Towards a universal model of reading

Ram Frost

*Department of Psychology, The Hebrew University, Jerusalem 91905, Israel,
and Haskins Laboratories, New Haven, CT 06511*

frost@mscc.huji.ac.il
http://psychology.huji.ac.il/en/?cmd=Faculty.113&letter=f&act=
read&id=42~frost/
http://www.haskins.yale.edu/staff/ramfrost.html
http://psychology.huji.ac.il/en/

Abstract: In the last decade, reading research has seen a paradigmatic shift. A new wave of computational models of orthographic processing that offer various forms of noisy position or context-sensitive coding have revolutionized the field of visual word recognition. The influx of such models stems mainly from consistent findings, coming mostly from European languages, regarding an apparent insensitivity of skilled readers to letter order. Underlying the current revolution is the theoretical assumption that the insensitivity of readers to letter order reflects the special way in which the human brain encodes the position of letters in printed words. The present article discusses the theoretical shortcomings and misconceptions of this approach to visual word recognition. A systematic review of data obtained from a variety of languages demonstrates that letter-order insensitivity is *neither* a general property of the cognitive system *nor* a property of the brain in encoding letters. Rather, it is a *variant* and idiosyncratic characteristic of some languages, mostly European, reflecting a strategy of optimizing encoding resources, given the specific structure of words. Since the main goal of reading research is to develop theories that describe the *fundamental and invariant* phenomena of reading across orthographies, an alternative approach to model visual word recognition is offered. The dimensions of a possible universal model of reading, which outlines the common cognitive operations involved in orthographic processing in all writing systems, are discussed.

Keywords: learning models; letter position coding; lexical organization; lexical space; morphological processing; structured models; visual word recognition

1. Introduction

The business of modeling visual word recognition has never been better. In the last decade, computational models of reading[1] have been produced at an impressive rate. However, whereas the previous generation of reading models of the 1980s and 1990s (e.g., the Serial Search Model, Forster 1976; the Interactive Activation Model [IAM], McClelland & Rumelhart 1981; the Distributed Developmental Model, Seidenberg & McClelland 1989; and the Dual Route Cascaded Model (DRC), Coltheart et al. 2001) aimed at providing a *general* framework of lexical structure and lexical processing, addressing a relatively wide range of reading phenomena (e.g., word superiority effect, context effects, phonological computation, consistency by regularity interaction, reading aloud and reading disabilities, etc.), the new wave of modeling seems to have focused mostly on the front end of visual word recognition. The influx of such models, which center on orthographic processing, stems mainly from consistent findings coming from a variety of languages, such as English, French, and Spanish, regarding an apparent insensitivity of skilled readers to letter order. Typically, these findings have demonstrated a surprisingly small cost of letter transpositions in terms of reading time, along with robust priming effects when primes and targets share all of their letters but in a different order (e.g., Duñabeitia et al. 2007; Johnson et al. 2007; Kinoshita & Norris

2009; Perea & Carreiras 2006a; 2006b; 2008; Perea & Lupker 2003; 2004; Rayner et al. 2006; Schoonbaert & Grainger 2004).

The important role of registering letter position during the process of visual word recognition and reading seems almost self-evident. Printed letters are visual objects, and the fast saccades that characterize text reading necessarily involve some level of uncertainty regarding their exact identity and location. Indeed, general concerns regarding letter-position coding have already been acknowledged in the seminal discussion of the Interactive Activation Model (Rumelhart & McClelland 1982), and some proposals for alternative coding schemes have been subsequently

---

RAM FROST is a full professor in the Department of Psychology at the Hebrew University of Jerusalem, and a member of Haskins Laboratories in New Haven, Connecticut. He received his Ph.D. in Cognitive Psychology from the Hebrew University. His research focuses on the cognitive processes involved in visual word recognition, investigating what is universal in the reading process across diverse languages, and what aspects of reading are unique to each language's orthographic and morphological system. Among his theoretical contributions to reading research are the Orthographic Depth Hypothesis and the Strong Phonological Theory of Visual Word recognition.

offered (e.g., Seidenberg & McClelland 1989; see also Bruner & O'Dowd 1958).

In this context, the apparent indifference of readers to letter order, reported in many studies, has revolutionized the modeling of visual word recognition. Underlying this revolution is the theoretical assumption that insensitivity to letter order reflects the special way in which the human brain encodes the position of letters in printed words (e.g., Grainger & Whitney 2004; Whitney 2001; Whitney & Cornelissen 2005). As a consequence, the old computational models that encoded letter positions in rigid and absolute terms (e.g., IAM, McClelland & Rumelhart 1981; DRC, Coltheart et al. 2001; or CDP [connectionist dual-process model], Zorzi et al. 1998) were out, to be replaced by models involving letter position uncertainty, either through various forms of context-sensitive coding or by introducing noisy letter positions (e.g., the sequential encoding regulated by inputs to oscillating letter [SERIOL] model, Whitney 2001; the self-organizing lexical acquisition and recognition [SOLAR] and the Spatial Coding model, Davis 1999; 2010; the Bayesian Reader model, Norris et al. 2010; the Overlap model, Gomez et al. 2008; the dual-route model of orthographic processing, Grainger & Ziegler 2011; see also Grainger & van Heuven 2003; Grainger et al. 2006). This constitutes a dramatic paradigm shift, since the fuzzy encoding of letter order has become a primary component of modeling visual word recognition and reading. More importantly, by focusing almost exclusively on issues of processing letter sequences and on letter position, reading, and visual word recognition, research has shifted to produce theories of orthographic processing per se, some with the explicit aim of "cracking the orthographic code" (for a detailed discussion, see Grainger 2008).

Admittedly, some of the extensive empirical work regarding indifference of readers to letter order has focused on whether the locus of the effect is morphological (e.g., Christianson et al. 2005; Duñabeitia et al. 2007), or phonological (e.g., Acha & Perea 2010; Perea & Carreiras 2006a; 2006b; 2008), and some experiments examined the interaction of letter-position coding with consonant versus vowel processing (e.g., Perea & Lupker 2004). Nevertheless, the main conclusion of these studies was that transposed letter (TL) effects are orthographic in nature (e.g., Perea & Carreiras 2006a; 2006b). Purely orthographic models were considered, therefore, to have substantial descriptive adequacy, thereby accounting for a large set of data. Consequently, they were taken to represent a viable approach to visual word recognition without the need to revert to phonological or morphological considerations (for a discussion, see, e.g., Davis 2010). This inevitably narrows the array of phenomena that can be explained by the models, limiting them mainly to effects related to various aspects of orthographic form.

Paradigmatic shifts, however, should emerge only following extensive theoretical debates. If not, they may reflect only occasional fluctuations of trends and fashion, to which even scientific inquiry is not immune. The present article takes the recent wave of modeling visual word recognition as an example of how interesting findings can eventually lead to a generation of narrow, and therefore, ill-advised models. Through a comprehensive discussion of the theoretical shortcomings underlying the basic approach of current trends of modeling reading, it aims

to outline alternative directions. These directions emerge from the following claims: Orthographic effects in visual word recognition, such as sensitivity or insensitivity to letter order or any other phenomena, are the product of the *full* linguistic environment of the reader (phonology, morphology, and semantic meaning), not just the structure of orthographic letter sequences. Orthographic processing cannot be researched, explicated or understood, without considering the manner in which orthographic structure represents phonological, semantic, and morphological information in a given writing system. Therefore, only models that are tuned, one way or another, to the full linguistic environment of the reader can offer a viable approach to modeling reading. A word of caution though: The following discussions are not aimed at proposing specific blueprints for a new computational model of orthographic processing, nor do they point to specific modeling implementations. Their goal is to set the principles for understanding, researching, and consequently modeling the processing of printed information.

1.1. The "new age" of orthographic processing

The recent wave of modeling visual word recognition has focused on a series of findings, all related to the manner by which readers treat the constituent letters of printed words. The original demonstration that letter transposition in the prime results in significant facilitation in recognizing the target, was reported by Forster et al. (1987), who showed that TL primes (anwser–ANSWER) produce priming as large as identity primes (answer–ANSWER). This surprising effect was followed up by Perea and Lupker who systematically examined whether and how this effect varies as a function of letter position (Perea & Lupker 2003, 2004). Subsequent research on eye movements argued that letter transpositions result in some cost in terms of fixation-time measures on target words during reading (Johnson et al. 2007; Rayner et al. 2006). This cost, however, seemed relatively small in magnitude. In parallel, in 2003, a demonstration of how reading is resilient to letter transposition became well known via a text composed entirely of jumbled letters which was circulating over the Internet. This demonstration, labeled "the Cambridge University effect" (reporting a fictitious study allegedly conducted at the University of Cambridge), was translated into dozens of languages and quickly became an urban legend. Consecutive follow-up studies reported that insensitivity to letter transpositions in reading can be revealed in a variety of languages, such as French (Schoonbaert & Grainger 2004), Spanish (Perea & Carreiras 2006a; 2006b; Perea & Lupker 2004), Basque (Duñabeitia et al. 2007; Perea & Carreiras 2006c), and Japanese Kana (Perea & Perez 2009). The facilitation caused by TL primes was shown even with extreme distortions when several letters are jumbled (snawdcih–SANDWICH; Guerrera & Forster 2008). The abundant evidence regarding TL priming converged with other forms of priming that suggested non-rigidity of letter-position coding. For example, in an extensive investigation, Humphreys et al. (1990) showed that primes consisting of a subset of the target's constituent letters, which kept the *relative* but not the absolute position of letters (blck–BLACK), produce significant priming. Similar effects of relative-position priming were reported by Peressotti and Grainger

(1999) and by Grainger et al. (2006). Relative-position priming has also been demonstrated with superset priming where primes contain more letters than the target (juastice–JUSTICE; Van Assche & Grainger 2006).

The "new age of orthographic processing" reflects an increased interest and preoccupation with how the cognitive system encodes and registers letter sequences. Underlying this paradigmatic approach is an implicit and almost self-evident assumption that *the game of visual word recognition is played mainly in the court of constituent letter recovery*. The main focus of the new-age approach is, therefore, the level of processing where letter-position coding is approximate rather than specific (for a discussion, see Grainger 2008; Grainger & Ziegler 2011). Given the abundant evidence regarding relative insensitivity to letter position, the emergent new models of reading focused on finding creative solutions to produce what seemed to be the main characteristic of reading: letter-position flexibility.

For example, both the SOLAR model offered by Davis (1999) and the recent Spatial Coding model (Davis 2010) adopt the idea of spatial coding and encode relative letter position by measures of relative pattern of activity across letters in a word (see also Davis & Bowers 2004; 2006). The SERIOL model (Grainger & Whitney 2004; Whitney 2001; 2008; Whitney & Cornelissen 2008) is based on a serial activation of letter detectors that fire serially in a rapid sequence (but see Adelman et al. [2011] for counterevidence regarding serial processing). This firing sequence serves as input to a layer of "open bigram" units, which do not contain precise information about letter contiguity but preserve information regarding relative position. For example, the word *FORM* would be represented by activation of the bigram units #F, FO, OR, RM, but also FR, OM, and M#, where # represents a word boundary. A transposition prime, such as FROM, would then share all but one of these units, namely, #F, FR, FO, RM, OM, and M#, resulting in substantial priming.

Other models obtain letter-position flexibility by assuming noisy slot-based coding. For example, The Overlap model (Gomez et al. 2008) posits a noisy letter-order scheme in which information regarding order of letters becomes available more slowly than information about letter identity. Similarly, to accommodate TL effects, Kinoshita and Norris (2009), Norris and Kinoshita (2008), and Norris et al. (2010) have implemented as part of their computational model a noisy letter-position scheme in which, in the limited time available for which the prime is presented briefly, information regarding order of letters, as well as information about letter identity, is ambiguous. In a similar vein, a combination of noisy retinotopic letter coding with either contiguous bigram detectors (Dehaene et al. 2005) or location-specific letter detectors (Grainger et al. 2006) was suggested as well to account for letter-position flexibility. Note that although all of the aforementioned models deal in one way or another with letter-position flexibility, they naturally differ in the scope of phenomena they describe. Hence, while context-sensitive coding models such as SERIOL focus on finding inventive solutions for representing a string of letters, models like the Bayesian Reader model (Norris et al. 2010) or the Spatial Coding model (Davis 2010) offer a rather broad and comprehensive view of visual word recognition and reading. Nevertheless, discussions regarding the descriptive adequacy of all of these models have centered mainly on their relative ability to predict effects of TL priming and to reproduce a continuum of TL priming effects, given different types of distortion in the sequence of letters. For example, almost all of the 20 simulations offered to validate the recent Spatial Coding model (Davis 2010) deal in some way with transposed-letter priming effects.

Interestingly, most of the abovementioned models have argued that letter-position flexibility reflects *general and basic brain mechanisms* (e.g., neural temporal firing patterns across letter units, Whitney 2001; noisy retinotopic firing, Dehaene et al. 2005; split of foveal vision and interhemispheric transfer costs, Hunter & Brysbaert 2008; Shillcock et al. 2000). This claim, in the context of modeling visual word recognition, does not merely aim to make the models neurologically plausible, or to extend reading research to include in it also a description of the neurocircuitry of the visual system – the claim is deeply theoretical in terms of reading theory, because it is based on a general argument regarding *the brain and lexical processing*.

The present article attempts to discuss the theoretical shortcomings of this approach to visual word recognition. As will be argued, sensitivity to letter order per se does not tell us anything interesting about how the brain encodes letter position, *from the perspective of a theory of reading*. Instead, it tells us something very interesting about how the cognitive system treats letters *in specific linguistic environments*. To reiterate, it is not the neurological claims about noisy retinotopic firing or about neural temporal firing which are being contested. Obviously, the architecture of neural circuitry determines the way visual information is encoded and consequently processed in the cortex. What is being challenged is the implication of these facts for lexical architecture and understanding reading. As a corollary claim I will argue that, as a general strategy, to focus only on orthographic coding in a model, by mapping various types of input structure of letter units to an output structure of word units while disregarding the contribution of phonological, semantic, or morphological factors to the process, can perhaps produce a desired behavior in terms of letter flexibility, but misses the complexity and interactivity of the reading process.

2. Preliminary assumptions

The main goal of reading research is to develop theories that describe and explicate the *fundamental* phenomena of reading. Our models are major tools in developing such theories, so that they have descriptive and explanatory adequacy. I propose, therefore, two main criteria for assessing their potential contribution. Since the merits or shortcomings of approaches for modeling reading are a major focus of the present article, a brief exposition of these criteria will set common ground for the following discussion.

2.1. The universality constraint

Our first criterion is that models of reading should be universal in the sense that they should aim to reflect the *common* cognitive operations involved in treating printed language across different writing systems. Languages naturally differ in their scripts and orthographic principles.

A good theory of reading should be able to describe and explicate, as a first step, the cognitive procedures that are implicated in processing printed words in *any* orthography, focusing on (1) what characterizes human writing systems, and (2) what characterizes the human cognitive system that processes them. I will label these common cognitive procedures *reading universals*. Only when the reading universals are well defined and well understood can diverging predictions in cross-linguistic research be formulated a-priori (see Perfetti [2011] for a discussion of a universal reading science). Consider, for example, language X that shows some consistent pattern of behavior across readers, and language Y that consistently does not. Our theory of reading should be able to suggest a higher-level principle that simultaneously accounts for both phenomena. If it cannot, then our set of reading universals is probably incomplete or possibly wrong. Naturally, the set of reading universals ought to be quite small, general, and abstract, to fit all writing systems and their significant inter-differences.

Reading universals are empirically established, and can be supported or falsified only through cross-linguistic research. Obviously, models of reading could be locally formulated to describe the idiosyncratic properties of reading one specific language or even a group of languages, thereby not satisfying the universality constraint. However, in this case, their narrower aim should be stated explicitly. The impact of these models would be greatly reduced since they are not actually part of a general reading theory. As I subsequently argue and demonstrate, most current models of orthographic processing are not universal.

2.2. Linguistic plausibility

Models of visual word recognition deal with words, and words have orthographic, phonological, semantic, and morphological characteristics. Although any given model may focus on any one of these properties and not on others, it should be nevertheless constrained by findings related to the other linguistic properties of words. A model of orthographic processing, therefore, could exclusively describe the processes involved in the perception and analysis of printed letters, and, consequently, the model may not derive predictions regarding, say, phonological, semantic, or morphological priming. *The requirement of linguistic plausibility simply states that the model should, in principle, be able to accommodate the established findings related to all linguistic dimensions of printed words, or at least it should not be structured in a way that goes counter to the established findings for other linguistic dimensions.* Thus, if, for example, a model of orthographic processing accurately predicts letter-transposition effects, but its architecture runs counter to what we know about morphological or phonological processing, then the model does not maintain linguistic plausibility. The requirement regarding linguistic plausibility is based on a simple argument: *Orthographic processing by itself is not an independent autonomous process in cognition, separable from other aspects of language, because its output must be consistent with other linguistic dimensions it is supposed to represent or feed into.* Printed words were designed from the outset in any writing system to represent spoken forms, which bear meaning. Hence, orthographic structure represents a single dimension of a complex lexical

architecture. Our theory of orthographic processing should, therefore, in principle, fit into a general theory of meaning recovery.

Having set the two main criteria for assessing models of visual word recognition, I will first proceed with a detailed exposition of the nature of writing systems in general and orthographic structure in particular. What drives this exposition is the claim that the orthography of any given language has evolved as a result of the linguistic environment specific to that language, and naturally it cannot be treated as independent of it. Since in every language a different solution for representing phonology and meaning by print has evolved, the process of extracting linguistic information from the graphemic array in one language may be quite different than in another language, already at the early phases of print processing. The aim of the following section is, then, to set the grounds for explicating why readers in different writing systems extract from similar sequences of letter strings different types of information, and why orthographic coding in one language may be quite different than in another language.

3. Every language gets the writing system it deserves[2]

Humans speak about 3,000 languages,[3] and a significant number of these languages have their own writing system. At first blush, what determines the large variance in spoken languages and writing systems seems arbitrary, in the sense that it reflects mainly historical events or chance occurrences such as emerging local inventions or diffusion due to tribal migration. However, although such chance events lie at the origin of many writing systems, close scrutiny suggests that, to a large extent, the way they have eventually evolved is not arbitrary. Rather, orthographies are structured so that they optimally represent the languages' phonological spaces and their mapping into semantic meaning; and simple principles related to *optimization of information* can account for the variety of human writing systems and their different characteristics. *Outlining these principles is important from the perspective of modeling reading because they provide critical insight regarding how the cognitive system picks up the information conveyed by print.* Here I promote a view that has the flavor of a Gibsonian ecological approach (Gibson 1986) and assumes that, to be efficient, the cognitive system that processes language must be tuned to the structure of the linguistic environment in which it operates.

The common taxonomy of writing systems focuses on the way the orthographic units represent the phonology of the language. This is the origin of the orthographic depth hypothesis (ODH; Frost et al. 1987; Katz & Frost 1992) and of the grain-size theory (Ziegler & Goswami 2005), which classify orthographic systems according to their letter-to-phoneme transparency. This approach to reading originates from extensive research in European languages where the main differences in reading performance, the speed of reading acquisition, and the prevalence of reading disabilities were taken to result mainly from the opaque or transparent relations of spelling to sound in a given language (e.g., Seymour et al. 2003; Ziegler et al. 2010). The view that the recovery of phonological information is the main target of reading (see Frost [1998] for

an extensive review and discussion of the strong phonological theory) underlies the common characterization of writing systems as differing mainly on the dimension of phonological transparency. The aim of the present section of our discussion is to widen the perspective of what writing systems are, beyond the typical (and probably simplistic) distinctions regarding phonological transparency. The focus on this factor alone for characterizing writing systems is heavily influenced by research in European languages, mostly English (see Share [2008a] for a discussion of extensive Anglocentricities in reading research). Thus, by describing the writing system of five distinctive languages, the way they have evolved, and the manner by which the orthographic information optimally represents the phonological space of the language *and* its semantic and morphological structure, possible inferences can be drawn regarding how print is processed.

3.1. Print as an optimal representation of speech and meaning

One important fact guides this part of the discussion: Although print was invented to represent speech, spoken communication is much richer than the writing system that represents it. Specific lexical choices of words and meaning are conveyed in spoken communication by a wide array of signals, such as stress, intonation, timing of spoken units, or even hand movements, which do not usually exist in print. This means that, as a rule of thumb, *print is underspecified in any language relative to the speech it is supposed to represent. The evolution of writing systems reflects, therefore, some level of optimization aimed at providing their readers with maximal phonological and semantic information by the use of minimal orthographic units for processing.* However, given the specific characteristics of a particular language, what constitutes "optimization" in language A may be quite different from what constitutes optimization in language B. This, as I will show, is crucial for understanding orthographic processing.

Considering the variety of human languages, they differ, first, in the structure of their phonological space, and in the way that phonological units represent morphemes and meaning. This structure represents the *ecological environment* in which orthographies have evolved in a process similar to natural selection, to allow native speakers the most efficient representational system. Putting the conclusion of this section first: In order to be efficient, the cognitive operations that readers launch in processing their print, that is, the "code" they generate for lexical processing, must be tuned to the idiosyncratic characteristics of their own representational system. I label this *linguistic coherence*. Thus, to process orthographic structure, the system must be sensitive to the optimal representation of *several* linguistic dimensions, in order to extract from the print maximal information. Hence, a model of reading that is linguistically coherent must likewise include a level of description that contains *all* aspects of the language in which reading occurs. *This means that a theory of visual word recognition cannot be simply "orthographic," because the information that is extracted from print concerns complex interactions of orthography, phonology, morphology, and meaning. A model of orthographic processing, therefore, cannot be blind to this factor.*

In the following exposition, five contrasting languages are described: Chinese – a Sino-Tibetan language; Japanese – an Altaic language; Finnish – a Finno-Ugric language; English – an Indo-European language; and Hebrew – a Semitic language. These five languages have distinct phonological, grammatical, and orthographic features, providing good coverage of the linguistic diversity in the world. The aim of this brief exposition is to demonstrate that the evolution of writing systems is not arbitrary, but mirrors a process of optimization, which is determined by constraints of the cognitive system (see Gelb [1952] for similar arguments). These constraints concern efficiency of processing, where a substantial amount of information needs to be packed in a way so that readers of the language are provided with maximal semantic, morphological, and phonological cues via minimal orthographic units. I should emphasize, then, that the purpose of the following description of writing systems is not to provide a theory of structural linguistics. What underlies this description is a deep theoretical claim regarding reading universals. *For, if there are common principles by which writing systems have evolved to represent orthographic information in all languages, then this must tell us something interesting about how the cognitive system processes orthographic information.* If writing systems in different languages all share common strategies to provide their readers with optimal linguistic information, then it must be that the processing system of readers is tuned to efficiently pick up and extract from print this optimal level of linguistic information. From this perspective, finding commonalities in the logic behind the evolution of different orthographies should have consequences for our theory of orthographic processing.

3.2. Five contrasting languages

3.2.1. Chinese. In Chinese, words are in most cases monomorphemic without much affixation, and the morphemic units (the words) are also monosyllabic. The permissible syllable in Chinese has no more than four phonemes (relative to seven in English). This basic structure of the language can be considered arbitrary, in the sense that the phonological space of Chinese could, in principle, have been different. However, once this phonological space has been established in the way it has, all resulting linguistic developments are to some extent entirely predetermined. For example, if all words in a language are monosyllabic, and if the syllabic structure is constrained to no more than four phonemes, then the number of possible Chinese words is necessarily small because the number of permissible syllables is small. This determines extensive homophony to represent the large variety of semantic meanings for meaningful complex communication (see, e.g., Chao 1968). Homophony is indeed a main feature of Chinese: sometimes up to 20 different words (different meanings) are associated with a given syllable. In the spoken language, some of this homophony is resolved and disambiguated by the tones added to the syllable: high or low, rising or falling. Print, however, is underspecified relative to speech. Hence, a solution for disambiguating the extensive syllabic homophony in print had to evolve for accurate communication. It is in this perspective that the logographic writing system of Chinese should be considered – a writing system in which different semantic

radicals accompany similar phonetic radicals, to denote and differentiate between the large number of morphemes that share a given syllabic structure (for a detailed review, see Wang et al. 2009).

The structure of Chinese characters provides an additional insight. Most characters are lexically determined by a semantic radical appearing in most cases on the left side, and then the phonetic radical suggesting how to pronounce the character is added on the right side. Looking up characters in the Chinese dictionary follows the same principle: The semantic component of a character determines the initial entry, and then the cues regarding how to pronounce it consist of necessary complementary information. Semantic information comes first, therefore, and phonetic information comes second. Indeed, in his taxonomy of languages, DeFrancis (1989) categorized Chinese as a "meaning-plus-sound" syllabic system (for a similar characterization, see Wang et al. 2009).

The lesson to be learned from Chinese is that writing systems are not set to simply provide their readers with a means for retrieving, as quickly as possible, a phonological structure. If that were the case, an alphabet that represents the syllables of Chinese would have been employed. Writing systems evolve to provide *optimal* information by weighting the need for maximal cues about the spoken words and their specific meanings while using minimal orthographic load.

3.2.2. Japanese. In comparison to Chinese, the permissible syllabic structure of Japanese is even more constrained and consists mostly of CV or V units.[4] However, in contrast to Chinese, words are not monosyllabic. Since words in Japanese can be composed of several syllables, tones were not necessary for constructing the sufficient number of lexical units that are required for a viable language, and indeed Japanese is not a tonal language. With about 20 consonants and 5 vowels, Japanese has 105 permissible phonological units, named *mora*, which consist of the basic sublinguistic phonological units of the language. A mora is a temporal unit of oral Japanese, the unit with which speakers control the length of word segments, and it eventually determines the length of spoken words (see Kubozono 2006). This is a very brief and rudimentary description of Japanese phonological space; however, the consequent implications for their writing system can be explicated using the same form of evolutionary arguments as in Chinese.

Historically, the first writing system of Japanese was *kanji*, a logographic script whose characters were imported from Mainland China (see Wang [1981] for a review). About 2,130 characters represent the current kanji script of Japanese. Since the Chinese characters along with their phonetic radicals were imported and used to represent Japanese words, which have an entirely different phonological structure, an interesting question is why kanji characters were at all appealing to Japanese speakers. Although any kind of answer would be speculative at best, a probable account seems to lie again in the restricted phonological units (words) that can be formed in Japanese, given the strict constraints on syllabic (mora) structure. If the number of permissible morae is relatively small given their very constrained structure, in order to create a sufficient number of words necessary for rich communication, the only solution is to allow for relatively large strings of

morae. This, however, is not an optimal solution in terms of spoken communication (for a discussion of word length and efficient communication, see Piantadosi et al. 2011). In Japanese, words consist then in most cases of two to four morae. This again inevitably leads to a significant level of homophony, as a relatively small number of phonological forms denote a large amount of semantic meanings that are necessary for rich communication. Japanese indeed has significant homophony (although to a much lesser extent than Chinese). The use of kanji served the purpose of resolving the semantic ambiguity underlying a high level of homophony. Indeed, the kanji characters in Japanese help in denoting specific meanings of homophones (see Seki [2011] for a detailed description).

However, following the introduction of Chinese characters to Japan, another phonographic writing system (*hiragana* and *katakana*) evolved to represent the spoken language, and this evolution was to some extent inevitable as well. Note that in contrast to Chinese, Japanese is not a mono-morphemic language. The kanji characters could not be used to denote morphological inflections. Since writing systems are primarily designed to represent meaning to readers often through morphological information (e.g., Mattingly 1992), some phonetic symbols had to be inserted to convey inflections and derivations. This is the origin of the phonographic hiragana, a script that emerged given the morphological structure of the language. In addition to hiragana, katakana graphemes were also added to denote loan words, which obviously cannot be represented by the kanji characters. It could be argued that the use of two phonographic scripts, hiragana and katakana, is a luxury of dubious utility; however, the advantage of this notation is that it emphasizes morphological internal structure, by assigning a separate writing system to denote morphological information. This "choice" of writing systems to emphasize morphemic constituents is consistent, and can also be demonstrated in English or in Hebrew, although with the use of different principles.

The manner with which Japanese phonograms represent the spoken subunits of the language is also not arbitrary. From a perspective of information efficiency, the optimal solution for representing the sub-linguistic units of Japanese is graphemes representing the relatively small number of morae. An alphabet where letters represent single phonemes would not do, since Japanese is a *morae-timed* language,[5] and phoneme representation would not be optimal. Memorizing 105 graphemes for decoding is pretty easy. Not surprisingly then, in the phonographic kana, letters represent morae, and Japanese children easily master the kana writing system at the beginning of the first grade, with a relatively low rate of reading disabilities in this writing system[6] (Wydell & Kondo 2003; Yamada & Banks 1994). More important, given the perfect match between Japanese phonological space and its representing writing system, children acquire a meta-awareness of morae at about the time they learn to read (Inagaki et al. 2000), similar to the development of phonemic awareness following reading acquisition in alphabetic orthographies (e.g., Bentin et al. 1991; Bertelson et al. 1985; Cossu et al. 1988; Goswami 2000). The lesson to be learnt from Japanese is, again, that the phonological space, the manner by which it conveys meaning, and the morphological structure of the language predetermine

the main characteristics of the writing system. Indeed, using kana-kanji cross-script priming, Bowers and Michita (1998) have elegantly demonstrated how the orthographic system of Japanese must interact with phonology and semantics to learn abstract letter and morphological representations.

3.2.3. Finnish. Finnish is considered a "pure phonemic system" like Greek or Latin (DeFrancis 1989). There are 24 Finnish phonemes, 8 vowels, and 16 consonants (one consonant conveyed by the two-letter grapheme NG). The consistency of grapheme-to-phoneme is perfect, with 24 correspondences to be learnt only. Some phonemes are long, but doubling the corresponding letters conveys these. Finnish thus represents the perfect example of an orthography that is fully transparent phonologically (Borgwaldt et al. 2004; 2005; Ziegler et al. 2010).

In the context of the present discussion, the interesting aspect of Finnish is its morphological structure as reflected by its agglutinative character (Richardson et al. 2011). In Finnish, compounding is very common, and printed words often have even 18–20 letters, so printed entities such as *liikenneturvallisuusasiantuntija* (expert in travel safety) are not rare (see, e.g., Bertram & Hyönä 2003; Kuperman et al. 2008). Here again, the question of interest concerns the relation between the excessively agglutinative aspect of the language and the complete transparency of the orthographic system. This relation can be explicated by using the same principles of optimization of information. Condensing information in a letter string has the advantage of providing more semantic features in a lexical unit. The question is whether the writing system can support this information density, considering the decoding demands imposed by very long letter-strings. If only 24 letter–phoneme correspondences need to be used, then the reading of very long words is easy enough. Thus, the combination of extreme transparency and compounding provides speakers of Finnish with an optimal ratio of semantic information to processing demands. The lesson to be learnt from Finnish is, again, that nothing is arbitrary when it comes to orthographic structure. If entropy of letter to sound is zero, orthographic structure becomes denser, to pack maximal morphological information. The orthographic processor of Finnish readers must be tuned to this.

3.2.4. English. English is an Indo-European language with an alphabetic writing system which is morpho-phonemic. Two main features characterize the very complex English phonological space. First, English has about 22 vowels,[7] 24 consonants, and the permissible syllable can be composed of 1–7 phonemes (Gimson 1981). This brings the number of English syllables to about 8,000 (DeFrancis 1989). Obviously, this huge number does not permit any syllabic notation such as in Japanese, and, not surprisingly, English is alphabetic-phonemic. There has been abundant discussion of the extreme inconsistencies in the representation of individual phonemes in English (e.g., Borgwaldt et al. 2004; 2005; Frost & Ziegler 2007; Ziegler et al. 2010). Some of these inconsistencies stem from simple historical reasons – mainly influences from German or Dutch (e.g., *knight/knecht*) – and some have to do with the dramatic disproportion of number of vowels and vowel letters; but the main source of the English writing system inconsistency is its morpho-phonemic structure.

In English, unlike most, if not all, Indo-European languages, morphological variations are characterized by extensive phonological variations. Thus, derivations and inflections, addition of suffixes, changes in stress due to affixation, and so forth, very often result in changes of pronunciation (e.g., h<u>ea</u>l/h<u>ea</u>lth, courage/courag<u>e</u>ous, cat<u>s</u>/dog<u>s</u>). Given this unique aspect of spoken English, the evolution of its writing system could have theoretically taken two possible courses. The first was to follow closely the phonological forms of the language and convey to the reader the different pronunciations of different morphological variations (e.g., heal–helth). The second was to represent the morphological (and thereby semantic) information, irrespective of phonological form. Not surprisingly, the writing system of English has taken the second path of morphophonemic spelling, and, given the excessive variations of phonological structure following morphological variations, English orthography has evolved to be the most inconsistent writing system of the Indo-European linguistic family. The lesson to be learnt from English is that writing systems, whenever faced with such contrasting options, necessarily evolve to provide readers with the meaning of the printed forms by denoting their morphological origin, rather than simplifying phonological decoding. Hence, recent suggestions that English spelling should be reformed[8] and be "made consistent" stem from a deep misunderstanding of the evolution of writing systems. As already stated, every language gets the writing system it deserves. The inconsistent writing system of English is inevitable, given the characteristics of the language's phonological space. In spite of its excessive inconsistency, it still reflects an optimization of information by providing *maximal* morphological (hence semantic) cues along with relatively impoverished phonological notations, using *minimal* orthographic symbols. Again, as will be explicated, this has immediate implications for lexical structure and lexical processing.

3.2.5. Hebrew. In the context of the present discussion, Hebrew provides the most interesting insights regarding the rules that govern the logic of evolution of writing systems. Its description, therefore, will be, slightly extended. Hebrew is a Semitic language, as are Arabic, Amharic, and Maltese. Semitic languages are all root-derived, so that the word's base is a root morpheme, usually consisting of three consonants, and it conveys the core meaning of the word. Semitic words are always composed by intertwining root morphemes with word-pattern morphemes – abstract phonological structures consisting of vowels, or of vowels and consonants, in which there are "open slots" for the root's consonants to fit into. For example, the root Z.M.R. that conveys the general notion of "singing," and the word pattern /ti– –o–et/, which is mostly used to denote feminine nouns, form the word /tizmoret/ meaning "an orchestra." Thus, the root consonants can be dispersed within the word in many possible positions. There are about 3,000 roots in Hebrew, 100 nominal word patterns, and 7 verbal patterns (see Shimron [2006] for a review).

Since Semitic words are generally derived from word patterns, they have a recognizable and well-defined internal structure. Word patterns can begin with a very restricted number of consonants (mainly /h/, /m/, /t/, /n/, /l/), and these determine a set of transitional probabilities regarding

the order and identity of subsequent consonants and vowels. To cast it again in evolutionary terms, this bi-morphemic structure is obligatory. If the language is root-based, and the roots convey the core meaning of words, they need to be easily extracted and recognized by the speaker. Because there are no a priori constraints regarding the location of root consonants in the word, the only clue regarding their identity is the well-defined phonological structure of the word, which allows the root consonants to stand out. This, as will be shown, has important implications for orthographic processing in Hebrew.

The major characteristic of the Hebrew writing system is its extreme under-specification relative to the spoken language. Hebrew print (22 letters) was originally designed to represent mostly consonantal (root) information. Most vowel information is not conveyed by the print (Bentin & Frost 1987). There are two letters that, in certain contexts, convey vowels: one for both /o/ and /u/, and one for /i/; however, these letters also convey the consonants /v/ and /y/, respectively. Hebrew print consists, then, of a perfect example of optimization of information, where crucial morphological (and therefore semantic) features are provided, along with sufficient phonological cues, through the use of minimal orthographic symbols. The minimalism of orthographic notation serves an important purpose: It enables an efficient and very fast extraction of root letters from the letter string; the smaller the number of letters, the easier the differentiation between root letters and word-pattern letters. This obviously comes with a heavier load on the reader when it comes to phonological decoding demands, since a substantial part of the phonological information is missing (see Frost 1994; 1995). However, because the structure of spoken words is highly constrained by the permissible Semitic word patterns, these decoding demands are significantly alleviated. Readers can converge on a given word pattern quite easily with minimal orthographic cues, especially during text reading when the context determines a given word pattern with relative high reliability; and once a word pattern has been recognized, the full vowel information is available to the reader, even if it is not specified by the print (Frost 2006).

The logic of this flexible evolutionary system can be demonstrated in considering the changes introduced into the Hebrew writing system throughout history. As long as biblical Hebrew was a live spoken language, its writing system was mainly consonantal, as described so far. However, following the historical destruction of the Hebrew-speaking national community by the Romans, Hebrew became a non-living language. If the language ceases to be spoken on a regular basis, the missing vowel information is not available to the reader at the same ease and speed as it is with spoken languages, and this increases the load of phonological decoding demands. Since the balance of optimization of information has shifted, around the 8th century vowel signs were introduced into Hebrew through the use of diacritical marks in the form of points and dashes under the letters ("pointed Hebrew"), to alleviate the problem of phonological opacity. This served the purpose of reading religious scripts and prayer books fluently enough, without the need for semantic feedback or morphological analysis (i.e., decoding without understanding).[9]

The move from consonantal to pointed Hebrew demonstrates how the weight of orthographic, semantic, and

phonological information in writing systems can dramatically shift due to changes in the linguistic environment. From the moment that phonological decoding could no longer rely on semantic feedback, orthographic structure had to change to become more complex and overburdened to supply the missing phonological information. At the end of the 19th century, Hebrew began to be reinstated as a spoken language. Without any formal decision regarding reforms in writing, and in less than a few decades, the vowel marks were naturally dropped from the Hebrew writing system, as was the case in ancient times. Thus, from the moment that the Hebrew language was revived, the balance of optimization shifted as well, and naturally reverted towards the use of minimal orthographic symbols. Today, Hebrew vowel marks are taught in the first grade, assisting teachers in developing their pupils' decoding skills during reading acquisition. However, starting from the end of the second grade, printed and written Hebrew does not normally include diacritical marks.

3.2.6. Summary. To summarize this section, we have examined five writing systems that evolved in five languages, demonstrating that orthographic structure provides readers with different types of information, depending on the language's writing system. The question at hand is whether this description is at all relevant to orthographic processing. *The crucial debate then centers on whether the fact that different orthographies consist of different optimization of phonological, morphological, and orthographic information has behavioral implications in terms of processing orthographic form. If it does, then any model of orthographic processing should be somehow tuned to the structure of the language.* This, however, is a purely empirical question, and the following review examines the relevant evidence.

A large part of the findings reported are from Hebrew or Arabic, for two main reasons. First, visual word recognition in Semitic languages has been examined extensively, and a large database is available from these languages. Second, and more important, in the present context language is considered as a factor akin to an experimental manipulation, in which important variables are held constant by the experimenter, and only a few are manipulated to pinpoint their impact on orthographic processing. For example, recent studies from Korean (Lee & Taft 2009; 2011) suggest that letter-transposition effects are not obtained in the alphabetic *Hangul*[10] as they are in European languages. However, because the Korean Hangul is printed as blocks, where phonemes are spatially clustered both horizontally and vertically, the characteristics of the visual array are different than those of European languages. The significant advantage of Semitic languages is that they have an alphabetic system like English, Spanish, Dutch, or French, and from a purely orthographic perspective, they are based on the processing of letter strings just like European languages are. Hence, what is held constant is the superficial form of the distal stimulus on which the processing system operates. What is "manipulated" are the underlying or "hidden" linguistic characteristics of the orthography, which determine the ecological valence of the constituent letters. The following review centers on whether the underlying linguistic characteristics of the orthography affect the basic processing of orthographic structure.

4. Orthographic processing in Semitic languages

Although the Hebrew writing system is not different than any alphabetic orthography, the striking finding is that the benchmark effects of orthographic processing which are revealed in European languages, such as form-orthographic priming, and most important to our discussion, letter-position flexibility, are not obtained in Hebrew, nor are they in Arabic.

4.1. Form orthographic priming

In a series of eight experiments in Hebrew and one in Arabic, Frost et al. (2005) examined whether almost full orthographic overlap between primes and targets in Hebrew results in masked orthographic priming, as it does in English (e.g., Forster & Davis 1991; Forster et al. 1987), French (e.g., Ferrand & Grainger 1992), Dutch (Brysbaert 2001), and Spanish (Perea & Rosa 2000a). The results were negative. None of the experiments produced significant priming effects either by subjects or by items. Especially revealing were two experiments that involved bilingual participants. In these two experiments, Hebrew–English and English–Hebrew bilinguals were presented with form-related primes and targets in Hebrew and in English. When tested in English, these bilingual speakers indeed demonstrated robust form priming. However, in both experiments, no such effect was obtained when these same subjects were tested with Hebrew material (and see Velan & Frost [2011] for a replication). These findings lead to two dependent conclusions. First, the lexical architecture of Hebrew probably does not align, store, or connect words by virtue of their full sequence of letters. Second, the orthographic code generated for an alphabetic language such as Hebrew does not seem to consider all of the constituent letters (Frost 2009). Indeed, considering the overall body of research using masked priming in Semitic languages, reliable facilitation is consistently obtained whenever primes consist of the *root letters*, irrespective of what the other letters are (e.g., Frost et al. 1997; 2000a; Perea et al. 2010; Velan et al. 2005). This clearly suggests that the orthographic coding scheme of Hebrew print focuses mainly on the few letters that carry morphological information, whereas the other letters of the word do not serve for lexical access, at least not initially.

4.2. Letter-position flexibility

This is the crux of the present discussion, since letter-position flexibility is supposed to reflect the manner by which the brain encodes letters for the reading process. A large body of research has examined letter-position effects in Semitic languages, reaching unequivocal conclusions: The coding of Hebrew or Arabic letter position is as rigid as can be, as long as words are root-derived.

The first demonstration of letter-coding rigidity was reported by Velan and Frost (2007). In this study, Hebrew–English balanced bilinguals were presented with sentences in English and in Hebrew, half of which had transposed-letter words (three jumbled words in each sentence) and half of which were intact. The sentences were presented on the screen word by word via rapid serial visual presentation (RSVP), so that each word appeared for 200 msec. Following the final word, subjects had to

produce the entire sentence vocally. The results showed a marked difference in the effect of letter transposition in Hebrew compared to English. For English materials, the report of words was virtually unaltered when sentences included words with transposed letters, and reading performance in sentences with and without jumbled letters was quite similar. This outcome concurs with all recent findings regarding letter-position flexibility reported in English or other European languages (e.g., Duñabeitia et al. 2007; Perea & Carreiras 2006a; 2006b; 2008; Perea & Lupker 2003; 2004; Schoonbaert & Grainger 2004). For Hebrew materials, on the other hand, letter transpositions were detrimental to reading, and performance in reading sentences that included words with jumbled letters dropped dramatically.

Perhaps the most revealing finding in the Velan and Frost (2007) study concerns subjects' ability to *perceptually detect* the transposition of letters in Hebrew versus English, as revealed by the sensitivity measure d'. At the rate of presentation of 200 msec per word in RSVP, subjects' sensitivity to detection of transposition with English material was particularly low ($d'' = 0.86$). Moreover, about one third of the subjects were at chance level in perceiving even one of the three transpositions in the sentence. In contrast, subjects' sensitivity to detecting the transposition with Hebrew material was exceedingly high ($d' = 2.51$), and not a single subject was at chance level in the perceptual task. Since d' taps the early perceptual level of processing, this outcome suggests a genuine difference in the characteristics of orthographic processing in Hebrew versus English.

The substantial sensitivity of Hebrew readers to letter transpositions raises the question whether the typical TL priming effects obtained in European languages are obtained in Hebrew. The answer seems, again, straightforward. Hebrew TL primes do not result in faster target recognition relative to letter substitution, as is the case for English, Dutch, French, and Spanish. More important, if jumbling the order of letters in the prime results in a letter order that alludes to a different root than that embedded in the target, significant inhibition rather than facilitation is observed (Velan & Frost 2009). This double dissociation between Hebrew and European languages regarding the effect of letter transposition clearly suggests that letter-position encoding in Hebrew is far from flexible. Rather, Hebrew readers display remarkable rigidity regarding letter order (for similar results in Arabic, see Perea et al. 2010).

The extreme rigidity of letter encoding for Semitic words stems from the characteristics of their word structure. Hebrew has about 3,000 roots (Ornan 2003), which form the derivational space of Hebrew words. Since these tri-consonantal entities are conveyed by the 22 letters of the alphabet, for simple combinatorial reasons, it is inevitable that several roots share the same set of three letters. To avoid the complications of homophony, Semitic languages alter the order of consonants to create different roots. Typically, three or four different roots can share a cluster of three consonants (and thereby three letters), so it is rare for a set of three consonants to represent a single root. For example, the consonants of the root S.L.X ("to send") can be altered to produce the root X.L.S ("to dominate"), X.S.L ("to toughen"), L.X.S ("to whisper"), and S.X.L ("lion"). If the orthographic processing system has to pick

up the root information from the distal letter sequence, letter order cannot be flexible but has to be extremely rigid. Moreover, for a system to differentiate efficiently between roots sharing the same letters but in a different order, inhibitory connections must be set between different iterations of letters, each of which represents a different meaning.

The results from Hebrew and Arabic have major implications for any theory of orthographic processing. Findings from Semitic languages presented so far demonstrate that the cognitive system may perform on a distal stimulus comprising a sequence of letters, very different types of processing, depending on factors unrelated to peripheral orthographic characteristics but related to the deep structural properties of the printed stimuli. These concern firstly the morphological (and therefore the semantic) contribution of individual letters to word recognition. For Indo-European languages, individual letters of *base words* do not have any semantic value. Since models of reading today are exclusively Anglocentric, not surprisingly, this factor has never really been taken into account. A theory of reading, however, that is linguistically coherent must include some parameters that consider the semantic valence of individual letters in order to satisfy the universality constraint.

We should note that these conclusions by no means imply that the *neurocircuitry of the visual system* operates on different principles for Hebrew than it does for English or Spanish. Temporal firing patterns due to the sequential array of letters (Whitney 2001), or noisy retinotopic firing (Dehaene et al. 2005), are probably shared by all printed forms in all languages. The conclusion so far is that these characteristics of the neural system are independent of lexical processing and do not come into play during the coding of orthographic information. Hence, they should not be a component of our theory of reading.

Perhaps the most convincing demonstration that orthographic processing and the coding of letter position in alphabetic orthographies is entirely dependent on the type of information carried by individual letters can be shown, again, in Semitic languages. Both Hebrew and Arabic have a large set of base words that are morphologically simple, meaning that they do not have the typical Semitic structure since they are not root-derived and thus resemble words in European languages. Such words have infiltrated Hebrew and Arabic throughout history from adjacent linguistic systems such as Persian or Greek, but native speakers of Hebrew or Arabic are unfamiliar with their historical origin. The question at hand is, what is the nature of their orthographic processing? From the present perspective, the different types of words (Semitic root-derived versus non-Semitic, non-root-derived words) are taken as an experimental factor, where both the alphabetic principle and the language are held constant, and only the internal structure of the distal stimulus is manipulated.

In a recent study, Velan and Frost (2011) examined the benchmark effects of orthographic processing when these two types of words are presented to native speakers of Hebrew. The results were unequivocal: morphologically simple words revealed the typical form priming and TL priming effects reported in European languages. In fact, Hebrew–English bilinguals did not display any differences in processing these words and processing English words. In contrast, whenever Semitic words were presented to the

participants, the typical letter-coding rigidity emerged. For these words, form priming could not be obtained, and transpositions resulted in inhibition rather than in facilitation. These findings demonstrate that flexible letter-position coding is not a general property of the cognitive system, nor is it a property of a given language. *In other words, it is not the coding of letter position that is flexible, but the reader's strategy in processing them.* Therefore, structuring a model of reading so that it produces flexible letter-position coding across the board does not advance us in any way towards understanding orthographic processing or understanding reading. *The property that has to be modeled, therefore, is not letter-position flexibility, but rather flexibility in coding letter position, so that in certain linguistic contexts it would be very rigid and in others it would be less rigid.* Only this approach would satisfy the universality constraint.

So far, I have established an evident flexibility of *readers* in terms of whether or not to be flexible about letter-position coding. Two questions, however, remain to be discussed so that our theoretical approach can maintain both descriptive and explanatory adequacy. First, what in the distal stimulus determines *a priori* flexibility or rigidity in coding its letter positions? Second, why is flexible or rigid coding advantageous in different linguistic contexts?

5. Word structure determines orthographic processing

After demonstrating that, even within language, the cognitive system performs different operations on a sequence of letters, given the deep structural properties of the printed stimuli, what remains to be explicated is what cues trigger one type of orthographic processing or another. The answer seems to lie in the structural properties of the sequence of letters that form base words.

European languages impose very few constraints on the internal structure of base words. For example, word onsets can consist of any consonant or any vowel, and since the permissible syllables are numerous, in principle, phonemes could be located in any position within the spoken word and at equal probability. There are very few phonotactic and articulatory constraints on the alignments of phonemes (such as no /p/ after /k/ in English). Although onset-rime structure determines word structure to some extent, at least in English (see Kessler & Treiman 1997; Treiman et al. 1995), the predictive value of a given phoneme regarding the identity of the subsequent one is relatively low. To exemplify, *comet* is a word in English, and *bomet* is not, but it could have been otherwise, and the word for *comet* could have been, in theory, *temoc, tomec, motec, omtec,* or *cetom,* and so on. Since letters in European languages represent phonemes, all of the points noted here apply to written forms, as well.

