction. However, these improvements are localized rather than general and, in the U.S., have not penetrated teacher training as widely as is needed. As explained by Marilyn Adams (1998), aspiring and practicing teachers in the late 20th century—and even now (Hanford, 2019)—are taught a "three-cuing system", the use of syntactic, semantic, and grapho-phonic "cues" to identify a word. This strategy, rather than supporting the child's developing word-identification system, encourages guessing. In contrast, teaching in other alphabetic languages generally places direct support for decoding as central in beginning instruction (Verhoeven & Perfetti, 2017a). This difference may matter more for reading success than details about orthography.

A Final Observation

In skilled reading, the reading systems—the knowledge sources and the processes that use them—can combine to present a smooth surface 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 different, 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 depends crucially on effective experience that can come only through reading itself.

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Table 1
Properties and Functions of Phonology During Word Identification

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

Table 2
Examples of Adaptations 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 multi-syllabic, multi-morpheme 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.

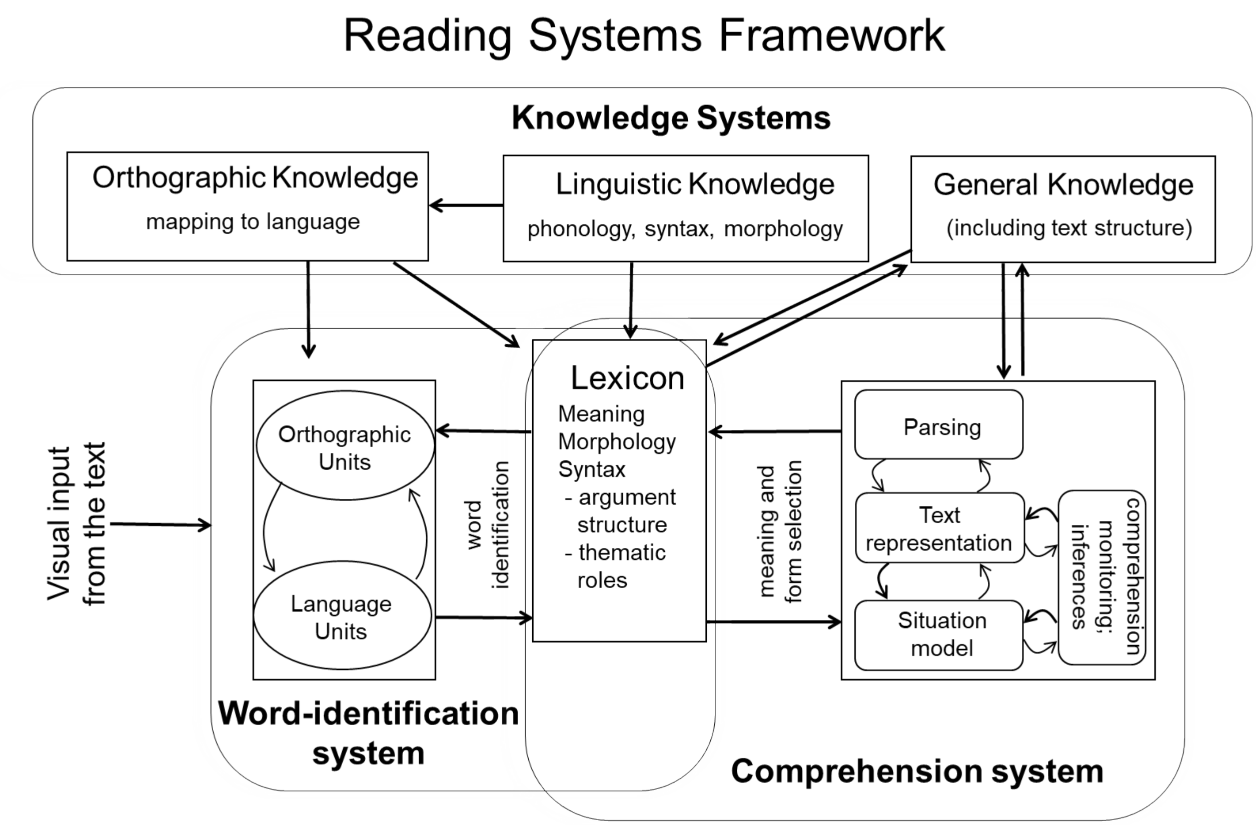

Figure 1. The Reading Systems Framework (modified from Perfetti & Stafura, 2014) consisting of word-identification, comprehension, and knowledge systems, with a central role for the lexicon.

