CHAPTER 9

Reading in Different Writing Systems

One Architecture, Multiple Solutions

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Computational models can be useful tools for exploring how writing systems influence learning to read, skilled reading, and the neural representation of reading. Although I am invited to conferences such as the (lovely) one that inspired this volume on the basis of my computational modeling work, my real interest is in language—not models—and in reading as a particular realization of language. We usually emphasize the differences between language and reading: one evolved in the species, the other was invented (via writing); one is learned through immersion and exposure, the other through instruction and feedback; one is universal, the other is not; and so forth. Yet despite these differences, the same principles govern most aspects of both. For example, whatever the biological predispositions for spoken language turn out to be (e.g., whether they are specific to language, or language takes advantage of many enabling capacities), children still have to learn the language to which they are exposed. The procedures that underlie this learning are, apparently, the same as those that govern learning to read. Thus, the same computational architectures and learning procedures are being used to explain *statistical learning* in language acquisition and the child's later transition into reading (Saffran, 2009; Seidenberg, 2007). For such reasons, I see more similarities across reading and language than are usually acknowledged. One can study reading qua reading, which is interesting enough, but also because it sheds light on language more broadly.

WHAT ARE COMPUTATIONAL MODELS FOR?

In my view, the main goal of reading research is to develop theories of the essential characteristics of reading and to understand how these characteristics are determined by the other capacities out of which reading arose: language, vision, hearing, learning, memory, perception, reasoning, and so forth. We also want to understand the neural structures and circuits that support reading, and how they develop, under genetic and environmental control. Our models are tools in the service of developing such theories, used in conjunction with tools for gathering and evaluating data. Why such models are useful has been described elsewhere (e.g., Seidenberg & Plaut, 2006). Here, I will mention three ways. First, the models are based on a small number of principles concerning knowledge representation, learning, and processing. We do not fully understand all of the relevant principles, and they are modified as necessary in response to new findings and insights. However, the appeal to

these general principles reflects both a strong theoretical claim—that the same general principles underlie most aspects of cognition—and an attempt to avoid the circularity that afflicts much theorizing in psychology and cognitive neuroscience, insofar as the candidate principles are independent of reading rather than developed in response to particular findings or *effects*. In fact, our models were initially developed both because of an interest in reading and because reading happened to provide a domain in which to explore these general principles.

Second, the models provide a unique method for testing hypotheses and establishing closer causal relations. For example, most studies of the bases of dyslexia are correlational: dyslexics exhibit an impairment *X* (e.g., in phonemic awareness) that is thought to have an impact on aspects *Y* and *Z* of reading (e.g., learning spelling–sound correspondences, developing fluency). Often it is hard to tell if the deficit is a cause or effect of poor reading. Models provide strong tests of etiological hypotheses: Does the introduction of the candidate impairment in a model that simulates learning basic reading skills give rise to disordered behavior that corresponds to that which is seen in dyslexic children—or to some other pattern (Harm & Seidenberg, 1999)? Sometimes these simulations corroborate existing views in a new way; sometimes they provide new insights (e.g., about why the effectiveness of a given type of intervention depends on the timing of its introduction; Harm, McCandliss, & Seidenberg, 2003).

Third, although our models were initially developed as frankly cognitive accounts of reading behavior (acquisition and skilled performance; normal and disordered performance), they can also be viewed as providing links between behavior and its brain bases. The latter goal is becoming more realistic, with advances in the understanding of the brain circuits that support reading and the growing use of neural network models and related pattern classifier techniques in the analysis of neuroimaging data. For example, as data about the putative visual word form area (VWFA) accumulate (see Dehaene, Chapter 6 of this volume), the models can be used to address why the VWFA exhibits particular characteristics, why it is organized in the observed way, and other questions, as well as to develop predictions that distinguish between competing theories (e.g., as to whether it is strictly visual and whether it represents *word forms*).

The goal of my own work is to contribute to the development of a theory that identifies fundamental principles which underlie reading, abstracting away from details of individual experiments or models. It is definitely *not* the goal to develop a single enormous model that simulates all aspects of reading. My view contrasts with the "bigger is better" school associated with Coltheart and his students and followers (e.g., Coltheart, Rastle, Perry, & Langdon, 2001; Perry, Ziegler, & Zorzi, 2007), in which the explicit goal is to account for as many behaviors as possible within a single computational model. The principal criterion for evaluating a model, on this view, is how many phenomena it addresses. Problems with this approach are discussed elsewhere (Seidenberg & Plaut, 2006; Seidenberg, Zevin, Sibley, Woollams, & Plaut, submitted). We provide evidence that it leads to models that have the undesirable characteristics that create skepticism, for many, about the value of modeling: components that are introduced in response to the specific data they are intended to explain; model performance that is highly sensitive to the settings of large numbers of parameters whose values have no interpretation; models that are brittle insofar as they recreate the results seen in some studies but not the patterns observed across studies; a level of complexity that makes it difficult to tell not only how the model works but whether it works in the sense of accounting for any phenomena.

An Alternative Approach

According to our alternative approach, which might be called *more is better*, there are many models, not one, each of which draws from the same pool of computational principles, with different models focused on identifying basic properties of components of the reading system (e.g., how different tasks are performed; how different codes are represented; learning; bases of dyslexia). Each model implements only part of the broader theoretical framework, incorporating computational principles thought to be relevant to understanding particular phenomena. Each implementation is necessarily limited in scope and lags behind what we think is really true (because building, testing, and interpreting models is hard; also, sometimes implementing something in a model does not add a great deal to what has been discovered by other means). Each model differs from every other model in detail; experiments with a given model and comparisons across models allow one to determine which aspects of the models are critical to their performance and which are not (because they are mere implementational necessities). Models are similar to experiments in this regard. We do not conduct one giant experiment to understand reading either.