Semitic words, spoken or printed, are very different from European-based ones because they are always structured with a relatively small number of word patterns. Word patterns in Hebrew or Arabic have very skewed probabilities regarding phoneme sequences, so that Semitic words present to speakers and readers a set of *transitional probabilities,* where the probability of a phoneme or letter in a given slot depends on the identity of the previous

phoneme or letter. Using the earlier example of the word /comet/, the game of possible theoretical iterations of phonemes in Hebrew is constrained mainly to the root-consonantal slots because all base words with the same word pattern differ only in the sequence of root consonants (e.g., tizmoret, tiksoret, tisroket, tifzoret, tikrovet, tirkovet, and so on, where root letters are underlined). The substantial difference in the structural properties of words in Semitic and European languages has immediate implications for orthographic processing because the uptake of information from the distal stimulus is necessarily shaped by stimulus complexity. For Semitic words, the most relevant information is the three letters of the root, and the other letters of the word assist in locating these. For English, the game of "cracking" the distal stimulus is quite different. All letters have a more or less similar contribution to word identity, the function of the individual weight of each letter to correct identification is more or less flat, and the significance of each letter to the process varies with the number of letters, depending on the position of those letters within onset-rime linguistic units.

To account for the difference in orthographic coding of "English-like" and "Hebrew-like" words, our question thus concerns the possible cues that could govern one type of orthographic processing or another: the "English-like" coding system, which considers all letters equally and is flexible regarding their position, and the "Hebrew-like" coding system, which focuses on a specific subset of letters and is rigid regarding their position. I suggest that the primary cue that determines the orthographic code is whether the distribution of letter frequency is skewed or not. In linguistic systems with letter frequency that is skewed, such as Hebrew, the highly repeated word-pattern letters flash out the few letters that carry distinctive information regarding root identity and meaning. In contrast, in linguistic systems in which letters do not predict other letters, and the distribution of transitional probabilities of letters is more or less flat, orthographic coding considers all letters, focusing on their identity rather than on their position.

This account suggests that, for efficient reading, the statistical properties of letter distributions of the language, and their relative contribution to meaning, have to be picked up, and the transitional probabilities of letter sequences have to be implicitly assimilated. In the case of Hebrew, this is achieved following the repeated exposure to Semitic words that are root-derived, versus non-Semitic words that do not have the same internal structure. These implicit learning procedures are entirely contingent on the exposure to the spoken language, and possible suggestions of how this is done are outlined later in this article. At this point, however, a cardinal conclusion regarding the main characteristic of a universal model of orthographic processing is already emerging. *For a model to produce different behavior as a function of the statistical properties of the language, the model has to be able to pick up the statistical properties of the language.*

6. Advantages and disadvantages of flexible and rigid letter coding

The new age of modeling orthographic processing has focused mainly on the question of "how," that is, how

does the cognitive system produce letter-position flexibility? The relative high number of such models of visual word recognition shows that there are many computational solutions to the problem. The "why" question is deeper and more fundamental because our aim in modeling is to eventually understand reading rather than to simply describe it. To a large extent, the explanation offered by the current wave of models for letter-position flexibility is, in simple terms, that *this is the way the brain works*. However, once we have established that it is the way the brain works only for languages like English, French, or Spanish, the question at hand is, what does letter-position flexibility buy in terms of processing efficiency? Operating within an ecological approach, the answer to this question will focus again on the specific interaction of the reader and the linguistic environment.

For Semitic languages such as Hebrew, orthographic lexical space is exceedingly dense. If all words are derived by using a relatively small number of phonological patterns, and all words sharing a word pattern share a skeletal structure of phonemes (and therefore letters), *words are differentiated only by the three root consonants* (or letters). This necessarily results in a dense lexical space, in the sense that the large variation of words that are necessary for meaningful communication is created mainly by manipulating *the order* of few constituent phonemes. Thus, in Hebrew, spoonerism very often results in other lexical candidates, and words sharing the same set of letters but in a different order are the rule, rather than the exception.

The interesting question, therefore, is not why orthographic processing in alphabetic languages such as Hebrew is exceedingly rigid in terms of letter position. It could not have been otherwise, as it must fit the structure of Hebrew lexical space. The interesting question is why it is flexible in English. Why wouldn't the brain rigidly encode letters in all orthographies? What is gained by letter-position flexibility? The answer is probably twofold. First, languages such as English, which are not constrained to a small set of phonological word patterns, create a variation of words by aligning, adding, or substituting phonemes, and not by changing their relative position, as Semitic languages do. Thus, anagrams such as "calm–clam," "lion–loin," which are the rule for Hebrew and occur in Hebrew words of any length, exist mostly for very short words of 3–5 letters in English (e.g., Shillcock et al. 2000). This feature is not exclusive to English, but is shared by other European languages, because unnecessary density of lexical space is not advantageous for fast discrimination between lexical candidates. Thus, the option of assigning to different base words a different set of phonemes rather than changing their order seems to reflect a natural selection. Considering reading: This feature of the language has an obvious advantage when letter sequences have to be recognized, because most words are uniquely specified by their specific set of letters, irrespective of letter order. Hence, a transposed-letter word such as *JUGDE* can be easily recognized since there are no word competitors that share the same set of letters. This type of linguistic environment can naturally allow for noisy letter-position processing. In general, the longer the words are, the higher is the probability that they would have a unique set of letters. Consistent with this assertion, TL priming effects in European languages are indeed largely modulated by word length, with large benefit

effects for long words and small effects for short words (e.g., Humphreys et al. 1990; Schoonbaert & Grainger 2004). In the same vein, Guerrera and Forster (2008) have shown that, with relatively long words, even extreme jumbling of letters in the prime (only two out of eight letters are correctly positioned), target recognition is facilitated, so that the prime SNAWDCIH primes SAND-WICH. Since not a single word shares with SANDWICH this specific set of letters, SNAWDCIH can produce a priming effect.

An illustration of the behavioral implications of the major differences in the structure of lexical space between Hebrew and English is shown in patients with deficits in registering the position of letters within the word. According to Ellis and Young (1988), three distinct functions are relevant to peripheral disorders related to visual analysis of print: letter identification (or letter agnosia; e.g., Marshall & Newcomb 1973), letter-to-word binding (letter migration problems; e.g., Shallice & Warrington 1977), and encoding of letter position. In letter-position dyslexia (LPD), patients demonstrate deficits in registering the position of each letter within the word. Friedmann and her colleagues (Friedmann & Gvion 2001; 2005; Rahamim & Friedmann 2008) have reported several cases of Hebrew-speaking patients with both acquired and developmental LPD. Interestingly, Friedmann and her colleagues have argued that pure cases of LPD are rarely reported in Indo-European languages, whereas in Hebrew they are much more prevalent. Obviously, this does not have to do with differences in brain architecture of Hebrew versus English speakers. Rather, this has to do with the characteristics of lexical space. A case study reported by Shetreet and Friedmann (2011) demonstrates this elegantly. The patient, a native speaker of English, complained about reading difficulties after an ischemic infarct. Reading tests in English could not reveal why, because the patient's reading performance was close to normal. Only when tested with Hebrew material was a diagnosis of LPD confirmed. Since, in Hebrew, errors in letter position mostly result in another word, the patient had significant difficulties in reading Hebrew. In English, however, errors in letter position seldom result in another word; LPD, therefore, did not hinder his reading significantly. Recently, Friedmann and Haddad-Hanna (in press a) have reported four cases of LPD in adolescent Arabic speakers and have also described the characteristics of developmental LPD in young Hebrew readers (Friedmann et al. 2010), demonstrating again how LPD significantly and consistently hinders reading in Semitic languages.

If words in a language, in most cases, do not share their set of letters, and changes in letter order do not typically produce new words, then orthographic processing can relax the requirement for rigid letter-position coding without running the risk of making excessive lexicalization errors. This relaxation has a major advantage in terms of cognitive resources. Given the fast saccades during text reading, some noise must exist in registering the exact sequence of letters. A fine-grained coding system that requires overriding such natural noise is more costly in terms of cognitive resources than a coarse-grained system that is indifferent to noise (for a similar taxonomy, see Grainger & Ziegler 2011). *Note, however, that the "noise" described in the present context is not hardwired within the perceptual system (i.e., noisy retinotopic firing, etc.). Rather, it is an environmental noise, tied to the characteristics of print, where long sequences of letters are aligned one next to the other and are scanned and registered at a very fast rate.* Relaxing the requirement for accurate letter-position registering without consequent damage to lexical access has a clear advantage, and is, therefore, an emergent property of skilled reading. By this view, beginning readers who are learning to spell and have difficulties in letter decoding should not display such flexibility. I further expand on the feature of cognitive resources later in this article.

The sum of these arguments leads us then to the same conclusion: *Letter-coding flexibility in reading is not a characteristic of the brain hardware, as current models of orthographic processing seem to suggest. It is a cognitive resource-saving strategy that characterizes reading in European languages, given the characteristics of their lexical space.* Models of orthographic processing have to account for this.

The following discussions thus center on a new approach to modeling visual word recognition. The aim of these discussions is to outline the blueprint principles for a universal model of reading that would be linguistically plausible and linguistically coherent.

7. Structured models versus learning models

A common feature of most current models of orthographic processing is that they are explicitly structured to predict certain behaviors. Thus, the modelers shape their model's architecture so that its output will generate a desired outcome – in the present context, form priming or letter-position flexibility. This can be done, for example, by introducing open bigram units into the model (e.g., Dehaene et al. 2005; Grainger & van Heuven 2003; Whitney 2001), or by lagging the information about letter order relative to letter identity (e.g., Gomez et al. 2008). Although this approach has substantial merits in generating hypotheses regarding how specific behaviors can be produced, almost inevitably it leads modelers to focus on a narrow set of phenomena, constraining their models to deal with one dimension of processing. As I have argued at length so far, within the domain of language, this approach can be detrimental. Since reading behavior is shaped and determined by the complex linguistic environment of the reader, focusing on specific computations within the system would most probably miss the perspective of the context of these computations, thereby leading to possible misunderstandings regarding the origin of the behavior which is being modeled.

To exemplify, any of the current models of orthographic processing could easily reproduce the effects obtained with Hebrew Semitic words by implementing slight modifications. Suffice to introduce tri-literal root units in the model, and then set inhibitory connections between all roots units that share sets of letters in a different order, and rigid letter position would show up. This approach may eventually yield a computational model of reading Hebrew Semitic words with a relatively good fit for the Hebrew data, but the explanatory benefit of the model remains questionable. *It should be emphasized that the theoretical value of a model is independent of the prevalence of the language that is being modeled. In the present*

context, the theoretical contribution of a similar model of reading English would be exactly the same. The conclusion that emerges from the present discussion is that structured models that are explicitly set to produce effects of orthographic processing, in all probability, will not be universal. Their chances of satisfying the universality constraint and achieving a full linguistic coherence are low. Following the foregoing example, if, say, letter-order rigidity would be hardwired into a model of reading Hebrew, and the model would then indeed display the desired behavior in terms of root priming, this model would then not display the opposite effects with English-like words. That is, the model will be language-specific, or even worse, it would be "sub-language"-specific, in the sense that it would simulate reading of a subset of words in Hebrew – not even all types of words.

In contrast to structured models, learning models are set to pick up the characteristics of the linguistic environment by themselves. A typical example is the influential model of past-tense production offered by Rumelhart and McClelland (1986). The dramatic impact of this model was in its demonstration that both rule-like behavior (regular forms of past tense) and non-rule-like behavior (exception forms of past tense) can be produced by training a network on a representative corpus of the language environment of children. In learning models, behavior *emerges* rather than being structured. The approach of these models focuses on the statistical regularities in the environment and on the way that these are captured by the model and shape its behavior, either through supervised or through unsupervised learning (for a detailed review, see Rueckl 2010).

The aim of the present discussion is not to promote a connectionist approach. Connectionist models have been criticized, and rightly so, for simulating only monosyllabic words in English, but a debate regarding the merits and shortcomings of connectionism is beyond the scope of this article. There is, however, an important analogy between the approach that lies at the heart of the architecture of learning models and what we know about learning language in general, and learning to read in particular. The internal structure of words, which determines orthographic processing, is not explicitly taught to native speakers. *Similarly, lexical organization of words in any language implicitly emerges so that, for any language, orthographic codes would be optimal, given the language's phonological space and how it represents meaning and morphological structure.* This is a reading universal, and therefore it is an emergent property of the reading environment, which is picked up by readers through simple implicit statistical learning and by explicitly learning to spell. Considering Hebrew for example, Frost et al. (2010) have shown that sensitivity to root structure in reading, as revealed by robust cross-modal morphological priming effects (e.g., Frost et al. 2000b), can be demonstrated already in the first grade, when children have no clue regarding the formal morphological taxonomies of their language and what governs the internal structure of printed letters. Moreover, Frost et al. (2010) have shown that English speakers who learn to read Hebrew as L2 (second language) display at the onset of learning the typical characteristics of orthographic processing in European languages. With a time course of less than a year, they assimilate the statistical properties of the language and capture the root structure of Semitic languages, showing the same effects as Hebrew readers.

The earlier description of the five languages that opened the present discussion demonstrates that languages differ in a rich array of statistical properties. These concern the distribution of orthographic and phonological sublinguistic units, their adjacent and non-adjacent dependencies, the correlations between graphemes and phonemes (or syllables), the correlation between form and meaning, and so forth. Native speakers pick up these dependencies and correlations implicitly, without any need for formal instruction, presumably through pure procedures of statistical learning. An illuminating example of how the statistical properties of the language are implicitly assimilated comes from the logographic Chinese. Although Chinese is not an alphabetic language, and reading Chinese characters involves the recognition of a complex visual pattern, by reviewing a large corpus of behavioral and event-related potential (ERP) studies, C. Y. Lee (2011) demonstrates that Chinese readers are sensitive to the statistical mapping of orthography to phonology in their language. Lee offers a statistical learning perspective to account for Chinese reading, and reading disabilities, by considering the distributional properties of phonetic radicals. Overall, the findings reported by Lee suggest that Chinese readers extract from their linguistic environment information regarding the consistency of character and sound and use it in the reading process (see also, Hsu et al. 2009).

The robust power of statistical learning has been demonstrated in a large number of studies, with both linguistic and nonlinguistic stimuli (e.g., Endress & Mehler 2009; Evans et al. 2009; Gebhart et al. 2009; Perruchet & Pacton 2006; Saffran et al. 1996). Typically, these studies show that adults, young children, or even infants rapidly detect and learn consistent relationships between speech sounds, tones, or graphic symbols. These relationships can involve adjacent as well as non-adjacent dependencies (e.g., Gebhart et al. 2009; Newport & Aslin 2004). Our discussion so far has shown that writing systems have evolved to condense maximal phonological and semantic information about their language by using minimal orthographic units, and that the cognitive system learns to pick up from the distal stimulus this optimal level of information, given the structure of the language. A model of reading that is set to operate on similar principles has, therefore, the potential to satisfy the universality constraint and be linguistically coherent, but mostly, it has the important advantage of having ecological validity. Our theory of skilled reading cannot be divorced from our theory of how this skill is learnt, and skilled visual word recognition reflects a long learning process of complex linguistic properties. If the model indeed picks up the statistical regularities of the language and the expected reading behavior emerges, it most probably reflects the actual learning procedures of readers.

It should be emphasized that the aim of the present discussion is not to contend that learning models provide simple solutions for testing hypotheses regarding the statistical regularities that are picked up by readers during the course of literacy acquisition. Proponents of structured models would rightly argue that learning models are structured as well, in the sense that they posit an input-coding scheme, which determines to a great extent what will actually be learnt by the model. From this perspective, learning

models, like structured models, also hardwire distinct hypotheses regarding the form of input that serves for the learning process. Although this argument has some merit, some critical distinctions regarding the utility of the two modeling approaches in the context of understanding reading can, and should, be outlined.

First, structured models and learning models differ *in the ratio of the scope of phenomena that are produced by the model versus the amount of "intelligence" that is put into the model* – narrow scope with maximum intelligence for structured models versus large scope with minimum intelligence for learning models. This has important implications regarding what the modeling enterprise can actually teach us. When the model's behavior is too closely related to the intelligence that is put into it, little can be learned about the source of the behavior that is produced by the model. Second, at least in the context of visual word recognition, the modeling approaches differ in the scope of the linguistic theory that determines the *content* of intelligence that is put into the model. As explicated at length, the phenomena that constrain the architecture of current structured models of visual word recognition are by definition narrow in scope, as they concern only orthographic effects. Third, and perhaps most important, there is a major difference in the *goal* of the modeling enterprise. The aim of learning models is to learn something about the possible behaviors emerging from the model, given specific input-coding schemes. The visible representations do not do all the work. A learning model would not work right if the environment did not have the right structure and if the learning process could not pick up this structure. More broadly, the emphasis on learning requires that our theory pay attention to the structure of the linguistic environment, and a failure in the modeling enterprise has, therefore, the potential of teaching us something deeply theoretical (see Rueckl & Seidenberg [2009] for a discussion). In contrast, the aim of structured models is often to produce a specific behavior, such as letter-position flexibility. This approach almost inevitably results in circularity. The hardwired behavior in the model is taken to reflect the mind's, or the brain's, circuitry, and consequently, the model's organization is taken as behavioral explanation. Thus, as a rule of thumb, *the distance between organization and explanation is by far narrower in structured models than in learning models*. To exemplify, once a level of open bigrams that is hardwired in the model is shown to reproduce the desired typical effects of letter-position flexibility, letter-position flexibility is suggested to emerge from a lexical architecture that is based on open bigrams (e.g., Grainger & Whitney 2004; Whitney 2001). This circularity between organization and explanation may have detrimental consequences for understanding the fundamental phenomena of reading.

8. The linguistic dimensions of a universal model

As explicated at length in the initial part of our discussion, the assumption underlying most current computational models of orthographic processing is that *the game of visual word recognition is played in the orthographic court, in the sense that an adequate description of the cognitive operations involved in recognizing printed words is constrained solely by the properties of orthographic structure (letters or characters, letter identity, letter location, letter sequences, etc.)*. However, as we have shown in the description of various writing systems, orthographic structure is determined by the phonological space of the language and the way phonological space represents morphology and meaning. This means that letters in different languages might provide different type of information, and this must be part of a universal model of reading. Conceptual models that offer a generic lexical architecture (e.g., the bimodal interactive activation model; Diependaele et al. 2010; Grainger & Ferrand 1994) do include phonological and semantic representations, but when it comes to produce a *computational* model, the focus is on orthographic entities per se. The inherent limitation of this approach is that it inevitably leads to linguistic implausibility. This problem was recently outlined by Grainger and Ziegler (2011), who argued that orthographic processing should also be constrained by correlations of letter clusters with phonological units, and by the fact that prefixes and suffixes are attached to base words and need to be correctly detected as affixes in the process of word recognition (e.g., Rastle & Davis 2008; Rastle et al. 2004). Thus, mapping of letter clusters such as "sh" or "th" into phonemes, as well as affix stripping (e.g., teach-er), both required for the morphological decomposition that is necessary for base word recognition, cannot allow flexibility of letter order. The solution offered by Grainger and Ziegler (2011) was to include in a model of orthographic processing two types of orthographic codes, differing in their level of precision: one that is coarse-grained and allows for fast word recognition, and one that is fine-grained and precise and allows for correct print-to-sound conversion and correct morpho-orthographic segmentation.

Grainger and Ziegler (2011) were right on target in realizing the severe limitation of the present approach to modeling orthographic processing. This approach has inevitably led to impoverished and narrow theories of *correctly recognizing orthographic forms of morphologically simple base-words in English that are more than four letters long*. However, "patching up" models by appending to them parallel computational procedures that do whatever the original computational procedures did not do, is hardly a solution. It may conveniently fix the model's inevitable problems, but more than fixing them, it demonstrates the basic conceptual weakness of the modeling approach. Such a strategy eventually leads to explaining *any* possible finding simply by arguing *post hoc* that one route rather than the other was probably used, and this would hardly advance our understanding of reading. The question to be asked is why current computational approaches result in impoverished solutions, describing only a very limited set of phenomena. This leads our present discussion to the linguistic dimensions, which are necessary for a universal model of orthographic processing; necessary, in the sense that the model would satisfy the requirement for linguistic plausibility.

8.1. Three basic dimensions: orthography, phonology, and semantics

Our foregoing description of the logic underlying the evolution of the five contrasting writing systems – Chinese, Japanese, Finnish, English, and Hebrew – suggests an intricate weighting of *both* phonological and semantic factors

affecting the structure of *orthographic* forms in a language, so that these convey optimal phonological and morphological information to the reader. *Assuming that readers are tuned to pick up and extract from the print this linguistic information, phonological and semantic considerations must be part of a universal model of orthographic processing.* It should be emphasized that in the present context, semantic features and phonological structure are not taken as higher levels of representation into which orthographic letters are mapped. This view is common to *all* current models of reading. The claim here goes deeper, suggesting that the actual computation of an orthographic code in a given language is determined *online* by the transparency of mapping of graphemes into phonemes, on the one hand, and by morphological and semantic considerations, on the other, given the language properties in which reading occurs. To some extent, a similar approach is advocated by "triangular models" which describe reading in terms of a division of labor between the mapping of orthography to both phonology and semantics, and propose that such mappings are learned via associative mechanisms sensitive to the statistical properties of the language (e.g., Harm & Seidenberg 1999; Plaut et al. 1996; for a review, see Rueckl 2010).

The claim that phonological and morphological considerations affect orthographic processing is not only theoretical but also has empirical support. Hebrew, for example, clearly demonstrates why morphological and semantic considerations must be part of a theory of orthographic processing. The different orthographic codes that were shown to be involved in processing Semitic versus "English-like" base words (Velan & Frost 2011) are entirely predetermined by the semantic value of the individual letters, that is, whether they belong to a root morpheme or not. Thus, the initial cognitive operation that Hebrew readers launch when presented with a letter string is a search for meaningful letters that are dispersed within the word – meaningful in the sense that they convey root information. This process of searching for noncontiguous meaningful letters is early, prelexical, and can be easily demonstrated by monitoring eye movements. For example, the *optimal viewing position* (OVP), the position in a word where word identification is maximal, is entirely modulated by the location of the first root letter within the word (Deutsch & Rayner 1999). More important, Hebrew readers have been shown to search for the root letters already parafoveally. Thus, presenting the root information in the parafovea (see Rayner [1998; 2009] for a review of parafoveal presentation and the boundary technique) results in robust parafoveal preview benefit effects, either with single-word reading (Deutsch et al. 2000), or during sentence reading (Deutsch et al. 2003). Interestingly, similar morphological manipulations conducted with English readers did not result in any parafoveal preview benefit (Rayner et al. 2007; and see Rayner [2009] for a discussion of the lack of morphological preview benefit in English). The evidence from eye movements in Hebrew is especially compelling, since it reflects the initial phases of orthographic processing that are below the level of awareness and not governed by any conscious strategy. The contrasting findings of English versus Hebrew regarding eye-movements demonstrate that (1) the prelexical search for letters carrying morphemic information in the parafovea is language specific, (2) different orthographic operations are performed on a distal stimulus composed of letter sequences in different languages, and (3) *individual* letters are processed differentially across the visual array, given their morphological status and their contribution to recovering semantic meaning.

However, from an even more general perspective, the results from Hebrew seem to reveal an important reading universal. They exemplify the perfect fit between the optimization of information that the writing system has evolved to convey and the cognitive operations that are launched to pick up that information. Recall that this was the starting point of the present discussion. As explicated, the Hebrew orthography was designed to be severely phonologically underspecified in order to emphasize morphological (and thereby semantic) information. The behavior of readers mimics this evolutionary design to perfection. Already in the parafovea, orthographic processing zooms in on the letters which are root letters, that is, letters that will lead as fast as possible to meaning, although this may be only a vague meaning. *Thus, the main target of orthographic processing are letters that carry the highest level of diagnosticity, but not in terms of word form, as in English, but in terms of the morphemic units from which the word is derived.* This account also provides a coherent explication of why phonological computation in Hebrew is underspecified. As Frost and his colleagues have repeatedly shown, the prelexical phonological code computed in Hebrew is indeed impoverished (Frost & Yogev 2001; Frost et al. 2003; Gronau & Frost 1997). Although Frost and his colleagues focused on the depth of Hebrew orthography in discussing their results, it seems that their arguments should be expanded to include what seems to be a reading universal: *The representation of morphological information takes precedence over the representation of detailed phonological information when it comes to the evolution of writing systems. Given that, it also takes precedence when it comes to the cognitive processing of orthographic structure by skilled readers.* Thus, a universal model of reading that is a learning model must include, one way or another, an architecture which considers the intricate relations of orthography, phonology, and morphology (and therefore of meaning) in the language.

8.2. Incorporating parameters of cognitive resources

The notion of optimization of information and the allocation of optimal cognitive resources to orthographic processing provides an important explanatory dimension to the present theoretical approach. However, if, as argued, an important universal principle of processing orthographic structure is a flexibility of the processing system (i.e., whether to be flexible or not about letter coding), and if this flexibility (or the lack of it) is constrained by the cognitive resources that have to be allocated for processing (more resources for rigid slot coding, less for flexible), and if these constraints are determined by the statistical properties of the language, *then cognitive resources should be an integral part of the model*.

How to go about that is not evident; however, computational work by Tishby and colleagues provides challenging potential conceptual solutions. Tishby, Bialek, and colleagues have developed a general theoretical framework for calculating optimal representations for predictability of a stimulus, given the complexity of the environment, as a

function of the resources that a system allocates (Bialek et al. 2001; Shamir et al. 2009; Tishby et al. 1999). In a nutshell, the computational approach developed by Tishby and his colleagues considers, in parallel, information capacity, information rate, and limitation in overall resources, and consequently computes the optimization procedures for allocating minimal resources for a given processing event, to obtain the best performance in terms of predicting stimuli, given the complexity of the environment. Tishby et al. (1999) and Tishby and Polani (2010) demonstrate how the precision of representations depends, among other things, on the complexity of the environment as characterized by its predictive information regarding future events. The parallel of this computational approach to orthographic processing seems compelling. Applying this framework to visual word recognition will require including a parameter of cognitive resources necessary for precise slot coding as compared with a coarse-grained one. This choice can then be optimized given the complexity of the linguistic environment, as reflected by the statistical properties of the language. How exactly to implement this form of computation in a universal learning model of reading obviously requires extensive investigation. However, because flexibility should be part of the model, the allocation of cognitive resources to modulate it is a possible solution.

9. Summary and conclusions

The present article has discussed the recent paradigmatic shift in reading research and the resulting new wave of computational models of orthographic processing that center on letter-position flexibility. The main claim is that the extensive focus on insensitivity to letter order has led to a generation of models that are non-universal, lack linguistic plausibility, and miss the complexity of the reading process. My critique is based on a set of inter-related arguments as follows: The first step in formulating a theory of orthographic processing is to provide an accurate and full description of the type of information provided by the orthographic structure. This information is not necessarily transparent and goes way beyond a surface description of letters, letter sequences, or letter location. It reflects the phonological space of the language and the way the phonological space represents meaning through morphological structure. The cognitive system is tuned to pick up this information in an optimal way by implicitly capturing the statistical regularities of the language, and registering the inter-correlations of orthography, phonology, and morphology. This necessarily results in lexical organization principles that are language-dependent and allow readers optimal and differential performance in different linguistic environments. As a consequence, orthographic processing in one language may be quite different than in another language; moreover, qualitatively different computations may be found even within a single language. Thus, a universal theory of reading should focus on what is *invariant* in orthographic processing across writing systems.

This set of claims leads us to suggest what is fundamentally wrong with the current wave of modeling orthographic processing. I argue that most recent models examine the *surface form* of orthographic structure, focusing on a *variant* characteristic, which is idiosyncratic to

skilled reading in European languages: flexibility of letter-position coding. I suggest that this specific feature of processing letter sequences, being a variant characteristic, does not reflect in any way the manner by which the brain encodes orthographic information for lexical processing. Rather, it reflects a strategy of optimizing encoding resources in a highly developed or skilled system, given the specific structure of words in English, French, or Spanish.

This line of criticism brings us to a set of criteria for a universal model of reading that has linguistic plausibility and is linguistically coherent. Within this context, I outline the advantage of learning models, in that they have ecological validity. Learning models are set to pick up the statistical regularities underlying the *full linguistic environment* of the reader through implicit learning; similar to the way the cognitive system implicitly picks up the relevant information from the orthographic array in the language. In parallel, I outline the pitfalls of structured models that hardwire a given behavior in the model. Structured models almost inevitably result in circularity when the model's organization is taken as behavioral explanation. Structured models of orthographic processing also run the risk of mistaking a variant behavior for an invariant one, thereby hardwiring it into the model. The only way of enabling additional flexibility in processing in a structured model is to assume a duality of processing in the form of parallel routes that permit opposing computations. This strategy of "patching up" structured models does not advance us in any way in understanding human behavior. Rather, it sets us back, leading inevitably to explaining any possible finding by reverting to post hoc argumentation.

Regarding the dimensions that need to be part of a model of orthographic processing, they should mirror the dimensions that determine orthographic structure in a language. The logic underlying this claim is that writing systems do not evolve arbitrarily, and their manner of packing and optimizing information must reflect the cognitive procedures by which readers unpack and decode this information. I have shown that only by considering phonological space and morphological structure can a full account of orthographic structure be provided. Similarly, orthographic processing must be tuned to both the phonological and the morphological information that graphemes carry. Thus, the only viable approach to modeling visual word recognition is an approach that considers, simultaneously, the full statistical properties of the language, in terms of covariations between orthographic, phonological, semantic, and morphological sublinguistic units. Our cognitive system is, first of all, a correlation-seeking device. Hence, universal models of reading should be structured to pick up covariations and conditioned probabilities that exist between *all* of the language components.

NOTES

1. In the context of the present article, the term "models of reading" refers mainly to the modeling of visual word recognition, rather than to the complex operations involved in full text reading.

2. I am indebted to Ignatius Mattingly, who coined this expression.

3. The number of human languages reflects an approximation, since the distinction between a language and a dialect often remains in question.

4. Some Japanese syllables are non-open syllables such as geminate consonants (/Q/) or nasal N, which is often lengthened. Japanese has also two semi-vowels (or glides): /y/ and /w/.

5. Spoken Japanese is based on equitemporal (or isochronous) rhythmic sequences of syllables having the same temporal length, whether it is a CV segment, a V segment, et cetera.

6. Reading disabilities in kanji are more prevalent in Japanese, making the overall rate of reading disabilities in Japan similar to the typical 7% found elsewhere.

7. The exact number of English vowels and consonants varies across dialects.

8. For example, the Serbo-Croatian spelling was reformed at the end of the 19th century and was made entirely transparent. This successful change, however, stems from the fact that in Serbo-Croatian, in contrast to English, morphological variations never result in phonological variations; therefore, as a rule, the phonological structure of base words does not change with derivational morphology.

9. The phenomenon of reading Hebrew without understanding it is still common in religious Jewish communities outside of Israel, and, indeed, this is still done with pointed text.

10. The Korean orthography has two writing systems: one that is alphabetic – *Hangul* – and another that is logographic (with many characters imported from Chinese) – *Hanza*.

Open Peer Commentary

Can evolution provide perfectly optimal solutions for a universal model of reading?

Christina Behme

Department of Philosophy, Dalhousie University, Halifax B3H 4P9, Canada.
Christina.Behme@dal.ca

Abstract: Frost has given us good reason to question the universality of existing computational models of reading. Yet, he has not provided arguments showing that all languages share fundamental and invariant reading universals. His goal of outlining the blueprint principles for a universal model of reading is premature. Further, it is questionable whether natural evolution can provide the optimal solutions that Frost invokes.

Ram Frost's article is a valuable contribution to the debate about models of the reading process. His suggestion that different kinds of language/script pairing require different processing strategies, and that the strategies actually used differ as predicted, is plausible. And including structurally different languages is a commendable advance on earlier, unduly Eurocentric theorizing about reading.

Nevertheless, I would question several points. These all relate to Frost's claim that "the main goal of reading research is to develop theories that describe the *fundamental and invariant* phenomena of reading across orthographies" (target article, Abstract, original emphasis). Surely, given the facts about the five languages as Frost presents them, one would expect diverse orthographies to require diverse reading systems. Further, one might also wonder whether Japanese (or Chinese) store words the same way English speakers do. Given that *kanji* are rich visual images, visual recognition of Japanese (or Chinese) might result in a mapping to an inner representation that is very different from that of English. Frost acknowledges that some representation/strategy might be optimal in one dimension but not in another, which results in a large space of possible mappings. At the very least, in view of the data presented, one might expect the assumption of invariant reading universals to be defended. Yet, while Frost clearly believes that such universals exist, he never tells us why he holds this belief. One could argue that because reading and orthography are phenomena that depend on language, reading universals could be derived from language universals of the kind proposed by Chomsky (1965; 1995). But in recent years the existence of language universals has been challenged (e.g., Evans & Levinson 2009; Everett 2005). The debate on the issue is far from over, and Frost provides no independent reasons to assume there are any significant, specifically *reading* universals. Universals of reading need to be argued for rather than simply assumed.

Frost's detailed discussion of the role of letter position in English and Hebrew provides support for his critique of models that focus on a single dimension of processing. However, given the variation that Frost finds among only five languages, it is at least questionable whether the aim of "outlin[ing] the blueprint principles for a universal model of reading" (sect. 6, para. 7) is realistic. And, if one aims at such a universal model, it seems misguided to focus on differences between English and Hebrew (and the differences within Hebrew), which seem to suggest different processing mechanisms. Instead of arguing for either letter-position rigidity or flexibility, one might argue that these languages are located on (opposite ends of) a spectrum. It is probably true that the described strong priming effect holds for Frost's examples (e.g., SANDWICH/SNAWDCIH; sect. 6, para. 3) and many other polysyllabic English words. However, it hardly seems that "anything goes" (i.e., complete letter-position flexibility): Would WASHDINC still be recognized as SANDWICH? And, a badly scrambled UNDERDOG turns into GROUNDED with several indeterminate intermediaries.

Possibly, then, letter-position flexibility in English is a superficial phenomenon that masks the rigidity of some letters in the target; posing processing demands that are not fundamentally different from Hebrew. But this is only one aspect of the task a truly universal reading model has to account for. Whether it is possible to develop learning models that can satisfy Frost's universality requirement remains to be seen. Different models might be needed to explain the facts specific to reading in different languages. Recent cross-linguistic modeling work on word segmentation has shown that models that performed well for English failed miserably for Sesotho (Blanchard et al. 2010). And, anyone attempting to reach Frost's ambitious goal of "full linguistic coherence" (sect. 7, para. 2) would also need to consider cognitive limitations that may be in place when children first learn to read, and the interactions between the different modalities (visual, auditory) that are involved in statistical learning (for recent findings on such interactions, see Emberson et al. 2011). Models that can account for all aspects of the reading task are beyond the reach of available technology. Moreover, given the lack of evidence supporting the notion that significant universals exist specifically for reading, it would make more sense to start without preconceptions and generalize from a diverse set of specific cases. Postulating untestable universals at this stage seems at best to be premature. Frost is correct, of course, to insist that models need to be informed by facts from a wide range of reading phenomena and that the scope of any model needs to be clearly acknowledged.

Turning to the most serious problem with Frost's article: The claim that "every language gets the writing system it deserves" (sect. 3) is too strong, as it implies that scripts have evolved to be "perfectly" optimal for their respective spoken languages. I did not find convincing justification for the suggestion that all writing systems necessarily develop "*optimization aimed at providing their readers with maximal phonological and semantic*

information by the use of minimal orthographic units for processing" (sect. 3.1, para. 1, emphasis in the original). Certainly, arbitrary historical facts about which scripts have been available when a language was first reduced to writing have also been important. Frost's discussion of Chinese and Japanese only hints at the complex interaction of arbitrary components (e.g., adoption of Chinese *kanji* by Japanese) and non-arbitrary ones (e.g., introduction of *hiragana* and *katakana*) affecting the evolution of reading systems. The examples provided are suggestive at best, and one is reminded of largely unsupported claims regarding optimal design of language (e.g., Berwick & Chomsky 2010; Boeckx 2010; Chomsky 1995; 2007; 2010; Fitch 2007; Uriagereka 1998). These claims have been challenged by Johnson and Lappin (1997), Postal (2003; 2004), and Seuren (2004), and similar challenges would need to be addressed by Frost. The repetitive reference to terms like "optimization," "optimal representation," "optimal information," "optimal solution," "optimization of information," "perfect match," and "perfect example of optimization of information" (in sect. 3 and its subsections) is question-begging. And, from an evolutionary perspective, claims such as "all resulting linguistic developments are to some extent entirely predetermined" (sect. 3.2.1, para. 1), "this evolution was to some extent inevitable" (sect. 3.2.2, para. 3), "nothing is arbitrary" (sect. 3.2.3, para. 2), and "[reading systems] necessarily evolve to …" (sect. 3.2.4, para. 2) are either incorrect or virtually meaningless. Little would have been lost had Frost made appropriately measured claims, and I hope future discourse will be conducted with more attention to the limitations of natural evolution. Nevertheless, these criticisms do not undermine the validity of Frost's main points about the psychology of reading and the importance of cross-linguistic comparative work.

Beyond one-way streets: The interaction of phonology, morphology, and culture with orthography

Madeleine E. L. Beveridge and Thomas H. Bak

School of Philosophy, Psychology, and Language Sciences, University of Edinburgh, Edinburgh EH8 9JZ, United Kingdom.

m.e.l.beveridge@sms.ed.ac.uk   **thomas.bak@ed.ac.uk**
http://www.ppls.ed.ac.uk/psychology/people/madeleine-beveridge
http://www.ppls.ed.ac.uk/people/thomas-bak

Abstract: Frost's claim that universal models of reading require linguistically diverse data is relevant and justified. We support it with evidence demonstrating the extent of the bias towards some Indo-European languages and alphabetic scripts in scientific literature. However, some of his examples are incorrect, and he neglects the complex interaction of writing system and language structure with history and cultural environment.

We emphatically agree with Frost that linguistic diversity is a pre-requisite for the development of universally applicable models of reading. Indeed, we argue that linguistic diversity is a pre-requisite for any meaningful study of language, including research into the representation of language in the brain and its breakdown in brain lesions (aphasia). However, linguistically diverse data in visual word recognition are sadly lacking (Share 2008a). Similarly, in a recent review of aphasia research since the year 2000, we found a dramatic imbalance in the languages investigated (Beveridge & Bak 2011). A small number of closely related Western European languages accounted for the vast majority of aphasia literature:

62% of the articles investigated were in English, 89% in Germanic or Romance languages. In contrast, less than 8% of studies examined non–Indo-European languages.

Inspired by Frost's article, we revisited our database, focusing on writing systems and examining separately articles dealing with disorders of written language: alexia and agraphia. Languages using alphabetic writing were the focus of 94% of total studies and 89% of alexia/agraphia studies (Table 1).

We are currently extending the scope of this investigation by conducting a systematic review of language research in non-clinical populations. Here, too, we find a bias towards alphabetic scripts, albeit less dramatic: Languages using non-alphabetic scripts account for 113 of 750 studies. The dominance of alphabetic languages becomes more apparent when we examine the number of citations generated by each article: Of 181 studies with 10 or more citations, only 4 featured non-alphabetic languages (3 Hebrew, 1 Arabic). Moreover, within the non-alphabetic group, we encounter a very limited number of languages. At the time of writing, the two reviews encompassed 1,935 articles from 114 journals, yet between them they feature only nine non-alphabetic scripts: Arabic, Bengali, Chinese, Hebrew, Hindi, Japanese, Kannada, Persian and Thai. Of these, only four (Chinese, Hebrew, Japanese, and Thai) appear in the non-clinical review, with Chinese and Japanese accounting for 102 of 113 studies.

Moreover, "non-alphabetic" scripts cannot be treated as a uniform group, showing at least as many differences between themselves as they do in comparison to alphabetic ones. Their classification is complex and controversial; almost any term applied can be seen as inadequate (Daniels 1996b). The "logographic" Chinese script includes radicals coding for sounds. "Consonantal" scripts (*abjad*) are not entirely consonantal, since they include signs for long vowels. "Semi-syllabic" scripts of Ethiopia and India (*abugida*) are orthographically "alphabetic" (expressing vowels as well as consonants) but visually "syllabic" (characters arranged in form of syllables). These semi-syllabic writing systems, used by hundreds of millions of people in Africa, South and South-East Asia, have been particularly neglected by researchers. Tellingly, they were not among the five example languages chosen by Frost.

Ironically, although we agree with Frost on the importance of cross-linguistic data, it is exactly on the basis of language comparison that we have to reject some of his examples. Far from being a uniquely English phenomenon, morphologically induced phonological alternations are among the most characteristic features of Indo-European languages. Accordingly, many languages developed a trade-off between phonological and morphological transparency. In German, for instance, the plural of *Buch* (book) is *Bücher*: the letter "ü" has a similar shape to the "u" of the singular, but the diacritics mark a different pronunciation. Similar phenomena can be observed in Polish (*Bóg/Boga*, nominative/genitive of "God") or, expressed through an additional letter rather than a diacritic, in Italian (*bianco/bianchi*, masculine singular/plural of

Table 1 (Beveridge and Bak). *Number of studies in a major review of aphasia literature, by script type (proportions in parentheses)*

Script	Total studies (*n*=1,268)	Alexia/Agraphia (*n*=115)
Alphabetic	1,195 (94.2%)	101 (87.8%)
Consonantal (abjad)[a]	24 (1.9%)	2 (1.7%)
Logographic[b]	32 (2.5%)	8 (7%)
Mixed (logographic/ syllabic)[c]	11 (0.9%)	1 (0.9%)
Semisyllabic (abugida)[d]	7 (0.6%)	3 (2.6%)

[a]Arabic, Hebrew, Persian; [b]Chinese; [c]Japanese; [d]Hindi, Bengali, Kannada.

"white"). An example of related languages solving the same problem in different ways is provided by Welsh and Scottish Gaelic. Both languages are characterised by mutations (lenition) of initial sounds in certain environments (e.g., possessives, propositions). In Welsh, the spelling of the mutated word reflects its pronunciation and is, therefore, visually different from the non-mutated form (e.g., *mawr/fawr*, masculine/feminine of "big"). In Gaelic, however, the lenited form is expressed through the addition of "h," making the resulting word morphologically, but not phonologically, transparent (*mòr/mhòr*, masculine/feminine of "big"; "mh" pronounced as "v").

Hence, the conservatism of English spelling cannot be attributed to its unique morphology but rather to historical, social, and cultural factors (which also play a major role in other languages cited by Frost, such as Chinese and Japanese). Examples of political, religious, and ideological decisions determining the written form of a language can be found through centuries and across continents. A frequently cited case is the change of Turkish from Arabic to Latin script in 1928 (incidentally, the closely related Azeri language was written in Cyrillic in the Soviet Union and in Arabic script in Iran). Another example is the 19th century change of Romanian from Cyrillic to Latin, motivated by nationalist ideology (Gheţie 1978). The new spelling was originally strongly etymologising, emphasising the language's Romance morphology (like Frost's English example), but progressive reforms led to today's nearly consistent surface phonemic system (like Frost's Finnish example).

In most cases, the relationship between phonology, morphology, culture, and orthography is not a one-way street. In India, most languages adopted a script including characters representing all sounds of Sanskrit. A notable exception is Tamil, in which voiced and voiceless stops (e.g., "g/k," "b/p," etc.) are written with the same character. This makes perfect sense within the rules of Tamil phonology, in which voiced and voiceless stops are allophones, with pronunciation determined by its position within the word. Yet, the same phonological rule applied also to proto-Dravidian and, therefore, to other Dravidian languages such as Malayalam, Telugu, or Kannada (Steever 1998). However, unlike Tamil, these languages adopted the full Sanskrit inventory as well as many Sanskrit loanwords, in which sounds like "g" and "k" form distinct phonemes. The adoption of Sanskrit words encouraged a Sanskrit-based orthography, but equally, Sanskrit-based orthography facilitated Sanskrit borrowings. In contrast, both the orthographic and the lexical influence of Sanskrit is least pronounced in Tamil, which tends to emphasise its own cultural, political, and linguistic identity. We argue, therefore, that orthography is a product of a long and complex interaction of language structure with cultural environment and historical circumstance.

Position-invariant letter identification is a key component of any universal model of reading

Jeffrey S. Bowers
School of Experimental Psychology, University of Bristol, Bristol BS8-1TU, United Kingdom.
j.bowers@bris.ac.uk
http://psychology.psy.bris.ac.uk/people/jeffbowers.htm

Abstract: A universal property of visual word identification is position-invariant letter identification, such that the letter "A" is coded in the

same way in CAT and ACT. This should provide a fundamental constraint on theories of word identification, and, indeed, it inspired some of the theories that Frost has criticized. I show how the spatial coding scheme of Colin Davis (2010) can, in principle, account for contrasting transposed letter (TL) priming effects, and, at the same time, position-invariant letter identification.

I agree with many of the points made by Frost, most notably, that (a) visual word identification should be studied in the context of language processing more generally, (b) there are important differences between languages, and (c) learning matters. Taken together, these factors suggest that visual word identification may differ across languages, and, indeed, Frost and colleagues appear to have identified an important difference (that is, letter position uncertainty varies across languages). I think Frost downplays the insights that have been made by studying a restricted set of languages (most often English), but I agree that there is value in looking for general principles of visual word identification that apply across languages.

However, I think Frost has missed a universal property of visual word identification that inspired some of the models he criticizes, namely, position-invariant letter identification. According to Frost, the recent "revolution" in modeling word identification was motivated by the many demonstrations of letter-transposition priming, and this inspired the development of models with letter position uncertainty. However, contrary to this account, the revolution started with models designed, in large part, to support position-invariant identification of letters. This enables readers to identify familiar words in novel contexts (e.g., the word *play* in *treeplay*). Position-independent letter identification was central to the development of the self-organising lexical acquisition and recognition (SOLAR) model of visual word identification (Davis 1999) and the more recent spatial coding model (Davis 2010), both of which were inspired by the neural networks Grossberg (e.g., Grossberg 1978) designed to solve the so-called *LTM invariance principle* – networks developed long before the literature on transposed priming was established. More generally, context-independent identification of items is central to symbolic theories of object identification (Hummel & Biederman 1992), semantic knowledge (e.g., Fodor & Pylyshyn 1988), and short-term memory (Bowers et al. 2009), amongst other domains. This is not to deny that transposed letter (TL) priming effects provide a rich data source for constraining models of visual word identification, but, contrary to Frost, this was not the only (nor primary) motivation for some of the current theories of letter position coding.[1]

The task of supporting position-invariant identification led to theories that are quite different than characterised by Frost, and a better appreciation of these models is critical for interpreting the reduced TL priming effects in Hebrew. I agree that the reduced TL priming suggests that position uncertainty is reduced in Hebrew compared to alphabetic scripts, plausibly for the reasons that Frost advances. But what the findings do not show is that letters are more rigidly bound to position in Hebrew compared to other (alphabetic) languages. Such a solution can account for the absence of TL priming in Hebrew, but at the cost of achieving position-independent letter identification. The challenge is to develop a (universal) model of letter coding that under some conditions includes very little positional uncertainty and, at the same time, achieves positional invariance (in Davis's terminology, solves the *alignment problem*).

In fact, the combination of universal positional invariance and language-specific TL priming is highly constraining for theories. On the one hand, the position-invariant identification rules out rigid as well as noisy slot coding (noisy slot coding includes some positional uncertainty; Gomez et al. 2008). That is, any model in which letters are bound to position, such that the word *play* is coded as P-in-position-1, L-in-position-2, L-in-position-3, and Y-in-position-4, will not recognize *play* in *treeplay* (noisy slot coding will not help, as the noise cannot be so great that P-in-position-1 in *play* and P-in-position 5 in *treeplay* are similar). On the other hand, the lack of TL priming in Hebrew

appears to challenge the open bigram account of letter position coding. Open bigrams support position-invariant identification by relying on the positional uncertainty of the bigrams (bigrams are not coded by position at all), and, accordingly, TL priming and position-invariant identification go hand-in-hand (which is not the case in Hebrew).

The spatial coding scheme of Davis (2010), however, can accommodate the range of TL priming effects across languages, and at the same time, support position-independent identification. A key feature of this model is that it does not rely on positional uncertainty in order to achieve position-invariant identification, and, accordingly, it is possible for the model to accommodate both sets of results. Indeed, Table 5 of Davis (2010) describes the results of the model when the position-uncertainty parameter is set to zero. Under these conditions, the model predicts no TL priming (like Hebrew; e.g., see simulations 21 and 22) and, at the same time, supports positional invariance as reflected in robust position-invariant priming (e.g., when the prime is composed of the last four letters of an eight-letter target; prime = *stic*, target = *PLASTIC*; simulation 60).

Still, the current spatial coding model does not predict that letter position uncertainty is reduced in Hebrew compared to alphabetic languages. Accordingly, findings of Frost and colleagues do suggest that additional constraints need to be added to the spatial coding model so that the positional uncertainty varies as a function of the orthographic density of words or morphemes in a lexicon (or perhaps other idiosyncratic aspect of the a given language). This is an important conclusion, but it is even more important not to lose sight of a key universal constraint of visual word identification, namely, letter position invariance. The parallel distributed processing (PDP) models of word identification that Frost points to do not solve the alignment problem (despite their learning), nor do more recent PDP models that attempt to directly address this issue (Bowers & Davis 2009).

NOTE
1. In addition to SOLAR, open bigram models were designed to achieve position-independent word identification (Grainger & van Heuven 2003; Whitney 2001). More in line with Frost's description of the literature, a number of subsequent letter-coding schemes were developed in response to the TL-priming data (Gomez et al. 2008; Norris et al. 2010). These later models do not support position-invariant word identification.

Are there universals of reading? We don't believe so

Max Coltheart and Stephen Crain
Centre for Cognition and its Disorders, Macquarie University, Sydney, NSW 2109, Australia.
max.coltheart@mq.edu.au   stephen.crain@mq.edu.au
http://www.maccs.mq.edu.au/~max/
http://www.ccd.edu.au/people/profile.html?memberID=55

Abstract: There are universals of language; but is it also true, as the target article claims, that there are universals of reading? We believe there are no such universals, and invite others to refute our claim by providing a list of some universals of reading. If there are no universals of reading, there cannot be a universal model of reading.