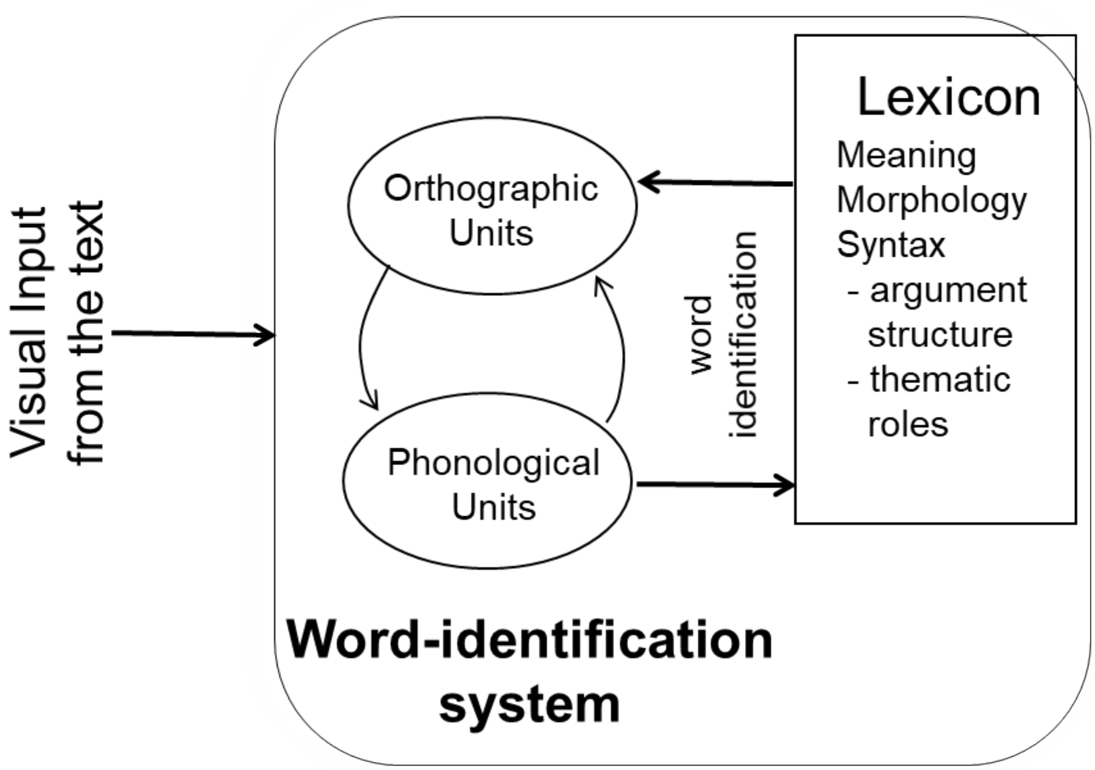

Figure 2. The word-identification system of the Reading Systems Framework. “Phonological units” rather than “Language units” are highlighted to reflect their specific importance in dyslexia.

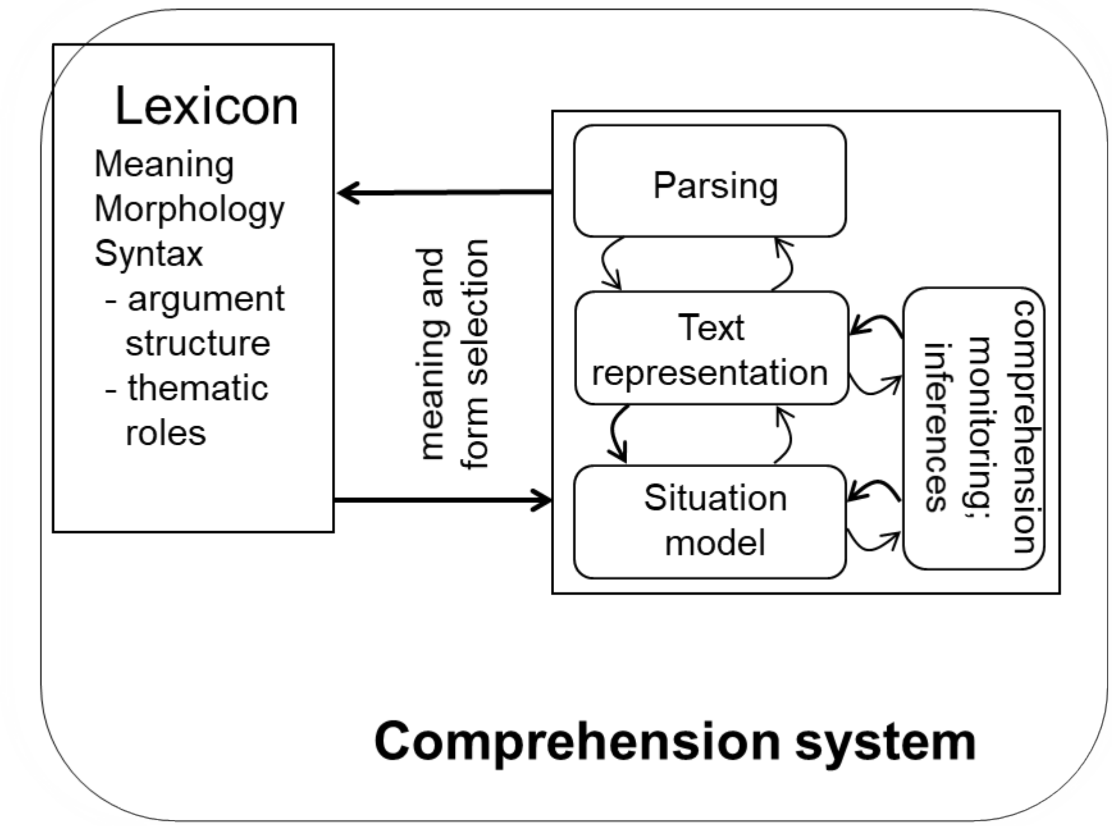

Figure 3. The comprehension system of the Reading Systems Framework.