What has emerged from this work is not a model per se, but a theoretical framework (see Figure 9.1). The framework reflects experiences with specific models that were tied to various empirical phenomena in conjunction with the development of the connectionist or parallel distributed processing framework, which provides most of the underlying principles. There is considerable skepticism about the utility of these models, some of which surfaced at the Taiwan meeting on which this volume is based. The models are too powerful and can simulate any pattern of results; the models are too weak because they cannot, in principle, account for important characteristics of behavior (e.g., language). The models never work correctly; even when they do, it is too hard to understand why they produce the behavior they do. The models are unnecessary because we can understand reading by

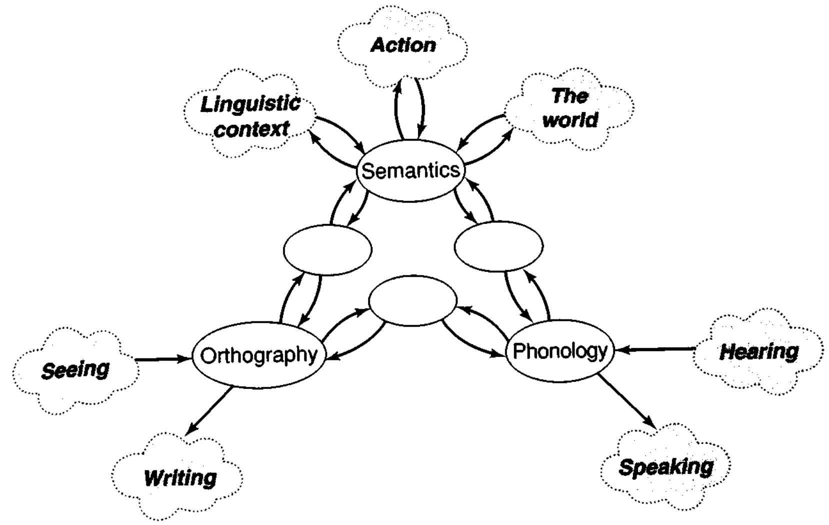

Figure 9.1. General framework for word reading. In contrast to Seidenberg and McClelland's original framework, we now explicitly emphasize the view that the *orthographic, phonological,* and *semantic* representations are themselves learned on the basis of perception, action, interaction with the world, and so on. Thus they too are like hidden unit representations, insofar as their functions are not determined in advanced but rather shaped by their inputs and outputs and participation in different tasks (e.g., reading aloud, comprehending speech).

directly investigating the neural systems that underlie it. Finally, all the models are missing this or that (e.g., serial aspects of processing; impact of explicit instruction).

Addressing these concerns is a topic for another chapter. The short answers are that facts about people (e.g., their perceptual, memory, and learning capacities) and about the world (e.g., the structure of language) impose severe constraints on model behavior. Models tend to fail to learn under conditions that also cause people to fail. Every model is false in detail but can nonetheless contribute to understanding. It is easy to overestimate the difficulty of analyzing model behavior; as with other empirical research, studies of the brain have to be guided by theories in order to know what questions to ask. Brain images do not come with labeled circuits and functions; given the complexity of the system in question (e.g., reading as behavior, brain bases of reading), it takes a computational model to generate hypotheses that overcome the limits of intuition and analogy, and the illusion that understanding can be achieved by just doing enough experiments. Finally, all of the computational models of reading taken together leave most of reading unaddressed. There is a great deal about how words and nonwords are pronounced and much less about how people comprehend phrases, sentences, and texts. It's easy to create a long list of things the models do not incorporate because that would include most of reading. What is the alternative? Theorizing at the level of the box-and-arrow models of the past?[1]

In this chapter, I focus on one area that illustrates how the models can be useful. This focus is relevant to a central theme of the Taiwan conference: reading in different writing systems. I will assume the framework illustrated in Figure 9.1, from which a variety of models can be derived. For this discussion, three properties of this framework are particularly relevant (see Harm & Seidenberg, 1999, 2004, for fuller explanations):

1. *Lexical computations are statistical rather than categorical.* The mappings between different types of information (e.g., spelling, sound, meaning) are better characterized in terms of the statistical relations between them than by other types of knowledge representation, such as rules.
2. *Constraint satisfaction.* The output that a model produces is determined by combining bits of information that are not highly constraining when taken independently. The nonlinear effects of combining disparate sources of information are an important mechanism underlying human intelligence.
3. *Division of labor.* A complex, multicomponent system (e.g., a triangle model of reading; the brain) that is given a task to solve (e.g., computing the meaning of a word from print) does so by converging on an efficient division of labor among its components. In models employing distributed representations (another basic principle) an output pattern (e.g., a meaning) is built out of and subject to constraints from multiple sources: spelling, phonology, context, beliefs and expectations, and so forth. This model contrasts with the either/or approach inherent in models that emphasize different *routes* to meaning (e.g., visual versus phonological). I sketched how this concept might play out with respect to different writing systems in Seidenberg (1992) and will revisit the issue later in this chapter.

[1]Actually, box-and-arrow theorizing is already back. As occurred in Taiwan, concerns about the limitations of computational models are usually raised by researchers who do not employ modeling in their own work, preferring a kind of quasi-computational description of the "logic" of a problem such as word identification or language acquisition. A diagram such as Figure 1 in Dehaene, Cohen, Sigman, and Vinckier (2005) is missing the boxes and arrows but is otherwise similar in character to the famous precomputational neuropsychological models of the 1980s (see, e.g., chapters in Patterson, Marshall, & Coltheart, 1985). The same type of informal argumentation from data to theoretical conclusions that was utilized in the neuropsychological work is seen in the interpretation of contemporary neuroimaging studies (e.g., Glezer, Jiang, & Riesenhuber, 2009). This intuitive approach to data interpretation, widely used in studies of brain-injured patients, was strongly called into question by subsequent computational modeling (e.g., Plaut, 1995; Woollams, Lambon Ralph, Plaut, & Patterson, 2007). Repeatedly, such models have shown that behavior which seems to have an intuitively obvious basis can be explained by other mechanisms familiar from computational modeling. The interpretation of neuroimaging studies is largely still at the box-and-arrow level, raising similar concerns.

WRITING SYSTEMS AND SKILLED READING

Many types of writing systems exist, and people manage to learn and use them every day. The wide variation in how writing systems are organized raises an obvious question: Do people read different types of writing systems in the same way, or differently? This question invites other queries such as: Are some writing systems easier to learn than others? Do they make use of the same neural circuits? Does dyslexia have a universal basis, or does it vary depending on the writing system? All of these questions are the focus of extensive research, with rapid progress being made—even if we have not yet converged on definitive answers.