The target article makes a plea for the development of a universal model of reading "which outlines the common cognitive operations involved in orthographic processing in all writing systems" (Abstract) – that is, a model that is based on the universals of reading. But are there any universals of reading?

It is clear that there are universals of *language*. There are two kinds of language universals: *formal* and *substantive* (Chomsky

1965). A few examples of each will illustrate the difference. Probably the most discussed formal linguistic universal is *recursivity* (a.k.a. "discrete infinity"). Recursive procedures create outputs that suffice for their own reapplication. Recursive procedures account for the *creativity* of human language, yielding potentially unbounded expressions, for example, possessives (*Bob's mother's aunt's nephew's…*) and verbs with sentences as complements (*Bob told mother that aunt Betsy believes her nephew Ben said…*). Another formal universal is *structure dependence*. The sequences of words that are produced and understood by language users are *hierarchically* organized, as opposed to being organized in a linear fashion, like beads on a string. For example, no human language derives a question from a statement by pronouncing the last word of the statement first, and even adults find it difficult to learn to play the part of a puppet that responds to other people by omitting the first three words of whatever they say (Read & Schreiber 1982). Although structure-independent operations are conceptually quite simple, human languages and their learners never adopt them (see, e.g., Crain & Nakayama 1987; Smith & Tsimpli 1995).

Substantive universals provide inventories of linguistic types, including the syntactic and semantic primitives of human languages. For example, all human languages have phrases that contain nouns and verbs. Verbs take noun phrases as their "arguments," and each argument noun phrase is associated with a unique thematic role (e.g., *agent, theme, experiencer*). Some verbs take a single argument (e.g., *sleep, dine*), some take two arguments (e.g., *donate, meet*) and some take more than two arguments (e.g., *give, put*). Turning to semantics, all languages express negation (e.g., *no, not*), and all languages use adverbial quantificational expressions (e.g., *all, always*). Finally, when two or more logical expressions appear together in sentences, different "scope" relations among these expressions are computed. This yields semantic ambiguities: for example, *All planes do not carry pets*.

Linguistic universals make important contributions to language acquisition. Universals like structure-dependence reveal that certain linguistic operations, although logically possible and computationally simple, are never found. It follows that children are not expected to try out such operations in the course of language development. This explains, in part, the *universal mastery* of human languages by young children; that is, the fact that every normal child is able to rapidly acquire any human language by age 3 or 4, without formal instruction or carefully sequenced input. This includes both spoken and visual-gestural (sign) languages. Notably, universal mastery is not paralleled in children's attempts to master writing systems.

Another relevant observation about linguistic universals is that they are *contingent facts* about human language. Human languages could have evolved differently. Human languages might have consisted of lists of word sequences, rather than sentences generated by a recursive procedure; human languages might not have included adverbial quantifiers; and logical expressions might have been interpreted in linear order, rather than being assigned different scope relations.

Are there reading universals, in the way in which there are language universals? The target article claims this to be true. In contrast, we take the view that there are no reading universals. One problem is that it is not clear what Frost means by "reading universal." Sometimes the idea seems to be that reading universals are general properties of writing systems; at other times, the idea seems to be that reading universals are general properties of the cognitive information-processing systems used for reading. We consider both of these ideas.

As the target article states, the definition of "writing system" is: any system by which visual symbols can be used to express meanings and pronunciations. The world has had hundreds, probably thousands, of writing systems. Can one identify any properties of this collection of systems that are contingently true of all of them, in the way that, as we have noted above, there are various features of language which are contingently true of all

human languages? Note that one cannot reply to this challenge by saying "All writing systems represent meaning on the page" or "All writing systems represent pronunciation on the page" because these statements are not contingently true; they are true by definition of the term *writing system*. Can Frost offer a short list of properties which all of the world's writing systems just happen to have, as one can do with all the world's languages? We doubt that such a list can be compiled. But in the absence of such a list, the claim that there are reading universals in the sense of universal features of writing systems has no justification.

Frost might instead mean, by his claim that there are reading universals, that the cognitive information-processing systems that are used by readers of all the world's writing systems happen to have certain features in common. But, again, to justify such a claim one would have to produce a list of those properties that contingently hold for every reading system regardless of which writing system it is used for. We doubt that this kind of list could be compiled either.

In sum, then, our view is that whichever of these two different senses of "reading universal" is adopted, there are no reading universals. All that need be done to refute our view is to provide a list of some of these reading universals, just as we have provided a list of some of the universals of language.

But if there are no universals of reading, then Frost's desire for the development of a universal model of reading can never be fulfilled.

Developing a universal model of reading necessitates cracking the orthographic code

Colin J. Davis

Department of Psychology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom.

c.davis@rhul.ac.uk

http://www.pc.rhul.ac.uk/staff/c.davis/

Abstract: I argue, *contra* Frost, that when prime lexicality and target density are considered, it is not clear that there are fundamental differences between form priming effects in Semitic and European languages. Furthermore, identifying and naming printed words in these languages raises common theoretical problems. Solving these problems and developing a universal model of reading necessitates "cracking" the orthographic input code.

A surprising claim made by Frost in the target article is that (in Hebrew) "letter order cannot be flexible but has to be extremely rigid" (sect. 4.2, para. 5). The basis for this claim is the observation that different roots often share different orderings of the same three consonants. But of course the same problem arises in English when distinguishing words like *calm* and *clam*. Successful identification of printed words in English and Hebrew requires a combination of exquisite sensitivity to relative position and considerable flexibility with respect to absolute letter position. "Extreme rigidity" might work very well if all of the Hebrew words that shared the same root contained the letters of that root in the same positions, as is the case for the root Z.M.R in *zemer* (song) and *zamir* (nightingale). But Hebrew orthography does not admit such a simple solution, as is illustrated by words like *zimra* (singing, music), *z'miryah* (music festival), and *kleizemer* (musical instruments). Once again, the same problem arises in English. To appreciate the relationship between *build*, *builder*, *rebuild*, and *shipbuilding*, there must be commonality in the orthographic code for the *build* morpheme in these strings. Rigid, position-specific coding (whether left- or right-aligned) cannot accommodate this requirement, because the letters of *build* occur in different positions within these strings. This *alignment problem* (Davis 1999) was a key motivation for the development of spatial coding, and it is the fundamental reason why models of reading must address the issue of orthographic input coding. The alignment problem is common to many different orthographies, and models that attempt to solve this problem are addressing a universal constraint.

Frost's invocation of a *universality constraint* to critique current models is based chiefly on a consideration of masked form priming effects. His review may give the impression that form-priming effects are found without fail in European languages (and virtually never in Semitic languages), but the full story is more complicated. First, masked form primes give rise to inhibition when the prime is itself a word; for example, the prime *calm* inhibits identification of the target *clam* (Andrews 1996; see also Davis & Lupker 2006). This finding is predicted by models like the spatial coding model (Davis 2010), because the ability to discriminate words like *calm* and *clam* depends both on accurate encoding of letter order *and* on lexical inhibition. The latter mechanism ensures that the lexical representation that is most strongly supported by the orthographic input is able to suppress its competitors. By extension, representing root morphemes at the processing level above letters (e.g., Andrews & Davis 1999; Davis 1999, pp. 324–53) would lead to the prediction that transpositions that give rise to a different root than that embedded in the target should result in inhibitory priming, which is what Velan and Frost (2009) observed in Hebrew. Second, null form-priming effects are found in European languages for words with dense orthographic neighbourhoods (e.g., Forster & Davis 1991; Perea & Rosa 2000b). Thus, it is not at all clear that either the inhibitory or the null form-priming effects that have been reported in Hebrew (a notoriously dense orthography) are inconsistent with findings from European languages. Furthermore, monomorphemic words with sparse neighbourhoods show the same pattern of facilitatory priming effects in Semitic and European languages. There is every reason to think that a successful model of Hebrew word identification could incorporate the same coding and processing mechanisms as the spatial coding model (Davis 1999; 2010).

The other constraint discussed by Frost is what he refers to as the *linguistic plausibility constraint*. In criticising the "new wave" of "orthographic models" for failing this constraint, Frost appears to suggest that the spatial coding model is "*structured in a way that goes counter to the established findings for other linguistic dimensions*" (sect. 2.2, para. 1, emphasis in the target article). But if so, it is unclear what aspect of the model he is referring to. Elsewhere Frost criticises the model for focussing exclusively on orthographic processing, but as Davis (2010) notes, this is not intended as a claim regarding the structure of the visual word recognition system, but rather as a commitment to nested modelling (e.g., Jacobs & Grainger 1994) and what Andrews (2006) has referred to as temporal (as opposed to structural) modularity. That is, like other modellers, I have taken the approach of focussing on specific components of the full problem, but using a modelling framework that has been successful in capturing other aspects of performance, including effects in the Reicher–Wheeler test, speeded naming and lexical decision (e.g., Coltheart et al. 2001; McClelland & Rumelhart 1981; Perry et al. 2007). The commitment to temporal modularity does not imply "*that an adequate description of the cognitive operations involved in recognizing printed words is constrained solely by the properties of orthographic structure*" (sect. 8, para. 1, emphasis in original), but rather that, for skilled readers, printed words are most often identified principally on the basis of orthographic information, with phonological and semantic information being retrieved later.

Frost argues that models which learn will provide the ultimate answer to our modelling problems. I am a proponent of such models, but also appreciate the value of using hardwired models to better understand what must be learnt. Correlations between orthography and semantics or phonology cannot be discovered by any learning algorithm unless the input is structured in a way that preserves these correlations. Frost notes that, well before the new wave of models, Seidenberg and McClelland (1989) offered an

alternative to position-specific coding. What he doesn't note is that subsequent iterations of this modelling framework (correctly) blamed this alternative for the failure of this model to satisfactorily learn the mapping from orthography to phonology (Plaut et al. 1996). The need to learn context-invariant mappings from letters to phonemes highlights another aspect of the alignment problem, and another motivation for assuming position-independent letter representations (Davis 2010). In summary, cracking the orthographic input code is not simply an intellectual puzzle concerned with explaining transposed letter effects – it is a fundamental requirement for developing a general theory of reading.

Bringing development into a universal model of reading

S. Hélène Deacon

Psychology Department, Dalhousie University, Life Sciences Centre, Halifax, Nova Scotia B3H 4R2, Canada.

Helene.deacon@dal.ca   **http://langlitlab.psychology.dal.ca/**

Abstract: Reading development is integral to a universal model of reading. Developmental research can tell us which factors drive reading acquisition and which are the product of reading. Like adult research, developmental research needs to be contextualised within the language and writing system and it needs to include key cross-linguistic evaluations. This will create a universal model of reading development.

Frost's review inspires reading researchers to take seriously the diversity in languages and writing systems in which reading occurs. Appropriately, Frost focuses on adult visual word recognition research, where the debates have been most heated as to the flexibility of letter-order processing. Frost alludes to the developmental implications of his proposal. I review here three relevant dimensions from, and with implications for, development research that will expand this picture – moving us towards a universal model of reading *development*.

First, recent developmental research provides a direct test of Frost's proposal that, "*for a model to produce different behavior as a function of the statistical properties of the language, the model has to be able to pick up the statistical properties of the language*" (sect. 5, para. 5, italics in the original). Learning about letter-order regularities would be considered, in child reading research, within the construct of orthographic processing, or the "ability to form, store, and access orthographic representations" (Stanovich & West 1989, pp. 404). Frost's statement suggests that children learn about orthographic processing through their reading. This is also the prediction of several prominent models of reading development (e.g., Ehri 2005; Share 1999). There is, however, a competing proposal from empirical research: that children's orthographic processing determines their progress in learning to read (e.g., Wagner & Barker 1994; for a review, see Burt 2006). Perhaps surprisingly, there has only been one empirical test to date of the direction of the relationship between orthographic processing and reading. In a longitudinal study of English children between grades 1 and 3 including the most common measures of orthographic processing, Deacon et al. (2012) have demonstrated that children's reading determines their growth in orthographic processing rather than the other way around. This is the key advantage of developmental research: It can tell us about which skills drive reading acquisition and which are the product of reading.

This developmental approach provides empirical confirmation of Frost's suggestion that children learn about orthographic regularities through their reading experience. Considering this cross-linguistically, Abu-Rabia (1997) found that orthographic processing did not correlate with reading for Hebrew-learning children, even at the same point in time; this finding diverges considerably from similar studies done with children learning English, where such relationships abound (e.g., Cunningham et al. 2001). Abu-Rabia's finding makes sense if one considers the relative paucity of the orthographic regularities to be learned in Hebrew, where, as Frost points out, transitional probabilities are far less informative as to word identity. Clearly, cross-linguistic extensions of these developmental studies will be informative in identifying the language-specific and universal mechanisms that underlie learning to read.

Second, the concern that Frost raises about a hyper-focus on orthographic processing needs to be brought to bear on models of reading development. The two most prominent models propose that early reading acquisition is driven by phonological processes with a shift to orthographic processing, either in a later phase (Ehri 2005) or with specific items (Share 1995). Ehri's (2005) phase theory of reading development considers children's learning of letter patterns to be of both syllables and morphemes. According to this approach, all frequent letter patterns are processed similarly, regardless of whether these have a basis in meaning (e.g., *-ion* versus *-ight*, respectively). Share's (1995) self-teaching hypothesis is effectively a model of orthographic learning; through phonological decoding, children learn word-specific representations. Morphological effects are conceptualised as indexing reading efficiency. It is appropriate that both models include orthographic processing; children have a great deal to learn about the orthographic patterns in a writing system and the orthographic representations of individual words. And yet an over-emphasis on orthographic processing has led the vast majority of developmental research to consider only two facets of the linguistic context. The majority focuses on phonological and orthographic processing (e.g., Cunningham et al. 2001). Even the extension to morphological processing in more recent research tends to focus on only two dimensions, in this case phonological and morphological processing (e.g., Carlisle 2000; Deacon & Kirby 2004).

Recent developmental studies have begun to take seriously the full context suggested by Frost. Orthographic processing and morphological awareness have been shown to make distinctive contributions to reading outcomes (from each other and from phonological awareness) both in younger (Deacon 2012) and older child readers (Roman et al. 2009; see also, Garcia et al. 2010; Tong & McBride-Chang 2010). Children are clearly attending to more than orthographic dimensions in the process of learning to read, and so should models of reading development.

The final critical step is to bring together a full linguistic and writing system context with rich cross-linguistic comparisons. All discussions, both developmental and adult, need to be framed in the context of the relative weighting that each language places on these linguistic dimensions, a point duly taken from Frost. As we have already reviewed, orthographic processing does not appear to be predictive of reading outcomes in Hebrew (Abu-Rabia 1997). Clearly, the role of orthographic processing might depend on its place in the writing system in which children are learning to read. Similarly, turning to morphology, McBride-Chang et al. (2005) demonstrated that morphological awareness was more strongly associated with children's reading outcomes in Chinese and Korean than in English. Both Chinese and Korean represent morphology in the writing system to a much greater extent than does English, and so these data demonstrate the clear need to consider the language context in which reading occurs. The next key move is to integrate these developmental and cross-linguistic comparisons with the full linguistic context of learning (e.g., Share 2008a).

I share Frost's quest for a universal model of reading; I would put forward that it must be a universal model of reading *development*. It needs to be universal in considering the phonological, orthographic, and morphological dimensions of the context in which the reading occurs. It needs to be developmental in evaluating the factors that underlie children's reading acquisition, as well as those that continue to inform adult word recognition. Reading researchers across all orthographies need to keep this laudable goal in their sights.

Does a focus on universals represent a new trend in word recognition?

Laurie Beth Feldman[a] and Fermín Moscoso del Prado Martín[b]

[a]*Department of Psychology, State University of New York at Albany, Albany, NY 12222, and Haskins Laboratories, New Haven, CT 06511;* [b]*Laboratoire Dynamique du Language, Centre National de la Recherche Scientifique, Institut de Sciences de l'Homme, 69363 Lyon Cedex 07, France.*

lfeldman@albany.edu   fermosc@gmail.com
http://www.albany.edu/~lf503/   http://www.moscosodelprado.net

Abstract: Comparisons across languages have long been a means to investigate universal properties of the cognitive system. Although differences between languages may be salient, it is the underlying similarities that have advanced our understanding of language processing. Frost is not unique in emphasizing that the interaction among linguistic codes reinforces the inadequacy of constructing a model of word recognition where orthographic processes operate in isolation.

By allowing for the interaction of orthographic with other types of linguistic structure, Frost becomes an advocate for a more universal and less Hebrew-centered theoretical approach. For those of us who have long held that view, we welcome this change. In the past, Frost and his colleagues frequently offered up Hebrew as the exceptional language, citing its infixing rather than concatenation of morphemes as the reason why a model based on the principles that apply to English will not work (Frost et al. 1987; 1997; 2000a; 2000b; 2005). It is they who characterized Hebrew as special and defined English as the default against which to evaluate other languages.

Variation among languages in reading and visual word recognition has long provided a tool with which to investigate universal properties of the cognitive system. Although differences between languages may be striking, it is the more abstract similarities, often captured in terms of complex interactions among linguistic codes (e.g., orthography × morphology) that have been more useful in advancing our understanding of the processes that underlie reading and word recognition. We highlight two well-established lines of research to make this point. Both capture the interaction of semantic with orthographic processing.

A common assumption in models of word recognition is that morphologically structured words are decomposed into their morphemes and that the initial process is semantically blind and based solely on the orthographic form of the stem (e.g., Rastle et al. 2004). Accordingly, analysis of a word composed of multiple morphemes (i.e., morphologically complex) proceeds without recourse to the meaning of its constituents or to the word as a whole. Counter to this claim, we have reported that semantically similar (e.g., coolant–COOL) prime-target pairs produce greater facilitation than do dissimilar (e.g., rampant–RAMP) pairs when English words appear in the forward masked primed lexical decision task (Feldman et al. 2009). Likewise in Serbian, with its many words formed from an orthographically (and phonologically) identical stem, semantically similar primes produce greater facilitation than do semantically dissimilar primes (Feldman et al. 2012). Results in morphologically rich Serbian, like those in relatively impoverished English, show very early effects of semantics under conditions that are purported to foster orthographic processing of a morpheme. In this respect, both studies confirm statistically a pattern that is revealed meta-analytically even when it is not uniformly significant in individual studies (Feldman et al. 2009). Note that English and Serbian are at opposite ends of the continuum with respect to systematicity in the mapping between form and meaning (with morphologically rich Serbian showing greater systematicity than English). Yet, despite differences in their morphological complexity, both languages reveal contributions of semantics under conditions where others have asserted that orthographic processing dominates (for a review, see Rueckl & Aicher 2008).

The second and more established line of research shows morphological influences on orthographic processing in both English and Hebrew (Feldman et al. 1995), minimal consequences of orthographic disruptions to the root morpheme introduced by Hebrew's infixing structure (Feldman & Bentin 1994), and robust effects of morphological family size despite the contrast between Hebrew's infixing morphology and the concatenative morphology in English (Moscoso del Prado Martín et al. 2005). Data derive from varied tasks. In the segment-shifting variant of a naming task, participants decompose a word into its morpheme constituents, shift a letter sequence (ER in the following examples) from prime to target, and then name the target aloud. Latencies were faster (15 msec) to form PAINTER from PAINT after seeing DRUMMER than after SUMMER. The critical manipulation is that ER on the former but not the latter is morphemic and thus changes the stem in a semantically predictable way. Analogous effects were reported in Hebrew (Feldman et al. 1995) and Serbian (Feldman & Andjelković 1992). A specifically Hebrew finding is that orthographic disruptions to a Hebrew prime (e.g., GMR) introduced by a word pattern that disrupts the root (GOMaR vs. GaMaR, where uppercase letters are represented by letters and lowercase letters by optional diacritics) did not alter facilitation to a morphologically related target in the lexical decision task (Feldman & Bentin 1994). The failure to detect orthographic effects in Hebrew led Frost and his colleagues to claim that morphological roots provide the organizing principle for the lexical space of Hebrew, while constituent letters and their position function to organize the space for English and other Indo-European languages (Frost et al. 2005; p. 1295). The results discussed above fail to provide compelling evidence that the lexicons of Hebrew speakers are organized in a fundamentally different manner, however.

Family size (i.e., the number of words sharing a base morpheme) predicts decision latencies in languages such as Dutch, Finnish, German, and English, where base morphemes can stand alone as words or be affixed, but also in Hebrew, where a second morpheme is infixed inside the root morpheme. Compounds constitute proportionally more morphological family members in English or Dutch than in Hebrew, but the languages do not differ in morphological family size (Moscoso del Prado Martín et al. 2005). Despite some variation in the manner by which morphemes combine, Hebrew, like the other languages, shows robust effects of morphological family size on single word recognition.

It is evident that the consequences of orthographic differences across languages can get exaggerated when orthographic structure is examined in isolation. The results of many studies that have been conducted over the past decade in languages other than English challenge the claim that orthographic processing remains isolated from phonological, morphological, and semantic effects. Frost is not unique in claiming that serious consideration of the interaction among linguistic codes across languages reinforces the inadequacy of constructing a model of a stage of word recognition in English, or in Hebrew or Chinese for that matter, around isolated orthographic processes.

An even more universal model of reading: Various effects of orthography on dyslexias

Naama Friedmann[a,d] and Aviah Gvion[a,b,c]

[a]*Language and Brain Lab, Tel Aviv University, Tel Aviv 69978, Israel;* [b]*Department of Communications Sciences and Disorders, Ono Academic College, Kiryat Ono 55000, Israel;* [c]*Reuth Medical Center, Tel Aviv 67728, Israel;* [d]*Sagol School of Neuroscience, Tel Aviv University, Tel Aviv 69978, Israel*

naamafr@post.tau.ac.il   http://www.tau.ac.il/~naamafr/
aviah.g@ono.ac.il

Abstract: The properties of a specific orthography dictate the way people read it. We bring considerations from dyslexia to suggest that the claim can be extended further. First, the effect of orthographic neighborhood density can be extended beyond letter-position encoding and beyond the orthographic lexicon. Second, Hebrew and Arabic differ with respect to letter forms, and hence, in letter-position encoding.

The research of dyslexia and patterns of reading in various dyslexias can be revealing with respect to the characterization of normal cognitive processes. One of the domains in which dyslexia is informative is the effect of the properties of the various orthographies on reading. On the basis of studies of dyslexia, we suggest that Frost's proposal regarding the interaction between the nature of an orthography and reading can be further extended along several lines.

The varied effects of orthographic neighbors. Frost discusses density of orthographic space and its effect on letter-position encoding in reading. We suggest that density effects on reading go beyond orthographic density in the orthographic input lexicon, beyond letter-position encoding, and beyond normal reading. First, when thinking about the process of single word reading (for which we assume the dual route model; Coltheart 2006; Coltheart et al. 2001; Ellis & Young 1996; Marshall 1984), lexical density affects reading in two ways. One way relates to the orthographic input lexicon, the other to output stages and the lexicality of response. Take, for example, a case in which the information that arrives from the orthographic-visual analyzer is partial (or underspecified). If this partial output matches a single item in the orthographic input lexicon, the reading is expected to be correct, even if the early encoding failed. For example, if the target word is *frog*, underspecified information about the order of the middle letters would still activate the correct entry in the lexicon. However, if the neighborhood is dense, then partial information might activate other lexical items that match the partial information. For example, for the word *bared*, underspecified order of middle letters might activate other entries in the orthographic lexicon, which might end up in reading the more frequent *bread* or *beard*.

The density of the lexical space has an important effect beyond the orthographic input lexicon. One can see such effects acting on later stages of reading that involve oral responses. Individuals with dyslexia tend to produce lexical responses in reading aloud. Therefore, target words for which an error creates another existing word are more liable to be read incorrectly. This is the case even when the orthographic input lexicon is not involved in reading, as in surface dyslexia. Individuals with impaired orthographic input lexicon, who therefore cannot read via the lexical route, read via the sublexical route. For these individuals, the density of the lexical space is still a crucial factor, determining whether or not they will make an error in reading. This can be most clearly viewed in the effect of potentiophones on reading in surface dyslexia. Potentiophones are words that are written differently and sound differently, but when read solely via grapheme-to-phoneme conversion, can be read aloud as the other word, which sounds differently. An example is the word *none*, which can be read as *known* if read via grapheme-to-phoneme conversion.

Potentiophones are significantly more difficult for individuals with surface dyslexia than words for which a surface-dyslexia error does not create another word (Friedmann & Lukov 2008). Because they do not read aloud via the orthographic input lexicon, the lexical density effect should be attributed to the output stages, rather than to the orthographic input lexicon. Namely, beyond the basic classification of languages into deep and shallow languages, the manifestation of surface dyslexia would depend crucially on another property: the availability of potentiophones. Thus, reading mechanisms

may be identical in different languages, but the different orthographies may lead to different reading outcomes.

Moreover, the effect of orthographic-space density extends beyond letter-position encoding, to abstract letter identity. If letter-identity encoding fails, dense neighborhoods should also hamper reading. The underspecified letter-identity information would activate other entries in the orthographic input lexicon that match this partial information. Take, for example, the word *fold*, which has a large Coltheart's *N* (Coltheart et al. 1977). If the reader fails to encode the identity of a letter in the target word *fold*, many other words (like *cold*, *hold*, *fond*, and *folk*) can be activated. This point has a crucial effect on the manifestation of various dyslexias resulting from impairments in the orthographic-visual analyzer, including: visual dyslexia (Friedmann et al. 2012), neglect dyslexia (Vallar et al. 2010), and attentional dyslexia (Davis & Coltheart 2002), dyslexias in which letter-identity errors result in existing words.

Hebrew and Arabic: Similar, yet different. Hebrew and Arabic share the pivotal role of morphology, as well as the effect of morphological structure on reading. However, whereas Frost's target article treats all Semitic languages as one group with identical properties, and hence predicts similar reading patterns with respect to letter-position encoding, Hebrew and Arabic present important differences that create different reading patterns and different manifestations of dyslexia in the two languages (Friedmann & Haddad-Hanna, in press a; in press b). This point can be demonstrated by a property that is one of the main pillars of the target article: letter-position encoding.

Arabic orthography presents a unique orthographic feature: Letters take different forms in different positions in the word. The form of each letter is determined by its position in the word – initial, middle, or final, and whether or not it ligates to the letter that precedes it. The ligation status of a letter depends on whether the preceding letter is one of the six non-ligating letters, in which case it would not ligate to the previous letter, or one of the other letters. This factor of letter forms that are determined by letter position crucially affects letter-position encoding in Arabic. Friedmann and Haddad-Hanna (in press a; in press b) found that letter form had a substantial effect on the rate of letter-position errors of Arabic-speaking individuals with letter-position dyslexia (LPD). Twelve individuals with developmental LPD made letter-position errors almost only when the change of letter position did not require a change in letter form.

Importantly, the difference in this property between Arabic and Hebrew orthography led to differences in letter-position errors in the two languages. In a study of a bilingual Arabic-Hebrew man with acquired LPD, Friedmann and Haddad-Hanna (in press a) reported that, in reading lists of single words, he made significantly more letter-position errors in Hebrew than in Arabic. This difference was due to the fact that whereas both lists included migratable words, in Arabic a migration of the middle letters in many of these migratable words required letter-form change. Because Arabic readers with LPD do not make letter-position errors that change letter form, the participant made significantly fewer letter-position errors in the Arabic list. When given a list that only included migratable words in which the migration does not change letter form, his error rates in Hebrew and Arabic were the same (see also Friedmann & Gvion [2005] for the effect of letter forms on the manifestation of another type of dyslexia – word-based neglect dyslexia). Thus, Hebrew and Arabic differ along dimensions that create different outcomes in reading. More generally, there are various dimensions along which orthographies differ; the exact same reading mechanism, when faced with different orthographies and languages, may give rise to different reading outcomes in normal reading and in dyslexia.

Visual word recognition models should also be constrained by knowledge about the visual system

Pablo Gomez[a] and Sarah Silins[b]

[a]Psychology Department, DePaul University, Chicago, IL 60614; [b]Law School, Northwestern University, Chicago, IL 60611.
pgomez1@depaul.edu   ssilins@gmail.com
http://condor.depaul.edu/~pgomez1/WNPL

Abstract: Frost's article advocates for universal models of reading and critiques recent models that concentrate in what has been described as "cracking the orthographic code." Although the challenge to develop models that can account for word recognition beyond Indo-European languages is welcomed, we argue that reading models should also be constrained by general principles of visual processing and object recognition.

Any computational or mathematical model has to negotiate the tension between parsimony and a diverse and often fragmented empirical landscape. Frost's article correctly points out that the field is extremely Anglocentric, and that there is overwhelming evidence (particularly from studies done with Semitic languages) which indicates that current models of visual word recognition have a rather limited descriptive adequacy beyond the data sets (obtained mostly from English readers) that are used as benchmarks.

We interpret Frost's call for a universal model of reading to mean that the same general architecture, with different parameter values, should account for reading behavior (or at least visual word recognition) across a variety of languages. In other words, a universal model of reading should assume that Hebrew readers and English readers engage in basically the same processes while identifying written words. This process might produce different outcomes depending on the linguistic context (e.g., the presence or absence of roots or prefixes). A key finding pointing towards a unified mechanism with different parameters is that Hebrew readers show flexibility in the encoding of letter position (just like English readers) when presented with Hebrew words that are non-root-derived. It is impossible for the readers to anticipate whether they are about to encounter a root-derived or non-root-derived word, so one could not argue for different strategies depending on the kind of word; instead, the same process produces different outcomes depending on the nature of the input.

We argue that the starting point of a "universal" theory of visual word recognition should be the visual system that is shared by readers in all languages. In fact, some of the current models that Frost is critical of assume that the process of letter-position coding shares principles with other forms of visual processing. Namely, both the overlap model (Gomez et al. 2008) and the Bayesian reader (Norris & Kinoshita, in press) claim that there is no "code to crack," and that the transposed letter (TL) effects are a by-product of object-position uncertainty as described by general models of visual attention (e.g., Ashby et al. 1996; Logan 1996).

The overlap model as currently formulated could not account for the data presented by Velan and Frost (2011), which show different outcomes depending on the type of word presented. So, how would a model that assumes that TL effects are merely a by-product of the visual system's organization account for the linguistic context effects mentioned by Frost? The target article raises important issues in its discussion of the differences between Hebrew and English. Whereas in English the presence of a particular letter is rather uninformative about other letters in a word, in Hebrew the probability of a letter being in a given position is highly predictive of the other letters present in the word. From a Bayesian point of view, one can think of this process as generating posterior functions from a prior and a

likelihood (see Mamassian et al. 2002). In English, the priors are essentially uninformative because almost any letter can go into any letter position. In Hebrew, on the other hand, the priors may be quite informative especially for the majority of Hebrew words that include a root. So, the mere identification of one of the letters in a root-derived Hebrew word constrains the other possible letters in the word reducing position uncertainty. Models could be modified in order to implement informative prior knowledge.

In short, we believe that the target article by Frost is a timely piece that hopefully will push researchers into expanding the frontiers of the benchmark phenomena in visual word recognition. We believe that these extensions can be done in a principled manner, and that cross-linguistic work might be the next frontier for visual word recognition models.

Universals of reading: Developmental evidence for linguistic plausibility

Usha Goswami

Centre for Neuroscience in Education, Department of Experimental Psychology, University of Cambridge, Cambridge CB2 3EB, United Kingdom.
ucg10@cam.ac.uk
http://www.cne.psychol.cam.ac.uk/

Abstract: Children's reading and spelling errors show that orthographic learning involves complex interactions with phonology, morphology, and meaning throughout development. Even young children seek to make their visual word recognition strategies linguistically coherent. Orthographic knowledge gained through spelling affects reading, and vice versa. Developmental data support Frost's claim that letter-coding flexibility reflects the optimization of encoding resources in a highly developed system.

Frost has gathered compelling data from Semitic languages showing that skilled readers are sensitive to letter order. He therefore argues that paradigms such as transposed-letter priming (TLP) cannot tell us anything of universal significance regarding the brain and lexical processing. Here I argue that developmental data from an orthography showing TLP (English) lead to the same conclusion. Children do not learn to read, nor spell, in a cognitive vacuum. Instead, their errors during learning demonstrate that "orthographic" learning cannot be separated from other aspects of language development. Learning to recognize printed words involves complex interactions with phonology, morphology, and meaning from the very beginning of learning.

When children are learning to spell, letter-order sensitivity is mandatory. If young children produce spellings that are insensitive to letter order, perhaps writing "GAOL" for "goal" or "LOIN" for "lion," these spellings are wrong. In orthographically inconsistent languages like English, children make many such errors, and therefore rote-learning of spelling conventions and weekly spelling tests are a ubiquitous part of primary (elementary) education. Indeed, children who are sensitive to letter order but who produce spellings that are not phonetically acceptable (e.g., "COUGE" for "cough" or "SUARCH" for "search") are those children who are educationally at risk for disorders of literacy (Frith 1980). Frith reported that 12-year-old children whose spelling errors were phonetically acceptable (e.g., "COFF" for "cough," "SURCH" for "search") usually resolved their spelling problems after further rote-learning. In contrast, children who had produced spellings like "COUGE" went on to have literacy difficulties.

Early reading errors show the strong influence of meaning in English children's early orthographic behaviour. For example, Seymour and Elder (1986) noted visual word recognition errors like "TIGERS" for "lions," "WHEELS" for "car," and "GIRL" for

"children." These substitutions are semantically appropriate, but they ignore the letter–sound correspondences in the target words: Meaning can trump phonology in early reading. However, at the same time, when learning to spell, young children will spell words accurately that they cannot read (e.g., "bun," "mat," "leg"; Bradley & Bryant 1979; Bryant & Bradley 1980). This suggests that in early spelling, phonology is the trump card. Children can build up a spelling pattern like "bun" by analyzing the sounds in the target word, but they then fail to recognize the visual word that they have just written down when asked to read it aloud.

Many of children's spelling errors show the importance of phonology. Very young spellers use phonological insights that conventional English orthography ignores. Thus, words like "chair" and "truck" are spelled with the same onset ("CH"). This is phonologically appropriate because the first sound in the word "truck" is affricated, hence children misspell "truck" as "CHRAC." Other examples include "ASCHRAY" for "ashtray" and "CHRIBLS" for "troubles" (Read 1986). Spelling errors will even differ by English dialect. American 7-year-olds (rhotic dialect) will misspell "girl" as "GRL," whereas British 7-year-olds (non-rhotic dialect) will misspell "girl" as "GEL" (Treiman et al. 1997). The rhotic dialect of American phonology pronounces the letter "R" after the vowel, and this linguistic knowledge affects orthographic learning. Very young spellers add more letters than conventional to reflect phonology; for example, "SOWEMEG" for "swimming" (complex onset SW). They also use letter names in spelling (as in "TOM NICTA CR" for "Tom nicked a car"; Read 1986; Treiman 1993). The letter name of "R" sounds like the phonological rime of "car."

Children's spelling errors also show that morphological knowledge affects orthographic learning. For example, young children produce errors like "KIST" for "kissed" and "CLAPT" for "clapped." However, after learning the "ed" rule, some children over-apply the rule to spell words that are not verbs, for example, producing "SOFED" for "soft" and "NECSED" for "next" (Nunes & Bryant 2006). This is not a rare anomaly: More than half of the children in this longitudinal study produced errors of this kind. Gradually, children realize that words like "kissed" have two morphemes, whereas "mist" has only one morpheme, and stop producing these spelling errors (by the age of around 9 years). Nunes and Bryant (2006) argue that this is not because of direct teaching, as they measured the teachers' morphological knowledge and found they were unaware of which verbs added "ed" ("kiss–kissed") and which did not ("sleep–slept"). Rather, such errors decline via *implicit* learning of the complex interactions between phonology, morphology, and meaning.

Clearly, therefore, young learners apply multiple linguistic strategies to the processing of orthographic form. Implicit orthographic learning also affects the recovery of phonology from print, showing that implicit learning is bi-directional. English 7-year-olds are better at reading non-words like "BICKET," which use orthographic segments of real words like "TICKET" to represent phonology, than matched non-words like "BIKKET" (51% versus 39%; see Goswami et al. 1997). Implicit knowledge also affects silent reading. In a proofreading task, 12-year-olds detected significantly more silent-letter omissions ("SISSORS" for "scissors") than pronounced-letter omissions ("SCARELY" for "scarcely"; Frith 1978). This shows the influence of implicit morphological knowledge. Silent letters often reflect morphological roots (Latin "scissor" for "cutter"). Similarly, 8-year-olds recall more words on the basis of a silent-letter prompt ("C" for "SCISSORS") than a pronounced-letter prompt ("C" for "SCRIBBLE"; Ehri & Wilce 1982). Just as for skilled adults, the task in hand matters for the strategy that is employed. Letters are treated differently by the cognitive system, depending on the specific linguistic environment created by the (experimental) task.

Data like these provide a wealth of evidence supporting Frost's argument that models of visual word recognition must reflect the basic fact that words have phonological, semantic,

and morphological characteristics as well as orthographic characteristics. The errors made by young learners of English show that children learning to recognize visual word forms seek linguistic coherence throughout the skill acquisition process. A universal model of reading hence needs to take account of developmental data as well as cross-linguistic data. Even though TLP is found in skilled readers of English, data from English learners support Frost's theoretical view. Letter-order insensitivity is an idiosyncratic strategy used by skilled readers to optimize encoding resources in certain linguistic environments.

Explaining word recognition, reading, the universe, and beyond: A modest proposal

Jonathan Grainger and Thomas Hannagan
Laboratoire de Psychologie Cognitive, Aix-Marseille University, 13331 Marseille, France.
jonathan.grainger@univ-amu.fr   thom.hannagan@gmail.com
www.univ-provence.fr/lpc

Abstract: Frost proposes a new agenda for reading research, whereby cross-linguistic experiments would uncover linguistic universals to be integrated within a universal theory of reading. We reveal the dangers of following such a call, and demonstrate the superiority of the very approach that Frost condemns.

Frost's appeal for universal theorizing contrasts with the recommendation formulated by Jacobs and Grainger (1994) to "grow" models not wildly but in accord with a few general principles and a few pragmatic stratagems. Frost proposes a two-tier approach to modeling that comprises a "universal" level and a "local" level. This two-tier approach is analogous to Marr's (1982) distinction between the computational theory (that answers the "why?" question) and its implementation (that addresses the "how?" question). Frost is therefore following in the footsteps of a number of protagonists of this top-down approach to scientific theorizing, championed in recent years by the Bayesian tradition. In a nutshell, the claim is that it is the computational theory that is important and we can basically ignore the details of its implementation.

With respect to understanding reading, Frost's major claim is that language-specific research does not contribute to a general theory of reading. Taking the example of research on orthographic processing in Indo-European languages, he states that "sensitivity to letter order per se does not tell us anything interesting about how the brain encodes letter position, *from the perspective of a theory of reading*. Instead, it tells us something very interesting about how the cognitive system treats letters *in specific linguistic environments*" (sect. 1.1, para. 6, original emphasis). This is a statement that is just as much perplexing as it is logically flawed. Since a theory of reading must encompass a model of how the cognitive system treats letters in specific linguistic environments, then if the latter is deemed to be of interest, this interest must still hold in the former. Moreover, we would argue that taking Frost's appeal seriously would likely lead research as far astray as the Chomskyan movement's focus on uncovering innate linguistic abilities in a quest for the "universal grammar."

What might a universal theory of reading look like? First, and here we agree with Frost (but who could disagree?), that it would need to be founded on basic principles of human information processing. Now, recent years have seen a consensus develop around at least two such principles: (1) The brain is an information-processing device that strives to make optimal decisions; and (2) behavior adapts optimally to environmental

constraints via the principles of statistical learning. In fact, it is precisely these two principles that, for the moment, constitute Frost's universal model of reading. Not a major breakthrough, we would argue, since (1) such general principles are often acknowledged by theorists working at a more local level (e.g., Dufau et al., in press); and (2) although they certainly provide important constraints on theories of reading, without the details of the implementation they would not be much use to a speech therapist trying to understand why a child cannot learn to read.

Here we describe a universal theory of reading that has been slowly nurtured by the kind of refinement process for scientific progress advocated by Jacobs and Grainger (1994). Indeed, applying a language-specific approach has helped uncover a number of universal *clues*. These clues are neural, developmental, and computational. The *neural clue* is that reading involves a quite particular piece of neural machinery (the visual system and the visual word form area; see Dehaene & Cohen 2011). The *developmental clue* is that humans are already experts at object recognition when they start to learn to read. The *computational clue* is that there is one way to represent and compare sequences that has proved very efficient from a purely computational perspective, and goes by the name of "string kernels" (Hannagan & Grainger, in press).

Like three lines crossing at the same point, these cross-language – even cross-domain – clues lead to the proposal that humans must represent words not by assigning absolute positions to different parts, but by keeping track of the relationship between parts – that is, by detecting feature combinations (see also Whitney 2001). In English, for instance, orthographic processing would involve extracting ordered letter combinations: Reading TIME requires extracting, among others, the combination TI but not IT. This is equivalent to representing words as points in a high-dimensional space, the space indexed by all possible letter combinations. In machine learning, the function that compares sequences in this space is known as a *string kernel*. String kernels drastically improve the linear separability of word representations, a property that is desirable in English as in Hebrew, or whatever the statistics of one's particular lexicon turn out to be. Given that the primate visual system is already believed to use feature combinations to represent visual objects (e.g., Brincat & Connor 2004), it is also the minimal modification to the child's pre-existing visual object recognition system. In addition, string kernels form a quite versatile solution that has recently found success in disciplines ranging from bioinformatics to automatic language processing. These successes were obtained parsimoniously by varying only three parameters (length of letter combinations, gap penalty, and wildcard character), demonstrating that different kernels can capture the particulars of many application domains. String kernels can also be trained so as to ignore certain dimensions in the letter combination space and to favor others. In this view, the task of learning the visual word code becomes the task of learning to represent words by adequate feature combinations – learning the right string kernel function.

The theory thus follows Frost's first criterion for model evaluation, the "universality constraint," since it applies to different languages, and indeed goes beyond this restricted universality because it applies to different modalities, different object categories, and even in very different fields of science. It also follows Frost's criterion 2 for model evaluation ("linguistic plausibility"), since, following Grainger and Ziegler (2011), we argue that the nature of the mapping of orthographic features onto higher-level linguistic representations (i.e., the appropriate string kernel) is constrained by the very nature of these higher-level representations. Finally, and most importantly, the theory also exhibits explanatory adequacy. It provides a better fit to a set of independently established benchmark phenomena (Davis 2010) than do competing models, and it does so with a much smaller number of free parameters.

Flashing out or fleshing out? A developmental perspective on a universal model of reading

Bruce D. Homer,[a] Russell Miller,[a,b] and Seamus Donnelly[a]
[a,b]*Program in Educational Psychology, The Graduate Center, City University of New York (CUNY), New York, NY 10016;* [b]*Center for Intentional Media, New York, NY 10027.*
bhomer@gc.cuny.edu
rm@intentionalmedia.net   SDonnelly@gc.cuny.edu
http://web.gc.cuny.edu/content/edpsychology/pages/BHomer.html

Abstract: The principles for universal reading models proposed by Frost correspond to developmental theories, in which neurocognitive constraints and cultural experiences shape development. We question his contention that Hebrew word identification is fundamentally about roots, excluding verbal and nominal word-pattern morphemes; and we propose that readers use all information available in stimuli, adjusting for volume and usefulness.

Frost proposes two principles for universal reading models: They must apply to any writing system and accommodate findings related to all linguistic dimensions. These correspond to a central theme in developmental theory: Development is intimately bound with experience, particularly cultural experience.

In Frost's view, neurocognitive and cultural constraints shape languages to idiosyncratically maximize the information packed into each word. Complementarily, individuals' brains learn to extract information efficiently from their linguistic environment. While we strongly agree with this claim, our attention was drawn to Frost's contention that reading Hebrew is fundamentally about identifying morphemic roots, and that "the other letters of the word do not serve for lexical access, at least not initially" (sect. 4.1). Those other letters comprise the root's sibling in morphological decomposition: the *word pattern* (WP). We believe it is important to recognize WPs as a source of information, processed alongside their big brother, the root.

Frost suggests that the WP morpheme's primary role in visual word identification is to "flash out" (sect. 5, para. 4) the all-important root, due to the skewed frequency distribution of WP letters. In fact, as he has acknowledged elsewhere (Frost et al. 2005), the Semitic WP can independently pack a substantial volume of information – pronunciation, part of speech, person, number, gender, tense, voice, and reflexivity. Far from merely flashing out a root, word-pattern morphemes *flesh* out the meaning of a word.

Analyses of Hebrew print generally distinguish three groups of morphemes: some 3,000 roots, about 100 nominal WPs, and about 100 verbal WPs, the latter grouped into seven "constructions" (Shimron 2006). These distributions lead Frost to argue statistical invisibility for the WP. However, the forms are distinguished not only by number and linguistic class. They lie along a continuum of information volume. At one extreme, roots anchor mutually exclusive morphemic families. At the other, most nominal WPs carry little more information than "this word, pronounced this way, is a noun," occasionally signaling narrower semantic categories, such as "professional," "craftsman," or "event." Somewhere in the middle fall verbal WPs.

This notion of a continuum of information volume, from roots to verbal patterns to noun patterns, is not inconsistent with Frost's research. In a series of priming experiments, Frost and colleagues have demonstrated reaction-time and fixation-duration facilitation by shared roots (Deutsch et al. 2003; Frost et al. 1997) or verbal word patterns (Deutsch et al. 1998; 2005). Although facilitation by nominal word patterns has not reached statistical significance (Deutsch et al. 1998;), Frost et al. (2005) found consistent benefits for shared nominal word patterns; these were especially large – up to 22 msec – in pseudo-words, where noun patterns, the sole information-bearing morphemes, reduced reaction time by 12 msec more than did identity primes.

Since roots and verbal patterns carry large volumes of information, it makes sense that priming them significantly shortens

fixations and reaction time. And since nominal patterns carry little information, it makes sense that they would not produce as strong an effect. However, these findings do not imply that nominal WPs are unimportant in word identification; their contribution may be too small or too early to affect behavioral measures.

Electrophysiological research has found indexes of multiple types of information bound to single written words within 200 msec of exposure (Pulvermüller et al. 2009), including morphological analysis as early as 180 msec (Kellenbach et al. 2002). Pulvermüller and colleagues make the case for near-simultaneous processing of multiple, overlapping information components, a case strengthened with respect to morphemes by Kuperman et al. (2009). Event-related potentials (ERPs), a measure at the temporal scale of eye-tracking but with access to hidden neural events, might provide evidence of the role of nominal WPs in Semitic word identification.

Such findings would support the general principle that readers learn to use every scrap of information provided by written language. Evidence of word identification guided by the volumes of information in cognitively defined segments of a visual stimulus, whether single or multiple-letter, consecutive or interdigitated, would go beyond Frost's demonstration that the extraction of information from written words is not universally controlled at the level of letter identity. It would suggest that extraction tactics may not map to categories like orthography, morphology, phonology, and semantics at all, nor to theoretical timetables distinguishing prelexical perception from lexical cognition, but emerge in response to both linguistic and non-linguistic qualities of the stimuli, including information volume or real-time usefulness (Miller 2012). For instance, Holcomb and colleagues, using ERPs to study repetition and associative priming, proposed that differences might derive not from the linguistic categories, form, and meaning, but from the processes evoked by relationships between neural representations of prime and target: activation of shared representations in the first case, connection across related representations in the second (Holcomb & Grainger 2009; Holcomb et al. 2005).

If minds extract all they can from every word, morpheme, and letter, guided by many characteristics of the segmented stimulus, then the role of formal patterns in reading Hebrew goes beyond probabilistic invisibility. In the same vein, developmental research indicates that experiences which enable reading extend far beyond the statistical learning invoked by Frost. Readers acquire cognitive tools through trial, error, and cumulative familiarity, to be sure, but also with adult guidance, during powerful one-trial events, and by forming their own insightful associations (Homer 2009). A universal learning model of reading will incorporate all these opportunities.

Frost does great service in going beyond models based rigidly on letter identity and position. He points toward a model that respects the phylogenetic capacity to devise symbolic systems that extend memory into non-biological space, as well as the ontogenetic capacity to develop culturally specific schemata that recapture embedded information. Our interpretation of the research suggests the need for an even more capacious explanation of how we develop and apply those schemata – associating each visual stimulus with prior knowledge, seeking and extracting the information available in each word.

Flexible letter-position coding is unlikely to hold for morphologically rich languages

Jukka Hyönä[a] and Raymond Bertram[b]

[a]*Department of Psychology, University of Turku, FI-20014 Turku, Finland;*
[b]*Department of Teacher Education, University of Turku, FI-20014 Turku, Finland.*

**hyona@utu.fi   rayber@utu.fi   http://users.utu.fi/hyona/
http://users.utu.fi/~rayber/**

Abstract: We agree with Frost that flexible letter-position coding is unlikely to be a universal property of word recognition across different orthographies. We argue that it is particularly unlikely in morphologically rich languages like Finnish. We also argue that dual-route models are not overly flexible and that they are well equipped to adapt to the linguistic environment at hand.

In his target article, Ram Frost argues that current models of word recognition are "ill-advised" (sect. 1, para. 5) because they (1) focus mainly on orthographic processing, and (2) incorporate flexible letter-position coding as a general property of the cognitive system. We warmly welcome his criticism. As noted by Frost, in many languages the morphological structure of words has a key role to play in word recognition. Finnish is a prime example of a morphologically rich language. Although the crucial experiments have not been done, it appears likely that letter-position coding in Finnish is not as flexible as in some other alphabetic languages. When words as a rule contain multiple morphemes, letter positions become more constrained than in languages with restricted morphology (e.g., English). In Finnish, transposing two letters at morpheme boundary can completely change the word meaning. For example, transposing two letters in *valalta*, an inflected form of *vala* (oath), results in *vallata*, which has a completely different meaning (to conquer). Thus, although not yet demonstrated, it is highly likely that in these kind of instances Finnish would not show transposed letter priming (i.e., *vallata* would not prime *valalta*), similarly to Hebrew.

Although the relevant empirical evidence concerning transposed letter priming is still missing for Finnish, there is supportive evidence (Duñabeitia et al. 2007) from a morphologically poorer language, Spanish, and a morphologically rich language, Basque, for the claim that in morphologically productive languages flexible letter-position coding across morphemes may lead to insurmountable problems for the processing system. This study was mentioned only in passing in Frost's target article. In a priming study, Duñabeitia et al. (2007) obtained no transposed letter effect for letter transpositions spanning the morpheme boundary either for suffixed Basque words, or for prefixed or suffixed (*mesoenro→mesonero* = landlord) Spanish words. Similar results have been obtained by Christianson et al. (2005) in English for suffixed words (see, however, Rueckl & Rimzhim 2011) and compound words (*susnhine→sunshine*). If the compound word experiment is replicable in Finnish (as argued above, it should be) and other languages where compounding is highly productive (e.g., Dutch and German), it would further undermine the notion of flexible letter-position coding as a universal feature of written-word recognition. In Finnish, for example, more than 60% of all word entries in the dictionary are compound words.

In addition to morphological complexity, Finnish has other features that stress the significance of individual letters (and their positions). It is not infrequent that doubling a letter (either consonant or vowel) creates a new word, as in *tuli* (fire) versus *tulli* (customs) or *sika* (pig) versus *siika* (white fish). In other words, vowel and consonant length bears significance to word meaning. As phoneme–grapheme correspondence is nearly complete, short and long phonemes are transparently marked in written Finnish.

The second issue we would like to comment on is Frost's argument about languages possessing the most efficient representational system given the "ecological environment" of the language (sect. 3.1, para. 2). For instance, he argues that the extreme phonological transparency of Finnish has made it suitable for the creation of long words with morphologically densely packed information. This is to some extent true. However, the unpacking of morphological information during recognition – due to lack of clear segmentation cues and due to visual acuity limitations of the eye – is by no means straightforward. This is demonstrated by Bertram et al. (2004), who found that the identification of long compound words is slowed down when the letters spanning the morpheme boundary could create a frequent within-syllable bigram (i.e., the possibility for a misparse is created). On the other hand, when the morphological structure in long, three-constituent compound words is signaled

by a hyphen positioned at a morpheme boundary, recognition is facilitated (Bertram et al. 2011). These data cast doubt on whether a language with such an abundance of long, multimorphemic words like Finnish would indeed have created the most efficient representational system possible. In reading, a price has to be paid for dense packaging of information in long words, as unpacking the information is not straightforward. The eye is simply not equipped to extract all letter information from long words; hence, as long as morpheme boundaries are not clearly marked, the identification of sublexical units seems problematic.

Finally, Frost criticizes dual-route models like the one of Grainger and Ziegler (2011) by claiming that they can explain any possible finding (sect. 8, para. 2). We think this is not the case. In the Grainger and Ziegler model, the full-form route is assumed to be coarse-grained, as it allows flexibility in letter positions. On the other hand, the decomposition route is more fine-grained, meaning that letter position coding is rigid. This has two consequences for the present discussion. First, this type of model is not overly flexible. It predicts, for example, that the coarse-grained route would be much more likely to be successful with frequent rather than infrequent morphologically complex words. However, morphological structure would be more readily detected by the fine-grained route in infrequent words and in words containing productive (rather than unproductive) sublexical units. A pattern of results pointing to the opposite would be hard to explain by such model. Second, such a model is able to capture the kind of morphological constraints discussed earlier in this commentary. It can explain a transposed-letter effect within a morpheme as well as a failure to find such an effect across a morphological boundary. By allowing both free and rigid letter coding, it reflects the strategy of optimizing encoding resources – a modeling feature pleaded for by Frost. Generally speaking, dual-route models are well equipped to adapt to the linguistic environment at hand. As Frost argues, this is one of the requirements of a universal model of reading and cannot thus be held against them. Given these considerations, we would like to inspire the author to come up with more solid arguments to discard these models.

Consideration of the linguistic characteristics of letters makes the universal model of reading more universal

Kyungil Kim[a], Chang H. Lee,[b] and Yoonhyoung Lee[c]

[a]*Department of Psychology, Ajou University, Suwon 443-749, Republic of Korea;* [b]*Department of Psychology, Sogang University, Seoul 121-742, Republic of Korea;* [c]*Department of Psychology, Catholic University of Daegu, Daegu 712-702, Republic of Korea.*

kyungilkim@ajou.ac.kr   **chleehoan@sogang.ac.kr**
hyounglee@cu.ac.kr
http://ajou.ac.kr/~tetross

Abstract: We suggest that the linguistic characteristics of letters also need to be considered to fully understand how a reader processes printed words. For example, studies in Korean showed that unambiguity in the assignment of letters to their appropriate onset, vowel, or coda slot is one of the main sources of the letter-transposition effect. Indeed, the cognitive system that processes Korean is tuned to the structure of the Korean writing system.

We agree with Frost's target article that orthographic effects in visual word recognition, including the letter transposition (or transposed letter [TL]) effect, reflect a cognitive processing strategy of optimizing cognitive resources under the specific linguistic environments in which letters are used. We also agree that existing models of visual word recognition focusing mostly on orthographic processing (while disregarding phonology, morphology, and semantics) do not capture the various known phenomena relating to how the human cognitive system processes printed words. However, we

suggest that, just like other linguistic aspects such as phonology and morphology, linguistic characteristics of the orthography (e. g., the function of a letter in a word) must also be considered as an important linguistic aspect in visual word recognition models.

As Frost mentions, recent studies of alphabetic Hangul (the Korean writing system) showed no TL effects, unlike the European languages (Lee & Taft 2009; 2011). Other than Semitic languages (e.g., Hebrew and Arabic), which are discussed heavily in the target article, Hangul might be the only other type of alphabetic orthography that has failed to show TL effects.

For example, Lee and Taft (2009) demonstrated that phonological and morphological factors cannot account for such a lack of a letter transposition effect in Hangul. Hangul is a concatenating alphabetic script that is nonlinear. Words are separated into syllables, and each syllable has a predictable structure in terms of the positioning of its vowel and consonants within a square block. The vowel is always a variation of either a horizontal line or a vertical line. The consonantal onset (which is always orthographically present, though sometimes silent) appears either above a horizontally oriented vowel or to the left of a vertically oriented vowel.

The consonantal coda, when there is one, always appears at the bottom. For example, the Korean spelling of the word "Hangul" is 한글, where the first syllable 한 ("han") is composed of the onset ㅎ ("h") placed to the left of the vertically oriented vowel ㅏ ("a"), with the coda ㄴ ("n") at the bottom. The second syllable 글 ("gul") is composed of the onset ㄱ ("g") placed above the horizontally oriented vowel ㅡ ("u"), which, in turn, is placed above the coda ㄹ ("l").

Lee and Taft (2009) observed little difficulty for Korean readers in making lexical decision responses to TL-generated nonwords in Hangul (e.g., 납묵 generated from the word 남북, "nambuk," through the transposition of ㅁ and ㅂ), unlike the considerable difficulty experienced by English readers responding to nonwords of the same structure in English (e.g., "warlus" for "walrus"). Lee and Taft suggested that this was because letters are assigned to an orthographic onset, vowel, or coda position at an early stage of processing and that, unlike linear scripts, such assignment is unambiguous in Hangul. The consonant at the top or at the top left of the syllable block is always assigned to the onset slot, and any consonant at the bottom of the block is always assigned to the coda slot.

Because Hangul physically demarcates the onset and coda positions for every consonant, it is argued that it is ambiguity in assignment of a consonant to an onset or coda slot that leads to the letter transposition effect in a linear script such as English. That is, the available physical cues offered by Hangul (i.e., the onset, vowel, and coda positions, which can be unambiguously determined from the orthographic input) prevent confusion when letters are placed in an incorrect position. It suggests that models of letter processing should incorporate the involvement of subsyllabic structure, something that is currently lacking.

Also, observation of the pattern of responses arising from letter transpositions within a syllable in the Hangul script provides insight into core aspects of Korean subsyllabic structure (Lee & Taft 2011). For example, in reading Hangul, no confusion occurred when the onset and coda of one syllable of a disyllabic word were transposed. However, confusion with the base word was observed when the two consonants within the complex coda were themselves transposed. The patterns of responses indicate that Hangul (and possibly all concatenating orthographic scripts) is processed based on its onset, vowel, and coda structure (Lee & Taft 2011). There are more alphabetic orthographies that have failed to show the TL effect. As discussed by Frost, two good examples are the non-concatenating orthography of the Semitic languages of Hebrew (Velan & Frost 2007) and Arabic (Andrews 1996; Perea et al. 2010). Taken together with the observations reported from Lee and Taft's (2009; 2011) studies, it was therefore apparent that letter coding in these Semitic languages is organized in terms of the word root.

To clarify, we are not suggesting that ambiguity in the assignment of letters to their appropriate onset, vowel, or coda slot is the only source of the letter transposition effect. Rather, we

suggest that letter-position information can be used differently, depending on the nature of the orthographic structure of the language. In light of this, we suggest that such characteristics of the orthography need to be considered in order to fully understand how humans process printed words. Indeed, the cognitive system that processes Korean (or English or Hebrew) is tuned to the structure of the Korean (or English or Hebrew) writing system.

Orthographic consistency and parafoveal preview benefit: A resource-sharing account of language differences in processing of phonological and semantic codes

doi:10.1017/S0140525X12000209

Jochen Laubrock and Sven Hohenstein
Department of Psychology, University of Potsdam, 14476 Potsdam, Germany.
laubrock@uni-potsdam.de   sven.hohenstein@uni-potsdam.de
http://www.psych.uni-potsdam.de/people/laubrock/index-e.html
http://www.psych.uni-potsdam.de/people/hohenstein/index-e.html

Abstract: Parafoveal preview benefit (PB) is an implicit measure of lexical activation in reading. PB has been demonstrated for orthographic and phonological but not for semantically related information in English. In contrast, semantic PB is obtained in German and Chinese. We propose that these language differences reveal differential resource demands and timing of phonological and semantic decoding in different orthographic systems.

Frost suggests that transposed-letter priming is obtained in some languages and not others because of the variable rigidity of the writing systems, which evolved to optimally transmit phonological and semantic information, given pre-established language-specific phonological spaces. We comment here on differences in the time course of phonological and semantic processing between languages within the Indo-European, alphabetic cluster, German and English, as supported by early indicators of processing obtained from eye-tracking measures. Additionally, we consider logographic Chinese. In particular, we focus on parafoveal preview benefit (PB) obtained by using the gaze-contingent boundary technique (Rayner 1975), in which a preview at the parafoveal target-word location is visible only until the gaze crosses an invisible boundary before the target; participating cognitive processes can be inferred by measuring target processing as a function of the relationship between preview and target.

In English, phonologically and orthographically related previews have repeatedly been shown to produce PB (Balota et al. 1985; Inhoff 1989; Rayner et al. 1978; 1980; 1982), whereas no evidence for semantic PB has been found in either sentence reading (Altarriba et al. 2001; Rayner et al. 1986) or naming (Rayner et al. 1980) – despite significant semantic priming in a standard (foveal) priming task (Rayner et al. 1986). This has led Rayner et al. (2003) to conclude that "the basis for the robust parafoveal preview benefit obtained in numerous studies is not any type of semantic code" (pp. 229–30). In contrast, in German, we have repeatedly obtained semantic PB by using a parafoveal fast-priming technique (Hohenstein et al. 2010), as well as the more traditional boundary technique (Hohenstein & Kliegl 2011).

What could be the reason for this striking difference between two related languages? Further considering that PB can be obtained from word *n*+2 in German (Kliegl et al. 2007), we believe that extraction of parafoveal information is easier in German, mainly because of orthographic consistency: In German, the correspondence between graphemes and phonemes is relatively high, whereas the relation is rather opaque in English because of its very complex phonological space. Orthographic consistency likely affects both the strategies and the mechanisms of word processing.

There is good evidence that phonological codes are routinely co-activated during reading and can influence semantic processing (McCutchen & Perfetti 1982; van Orden 1987; but see Rastle & Brysbaert 2006). This does not necessarily imply a strong phonological account (Frost 1998) in which semantic access is through phonology; alternatives are either feedback from phonology to semantics as in the dual-route cascaded (DRC) model (Coltheart et al. 2001), or a triangular model (Seidenberg & McClelland 1989) in which both orthography and phonology activate semantics. Critically, however, the pattern of empirical PB effects suggests a language-differential distribution of limited resources between phonological and semantic activation. Given that orthography codes for both semantic and phonological information, in a language with opaque spelling-to-sound relations like English, more cognitive resources are occupied by phonological decoding, and hence are unavailable for decoding of semantic meaning.

This reasoning is supported by developmental differences: Children learning to read languages with low transparency have to acquire a much larger set of ambiguous orthographic-phonological relations, resulting in slower learning (Goswami et al. 2001; 2003; Landerl et al. 1997; Wimmer & Goswami 1994). In a large study comparing 13 European orthographies, the rate of development of basic decoding skills was slowest in English (Seymour et al. 2003). Using pseudo-homophone priming, Goswami et al. (2001) demonstrated that for German but not English children the activation of phonological information is relatively automatic. Landerl et al. (1997) concluded that consistency of grapheme–phoneme relations affects the working-memory demands of recoding.

Results from other alphabetic languages with more transparent orthographies are not currently decisive. In very transparent Spanish, despite many reports of parafoveal semantic priming (Fuentes & Tudela 1992; Fuentes et al. 1994; Ortells et al. 2001), a study using the boundary paradigm failed to find semantic PB (Altarriba et al. 2001). However, that study used bilingual readers of Spanish and English and always employed cross-language priming; thus, an opaque word was either preview or target. We are unaware of a direct study of semantic PB in highly transparent Finnish. Semantically unassociated emotional previews did not produce preview benefit or cost (Hyönä & Häikiö 2005). However, Finnish has many compound words, and semantic PB can be obtained from the second constituent of a compound word (White et al. 2008). Finnish words tend to be long, and acuity limitations might weaken parafoveal effects. Note that also for morphological information, closely related to semantics, there is no evidence for parafoveal processing during the reading of English (Inhoff 1989; Kambe 2004; Lima 1987), whereas morphological PB effects are reliable in morphologically rich Hebrew (Deutsch et al. 2000; 2003; 2005).

In general, to the degree that phonological decoding is easy in alphabetic languages, we expect semantic PB effects to emerge, although they might not be quite as strong as in some non-alphabetic (logographic) languages like Chinese, in which "semantic information comes first" (sect. 3.2.1, para. 2), as reflected in the position of semantic and phonetic radicals in compound characters. Semantic decoding is fast and phonological decoding relatively slow in Chinese (Zhou & Marslen-Wilson 2000). Consequently, there is fairly unequivocal evidence for semantic PB (Yan et al. 2009; in press; Yen et al. 2008). In fact, semantic PB is even larger than phonological PB in Chinese (Yan et al. 2009), and the latter is somewhat delayed (Liu et al. 2002; Pollatsek et al. 2000; Tsai et al. 2004).

Processes of semantic and phonological activation not only share resources, but also differ in timing, with relative speed and timing a function of the writing system. Whereas phonological processing has a head start in alphabetic languages, semantic processing may start drawing resources earlier in logographic systems. Computational models of eye-movement control during reading (Engbert et al. 2002; 2005; Reichle et al. 1998;

2003) could provide a good starting point for modeling such differences. More generally, in the spirit of the target article, the pattern of results calls for more language-comparative studies using comparable material, methods, and design to arrive at a universal model of reading.

No reason to expect "reading universals"

Yonata Levy

Department of Psychology, The Hebrew University, Mount Scopus, Jerusalem 91905, Israel.

yonatalvey@gmail.com   http://psychology.huji.ac.il/

Abstract: Writing systems encode linguistic information in diverse ways, relying on cognitive procedures that are likely to be general purpose rather than specific to reading. Optimality in reading for meaning is achieved via the entire communicative act, involving, when the need arises, syntax, nonlinguistic context, and selective attention.

In an eloquent and coherent exposition, Frost makes a convincing case for the argument that reading for meaning is a complex operation and that "orthographic effects in visual word recognition … are the product of the *full* linguistic environment of the reader (phonology, morphology, and semantic meaning)" (sect. 1, para. 5, emphasis in original). Syntax is not mentioned as part of this environment, yet note that some orthographies may reflect syntactic phenomena. For example, alphabetic systems are sequential, even if non-linear, and adhere to sentential word order.

Frost argues that a theory of reading should be universal and therefore contain "the invariant" among orthographies of the world languages. Frost's program postulates that "a good theory of reading should describe and explicate … the cognitive procedures that are implicated in processing printed words in *any* orthography, focusing on (1) what characterizes human writing systems, and (2) what characterizes the human cognitive system that processes them. I [i.e., Frost] will label these common cognitive procedures *reading universals*" (sect. 2.1, para. 1, emphases in original). Yet, what might be universal and invariant among systems that serve speakers of Chinese, English, Hebrew, Japanese, or Finnish?

The search for "reading universals" brings to mind linguistic theories of generative persuasion in which the notion of Universal Grammar (UG) refers to the computational properties of language – any human language (e.g., Chomsky 2006). But writing systems need not encode UG, since these principles are presumed to be at the core of all human languages and are given "for free" to speakers. It is primarily the language-specific properties, which by definition are not universal, that the system must be attuned to. So it is the **variant** among human languages that orthographies encode, as Frost's examples amply demonstrate.

Frost correctly states that writing systems rely on cognitive parameters. Put differently, writing systems select from among information-encoding principles those that will highlight the relevant features of the language that the message is cast in, *and* can guarantee fast-enough decoding. Chief among these cognitive devices is order (e.g., the invariance of clusters, seen in the phonological composition of English words), but there are others: For instance, differential prominence among constituent units (e.g., the prominence of Hebrew root consonants vis-à-vis word patterns), or simultaneous processing of parallel systems of codes (e.g., Hebrew letters and diacritics).

Although the foregoing examples, all drawn from Frost, indeed relate to the encoding of information within writing systems, there is nothing linguistic or orthographic about the principles underlying these procedures. Rather, they are general-purpose

devices that are available to writing systems but not specific to them. Writing systems exploit such parameters, as do other cognitive systems: for example, navigation in different environments, or conceptual categorization. Thus, rather than setting the stage for "reading universals," writing systems realize general cognitive principles for encoding information.

Exhibiting one or several of these principles, the system may still not be perfect, for example, in non-optimal circumstances, a writing system may fail to transmit a sufficient amount of information to the reader. Within an interactive, task-oriented cognition, this shortcoming is manageable and can often be resolved, for example, through stronger dependence on context, whether linguistic or even nonlinguistic.

Hebrew provides a case in point. Many Hebrew words have more than one reading when presented without diacritics. Yet, while diacritics enrich the informational value for readers, they slow down writing and require additional expertise. Hebrew readers routinely give up diacritics, relying instead on syntax and lexicon, which generally resolve such ambiguities. Faced with written texts that have no diacritics, readers who do not know Hebrew grammar may not be able to fully decode "unpointed" script. Occasionally, nonlinguistic context can provide support, as well. For example, single, unpointed words used in street signs can be disambiguated within this extralinguistic context.

Thus, optimality need not be achieved within the writing system, as argued by Frost. Rather, it is a product of the entire communicative act. Impoverished systems, for example, unpointed Hebrew, need fallback strategies, such as reliance on context. On the other hand, the non-overlapping word-internal order of letters and full spelling that is characteristic of English orthography, result in a redundant writing system that is well suited for non-optimal reading conditions (e.g., messy scribble, insufficient light, or reduced texts such as in the "Cambridge effect"). Such redundancy frees the reader from strong reliance on sentential context and helps tip the balance in that it allows attention to focus on the complexities of the phonological representations that can be effortful for readers of English.

Beyond isolated word recognition

Simon P. Liversedge, Hazel I. Blythe, and Denis Drieghe

University of Southampton, Psychology, Highfield Campus, Southampton SO17 1PS, United Kingdom.

s.p.liversedge@ soton.ac.uk   hib@soton.ac.uk
d.drieghe@soton.ac.uk
http://www.southampton.ac.uk/psychology/about/staff/spl1.page
http://www.southampton.ac.uk/psychology/about/staff/hib.page
http://www.denisdrieghe.com

Abstract: In this commentary we concur with Frost's view of the centrality of universal principles in models of word identification. However, we argue that other processes in sentence comprehension also fundamentally constrain the nature of written word identification. Furthermore, these processes appear to be universal. We, therefore, argue that universality in word identification should not be considered in isolation, but instead in the context of other linguistic processes that occur during normal reading.

We are broadly sympathetic with Frost's target article, his considerations in relation to universality, and the stance he takes. We share his view that it is extremely important to explore lexical processing, and other aspects of reading, across languages, in order to be able to investigate issues of universality and, specifically, how universal principles might constrain theoretical accounts of language processing.

At a critical level, we question the use of the word "reading" in the title, and throughout the article. Frost's Note 1 notwithstanding, while we accept that lexical processing is a central and fundamental sub-process of reading, it is just one aspect of a more complex psychological processing system involving numerous other sub-processes. We do not consider the theoretical account in the target article to constitute a move towards a "theory of reading"; rather, this is a move towards a theory of lexical identification. Let us now turn to our main points.

The majority of work investigating word recognition (some of which is cited in the target article) employs methodologies in which words (or nonwords) are presented in isolation, and we question the ecological validity of such methods as an approximation of how lexical identification occurs during normal reading (Rayner & Liversedge 2011). The use of more natural methodologies such as recording eye movements to study reading leads us to consider whether there are other important (and potentially universal) aspects of reading that themselves constrain, or even determine, the nature of word identification.

Reading is a visually mediated process (except in the special case of Braille), and people of all cultures make the same stylised patterns of *saccades* (orienting the eye such that light reflected from as yet unread words is caused to fall on the fovea), and *fixations* (brief pauses during which the orthographic code is extracted from the page) in order to read. The nature of eye movements during reading, along with attention and the physiological make-up of the retina, means that information about words is delivered piecemeal to the language processing system via a series of "snapshots," rather than as a steady, smooth stream. It is not the case that all the orthographic code associated with a word is necessarily available during a particular fixation. Also, the quality of the orthographic information that the visual system delivers varies contingent on where it falls on the retina and how attention is allocated to that area of the visual array. Given that fixations are temporally (and spatially) distributed, the sequential delivery of orthographic information fundamentally determines the nature and time course of the word identification process. Furthermore, since the basic characteristics of eye movements are cross-culturally uniform, then it is plausible that their constraint on word identification might be considered one of the universal characteristics that should be incorporated into any realistic model of such processes as they occur during normal reading.

Our second, main point focuses on Frost's argument that fuzzy encoding of letter order is a cognitive resource-saving strategy that characterizes reading in European languages, and that this strategy would only be meaningful given the characteristics of the lexical space of these languages. While we believe this statement to be well thought through and, indeed, thought-provoking, we would argue that fuzzy encoding in European languages (as a cognitive resource-saving strategy) is in all likelihood only possible due to a reliance on sentential context during normal reading. The sentential context facilitates resolution of lexical ambiguity due to fuzzy letter-order encoding. Thus, complementary to our foregoing argument, word identification (particularly in relation to transposed letter [TL] effects) cannot be considered in isolation from other aspects of processing associated with sentence interpretation. Note also that it is universally the case that during normal reading words are identified within a sentential context.

To support this point, we offer a very brief summary of some of our recent experimental work demonstrating that when readers attempt to identify TL words presented in isolation, performance is poor (Blythe et al., under review).

Participants were presented with isolated letter strings and were required to decide whether each was a misspelled word or a nonword (stimuli were 50% six-letter TL words, e.g., "ANEVUE" for base word "AVENUE," and 50% six-letter nonwords, with no retrievable base word). Response accuracy was

quite low (82%) for adjacent TL words, and when a letter intervened between TLs, performance did not differ from chance; participants were effectively guessing (note, however, that for eight-letter words where a smaller proportion of the word was disrupted by the TL manipulation, performance improved to better than chance). Recall, participants were responding to isolated words in this study. In contrast, when the same six-letter TL words were presented within meaningful sentential contexts (in an eye movement experiment), we found that readers experienced little, if any, difficulty understanding the sentences even when a letter intervened between TLs; also, accuracy on comprehension questions was high (91%). Thus, it appears that lexical identification of TL words is facilitated by contextual information when this is available.

In summary, we welcome the concerns raised by Frost in relation to universality and generic models of word identification that account for phenomena restricted to a specific group of languages. However, we have voiced our own concerns regarding aspects of word identification that occur in the context of normal reading, but do not occur in isolated word identification. We believe that these are important and may be universal. Lexical identification in the context of sentence processing will be the foundation of a general theory of reading, taking into account the specificities associated with processing coherent passages of text.

Visual perceptual limitations on letter position uncertainty in reading

Marialuisa Martelli,[a,b] Cristina Burani,[c] and Pierluigi Zoccolotti[a,b]

[a]Department of Psychology, Sapienza University of Rome, 00185 Rome, Italy; [b]Neuropsychology Unit, Scientific Institute for Research, Hospitalization, and Health Care (IRCCS, Istituto di Ricovero e Cura a Carattere Scientifico), Fondazione Santa Lucia, 00142 Rome, Italy; [c]Institute of Cognitive Sciences and Technologies (ISTC), National Research Council (CNR), 00185 Rome, Italy.

marialuisa.martelli@uniroma1.it   cristina.burani@istc.cnr.it   pierluigi.zoccolotti@uniroma1.it

Abstract: Frost presents an explanatory theory of reading that generalizes across several languages, based on a revised role of orthographic coding. Perceptual and psychophysical evidence indicates a decay of letter position encoding as a function of the eccentricity of letters (crowding); this factor may account for some of the differences in the languages considered by Frost.

Frost analyzes how reading is affected by the linguistic demands of written languages and concludes that letter position insensitivity results from reading strategies and is not a general characteristic of brain computation. Here, we propose that reading strategies are also influenced by perceptual limitations inherent in the visual system.

Text legibility depends more on letter size than might be expected based on acuity for single-letter identification. In psychophysical studies, *reading rate* is defined as the number of words read in a minute and is often measured by presenting a rapid sequence of words at the same spatial location (rapid serial visual presentation [RSVP]). Presentation time is adjusted to the time needed to obtain an accuracy criterion (e.g., 90%; Legge et al. 1997). Reading rate increases up to a critical print size (CPS), levels off at intermediate sizes, and drops again with larger text sizes. CPS measures about 0.2 degrees and the flat plateau extends to about 2 degrees (e.g., Legge et al. 2001). Over the centuries, books have been printed to meet visual demands, and font size is always in the plateau range, usually close to the CPS (Legge & Bigelow 2011).

How can we explain the reading rate curve? Reading rate is inversely proportional to the size of *visual span* (Legge et al. 2001), that is, the number of adjacent letters that can be recognized without moving the eyes. Visual span and reading rate depend to the same degree on several variables, including size, contrast, and eccentricity (e.g., Legge et al. 2001). Legge et al. (2001) introduced a psychophysical method for measuring the size of the visual span using random letter triplets. According to these authors, however, this can also be estimated from the relationship between reading time and word length. Figure 1 shows that when Italian and English readers are compared, reading time varies with word length. Stimuli in the two languages differ for uncontrolled linguistic variables (see Fig. 1 caption); nonetheless, all data points lie on the same regression line (with a slope of 33 msec per letter), indicating similar dependency on length across the two languages. Visual span can be estimated from these data. Knowing that reading involves a series of fixations of about 250 msec each (Rayner & McConkie 1976), the number of letters identified in a glance can be estimated from the reciprocal of the slope of the regression line times 250 msec; that is, a span of about 7.5 characters. Note that the visual span profile is not homogeneous (Legge et al. 2001): Performance for letters at the CPS (or in the optimal range) is perfect in the fovea but drops off eccentrically to reach the criterion level (typically 80% correct). Overall, we expect higher reading speeds in languages in which mean word length is shorter than the visual span, compared to languages characterized by generally longer words.

Pelli et al. (2007) proposed that the visual span is limited by *crowding*, a phenomenon in which letter identification is impaired by the presence of neighboring letters. Crowding depends on center-to-center letter spacing, not on letter size. (Note that the two factors covary in standard printed texts.) The *crowding range* (or critical spacing [CS]) is defined as the distance between adjacent letters needed to restore recognition. CS scales with a proportionality of 0.5 to target eccentricity (i.e., at

4 degrees CS must be at least 2 degrees for a stimulus to be recognized) and is independent of stimulus size (e.g., Pelli et al. 2004). CS is about the size of the CPS in the fovea; below the CPS, letters fall within the CS, the visual span shrinks, and reading slows down rapidly. Above the CPS, the central letters are available for identification, but at a certain eccentricity (determined by letter distance) the letters farther away from fixation have smaller spacing than the CS and cannot be identified.

Crowding indicates faulty integration of features within an integration field. Therefore, it must be distinguished from a more peripheral phenomenon, that is, *masking*, in which the mask makes the signal disappear; or rather, the crowded letter is visible but unidentifiable (Pelli et al. 2004). Within the crowding range, features belonging to different objects are combined through compulsory pooling or averaging of signals (Parkes et al. 2001), and observers erroneously attribute features at the distractor location to the target (Nandy & Tjan 2007). Popple and Levi (2005) presented letter strings of variable length and asked observers to identify letters. Increasing the spacing (i.e., reducing crowding) decreased the number of letters reported without permutations. Thus, within the crowding range, letter/feature position uncertainty influences the perceived spatial order of characters. Scrambling the letters in words (so the substitutions are undetectable in crowding conditions) disrupts the text and accounts for variance in reading rate more than modifying word shape (case alternation) or scrambling word order (Pelli & Tillman 2007).

Written alphabets differ dramatically but share the same visual parts (Changizi et al. 2006); hence, visual integration limits may affect them similarly. In particular, crowding constrains the size of the visual span and is presumably invariant across languages, thus posing visual constraints on the orthographic code. Therefore, we propose that crowding should be considered in general models of orthographic decoding in addition to and in interaction with the linguistic environment identified by Frost. Consequently, smaller effects of length and letter transposition should be found in some European languages (such as English and French). Conversely, length may be particularly disruptive in words longer than the visual span in languages such as Hebrew that do not allow for letter position insensitivity. Indeed, the omission of vowels in written Hebrew might be interpreted as a means of overcoming the intrinsic position uncertainty arising from the bottleneck of increasing word length/eccentricity (which in Hebrew would be particularly disruptive because of its linguistic structure). This is consistent with Legge and Bigelow's (2011) proposal that scripts have been optimized for the visual requirements of reading, not the motor demands of writing.
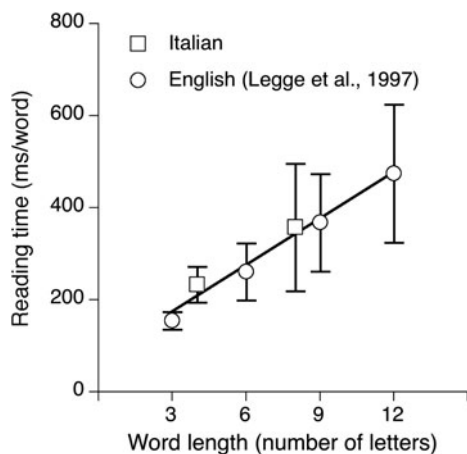

Figure 1 (Martelli et al.). Reading time (ms) as a function of word length for Italian (data collected by the authors) and English readers (replotted from Legge et al. 1997). Reading time was measured with the rapid serial visual presentation (RSVP) procedure: Words were presented one at a time in a four-word trial in the same central location with no interword time delay. For the Italian sample, 40 trials (160 words) were conducted to estimate the word duration necessary to keep performance at around 80% of correct naming (ranging from 75% to 94% for English). Words were high contrast; letter size (i.e., the height of the letter "x") was 0.83 degrees and 0.8 degrees in the English and Italian samples, respectively. Both data sets are collected on lists of words matched in frequency. Data are averaged across four adult observers for each word length in each language group. Standard errors are shown.

What and where is the word?

Catherine McBride-Chang,[a] Hsuan-Chih Chen,[a] Benjawan Kasisopa,[b] Denis Burnham,[b] Ronan Reilly,[b,c] and Paavo Leppänen[d]

[a]*Department of Psychology, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong;* [b]*MARCS Institute, University of Western Sydney–Bankstown, Milperra, NSW 2144, Australia;* [c]*Department of Computer Science, National University of Ireland, Maynooth, County Kildare, Ireland;* [d]*Department of Psychology, University of Jyväskylä, FIN-40014 Jyväskylä, Finland.*

cmcbride@psy.cuhk.edu.hk   hcchen@psy.cuhk.edu.hk
b.kasisopa@uws.edu.au   d.burnham@uws.edu.au
ronan.reilly@nuim.ie   paavo.ht.leppanen@jyu.fi
http://www.psy.cuhk.edu.hk/en/people/cmcbride/cmcbride.php
http://www.psy.cuhk.edu.hk/en/people/hcchen/hcchen.php
http://marcs.uws.edu.au/?q=people/benjawan-kasisopa%C2%A0
http://marcs.uws.edu.au/?q=people/professor-denis-burnham
http://www.cs.nuim.ie/~ronan/
https://www.jyu.fi/ytk/laitokset/psykologia/henkilokunta/leppanen_p

Abstract: Examples from Chinese, Thai, and Finnish illustrate why researchers cannot always be confident about the precise nature of the word unit. Understanding ambiguities regarding where a word begins and ends, and how to model word recognition when many derivations of a word are possible, is essential for universal theories of reading applied to both developing and expert readers.

Frost's main argument rests on the somewhat tenuous assumption that the concept of word recognition is constant across scripts. His and other theories in alphabetic languages attempting to model visual word recognition have been based on single-syllable words, though there have been recent attempts to explain how longer words, with prefixes and suffixes, for example, are read (Grainger & Ziegler 2011; Perry et al. 2010). Most such models of visual word recognition assume that the concept of a word as the unit of analysis in reading across scripts is always clear.

Frost's description of Chinese is particularly problematic in this respect. To be sure, Chinese characters are monosyllabic (he argues that almost all Chinese *words* are monosyllabic), and most characters can also serve as words. However, the majority of words in Chinese consist of two or more morphemes. Moreover, recognition of both two-morpheme words and characters can be affected uniquely by character as well as word frequency, and for both children and adults. The structures of characters and words are also different, as indicated by experimental manipulations (Liu et al. 2010) that highlight the importance of semantic/morphological information in Chinese (Chen & Shu 2001; Tsang & Chen 2010; Wong & Chen, in press). For example, whereas parents tend to teach children to write words based primarily on phonological information in alphabetic languages such as Hebrew (Aram & Levin 2001; 2004), they almost never focus on phonological information in teaching words or characters in Chinese (Lin et al. 2009; 2012); rather, they point out either visual-orthographic or morphological information as they talk about print.

The actual unit of reading as word versus character continues to be debated in Chinese (Chen et al. 2003). A crude analogy in English might be that *wallpaper* and *paperweight* or *toenail* and *tiptoe* are all common words consisting of common morphemes (e.g., *paper*; *toe*). Yet not all English speakers analyze these words as made up of separate morphemes or acquire each morpheme comprising compound words before learning these words themselves; some compound words are learned holistically first. Chinese multimorphemic words are often learned as single entities, with the individual characters comprising them becoming salient only when explicitly analyzed. The way in which Chinese appears on a page, with each character equally spaced and no differences in spacing distinguishing what are conceptual words, may also make the concept of a word confusing. This issue is not a problem for the alphabetic languages highlighted by Frost, because words are spatially distinguished in these orthographies.

However, this is not the case in Thai, another alphabetic script. Thai has no spaces between words, so words cannot be defined by using spaces. Importantly, whereas spacing between words in Chinese does not change the speed of reading for adults, in Thai (artificial, experimental) spacing between words actually facilitates word reading, particularly for poor readers (Kasisopa et al. 2010). In Thai, word-position frequencies (i.e., statistical regularities) of particular graphemes within words are used to help identify where a word is likely to begin and end. For example, some graphemes that have a high probability of occurring as the initial or the final grapheme may assist readers operationally in defining word boundaries: They effectively direct eye movements to the optimal viewing position in a word (Kasisopa et al. 2010). Nevertheless, there is relatively high ambiguity in defining words in Thai since word segmentation relies heavily on sentential context (Aroonmanakun 2007). Thus, what is segmented as a single word in one sentence may be a phrase or even a sentence in another context. For example, the string "คนขับรถ" can be a single word or a whole sentence, depending on the context in which it occurs: It is a word in the sentence คนขับรถเป็นผู้ชาย – that is, คนขับรถ (driver) เป็น (is) ผู้ชาย

(man) ("the driver is a man") – but a three-word phrase in the sentence คนขับรถเร็ว – that is, คน (man) ขับ (drive) รถ (car) เร็ว (fast) (i.e., "The man drives the car fast"). In addition, many Thai word strings are ambiguous. For example, ตากลม can be read either as ตาก + ลม (exposed + wind = "exposed to wind") or ตา + กลม (eye [s] + round = "round eyes"). Such ambiguities and the aforementioned contextual effects make it difficult to design automatic segmentation strategies because the number of decisions that cannot be made by machine is surprisingly high (Aroonmanakun 2002). Extensive top-down processing is required for resolving these ambiguities. Thus, in both Chinese and Thai, the reading process involves a certain amount of flexibility in order for *word recognition* to be a clear and salient concept.

For Finnish, an alphabetic orthography with word boundaries marked by spaces, defining the nature of a visual word is also potentially important. Because Finnish has highly inflectional morphology with 15 cases, plural markers, and different clitics, each noun can have more than 2,000 orthographic variants (Niemi et al. 1994). The root also often changes together with inflections. Moreover, it is possible to express a complicated concept that in other languages might require multiple words by using a single word, especially for verbs, because Finnish allows so much compounding. For example, "lukea" is the basic form of "to read," whereas "(vielä) luettuammekin…" means "(even) after we had also read…". In the latter example, the stem change ("lu*ettua*") denotes the past event, "mme" is an inflectional form for "we," and "kin" is a common ending meaning "also." These characteristics have prompted Hirsimäki et al. (2006) to suggest that, for Finnish, "traditional models based on full words are not very effective" (p. 539). Rather, these researchers advocate a word fragment model. Thus, expert Finnish readers efficiently use frequently occurring sub-units of words for which there are well-formed/strong representations and which often do not obey classical word or syllable boundaries.

From these three examples, it is not entirely clear that there can or should be a universal model of visual word recognition. Indeed, what constitutes a word across scripts may be somewhat ambiguous, though dimensions of orthography, phonology, morphology, syntax, and semantics are clearly universal components of reading.

Orthographic processing is universal; it's what you do with it that's different

Dennis Norris[a] and Sachiko Kinoshita[b]

[a]*MRC Cognition and Brain Sciences Unit, Cambridge CB2 7EF, United Kingdom;* [b]*Department of Psychology and Centre of Excellence in Cognition and Its Disorders (CCD), Macquarie University, Sydney, NSW 2109, Australia.*
dennis.norris@mrc-cbu.cam.ac.uk   sachiko.kinoshita@mq.edu.au
http://www.mrc-cbu.cam.ac.uk/people/dennis.norris/
http://www.ccd.edu.au/people/profile.html?memberID=59

Abstract: We agree with Frost that the variety of orthographies in the world's languages complicates the task of "cracking the orthographic code." Frost suggests that orthographic processing must therefore differ between orthographies. We suggest that the same basic orthographic processes are applied to all languages. Where languages differ is in what the reader must do with the results of orthographic processing.

Frost's timely review reminds visual word recognition researchers of the rich variety of orthographies in the world's languages. We argue, however, that the variety of orthographies does not lead to the view that "letter-order insensitivity is *neither* a general property of the cognitive system *nor* a property of the brain in encoding letters" (target article, Abstract). It is actually unclear what Frost means by the "cognitive procedures that are implicated in processing printed words" (sect. 2.1, para. 1). He could, for example, be referring to the entire process of deriving sound and meaning from the visual form of written symbols, or simply to the process

of identifying the symbols and the order in which they appear. We feel that some of Frost's conclusions follow from confusion between these two possibilities. We suggest that the basic perceptual processes supporting the identification of written symbols are universals, and are governed by exactly the same principles as all other forms of visual object recognition. However, what the reader does with those symbols will depend crucially on the properties of the language and on the mapping between those symbols and the sound and meaning of the language.

Consider first the contrast between English, where there is transposed-letter priming, and Hebrew, where there is no transposed letter (TL) priming in lexical decision. As Frost suggests, it might be possible to make some ad hoc structural changes to a model of reading to accommodate this difference. An alternative is to suggest that this difference follows from a fixed and universal model of object/symbol recognition combined with the differing processing demands imposed by languages with contrasting phonological, morphological, and lexical properties. Norris et al. (2010) and Norris and Kinoshita (in press) have proposed a noisy-sampling model of word recognition in which evidence for both letter identity and letter position/order accumulates over time. Early in time, order information may be very ambiguous, but, as more samples arrive, that ambiguity will be resolved. Even in English, readers are able to tell that JUGDE is not a real word, even though JUGDE will prime JUDGE as much as an identity prime in a task where the prime is presented for about 50 msec. Now consider the implications of this process for the difference in TL priming between English and Hebrew. In Hebrew the lexical space is very dense. Transposing two letters in a root will typically produce a different root. In English, transposing two letters will generally produce a nonword; that is, the closest word may still be the word that the TL prime was derived from. Identifying words in Hebrew will therefore require readers to accumulate more evidence about letter order than in English; that is, because of the differences between the two languages, English readers can tolerate more slop in the system, but the underlying process of identifying the orthographic symbols remains the same. The characteristics of the language impose different task demands on word recognition, but the structural properties of the model remain the same. Note also that whereas Frost suggests that many of the linguistic differences are a consequence of learning different statistical regularities, in this case at least, the difference follows primarily from the contents of the lexicon and does not require the reader to learn about the statistical properties of the language. In line with this view, in the same–different task in which the input is matched against a single referent, not the entire lexicon, robust TL priming effects are observed with Hebrew words (Kinoshita et al., in press). This example is also a counter to Frost's suggestion that the orthographic processing system is not autonomous and is influenced by the language. Here the basic perceptual processes are not modulated by the language at all.

In describing the variety of orthographies, Frost also argues that the way writing systems eventually evolved is not arbitrary, and that orthographies are structured so that they "optimally represent the languages' phonological spaces and their mapping into semantic meaning" (sect. 3, para. 1). But appeals to optimality make little sense unless accompanied by a formal definition of optimality and a procedure for determining what constitutes an optimal solution. Frost's definition of optimality seems to be post hoc, and depends entirely on assumptions about the relative difficulty of different cognitive processes. Note that the development of writing systems is strongly influenced by the writing material available. Cuneiform may be a more "optimal" form of orthography than pictograms containing many curved features to a Sumerian tax collector who has access only to clay tablets and a blunt reed for a stylus. Frost's evolutionary argument also seems to be based on the assumption that writing systems have evolved to some optimal state. Even if there is an element of truth to the evolutionary

argument, there is no reason to assume that writing systems have reached the optimal end of their evolution. This is particularly apparent in cases where there are alternative writing systems for a single language. For example, Japanese uses both *kanji*, a logographic script imported from China, and *kana*, a syllabary, which was derived from kanji. Is kana more optimal than kanji? The writing system that is adopted by a particular language necessarily reflects the constraints imposed by the language (e.g., in Japanese, potentially all words can be written by using only the kana syllabary, but this would result in too many homophones which are disambiguated by the use of different kanji characters). But that does not mean that its evolution was driven by the "process of optimization" based on linguistic constraints. In human evolution, writing systems have a very short history (mass literacy is only about 500 years old), and historical and chance cultural events – for example, contact between two cultures, invention of a writing medium, spelling reform, to name just a few – seem to have played a large role, and interacted with, the linguistic constraints in shaping the particular writing system used in a language.

Theories of reading should predict reading speed

Denis G. Pelli,[a] Susana T. L. Chung,[b] and Gordon E. Legge[c]

[a]Department of Psychology and Center for Neural Science, New York University, New York, NY 10003; [b]School of Optometry, University of California, Berkeley, CA 94720-2020; [c]Department of Psychology, University of Minnesota, Minneapolis, MN 55455.

denis.pelli@nyu.edu   s.chung@berkeley.edu   legge@umn.edu
http://psych.nyu.edu/pelli/   http://vision.berkeley.edu/selab/
http://vision.psych.umn.edu/users/legge/

Abstract: Reading speed matters in most real-world contexts, and it is a robust and easy aspect of reading to measure. Theories of reading should account for speed.

Frost notes that there is a vast range of languages and reading phenomena that one can measure and model. In order to not lose sight of the goal of a universal theory of reading in the thicket of language-specific phenomena, Frost proposes two criteria that such a theory must possess: first, universality across writing systems, and, second, linguistic plausibility. However, Frost's treatment ignores reading speed, which is the easiest aspect of reading to measure and has the greatest practical significance. Reading speed limits the rate at which information is processed by the reader. When impaired vision or dyslexia slows reading, the reader experiences a disability. The range of print sizes that maximize reading speed is highly correlated with the character sizes used in printed materials and affects typographic design quite generally (Legge & Bigelow 2011). In addition to Frost's two criteria for a universal theory of reading, we would like to propose a third criterion. Note that *visual span* is the number of characters that one can recognize without moving one's eyes. A theory of reading should assume or explain the observed proportionality between visual span and reading speed (Legge et al. 2007; Pelli & Tillman 2008; Pelli et al. 2007).

It has been known for a century that reading proceeds at about four fixations per second (Huey 1908/1968). This rate is preserved across the wide range of reading speeds encountered in low vision and peripheral reading (Legge 2007; Legge et al. 2001). This makes it natural to express reading speed as the product of fixation rate and visual span, the number of characters acquired in each fixation.

Woodworth (1938) asks,

> How much can be read in a single fixation? Hold the eyes fixed on the first letter in a line of print and discover how far into the line you can see the words distinctly, and what impression you get of words still farther to the right. You can perhaps see one long word or three short ones

distinctly and beyond that you get some impression of the length of the next word or two, with perhaps a letter or two standing out. (Woodworth 1938, p. 721)

For ordinary text, reading is limited by spacing (crowding) not size (acuity) (Pelli et al. 2007). As text size increases, reading speed rises abruptly from zero to maximum speed. This classic reading-speed curve consists of a cliff and a plateau, which are characterized by two parameters: critical print size and maximum reading speed. Two ideas together provide an explanation of the whole curve: the Bouma law of crowding and Legge's conjecture that reading speed is proportional to visual span (Bouma 1970; Legge et al. 2001; Pelli et al. 2007).

Reading speed captures two essential properties of the early sensory part of reading: the recognition of written words and the processing of a rapid temporal sequence of stimuli. Thus, reading speed is more informative about a reader's reading ability than is simple word recognition.

Reading speed is closely linked to eye movements. The rate of eye movements is about four per second, with very little variation. Slower reading is associated with shorter eye movements. When reading slows because text is difficult to *see*, as in many forms of impaired vision, the main effect on eye movements is a reduction in the length of saccades, which may reflect a reduced visual span (Legge 2007, Ch. 3). When reading slows because the meaning of the text is difficult to *comprehend*, the time per fixation increases as well.

Reading speed receives distinct contributions from three reading processes: letter-by-letter decoding (i.e., recognition by parts), whole-word shape, and sentence context. Simple manipulations of text can knock out each reading process selectively, while sparing the others, revealing a triple dissociation. The independence is amazing. Each reading process always contributes the same number of words per minute, regardless of whether the other processes are operating (Pelli & Tillman 2007).

What about comprehension? Popular speed reading classes convince their clients to skim through text at arbitrarily high speeds, with commensurate loss of comprehension, so one might question whether silent reading speeds tell us much, unless comprehension is measured, to assess the speed–comprehension trade-off. In our experience, participants in reading experiments asked to read as quickly as possible with full comprehension read at stable speeds, and can readily produce a gist of what they read. Most of our work is done with short passages; for example, eight words presented quickly in the rapid serial visual presentation (RSVP) paradigm. That is, words are presented one at a time in a rapid sequence and are read aloud by the participant, with no time pressure on the verbal response. Masson (1983) made a thoughtful comparison of several measures of comprehension and reading speed. A new development is automatic generation of text that allows easy assessment of comprehension by asking the reader to classify each four-word sentence as true or false (Crossland et al. 2008).

Can anyone claim to explain reading without accounting for speed?

Postscript: Let us all cite Rawlinson (1976; 1999) for "reibadailty." In the target article (sect. 1.1, para. 1), Frost reports "a text composed entirely of jumbled letters which was circulating over the Internet. This demonstration, labeled 'the Cambridge University effect' (reporting a fictitious study allegedly conducted at the University of Cambridge), was translated into dozens of languages and quickly became an urban legend." In fact, that infamous e-mail was based on Rawlinson's 1976 doctoral dissertation at Nottingham University, but fails to cite it, instead misattributing the research to various other universities. Michael Su, an undergrad working with Denis Pelli, tracked down the source, and Dr. Rawlinson provided a copy of his thesis and granted permission to post it on the Web (Rawlinson 1976).