At the conference, I suggested two "obvious" answers to whether people read different types of writing systems in the same way or differently:

- *Same way.* The brains of the readers of these writing systems are essentially identical; reading involves the same types of capacities (perceptual, learning, conceptual, etc.) regardless of the writing system, and reading is universally the process of deriving meanings from print by using visual, phonological, semantic, and other types of information.
- *Differently.* Writing systems differ in how they are organized; the person/brain responds to these differences, yielding different ways of accomplishing the reading task. Some writing systems are easier to learn than others; dyslexia does not have a universal basis, but rather depends on how anomalies in brain organization relate to the demands of the orthography to which a person is exposed.

Therefore, is the glass half empty or half full? There is an extensive literature in this area, relying mainly on behavioral data and logical analyses of how the reading system must work, given properties of a writing system; there is also a growing body of relevant neuroimaging data. I will review some of this work, identify some questions that seem to be unresolved, and then consider how the issues can be viewed within our computational modeling framework and some new questions that arise.[2]

The Real Significance of My Bar Mitzvah

The first interesting and deservedly influential hypothesis about writing systems and reading was the Orthographic Depth Hypothesis (ODH; Frost, Katz, & Bentin, 1987; Katz & Feldman, 1981). Building on the earlier concept of independent visual versus phonological processing

[2]To save space and avoid repetition, the following abbreviations are used: orth, orthography; phon, phonology; sem, semantics. Orth-sem refers to a computation linking orthographic and semantic representations; orth-phon-sem, a computation from orthography to phonology to semantics; and so forth.

systems (Baron & Strawson, 1976; Rubenstein, Lewis, & Rubenstein, 1971), the ODH held that the degree of reliance on each of the pathways would depend on properties of the writing system—specifically, how transparently it encoded phonology. Thus shallower orthographies (the much-studied example was Serbo-Croatian) afford greater reliance on phonological reading, whereas deeper orthographies (Chinese perhaps) rely more on the visual pathway. Baron and Strawson (1976) coined the terms *Chinese* and *Phoenecian* to refer to readers of English who differed in the analogous way (although *Chinese* turns out to be a particularly inapt epithet for *visual reader,* as discussed shortly). English could be seen as requiring a mix of the two, depending on whether a written word had a regular or irregular pronunciation. The ODH was an elegant, original idea—it was an early *division of labor* theory—and it greatly stimulated the science of reading, particularly cross-orthography research. On this view, different writing systems afford different reading mechanisms or strategies.

Two types of findings presented challenges for this account:

1. *Computational evidence.* The ODH was developed at a time when people used rules to characterize spelling–sound regularities. Exceptions to the rules, which seem rife in English, require a second mechanism. Early on, there were two proposals. One proposal assumed a *dual-route* model in which there are visual (orth→sem) and phonological (orth→phon→sem) routes to meaning (Baron & Strawson, 1976; Rubenstein et al., 1971). Exception words could be pronounced by first computing from orth to sem, and then using the sem→phon pathway known from speech production. Other "dual-route" models (Marshall & Newcombe, 1973; Coltheart, Davelaar, Jonasson, & Besner, 1977) split the orth→phon computation into two pathways, a rule-based procedure (for pronouncing nonwords) and a lexical procedure (for pronouncing exceptions such as PINT). The third, orth→sem→phonology procedure was considered relevant only to brain-injured "semantic" readers (e.g., Friedman, 1996).

   For Coltheart et al. (2001), the conclusion that reading aloud in English required two pronunciation mechanisms was "inescapable." However, our first connectionist model (Seidenberg & McClelland, 1989) showed that "rule-governed" and "irregular" words did not demand separate naming mechanisms. Using a single mechanism captured the fact that the pronunciations of irregular words are not arbitrary (PINT is not pronounced "glorph"), but rather overlap with putative regulars (PINT overlaps with PINE, PUNT, and other words). The model could then account for some important additional facts; namely, effects of spelling–sound consistency (Jared, McRae, & Seidenberg, 1990) that remain seriously problematic for traditional dual-route models (see Seidenberg et al., submitted).

   The important implication for the ODH was that the computational mechanisms underlying pronunciation can cope with different degrees of spelling–sound consistency. Therefore, different orthographies might be processed more similarly than the ODH assumed.

2. *Phonology all the way down.* If most words (except perhaps some highly irregular, low-frequency ones) can be pronounced via orth-phon in English as in our models, and a person already knows the spoken language, the orth-phon-sem mechanism might carry more of the burden than usually assumed in comparisons with shallow orthographies. A large body of behavioral evidence eventually showed that people use phonology in reading writing systems that differ greatly with respect to the nature of the mappings between written and spoken forms. Van Orden (1987) showed that people rely heavily on phonology in reading English—an effect that replicates in other writing systems. Xu, Pollatsek, and Potter (1999) showed that phonology is activated in silent word reading in Chinese (see also Zhang & Perfetti, 1993). Phonological properties of words and sentences affect silent reading, as measured by eye fixations (e.g., Pollatsek, Lesch, Morris, & Rayner, 1992; Yates, Friend, & Ploetz, 2008). This body of findings was synthesized by the Ziegler and Goswami (2005) theory, according to which readers use phonological information at whatever grain size their writing system affords: graphemes in alphabetic writing systems, syllables in Japanese kana, phonetics or whole words in Chinese. English makes use of orthographic units that vary in size and complexity: single letters, digraphs, trigraphs, subsyllabic units such as onsets and rimes, idiosyncratic units such as noncontiguous contingencies between letters (the silent *e* rule is an obvious example, but there are other, more subtle statistical regularities hidden there). These facts seem to imply that phonological mediation is pervasive and not highly dependent on writing system.

Are we all Phoenicians then? The role of phonology in skilled reading is established beyond question. What is at issue is whether other mechanisms and types of knowledge contribute as well. The answer is not yet fully known. One problem is that whereas there now are several excellent methods for diagnosing the use of phonology in the computation of meaning from print, there are no corresponding methods for diagnosing the use of orth-sem. The model developed by Harm and myself (Harm & Seidenberg, 2004) instantiated the division-of-labor concept with respect to English: The meaning of a word developed out of input from both arms of the triangle (orth-sem, orth-phon-sem), with context assumed to provide additional input (but not implemented). Evidence that phonology has been activated does not rule out a contribution from orth-sem, but there is no obvious way to assess this possibility using behavioral methods. In the Van Orden (1987) paradigm, false positives are taken as evidence of phonological activation, but correct rejections are not taken as evidence that phonology was deactivated. Rather, they are taken as evidence that participants made the correct answer using a hypothetical spelling check. Thus, unless participants made no false positives at all, the data were taken as implicating phonology regardless of the actual response. This interpretation exemplifies a situation in which neuroimaging may provide more decisive evidence than strictly behavioral studies.