Perceptual uncertainty is a property of the cognitive system

Manuel Perea[a] and Manuel Carreiras[b]

[a]*Departamento de Metodología and ERI-Lectura, Universitat de València, 46010 Valencia, Spain;* [b]*Basque Center on Cognition, Brain, and Language, 20009 San Sebastián-Donostia, Spain.*
mperea@uv.es   m.carreiras@bcbl.eu
http://www.uv.es/mperea
http://www.bcbl.eu/people/staff/manuel_carreiras

Abstract: We qualify Frost's proposals regarding letter-position coding in visual word recognition and the universal model of reading. First, we show that perceptual uncertainty regarding letter position is not tied to European languages – instead it is a general property of the cognitive system. Second, we argue that a universal model of reading should incorporate a developmental view of the reading process.

In his target article, Frost claims that flexibility in letter-position coding is "is a *variant* and idiosyncratic characteristic of some languages, mostly European" (Abstract, emphasis in the original) – mainly on the basis that root-based words in Semitic languages do not show transposed-letter effects (Velan & Frost 2011; see also Perea et al. 2010). Here we re-examine Frost's claim under one critical criterion: how letter-position coding is developed during reading acquisition. But first, it is important to briefly re-examine the origins of the assumption of perceptual uncertainty that underlie most of the recently implemented models of visual word recognition.

When implementing a model of visual word recognition, cognitive modelers face one basic challenge: Models should be kept as simple as possible while providing both a reasonable account of the phenomena and heuristic power to predict new phenomena. In the most influential models of word recognition of the 1980s and 1990s (the interactive activation model of Rumelhart & McClelland [1982] and its successors), modelers assumed, for simplicity purposes, that letter-position coding occurred hand in hand with letter identity. However, a large number of experiments have revealed that letter-position coding is rather flexible and that items like JUGDE and JUDGE are perceptually very similar (i.e., the so-called transposed-letter effect). This phenomenon, together with other phenomena (e.g., relative-position effects [blcn activates BALCONY]; see Carreiras et al. 2009a), falsify a slot-coding scheme. It is important to bear in mind that letter transposition effects have been reported not only in the Roman script, but also in other very different orthographies: Japanese Kana (Perea et al. 2011b), Korean Hangul (Lee & Taft 2009), and Thai (Perea et al. 2012); furthermore, letter transposition effects have also been reported in Semitic languages (e.g., for morphologically simple words in Hebrew; see Velan & Frost 2011; see also, Perea et al. 2010).

In our view, letters are visual objects, and, as such, they are subject to some degree of perceptual uncertainty regarding their position within an array (e.g., via randomness of neuronal activity in the visual system; see Barlow 1956; Li et al. 2006). As Logan (1996) indicated in his model of visual attention, "the representation of location is distributed across space" (p. 554). Indeed, Rumelhart and McClelland (1982) acknowledged that "information about position and information about the identity of letters may become separated in the perceptual system if the set of retinal features for a particular letter end up being mapped onto the right set of canonical features but in the wrong canonical position" (p. 89). Thus, is it not surprising that a number of recently proposed models of visual word recognition have incorporated the assumption of perceptual uncertainty (e.g., overlap model, Bayesian Reader, overlap open-bigram model, spatial coding model).

Let us now turn to the key issue in the present commentary: the role of letter-position coding in the acquisition of reading – which

is an aspect that is missing in the target article. The human brain has not been specifically designed to read. Structural brain changes occur during learning to read (Carreiras et al. 2009b), and, unsurprisingly, the brain areas that are initially activated by letters/words are very close to the brain areas that are activated by objects or faces (Dehaene & Cohen 2011). Given that letters/words are visual objects, it is reasonable to assume that, in the initial stages of reading, an immature reading system adopts a higher degree of perceptual uncertainty in assigning letter position within words. As Castles et al. (2007) have indicated, orthographic development may be regarded as "proceeding from a broadly tuned mechanism to a very precisely tuned mechanism" (pp. 180–81). Consistent with this view, transposition letter errors are more common among younger children than among older children (see Acha & Perea 2008; Castles et al. 2007; Perea & Estévez 2008). Importantly, lack of an appropriately tuned mechanism may lead to so-called developmental letter-position dyslexia (Friedmann & Rahamim 2007). Two questions for future research are: (i) the specification of the mechanisms by which some young readers are differently sensitive to perceptual uncertainty in the process of visual word recognition (see Andrews & Lo 2012), and (ii) why skilled adult readers still show letter transposition effects – and how this may be modulated by reading skill (or any other potentially relevant factors).

One critical aspect here is that the way a written language is initially learned may induce a different flexibility in letter-position coding. On the one hand, because of the inherent characteristics of Semitic languages (e.g., vowel information is typically omitted and the root plays a critical role), flexibility in letter-position coding may be quite rigid in root-based words, relative to Indo-European languages (Velan & Frost 2011; but see Duñabeitia et al. [2009] for lack of transposed-letter priming with word–word stimuli [e.g., causal–casual] in Spanish). On the other hand, orthographies like Thai in which some vowels may be misaligned and there are no spaces between words may lead to a particularly flexible process of letter-position coding (see Perea et al. 2012). Thus, one relevant issue is the differences between the flexibility of letter-position coding across languages – in particular, for bilinguals of different families of languages. This should be investigated not only for reading acquisition in children, but also for adult learners of a second/third language (see Perea et al. 2011a).

In sum, while we agree with Frost in that the characteristics of a given language shape the way it is processed, we would like to stress that perceptual uncertainty regarding letter position is not tied to a particular family of languages. Instead, it is a general property of the cognitive system. In addition, we believe that a universal model of reading should account not only for results obtained from different languages but should also incorporate a developmental view of the reading process. Finally, more attention should be devoted to considering how the acquisition of two languages shapes the process of reading in the current multilingual world.

Thru but not *wisht*: Language, writing, and universal reading theory

Charles Perfetti
Learning Research and Development Center, University of Pittsburgh, Pittsburgh, PA 15260.
Perfetti@pitt.edu
http://www.lrdc.pitt.edu/people/person-detail.asp?Dir_ID=308

Abstract: Languages may get the writing system they deserve or merely a writing system they can live with – adaption without optimization. A universal theory of reading reflects the general dependence of writing on language and the adaptations required by the demands of specific

languages and their written forms. The theory also can be informed by research that addresses a specific language and orthography, gaining universality through demonstrating adaptations to language and writing input.

Frost provides a strong, refreshed case for the idea that reading is "parasitic on language," a correction on the claim by Mattingly (1972) that reading is "parasitic on speech" (Snowling & Hulme 2005, p. 397). Similar expressions of the idea that language rather than speech is the reference point for reading are found in Perfetti (2003) and Seidenberg (2011), among others.

Frost's focus on language provides a reminder: Successful skilled reading enables the language system to take over from the visual system with astonishing speed. It does this because the orthography has somehow managed to enable the language to be "seen" through the print.

Language is more than speech, and orthographies are more than the spellings of phonemes. The big issue is how to understand why writing systems have come to work the way they do. Alphabetic writing systems are not generally notational systems for speech but notational systems for language: the morphology as well as the phonology. One general statement of this tradeoff is, "Alphabetic writing picks out the phonemic level … and then makes various adaptations to the morphological level" (Perfetti 2003, p. 22). (See also Perfetti & Harris [under review] for a fuller treatment of the language-writing connection that draws on both Frost's target article and Seidenberg [2011].)

Frost's claim, however, is stronger than this "various adaptations" idea: He writes, "orthographies are structured so that they optimally represent the languages' phonological spaces, and their mapping into semantic meaning" (sect. 3, para. 1). The more memorable rendering of this claim is that "every language gets the writing system it deserves" (sect. 3). It is worth a brief digression to note that both the underlying idea and the literal form of the claim have resonated for other scholars. Frost attributes the quote to Ignatius Mattingly. Another source is M. A. K Halliday, who, in a 1976 lecture, observed that the development of writing was an incremental process over long periods of time. "In the course of this process (unlike the conscious efforts, which are often subject to the fads and fashions of linguistics of the time), a language usually gets the sort of writing system it deserves" (Halliday 2003, p. 103, reprinted from Halliday 1977).

Recently, Seidenberg also has expressed this claim in some interesting detail by noting a correlation between language typologies and writing systems: Complex inflectional morphology begets shallow orthography. Seidenberg captured the tradeoffs writing makes between exposing phonemes and exposing morphemes with the "grapholinguistic equilibrium hypothesis" (Seidenberg 2011). At the equilibrium point, "spoken languages get the writing systems they deserve" (p. 169).

The writing system that is deserved might not be one that is literally optimal in the sense defined by Frost. Indeed, the optimization hypothesis is elegantly startling in its implausibility. Perhaps optimization algorithms could be run on the phonological spaces of a sample of a couple dozen languages to see what the theoretically optimal orthography should be – that is, if one could also map the morpheme semantic spaces as well. Underlying optimization is the assumption that writing systems "learn" over time, by analogy to network models that self-correct in response to environmental input. Applied to writing systems, this self-correcting network would modify spellings in response to feedback that pushes the network to spell more in relation to morphology or to phonology. It is an intriguing idea that might work, if there were sufficient tolerance about spelling variability to allow the "votes" of usage to lead to increasing stability. There are strong conservative forces at play in writing, and while some change can and does occur, its reach is checked by these forces. Depending on the net result of change forces and conservative forces, orthographies will wind up considerably short of optimality.

Of course, the optimality hypothesis may be taken to mean that, by now, all orthographies have reached the equilibrium state

proposed by Seidenberg and are now optimal. But to avoid test by presumption (optimality is asserted to have resulted in the world's current distribution of writing), it remains to develop optimization algorithms that will reveal the equilibrium point for any realistically large vocabulary for a given language.

To return to the weaker claim of adaptability: Adaptations can occur. Some are gradual, as when Chinese characters moved from more iconic to more abstract over time. (Similar changes occurred in Middle Eastern writing systems.) Some are rather sudden, as when King Sejong invented an alphabet for Korean in 1446. It is interesting for the adaptations argument that this pure Hangul alphabet, with one-to-one mapping of graphs to phonemes, gave way to a certain degree of one-to-many mappings in order to allow words that shared root morphemes but not exact pronunciations to be represented by a single spelling (Perfetti 2003).

In the absence of an enlightened monarch, attempts at sudden change (spelling reform) meet strong resistance. In 1906, Andrew Carnegie's Simplified Spelling Board made recommendations for English spelling change with mixed success. While *thru* has become a competitor to *through*, the recommendations to spell *tapped* as *tapt* and *wish* as *wisht* died the death of the morphologically opaque.

Finally, whether writing systems adapt to language optimally or only roughly, there is the question of what makes a theory of reading universal. Models that allow neuronal flexibly in coding graph order are not wrong just because languages vary in their tolerance for graph order. The neural resources for reading are modified through experience with specific languages and orthographies (Bolger et al. 2005; Paulesu et al. 2000) and both brain circuits and reading behavior show "accommodation" (Perfetti et al. 2007) to the mapping principles and their orthographic implementation. The neural basis of alphabetic reading certainly can allow adaption to the specific demands of order-coding. Chinese complicates matters by placing weak demands on serial order of graph-to-speech mapping and strong demands on spatial relations. These variations do not rule out a universal mechanism that accommodates such differences.

It is intriguing to consider that these differences among languages and writing systems could fall out from a single high-level universal based on optimizing language-writing mappings. However, specific models that can actually account for these differences more directly, for example, by specifying reading's behavioral and brain adaptations to experience, have the major burden of explanation.

Vision, development, and bilingualism are fundamental in the quest for a universal model of visual word recognition and reading

Nicola J. Pitchford, Walter J. B. van Heuven, Andrew N. Kelly, Taoli Zhang, and Timothy Ledgeway
School of Psychology, University of Nottingham, Nottingham NG7 2RD, United Kingdom.
nicola.pitchford@nottingham.ac.uk
walter.vanheuven@nottingham.ac.uk
lpxak@nottingham.ac.uk   lpxtz@nottingham.ac.uk
timothy.ledgeway@nottingham.ac.uk

Abstract: We agree with many of the principles proposed by Frost but highlight crucial caveats and report research findings that challenge several assertions made in the target article. We discuss the roles that visual processing, development, and bilingualism play in visual word recognition and reading. These are overlooked in all current models, but are fundamental to any universal model of reading.

Frost presents a compelling argument for constraining models of visual word recognition by the linguistic properties of language, and attempting to find universals across languages. As noted in the target article, there is a large body of research focussing on linguistic elements that modulate the speed of word recognition (e.g., semantic, phonological, and morphological priming) and several models, such as the CDP++ (Perry et al. 2010), and the bi-modal interactive activation model (Diependaele et al. 2010), accommodate these factors within a structural framework of orthographic word recognition. There are, however, several problems with these models, the most striking being that for the majority the first explicit stage of processing does not begin until after perceptual information has been encoded into an abstract form, that is, abstract letter representations. Hence, the crucial "visual" aspect of "visual word recognition" is absent from these models. Although linguistic factors are likely to shape the development and functioning of abstract letter units, visual processes must constrain these representations, given that, for sighted individuals, vision is the sensory input system for processing printed text. The fundamental role of early visual processing in reading research has been largely overlooked, but there is an emerging body of research showing the effects of visual regularities on recognising letters and words. For example, the overall shapes of words, not just the constituent letters, influence word recognition in children (e.g., Webb et al. 2006), skilled readers (e.g., Healy & Cunningham 1992), and dyslexics (e.g., Lavidor 2011), by constraining the set of potential lexical candidates. This is most evident in lowercase scripts with ascenders and descenders that appear in the middle of words (e.g., Kelly et al. 2011). We propose that these factors originate from general mechanisms associated with visual object perception, such as pattern recognition and episodic memory, which become specialised for processing text across development.

We agree with Frost that the cognitive system is tuned to *pick up* statistical regularities of the language. A series of studies have shown that letter and word recognition is mediated by positional letter frequency but only for some positions, such as the first letters (e.g., English and Greek) and last letter (shown in English) (Ktori & Pitchford 2009; Pitchford et al. 2008). In contrast to Frost's assertion that, in English, all letters have a more or less similar contribution to word identity and the distribution of transitional probabilities is more or less flat, our data suggest that different letter positions may be more or less informative for constraining word recognition. Also, this varies across different alphabetic languages and within bilinguals, perhaps reflecting the statistical properties of letter distributions of each language (Pitchford et al. 2011). Interestingly, insensitivity to statistical regularities may be indicative of failure to become a skilled reader, such as in developmental dyslexia (Pitchford et al. 2009). Sensitivity to statistical orthographic regularities could emerge implicitly within structural models of word recognition, for example, in interactive activation models (Dijkstra & van Heuven 1998; McClelland & Rumelhart 1981) that have feedforward and feedback connections between multiple levels of representation at the feature, letter, and word level. If top-down processing can modify activation at other levels, where relative letter position is encoded, this would provide a possible mechanism whereby orthographic regularities present in the lexicon could influence letter and word recognition.

Frost also argues that learning models have more to offer than the popular structural models of orthographic processing that have recently been proposed. However, the argument is not as straightforward as Frost presents (e.g., Page 2000; Thomas & van Heuven 2005). Learning models account for the acquisition of reading processes when a child is also developing spoken language skills. In contrast, structural models account for skilled reading processes that are optimised for recognising familiar words, rather than learning new words. Ideally, each type of model should inform the other regarding the key parameters

needed to construct a cogent and "ecologically valid" theory of visual word recognition and reading. The end point of learning models should be structural representations, and structural models should emerge through learning (Johnson & Karmiloff-Smith 1992).

One of the criticisms that Frost raises in relation to structural models of orthographic processing is that letter-order insensitivity is not a general property of the cognitive system. This is based on the lack of orthographic priming in non-alphabetic scripts, such as Hebrew (Frost et al. 2005). However, letter-order insensitivity in non-alphabetic scripts may be more pervasive than Frost suggests. For example, orthographic priming by transposed characters (Wang & Peng 2000) and radicals (Ding et al. 2004) has been shown in Chinese monolinguals. This demonstrates that insensitivity to order operates across different levels of representation even within a logographic writing system. This raises the possibility that analogous effects exist in Hebrew at some level of representation not yet reported. Additionally, the finding that English–Hebrew bilinguals only show form priming when tested in English but not in Hebrew (Frost et al. 2005) may not be as revealing about the encoding of letter position as first appears. The lack of form priming when reading Hebrew may have resulted from automatic activation of the English translations of printed Hebrew words, which do not necessarily share any orthographic features and/or interfere with the encoding of Hebrew. Indeed, it has recently been shown that when bilinguals read in one language they automatically translate into the other language, even with two distinctive scripts, such as English and Chinese (e.g., Zhang et al. 2011). Furthermore, Chinese is not simply a logographic language as implied by Frost, as its phonology in Mandarin is represented using Hanyu Pinyin, a transparent alphabetic script, used in learning to read Chinese. This has been shown to impact on recognising printed English words in Chinese–English bilinguals (van Heuven & Conklin 2007). So, letter-order insensitivity may not be a strategy of optimising encoding resources as Frost suggests, but rather may reflect a fundamental property of the cognitive system, and therefore the brain.

Giving theories of reading a sporting chance

David C. Plaut

Departments of Psychology and Computer Science, and the Center for the Neural Basis of Cognition, Carnegie Mellon University, Pittsburgh, PA 15213-3890.

plaut@cmu.edu   **http://www.cnbc.cmu.edu/~plaut**

Abstract: The search for a universal theory of reading is misguided. Instead, theories should articulate general principles of neural computation that interact with language-specific learning environments to explain the full diversity of observed reading-related phenomena across the world's languages.

Frost provides compelling arguments that efforts to understand orthographic representation and processing should not treat orthography as an isolated domain but must consider what orthography is for. That is, orthography is fundamentally a visual code for conveying meaning, and as such takes advantage of, and is thus shaped by, the phonological and morphological structure of a given language. Because the world's languages vary so much in these properties, their orthographies do as well, and in this sense "languages get the writing systems they deserve" (Seidenberg 2011; cf. Frost's Note 2 in the target article). Thus, understanding orthography must be done in the context of a broader theory of the

full reading system, encompassing orthography, phonology, morphology, semantics, and syntax.

While I fully concur with Frost on the nature of the problem, I disagree with him on the nature of the solution. Frost advocates the development of a universal theory of reading which "should focus on what is *invariant* in orthographic processing across writing systems" (sect. 9, para. 1, emphasis in the original). Harking back to Chomsky's (1965) notion of a Universal Grammar (despite its drawbacks; Sampson 2005), Frost anticipates that "the set of reading universals ought to be quite small, general, and abstract, to fit all writing systems and their significant inter-differences" (sect. 2.1, para. 1).

Therein lies the problem. …

Suppose a large group of researchers spent decades running studies and developing theories about how people play soccer. After all, most of the world plays soccer, it is a very socially important skill, and children are taught to play from a very young age. In fact, given that soccer is a relatively recent cultural invention and we are unlikely to have evolved dedicated brain mechanisms for it, someone might propose a "neural recycling hypothesis" (cf. Dehaene & Cohen 2007) about how brain regions that would otherwise be doing other things become recruited for soccer.

Now, of course, in some parts of the world, instead of soccer, people play baseball, or table tennis, or do cross-country skiing. Given that any given child might have been born into a completely different sporting environment, we can't have a theory of soccer playing that doesn't also explain how people play all of these other sports. Apparently what we need is a universal theory of sports that identifies and explains just those "fundamental and invariant phenomena" (target article, Abstract) that are true of all sports.

As it turns out, it is quite straightforward to formulate general principles that are important across sports, such as being fast, strong, coordinated, and fit (although each admits exceptions – e.g., strength is irrelevant in table tennis). Such generalities are no doubt relevant to understanding sporting activities. The problem is, of course, that by themselves they tell us almost nothing about how a given sport like soccer is actually played (and why someone like Lionel Messi is so much better at it than the rest of us). The real explanation comes from working out how the general principles manifest in, and interact with, the specifics of a particular sport to give rise to both its general and idiosyncratic aspects (e.g., the importance of eye–foot coordination). Put bluntly, the things that are universal are so general that they are the starting point for theory building, not the theory itself.

The same holds for reading. The relevant "universals" probably aren't about reading at all – they're more likely to be very general principles of neural representation, processing, and learning that interact with specific reading/linguistic environments to give rise to the observed range of behaviors (across both individuals and scripts). If so, there's no such thing as a universal theory of reading – instead, maybe there's something like a universal theory of neural computation that can, among other things, learn to read.

Frost is right to emphasize learning as fundamental to theories of reading (although why he would consider this a "new approach to modeling visual word recognition" [sect. 6, para, 7] is anyone's guess). However, one gets the sense that he hasn't quite embraced the depth of the implications of this commitment.

For example, although the general idea behind Frost's "universality constraint" is important, I disagree with his specific formulation. It's not that "models of reading should … aim to reflect the *common* cognitive operations involved in treating printed language across different writing systems" (sect. 2.1, para. 1, emphasis his). Rather, models should be grounded in computational principles that can apply to any writing system. The actual "cognitive operations" within the model are the result of complex interactions between these principles and learning in a

particular linguistic environment, and would be expected to become tailored to that environment (and hence highly idiosyncratic).

Similarly, his treatment of the issue of sensitivity to letter position has the feel of a "principles and parameters" perspective (Chomsky 1981) in which all that is required of learning is the binary determination of "whether or not to be flexible about letter-position coding" (sect. 4.2, para. 10). Frost suggests that this determination might be made on the basis of "whether the distribution of letter frequency is skewed or not" (sect. 5, para. 4) but admits that this doesn't explain why non-derived Hebrew words show transposed-letter priming but most (derived) Hebrew words do not (Velan & Frost 2011). Without a fully developed learning theory, all that is left to fall back on is the implausible suggestion that subjects adapt their coding strategy on a word-by-word basis: "*it is not the coding of letter position that is flexible, but the reader's strategy in processing them*" (sect. 4.2, para. 9, italics in the original). Perhaps, instead, the system has simply learned to adapt its orthographic coding of each item in a way that takes into account its relationship with other items, in much the same way that networks can learn to treat exception words differently than orthographically similar regular words and nonwords (Plaut et al. 1996).

In summary, while applauding the focus on learning-based theories of reading that generalize across languages, I would discourage the search for a universal theory that captures all and only those aspects of reading shared by all languages. Instead, it would be more fruitful to formulate general computational principles that combine with language-specific learning environments to yield the full complexity and diversity of reading-related phenomena observed across the world's languages.

The case of the neglected alphasyllabary: Orthographic processing in Devanagari

Chaitra Rao, Shweta Soni, and Nandini Chatterjee Singh
National Brain Research Centre, NH-8, Nainwal Mode, Manesar –122050, India.
chaitlee@gmail.com   **shwetanbrc@gmail.com**
nandini@nbrc.ac.in   **http://www.nbrc.ac.in/faculty/nandini/**
mindinyourlanguage.blogspot.com

Abstract: We applaud Ram Frost for highlighting the need for multicultural perspectives while developing universal models of visual word recognition. We second Frost's proposal that factors like lexical morphology should be incorporated besides purely orthographic features in modeling word recognition. In support, we provide fresh evidence from Hindi (written in Devanagari), an example of hitherto underrepresented alphasyllabic orthographies, in which flexible encoding of *akṣara* (character) position is constrained by the morphological structure of words.

In the target article, Frost contends that current-day approaches over-emphasize purely orthographic features (specifically letter position) in modeling visual word recognition. A truly universal model of word recognition, he argues, should instead consider phonological, orthographic, morphological, and semantic linguistic features in toto.

Although transposed letter (TL) experiments overall support flexible orthographic encoding of relative letter position within words, evidence suggests that phonology and morphology constrain TL effects. Of relevance here, TL priming is sensitive to lexical morphological structure: Transposed letters within (GAREDN–GARDEN) but not across morpheme boundaries (WAREDN–WARDEN) elicit TL priming (Christianson et al.

2005; Duñabeitia et al. 2007). Nevertheless, mainstream models of orthographic processing in word recognition are yet to incorporate the role of morphology (Grainger 2008).

Despite representing an orthographic confluence, alphasyllabaries are not included in Frost's critique, probably because of the paucity of evidence on orthographic processing in these languages. We provide here a brief description of Hindi alphasyllabary (henceforth, Devanagari), one of the Indic languages written in the Devanagari script, along with recent experimental evidence that highlights the role of morphological structure in orthographic processing in Devanagari.

Also called *abugida*, the alphasyllabary is a segmental writing system wherein consonant–vowel (CV) sequences are combined within character units: Akin to alphabets, alphasyllabaries distinguish vowels and consonants, but as in a syllabary, each alphasyllabic character or akṣara (pronounced /ʌkʃʌrʌ/) maps onto a CV syllable.

Devanagari has highly transparent sound-to-spelling mapping, in consonance with its origins in Brahmi, the ancient Indian orthography designed especially to encode the finer articulatory details of Vedic chants. Accordingly, the Devanagari *akṣaramāla* (alphabet) has a phonetic layout: vowels and diphthongs are followed by consonants classified by place of articulation. Unlike Hebrew, where vowel information is underspecified, Devanagari employs obligatory vowel diacritics that substitute the inherent schwa (/ʌ/) of consonant characters wherever necessary (for a detailed description, see Vaid & Gupta 2002). The use of vowel diacritics and ligatured consonants renders Devanagari orthography visually nonlinear and spatially complex.

The limited data available suggest that the neural underpinnings of Devanagari word recognition are appreciably influenced by its structural hybridity (Das et al. 2011), engaging brain regions involved in phonemic, syllabic, as well as complex visuospatial processing. An insightful behavioral study by Vaid and Gupta (2002) demonstrated that readers of Devanagari are sensitive to both syllabic and phonemic level features during orthographic processing.

In addition to a hybrid orthography, Hindi/Devanagari possesses a rich, productive morphology with extensive inflectional marking of semantic and syntactic concepts like gender, number, and tense (Kachru 2008; Masica 1991). Following Frost's discussion, we present recent evidence that orthographic processing in Hindi/Devanagari is also constrained by lexical morphology: Akṣara transposition (henceforth termed TL per convention) effects in Hindi/Devanagari are evident in morphologically simple (monomorphemic) but not morphologically complex (bimorphemic) words.

Transposed akṣara (TL) priming in Devanagari. Forty proficient, right-handed native readers of Hindi made dominant-hand lexical decisions to a list of 80 four-akṣara Hindi targets which were preceded by one of four prime types: identity (ID), orthographic nonword (NW: मजलब–मतलब, <majlab>[1]–<matlab>), transposed akṣara (TL: मलतब–मतलब, <maltab>–<matlab>), or unrelated word primes (WD: मनसब–मतलब, <mansab>–<matlab>, *district–meaning*). Forty targets were morphologically simple (analogous to GARDEN), while 40 were complex (analogous to WARDEN, for example कसरत <kasrat>, *exercise*, from कसर <kasar>, *effort*). An informal poll was used to ensure familiarity of target and unrelated word primes to native readers. Targets comprised only basic consonant akṣaras and had no nonlinear diacritics, while primes had minimal diacritics; none of the stimuli had ligatured consonants. TL primes involved the transposition of medial (second and third) akṣaras of targets, while NW primes were created by replacing the second akṣara, and WD primes were selected to share the first and last (wherever possible) akṣaras with respective targets. The orthotactic legality of all nonword bigrams was carefully checked. Forty nonword as well as twenty filler word targets were similarly compiled, with matching primes in all four categories. A practice block of ten

https://doi.org/10.1017/S0140525X11001841 Published online by Cambridge University Press
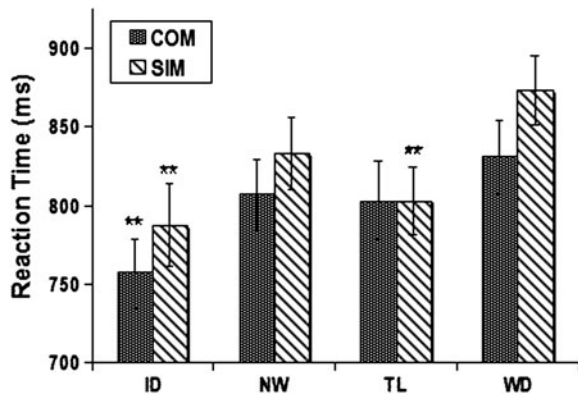
Figure 1 (Rao et al.). Lexical decision latencies to morphologically simple (SIM) and complex (COM) four-akṣara Hindi/Devanagari words preceded by identity (ID), nonword (NW), transposed letter (TL), and unrelated word (WD) primes (n = 40). Significant priming (Bonferroni-adjusted α = .004) relative to control (WD) indicated by asterisks.

words and nonwords each preceded the main task. Per trial, a forward mask (######) of 500 msec was followed by a 67-msec prime in white akṣaras, which was immediately replaced on screen by the target in yellow akṣaras (as Hindi/Devanagari makes no case distinction).

Across both simple and complex words, participants' target recognition in the identity priming condition was significantly faster (74 msec and 85 msec, both p ≤ ..004) with respect to the unrelated word (control) condition. For morphologically simple words, facilitation by TL primes (<maltab>–<matlab>, comparable to GADREN–GARDEN, 70 msec, p < .001) was equivalent to that by identity primes, while orthographic nonword primes (<majlab>–<matlab>, GALDEN–GARDEN) did not facilitate targets significantly (40 msec, p > .02). By contrast, recognition of morphologically complex words was not facilitated (p > .10) by either TL (<karsat>–<kasrat>, WADREN–WARDEN, 28 msec) or NW primes (<kabrat>–<kasrat>, WABDEN–WARDEN, 24 msec), although a numerical advantage over control primes was discernible (see Fig. 1).

Discussion. The preliminary evidence supports a robust transposed akṣara (TL) priming effect in the alphasyllabic orthography of Devanagari, although TL primes facilitate recognition of *only* morphologically simple words. By contrast, TL primes *fail* to facilitate identification of morphologically complex Hindi/Devanagari words, similarly to previous reports on English and Spanish (Christianson et al. 2005; Duñabeitia et al. 2007).

It is noteworthy that, unlike previous studies wherein primes violated morpheme boundaries (e.g., WAREDN), two-fifths of the TL primes of morphologically complex words in our experiment preserved morphemic boundaries (e.g., WADREN). The present results suggest that initial orthographic processing in Hindi/Devanagari is critically modulated by the *morpho-orthographic structure* of written words (Gold & Rastle 2007).

To conclude, our data offer support for Frost's claim, showing that orthographic feature encoding in Hindi/Devanagari is modulated by morphological context. The current results underline the need for revising word recognition models to extend their universality to encompass alphasyllabaries. Based on these results, we also propose the syllabic CV akṣara as the probable input unit for orthographic encoding in Hindi/Devanagari, similarly to syllabic–moraic Kana in Japanese (Perea & Perez 2009).

NOTE
1. Transcription follows Vaid and Gupta (2002).

Rethinking phonological theories of reading

Kathleen Rastle
Department of Psychology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom.
Kathy.Rastle@rhul.ac.uk

Abstract: One key insight of Frost's target article is that morphology has priority over phonology in writing and in cognitive processing. I argue that this insight raises challenges for theories that put phonology at the heart of the reading process. Instead, it highlights the potential importance of a morphemically based visual pathway to meaning in this process.

Nearly fifteen years ago, Frost published a ground-breaking article, offering a "unified approach for investigating visual word recognition" (Frost 1998, p. 94). This approach was predicated on the assertions that (a) reading is a secondary system parasitic on the spoken language system; and (b) written language is an expression of spoken language and, as such, maps systematically to phonology as opposed to meaning. Frost argued that the theory which necessarily emerges from these underlying premises is one in which the core lexical representations that underpin visual word recognition are phonological, and thus, that phonological processing is a mandatory part of the recognition process. This and related work has inspired an almost singular focus on the central role of phonology in reading, reading development, and reading impairment across the world's writing systems (see, e.g., Perfetti 2011).

Intriguingly, approaches which put phonology at the heart of the reading process sit rather uncomfortably with the new approach offered by Frost in the target article. One of the crucial insights of the present article is that writing systems necessarily evolve to provide maximal morphological information even at the expense of communicating phonological information faithfully. This principle is illustrated across all five of the writing systems considered, but is most dramatic in the writing systems of Hebrew and English, in which phonological information is very seriously compromised in order to convey morphological information (e.g., spelling "health" irregularly in order to preserve the stem morpheme "heal"). This state of affairs raises questions about the purpose of orthographic processing in reading. If the reading system is tuned to extract information communicated by the writing system, as Frost suggests, and if phonological information is routinely compromised through the preservation of morphological information, then where does that leave theories that view reading as based on access to phonological representations? Does it make sense to suggest that the purpose of orthographic processing is to drive activation of the phonological lexical representations purportedly essential for the computation of meaning (Frost 1998)? Frost in the present *BBS* article does not offer a direct answer to these questions.

Frost, in the target article, ultimately argues that the precedence of morphological information over phonological information – *in writing and in cognitive processing* – should be regarded as a new universal in the theory of reading. This is an important and welcome conclusion which provides a powerful rationale for an enhanced focus on the role of morphological processing in reading. It is already well established that skilled readers extract morphemic information during their processing of orthography in visual word recognition (for a review, see Rastle & Davis 2008). My position is that the rapid recovery of this morphemic information underpins a direct visual pathway to meaning that allows skilled readers to compute the meanings of words without the need for phonological recoding (Rastle & Davis 2008). In contrast to the arguments of theories which put phonology at the heart of the reading process (e.g., Frost 1998), written language *does* map very systematically to meaning, once one goes beyond the relatively small number of single-morpheme words that have dominated most models of reading. Stems surface repeatedly in words with similar meanings (e.g., cleaner, cleanly, unclean), and affixes alter the meanings of stems in highly

predictable ways (e.g., repaint, relock, retype). Further, while these regularities also characterise the mapping between phonology and meaning, they are far easier to capture in writing than in speech (e.g. health versus /hɛlθ/; magician versus /məˈdʒɪʃən/). Thus, the new approach to a universal theory of reading that Frost offers in the target article would appear to suggest that we should rethink those theories that put phonology at the centre of the reading process, and instead begin to consider seriously the part played by a morphemically based *visual* pathway to meaning in reading, reading development, and reading impairment.

Phono-morpho-orthographic construal: The view from spelling

Dorit Ravid
School of Education, Tel Aviv University, Tel Aviv 69978, Israel.
doritr@post.tau.ac.il
http://www.doritravid.name/index.php?
option=com_frontpage&Itemid=63&lang=english

Abstract: A spelling model which has evolved in the parallel universe of spelling research resonates with Frost's reading model. Like reading, spelling cannot be based solely on phonology or orthography, but should accommodate all linguistic facets. The cognitive domain of spelling does not take place at the level of single grapheme or phoneme or syllable, but rather, at the lexical level.

Frost's timely article launches a theory of reading single words that stands in sharp contrast to previous, English-oriented models focusing solely on orthographic or phonological patterns. Two critical features render this reading model linguistically plausible and ecologically valid: It intrinsically accommodates different orthographic systems tailored to highlight the *meaning-carrying units* of the languages they express; and it assumes *learning* to be the main mechanism which picks up statistical patterns inherent in the input to recover meaning.

This commentary is about a model which has evolved in the parallel universe of spelling research and resonates with Frost's reading model, albeit being informed by different schools of thought and based on rather different evidence sources. This model of spelling (Ravid 2012) construes the psycholinguistic underpinnings of Hebrew spelling as a network of phono-morpho-orthographic statistical patterns in the printed input from which reader and writers extract meaning. It is grounded in four main conceptual arenas. One is *the encyclopedic approach to language* held by the schools of Cognitive Linguistics (Croft & Cruse 2004; Langacker 1987) and Construction Grammar (Goldberg 2003), which assume the existence of linguistic networks of subtle form–function relations learned on the basis of the input coupled with general cognitive mechanisms. Another is *development* as the emergent process that drives learning in interaction with the environment (Elman 2003, p. 430). The spelling model is next predicated on the *typological imperative* (Berman 1986; Slobin 1996), as the set of salient characteristics of a language that shapes its acquisition. Finally, the domain of *literacy* makes a major contribution via Olson's view of the "script as model" (Olson 1994), which provides the link between language typology and orthographic variation in spelling development. The spelling model is informed by analyses of Modern Hebrew and its orthography, as well as by cross-linguistic developmental evidence of spelling acquisition (for reviews, see Ravid 2012; Sandra 2007).

The spelling model delineates a path to overcome homophonous letters in Hebrew, which derive from the loss of historical phonological distinctions, such as the distinction between emphatic *q* and non-emphatic *k* (Bolozky 1997; Ravid 1995; Schwarzwald 2001). Homophony is offset by the powerful impact of the morphological root and function roles of letters, occupying different

sites in the written word. For example, *v* can be written by either ו or ב, however the conjunction *ve* ("and") is exclusively spelled as ו at word-initial position. Clear participation in the function "envelope" at both sides of the root or stem is a shortcut to correct spelling, supporting only one possible path between homophonous sound and letter, leading to early correct spelling of function letters in Hebrew (Gillis & Ravid 2006; Ravid 2001; 2005).

This analysis of a non–Indo-European system indicates that a spelling model, like a reading model, cannot simply be based on one linguistic facet such as phonology or orthography, but should accommodate all linguistic facets of a word. While an alphabetical orthography certainly holds an intimate relationship with phonology, it is not merely a reflection of phonology in graphic form – a role restricted to linguistic transcription systems. The goal of spelling is to achieve a high-quality fit with correct orthographic representation, which by definition expresses *lexical* and *morphological* information. In many languages with alphabetical orthographies, *morphology* – the structural organization of meaning within the word – constitutes the architecture of hidden units mediating the complex and often opaque relationships between phonology and orthography (Ravid 2012). In learning to spell, learners would be looking for the same meaningful word-internal units that they have mapped out for spoken language. Spelling thus involves the implementation of morphological and morpho-phonological knowledge within the boundaries of a word.

As an illustration of the role of networks relating orthographic patterns to morpho-phonological knowledge in gaining command of spelling, consider the erroneous spelling of *meida* ("information") as מידה rather than מידע – that is, treating masculine *meida* as feminine because it ends with a stressed *a*. Correct spelling requires a knowledge network that would let the speller know that despite the superficial phonological similarity to feminine nouns, *meida* is masculine, and therefore does not end with feminine ה. Specific morphological knowledge would relate *meida* to root ידע ("know"), extracted from a lexical inventory of this morphological family, such as *hodía* ("inform," הודיע), *mada* ("science," מדע), or *moda'a* ("notice," מודעה). General morpho-phonological knowledge would inform one that ע typically attracts the low vowel *a* at word final position, based on masculine items containing ע-final roots, such as verb *hirgía* ("calm," הרגיע) or noun *masa* ("journey," מסע). These two converging networks – the morphological family, relating *meida* to other words based on the same root, and morpho-phonological generalizations based on phonologically similar items with similar roots – specify a small but consistent class of ע-final masculine items that superficially resemble the vastly larger ה-final feminine class. In experienced and literate speakers/writers, this knowledge motivates the choice of ע over ה in spelling *meida*.

A flexible and universally applied model of spelling cannot be mired at the level of the grapheme–phoneme link and grapheme combination. As a cognitive domain, correct spelling does not take place at the level of grapheme, phoneme, or syllable, but rather at the lexical level. This attention to meaning is at the heart of the new view of spelling as – alongside with phonology – deriving from the lexicon. Empiricist approaches (e.g., Oller 2000) regard the lexicon as the core of phonological generalizations. Phonological representations can thus be viewed as "emergent properties of … word shapes the language user encounters and stores in memory" (Beckman & Edwards 2000, p. 241). In the same way, spelling is regarded as a lexical operation that fosters the production and comprehension of words – and is thus nested within a complex network of phonological, morphological, and orthographic categories and patterns. As in spoken language, learners need to extract distributional frequencies about mapping these three domains in words. Spelling phenomena such as frequent letter sequences, phoneme–grapheme correspondences, and classification of letters by morphological role (such as root or function letters) are all entailed by the fact that correct or conventional spelling supports the production and recognition of *words*.

The limitations of the reverse-engineering approach to cognitive modeling

Jay G. Rueckl

Department of Psychology, University of Connecticut, Storrs, CT 06268; and Haskins Laboratories, New Haven, CT 06511.
Jay.Rueckl@Uconn.edu
http://web.uconn.edu/psychology/people/Faculty/Rueckl/Rueckl.html

Abstract: Frost's critique reveals the limitations of the reverse-engineering approach to cognitive modeling – the style of psychological explanation in which a stipulated internal organization (in the form of a computational mechanism) explains a relatively narrow set of phenomena. An alternative is to view organization as both the explanation for some phenomena and a phenomenon to be explained. This move poses new and interesting theoretical challenges for theories of word reading.

Generally, models of skilled word reading are constructed via a process of *reverse engineering*: (i) A body of findings concerning a relatively small set of phenomena is identified (e.g., effects of word frequency, orthographic-phonological regularity, letter transpositions); (ii) an internal organization is hypothesized in the form of a system of computational or neural mechanisms; and (iii) the model is evaluated in terms of whether the hypothesized organization would generate the patterns of behavior that it was designed to explain. This form of theorizing is not entirely circular: The models are also evaluated in terms of their capacity to generate accurate predictions about new facets of the phenomena of interest and, less often, their capacity to address other kinds of phenomena. The reverse-engineering approach is not specific to the study of word reading, but theorists in the domain of skilled word reading are especially adept practitioners of this approach; there are many word reading models, and as a group they are perhaps as detailed and mechanistically explicit as can be found in any subfield of cognitive science.

Frost's article reveals the bankruptcy of the reverse-engineering approach. At one level, his article is largely a criticism of the "new age of orthographic processing" (sect. 1.1, para. 2) – the proliferation of models inspired by the discovery that letter position is coded far less rigidly (in some languages!) than previous models would have led us to believe. Frost demonstrates that the effects of letter transpositions (and other manipulations) are quite different for Hebrew readers than for readers of English (and Spanish and French), and thus, that flexible position coding is not a necessary consequence of how our minds/brains are predisposed to represent strings of letters, but instead depends on the interaction of the reader and his or her linguistic environment.

At a broader level, Frost's article is not simply about how readers represent the orthographic properties of printed words; rather, it is an exploration of how cross-language differences (and commonalities) in word reading should be explained more generally. To the extent that reverse-engineering models can account for these differences, it is by stipulating language-specific differences in the organization of the reading system (in the simplest case, differences in parameterization; in the more extreme case, by positing different sets of underlying mechanisms). In this approach, the impact of the structure of the writing system on the organization of the reading system is more a matter of rationalization than explanation; that is, the model provides no explanation of how experience with a given writing system results in the reading system having a particular organization. Relatedly, although reverse-engineering models can serve to generate hypotheses about the relationship between the organization of skilled and beginning readers, or about the relationship between skilled and disordered reading, they provide little insight about the processes that transform a beginning reader to a skilled reader or how these processes differ in typically developing and reading-disabled individuals.

Given these considerations, Frost's endorsement of learning models over the reverse-engineering approach ("structured models," in his terms) is precisely the right move. I would add to his analysis two key points: First, I believe the field has generally failed to appreciate that these two kinds of approaches represent different understandings of what counts as scientific explanation. For the reverse-engineering approach, the question is how to explain the behavior exhibited by readers in word recognition experiments, and the answer is the organization stipulated by the theorist, which describes the millisecond-scale processes by which the meaning and pronunciation of a printed word are computed. For learning models, the organization of the reading system plays a dual role. It describes the millisecond-scale processes by which a written word is read, and thus provides an explanation of the same kinds of phenomena addressed by reverse-engineering models. At a slower time scale, the organization itself changes as a consequence of learning, and the theory must explain how and why this happens. Thus, organization is both the explanation and the explanandum.

The second point I would add to Frost's analysis is that the acknowledgment that organization must itself be explained, and that learning is central to understanding this explanation, raises a new set of theoretical challenges. (1) We need to understand the nature of the learning process. For example, to what extent is reading acquisition a form of statistical learning? Are the mappings among orthography, phonology, and semantic learned independently, or does knowledge of one mapping constrain how the other mappings are learned? (2) How should the properties of a language or writing system be characterized? It has proven constructive to think that writing systems vary in their phonological transparency (Frost et al. 1987), the grain size of the mapping between orthography and phonology (Ziegler & Goswami 2005), and the richness of their morphology (Plaut & Gonnerman 2000). But these characterizations are imprecise; we need much better ways to quantify these and other dimensions of statistical structure. (3) The properties of an orthography are determined by the properties of the language it represents. Frost hypothesizes in the target article that orthographies are optimized to provide *"maximal phonological and semantic information by the use of minimal orthographic units"* (sect. 3.1, para. 1, italics in the original). Similarly, Seidenberg (2011) proposed that languages with complex inflectional morphologies generally have phonologically transparent orthographies. Our theories should provide a basis for understanding how and why orthographic systems are constrained by the properties of spoken languages. (4) Knowledge is not an all-or-none thing. Stipulated models typically assume otherwise: For example, a lexical unit either exists or not. But an impressive array of evidence indicates that the quality of lexical representations (their precision and stability) can vary substantially, even for skilled readers (Perfetti 2007). Our theories must provide the means to capture these "in-between" states. (5) The organization of the reading system differs for readers of different languages, but also among readers of the same language (Andrews & Hersch 2010; Yap et al. 2012). On what dimensions do these individual differences occur, and what gives rise to them?

Writing systems: Not optimal, but good enough

Mark S. Seidenberg

Psychology Department, University of Wisconsin–Madison, Madison, WI 53706.
seidenberg@wisc.edu   **http://lcnl.wisc.edu**

Abstract: Languages and writing systems result from satisfying multiple constraints related to learning, comprehension, production, and their

biological bases. Orthographies are not optimal because these constraints often conflict, with further deviations due to accidents of history and geography. Things tend to even out because writing systems and the languages they represent exhibit systematic trade-offs between orthographic depth and morphological complexity.

Frost's article is a discursive tour through some issues about the nature of writing systems, spoken languages, and reading. These issues have been extensively studied from linguistic, behavioral, neurobiological, and computational perspectives (see, e.g., Chomsky & Halle 1968; Daniels & Bright 1996; Hung & Tzeng 1981; Joshi & Aaron 2006; Sproat 2000; Perfetti et al. 2010). The target article achieves the appearance of originality by failing to credit much of this body of work, nor did it benefit from seriously engaging it.

For years, research on reading in different writing systems has focused on the putative advantages provided by more transparent, consistent representations of phonology (the Orthographic Depth Hypothesis; Katz & Frost 1992). For example, researchers have repeatedly demonstrated that children learn to read more quickly in shallow orthographies compared to English, which is notoriously "deep" (Joshi & Aaron 2006). This approach never worked for me (Seidenberg 1992; 2011). If shallow orthographies are easier to learn, why are so many deep ones represented among the highest-scoring countries on the Organisation for Economic Co-operation and Development (OECD), Pisa, literacy assessments? If reading Albanian is "a skill easily acquired" (Hoxhallari et al. 2004), how do the poor Anglos manage? The problem with this research is that it emphasized reading aloud rather than comprehension. People can read aloud with zero comprehension (cf. my Bar Mitzvah), and comprehend texts they cannot read aloud (cf. non-speaking deaf readers). The major limiting factor on reading comprehension is spoken language, not orthography (Hoover & Gough 1990).

In Seidenberg (2011) I have tried to nudge research toward considering both writing systems and the spoken languages they represent. It turns out that they are related in an interesting way. The languages with shallow orthographies (Finnish, Serbo-Croatian, and others) have complex inflectional morphology. Those with deep orthographies (Chinese, English) do not. This relation suggested to me the notion of "grapholinguistic equilibrium" (Seidenberg 2011). The writing systems that have survived support comprehension about equally well. Reading comprehension is a constant that is maintained via trade-offs between orthographic complexity ("depth," number and complexity of symbols, etc.) and spoken language complexity (particularly morphological). So, in Serbo-Croatian, you, the learner gets the spelling-sound correspondences for free, but then spends years mastering the ferocious inflectional system. English is deep, but the words are shorter, the irregularities are partial and concentrated among the high frequency words, and the inflectional system is trivial. Whereas Serbian would be too hard to learn if it were deep (Seidenberg 2011, pp. 164–65), English would be too hard to comprehend if it were shallow (all that abandoned morphology; Chomsky & Halle 1968). I summarized this conjecture by stating, with some hyperbole, "spoken languages get the writing systems they deserve" (Seidenberg 2011, p. 169).

This is a functionalist argument: The characteristics of both languages and writing systems result from satisfying a varied set of constraints related to our capacities to acquire, comprehend, and produce language for multiple communicative functions in characteristic environments. These constraints arise from different sources and often conflict. For example, elisions that promote fluency in speech production can increase comprehension difficulty. Including the vowels facilitates learning to read Hebrew but interferes with skilled reading, as Frost has shown. Billions of people read Chinese, but the writing system is under pressure because it is ill-suited for keyboarding. Writing systems and languages tend to come into alignment (or are placed there by fiat; see point 3 below), but these competing constraints ensure that the result is a compromise and inherently subject to ongoing modification.

Frost is correct in asserting that writing systems need to be understood in terms of the "full linguistic environment" (sect. 1, para. 5), which was the main point of Seidenberg (2011), a chapter in a book to which we both contributed, resulting from a conference we both attended. My chapter is also the proximal source for the "spoken languages get the writing systems they deserve" epigram (which Frost now attributes to a personal communication with the late Ignatius Mattingly). The wording is identical, but the claims are not. Whereas I think languages and writing systems are probably pretty well matched because they satisfy functional constraints arising from multiple sources, Frost claims that writing systems are optimal, their properties largely dictated by a language's phonological structure.

Among the many problems with Frost's account are the following:

1. The argument proceeds by analogy to a version of evolution whereby natural selection creates movement toward optimality, a basic misunderstanding of the theory (http://evolution.berkeley.edu/evolibrary/misconceptions_faq.php#a3). Orthographies evolved, but there is no magic hand directing progress and the outcomes were not as "inevitable" as Frost repeatedly asserts. Accidents of geography and history are to writing systems as mutation, migration, and genetic drift are to evolution.

2. There are ways to assess whether the solution to a problem is "optimal," but they require formalizing the problem and doing some math, which is what distinguishes Claude Shannon from Dr. Pangloss. Frost hasn't established that *any* writing system is optimal. To do so would require deciding, optimal for what? Acquisition? Comprehension? Texting? The erudite Mattingly (1992) wasn't careless enough to write that languages get the writing systems they deserve. Rather, he discussed the *mismatches* between languages and writing systems, and how they tend to diminish over time (because orthography changes the mental representation of spoken language as much as the opposite). This is satisficing, not optimizing.

3. Major changes to writing systems have repeatedly come about through legislative fiat – writing reform. These developments (e.g., Vuk's revision of Serbo-Croatian; the creation of Hangul in 15th-century Korea; character simplification in modern China) were planned rather than "natural," "inevitable" occurrences. Such abrupt innovations (punctuated equilibria?) have often led to great increases in literacy. Many countries have agencies that actively manage their writing systems (e.g., the Turkish Language Association, the Academy of the Hebrew Language).

4. Frost's descriptions of the five writing systems deviate from scholarly treatments (see especially Ramsey [1987, pp. 57–62] on the questionable status of "word" in Chinese; cf. Coulmas 2003; Daniels & Bright 1996). Solecisms abound – here are a few examples: Morphological variations in Serbo-Croatian do result in phonological variations, for example, systematic deformations of stems (Mirković et al. 2011), contrary to Frost's assertion. Writing systems that represent syllables are not alphabets. Frost writes that "nothing is arbitrary when it comes to orthographic structure" (sect. 3.2.3, para. 2), but many things are, starting with the arbitrary association between a visual sign and a pronunciation for many words in languages such as English and French, of which several possible spellings happen to be used).

Regarding Frost's characterization of recent psycholinguistic history, more research is now being conducted on orthographic representation, but there was no "paradigm shift" (sect. 1, para. 3). People did not change their fundamental assumptions about how reading works or how to study it; the science simply expanded. Frost is correct that orthography is shaped by its relations to phonology and meaning (Price & Devlin 2011; Seidenberg 2011, Fig. 9.1). The better accounts of orthographic knowledge that are indeed needed will emerge by taking a neuro-developmental perspective on how such systems are learned and constraints on what is learnable, as well as differences between writing systems. Finally, the differences in sensitivity to letter

position that Frost emphasizes need to be assessed against statistical properties of writing systems – for example, the frequencies and distributions of letters in words – information that is lacking in most studies. Hebrew roots may resist letter transposition because of their statistical salience, derived from properties of the spoken language, which cause them to be more robustly encoded than most letter patterns in English. Given such statistical differences, the same underlying mechanisms can give rise to different sensitivities to letter position.

Frost and fogs, or sunny skies? Orthography, reading, and misplaced optimalism

David L. Share
Department of Learning Disabilities and Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Faculty of Education, University of Haifa, Mt. Carmel, Haifa 31905, Israel.
dshare@edu.haifa.ac.il

Abstract: I argue that the study of *variability* rather than *invariance* should head the reading research agenda, and that strong claims of orthographic "optimality" are unwarranted. I also expand briefly on Frost's assertion that an efficient orthography must represent sound *and* meaning, by considering writing systems as dual-purpose devices that must provide *decipherability* for novice readers and *automatizability* for the expert.

Frost has sounded a timely wake-up call to reading researchers and other cognitive scientists who are wont to draw universal generalizations on the basis of data collected from a specific culture, language, or orthography. He then asserts that the main goal of reading research is to develop theories that describe the *fundamental* and *invariant* phenomena of reading across orthographies. Among experimental psychologists, elucidation of the cognitive operations common to all readers, and, more generally, to human cognition, has always headed the agenda; "*variant* and *idiosyncratic*" (target article, Abstract, emphasis in original) factors are less important. But should invariance be our overriding concern? For biologically primary abilities such as depth perception or auditory localization that are acquired early, rapidly, and universally, invariance is unquestionably the rule; variability or individual differences is of lesser concern, often denigrated as the "noise" in the system. However, because learned skills such as reading and writing represent recent cultural innovations that are not part of humans' evolutionary heritage, *variability* rather than invariance is fundamental. Even in the field of spoken-language processing, which is widely regarded by reading researchers as biologically primary (in contrast to written-language processing), it has been argued that there are few, if any, language universals once we consider the full compass of spoken language variety (Evans & Levinson 2009; see also the discussion of WEIRD psychology in Henrich et al. 2010 – both in previous issues of *BBS*). If universals exist in reading – and this is a hypothesis, not an axiom – these are likely to be overshadowed by culture-specific, language-specific, and script-specific differences, as well as by massive inter-individual variance. As Evans and Levinson (2009, p. 429) argue, "Linguistic diversity then becomes the crucial datum for cognitive science."

Does every language get the orthography it deserves? Frost makes the strong claim that orthographies optimally represent speech and meaning, and that the evolution of writing systems is the culmination of a process of optimization. I suggest this note of finality and "optimality" is unwarranted. Every writing system, like spoken language, is a living, breathing organism that must adapt to the ever-changing needs of its users, their culture, and the technology of communication. Written language, like spoken language, ceases to change only when it dies. Frost's

"optimalism" may be true of a few languages in societies with a long-standing literacy tradition, but is highly doubtful when it comes to the many developing societies which are relative newcomers to writing and literacy. For example, approximately one third of the world's languages are spoken in Africa (Bendor-Samuel 1996), yet only some 500 have a written form – the vast majority using a European Roman-based alphabetic orthography disseminated by missionaries who took it for granted that their own writing systems would be optimal for non-European languages. Indeed, many Western scholars still presume that European alphabets are inherently superior to non-alphabetic systems (see, e.g., Gelb 1952; Havelock 1982) But are they? The answer is we don't know yet, but as the following three illustrations suggest, Europe's "orthographic elitism," or rather "alphabetism," may be unfounded.

A study by Asfaha et al. (2009) investigated reading acquisition in four African languages in Eritrea that use either alphasyllabic (consonant-vowel [CV]) Ge'ez (Tigrinya and Tigre) or alphabetic Roman-based scripts (Kunama and Saho). All four languages are said to share a simple syllabic structure, a rich morphology, and a common national curriculum. All scripts, furthermore, are highly regular in either phoneme correspondences or CV (*fidel*) correspondences. The teaching of alphabetic Saho script focuses on CV units, whereas alphabetic Kunama is taught phonemically. A sample of 385 first-grade children who learned to read the alphasyllabic Ge'ez by far outperformed children who learned the alphabetic scripts, in spite of the larger number of signs/graphemes. Moreover, the CV-level teaching of alphabetic Saho produced superior results compared to alphabetic teaching of Kunama.

A second case in point comes from the Philippines, where the arrival of the Spanish in the 16th century lead to the marginalization of the indigenous Indic (alphasyllabic) scripts in all but the most remote regions. Kuipers and McDermott (1996) cite reports of unusually high literacy rates among the Hanunoo in the mountains of Mindoro.

A third example is from Southern Sudan, where the Dinka language is written in a European alphabetic orthography, which, according to some observers (John Myhill, personal communication, 2011), is almost impossible to read fluently. Myhill suggests this may be due to complex interactions between linguistic features not found in European languages, including voice quality and tone that can be both lexical and grammatical.

These few illustrations may not be isolated exceptions. There are documented cases of indigenous scripts invented *ex nihilo* by illiterate individuals aware only of the existence of writing systems among neighboring peoples or missionaries. Daniels (1996a) cites numerous examples (including the Cree and Vai syllabaries) and notes that almost all share a common design; signs for CV syllables alone (Daniels 1996a; see also Chen [2011], on Chinese).

A final comment relates to Frost's argument that an efficient writing system must represent sound *and* meaning. I have termed these two dimensions of orthography *decipherability* and *automatizability*. Orthographies can be regarded as dual-purpose devices serving the distinct needs of novices and experts (see Share 2008a). Because all words are initially unfamiliar, the reader needs a means of deciphering new letter strings independently (see Share [1995; 2008b] for more detailed discussion). Here, phonology and decipherability are paramount. To attain fluent, automatized reading, on the other hand, the reader needs unique morpheme-specific letter configurations that can be "unitized" and automatized for instant access to word meaning. Here morpheme-level representation takes precedence. (It may be morpheme *distinctiveness* [*know* versus *no*] rather than morpheme *constancy* [*know/acknowledge*] that is crucial for rapid, silent reading.)

This "unfamiliar-to-familiar" or "novice-to-expert" dualism highlights the developmental transition (common to all human skill learning) from slow, deliberate, step-by-step, unskilled performance to rapid, automatized, one-step skilled processing.

Without morpheme-level automatizability, the skill of reading might never have transformed modern cultures so profoundly (or at least those few with near-optimal writing systems).

Towards a universal neurobiological architecture for learning to read

Marcin Szwed,[a,b,c] Fabien Vinckier,[d,e] Laurent Cohen,[d,e,f] and Stanislas Dehaene[g,h,i,j]

[a]Zakład Psychofizjologii, Instytut Psychologii (Department of Psychophysiology, Institute of Psychology), Jagiellonian University, 31120 Kraków, Poland; [b]Département de Psychologie, Aix-Marseille Université, 13284 Marseille, France; [c]Laboratoire de Psychologie Cognitive, CNRS, UMR 6146, 13284 Marseille, France; [d]Faculté de Médecine Pitié-Salpêtrière, IFR 70, Université Pierre et Marie Curie (University of Paris 6), 75013 Paris, France; [e]Institut National de la Santé et de la Recherche Médicale, Institut du Cerveau et de la Moelle Épinière, UMRS 975, 75013 Paris, France; [f]Departement de Neurologie, Groupe Hospitalier Pitié-Salpêtrière, and Assistance Publique–Hôpitaux de Paris, 75651 Paris, France; [g]Collège de France, 75005 Paris, France; [h]Cognitive Neuroimaging Unit, Institut National de la Santé et de la Recherche Médicale, 91191 Gif sur Yvette, France; [i]Division of Life Sciences, Institute of Bioimaging, Neurospin, Commissariat à l'Energie Atomique, 91191 Gif sur Yvette, France; [j]Université Paris 11, 91405 Orsay, France.

mfszwed@gmail.com   fabien.vinckier@gmail.com
laurent.cohen@psl.ap-hop-paris.fr   stanislas.dehaene@cea.fr
www.unicog.org

Abstract: Letter-position tolerance varies across languages. This observation suggests that the neural code for letter strings may also be subtly different. Although language-specific models remain useful, we should endeavor to develop a universal model of reading acquisition which incorporates crucial neurobiological constraints. Such a model, through a progressive internalization of phonological and lexical regularities, could perhaps converge onto the language-specific properties outlined by Frost.

"Cmabirdge" reads almost as well as "Cambridge," but only in some languages. Ram Frost is right in pointing out that tolerance to letter-position swaps is not a universal feature of reading. His hypothesis that writing systems "optimally represent the languages' phonological spaces" (sect. 3, para. 1) is appealing and is indeed a crucial consideration when discussing the possibility of spelling reform – some variations in writing systems may be more "rational" than they first appear (Dehaene 2009, pp. 32–37). Does it follow, however, that current open-bigram models of orthographic processing are, in Ram Frost's words, "ill-advised"? And what is the best strategy to achieve a "universal model of reading"?

From a neuroscientific perspective, much insight can be gained from limited models that consider in detail not only the problems raised by a specific script and language, but also the neurobiological constraints on how the brain might solve them. Our *bigram neuron* hypothesis, which postulates that the left occipitotemporal visual word form area (VWFA) may contain neurons tuned to ordered letter pairs, was presented in this context as a useful solution to position-invariant recognition of written words in English, French, and related Roman scripts (Dehaene et al. 2005). A functional magnetic resonance imaging (fMRI) experiment aimed at testing the predictions of this model demonstrated that reading indeed relies on a hierarchy of brain areas sensitive to increasingly complex properties, from individual letters to bigrams and to higher-order combinations of abstract letter representations (Vinckier et al. 2007). These regions form a gradient of selectivity through the occipitotemporal cortex, with activation becoming more selective for higher-level stimuli towards the anterior fusiform region (Fig. 1) (see also Binder 2006). Interestingly, a similar gradient may also exist in Chinese script (Chan et al. 2009). It would be important to probe it in Hebrew readers.

We agree with Frost that developing a more general, language-universal model of reading acquisition is a major goal for future research. However, crucially, we would add that such a universal model should incorporate strong constraints from brain architecture and not just linguistics. Existing connectionist models typically incorporate few neurobiological constraints and, as a result, provide information-processing solutions that need not be realistic at the brain level. Reading is a ventral visual stream process that "recycles" existing visual mechanisms used for object recognition (Dehaene 2009; Szwed et al. 2009; 2011; however, see Reich et al. 2011) As such, it is heavily constrained by the limitations of the visual brain, for example, the necessity to process information

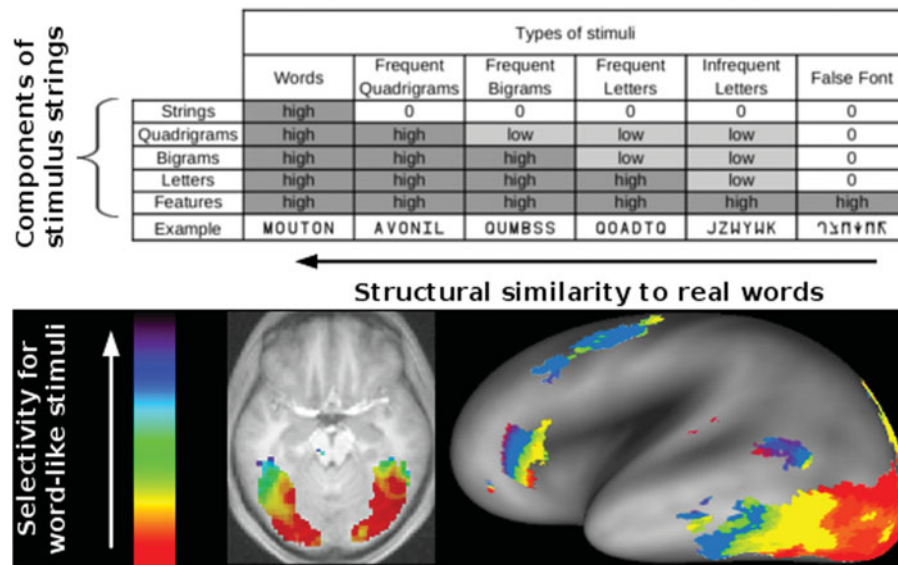| Components of stimulus strings	Types of stimuli					
	Words	Frequent Quadrigrams	Frequent Bigrams	Frequent Letters	Infrequent Letters	False Font
Strings	high	0	0	0	0	0
Quadrigrams	high	high	low	low	low	0
Bigrams	high	high	high	low	low	0
Letters	high	high	high	high	low	0
Features	high	high	high	high	high	high
Example	MOUTON	AVONIL	QUMBSS	QOADTQ	JZWYWK	ורעת+חא

Structural similarity to real words

Figure 1 (Szwed et al.).   Hierarchical Coding of Letter Strings in the Ventral Visual Stream. **Up:** Design and examples of stimuli used, with an increasing structural similarity to real words. **Down:** fMRl results The image illustrates the spatial layout of sensitivity of the occipitotemporal cortex to letter strings of different similarity to real words. Activations become more selective for higher-level stimuli (i.e., stimuli more similar to real words) toward the anterior fusiform regions. This is taken as evidence for a hierarchy of brain areas sensitive to increasingly complex properties, from individual letters to bigrams and to higher-order combinations of letters. (Adapted from Vinckier et al. 2007).

step by step through distinct visual areas with increasing receptive fields (V1, V2, V3, V4, V5, LO, MT …). Implementing these constraints into general models has proven very challenging so far (although see Mozer 1987). Indeed, important advances in the field have been predominantly guided by narrow, language-specific theories that hardwire these constraints into their architectures. Nevertheless, the vast neurobiological knowledge about these regions should ultimately be tapped by a more general model. Starting from a generic, biologically realistic neuronal architecture, and using realistic synaptic plasticity rules, the future model would converge on a specific architecture for the VWFA in any language. It could include a Bayesian implementation of the informative fragments model, which falls close to predicting the real-life responses of ventral visual stream neurons involved in object recognition (Ullman 2007).

Would such a model, once developed, substantiate Frost's claim that the internal code for letter strings varies strongly across languages, depending on their phonology and word structure? Here, we should clear up a frequent confusion. During *online* processing, when an actual word is read by a fluent reader, magnetoencephalography (MEG) experiments, with their high temporal resolution, have shown that the first major response of the visual system, peaking roughly 130 msec after seeing a word, is determined overwhelmingly by the frequency of letter combinations that make up a word, whereas lexical and phonological effects come into play much later (Simos et al. 2002; Solomyak & Marantz 2010). Thus, in adults, the VWFA may reflect a relatively isolated stage of orthographic processing that is essentially immune to phonological and semantic influences (Dehaene & Cohen 2011; but see Price & Devlin 2011). However, this is not to say that, in the course of *learning*, the acquired orthographical code cannot be influenced by the needs of the phonological and semantic systems to which the VWFA ultimately projects. The anatomical localization of the VWFA is strongly influenced, not only by bottom visual constraints (Hasson et al. 2002), but also by the lateralization of the target spoken language (Pinel & Dehaene 2009). MEG shows that, in English readers, the visual word form system decomposes the words' morphology into prefixes, roots, and affixes about 170 msec after stimulus onset (Solomyak & Marantz 2010). Such decomposition is automatic and operates even with pseudo-affixed words like "brother" that can be falsely decomposed into "broth" and "er" (Lewis et al. 2011). Thus, the visual system has internalized orthographic units that are relevant to morphological and lexical knowledge. Although not yet demonstrated, we consider it likely that the VWFA also codes for frequent substrings that facilitate the mapping onto phonemes, such as "th" or "ain" in English. Indeed, this hypothesis may explain why English reading, with its complex grapheme–phoneme mappings, causes greater activation in the VWFA than does Italian reading (Paulesu et al. 2000).

In this context, we have no difficulty in accepting Frost's argument that the optimal neural code for letter strings might have to be much less tolerant to letter swaps in Hebrew than in English. This view predicts root detectors in the more anterior part of VWFA of Hebrew readers and sharper tuning curves for letters and bigrams detectors. Testing such predictions for scripts other than Latin is an important goal for future neuroimaging experiments. A readily available tool is fMRI repetition suppression, which has proven sensitive to subtle properties of object, number, and letter tuning (Dehaene et al. 2004; Grill-Spector et al. 1999). Alternatively, multivariate pattern analysis may provide more direct access to the fine-tuning characteristic of the VWFA (Braet et al. 2012).

The study of orthographic processing has broadened research in visual word recognition

Carol Whitney

Independent Researcher, 629 Piping Rock Drive, Silver Spring, MD 20905.
cwhitney@cs.umd.edu

Abstract: Interest in orthographic processing reflects an expansion, not constriction, of the scope of research in visual word recognition (VWR). Transposition effects are merely one aspect of investigations into orthographic encoding, while open bigrams can accommodate differences across languages. The target article's inaccurate characterization of the study of orthographic processing is not conducive to the advancement of VWR research.

The target article accuses researchers in orthographic processing of inadvisedly narrowing the scope of investigation in visual word recognition (VWR). However, the article actually reflects the narrowness of the author's own outlook, rather than the existence of any constrictions on VWR research.

The article makes the obvious point that VWR is not limited to orthographic processing, but must include phonological, morphological, and semantic analysis. None of us who investigate orthographic processing would disagree. The current attention being paid to the topic of letter-position encoding simply reflects the fact that this aspect of VWR has been neglected in the past; we have now successfully pointed out the interesting and important questions associated with this topic.

Frost characterizes research in orthographic processing as focusing on transposed-letter effects, and points to the lack of transposed-letter priming for Hebrew roots as evidence that our research does not address universal questions in VWR. However, his article is inaccurate on both these counts. Research on orthographic processing attempts to answer the question of how a feature-based retinotopic representation is converted into abstract representations of letter identity and order that support morphological, lexical, and phonological analysis. It employs behavioral and brain-imaging experiments evaluating the effects of retinotopic position, within-string letter position, word length, and letter insertions, deletions, and transpositions within and across phonological and morphological boundaries.

Such investigations have led some researchers to propose an open-bigram encoding for lexicosemantic access, as noted in the target article. Although the proposal of open bigrams was based on research in European languages, this type of representation happens to be particularly suited for Hebrew roots, because it encodes the order of non-contiguous letters. Under a universal open-bigram encoding, the degree of sensitivity to transposed-letter priming may simply be a function of the relative strength of inhibitory and excitatory connections between open bigrams and morphological units. For example, a strong inhibitory connection from open-bigram BA to root ABC would prevent facilitation by the prime BAC. In fact, evidence for such inhibition comes from an English study that compared the effect on the target ABCD of the reversed prime DCBA versus a control prime containing none of the target's letters (Still & Morris 2010). The reversed prime yielded inhibition with respect to the control, suggesting the existence of inhibitory input from bigrams that are reversals of the word's bigrams. The relative influence of such inhibition may vary with morpheme length, language, and reading experience. Research, not ranting, is required to resolve the issue of whether differences in transposition effects across languages reflect *quanti*tative differences in orthographic processing (as suggested here) or *quali*tative differences (as claimed in the target article).

However, the study of orthographic processing encompasses much more than the question of what type of representation contacts the lexical/morphological level. It addresses lower levels of processing, asking how a retinotopic representation is converted into a location-invariant encoding, including the issue of how information

is integrated across hemispheres (Grainger et al. 2010; Tydgat & Grainger 2009; Whitney 2001; 2008; 2011). It asks whether orthographic representations are the same on the lexicosemantic and phonological pathways, and, if not, how and when they diverge (Grainger & Ziegler 2011; Whitney & Cornelissen 2008). It asks how these representations are learned and constrained by the innate visual and auditory systems, and why such learning may fail (Whitney & Cornelissen 2005).

Hence, a comprehensive model of VWR should characterize how the preliterate neural systems for phonological analysis, visual object recognition, audiovisual integration, and semantic representation adapt to support orthographic, phonological, morphological, and semantic processing in reading. It should characterize the end point of reading acquisition, and how it varies with language and individual differences. It should detail the ways in which reading acquisition can fail, potentially providing insights into how to provide more effective remediation for reading disability. These are ambitious goals; respect and cooperation among researchers in different aspects of VWR will be required to attain them. Unfortunately, the inaccurate account of orthographic research presented in the target article is not conducive to this mission.

Author's Response

A universal approach to modeling visual word recognition and reading: Not only possible, but also inevitable

Ram Frost

Department of Psychology, The Hebrew University, Jerusalem 91905, Israel, and Haskins Laboratories, New Haven, CT 06511.
frost@mscc.huji.ac.il
http://psychology.huji.ac.il/en/?cmd=Faculty.113&letter=f&act=read&id=42~frost/
http://www.haskins.yale.edu/staff/ramfrost.html

Abstract: I have argued that orthographic processing cannot be understood and modeled without considering the manner in which orthographic structure represents phonological, semantic, and morphological information in a given writing system. A reading theory, therefore, must be a theory of the interaction of the reader with his/her linguistic environment. This outlines a novel approach to studying and modeling visual word recognition, an approach that focuses on the *common* cognitive principles involved in processing printed words across different writing systems. These claims were challenged by several commentaries that contested the merits of my general theoretical agenda, the relevance of the evolution of writing systems, and the plausibility of finding commonalities in reading across orthographies. Other commentaries extended the scope of the debate by bringing into the discussion additional perspectives. My response addresses all these issues. By considering the constraints of neurobiology on modeling reading, developmental data, and a large scope of cross-linguistic evidence, I argue that front-end implementations of orthographic processing that do not stem from a comprehensive theory of the complex information conveyed by writing systems do not present a viable approach for understanding reading. The common principles by which writing systems have evolved to represent orthographic, phonological, and semantic information in a language reveal the critical distributional characteristics of orthographic structure that govern reading behavior. Models of reading should thus be learning models, primarily constrained by cross-linguistic developmental evidence that describes how the statistical properties of writing systems shape the characteristics of orthographic processing. When this approach is adopted, a universal model of reading is possible.

R1. Introduction

My target article is a critique of the recent paradigmatic shift in modeling visual word recognition, characterized by extensive preoccupation with noisy letter-position coding. The main theoretical claim driving this critique is that orthographic processing cannot be researched, explicated, or understood without considering the manner in which orthographic structure represents phonological, semantic, and morphological information in a given writing system. This is because any orthographic effect obtained in a given language, such as sensitivity to letter order, is an emerging product of the full linguistic environment of the reader, not just of the structure of the graphemic sequence. *In a nutshell, I have argued that a theory of reading should be a theory of the interaction of the reader with his/her linguistic environment.* This sets the criteria for a novel approach to studying and modeling visual word recognition. The models should describe and explain the common cognitive principles involved in processing printed words across orthographies, taking into account the commonalities and differences between systems.

The article presents, then, a series of related claims that logically follow from one another. The various commentaries refer to all of these claims – the general theoretical agenda, the constraints on the evolution of writing systems, the nature of orthographic processing, the universality of letter-position flexibility, and the advantages of different modeling approaches. Naturally, a number of commentaries have expressed contrasting views. Other commentaries have suggested important fine-tuning of some of the theoretical claims. Quite a few commentaries have extended the scope of the debate further, bringing into the discussion additional perspectives. My response deals with all of these issues with the aim of fleshing out fine distinctions, so as to settle on a broader theoretical approach that incorporates the additional input offered by the various commentaries.

The rest of the response therefore comprises eight sections: Section R2 is devoted to the general theoretical agenda I advocate, and the reciprocal relations between a reading theory and its possible implementations. Section R3 discusses the constraints of neurobiology and perception on modeling visual word recognition. Section R4 expands on the concept of *reading universals*. Section R5 deals with the scope of cross-linguistic research. Section R6 outlines the merits of a developmental approach to orthographic processing. This is an important extension of the target article, and it traces directions for future research. Section R7 discusses the descriptive adequacy of current implementations. Section R8 provides important extensions of the present theoretical framework to include phonological processing, and Section R9 summarizes the discussion by outlining possible future directions.

R2. Top-down theoretical scope and bottom-up implementations

The claim that a theory of reading is a theory of the interaction of the reader with his or her linguistic environment

sets the perimeter of possible sources of constraints for our models of reading. **Grainger & Hannagan** label the quest of finding commonalities in reading across different writing systems through cross-linguistic research a "top-down approach to scientific theorizing," which ignores "the details of implementation." This criticism deserves a lengthy discussion, as it concerns the basic foundations of scientific research in the domain of reading. Grainger & Hannagan see researchers of visual word recognition as faced with a binary choice: either pursuing bottom-up implementations using few general principles, which eventually leads to a model that provides an adequate description of the data (presumably the "right" approach to science), or engaging in a top-down search for a good theory without bothering about the details (the "bad" approach to science). Our scientific investigation, however, is always a combination of both, because the choice between possible bottom-up implementations is not and cannot be independent of our top-down theorizing regarding what constraints are relevant for assessing these implementations, and what set of data should be modeled to begin with. Without a theoretical framework that determines the full scope of relevant constraints and the range of data to simulate, the search for adequate bottom-up implementations may miss critical phenomena with important explanatory power.[1]

The question then is not whether one can suggest common operations in orthographic processing across writing systems, but rather, what type of information would be relevant for finding them. The common principles according to which writing systems have evolved to represent orthographic information in all languages seem critical because they reveal the complexity of information that is conveyed by orthographic structure, aside from letter identity and letter position. Borrowing **Perfetti**'s words, orthographic structure allows the language to be "seen" through the print, since writing systems are notational systems for *the language* – phonology and morphology included. This insight leads to further insight regarding how the cognitive system picks up this complex information and illuminates the nature of this information. The significant advantage of this ecological approach is that it considers in parallel the information processing system and the environment on which it operates. This theoretical perspective sets the perimeter of possible relevant implementations, and suggests that a much broader data set should be considered in our modeling enterprise.

R2.1. Sources of constraints on implementations

The intimate interaction of theory and consequent implementation is well exemplified by several of the commentaries. **Pitchford, van Heuven, Kelly, Zhang, & Ledgeway** (**Pitchford et al.**), for example, argue that vision, development, bilingualism, and the statistical properties of letter distribution across languages, are all relevant sources of constraints for implementation in modeling of visual word recognition. **Goswami** and **Deacon** very convincingly argue why data from reading acquisition across writing systems is imperative for understanding what information is picked up by readers from the orthography for the purpose of visual word recognition. **McBride-Chang, Chen, Kasisopa, Burnham, Reilly, & Leppänen** (**McBride-Chang et al.**) refer to the additional complexity

related to the nature of word units across orthographies, and the inherent ambiguity regarding the definition of word boundaries. **Friedmann & Gvion** discuss the implications of cross-linguistic differences considering the density of lexical space. **Liversedge, Blythe, & Drieghe** (**Liversedge et al.**) demonstrate how sentential context determines patterns of orthographic processing, such as sensitivity to letter position. **Feldman & Moscoso del Prado Martín** discuss the interaction of semantic and orthographic processing in different languages. **Pelli, Chung, & Legge** (**Pelli et al.**) show how letter-by-letter decoding, whole word shape, and sentence context determine eye movements and reading speed.

In this context, the approach advocated by **Grainger & Hannagan** represents a notable exception. Grainger & Hannagan would probably not deny that all of the aforementioned are important aspects of reading research. Nevertheless, by considering only the front-end part of visual word recognition, they focus mainly on the architecture of the visual system of primates and the child's pre-existing visual object-recognition system. This approach is best demonstrated in a recent report by Grainger and colleagues showing that baboons can be trained to efficiently distinguish hundreds of words from nonwords composed of nonsense combinations of letters (Grainger et al. 2012). Since baboons do not have any linguistic representations, but, nevertheless, can perform similar to humans in a lexical decision task, Grainger et al. (2012) reach the conclusion that orthographic processing in humans and primates probably employs similar principles of visual object processing. The logic of this argument lies on the inference that if primates can be shown to do what humans do, it must be that the underlying cognitive processing of humans and primates is similar. To reiterate, if primates lacking linguistic skills can do well in recognizing statistical dependencies of orthographic symbols relying solely on their object-recognition abilities, then orthographic processing in humans probably draws upon object-recognition as well.

Aside from the logical fault underlying such inference the "environment" in this approach to reading is consequently restricted to the world of visual objects, rather than the characteristics of the linguistic environment. This determines to a large extent the range of constraints that are relevant for testing specific implementation. **Grainger & Hannagan** are thus inspired by bioinformatics, suggesting that "string kernels," also used for protein function predictions, can be usefully applied to reading research (see Hannagan & Grainger, in press: "Protein analysis meets visual word recognition"). They argue that this approach provides a better fit to a set of established benchmark phenomena, but here is the snag: It is the theory that eventually determines the scope of actual "benchmark phenomena" that are considered relevant to validate a model, and it is this scope that traces the thin line between "a modest proposal" and a narrow one. Adopting **Grainger & Hannagan's** approach would inevitably lead to an impoverished theory of orthographic processing that does not consider the rich scope of statistical correlations that exist between various sublinguistic representations in a given language. Consequently, such theory indeed would not differentiate between performance of humans and performance of primates, who lack linguistic knowledge. The surprising richness of

information extracted from print by readers during orthographic processing is well described by **Homer, Miller, & Donnelly** (**Homer et al.**).

My critique of the "new age of orthographic processing" discusses in great detail the shortcomings of considering only front-end constraints when studying reading and visual word recognition, and of researching them only within one language – English. Not unexpectedly, some of the present commentaries focus on outlining the merits of the agenda of *cracking the orthographic code in a uniform linguistic environment*. Let me concede up front that any scientific investigation has merits. I therefore agree with **Grainger & Hannagan** that it is important to study how the cognitive system treats letters in a specific linguistic environment (in fact, I have been doing so myself in Hebrew for years). I agree with **Pitchford et al.** that the role of early visual processing in reading research has been largely overlooked. I agree with **Whitney** that this agenda has produced important insights regarding low-level processing, thereby describing the neurocircuitry involved in visual word recognition. The shift to explore the front end of word perception has no doubt contributed to a wealth of data, outlined meticulously by Whitney. *The question at hand, however, is whether front-end implementations of orthographic processing that do not stem from a comprehensive theory of the complex information conveyed by writing systems, and are not constrained by developmental and cross-linguistic evidence, present a viable approach for understanding reading. My answer to this is a decisive no.*

R3. Neurobiology, perception, and modeling visual word recognition

Admittedly, even if it is established that cross-linguistic evidence is a main source of constraints for any universal model of reading, as I have argued, the question of neurobiological constraints still lingers. Thus, the fact that a theory of visual word recognition cannot do without a detailed analysis of the properties of writing systems indeed does not imply that the theory should not be constrained by the properties of the visual system and the brain. Several commentaries have addressed this issue. **Szwed, Vinckier, Cohen, & Dehaene** (**Szwed et al.**) convincingly argue for a universal neurobiological architecture of reading acquisition. Their brief report provides helpful examples of the insights that neurobiological data can provide for understanding how the brain neurocircuitry adapts to deal with different writing systems, suggesting that in the course of learning, the visual system internalizes orthographic units that are relevant to morphological and lexical knowledge. I embrace this suggestion with both hands. A word of caution though: This research enterprise is contingent on working within a *developmental perspective*, as indeed suggested by Szwed et al. Observing correlations between a discovered reading behavior and some patterns of brain processing, then describing this behavior in terms of brain processing, and then using this description as explanation, would not advance us much in understanding reading. Insight is gained mainly by considering how the brain *adapts* to a writing system in the course of literacy acquisition.

R3.1. Linguistic modulation of perceptual processes

If both cross-linguistic evidence and neurobiological evidence are sources of constraints for a theory of reading, an important question concerns the extent of penetrability (or susceptibility) of primary visual processing to linguistic modulation. Returning to the question of letter transposition, several commentaries have addressed the question of what is universal and what is language-specific regarding letter coding. To put it in other words, where does vision "end" and language "begin" in reading? This is certainly not a simple question. For example, **Martelli, Burani, & Zoccolotti** (**Martelli et al.**) remind us that crowding poses visual constraints on orthographic codes, suggesting how constraints of visual span interact with word-length and letter-position insensitivity. Similarly, **Pelli et al.** provide an insightful account of the complex interactions of reading speed with crowding, text size, and comprehension.

In this context, the proposal offered by **Norris & Kinoshita** and by **Gomez & Silins** deserves a serious discussion. Both Norris & Kinoshita and Gomez & Silins suggest that the *primary* perceptual processes involved in visual word recognition are universal and that, akin to visual object recognition, they are characterized by perceptual noise. By this view, the product of the primary visual analysis, in which letter position is ambiguous, is then shaped by the properties of the language, producing cross-linguistic differences such as transposed-letter (TL) priming effects. Similarly, **Perea & Carreiras** argue in a convincing commentary that perceptual uncertainty is characteristic of the cognitive system. This account suggested by Norris & Kinoshita, Gomez & Silins, Perea & Carreiras, as well as **Whitney**, is probably true to some extent, and certainly hard to refute. I have acknowledged it at the onset of the target article. Obviously, there must be a primary level of visual processing that is common to all incoming visual information: objects, words, or visual scenes. Similarly, there must be some level of noise regarding letter position, given the properties of the visual system. As **Liversedge et al.** rightly argue, the common nature of eye movements in reading, along with the physiological make-up of the retina, determine how information is delivered to the cognitive system.

Having acknowledged that, the suggestion offered by **Norris & Kinoshita** – according to which the "perceptual system" *fully* completes its task, and only then does the "linguistic system" come into play to produce differential effects of transposition – has the flavor of bottom-up feed-forward processing, which is not very probable. The idiosyncratic distributional properties of letters in a language result in perceptual learning – a means to facilitating fast and efficient recognition of visual configurations that are frequently encountered by the organism (e.g., Gilbert et al. 2001; Sigman & Gilbert 2000). As demonstrated for both nonverbal and verbal stimuli, the frequency and amount of retinal training determines the way the distal stimulus is processed. For example, Nazir et al. (2004) have demonstrated reading-related effects of *retinal* perceptual learning that were stimulus specific (e.g., whether the stimulus is a word or a nonword), as well as language specific (whether the script is Hebrew or English). In this study, we found that legibility of target letters *differentially* varied with locations on the retina for Hebrew and Roman scripts. Nazir et al. (2004)

therefore concluded that reading habits affect the functional structure of *early stages in the visual pathway*. To some extent, this suggestion is echoed by **Szwed et al.**, and also resonates with **Laubrock & Hohenstein**'s review of how language modulates print processing already in the parafovea. Thus, the demarcation line beyond which "perceptual" processing ends and "linguistic" processing begins is hard to discern. The idea that the perceptual system feeds a uniform output to the linguistic system across orthographies is, therefore, not supported by the data. As **Perea & Carreiras** argue, the evidence regarding letter-position flexibility in many languages is uncontested, but so is the evidence regarding letter-position rigidity in other writing systems. *Thus, from a perspective of a theory of reading, the interesting discussion concerns the way the linguistic environment shapes readers' indifference or rigidity regarding letter order, as well as other characteristics of orthographic processing. This is the main thrust of the quest for a universal model of reading.*

R3.2. The time course of linguistic effects

A critical empirical question then is how "early" during processing the characteristics of writing systems exert their influence on the perceptual processes of print. As Nazir et al. (2004) suggest, reading habits that are related to writing systems develop at early stages in the visual pathway. **Szwed et al.** refer to brain evidence from magnetoencephalography (MEG) experiments, showing that already 130 msec after word onset, distributional properties of letter combinations modulate responses (e.g., Simos et al. 2002; Solomyak & Marantz 2010). Similarly, in behavioral studies, recent results from our laboratory suggest that readers of Hebrew differentiate between letter transpositions occurring in words with or without a Semitic structure already at first fixation (Velan et al., under review). Thus, TL interference is found for root-derived words, but not for simple words, *in the earliest measure of eye movements*. Interestingly, for first-fixation latencies, what matters for Hebrew readers is whether a legal root is contained in the letter sequence irrespective of whether the letter string is a word or a nonword. Thus, even if there is a phase of processing where all printed input is treated alike, the inevitable conclusion is that the statistical properties of the linguistic environment of readers shape letter processing very early on, resulting in systematic cross-linguistic differences. This suggestion is well supported by **Laubrock & Hohenstein**, who demonstrate differential parafoveal preview benefit effects (Rayner 1975) in various European languages and in Chinese. *All this should outline a shift in the agenda of reading research towards a developmental approach, focusing on how the information that readers pick up from their linguistic environment in general, and from their writing system in particular, shapes and determines visual analysis and orthographic processing characteristics, as reading proficiency increases.*

R4. The characteristics of reading universals

A major claim of the target article was that cross-linguistic empirical research should reveal common cognitive operations involved in processing printed information across writing systems. These I labeled *reading universals*, and the term incurred a variety of responses. Given the very strong opinions regarding Chomsky's theory of *universal grammar* (UG) (e.g., **Grainger & Hannagan**, and see Evans & Levinson 2009), the mere use of the word "universal" in the realm of psychology and language seems to involve significant risk, as well as possible misinterpretations. A preliminary discussion of the basic differences between "reading universals" and UG is, therefore, required.

Since writing systems are a code designed by humans to represent their language, in contrast to the notion of UG (e.g., Chomsky 1965; 1995; 2006), reading universals are *not* innate or modular linguistic computational abilities that mirror the common structure of natural languages. *Rather, they are general cognitive mechanisms designed to process the characteristic information provided by the code we call "orthography."* In this respect, both **Levy** and **Behme** overextend the concept of "reading universals," attaching to it incorrect and unnecessary Chomskyan associations. Similarly, **Coltheart & Crain** draw a parallel between Chomsky's linguistic universals (e.g., recursivity, structure-dependence, etc.) and reading universals, asking whether there is something common to all writing systems in the same sense as the allegedly common internal structure of natural languages, and whether there is something common in processing them. **Share** draws identical parallels.

Reading universals are labeled so because they mirror the universality constraint, which requires models of reading to entertain *high-level principles that simultaneously provide a systematic explanation for cross-linguistic similarities in processing printed words, on the one hand, and cross-linguistic differences, on the other*. Thus, a good theory of reading should explain why readers of different writing systems consistently display similar behaviors in a given experimental setting, and also why they consistently display different behaviors in other experimental settings. This explanation should be based on few high-level, basic, and general mechanisms that characterize the cognitive behavior of reading, given what writing systems are meant to convey. It is up to us scientists to reveal these mechanisms, and once we have revealed them, they should be part of our models.

This approach indeed suggests that there are common invariant cognitive operations involved in processing printed information across writing systems, which are not too general or trivial. **Coltheart & Crain** as well as **Behme** are right, however, in suggesting that this claim is not self-evident and requires convincing argumentation. The claim for "common operations" in reading rests then on two tiers. The first argues that there is something common to the type of information provided by writing systems and the way this information is conveyed in print. Writing systems with all of their variety, therefore, constitute an environment with specific characteristics. The second argues that human cognition is characterized by general procedures for picking up statistical information from the environment, and that processing printed information draws upon these general procedures.

R4.1. The evolution of writing systems

The discussion of the evolution of writing systems and the description of Chinese, Japanese, Finnish, English, and

Hebrew sets the grounds for the first tier. I agree with **Behme** that the evolution of writing systems should not be regarded as entirely deterministic in the sense that their final characteristics could not have been otherwise. **Norris & Kinoshita** provide arguments along the same lines, so do **Beveridge & Bak**, and so does **Share**. Clearly, some arbitrary historical events may have tilted the evolution of a given writing system this way or the other. However, as a general argument, historical events and cultural influences could not have resulted in just *any* arbitrary change in writing systems, because the structure of the language constrains and determines the array and direction of possible changes. Our theory of reading should draw upon the logic of these constraints. Considering, for example, Serbo-Croatian, if in the nineteenth century, Vuk Karadzic, a Serbian philologist and linguist, would not have reformed the Serbian alphabet to be entirely phonetic, perhaps the writing system of Serbo-Croatian would not have been as transparent as it is today. However, the point to be made in this context is that the reform of the Serbian-Cyrillic writing system was initiated and made possible given the phonological and morphological characteristics of that language.

Seidenberg (2011) has labeled this state of affairs "grapholinguistic equilibrium," but in the sense of a *functional* equilibrium of effort. By his view, languages with complex inflectional morphology move towards shallow orthographies because of constraints regarding the amount of complexity they can impose on their speakers. Whether this specific functional hypothesis is true or not, the trade-off of inflectional morphology and orthographic depth is but one example of equilibrium, of a trade-off found in writing systems. The tendency of shallow orthographies to allow for extensive compounding in order to pack in more orthographic information is yet another form of equilibrium, related to the trade-off between the transparency of phonological computation and orthographic complexity. The tendency of deep orthographies, such as Hebrew, to reduce phonological and thereby orthographic information in order to make morphological (root) information more salient, is another example of a trade-off. The "equilibrium" phenomenon, therefore, is much more complex than that noted by Seidenberg, and does not necessarily emerge from his suggested functionalist argumentation.

R4.2. The theoretical significance of optimality considerations

Several commentaries (**Behme**, **Perfetti**, **Levy**, **Norris & Kinoshita**, **Seidenberg**, and **Share**) discuss the claim that orthographies *optimally* represent the language, focusing on criteria of optimality, arguing that my claim for optimality is unwarranted for a variety of reasons. As explicated earlier, writing systems are an invention, a *code*, created to represent the spoken language and its morphological structure. The evolution of this code, like any invented code, is naturally shaped by efficiency constraints, as most forms of communication are. However, in contrast to the evolution of species, such shaping does not require thousands of years to develop, as Norris & Kinoshita seem to suggest. The introduction of vowel marks in Hebrew, and their subsequent natural omission, given changes in the linguistic environment of Hebrew speakers, is a typical example of this relatively fast process of natural evolution.

Phonological transparency at the expense of morphological saliency was introduced into the Hebrew writing system when the language ceased to be spoken by any one Jewish community, given historical events; morphological saliency at the expense of phonological transparency naturally evolved when the Hebrew language became widely spoken again, and in a relatively short period of time. Inefficient communication forms tend to vanish, to be replaced by more efficient ones, even without the intervention of an enlightened monarch, as Perfetti suggests.

I have to agree, however, with **Perfetti** and **Behme** that a strong claim regarding optimality requires a definition of an optimization algorithm. I also have to agree that writing systems are not analog to self-correcting networks, since historical events and cultural influences naturally come into play to shape their forms. **Seidenberg** makes a similar claim. In this context, the evidence provided by **Hyönä & Bertram** regarding the impact of compounding in Finnish is in line with the view that writing systems could be perhaps sub-optimal rather than optimal. Following the work of Bertram et al. (2011), Hyönä & Bertram make the case that hyphens introduced into three-constituent compounds at morphemic boundaries facilitate recognition, demonstrating that some price is incurred in excessive packing of orthographic information, thereby casting doubt on the idea of the optimal efficiency of Finnish.

These are convincing arguments, and I agree that it is indeed difficult, if not impossible, to assess whether the current form of a writing system is "fully optimal," or just "good enough." *However, for the purpose of the logic and theoretical stand advocated here, this is not a critical distinction.* I would be happy to concede that writing systems evolve and adapt to provide a representation of phonology and morphology that is just good enough or sub-optimal rather than mathematically optimal, whatever mathematically optimal means in this context. *The heart of the argument is that there are common principles that govern the direction and rules of this adaptation and evolution, and the main claim is that our theory of how the orthographic written code is processed must consider what exactly renders a writing system efficient for a specific linguistic environment.* So, yes, the statement that "languages get the writing systems they deserve" (Halliday 1977)[2] still stands, even though one could provide an argument why a specific language perhaps deserves a writing system that is even better than the one it currently has.

R4.3. Common cognitive operations underlying reading universals

As I have outlined, the claim for common operations in reading rests also on the assertion that there are typical procedures for picking up information in the environment of printed languages. Some commentaries voiced skepticism regarding the possibility of converging on such common operations. Similar to **Coltheart & Crain**, who question the likelihood of outlining linguistic features that are common to all writing systems, **Plaut** argues that if there are common operations in processing all writing systems, they would be too general to be informative. Reiterating Plaut's well-articulated Wittgensteinian analogy on the concept of "game," the expected commonalities in processing print across languages, according to Plaut, would be as

instructive for understanding reading as would be the theoretical commonalities of all sporting games for understanding soccer. However, in contrast to *Philosophical Investigations* (Wittgenstein 1953), this is an empirical question, not a philosophical one. Unlike sporting games, writing systems have a well-defined common goal – to convey meaning – and they do so by common and relatively simple principles, which are tuned to human cognitive abilities. Note that the position of the new age of orthographic processing was that letter-position flexibility *is* a commonality in processing print across writing systems. This view has been challenged by empirical evidence. Similarly, future cross-linguistic research would have to assemble evidence for alternative commonalities.

Admittedly, this task is not trivial. For example, **McBride-Chang et al.** raise a well-argued concern regarding the plausibility of finding common processing principles across orthographies, given the inherent inconsistency in defining word boundaries across writing systems. Analyzing Chinese, Thai, and Finnish, they show that the definition of a "word" unit is far from being unequivocal, and this ambiguity would make it impossible to offer universal parsing principles across writing systems. McBride-Chang et al. thus convincingly show that implemented solutions for producing in a model a behavior that fits the data for one language may not do the work in another language. Reading universals, however, are not common parsing routines. They are principles of efficiency in picking up semantic, morphological, and phonological information from the orthographic structure whatever it is, given the statistical properties of the language.

In concatenated morphological systems such as those of European languages, for example, processing involves decomposing affixes, and the target of search is the base form (e.g., Rastle & Davis 2008; Rastle et al. 2004; Taft & Nillsen, in press). What drives this process is the saliency of affixes, given their high distributional properties, and their predetermined location at the beginning or the end of the word. In Semitic languages, the game is quite different. The target of search is a noncontiguous root morpheme with its letter constituents distributed across the word without a predetermined location. Here, readers are tuned to the conditional probabilities of letters, which are determined by the distributional properties of word patterns. What is *different*, then, is the parsing procedure and the definition of units for lexical access (base forms vs. roots). However, *what is common* is *the principle of picking up the specific statistical properties of the language from print, zooming in on those sublinguistic units which are best correlated with meaning*. By this view, both rapid affix-stripping in European languages and root extraction in Semitic languages reflect a reading universal – the priority of locating and extracting units of morphological information in the distal stimulus. **McBride-Chang et al.** thus convincingly show that structured models would have immense difficulties in satisfying the universality constraint, whereas learning models are better fit for the task.

The efficiency of writing systems is determined, on the one hand, by the nature of the information that has to be transmitted (the language's phonological space, its morphological structure, and the way it conveys meaning), and by the characteristics of the cognitive system that has to pick this up, on the other. Reading universals are then related to both. Thus, to answer **Coltheart & Crain** as well as

Plaut, the claims – that the recovery of morphological information takes precedence in encoding orthographic structure; that letter processing is not determined just by letter position but mostly by the informational properties that individual letters carry; that orthographic coding *simultaneously* considers phonological, morphological, and semantic information; that the transitional probabilities of individual letters serve as critical cues for processing letter sequences; that eye-movement measures during reading such as length of fixation and landing position are modulated by such cues – *are all potential reading universals, and when validated, they should be part of our theory of reading and the models it produces*. **Liversedge et al.**, for example, present compelling arguments regarding universal stylized patterns of saccades during reading that are cross-culturally uniform. Since these saccade patterns determine how orthographic information is delivered to the language- processing system, Liversedge et al. rightly suggest that the regularities of eye movements could be considered as universal characteristics that should constrain a theory of reading (see also **Pelli et al.**). *This analysis brings us yet again to the understanding that cross-linguistic research in reading is a main source of constraints to modeling visual word recognition.* This claim is at the heart of the present approach.