A second problem is that other facts about writing systems, languages, and people seem to militate against a strictly phonological reading strategy. Consider again Serbo-Croatian, the quintessential *shallow* orthography. (The languages are now treated as separate; I will focus on Serbian.) The Serbian alphabet follows the principle that each letter corresponds to one and only one sound. Serbian is an example of what I call Bar Mitzvah languages. Jewish young people participate in a rite of passage called the Bar or Bat Mitzvah, which includes reading aloud a section of the Torah, the holy text. Many 13-year-olds manage this feat even though they do not know the Hebrew language. They can do so because written Hebrew is shallow in pointed form. Thus even mildly observant children can learn to read Hebrew aloud quickly and participate in the ceremony (I am proof of this). There would be many fewer Bar/Bat Mitzvahs if the holy text were written in hieratic glyphs.

Serbian is a fine Bar Mitzvah language insofar as learning the letter–sound correspondences is simple. Then, if one knows the spoken language, it should be easy to compute the meanings of words exclusively via orth-phon-sem. However, I am skeptical. First, correct computation of phonology in Serbian involves more than just grapheme–phoneme correspondences. Suprasegmental information not represented in the writing system is critical to disambiguating words. Thus there are minimal pairs that differ only with respect to stress, such as *zatvori* (first syllable stress, "prisons"; second syllable stress, "to shut," as in "shut the door!"); *proizvodi* (first syllable stress, "products"; second syllable stress, "to produce," as in "it produces nice graphs"). Similarly, *riba* is either "fish" or "to scrub," depending on pitch accent; *luk* is either "onion" or "arch." I do not know of any data about the frequencies of such words, but they are not occasional oddities, according to one native speaker informant. How much these ambiguities in orth-phon would limit reading by this pathway is not clear, but it is a concern. Second, leaving the shallowness of orth-phon conversion aside, what prevents the reader from developing orth-sem? Given enough pairings of spellings with meanings, as occurs every time the reader uses orth-phon-sem, how would a person fail to develop direct orth-sem connections? That is how orth-sem developed in the Harm and Seidenberg (2004) division of labor model of English (discussed later in this chapter). Take-home assignment: Reimplement the Harm and Seidenberg model; train it exactly as before, but treat English as though it were shallow. In Shallow English, *pint* will be pronounced to rhyme with *mint* and so on for the other irregular words. Will the model still develop a division of labor in which both pathways contribute?

My prediction is yes. In the published model, the orth-sem pathway developed for two reasons: 1) to disambiguate homophones such as *pair* and *pare,* and 2) speed: the orth-sem pathway, once trained, operated more rapidly than orth-phon-sem (intuitively, orth-phon-sem is slower because the phonological code has to settle sufficiently to drive the phon-sem mapping). Both considerations would continue to hold in Shallow English. Thus, shallowness is not itself a barrier to the development of orth-sem on this analysis.

What about Hebrew, the actual "Bar Mitzvah language"? I am not prepared to assess the complexity of syllabic stress assignment in Hebrew, except to observe that it has some interesting 5,000-year-old wrinkles. The more important point is that although the vowels are retained for learning purposes, they are deleted in texts for skilled readers. In fact, including the vowels interferes with skilled reading (Bentin & Frost, 1987). Fr smn wh rds nglsh, t's pzzlng hw ppl mng t rd th lngg n ths trnctd, ntrpc frmt. (For someone who reads English, it's puzzling how people manage to read the language in this truncated, entropic format.) Surely the reader relies on context (semantic input) to constrain the meaning of an otherwise ambiguous string of consonants. Ironically, then, even in a writing system that *could* be shallow, the deep form is preferred, suggesting that reading that does not wholly depend on orth-phon-sem can be highly efficient.[3]

In short, simple spelling–sound correspondences are a fine property, but may be either insufficient to support orth-phon-sem or less efficient than other processes (e.g., the full triangle—a system that also incorporates contextual influences).

DIVISION OF LABOR AND ORTHOGRAPHIC DEPTH

At this point, it is still not clear whether the glass is half empty or half full, making this a good time to look again at the models. Assume for the moment that there is a single architecture that supports reading—one that involves computations among orthography, phonology, and semantics, for all writing systems (ignoring context for the moment). If this assumption proves to be wrong, so be it: The goal is discovering what is true, not defending a particular model. Applying this framework to different writing systems requires two additional steps. First, we modify the model's input and output representations to reflect properties of the writing system and spoken language. In a more ambitious model, these representations would themselves be learned, based on relevant sensory (visual, auditory) and motor (writing, speaking)

[3]Ram Frost has drawn my attention to the fact that Hebrew was originally unpointed, functioning as a vowel-less writing system for about 2,000 years. Vowels were introduced to maintain standard pronunciations of the holy text, the Torah, during the Jewish diaspora.

information. However, a reasonable first step is to create plausible orthographic and phonological representations that reflect properties specific to a writing system or language (e.g., representations of characters in Chinese versus letters in alphabets). The second step is to find roughly comparable training corpora for the different writing systems and languages. Such corpora are now available for many languages. Doing the job right also requires reasonable estimates of the relative frequencies of words.

Now train two models—say, Chinese and English (because the writing systems are interestingly different)—to compute pronunciations and/or meanings from orthographic input. (We can approximate meaning using featural semantic representations employed in previous research—see, for example, Harm & Seidenberg, 2004—even if they do not fully capture everything about conceptual knowledge. We are not yet looking at cross-linguistic differences in meaning, so the representations will be adequate if they capture some basic facts about semantic similarity and dissimilarity.) The question "Do people read English and Chinese in the same way or differently?" can now be cast as "Do these models solve the tasks we give them in the same way or differently?" Division of labor is not stipulated in advance. The models converge on efficient ways to perform tasks (e.g., computing pronunciations or meanings), given the architecture, training corpus, and learning procedure.