R4.4. Reading universals and statistical learning

Considering the common cognitive operations for picking up the information packed into the orthography, the perspective I advocate then stands in sharp contrast to Chomsky's UG, because these cognitive operations are by no means modular abilities exclusive to the faculty of language. They reflect general learning mechanisms related to sensitivity to correlations in the environment, on the one hand, and the specific medium of writing systems – graphemes representing meaning and phonology – on the other. The claim that languages are characterized by idiosyncratic statistical regularities which encompass all of the word's dimensions (orthographic, phonological, and morphological structure) is hardly controversial. Similarly, it is well established that the cognitive system is a correlation-seeking device, and that adults, children, and even newborns can pick up subtle statistics from the environment (e.g., Evans et al. 2009; Gebhart et al. 2009; Gomez 2007). As convincingly argued by Winkler et al. (2009), predictive processing of information is a necessary feature of goal-directed behavior, whether language related or not, and thus brain representations of statistical regularities in the environment determine primary perceptual processes in the visual and auditory modalities. Hence, the appreciation that the processing of printed information is mainly governed by the statistical properties of writing systems is supported by studies from a variety of languages.

McBride-Chang et al. provide a nice example from Thai, where there are no spaces between words, and so eye movements to the optimal viewing position (OVP) are directed by the distributional properties of initial and final graphemes (e.g., Kasisopa et al. 2010). Additional arguments along this line are suggested by **Szwed et al.** and **Pitchford et al.**, and in fact, the notion of perceptual learning argued above is fully contingent on how the statistical properties of the environment train the perceptual system to process information efficiently. By this view,

language is considered an example of a very rich environment characterized by complex correlations and distributional properties to which the cognitive system is tuned. This stand is not the one advocated by the Chomskyan approach. *Our research should focus on understanding and mapping the statistical cues that determine orthographic processing in visual word recognition, such as flexibility or rigidity of letter position, as well as other benchmark effects of reading.* These cues would enable us to explore and test hypotheses regarding the architecture of our models.

R5. The scope of cross-linguistic research

Insights regarding the common operations involved in reading can be reached only by observing systematic differences across languages. Observing these differences through empirical research leads to higher-level theoretical constructs which provide a unified explanation as to why language X brings about behavior A and language Y brings about behavior B. This is the essence of reading universals. Once this approach to reading research is adopted, it becomes evident that the progress in formulating a universal theory of reading would benefit from evidence from a wide variety of languages. Note that this stand does not mean that visual word recognition should become a branch of structural linguistics. Rather, in the present context, examining different writing systems would be considered a clever experimental manipulation employed to test hypotheses regarding what determines reading behavior in a given linguistic environment.

A good example is provided by **Friedmann & Gvion**. By comparing TL effects in Hebrew and Arabic, they point to an important interaction of morphological and orthographic structure. Hebrew and Arabic are both Semitic languages with very similar morphological systems. However, among other things, they differ in that Arabic has a different form for some letters in the initial, middle, and final position, whereas Hebrew only has a few letters which are written differently when in final position.[3] Friedmann & Gvion elegantly demonstrate how letter-position errors in Arabic are constrained by this unique orthographic feature, in which readers learn complex interactions of letter identity by shape, that is dependent on position (Friedmann & Haddad-Hanna, in press a). Another example is provided by **Kim, Lee, & Lee** (**Kim et al.**), who review letter-transposition effects in Korean (e.g., Lee & Taft 2009; 2011). These studies took advantage of the special features of Hangul, mainly, that it demarcates space-wise between onset and coda positions for each consonant. By using this unique feature of Korean, Kim et al. convincingly argue that subsyllabic structure modulates letter-position coding, suggesting that modeling letter position requires a level of description that takes into account this constraint. In the same vein, **Rao, Soni, & Chatterjee Singh** (**Rao et al.**) provide evidence from the alphasyllabic Devanagari, showing how morphological complexity modulates orthographic processing.

Just as the Anglocentricity of reading research (Share 2008a) resulted in an overemphasis of the role of phonological awareness in reading, European "alphabetism," as **Share** calls it, resulted in an overemphasis on letter-position flexibility. **Beveridge & Bak** provide, in this context, important statistics regarding the extremely biased ratio of research articles on disorders of written language describing Indo-European languages versus other languages. This has implications for understanding (or perhaps misunderstanding) not only reading, but also aphasia, alexia, or agraphia. As Beveridge & Bak point out, the manner by which phonology and morphology interact to determine orthographic structure becomes transparent only by considering a wide variety of languages, so that the possible contribution of culture to this evolution can be assessed. Share brings into the discussion examples of other less researched languages.

This leads our discussion to the question of the range of data that should serve as the basis for our models. Models or theories of reading are constrained by benchmark effects. What makes an emergent effect "a benchmark effect" is its generalizability across experimental settings. Writing systems consist of such "experimental settings" no less than any clever within-language manipulation, since important variables such as phonological transparency, morphological saliency, and so forth, are systematically held constant. Hence, data reported from different writing systems must be part of any hypothesized computational reading mechanisms. Whether this approach will indeed result in a universal computational model of reading, remains to be seen. Some commentaries expressed optimism, whereas others expressed pessimism. What seems to be uncontested is the merit of this approach for understanding the common cognitive or computational principles that govern reading behavior, as well as the inadequacy of modeling approaches which are based on one homogeneous linguistic system.

R6. A developmental approach to orthographic processing

A caveat with most current structured models of reading is that the benchmark effects they describe focus solely on the behavior of proficient readers. Hence, these models are *end-state models*. They are set and built to reproduce end-state behaviors. The disadvantage of this approach is that it considers where the reader is in terms of his/her behavior without considering how he/she got there. However, for our theory of reading to have sufficient explanatory adequacy – that is, to provide "why" answers – it must consider the data describing how behavior emerges and how it is learned. Insights can be gained mainly by focusing on the *trajectory* that connects a beginning state to an end-state. This trajectory provides us with critical data regarding *what it is exactly that the reader learns to pick up from the orthography*. This information should tell us something interesting about the mechanisms underlying orthographic processing. The "why" answers are hidden there. This is well explicated by **Rueckl**, who describes the merits of learning models. As Rueckl argues, a developmental learning perspective has the significant advantage of *explaining* the organization of the reading system rather than just stipulating it, as structured models do.

Goswami's review of developmental evidence regarding spelling acquisition in English provides illuminating examples supporting this approach. Goswami points to a large set of patterns of spelling errors by school children, demonstrating how the phonological space of English and

its morphological structure are reflected in spelling errors, and in the developmental trajectory of learning correct spelling. The many examples provided by Goswami demonstrate how developmental data of the print production of beginning readers lead to important insights regarding print processing in proficient readers, thereby demonstrating how the linguistic environment of English leads to an idiosyncratic language-specific strategy of orthographic processing. The same approach is echoed in **Deacon**'s commentary, where she focuses on how reading experience shapes orthographic processing cross-linguistically, considering data from a variety of languages, such as English, Hebrew, Chinese, and Korean. This set of data brings Deacon to the same conclusion – a universal model of reading must involve a developmental perspective. A developmental approach is also the main message of **Perea & Carreiras**, who discuss a series of findings concerning brain plasticity as well as behavioral evidence, all demonstrating how letter-position flexibility develops with reading experience in European languages.

This has straightforward implications: To model the reader's end-state of orthographic processing, one should consider the information that has been picked up in the long process of literacy acquisition in a given linguistic environment. Each language presents to the reader a writing system that is characterized by a wide distribution of correlations. Some correlations determine the possible co-occurrences of letter sequences, which eventually result in establishing orthographic representations. Each writing system is also characterized by idiosyncratic correlations in the mapping of graphemes to phonemes, and these consistent correlations eventually result in mapping orthographic representations to phonological ones. In addition, writing systems are characterized by systematic correlations, where letter clusters consistently convey features of semantic meaning, which reflect morphological structure.

Ravid's commentary resonates very well with this triangular view. Like **Goswami**, Ravid reviews evidence from spelling rather than reading, and her spelling model is based on similar argumentation (see also Ravid [2012] for a detailed discussion). In languages where morphological variations often result in phonological variations, learning to spell cannot rely on simple mapping of phonology to orthography, but has to draw on a triangular system where phonological, morphological, and orthographic sublinguistic units are inter-correlated. In the process of learning to spell, what is acquired is a network of phono-morpho-orthographic statistical patterns, which are shaped by the idiosyncratic specificities of the language. This approach suggests that each language implicates a differential tuning to statistical structure, given the language's idiosyncratic linguistic characteristics. By this view, native speakers who are proficient readers implicitly develop differential sensitivities to the statistical properties of their own language in the long process of literacy acquisition. Effects of letter transposition, as **Perea & Carreiras** demonstrate, indeed change with reading proficiency in European languages, but, just as well, they do not evolve in the same way in Semitic languages because of differences in how phonology, morphology, and orthography are interrelated.

All of these arguments lead to the suggestion that to model the end-state behavior of readers, one should have a clear theory of what has been learned by readers and how their linguistic environment has shaped their processing system to extract specific cues from the graphemic array. *A model of orthographic processing, therefore, should be sensitive to the idiosyncratic developmental trajectory that characterizes readers in a given writing system, and, consequently, the model should be constrained by cross-linguistic developmental data.*

R7. Descriptive adequacy of current implementations

As expected, some of the commentaries addressed my general critique of current models of visual word recognition, arguing for the descriptive adequacy of a given model or approach. Since, from the onset, the aim of the target article was not to offer an alternative implementation, but to discuss the general approach to modeling, the following discussion does not go into the architectural details of any specific model, but rather centers on its main working hypotheses and its descriptive adequacy.

Bowers presents a well-argued case for position invariance and for context-independent processing in letter identification. However, he correctly concedes that the challenge is indeed to develop a model in which positional uncertainty varies as a function of the linguistic environment. Note that, to some extent, **Norris & Kinoshita**'s commentary has a similar flavor, arguing that primary perceptual processing is universally noisy, but then the processing demands of different languages shape the noisy product to produce the cross-linguistic differences in letter-position flexibility. However, even if positional invariance identification is universal, *the main constraint on any theory of reading is the combination of this invariance with language-specific processing demands*. Thus, the architecture of any universal model of reading should be tuned to the linguistic factors that determine actual flexibility or rigidity regarding letter position, along with positional invariance.

Considering the SERIOL model and the open-bigram approach, the question then is not whether they can produce results for Hebrew root-derived words as **Whitney** suggests. Open bigrams are perhaps well suited for Hebrew words because they encode the order of noncontiguous letters, and root letters are indeed non-contiguous. The critical question is whether the SERIOL model (Whitney 2001; Whitney & Cornelissen 2008), *inherently* produces differential flexibility and rigidity depending on the internal structure of words (Velan & Frost 2011). I agree with **Bowers** that the answer seems negative, given the nature of open bigrams. The solution that Whitney offers to overcome this problem and salvage her modeling approach is to insert inhibitory and excitatory connections with varying strength between bigrams and morphological units. This type of solution is rightly labeled by **Rueckl** as *reverse engineering*. The body of evidence regarding the processing of Hebrew root-derived words is identified, a lexical architecture and computational mechanism are then posited, they are evaluated in terms of their ability to generate the desired behavior, and finally they gain the status of theoretical explanations. Rueckl's commentary outlines very convincingly the dangers of this approach for understanding any complex phenomenon, and reading is no exception. His criticism then is right on target.

R7.1. Cracking the orthographic code

Both **Bowers** and **Davis** discuss the spatial coding model. All of the arguments provided by Davis and by Bowers regarding the need to solve the alignment problem are well taken. A theory of reading in alphabetic orthographies indeed has to furnish an adequate description regarding the commonality in processing (*build* and *rebuild*, for example), while the identification of letters cannot be bound to a specific position. My article, however, asserts that this is not the only phenomenon that has to be described and explained by the theory. The question is, then, whether a principled solution can be offered to account for data from different writing systems, and, if so, what are the blueprints for finding such a solution. On this issue, there seems to be a clear divergence between the approach I advocate here and the one suggested by Davis.

The main thrust of **Davis**'s commentary is that for skilled readers, printed words are identified on the basis of orthographic information, and once words have been identified via their constituent letters, phonological and semantic information *subsequently* follows. This view of *temporal* modularity indeed leads to the conclusion that one has to first "crack the orthographic code," as Davis suggests. Note that in the present context, temporal modularity (Andrews 2006) is not a pragmatic strategy for developing models (see **Grainger & Hannagan**). Rather, it reflects a theoretical stand regarding reading, and therefore merits careful scrutiny. What underlies Davis's approach is the assumption that orthographic processing is determined solely by the set of individual letters that carry little linguistic information. This is perhaps the case for some languages such as English, but it is *not* a universal feature of orthographic systems. The main thrust of the present response article is that phonological, semantic, and morphological characteristics penetrate *early* orthographic processing to determine its outcome. Hence, in contrast to Davis's approach, semantic or phonological features are not the *product* of orthographic processing, but are componential factors that often determine its outcome. The distributional characteristics of individual Hebrew letters, for example, are correlated with the semantic meaning the letters carry, and therefore control on-line eye movements and early perceptual processes. Similarly, **Kim et al.** demonstrate how the linguistic characteristics of individual letters in Korean (the ambiguity in their assignment to onset, vowel, or coda slots) affect orthographic processing and consequently affect letter transposition. A universal model of reading, therefore, cannot assume that a similar orthographic code is cracked across writing systems and then serves as the basis for subsequent phonological and semantic activation.

Bowers suggests that the spatial coding scheme offered by Davis (2010) can in principle accommodate the range of TL effects across languages when parameters of position uncertainty are set to zero. However, again, setting the parameters of a model to a given value to accommodate desired results would inevitably lead us into the reverse-engineering trap described by **Rueckl**. The question at hand is whether a model of orthographic processing learns to simultaneously produce TL priming for European words, inhibition rather than facilitation for Hebrew-like words (e.g., Velan & Frost 2011), then again TL priming for Hebrew morphologically simple words. Contra **Davis**, I am not confident that

simple orthographic neighborhood density considerations would suffice. As Bowers notes, additional constraints need to be added to the spatial coding model to produce and simulate reading in Semitic languages, and only time will tell whether it will emerge as a viable universal model of reading. Similarly, once the benchmark effects to assess the descriptive adequacy of a model include the differential sensitivity to letter position in different orthographies, given the internal structure of words, the promise of string kernel modeling, as suggested by **Grainger & Hannagan**, can be evaluated.

R7.2. The promise of learning models

This steers our discussion toward the clear advantage of learning models in the search for a universal model of reading. I agree with **Perea & Carreiras** that hardwired-structured models have the advantage of being simple models. However, whether they indeed advance us in understanding what must be learnt by the reader, as **Davis** suggests, is not at all evident. One could argue that it is actually the other way around. A hardwired model that does not stem from a comprehensive and general theory of reading *is often structured to mimic the modeler's intuition about the source of end-state behaviors of proficient readers*. Thus, instead of telling us something about what readers actually learn, the model reveals the *modeler's* emerging solution to computationally produce the reader's observed end-state behavior. When this solution is then presented as a behavioral explanation, we end up with the reverse-engineering pitfall of structured models as described by **Rueckl**.

If the main source of constraints for our theory of reading is the learning trajectory of readers in various linguistic environments, then obviously learning models have a much higher probability to advance our understanding of what is actually learnt by readers in a given writing system. Recent work by Baayen (under review) provides a good example. Using the framework of naïve discriminative learning (Baayen et al., 2011), Baayen (under review) compared the sensitivity to letter order and the costs of letter transposition in English versus biblical Hebrew, when strings of letters in the two languages (text taken from the book of Genesis, or random selection of words from the database of phrases from the British National Corpus) were aligned with their meanings. Baayen demonstrated that pairs of contiguous letters (which capture order information in naïve discriminative learning) had a much greater functional load than single letters in Hebrew relative to English, thereby confirming the greater sensitivity to letter order in Semitic languages. Moreover, the simulations revealed that the model captured the differential statistical properties of the two languages, resulting in much greater TL disruption in biblical Hebrew when compared with English.

The results of recent preliminary computational work done in our lab (Lerner & Frost, in preparation) are consistent with Baayen's results. We have shown that in a simple three-layer neural network, trained with the classical back-propagation algorithm to match orthographic information of Hebrew and English words to their meaning (as represented by COAL [correlated occurrence analogue to lexical semantic] vectors containing co-occurrence

measures), TL words lead to a smaller activation of the output layer, where meaning is stored, compared to their corresponding real words; but this difference was by far greater for Hebrew than for English. Thus, our results echo Baayen's findings using naïve discriminator learning. Unlike Baayen et al., we did not define any a priori restrictions on the representation of serial order (i.e., no specific bigram representations were hardwired to the input), and our network could use the order information in whatever way required by the algorithm to accomplish the learning phase. Therefore, our simple model emphasizes how the difference between the TL effects of Hebrew and English could be entirely dependent on the different statistical properties of Hebrew and English orthography. These preliminary results demonstrate that the differential effects of letter transposition indeed arise from the different distributional statistics of Hebrew and English. More relevant to the present discussion, they show the promise of learning models in teaching us something important about how the linguistic environment shapes different reading behaviors.

R8. The universal model of reading and the Strong Phonological Theory (SPT)

Rastle raises an important point: the implications of the present theoretical approach for previous claims regarding the *strong phonological theory* (SPT) (Frost 1998). The main driving argument of the SPT is that all human languages are meant to convey meaning by *spoken* words, and therefore the core of words' lexical representation is phonological. By this view, the connection between spoken words and semantic meaning is the primary association formed in the process of language acquisition. The main claim behind the SPT is that phonology is *always* implicated in visual word recognition and mediates the recovery of meaning from print. Note that in the context of reading universals, Perfetti (2011) has convincingly argued for a universal role of phonology in reading in any orthography. However, if writing systems aim to provide morphological information at the expense of phonological information, as I argue here, what then is the role of phonological representations in word recognition?

The theoretical construct that bridges the gap between the SPT and the present framework is the minimality constraint on lexical access assumed in the SPT (Frost 1998, p. 79), and the impoverished and underspecified character of phonological representations for lexical access (pp. 80–81). The SPT claims that the initial contact with the lexicon *is assumed to occur through an interface of phonological access representation that is relatively impoverished or underspecified*. This is characteristic mainly of deep orthographies in which morphological variations are characterized by phonological variations as in the case of "heal" and "health." Thus, according to the theory, the computation of phonology in deep orthographies, such as English or Hebrew, results in a non-detailed phonological representation in which vowel information is missing or underspecified. To reiterate, the precedence of morphology over phonological information does not mean that morphological information is provided *instead* of phonological information, or that meaning is computed without any reference to phonology. Rather, morphological considerations dictate that the computed phonological

information remains underspecified in the initial phase of lexical access. In a sense, what we have here is a morpho-phonological equilibrium.

R8.1. Morpho-phonological variations and phonological underspecification

Hebrew again can be taken as a good example. What I have shown so far is that orthographic processing of letter sequences in Hebrew aims at extracting the letters that provide highest diagnosticity in terms of *meaning*, that is, the letters belonging to the root. This was the basis for my claim that morphology and therefore semantics must be part of any universal model of reading, since morphology takes precedence over phonology in the evolution of writing systems. However, the core representation of roots in Hebrew is necessarily phonological, because native speakers acquire them by exposure to the spoken language. As more and more words with the same word pattern are perceived by the speaker of the language, their repetitive phonological structure is acquired, and the salience of the three consonants of the root emerges. Speakers of Hebrew, therefore, have a *phonological* representation of root consonants onto which orthographic representations map. The three phonemes of the root are one side of the coin, whereas the three corresponding consonant letters are the other side. The tri-literal entity is in fact a tri-consonantal entity. This observation was confirmed long ago by Bentin and Frost (1987). In this study, Bentin and Frost presented subjects with unpointed tri-literal consonantal strings (e.g., SFR) that could be read in more than one way by assigning different vowel configurations (e.g., *sefer/safar*). Bentin and Frost (1987) showed that lexical decision latencies for these heterophonic homographs were faster than latencies for any of the disambiguated pointed alternatives. These findings suggested that lexical access was based on the impoverished and underspecified representation shared by the different phonological alternatives (see also Frost 2003; Frost & Yogev 2001; Frost et al. 2003; Gronau & Frost 1997).

To summarize this point, the present theoretical framework is in line with the claim that phonological representations are the core mediating lexical representations of words. However, it extends this framework significantly to incorporate morphology into the approach, with a predictable morphology–phonology trade-off. This trade-off determines a priori in which writing systems mediating phonological representations would be fully specified, and in which they would be underspecified. The main theoretical claims advocated in the SPT of visual word recognition are therefore maintained in the present framework. However, the role of morphological structure, the intimate link between orthographic structure and the way phonological space represents meaning, and the consideration of orthographic structure as an equitable weighting of phonological and morphological information, are important expansions of the original SPT.

R9. Summary and future directions

As expected, the present large number of commentaries necessarily brings about a variety of opinions flashing out

disagreements, so that some fencing regarding theoretical stands is inevitable. Nevertheless, there is a surprising convergence of views on several key issues that enables the tracing of constructive directions for future reading research. Let me then summarize these issues:

1. Overall, most commentaries agreed one way or the other with the main claim of the target article, that orthographic representations are the product (whether optimal or just satisfactory) of the *full* linguistic environment of the reader, and that the modeling of orthographic processing requires considering the phonological space of the language and the way it conveys meaning through morphological structure.

2. There is a wide consensus that cross-linguistic research should serve as a primary constraint for a theory or a model of visual word recognition.

3. Quite a few commentaries suggested that an adequate theory of proficient reading has to be an acquisition theory that focuses on what readers pick up and learn from their linguistic environment. Modeling end-state behavior of readers without considering constraints of developmental data is often incomplete.

4. A significant number of commentaries, whether explicitly or implicitly, referred to the theoretical importance of understanding the underlying statistical properties embedded in a writing system for comprehending how it modulates eye movement or governs orthographic processing, either in isolated word recognition or in sentence reading. These statistical relations go far beyond bigram or trigram frequency or orthographic neighborhood density, as they concern the ortho-phono-morphological correlations of sublinguistic units.

These points of relative consensus should lead us to the appreciation that *any front-end implementation should be primarily constrained by what we know about the hidden cues packed into the orthography of a given writing system*. As I have argued, the mapping and understanding of these cues are questions of empirical investigation, whether through the assembly of comparative brain evidence, or comparative developmental and behavioral data. Once the scope of these cues across writing systems is mapped and understood, a universal theory that focuses on the fundamental phenomena of reading can be formulated. This approach outlines a series of research questions that are by no means novel, but gain perhaps greater saliency in the current framework. **Rueckl** provides a series of important theoretical challenges for future reading research. In the following, I mention just two examples of research questions that resonate with these challenges, mainly for the sake of demonstration.

R9.1. Individual differences in statistical learning

Given the accumulating evidence tying statistical properties of writing systems to processing strategies in visual word recognition, one challenge of reading research is to provide a comprehensive theory that directly links cognitive statistical learning abilities with literacy acquisition. A main empirical question, then, concerns the possible dimensions underlying the human capacity to pick up correlations from the environment. Another question concerns the predictive value of this capacity in determining ease or difficulty in registering the subtle correlations that exist in a language between orthography, phonology, morphology, and

meaning, thereby affecting reading performance. Thus, if individuals vary in their sensitivity to statistical information, these differences could potentially have consequences for the speed of reading acquisition, the organization of the reading system, the ability to learn the statistical properties of another language, and for efficiently processing orthographic information in a second language. Indeed, considerable work along these lines has already been conducted (e.g., Ahissar 2007; Banai & Ahissar 2009; Misyak & Christiansen 2012; Pacton et al. 2001). Expanding the scope of this research to include evidence from different writing systems could provide novel insight.

R9.2. Multilingualism and visual word recognition

Learning how to read in more than one language requires extensive plasticity when contrastive structural properties of writing systems have to be assimilated. For example, Bialystok et al. (2005) have shown that the transfer of literacy skills is indeed easy when both languages have a similar writing system. However, if languages present to their readers very different structural properties, the question at hand is how the acquired knowledge of the structural properties of one's native language and the assimilation of its characteristic statistical regularities hinders or facilitates the learning of the structural properties of a second language and its implicit statistical attributes.

To exemplify, Semitic languages are characterized by morphemic units that are noncontiguous, where roots and word patterns are intertwined. Therefore, speakers and readers of Hebrew and Arabic must develop an enhanced sensitivity to non-adjacent statistics. However, subsequent exposure to European languages presents to these readers a different form of statistical dependencies, mainly adjacent dependencies. How does knowing the statistical properties of one's native language affect the assimilation of a different type of statistical regularity? Note that parallel questions have been raised from the perspective of the neural circuitry involved in language processing. For example, results of the work by Perfetti and colleagues (Liu et al. 2007; Perfetti et al. 2007; Tan et al. 2003) suggest two possible mechanisms for neuronal reorganization triggered by learning to read in a second language: assimilation and accommodation – *assimilation* in the sense that the neural circuitry must pick up the new set of linguistic regularities which are characteristic to the new language, and *accommodation* in the sense that the neural circuits involved in mapping orthography, phonology, and meaning must be modified in order to deal with the demands of reading in the new language, given its statistical structure. Thus, although the data presented so far clearly suggest that flexibility in orthographic processing characterizes the cognitive system, what requires further investigation are the rules that govern and constrain this flexibility, given exposure to multiple linguistic environments.

These two research questions are examples of potential directions that could lead towards a universal model of reading. As argued in several commentaries, the new age of orthographic processing has contributed to reading research important theoretical discussions regarding front-end computational solutions. These should be harnessed to provide an adequate theory of the interaction of the reader with his or her linguistic environment. This

approach is not only possible; it is also the only viable one for understanding reading.

NOTES
1. This theoretical approach is indeed argued by Marr (1982) with reference to the visual system.

2. One unexpected preoccupation with this statement concerned the question of who should get the credit for coining the catchy sentence "Every language gets the writing system it deserves." Admitting from the onset that it is not mine, I would happily concur with **Perfetti** that the credit should be given to Halliday (1977), rather than to Mattingly. I hope that other contenders to the title accept the verdict.

3. Note the TL priming experiments in Hebrew never used transposition of final letters.

References

[The letters "a" and "r" before author's initials stand for target article and response references, respectively]

Abu-Rabia, S. (1997) Verbal and working memory skills of bilingual Hebrew–English speaking children. *International Journal of Psycholinguistics* 13:25–40. [SHD]

Acha, J. & Perea, M. (2008) The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology* 99:245–64. [MP]

Acha, J. & Perea, M. (2010) Does kaniso activate CASINO? Input coding schemes and phonology in visual-word recognition. *Experimental Psychology* 57:245–51. [aRF]

Adelman, J. S., Marquis, S. J. & Sabatos-DeVito, M. G. (2011) Letters in words are read simultaneously, not in left-to-right sequence. *Psychological Science* 21:1799–801. [aRF]

Ahissar, M. (2007) Dyslexia and the anchoring-deficit hypothesis. *Trends in Cognitive Sciences* 11:458–65. [rRF]

Altarriba, J., Kambe, G., Pollatsek, A. & Rayner, K. (2001) Semantic codes are not used in integrating information across eye fixations in reading: Evidence from fluent Spanish–English bilinguals. *Perception and Psychophysics* 63:875–90. [JL]

Andrews, S. (1996) Lexical retrieval and selection processes: Effects of transposed-letter confusability. *Journal of Memory and Language* 35(6):775–800. [CJD, KK]

Andrews, S. (2006) All about words: A lexicalist perspective on reading. In: *From inkmarks to ideas: Current issues in lexical processing*, ed. S. Andrews, pp. 314–48. Psychology Press. [CJD, rRF]

Andrews, S. & Davis, C. J. (1999) Interactive activation accounts of morphological decomposition: Finding the trap in mousetrap? *Brain and Language* 68:355–61. [CJD]

Andrews, S. & Hersch, J. (2010) Lexical precision in skilled readers: Individual differences in masked neighbor priming. *Journal of Experimental Psychology: General* 139:299–318. [JGR]

Andrews, S. & Lo, S. (2012) Not all skilled readers have cracked the code: Individual differences in masked form priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 38:152–63. [MP]

Aram, D. & Levin, I. (2001) Mother–child joint writing in low SES: Sociocultural factors, maternal mediation, and emergent literacy. *Cognitive Development* 16:831–52. [CMcB-C]

Aram, D. & Levin, I. (2004) The role of maternal mediation of writing to kindergartners in promoting literacy in school: A longitudinal perspective. *Reading and Writing* 17:387–409. [CMcB-C]

Aroonmanakun, W. (2002) Collocation and Thai word segmentation. In: *Proceedings of the Fifth Symposium on Natural Language Processing and the Fifth Oriental COCOSDA (International Committee for the Coordination and Standardization of Speech Databases and Assessment Techniques) Workshop*, ed. T. Theeramunkong & V. Sornlertlamvanich, pp. 68–75. Sirindhorn International Institute of Technology. [CMcB-C]

Aroonmanakun, W. (2007) Thoughts on word and sentence segmentation in Thai. In: *Proceedings of the Seventh Symposium on Natural language Processing, Pattaya, Thailand, December 13–15, 2007*, ed. A. Kawtrakul & M. Zock, pp. 85–90. Kasetsart University. [CMcB-C]

Asfaha, Y. M., Kurvers, J. & Kroon, S. (2009) Grain size in script and teaching: Literacy acquisition in Ge'ez and Latin. *Applied Psycholinguistics* 30:709–24. [DLS]

Ashby, F. G., Prinzmetal, W., Ivry, R. & Maddox, W. T. (1996) A formal theory of feature binding in object perception. *Psychological Review* 103:165–92. [PG]

Baayen, R. H. (under review). Learning from the Bible: Computational modeling of the costs of letter transpositions and letter exchanges in reading Classical Hebrew and Modern English. [rRF]

Baayen, R. H., Milin, P., Durdevic, D. F., Hendrix, P. & Marelli, M. (2011) An amorphous model for morphological processing in visual comprehension based on naive discriminative learning. *Psychological Review* 118:428–81. [rRF]

Balota, D. A., Pollatsek, A. & Rayner, K. (1985) The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology* 17:364–90. [JL]

Banai, K. & Ahissar, M. (2009) Perceptual learning as a tool for boosting working memory among individuals with reading and learning disability. *Learning and Perception* 1:115–34. [rRF]

Barlow, H. B. (1956) Retinal noise and absolute threshold. *Journal of the Optical Society of America* 46:634–39. [MP]

Beckman, M. E. & Edwards, J. (2000) The ontogeny of phonological categories and the primacy of lexical learning in linguistic development. *Child Development* 71:240–49. [DR]

Bendor-Samuel, J. (1996) African languages. In: *The world's writing systems*, ed. P. T. Daniels & W. Bright, pp. 689–91. Oxford University Press. [DLS]

Bentin, S. & Frost, R. (1987) Processing lexical ambiguity and visual word recognition in a deep orthography. *Memory and Cognition* 15:13–23. [arRF]

Bentin, S., Hammer, R. & Cahan, S. (1991) The effects of aging and first grade schooling on the development of phonological awareness. *American Psychological Science* 2:271–74. [aRF]

Berman, R. (1986) The acquisition of morphology/syntax: A crosslinguistic perspective. In: *Language acquisition*, 2nd edition, ed. P. Fletcher & M. Garman, pp. 429–77. Cambridge University Press. [DR]

Bertelson, P., Morais, J., Alegria, J. & Content, A. (1985) Phonetic analysis capacity and learning to read. *Nature* 313:73–74. [aRF]

Bertram, R. & Hyönä, J. (2003) The length of a complex word modifies the role of morphological structure: Evidence from reading short and long Finnish compounds. *Journal of Memory and Language* 48:615–34. [aRF]

Bertram, R., Kuperman, V., Baayen, R. H. & Hyönä, J. (2011) The hyphen as a segmentation cue in triconstituent compound processing: It's getting better all the time. *Scandinavian Journal of Psychology* 52:530–44. [rRF, JH]

Bertram, R., Pollatsek, A. & Hyönä, J. (2004) Morphological parsing and the use of segmentation cues in reading Finnish compounds. *Journal of Memory and Language* 51:325–45. [JH]

Berwick, R. & Chomsky, N. (2010) The biolinguistic program: The current state of its evolution and development. In: *Biolinguistic investigations*, ed. A. M. Di Sciullo & C. Aguero, pp. 19–42. MIT Press. [CB]

Beveridge, M. E. L. & Bak, T. H. (2011) The languages of aphasia research: Bias and diversity. *Aphasiology* 25(12):1451–68. [MELB]

Bialek, W., Nemenman, I. & Tishby, N. (2001) Predictability, complexity, and learning. *Neural Computation* 13:2409–63. [aRF]

Bialystok, E., Luk, G. & Kwan, E. (2005) Bilingualism, biliteracy, and learning to read: Interaction among languages and writing systems. *Scientific Studies of Reading* 9:43–61. [rRF]

Binder, J. R., Medler, D. A., Westbury, C. F., Liebenthal, E. & Buchanan, L. (2006) Tuning of the human left fusiform gyrus to sublexical orthographic structure. *NeuroImage* 33(2):739–48. [MS]

Blanchard, D., Heinz, J. & Golinkoff, R. (2010) Modeling the contribution of phonotactic cues to the problem of word segmentation. *Journal of Child Language* 37:487–511. [CB]

Blythe, H. I., Johnson, R., Tbaily, L. W., Liversedge, S. P. & Rayner, K. (under review) Reading transposed text: Effects of transposed letter distance and consonant–vowel status on eye movements. *Journal of Experimental Psychology: Human Perception and Performance*. [SPL]

Boeckx, C. (2010) Some reflections on Darwin's Problem in the context of Cartesian biolinguistics. In: *The biolinguistic enterprise: New perspectives on the evolution and nature of the human language faculty*, ed. A. M. Di Sciullo & C. Boeckx, pp. 42–64. Oxford University Press. [CB]

Bolger, D. J., Perfetti, C. A. & Schneider, W. (2005) A cross-cultural effect on the brain revisited: Universal structures plus writing system variation. *Journal of Human Brain Mapping* 25(1):92–104. [CP]

Bolozky, S. (1997) Israeli Hebrew phonology. In: *Phonologies of Asia and Africa*, ed. A. S. Kaye & P. T. Daniels, pp. 287–311. Eisenbrauns. [DR]

Borgwaldt, S. R., Hellwig, F. M. & De Groot, A. M. B. (2004) Word-initial entropy in five languages: Letter to sound, and sound to letter. *Written Language and Literacy* 7:165–84. [aRF]

Borgwaldt, S. R., Hellwig, F. M. & De Groot, A. M. B. (2005) Onset entropy matters: Letter-to-phoneme mappings in seven languages. *Reading and Writing* 18:211–29. [aRF]

Bouma, H. (1970) Interaction effects in parafoveal letter recognition. *Nature* 226:177–78. [DGP]

Bowers, J. S., Damian, M. F. & Davis, C. J. (2009) A fundamental limitation of the conjunctive codes learned in PDP models of cognition: Comments on Botvinick and Plaut (2006). *Psychological Review* 116:986–97. [JSB]

Bowers, J. S. & Davis, C. J. (2009) Learning representations of wordforms with recurrent networks: Comment on Sibley, Kello, Plaut, & Elman. *Cognitive Science* 33:1183–86. [JSB]

Bowers, J. S. & Michita, Y. (1998) An investigation into the structure and acquisition of orthographic knowledge: Evidence from cross-script Kanji–Hiragana priming. *Psychonomic Bulletin and Review* 5:259–64. [aRF]

Bradley, L. & Bryant, P. E. (1979) Independence of reading and spelling in backward and normal readers. *Developmental Medicine and Child Neurology* 21:504–14. [UG]

Braet, W., Wagemans, J. & Op de Beeck, H. P. (2012) The visual word form area is organized according to orthography. *NeuroImage* 59(3):2751–59. [MS]

Brincat, S. L. & Connor, C. E. (2004) Underlying principles of visual shape selectivity in posterior inferortemporal cortex. *Nature Neuroscience* 7:880–86. [JG]

Bruner, J. S. & O'Dowd, D. (1958) A note on the informativeness of parts of words. *Language and Speech* 1:98–101. [aRF]

Bryant, P. E. & Bradley, L. (1980) Why children sometimes write words which they do not read. In: *Cognitive processes in spelling*, ed. U. Frith, pp. 355–70. Academic Press. [UG]

Brysbaert, M. (2001) Prelexical phonological coding of visual words in Dutch: Automatic after all. *Memory and Cognition* 29:765–73. [aRF]

Burt, J. S. (2006) What is orthographic processing skill and how does it relate to word identification in reading? *Journal of Research in Reading* 29(4):400–17. [SHD]

Carlisle, J. (2000) Awareness of the structure and meaning or morphologically complex words: Impact on reading. *Reading and Writing* 12:169–90. [SHD]

Carreiras, M., Duñabeitia, J. A. & Molinaro, N. (2009a) Consonants and vowels contribute differently to visual word recognition: ERPs of relative position priming. *Cerebral Cortex* 19(11):2659–70. [MP]

Carreiras, M., Seghier, M., Baquero, S., Estévez, A., Lozano, A., Devlin, J. T. & Price, C. J. (2009b) An anatomical signature for literacy. *Nature* 461:983–86. [MP]

Castles, A., Davis, C., Cavalot, P. & Forster, K. I. (2007) Tracking the acquisition of orthographic skills in developing readers: Masked form priming and trans-posed-letter effects. *Journal of Experimental Child Psychology* 97:165–82. [MP]

Chan, S. T., Tang, S. W., Tang, K. W., Lee, W. K., Lo, S. S. & Kwong, K. K. (2009) Hierarchical coding of characters in the ventral and dorsal visual streams of Chinese language processing. *NeuroImage* 48(2):423–35. [MS]

Changizi, M. A., Zhang, Q., Ye, H. & Shimojo, S. (2006) The structures of letters and symbols throughout human history are selected to match those found in objects in natural scenes. *The American Naturalist* 167:117–39. [MM]

Chao, Y. R. (1968) *Language and symbolic systems*. Cambridge University Press. [aRF]

Chen, A. S.-W. (2011) Bodies and codas or core syllables plus appendices? Evidence for a developmental theory of subsyllabic division preference. *Cognition* 121:338–62. [DLS]

Chen, H.-C. & Shu, H. (2001) Lexical activation during the recognition of Chinese characters. *Psychonomic Bulletin and Review* 8:511–18. [CMcB-C]

Chen, H.-C., Song, H., Lau, W. Y., Wong, E. & Tang, S. L. (2003) Developmental characteristics of eye movements in reading Chinese. In: *Reading development in Chinese children*, ed. C. McBride-Chang & H.-C. Chen, pp. 157–69. Praeger. [CMcB-C]

Chomsky, N. (1965) *Aspects of the theory of syntax*. MIT Press. [CB, MC, rRF, DCP]

Chomsky, N. (1981) *Lectures on government and binding*. Foris. [DCP]

Chomsky, N. (1995) *The minimalist program*. MIT Press. [CB, rRF]

Chomsky, N. (2006) *Language and mind*, 3rd edition. Cambridge University Press. [rRF, YL]

Chomsky, N. (2007) Biolinguistic explorations: Design, development, evolution. *International Journal of Philosophical Studies* 15(1):1–21. [CB]

Chomsky, N. (2010) The mysteries of nature how deeply hidden? In: *Chomsky notebook*, by N. Chomsky, ed. J. Bricmont & J. Franck, pp. 3–33. Columbia University Press. [CB]

Chomsky, N. & Halle, M. (1968) *The sound pattern of English*. Harper & Row. [MSS]

Christianson, K., Johnson, R. L. & Rayner, K. I. (2005) Letter transpositions within and across morphemes. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31:1327–39. [aRF, JH, CR]

Coltheart, M. (2006) Acquired dyslexias and the computational modelling of reading. *Cognitive Neuropsychology* 23:96–109. [NF]

Coltheart, M., Davelaar, E., Jonasson, J. T. & Besner, D. (1977) Access to the internal lexicon. In: *Attention and performance VI*, ed. S. Dornic, pp. 535–55. Erlbaum. [NF]

Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001) DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review* 108:204–56. [CJD, NF, aRF, JL]

Cossu, J., Shankweiler, D., Liberman, I. Y., Katz, L. & Tola, G. (1988) Awareness of phonological segments and reading ability in Italian children. *Applied Psycholinguistics* 9:1–16. [aRF]

Coulmas, F. (2003) *Writing systems: An introduction to their linguistic analysis*. Cambridge University Press. [MSS]

Crain, S. & Nakayama, M. (1987) Structure dependence in grammar formation. *Language* 63(3):522–43. [MC]

Croft, W. & Cruse, D. A. (2004) *Cognitive linguistics*. Cambridge University Press. [DR]

Crossland, M. D., Legge, G. E. & Dakin, S. C. (2008) The development of an automated sentence generator for the assessment of reading speed. *Behavioral and Brain Functions* 4:14. doi:10.1186/1744-9081-4-14. [DGP]

Cunningham, A. E., Perry, K. & Stanovich, K. E. (2001) Converging evidence for the concept of orthographic processing. *Reading and Writing* 14:549–68. [SHD]

Daniels, P. T. (1996a) The invention of writing. In: *The world's writing systems*, ed. P. T. Daniels & W. Bright, pp. 474–84. Oxford University Press. [DLS]

Daniels, P. T. (1996b) The study of writing systems. In: *The world's writing systems*, ed. P. T. Daniels & W. Bright, pp. 3–17. Oxford University Press. [MELB]

Daniels, P. T. & Bright, W. ed. (1996) *The world's writing systems*. Oxford University Press. [MSS, DLS]

Das, T., Padakannaya, P., Pugh, K. R. & Singh, N. C. (2011) Neuroimaging reveals dual routes to reading in simultaneous proficient readers of two orthographies. *NeuroImage* 54:1476–87. [CR]

Davis, C. J. (1999) The self-organising lexical acquisition and recognition (SOLAR) model of visual word recognition. Unpublished doctoral dissertation, University of New South Wales. [JSB, CJD, aRF]

Davis, C. J. (2010) The spatial coding model of visual word identification. *Psychological Review* 117:713–58. [JSB, CJD, arRF, JG]

Davis, C. J. & Bowers, J. (2004) What do letter migration errors reveal about letter position coding in visual word recognition? *Journal of Experimental Psychology: Human Perception and Performance* 30:923–41. [aRF]

Davis, C. J. & Bowers, J. (2006) Contrasting five different theories of letter position coding: Evidence from orthographic similarity effects. *Journal of Experimental Psychology: Human Perception and Performance* 32:535–57. [aRF]

Davis, C. J. & Coltheart, M. (2002) Paying attention to reading errors in acquired dyslexia. *Trends in Cognitive Sciences* 6: 359–61. [NF]

Davis, C. J. & Lupker, S. J. (2006) Masked inhibitory priming in English: Evidence for lexical inhibition. *Journal of Experimental Psychology: Human Perception and Performance* 32:668–87. [CJD]

Deacon, S. H. (in press) Sounds, letters, and meanings: The independent influences of phonological, morphological, and orthographic skills on early word reading accuracy. *Journal of Research in Reading*. (Advance online publication. DOI: 10.1111/j.1467-9817.2011.01496.x). [SHD]

Deacon, S. H., Benere, J. & Castles, A. (2012) Chicken or egg? Untangling the relationship between orthographic processing and reading. *Cognition* 122:110–17. [SHD]

Deacon, S. H. & Kirby, J. (2004) Morphological awareness: Just more phonological? The roles of morphological and phonological awareness in reading develop-ment. *Applied Psycholinguistics* 25:223–38. [SHD]

DeFrancis, J. (1989) *Visible speech: The diverse oneness of writing systems*. University of Hawaii Press. [aRF]

Dehaene, S. (2009) *Reading in the brain: The science and evolution of a human invention*. Penguin Viking. [MS]

Dehaene, S. & Cohen, L. (2007) Cultural recycling of cortical maps. *Neuron* 56:384–98. [DCP]

Dehaene, S. & Cohen, L. (2011) The unique role of the visual word form area in reading. *Trends in Cognitive Sciences* 15(6):254–62. [JG, MP, MS]

Dehaene, S., Cohen, L., Sigman, M. & Vinckier, F. (2005) The neural code for written words: A proposal. *Trends in Cognitive Sciences* 9:335–41. [aRF, MS]

Dehaene, S., Jobert, A., Naccache, L., Ciuciu, P., Poline, J. B., Le Bihan, D. & Cohen, L. (2004) Letter binding and invariant recognition of masked words: Behavioral and neuroimaging evidence. *Psychological Science* 15(5):307–13. [MS]

Deutsch, A., Frost, R. & Forster, K. I. (1998) Verbs and nouns are organized and accessed differently in the mental lexicon: Evidence from Hebrew. *Journal of*

Experimental Psychology: Learning, Memory, and Cognition 24(5):1238–55. [BDH]

Deutsch, A., Frost, R., Peleg, S., Pollatsek, A. & Rayner, K. (2003) Early morphological effects in reading: Evidence from parafoveal preview benefit in Hebrew. *Psychonomic Bulletin and Review* 10(2):415–22. [aRF, BDH, JL]

Deutsch, A., Frost, R., Pollatsek, A. & Rayner, K. (2000) Early morphological effects in word recognition in Hebrew: Evidence from parafoveal preview benefit. *Language and Cognitive Processes* 15:487–506. [aRF, JL]

Deutsch, A., Frost, R., Pollatsek, A. & Rayner, K. (2005) Morphological parafoveal preview benefit effects in reading: Evidence from Hebrew. *Language and Cognitive Processes* 20(1):341–71. [BDH, JL]

Deutsch, A. & Rayner, K. (1999) Initial fixation location effects in reading Hebrew words. *Language and Cognitive Processes* 14:393–421. [aRF]

Diependaele, K., Ziegler, J. & Grainger, J. (2010) Fast phonology and the bi-modal interactive activation model. *European Journal of Cognitive Psychology* 22:764–78. [aRF, NJP]

Dijkstra, T. & van Heuven, W. J. B. (1998) The BIA-model and bilingual word recognition. In: *Localist connectionist approaches to human cognition*, ed. J. Grainger & A. M. Jacobs, pp. 189–225. Erlbaum. [NJP]

Ding, G., Peng, D. & Taft, M. (2004) The nature of the mental representation of radicals in Chinese: A priming study. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 30:530–39. [NJP]

Dufau, S., Grainger, J. & Ziegler, J. C. (in press) How to say "No" to a nonword: A leaky competing accumulator model of lexical decision. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. [JG]

Duñabeitia, J. A., Perea, M. & Carreiras, M. (2007) Do transposed-letter similarity effects occur at a morpheme level? Evidence for morpho-orthographic decomposition. *Cognition* 105(3):691–703. [aRF, JH, CR]

Duñabeitia, J. A., Perea, M. & Carreiras, M. (2009) There is no clam with coats in the calm coast: Delimiting the transposed-letter priming effect. *Quarterly Journal of Experimental Psychology* 62:1930–47. [MP]

Ehri, L. (2005) Learning to read words: Theories, findings and issues. *Scientific Studies of Reading* 9:167–88. [SHD]

Ehri, L. C. & Wilce, L. S. (1982) The salience of silent letters in children's memory for word spellings. *Memory and Cognition* 10:155–66. [UG]

Ellis, A. W. & Young, A. W. (1988/1996) *Human cognitive neuropsychology*. Erlbaum. [NF, aRF]

Elman, J. L. (2003) Development: It's about time. *Developmental Science* 6:430–33. [DR]

Emberson, L., Convey, C. & Christiuancen, M. (2011) Timing is everything: Changes in presentation rate have opposite effects on auditory and visual implicit statistical learning. *Quarterly Journal of Experimental Psychology* 64(5):1021–40. [CB]

Endress, A. D. & Mehler, J. (2009) The surprising power of statistical learning: When fragment knowledge leads to false memories of unheard words. *Journal of Memory and Language* 60:351–67. [aRF]

Engbert, R., Longtin, A. & Kliegl, R. (2002) A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research* 42:621–36. [JL]

Engbert, R., Nuthmann, A., Richter, E. & Kliegl, R. (2005) SWIFT: A dynamical model of saccade generation during reading. *Psychological Review* 112:777–813. [JL]

Evans, N. & Levinson, S. C. (2009) The myth of language universals: Language diversity and its importance for cognitive science. *Behavioural and Brain Sciences* 32:429–92. [CB, rRF, DLS]

Evans, J., Saffran, J. & Robe-Torres, K. (2009) Statistical learning in children with specific language impairment. *Journal of Speech, Language, and Hearing Research* 52:321–36. [arRF]

Everett, D. (2005) Biology and language: A consideration of alternatives. *Journal of Linguistics* 41:157–75. [CB]

Feldman, L. B. & Andjelković, D. (1992) Morphological analysis in word recognition. In: *Phonology, orthography, morphology and meaning*, ed. R. Frost & L. Katz, pp. 343–60. North-Holland. [LBF]

Feldman, L. B. & Bentin, S. (1994) Morphological analysis of disrupted morphemes: Evidence from Hebrew. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology* 47A:407–35. [LBF]

Feldman, L. B., Frost, R. & Pnini, T. (1995) Decomposing words into their constituent morphemes: Evidence from English and Hebrew. *Journal of Experimental Psychology: Learning, Memory and Cognition* 21:947–60. [LBF]

Feldman, L. B., Kostić, A., Gvozdenović, V., O'Connor, P. A. & Moscoso del Prado Martín, F. (2012) Early morpho-semantic processing in Serbian: A violation of form-then-meaning accounts of word recognition. *Psychological Bulletin and Review* 16:684–91. [LBF]