These modeling experiments have begun to be conducted, and some important results are in. In English, people compute pronunciations of words mainly relying on the orth-phon component of the triangle, because the writing system is alphabetic and the codes are correlated (if imperfectly). Input from the orth-sem-phon part of the triangle is mainly needed for lower-frequency, irregularly pronounced words, as seen in both behavioral (Strain, Patterson, & Seidenberg, 1995) and neuroimaging (Frost et al., 2005; Graves, Desai, Humphries, Seidenberg & Binder, 2010) studies. These effects may be modulated by reading skill and perhaps by individual difference factors that strengthen or weaken the contributions from different components. It is also possible to bias reliance on one or the other part of the system through manipulations of stimuli, instructions, and other aspects of an experimental design. The story is similar with respect to the computation of meaning: initially, the system depends mainly on the orth-phon-sem pathway, given that phon→sem is already known for many words from speech, and orth-phon are correlated (Van Orden, Pennington, & Stone, 1990). With additional practice, the more arbitrary orth-sem part of the network begins to come online. At high levels of performance, the computation of meaning relies on input from both parts of the triangle, with the balance between them depending on factors such as type of word (homophone, irregular spelling or pronunciation, frequency). Again, there may be individual difference variables, poorly

understood, that create somewhat different divisions of labor for different readers.[4]

The corresponding Chinese models have been developed by Yang, McCandliss, Shu, and Zevin (2008, 2009).[5] These researchers met the challenge of developing an orthographic representation for Chinese, which must include strokes and the spatial relations among components in complex characters. Similarly, their phonological representation is similar to English but also includes tone. Compared with English, there are similarities and differences in the resulting division of labor. In computing pronunciations, the Chinese model picks up on the statistical properties of the mapping in the same way as in English. The systematicity of these correspondences is often underestimated by Western observers. With regard to meaning, Yang et al.'s model (which simulated semantic input using the approach developed by Plaut, McClelland, Seidenberg, & Patterson, 1996) converged on a division of labor that relied more heavily on the orth-sem leg of the triangle and less on the orth-phon-sem leg than in English. Still, the results suggested that both components are implicated in reading most words.

Chinese is particularly interesting when viewed in terms of the division of labor and constraint satisfaction concepts. The most common type of character contains two components: a phonetic (clue to sound) and a radical (clue to meaning; Shu, Chen, Anderson, Wu, & Xuan, 2003). Such characters instantiate the concept of orth-sem and orth-phon-sem processing—both of the pathways are present *in the writing itself*. Moreover, these complex characters richly illustrate the concept of constraint satisfaction. At first these characters seem to present a computational problem: One needs to know the meaning of the whole (character) in order to understand the identities and functions of the parts (radical, phonetic) and vice versa. These component elements are typically ambiguous: 户 is a phonetic in 驴 (donkey) but a radical in 房 (house). Each component provides only partial information about sound or

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[4]Like every other model, Harm and Seidenberg's (2004) model implemented only part of the lexical system. One simplification was that we did not implement the feedback connections that are envisioned in the full-triangle system, which are also a prominent feature of neural systems. Harm and Seidenberg (1999) emphasized how orthographic knowledge shapes phonological representations, but in a system that implemented feedback loops from phon to orth, the converse would occur: *Orthography* would be shaped by phonological knowledge. Thus the representations we labeled *orthography* are more like hidden units shaped by relations between different codes, yielding a more abstract, mixed code rather than a strictly orthographic one. This does not change the basic division of labor account: The mapping to semantics from this code is still more arbitrary than the mapping to phonology. However, it does predict that representations in the putative visual word form area should be shaped by phonological and possibly other influences, rather than be strictly orthographic.

[5]Perfetti, Liu, and Tan (2005) also developed a model of reading in Chinese. It has a different character, so to speak, insofar as it is not a learning model and cannot develop division of labor. However, such models are useful for illustrating an existing idea or hypothesis.

meaning, respectively; however, the conjunction of the two is highly constraining, allowing the character's meaning to be computed. This is the classic kind of problem that interactive models (e.g., McClelland & Rumelhart, 1981) solve beautifully.

The same type of constraint satisfaction process also applies at a different level of structure: the combination of morphemes to form complex words in Chinese (McBride-Chang & Liu, Chapter 2 of this volume). As McBride-Chang and Liu note, many Chinese words are similar to compound words in English, insofar as they consist of two (or more) morphemes, each of which is itself a word. The morphemes are related to the meaning of the whole, but in different ways and degrees. For example, 鸣 (chirp) = 口 (mouth) + 鸟 (bird) is seemingly transparent, but even here the meanings of the components underdetermine the meaning of the whole. In 問 (ask) = 門 (door) + 口 (mouth), the relations between parts and the whole are even more abstract. Post hoc, it is easy to imagine how 明 (bright) is related to 日 (sun) + 月 (moon), but the meaning could as well have been *celestial body* or *bowl of milk* (Henkes, 2004). English has *boathouse,* a structure where boats are stored, and *lighthouse,* a structure with a big light, but also *ranch house,* which is a type of dwelling (as were some lighthouses). Thus, both the Chinese and English examples vary in how the meanings of the parts (morphemes) relate to the meaning of the whole (word). The same kind of constraint satisfaction process, operating over different types of units, occurs at different structural levels (combining phonetic and radical elements to form complex characters, combining morphemes to form complex words).

The similarities between Chinese and English may extend well beyond the ones that McBride-Chang and Liu discuss in Chapter 2 of this volume. They emphasize the fact that there are more compounds in Chinese than in English, which is true. However, English is full of noun phrases (or nounphrases) with the same modifier–head construction as English compounds, and there is no strong distinction between them (Seidenberg & Gonnerman, 2000). *Boathouse* is, conventionally, a compound word, but does it differ in any way except typographically from *ranch house?* The ability to manage the varying relations between morphemes is relevant to many other kinds of words in English as well. For example, the language has suffixes such as *-er* that attach to nouns. The meaning of the suffixed word is not a simple combinatorial function of the meanings of the parts. A *baker* bakes and a *runner* runs, but a *locker* is a metal compartment, not a person who locks; a *hanger* is used to hang clothing on (unless you are a wallpaper hanger); and—in the right context—*bangers* are food. In each case, the reader must provide additional information about the relations between the morphemes. Better readers are better at doing this (e.g., Singson, Mahony, & Mann, 2000).

Given such findings, what about our glass? perhaps the question isn't whether the glass is half empty or half full, but rather what is in the water. There is one glass, and we all need the same amount to

drink. The glass can contain only certain liquids, but the proportions of the liquids vary. That is, there is a single architecture that develops via the same learning procedures, solving the same tasks, under the same pressures (efficiency, accuracy), but converges on different solutions (divisions of labor among the components). These models are clearly first steps, and the account of what happens in various writing systems will undoubtedly change as a broader range of phenomena are addressed.[6] We know that existing models will not turn out to be correct in all details. This is unimportant. The goal is not defending a particular model; we known in advance that every model is false at some level. The more important point is that the models provide a productive, openended framework for investigating the issues. The theory that there is one common architecture (at both cognitive and neural levels) could be wrong; see, for example, the Perfetti, Liu, and Tan (2005) evidence that Chinese involves brain regions not seen in reading English. Say that the spatial relations among the written components are more relevant in Chinese than in English, and that there are brain circuits that are particularly well-suited to encoding these relations. The modeling framework might explain why spatial relations are more important in one case than the other (because, e.g., given the properties of written Chinese, encoding the spatial information creates a more efficient solution to the problem of computing meanings from print). Better understanding of the brain might also explain why a particular region or circuit picks up on this information and how it is combined with other constraints. The conjunction of facts about brain organization and behavior might then explain why a writing system with this structure could exist and be functional, whereas others could not. All this seems promising and very normal science to me.

In summary, the one architecture–multiple solutions theory is, at a minimum, a useful way to frame hypotheses about effects of writing systems on skilled reading. The point is not to ask if the glass is half empty versus half full, but rather how division of labor varies and why.[7]

[6]Our models emphasize gradual, implicit, statistical learning, which accounts for a great deal. However, humans learn in other ways as well—in particular through explicit instruction. Writing systems may differ with respect to the amount of explicit instruction they require in order to be learned within a given amount of time (Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004); the same may be true of the spoken languages they represent. It would certainly be a useful goal for future models to integrate these different types of experiences. However, this integration would require a better understanding of how explicit and implicit knowledge are integrated, behaviorally and neurally.

[7]Consistent with this analysis, Bolger, Perfetti, and Schneider (2005) concluded from a meta-analysis of neuroimaging studies that reading involves core neural circuitry with some orthography-specific variation. Division of labor concerns a further question: how the contributions of different parts of this system vary as a function of reader skill, writing system, reading strategies, and other factors.

WRITING SYSTEMS AND READING ACQUISITION

To this point, I have focused on skilled reading, but how do differences between writing systems affect learning to read? The general consensus seems to be that shallower orthographies are easier to learn than deeper ones. The logic seems obvious: The child's problem is to learn how to map written symbols onto phonological forms known from speech. This task is easier if units in the written language reliably correspond to units in the spoken language. I'm not prepared to evaluate the relative difficulty of learning to read all the world's many writing systems. I would note that something seems to be going on in Chinese, given two modern developments apparently intended to make the language easier to learn to read: the simplification of characters in China and the introduction of secondary alphabetic scripts in China (pinyin) and Taiwan (zhuyin). Keyboarding demands are also creating much greater reliance on the secondary alphabetic scripts. Japanese children learn kana quickly and easily, but there are the joyo kanji to conquer. All this manages to work out, but there could be differences in the trajectories toward becoming a skilled reader.

Instead, I will examine a narrower question: Are there differences in ease of acquisition among alphabetic writing systems, in particular, as a function of orthographic depth? Again, my reading of the literature is that most people think the issue is settled, based on converging evidence from studies of many languages. Again however, it may be that a different picture emerges if we consider a broader range of considerations.

The evidence is clear that it is easier to learn to pronounce words and nonwords in shallow alphabetic orthographies. For reviews, see Share (2008) and several chapters in Snowling and Hulme (2005) and in Joshi and Aaron (2006). My concern is that there is a tendency to conflate *reading* with *reading aloud.* Reading aloud is a task that many researchers (including me) have used as a way of gaining data about some parts of the reading system. The task isn't otherwise very interesting: people's goal in reading words is computing meanings, not pronunciations; reading aloud is highly relevant to learning to read, but mostly irrelevant to adult life unless you have young children, you like to read poetry (which should always be read aloud), or your job requirements include reading speeches from a teleprompter. The task has been useful, but let's not pretend that it is "reading," which is mainly the task of comprehending written language. In the rest of this chapter, I reserve the term *reading* for comprehending words or texts.

Most of the studies to have examined learning to read from a comparative rather than Anglocentric perspective have focused on decoding (assessed by reading aloud; see the references cited previously). All of these studies show advantages for shallower orthographies over English with respect to pronunciation accuracy, in individuals of varying ages. But reading involves other skills—in particular, knowledge of the spoken language represented by the written code. Thus we should ask, Are children who are better decoders also better readers? This question

requires data from other tasks. For example, does earlier decoding skill entail earlier comprehension skill? Do the children who are early good decoders also understand what they read? Does their decoding skill promote better understanding of the grammar of the language such that they comprehend a broader range of sentence structures? Do they also comprehend texts at a younger age? If reading only involved pronunciation, we would conclude from existing research that it is easier to learn to read in some writing systems than others. One could also imagine that, other factors aside, ease in acquiring decoding skills leads to better reading. Reading is not just pronunciation, and learners cannot just put other factors aside.

To my knowledge, the cross-orthography studies on this topic have all investigated word and/or nonword naming and have varied with respect to which other tasks were included. With younger children, there usually are measures of phonological awareness and vocabulary; studies with older children or adults may include an assessment of story or expository text comprehension. In some studies, the identification of reading with reading aloud is complete. For example, Ellis and Hooper (2001) compared three writing systems—English, Welsh, and Albanian—which range from deep to shallow to extremely shallow. The main result is given in the title, "Learning to Read Words in Albanian: A Skill Easily Acquired." The main finding was that "the rate of reading acquisition is faster the shallower the orthography" (2001, p. 163). However, the tasks were reading words and nonwords aloud. Comprehension was not assessed. Were the children reading or barking at print or some of both? In Spencer and Hanley's (2003) study of learning to read in Welsh and English, the primary data concerned differences in *word recognition.* The *word recognition* task was reading aloud; comprehension was not tested. In a follow-up study, Hanley, Masterson, Spencer, and Evan's (2004) title asked, "How Long Do the Advantages of Learning to Read a Transparent Orthography Last?" where the advantages in question are, again, in reading aloud. The study yielded a fascinating pattern of results. In the earlier study of 5-year-olds, children learning to read Welsh outperformed those learning English in reading aloud. The later study examined 10-year-olds. Not surprisingly, much of the decoding gap was eliminated by 10 years of age, although the poorest English readers were worse than the poorest Welsh readers, and the English readers as a group continued to show difficulty with some lower frequency, irregularly pronounced words. The most striking result, however, was that English children performed significantly better on a test of story comprehension. As the authors noted, "This result suggests that a transparent orthography does not confer any advantages as far as reading comprehension is concerned. As comprehension is clearly the goal of reading, this finding is potentially reassuring for teachers of English" (p. 1408). It is also reassuring for theories in which ability to pronounce words is not the only determinant of reading skill.

The Hanley et al. comprehension result is not without precedent. Consider Ellis and Hooper (2001), a careful study of children learning to read in English and in Welsh. The contrast (here as in other studies of these languages) seems nearly ideal, insofar as the writing systems differ in depth, but other potentially confounding cultural and socioeconomic factors are largely moot (the major remaining factor is that whereas English learners are monolingual, the Welsh learners have considerable knowledge of English). The stimuli were carefully developed to allow direct comparisons between the reader groups. The main finding was that the Welsh readers performed substantially better than the English readers on tests of word and nonword pronunciation. Again, however, the English children performed better on a test of comprehension. More interesting still, English children comprehend words that they do not pronounce correctly. This last finding strongly argues against equating pronunciation accuracy with level of understanding.

The most recent study of this type is Ziegler et al. (2010), which again compared reading aloud in English with shallow orthographies, replicating the pattern established in the earlier studies. Although the researchers provided interesting data about participants' performance on several other tasks, comprehension was not assessed.

Some studies in languages other than English have examined relations between reading aloud and comprehension in greater detail. I would single out Durgunoğlu's studies of Turkish, which provide a wealth of data. After reviewing studies of word and nonword naming in Turkish, Durgunoğlu noted, "Phonological awareness and decoding develop rapidly in both young and adult readers of Turkish because of the transparent orthography and the special characteristics of phonology and morphology. However, reading comprehension is still a problem" (2006, p. 226). She then goes on to discuss some of the challenges presented by the spoken language, which has agglutinative morphology (a system in which words can include many affixes) and vowel harmony, and consistent findings that comprehension lags substantially behind word pronunciation.

In summary, whereas it is well established that spelling–sound correspondences are learned more easily in shallow orthographies, the consequences for developing the ability to read with comprehension are by no means clear. Here is a purely speculative conjecture: Most of the studies establishing the importance of decoding in learning to read examined English. The evidence that mastery of spelling–sound correspondences is critical in learning to read English is unassailable (see, for example, the review of the National Reading Panel, 2002). Moreover, there are large individual differences in how difficult children find this initial step in English, and how they are taught has a major impact on success. Perhaps it is the case that in the shallow orthographies, mastery of spelling–sound knowledge is less predictive of the development of true reading skill and associated with smaller individual differences because the task is easier. After all, even dyslexics can learn to pronounce nonwords in shallow orthographies, accurately, if slowly (Mann & Wimmer, 2002). If this is correct, proficiency in reading aloud is not an appropriate metric for assessing ease of learning to read across writing systems.

THE GRAPHOLINGUISTIC EQUILIBRIUM HYPOTHESIS

In 1990, Hoover and Gough proposed a *Simple View of Reading* whereby comprehension is determined by decoding skills and spoken language comprehension. With the hindsight provided by subsequent research, it is easy to fault the theory in detail; for example, whereas Hoover and Gough emphasized the dependence of reading on spoken language, we now known that learning to read affects knowledge of spoken language in ways ranging from effects of alphabetic knowledge on the development of phonemic representations to the acquisition of vocabulary and knowledge of sentence structures that rarely occur in speech. Moreover, some properties of texts relevant to reading are not fully replicated in speech (e.g., writing styles, punctuation). Still, their essential insight was correct: A person's comprehension depends a great deal, if not exclusively, on knowledge of spoken language, modulo level of decoding skill (Braze, Tabor, Shankweiler, & Mencl, 2007). It is worth considering how this relation might play out across languages and orthographies.

For several years now, I've been tracking a tantalizing observation: Certain types of writing systems are used with certain types of languages. In particular, shallow orthographies are associated with languages with complex inflectional morphology (e.g., Serbo-Croatian, Finnish, German, Russian, Italian, Turkish), whereas the deeper orthographies are associated with relatively simple morphology (e.g., Chinese, English). I do not know of any systematic study of the relations between language typology and writing systems. I have probed for counterexamples to this generalization in many talks and have failed to uncover a convincing one. (French is the most frequently cited counterexample, insofar as the spelling–sound mappings are highly consistent and the inflectional morphology less complicated than in many European languages. However, the relevant metric is simplicity compared with English, which has minimal inflectional morphology, and Chinese, which has none. Also, it is the sound–spelling correspondences that are *très compliqué* in French.)

Perhaps the better way to state the generalization is that *if* a language has complex inflectional morphology, then it will have a shallow orthography. This correlation might be expected under an extension of the Simple View of Reading: Reading comprehension is a constant that is maintained via trade-offs between orthographic complexity (depth) and spoken language complexity (mainly realized in morphology, though other properties of languages probably also matter). For example, as the decoding difficulty term gets small (shallow orthography), the spoken language term gets large. I call this the Grapholinguistic Equilibrium Hypothesis. In exchange for getting spelling–sound correspondences for free, you, the reader, will also receive, at no extra charge, inflectional morphology that encodes number (2 levels), gender (3), and case (7). That would be Serbian. In English, you will have to suffer with irregularly pronounced words, but they will be mainly a) high-frequency words and b) shorter than you are used to because c) the inflectional system is trivial (mainly, number on nouns and tense on verbs, although Huddleston & Pullum, 2002, include a couple of other minor types). According to the Grapholinguistic Equilibrium Hypothesis, language typology and orthographic typology are linked with respect to reading comprehension. In essence, spoken languages get the writing systems they deserve.

Because spoken languages develop in advance of their written forms, how would this dependence between writing and speech come about? Clearly, flexibility is on the writing-system side. Consider again Serbo-Croatian, our quintessential shallow orthography. Serbo-Croatian has a complex inflectional system, no doubt. The system is so complex that it is difficult to merely state as a set of rules. Traditional grammars on this topic (e.g., Mirković & Vukadinović, 1991) run to hundreds of pages. There are often several-way contingencies that determine the overt form of a word, making it difficult to describe the system by using rules. For example, a representative rule is: the vocative singular form of singular nouns will have the suffix *-e* unless the stem ends in /ʃ/, /ʒ/, /tʃ/, /tɕ/, /dʒ/, /dʑ/, /j/, /λ/, or /ɲ/ when it will have *-u*; some of these nouns will also have variants ending in *-e*, as will some nouns with stems ending in /ar/ or /ir/.

We have developed connectionist models that learn parts of this system, treating it as statistical rather than rule-governed (Mirković, MacDonald, & Seidenberg, 2004; Mirković, Seidenberg, & Joanisse, in press). What we learned was that the inflections were not the only or even the principal source of learning difficulty; rather, it was deformations of the stem (base) morpheme conditioned on phonological properties of the inflection that were beastly. Consider the examples in Table 9.1: words that are morphologically related to the base form *savetnik* (masculine, *advisor*). The /k/ in the base form is either realized as a /k/ (in the genitive singular *savetnika* and the accusative plural *savetnike*), as /ts/ (nominative plural, *savetnici*), or as /tʃ/ (vocative singular, *savetniče*). In addition, the inflection *-e* is either preceded by /k/ (*savetnike*) or /tʃ/ (*savetniče*). Thus, it is not sufficient to merely learn the inflections associated with a given word in given gender, case, and number; the inflections and the base morphemes to which they attach are contingent on each other. Here is a clue as to why Serbian could not tolerate a deeper writing system: Imagine writing the language with the letters for vowels functioning as they do in English, each corresponding to several phonemes (e.g., *pop, pope, pond, port*). Or toss in a few random consonants with two pronunciations, such as the English *c* (as in *cap* or *cent*) and *g* (*goat, gin*). The complexity created by the inflectional system, including deformations of the stem morpheme, is high; adding ambiguity in the pronunciations of the written letters, might well create a writing

Table 9.1. Interdependence of morphological stem and inflection in Serbian

Word	Case and number	Inflection
SAVETNIK	Nominative singular	Zero inflected
SAVETNICI	Nominative plural	-I
SAVETNIKA	Genitive singular	-A
SAVETNIČE	Vocative singular	-E
SAVETNIKE	Accusative plural	-E

Note: All forms are masculine gender. K, = /k/ as in "Kevin," č = /tʃ/ as in "church," C = /ts/ as in "pizza."

system that is unreadable. There would be further problems if the full development of one's knowledge of the morphological system depended on instruction that itself involves reading.

These observations are speculative but seem to be worth pursuing further. What they suggest is that how reading occurs in different writing systems does not just depend on properties of the writing system; it also depends on properties of the language that the writing system represents, and the two appear to be closely interdependent. The hypothesis is that writing systems have to be adapted to the spoken language under functional constraints such as ease of learning and processing. Similarly, progress in learning to read depends in part on spoken language acquisition. Written Finnish is shallow, but Finnish children do not start formal education until they are age 6 or 7. Perhaps they need the extra time to work on their morphology.[8]

CONCLUSION

Our models provide a useful way to explore similarities and differences in how writing systems are read. The important concept concerns division of labor in a system that maps between different codes. The solution is driven by the need to compute meanings quickly and accurately and is modulated by properties of a writing system and the language it represents. Different balances between components of the reading model (including context) therefore result.

Most of the comparative research on reading that has been conducted to date has focused on one component of reading—orthography–phonology conversion—which underlies reading aloud. English is definitely deeper than other alphabetic writing systems, making reading aloud more difficult for young readers. I have cautioned against equating *reading aloud* with *reading,* and suggested that researchers begin looking beyond pronunciation to comprehension, which also reflects knowledge of a spoken language. Just as there are differences

[8]I say this in jest. Onset of formal schooling could well be determined by cultural rather than linguistic factors. It would be nice if whatever they are doing in Finland (which scores very high on Organization for Economic Cooperation and Development (OECD) cross-national comparisons of reading) could be exported to the United States, but per my analysis, it cannot because the writing systems and languages are so different.

across writing systems with respect to depth, there are differences across spoken languages with respect to the depth of components such as inflectional morphology. Conclusions about ease of learning to read, as opposed to ease of reading aloud, will depend on taking these spoken language differences into account.

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CHAPTER 10

Understanding Developmental Dyslexia Through Computational Modeling

An Individual Deficit-Based Simulation Approach

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Reading is a highly complex task that relies on the integration of visual, orthographic, phonological, and semantic information. The complexity of the reading task is clearly reflected in current computational models of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 1999; Perry, Ziegler, & Zorzi, 2007, 2010; Plaut, McClelland, Seidenberg, & Patterson, 1996; Zorzi, Houghton, & Butterworth, 1998). These models specify the ingredients of the reading process in a precise and detailed fashion, thus allowing researchers to simulate normal and impaired reading. Though models of skilled reading have become increasingly complex and detailed (Perry et al., 2007), theories of dyslexia have remained remarkably simple in the sense that most researchers in the field are committed to finding *single* deficits that would explain the abnormal reading performance of children with dyslexia, such as deficits in forming perceptual anchors (Ahissar, 2007), visual-attentional deficits (Vidyasagar & Pammer, 2010), cerebellar deficits (Nicolson, Fawcett, & Dean, 2001), rapid temporal processing deficits (Tallal & Piercy, 1973), or magnocellular deficits (Stein & Walsh, 1997).

A few dyslexia studies moved away from the single-deficit tradition by comparing competing accounts of dyslexia within the same participants—so-called *multiple-case studies* of dyslexia. For example, White et al. (2006) obtained data from 23 English-speaking children with dyslexia, ages 8–12 years, on a variety of tasks (phonology, visual motion, visual stress, auditory, and motor tasks) in order to contrast different theories of dyslexia. Though most of the participants with dyslexia showed severe phonological deficits, no evidence was obtained for visual deficits (although five dyslexics suffered from visual stress symptoms), a minority of children showed auditory deficits (4 out of 23), and a small group of dyslexics showed motor/cerebellar deficits (5 out of 23). In a similar study, Menghini et al. (2010) tested 60 Italian children with dyslexia and age-matched normally reading children on tests of phonological abilities, visual processing, selective and sustained attention, implicit learning, and executive functions. Although most of the dyslexics had phonological deficits (85% had deficits in phonological awareness and 75% had deficits in nonword repetition), there were other deficits noted: 16% of the dyslexics had deficits in visual-spatial