Feldman, L. B., O'Connor, P. A. & Moscoso del Prado Martín, F. (2009) Early morphological processing is morpho-semantic and not simply morpho-orthographic: A violation of form-then-meaning accounts of word recognition. *Psychological Bulletin and Review* 16:684–91. doi:10.3758/PBR.16.4.684. [LBF]

Ferrand, L. & Grainger, J. (1992) Phonology and orthography in visual word recognition: Evidence from masked nonword priming. *Quarterly Journal*

of *Experimental Psychology, Section A: Human Experimental Psychology* 45:353–72. [aRF]

Fitch, T. (2007) Linguistics: An invisible hand. *Nature* 449:665–67. [CB]

Fodor, J. A. & Pylyshyn, Z. W. (1988) Connectionism and cognitive architecture: A critical analysis. *Cognition* 28:3–71. [JSB]

Forster, K. I. (1976) Accessing the mental lexicon. In: *New approaches to language mechanisms*, ed. R. J. Wales & E. Walk, pp. 257–87. North-Holland. [aRF]

Forster, K. I. & Davis, C. (1991) The density constraint on form-priming in the naming task: Interference effects from a masked prime. *Journal of Memory and Language* 30:1–25. [CJD, aRF]

Forster, K. I., Davis, C., Schocknecht, C. & Carter, R. (1987) Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology* 39:211–51. [aRF]

Friedmann, N., Biran, M. & Gvion, A. (2012) Patterns of visual dyslexia. *Journal of Neuropsychology* 6:1–30. [NF]

Friedmann, N., Dotan, D. & Rahamim, E. (2010) Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia. *Cortex* 46:982–1004. [aRF]

Friedmann, N. & Gvion, A. (2001) Letter position dyslexia. *Cognitive Neuropsychology* 18:673–96. [aRF]

Friedmann, N. & Gvion, A. (2005) Letter form as a constraint for errors in neglect dyslexia and letter position dyslexia. *Behavioural Neurology* 16:145–58. [NF, aRF]

Friedmann, N. & Haddad-Hanna, M. (in press a) Letter position dyslexia in Arabic: From form to position. *Behavioural Neurology* 25. doi: 10.3233/BEN-2012-119004. [NF, arRF]

Friedmann, N. & Haddad-Hanna, M. (in press b) Types of developmental dyslexia in Arabic. In: *Arabic literacy: Theoretical insights and practical challenges. Language and Literacy Series,* ed. E Saiegh-Haddad & M. Joshi. Springer. [NF]

Friedmann, N. & Lukov, L. (2008) Developmental surface dyslexias. *Cortex* 44(9):1146–60. [NF]

Friedmann, N. & Rahamim, E. (2007) Developmental letter position dyslexia. *Journal of Neuropsychology* 1:201–36. [MP]

Frith, U. (1978) From print to meaning and from print to sound, or how to read without knowing how to spell. *Visible Language* 12:43–54. [UG]

Frith, U. (1980) Unexpected spelling problems. In: *Cognitive processes in spelling*, ed. U. Frith, pp. 495–515. Academic Press. [UG]

Frost, R. (1994) Prelexical and postlexical strategies in reading: Evidence from a deep and a shallow orthography. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 20:1–16. [aRF]

Frost, R. (1995) Phonological computation and missing vowels: Mapping lexical involvement in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 21:398–408. [aRF]

Frost, R. (1998) Toward a strong phonological theory of visual word recognition: True issues and false trails. *Psychological Bulletin* 123(1):71–99. [arRF, JL, KR]

Frost, R. (2003) The robustness of phonological effects in fast priming. In: *Masked priming the state of the art*, ed. S. Kinoshita & S. J. Lupker, pp. 173–92. [The Macquarie Monographs in Cognitive Science.] Psychology Press. [rRF]

Frost, R. (2006) Becoming literate in Hebrew: The grain-size hypothesis and Semitic orthographic systems. *Developmental Science* 9:439–40. [aRF]

Frost, R. (2009) Reading in Hebrew vs. reading in English: Is there a qualitative difference? In: *How children learn to read: Current issues and new directions in the integration of cognition, neurobiology and genetics of reading and dyslexia research and practice*, ed. K. Pugh & P. McCradle, pp. 235–54. Psychology Press. [aRF]

Frost, R., Ahissar, M., Gottesman, R. & Tayeb, S. (2003) Are phonological effects fragile? The effect of luminance and exposure duration on form priming and phonological priming. *Journal of Memory and Language* 48:346–78. [arRF]

Frost, R., Deutsch, A. & Forster, K. I. (2000a) Decomposing morphologically complex words in a nonlinear morphology. *Journal of Experimental Psychology Learning Memory, and Cognition* 26:751–65. [LBF, aRF]

Frost, R., Deutsch, A., Gilboa, O., Tannenbaum, M. & Marslen-Wilson, W. (2000b) Morphological priming: Dissociation of phonological, semantic, and morphological factors. *Memory and Cognition* 28:1277–88. [LBF, aRF]

Frost, R., Forster, K. I. & Deutsch, A. (1997) What can we learn from the morphology of Hebrew: A masked priming investigation of morphological representation. *Journal of Experimental Psychology: Learning Memory, and Cognition* 23(4):829–56. [LBF, aRF, BDH]

Frost, R., Katz, L. & Bentin, S. (1987) Strategies for visual word recognition and orthographical depth: A multilingual comparison. *Journal of Experimental Psychology: Human Perception and Performance* 13:104–15. [LBF, aRF, JGR]

Frost, R., Kugler, T., Deutsch, A. & Forster, K. I. (2005) Orthographic structure versus morphological structure: Principles of lexical organization in a given language. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31(6):1293–326. [LBF, aRF, BDH, NJP]

Frost, R., Narkiss, A., Velan, H. & Deutsch, A. (2010) Learning to read Hebrew as a second language: Acquiring "Semitic" markers of reading. Paper presented at the 51st Annual Meeting of the Psychonomic Society, St. Louis, November 2010. [aRF]

Frost, R. & Yogev, O. (2001) Orthographic and phonological computation in visual word recognition: Evidence from backward masking in Hebrew. *Psychonomic Bulletin and Review* 8:524–30. [arRF]

Frost, R. & Ziegler, J. (2007) Speech and spelling interaction: The interdependence of visual and auditory word recognition. In: *Oxford handbook of psycholinguistics*, ed. G. Gaskell, pp. 107–18. Oxford University Press. [aRF]

Fuentes, L. J., Carmona, E., Agis, I. F. & Catena, A. (1994) The role of the anterior attention system in semantic processing of both foveal and parafoveal words. *Journal of Cognitive Neuroscience* 6:17–25. [JL]

Fuentes, L. J. & Tudela, P. (1992) Semantic processing of foveally and parafoveally presented words in a lexical decision task. *Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology* 45:299–322. [JL]

Garcia, N. P., Abbott, R. D. & Berninger, V. W. (2010) Predicting poor, average, and superior spellers in grades 1 to 6 from phonological, orthographic, and morphological, spelling, or reading composites. *Written Language and Literacy* 13:61–98. [SHD]

Gebhart, A. L., Newport, E. L. & Aslin, R. N. (2009) Statistical learning of adjacent and nonadjacent dependencies among nonlinguistic sounds. *Psychonomic Bulletin & Review* 14:486–90. [arRF]

Gelb, I. J. (1952) *A study of writing: The foundations of grammatology*. University of Chicago Press. [aRF, DLS]

Gheţie, I. (1978) *Istoria Limbii Române Literare*. Editura Ştiinţifică şi Enciclopedică. [MELB]

Gibson, J. J. (1986) *The ecological approach to visual perception*. Erlbaum. [aRF]

Gilbert, C. D., Sigman, M. & Crist, R. E. (2001) The neural basis of perceptual learning. *Neuron* 13:681–97. [rRF]

Gillis, S. & Ravid, D. (2006) Typological effects on spelling development: A crosslinguistic study of Hebrew and Dutch. *Journal of Child Language* 33:621–59. [DR]

Gimson, A. C. (1981) *An introduction to the pronunciation of English*. Edward Arnold. [aRF]

Gold, B. T. & Rastle, K. (2007) Neural correlates of morphological decomposition during visual word recognition. *Journal of Cognitive Neuroscience* 19:1983–93. [CR]

Goldberg, A. E. (2003) Constructions: A new theoretical approach to language. *Trends in Cognitive Sciences* 7:219–24. [DR]

Gomez, P., Ratcliff, R. & Perea, M. (2008) The overlap model: A model of letter position coding. *Psychological Review* 115:577–601. [JSB, aRF, PG]

Gomez, R. (2007) Statistical learning in infant language development. In: *Oxford handbook of psycholinguistics*, ed. M. G. Gaskell. Oxford University Press. [rRF]

Goswami, U. (2000) Phonological representations, reading development and dyslexia: Towards a cross-linguistic theoretical framework. *Dyslexia* 6:133–51. [aRF]

Goswami, U., Porpodas, C. & Wheelwright, S. (1997) Children's orthographic representations in English and Greek. *European Journal of Psychology of Education* 12:273–92. [UG]

Goswami, U., Ziegler, J. C., Dalton, L. & Schneider, W. (2001) Pseudohomophone effects and phonological recoding procedures in reading development in English and German. *Journal of Memory and Language* 45:648–64. [JL]

Goswami, U., Ziegler, J. C., Dalton, L. & Schneider, W. (2003) Nonword reading across orthographies: How flexible is the choice of reading units? *Applied Psycholinguistics* 24:235–47. [JL]

Grainger, J. (2008) Cracking the orthographic code: An introduction. *Language and Cognitive Processes* 23:1–35. [aRF, CR]

Grainger, J., Dufau, S., Montant, M., Ziegler, J. C. & Fagot, J. (2012) Orthographic processing in baboons (*Papio papio*). *Science* 336:245–48. [rRF]

Grainger, J. & Ferrand, L. (1994) Phonology and orthography in visual word recognition: Effects of masked homophone primes. *Journal of Memory and Language* 33:218–33. [aRF]

Grainger, J. & van Heuven, W. (2003) Modeling letter position coding in printed word perception. In: *The mental lexicon*, ed. P. Bonin, pp. 1–24. Nova Science. [JSB, aRF]

Grainger, J., Granier, J. P., Farioli, F., Van Assche, E. & van Heuven, W. (2006) Letter position information and printed word perception: The relative-position priming constraint. *Journal of Experimental Psychology: Human Perception and Performance* 32(4):865–84. [aRF]

Grainger, J., Tydgat, I. & Isselé, J. (2010) Crowding affects letters and symbols differently. *Journal of Experimental Psychology: Human Perception and Performance* 36(3):673–88. doi:10.1037/a0016888. [CW]

Grainger, J. & Whitney, C. (2004) Does the huamn mnid raed wrods as a wlohe? *Trends in Cognitive Sciences* 8:58–59. [aRF]

Grainger, J. & Ziegler, J. (2011) A dual-route approach to orthographic processing. *Frontiers in Psychology* 2:54. doi:10.3389/fpsyg.2011.00054. (Web journal, online publication). [aRF, JG, JH, CMcB-C, CW]

Grill-Spector, K., Kushnir, T., Edelman, S., Avidan, G., Itzchak, Y. & Malach, R. (1999) Differential processing of objects under various viewing conditions in the human lateral occipital complex. *Neuron* 24(1):187–203. [MS]

Gronau, N. & Frost, R. (1997) Prelexical phonologic computation in a deep orthography: Evidence from backward masking in Hebrew. *Psychonomic Bulletin and Review* 4:107–112. [arRF]

Grossberg, S. (1978) Behavioral contrast in short-term memory: Serial binary memory models or parallel continuous memory models? *Journal of Mathematical Psychology* 17:199–219. [JSB]

Guerrera, C. & Forster, K. I. (2008) Masked form priming with extreme transposition. *Language and Cognitive Processes* 23:117–42. [aRF]

Halliday, M. A. K. (1977) Ideas about language. In: *Aims and perspectives in linguistics. Occasional Papers, No. 1*, pp. 32–55. Applied Linguistics Association of Australia. [rRF, CP]

Halliday, M. A. K. (2003) Ideas about language. In: *On language and linguistics: Collected Works of M. A. K. Halliday, vol. 3*, ed. Jonathan Webster, pp. 92–115. Continuum. [CP]

Hannagan, T. & Grainger, J. (in press) Protein analysis meets visual word recognition: A case for string kernels in the brain. *Cognitive Science*. doi:10.1111/j.1551-6709.2012.01236.x [rRF, JG]

Harm, M. W. & Seidenberg, M. S. (1999) Reading acquisition, phonology, and dyslexia: Insights from a connectionist model. *Psychological Review* 106:491–528. [aRF]

Hasson, U., Levy, I., Behrmann, M., Hendler, T. & Malach, R. (2002) Eccentricity bias as an organizing principle for human high-order object areas. *Neuron* 34 (3):479–90. [MS]

Havelock, E. A. (1982) *The literate revolution in Greece and its cultural consequence*. Princeton University Press. [DLS]

Healy, A. F. & Cunningham, T. F. (1992) A developmental evaluation of the role of word shape in word recognition. *Memory and Cognition* 20:141–50. [NJP]

Henrich, J., Heine, S. J. & Norenzayan, A. (2010) The weirdest people in the world? *Behavioural and Brain Sciences* 33:61–135. [DLS]

Hirsimäki, T., Creutz, M., Siivola, V., Kurimo, M., Virpioja, S. & Pylkkönen, J. (2006) Unlimited vocabulary speech recognition with morph language models applied to Finnish. *Computer Speech and Language* 20(4):515–41. [CMcB-C]

Hohenstein, S. & Kliegl, R. (2011) Semantic preview benefit during reading and the influence of German noun capitalization. In: *Abstracts of the 16th European Conference on Eye Movements, Marseille, August 21–25, 2011*, ed. F. Vitu, E. Castet & L. Goffart. Special Issue: *Journal of Eye Movement Research* 4:222. [JL]

Hohenstein, S., Laubrock, J. & Kliegl, R. (2010) Semantic preview benefit in eye movements during reading: A parafoveal fast-priming study. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 36:1150–70. [JL]

Holcomb, P. J. & Grainger, J. (2009) ERP effects of short interval masked associative and repetition priming. *Journal of Neurolinguistics* 22(3):301–12. doi:10.1016/j.jneuroling.2008.06.00. [BDH]

Holcomb, P. J., Reder, L., Misra, M. & Grainger, J. (2005) The effects of prime visibility on ERP measures of masked priming. *Cognitive Brain Research* 24 (1):155–72. doi:10.1016/j.cogbrainres.2005.01.003. [BDH]

Homer, B. D. (2009) Literacy and metalinguistic development. In: *The Cambridge handbook of literacy*, ed. D. R. Olson & N. Torrance, pp. 487–500. Cambridge University Press. [BDH]

Hoover, W. A. & Gough, P. B. (1990) The simple view of reading. *Reading and Writing* 2:127–60. [MSS]

Hoxhallari, L., van Daal, V. H. P. & Ellis, N. C. (2004) Learning to read words in Albanian: A skill easily acquired. *Scientific Studies of Reading* 8:153–66. [MSS]

Hsu, C. H., Tsai, J. L., Lee, C. Y. & Tzeng, O. J. (2009) Orthographic combinability and phonological consistency effects in reading Chinese phonograms: An event-related potential study. *Brain and Language* 108:56–66. [aRF]

Huey, E. B. (1908/1968) *The psychology and pedagogy of reading*. Macmillan/MIT Press. (Original Macmillan edition, 1908). [DGP]

Hummel, J. E., & Biederman, I. (1992) Dynamic binding in a neural network for shape recognition. *Psychological Review* 99:480–517. [JSB]

Humphreys, G. W., Evett, L. J. & Quinlan, P. T. (1990) Orthographic processing in visual word recognition. *Cognitive Psychology* 22:517–60. [aRF]

Hung, D. L. & Tzeng, O. J. (1981) Orthographic variations and visual information processing. *Psychological Bulletin* 90:377–414. [MSS]

Hunter, Z. R. & Brysbaert, M. (2008) Theoretical analysis of interhemispheric transfer costs in visual word recognition. *Language and Cognitive Processes* 23:165–82. [aRF]

Hyönä, J. & Häikiö, T. (2005) Is emotional content obtained from parafoveal words during reading? An eye movement analysis. *Scandinavian Journal of Psychology* 46:475–83. [JL]

Inagaki, K., Hatano, G. & Otake, T. (2000) The effect of Kana literacy acquisition on the speech segmentation unit used by Japanese young children. *Journal of Experimental Child Psychology* 75:70–91. [aRF]

Inhoff, A. W. (1989) Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance* 15:544–55. [JL]

Jacobs, A. M. & Grainger, J. (1994) Models of visual word recognition – Sampling the state of the art. *Journal of Experimental Psychology: Human Perception and Performance* 20:1311–34. [CB, CJD, JG]

Johnson, D. & Lappin, S. (1997) A critique of the minimalist program. *Linguistics and Philosophy* 20:273–333. [CB]

Johnson, M. H. & Karmiloff-Smith, A. (1992) Can neural selectionism be applied to cognitive development and its disorders? *New Ideas in Psychology* 10:35–46. [NJP]

Johnson, R. L., Perea, M. & Rayner, K. (2007) Transposed-letter effects in reading. Evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology: Human Perception and Performance* 33:209–29. [aRF]

Joshi, M. & Aaron, P. G. eds. (2006) *Handbook of orthography and literacy*. Erlbaum. [MSS]

Kachru, Y. (2008) Hindi-Urdu-Hindustani. In: *Language in South Asia*, ed. B. B. Kachru, Y. Kachru & S. N. Sridhar, pp. 81–102. Cambridge University Press. [CR]

Kambe, G. (2004) Parafoveal processing of prefixed words during eye fixations in reading: Evidence against morphological influences on parafoveal preprocessing. *Perception and Psychophysics* 66:279–92. [JL]

Kasisopa, B., Reilly, R. & Burnham, D. (2010) Orthographic factors in reading Thai: An eye tracking study. In: *Proceedings of the Fourth China International Conference on Eye Movements (CICEM), Tianjin, China, May 24–26, 2010*, ed. D. Shen, X. Bai, G. Yan & K. Rayner. p. 8. Tianjin Normal University. [rRF, CMcB-C]

Katz, L. & Frost, R. (1992) The reading process is different for different orthographies: The orthographic depth hypothesis. In: *Orthography, phonology, morphology, and meaning: Advances in Psychology, vol. 94*, ed. R. Frost & L. Katz, pp. 67–84. Elsevier/North-Holland. [aRF, MSS]

Kellenbach, M. L., Wijers, A. A., Hovius, M., Mulder, J. & Multer, G. (2002) Neural differentiation of lexico-syntactic categories or semantic features? Event-related potential evidence for both. *Journal of Cognitive Neuroscience* 14(4):561–77. doi:10.1162/08989290260045819. [BDH]

Kelly, A. N., van Heuven, W. J. B., Pitchford, N. J. & Ledgeway, T. (2011) Revisiting word shape effects: The influence of ascender letters in visual word recognition. Paper presented at the Architectures and Mechanisms for Language Processing meeting, Paris, France, August 31–September 3, 2011. [NJP]

Kessler, B. & Treiman, R. (1997) Syllable structure and the distribution of phonemes in English syllables. *Journal of Memory and Language* 37:295–311. [aRF]

Kinoshita, S. & Norris, D. (2009) Transposed-letter priming of prelexical orthographic representations. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 35:1–18. [aRF]

Kinoshita, S., Norris, D. & Siegelman, N. (in press) Transposed-letter priming effect in Hebrew in the same–different task. *Quarterly Journal of Experimental Psychology*. [DN]

Kliegl, R., Risse, S. & Laubrock, J. (2007) Preview benefit and parafoveal-on-foveal effects from word *n*+2. *Journal of Experimental Psychology: Human Perception and Performance* 33:1250–55. [JL]

Ktori, M. & Pitchford, N. J. (2009) Development of letter position processing: Effects of age and orthographic transparency. *Journal of Research in Reading* 32:180–98. [NJP]

Kubozono, H. (2006) The phonetic and phonological organization of speech in Japanese. In: *The handbook of East Asian psycholinguistics*, ed. M. Nakayama, R. Mazuka & Y. Shirai, pp. 191–200. Cambridge University Press. [aRF]

Kuipers, J. C. & McDermott, R. (1996) Insular Southeast Asian scripts. In: *The world's writing systems*, ed. P. T. Daniels & W. Bright, pp. 474–84. Oxford University Press. [DLS]

Kuperman, V., Bertram, R. & Baayen, R. H. (2008) Morphological dynamics in compound processing. *Language and Cognitive Processes* 23:1089–132. [aRF]

Kuperman, V., Schreuder, R., Bertram, R. & Baayen, R. (2009) Reading polymorphemic Dutch compounds: Toward a multiple route model of lexical processing. *Journal of Experimental Psychology: Human Perception and Performance* 35(3):876–95. doi:10.1037/a0013484. [BDH]

Landerl, K., Wimmer, H. & Frith, U. (1997) The impact of orthographic consistency on dyslexia: A German–English comparison. *Cognition* 63:315–34. [JL]

Langacker, R. W. (1987) *Foundations of cognitive grammar: Theoretical prerequisites*. Stanford University Press. [DR]

Lavidor, M. (2011) Whole-word shape effect in dyslexia. *Journal of Research in Reading* 34:433–54. [NJP]

Lee, C. H. & Taft, M. (2009) Are onsets and codas important in processing letter position? A comparison of TL effects in English and Korean. *Journal of Memory and Language* 60(4):530–42. doi:10.1016/j.jml.2009.01.002. [arRF, KK, MP]

Lee, C. H. & Taft, M. (2011) Subsyllabic structure reflected in letter confusability effects in Korean word recognition. *Psychonomic Bulletin and Review* 18 (1):129–34. doi:10.3758/s13423-010-0028-y. [arRF, KK]

Lee, C. Y. (2011) The statistical learning perspective on Chinese reading. In: *Dyslexia across languages: Orthography and the brain–gene–behavior link*, ed. P. McCardle, B. Miller, J. R. Lee, & O. J. L. Tzeng, pp. 44–61. Brookes. [aRF]

Legge, G. E. (2007) *Psychophysics of reading in normal and low vision*. Erlbaum/ Taylor & Francis. [DGP]

Legge, G. E., Ahn, S. J., Klitz, T. S. & Luebker, A. (1997) Psychophysics of reading: XVI. The visual span in normal and low vision. *Vision Research* 37:1999–2010. [MM]

Legge, G. E. & Bigelow, C. A. (2011) Does print size matter for reading? A review of findings from vision science and typography. *Journal of Vision* 11(5):8, 1–22. doi:10.1167/11.5.8. [MM, DGP]

Legge, G. E., Cheung, S.-H., Yu, D., Chung, S. T. L., Lee, H.-W. & Owens, D. P. (2007) The case for the visual span as a sensory bottleneck in reading. *Journal of Vision* 7(2):9, 1–15. doi:10.1167/7.2.9. Available at: http://journalofvision.org/7/ 2/9/. [DGP]

Legge, G. E., Mansfield, J. S. & Chung, S. T. L. (2001) Psychophysics of reading XX: Linking letter recognition to reading speed in central and peripheral vision. *Vision Research* 41(6):725–43. [MM, DGP]

Lerner, I. & Frost, R. (in press) Letter statistics in a learning network model accounts for cross-linguistic differences in letter transposition effects. [rRF]

Lewis, G., Solomyak, O. & Marantz, A. (2011) The neural basis of obligatory decomposition of suffixed words. *Brain and Language* 118(3):118–27. [MS]

Li, R. W., Klein, S. A. & Levi, D. M. (2006) The receptive field and internal noise for position acuity change with feature separation. *Journal of Vision* 6:311–21. [MP]

Lima, S. D. (1987) Morphological analysis in sentence reading. *Journal of Memory and Language* 26:84–99. [JL]

Lin, D., McBride-Chang, C., Aram, D., Levin, I., Cheung, R. Y. M. & Chow, Y. Y.-Y. (2009) Maternal mediation of writing in Chinese children. *Language and Cognitive Processes* 24(7–8):1286–311. [CMcB-C]

Lin, D., McBride-Chang, C., Aram, D., Shu, H., Levin, I. & Cho, J.-R. (2012) Maternal mediation of word writing in Chinese across Hong Kong and Beijing. *Journal of Educational Psychology* 104:121–37. [CMcB-C]

Liu, P. D., Chung, K. K. H., McBride-Chang, C. & Tong, X. (2010) Holistic versus analytic processing: Evidence for a different approach to processing of Chinese at the word and character levels in Chinese children. *Journal of Experimental Child Psychology* 107:466–78. [CMcB-C]

Liu, W., Inhoff, A. W., Ye, Y. & Wu, C. (2002) Use of parafoveally visible characters during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance* 28:1213–27. [JL]

Liu, Y., Dunlap, S., Fiez, J. & Perfetti, C. (2007) Evidence for neural accommodation to a writing system following learning. *Human Brain Mapping* 28:1223–34. [rRF]

Logan, G. D. (1996) The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review* 103:603–49. [PG, MP]

Mamassian, P., Landy, M. S. & Maloney, L. T. (2002) Bayesian modelling of visual perception. In: *Probabilistic models of the brain: Perception and neural function*, ed. R. Rao, B. Olshausen & M. Lewicki, pp. 13–36. MIT Press. [PG]

Marr, D. (1982) *Vision: A computational investigation into the human representation and processing of visual information*. W. H. Freeman. [rRF, JG]

Marshall, J. C. (1984) Toward a rational taxonomy of the acquired dyslexias. In: *Dyslexia: A global issue*, ed. R. N. Malatesha & H. A. Whitaker, pp. 211–32. Martinus Nijhoff. [NF]

Marshall, J. C. & Newcombe, F. (1973) Patterns of paralexia: A psycholinguistic approach. *Journal of Psycholinguistic Research* 2:179–99. [aRF]

Masica, C. (1991) *The Indo-Aryan languages*. Cambridge University Press. [CR]

Masson, M. E. J. (1983) Conceptual processing of text during skimming and rapid sequential reading. *Memory & Cognition* 11(3):262–74. [DGP]

Mattingly, I. G. (1972) Reading, the linguistic process, and linguistic awareness. In: *Language by ear and by eye: The relationship between speech and reading*, ed. J. F. Kavanaugh & I. G. Mattingly, pp. 133–47. MIT Press. [CP]

Mattingly, I. G. (1992) Linguistic awareness and orthographic form. In: *Orthography, phonology, morphology, and meaning*, ed. R. Frost & L. Katz, pp. 11–26. Elsevier/North-Holland. [aRF, MSS]

McBride-Chang, C., Cho, J.-Y., Liu, H., Wagner, R. K., Shu, H., Zhou, A., Cheuk, C. & Muse, A. (2005) Changing models across cultures: Associations of phonological awareness and morphological structure awareness with vocabulary and word recognition in second graders from Beijing, Hong Kong, Korea, and the United States. *Journal of Experimental Child Psychology* 92:140–60. [SHD]

McClelland, J. L. & Rumelhart, D. E. (1981) An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review* 88:375–407. [CJD, aRF, NJP]

McCutchen, D. & Perfetti, C. A. (1982) Coherence and connectedness in the development of discourse production. *Text* 2:113–39. [JL]

Miller, R. (2012) Early neural differentiation of word function in written Hebrew. Doctoral Dissertation, The Graduate Center, City University of New York. Manuscript in progress. [BDH]

Mirković, J., Seidenberg, M. S. & Joanisse, M. F. (2011) Probabilistic nature of inflectional structure: Insights from a highly inflected language. *Cognitive Science* 35:638–81. [MSS]

Misyak, J. B. & Christiansen, M. H. (2012) Statistical learning and language: An individual differences study. *Language Learning* 62(1):302–31. [rRF]

Moscoso del Prado Martín, F., Deutsch, A., Frost, R., Schreuder, R., De Jong, N. & Baayen, R. H. (2005) Changing places: A cross-language perspective on frequency and family size in Dutch and Hebrew. *Journal of Memory and Language* 53:496–512. [LBF]

Mozer, M. C. (1987) Early parallel processing in reading: A connectionist approach. In: *Attention and performance XII: The psychology of reading*, ed. M. Coltheart, pp. 83–104. Erlbaum. [MS]

Nandy, A. S. & Tjan, B. S. (2007) The nature of letter crowding as revealed by first- and second-order classification images. *Journal of Vision* 7:1–26. [MM]

Nazir, T., ben-Boutayab, N., Decoppet, N., Deutsch, A. & Frost, R. (2004) Reading habits, perceptual learning, and the recognition of printed words. *Brain and Language* 88:294–311. [rRF]

Newport, E. L. & Aslin, R. N. (2004) Learning at a distance: I. Statistical learning of non-adjacent dependencies. *Cognitive Psychology* 48:127–62. [aRF]

Niemi, J., Laine, M. & Tuominen, J. (1994) Cognitive morphology in Finnish: Foundations of a new model. *Language and Cognitive Processes* 9(3):423–46. [CMcB-C]

Norris, D. & Kinoshita, S. (2008) Perception as evidence accumulation and Bayesian inference: Insights from masked priming. *Journal of Experimental Psychology: General* 137:433–55. [aRF]

Norris, D. & Kinoshita, S. (in press) Reading through a noisy channel: Why there's nothing special about the perception of orthography. *Psychological Review*. [PG, DN]

Norris, D., Kinoshita, S. & van Casteren, M. (2010) A stimulus sampling theory of letter identity and order. *Journal of Memory and Language* 62:254–71. [JSB, aRF, DN]

Nunes, T. & Bryant, P. (2006) *Improving literacy by teaching morphemes*. Routledge. [UG]

Oller, D. K. (2000) *The emergence of the speech capacity*. Erlbaum. [DR]

Olson, D. R. (1994) *The world on paper*. Cambridge University Press. [DR]

Ornan, U. (2003) *The final word: Mechanism for Hebrew word generation*. (In Hebrew). Haifa University Press. [aRF]

Ortells, J. J., Abad, M. J. F., Noguera, C. & Lupiáñez, J. (2001) Influence of prime-probe stimulus onset asynchrony and prime precuing manipulations on semantic priming effects with words in a lexical-decision task. *Journal of Experimental Psychology: Human Perception and Performance* 27:75–91. [JL]

Pacton, S., Perruchet, P., Fayol, M. & Cleeremans, A. (2001) Implicit learning out of the lab: The case of orthographic regularities. *Journal of Experimental Psychology: General* 130:401–26. [rRF]

Page, M. (2000) Connectionist modeling in psychology: A localist manifesto. *Behavioral and Brain Sciences* 23:443–512. [NJP]

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A. & Morgan, M. (2001) Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience* 4:739–44. [MM]

Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S. F., Cotelli, M., Cossu, G., Corte, F., Lorusso, M., Pesenti, S., Gallagher, A., Perani, D., Price, C., Frith, C. D. & Frith, U. (2000) A cultural effect on brain function. *Nature Neuroscience* 3(1):91–96. [CP, MS]

Pelli, D. G., Palomares, M. & Majaj, N. J. (2004) Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision* 4:1136–69. [MM]

Pelli, D. G. & Tillman, K. A. (2007) Parts, wholes, and context in reading: A triple dissociation. *PLoS ONE* 2(8):e680. doi:10.1371/journal.pone.0000680. Available at: http://www.plosone.org/doi/pone.0000680. [MM, DGP]

Pelli, D. G. & Tillman, K. A. (2008) The uncrowded window of object recognition. *Nature Neuroscience* 11(10):1129–35. Available at: http://www.nature.com/neuro/journal/v11/n10/index.html#pe. [DGP]

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D. & Majaj, N. J. (2007) Crowding and eccentricity determine reading rate. *Journal of Vision* 7(2):20, 1–36. Available at: http://journalofvision.org/7/2/20/. [MM, DGP]

Perea, M., Abu Mallouh, R. & Carreiras, M. (2010) The search of an input coding scheme: Transposed-letter priming in Arabic. *Psychonomic Bulletin and Review* 17(3):375–80. [aRF, KK, MP]

Perea, M., Abu Mallouh, R., García-Orza, J. & Carreiras, M. (2011a) Masked priming effects are modulated by expertise in the script. *Quarterly Journal of Experimental Psychology* 64:902–19. [MP]

Perea, M. & Carreiras, M. (2006a) Do transposed-letter similarity effects occur at a prelexical phonological level? *Quarterly Journal of Experimental Psychology* 59:1600–13. [aRF]

Perea, M. & Carreiras, M. (2006b) Do transposed-letter similarity effects occur at a syllable level? *Experimental Psychology* 53:308–15. [aRF]

Perea, M. & Carreiras, M. (2006c) Do transposed-letter effects occur across lexeme boundaries? *Psychonomic Bulletin and Review* 13:418–22. [aRF]

Perea, M. & Carreiras, M. (2008) Do orthotactics and phonology constrain the transposed-letter effect? *Language and Cognitive Processes* 23:69–92. [aRF]

Perea, M. & Estévez, A. (2008) Transposed-letter similarity effects in naming pseudowords: Evidence from children and adults. *European Journal of Cognitive Psychology* 20:33–46. [MP]

Perea, M. & Lupker, S. J. (2003) Transposed-letter confusability effects in masked form priming. In *Masked priming: The state of the art*, ed. S. Kinoshita & S. J. Lupker, pp. 97–120. Psychology Press. [aRF]

Perea, M. & Lupker, S. J. (2004) Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language* 51:231–46. [aRF]

Perea, M., Nakatani, C. & van Leeuwen, C. (2011b) Transposition effects in reading Japanese Kana: Are they orthographic in nature? *Memory and Cognition* 39:700–707. [MP]

Perea, M. & Perez, E. (2009) Beyond alphabetic orthographies: The role of form and phonology in transposition effects in Katakana. *Language and Cognitive Processes* 24:67–88. [aRF, CR]

Perea, M. & Rosa, E. (2000a) Repetition and form priming interact with neighborhood density at a short stimulus-onset asynchrony. *Psychonomic Bulletin and Review* 7:668–77. [aRF]

Perea, M. & Rosa, E. (2000b) The density constraint also occurs with unmasked, visible primes in the lexical decision task. *Current Psychology Letters* 2:61–72. [CJD]

Perea, M., Winskel, H. & Ratitamkul, T. (2012) On the flexibility of letter position coding during lexical processing: The case of Thai. *Experimental Psychology* 59:68–73. [MP]

Peressotti, F. & Grainger, J. (1999) The role of letter identity and letter position in orthographic priming. *Perception and Psychophysics* 61:691–706. [aRF]

Perfetti, C. A. (2003) The universal grammar of reading. *Scientific Studies of Reading* 7(1):3–24. [CP]

Perfetti, C. A. (2007) Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading* 11:357–83. [JGR]

Perfetti, C. A. (2011) Reading processes and reading problems: Progress toward a universal reading science. In: *Dyslexia across languages: Orthography and the brain-gene-behavior link*, ed. P. McCardle, B. Miller, J. R. Lee, & O. J. L. Tzeng, pp. 18–32. Brookes. [arRF, KR]

Perfetti, C. A. & Harris, L. N. (under review). Reading universals are modulated by language and writing system. *Language Learning and Development*. [CP]

Perfetti, C. A., Liu, Y., Fiez, J., Nelson, J., Bolger, D. J. & Tan, L-H. (2007) Reading in two writing systems: Accommodation and assimilation in the brain's reading network. .*Bilingualism: Language and Cognition* 10(2):131–46. [Special issue on "Neurocognitive approaches to bilingualism: Asian languages," ed. P. Li.] [rRF, CP]

Perfetti, C. A., Nelson, J., Liu, Y., Fiez, J & Tan, L.-H. (2010) The neural bases of reading: Universals and writing system variations. In: *The neural basis of reading*, ed. P. Cornelissen, M. Kringelbach & P. Hansen, pp. 147–72. Oxford University Press. [MSS]

Perruchet, P. & Pacton, S. (2006) Implicit learning and statistical learning: One phenomenon, two approaches. *Trends in Cognitive Sciences* 10:233–38. [aRF]

Perry, C., Ziegler, J. C. & Zorzi, M. (2007) Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review* 114:273–315. [CJD]

Perry, C., Ziegler, J. C. & Zorzi, M. (2010) Beyond single syllables: Large-scale modeling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology* 61:106–51. [CMcB-C, NJP]

Piantadosi, S. T., Tily, H. & Gibson, E. (2011) Word lengths are optimized for efficient communication. *Proceedings of the National Academy of Sciences USA* 108:3526–29. [aRF]

Pinel, P. & Dehaene, S. (2009) Beyond hemispheric dominance: Brain regions underlying the joint lateralization of language and arithmetic to the left hemisphere. *Journal of Cognitive Neuroscience* 22(1):48–66. [MS]

Pitchford, N. J., Ktori, M. & van Heuven, W. J. B. (2011) Inhibitory effects of exterior letter frequency on visual word recognition: Differential patterns across English and Greek. Paper presented at the 18th Annual Meeting of the Society for the Scientific Study of Reading, St. Pete Beach, Florida, July 13–16, 2011. Available at: http://www.triplesr.org/conference/archive/2011/11conf.php. [NJP]

Pitchford, N. J., Ledgeway, T. & Masterson, J. (2008) Effect of orthographic processes in letter position encoding. *Journal of Research in Reading* 31:97–116. [NJP]

Pitchford, N. J., Ledgeway, T. & Masterson, J. (2009) Reduced orthographic learning in dyslexic adult readers: Evidence from patterns of letter search. *Quarterly Journal of Experimental Psychology* 62:99–113. [NJP]

Plaut, D. C. & Gonnerman, L. M. (2000) Are non-semantic morphological effects incompatible with a distributed connectionist approach to lexical processing? *Language and Cognitive Processes* 15:445–85. [JGR]

Plaut, D. C., McClelland, J. L., Seidenberg, M. S. & Patterson, K. (1996) Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review* 103:56–115. [CJD, aRF, DCP]

Pollatsek, A., Tan, L. H. & Rayner, K. (2000) The role of phonological codes in integrating information across saccadic eye movements in Chinese character identification. *Journal of Experimental Psychology: Human Perception and Performance* 26:607–33. [JL]

Popple, A. V. & Levi, D. M. (2005) The perception of spatial order at a glance. *Vision Research* 45:1085–90. [MM]

Postal, P. (2003) (Virtually) Conceptually necessary. *Journal of Linguistics* 39:1–22. [CB]

Postal, P. (2004) *Skeptical linguistic essays*. Oxford University Press. [CB]

Price, C. J. & Devlin, J. T. (2011) The interactive account of ventral occipitotemporal contributions to reading. *Trends in Cognitive Sciences* 15:246–53. [MSS, MS]

Pulvermüller, F., Shtyrov, Y. & Hauk, O. (2009) Understanding in an instant: Neurophysiological evidence for mechanistic language circuits in the brain. *Brain and Language* 110(2):81–94. [BDH]

Rahamim, E. & Friedmann, N. (2009) Developmental letter position dyslexia. [In Hebrew]. *Literacy and Language* 2:79–109. [aRF]

Ramsey, S. R. (1987) *The languages of China*. Princeton University Press. [MSS]

Rastle, K. & Brysbaert, M. (2006) Masked phonological priming effects in English: Are they real? Do they matter? *Cognitive Psychology* 53:97–145. [JL]

Rastle, K. & Davis, M. H. (2008) Morphological decomposition based on the analysis of orthography. *Language and Cognitive Processes* 23:942–71. [arRF, KR]

Rastle, K., Davis, M. H. & New, B. (2004) The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin and Review* 11:1090–98. [LBF, arRF]

Ravid, D. (1995) *Language change in child and adult Hebrew*. Oxford University Press. [DR]

Ravid, D. (2001) Learning to spell in Hebrew: Phonological and morphological factors. *Reading and Writing* 14:459–85. [DR]

Ravid, D. (2005) Hebrew orthography and literacy. In: *Handbook of orthography and literacy*, ed. R. M. Joshi & P. G. Aaron, pp. 339–63. Erlbaum. [DR]

Ravid, D. (2012) *Spelling morphology: The psycholinguistics of Hebrew spelling*. Springer. [rRF, DR]

Rawlinson, G. (1976) *The significance of letter position in word recognition*. PhD thesis, Psychology Department, University of Nottingham, United Kingdom. Available at: http://psych.nyu.edu/pelli/pubs/rawlinson1976phd.zip. [DGP]

Rawlinson, G. (1999) Reibadailty. [Letter] *New Scientist* 162(2188):55. [DGP]

Rayner, K. (1975) The perceptual span and peripheral cues in reading. *Cognitive Psychology* 7:65–81. [rRF, JL]

Rayner, K. (1998) Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin* 124:372–422. [aRF]

Rayner, K. (2009) The thirty fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology* 62:1457–506. [aRF]

Rayner, K., Balota, D. A. & Pollatsek, A. (1986) Against parafoveal semantic pre-processing during eye fixations in reading. *Canadian Journal of Psychology* 40:473–83. [JL]

Rayner, K., Juhasz, B. J., White, S. J. & Liversedge, S. P. (2007) Does morphological processing in the parafovea influence eye movements in reading? Paper presented at the Fifth Workshop on Morphological Processing, Marseille, June 2007. [aRF]

Rayner, K. & Liversedge, S. P. (2011) Linguistic and cognitive influences on eye movements during reading. In: *The Oxford handbook of eye movements*, ed. S. Liversedge, I. Gilchrist, & S. Everling, pp. 751–66. Oxford University Press. [SPL]

Rayner, K. & McConkie, G. (1976) What guides a reader's eye movements? *Vision Research* 16:829–37. [MM]

Rayner, K., McConkie, G. W. & Ehrlich, S. F. (1978) Eye movements and integrating information across fixations. *Journal of Experimental Psychology: Human Perception and Performance* 4:529–44. [JL]

Rayner, K., McConkie, G. W. & Zola, D. (1980) Integrating information across eye movements. *Cognitive Psychology* 12:206–26. [JL]

Rayner, K., Well, A. D., Pollatsek, A. & Bertera, J. H. (1982) The availability of useful information to the right of fixation in reading. *Perception and Psychophysics* 31:537–50. [JL]

Rayner, K., White, S. J., Johnson, R. L. & Liversedge, S. P. (2006) Raeding wrods with jubmled lettres: There is a cost. *Psychological Science* 17:192–93. [aRF]

Rayner, K., White, S. J., Kambe, G., Miller, B. & Liversedge, S. P. (2003) On the processing of meaning from parafoveal vision during eye fixations in reading. In:

The mind's eye: Cognitive and applied aspects of eye movement research, ed. J. Hyönä, R. Radach & H. Deubel, pp. 213–34. North Holland. [JL]

Read, C. (1986) *Children's creative spelling*. Routledge. [UG]

Read, C. & Schreiber, P. (1982) Why short subjects are harder to find than long ones. In: *Language acquisition: The state of the art*, ed. E. Wanner & L. Gleitman, pp. 78–101. Cambridge University Press. [MC]

Reich, L., Szwed, M., Cohen, L. & Amedi, A. (2011) A ventral visual stream reading center independent of visual experience. *Current Biology* 21:363–68. [MS]

Reichle, E. D., Pollatsek, A., Fisher, D. L. & Rayner, K. (1998) Towards a model of eye movement control in reading. *Psychological Review* 105:125–57. [JL]

Reichle, E. D., Rayner, K. & Pollatsek, A. (2003) The E–Z Reader model of eye movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences* 26:445–526. [JL]

Richardson, U., Aro, M. & Lyytinen, H. (2011) Prevention of reading difficulties in highly transparent Finnish. In: *Dyslexia across languages: Orthography and the brain–gene–behavior link*, ed. P. McCardle, B. Miller, J. R. Lee, & O. J. L. Tzeng, pp. 62–75. Brookes. [aRF]

Roman, A., Kirby, J., Parrila, R., Wade-Woolley, L. & Deacon, S. H. (2009) Towards a comprehensive view of the skills involved in word reading in Grades 4, 6, and 8. *Journal of Experimental Child Psychology* 102:96–113. [SHD]

Rueckl, J. G. (2010) Connectionism and the role of morphology in visual word recognition. *The Mental Lexicon* 5:371–400. [aRF]

Rueckl, J. G. & Aicher, K. A. (2008) Are CORNER and BROTHER morphologically complex? Not in the long term. *Language and Cognitive Processes* 23:972–1001. [LBF]

Rueckl, J. G. & Rimzhim, A. (2011) On the interaction of letter transpositions and morphemic boundaries. *Language and Cognitive Processes* 26:482–508. [JH]

Rueckl, J. G. & Seidenberg, M. S. (2009) Computational modeling and the neural bases of reading and reading disorders. In: *How children learn to read: Current issues and new directions in the integration of cognition, neurobiology and genetics of reading and dyslexia research and practice*, ed. K. Pugh & P. McCardle, pp. 101–34. Taylor & Francis. [aRF]

Rumelhart, D. E. & McClelland, J. L. (1982) An interactive activation model of context effects in letter perception: Part 2. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review* 89:60–94. [aRF, MP]

Rumelhart, D. E. & McClelland, J. L. (1986) On learning the past tenses of English verbs. In: *Parallel distributed processing: Explorations in the microstructure of cognition: Vol. 2. Psychological and biological models*, ed. J. L. McClelland, D. E. Rumelhart, & the PDP Research Group, pp. 216–71. MIT Press. [aRF]

Saffran, J. R., Aslin, R. N. & Newport, E. L. (1996) Statistical learning by 8-month-old infants. *Science* 274:1926–28. [aRF]

Sampson, G. (2005) *The "language instinct" debate*. Continuum International. [DCP]

Sandra, D. (2007) Skills and representations in learning to spell and in experienced spellers. In: *The mental lexicon: Core perspectives*, ed. G. Jarema, pp. 207–27. Elsevier. [DR]

Schoonbaert, S. & Grainger, J. (2004) Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes* 19:333–67. [aRF]

Schwarzwald, O. R. (2001) *Modern Hebrew. Languages of the World: Materials*, vol. 127. Lincom Europa. [DR]

Seidenberg, M. S. (1992) Beyond orthographic depth in reading: Equitable division of labor. In: *Orthography, phonology, morphology, and meaning*, ed. R. Frost & L. Katz, pp. 85–118. Elsevier/North-Holland. [MSS]

Seidenberg, M. S. (2011) Reading in different writing systems: One architecture, multiple solutions. In: *Dyslexia across languages: Orthography and the brain-gene-behavior link*, ed. P. McCardle, B. Miller, J. R. Lee & O. J. L. Tzeng, pp. 146–68. Paul H. Brookes. [rRF, CP, DCP, JGR, MSS]

Seidenberg, M. S. & McClelland, J. L. (1989) A distributed, developmental model of word recognition and naming. *Psychological Review* 96:523–68. [aRF, CJD, JL]

Seki, A. (2011) Functional MRI studies on Japanese orthographies: Studies in reading development and reading difficulties. In: *Dyslexia across languages: Orthography and the brain-gene-behavior link*, ed. P. McCardle, B. Miller, J. R. Lee, & O. J. L. Tzeng, pp. 117–32. Brookes. [aRF]

Seuren, P. (2004) *Chomsky's minimalism*. Oxford University Press. [CB]

Seymour, P. H. K., Aro, M. & Erskine, J. M. (2003) Foundation of literacy acquisition in European orthographies. *British Journal of Psychology* 94:143–74. [aRF, JL]

Seymour, P. H. K. & Elder, L. (1986) Beginning reading without phonology. *Cognitive Neuropsychology* 3:1–36. [UG]

Shallice, T. & Warrington, E. K. (1977) The possible role of selective attention in acquired dyslexia. *Neuropsychologia* 15:31–41. [aRF]

Shamir, O., Sabato, S. & Tishby N. (2009) Learning and generalization with the information bottleneck. *Theoretical Computer Science* 410:2696–711. [aRF]

Share, D. L. (1995) Phonological recoding and self-teaching: *Sine qua non* of reading acquisition. *Cognition* 55(2):151–218.   [SHD, DLS]

Share, D. L. (1999) Phonological recoding and orthographic learning: A direct test of the self-teaching hypothesis. *Journal of Experimental Child Psychology* 72(2):95–129.   [SHD]

Share, D. L. (2008a) On the Anglocentricities of current reading research and practice: The perils of overreliance on an "outlier" orthography. *Psychological Bulletin* 134(4):584–615.   [MELB, SHD, arRF, DLS]

Share, D. L. (2008b) Orthographic learning, phonology and the self-teaching hypothesis. In: *Advances in child development and behavior, vol. 36*, ed. R. Kail, pp. 31–82. Elsevier.   [DLS]

Shetreet, E. & Friedmann, N. (2011) Induced letter migrations between words and what they reveal about the orthographic-visual analyzer. *Neuropsychologia* 49:339–51.   [aRF]

Shillcock, R., Ellison, T. M. & Monaghan, P. (2000) Eye-fixation behavior, lexical storage, and visual word recognition in a split processing model. *Psychological Review* 107:824–51.   [aRF]

Shimron, J. (2006) *Reading Hebrew: The language and the psychology of reading it*. Erlbaum.   [aRF, BDH]

Sigman, M. & Gilbert, C. D. (2000) Learning to find a shape. *Nature Neuroscience* 3:264–69.   [rRF]

Simos, P. G., Breier, J. I., Fletcher, J. M., Foorman, B. R., Castillo, E. M. & Papanicolaou, A. C. (2002) Brain mechanisms for reading words and pseudowords: An integrated approach. *Cerebral Cortex* 12(3):297–305.   [rRF, MS]

Slobin, D. I. (1996) From "thought and language" to "thinking for speaking." In: *Rethinking linguistic relativity*, ed. J. J. Gumperz & S. C. Levinson, pp. 97–114. Cambridge University Press.   [DR]

Smith, N. V. & Tsimpli, I.-M. (1995) *The mind of a savant: Language learning and modularity*. Blackwell.   [MC]

Snowling, M. J. & Hulme, C. (2005) Learning to read with a language impairment. In: *The science of reading: A handbook*, ed. M. J. Snowling & C. Hulme, pp. 397–412. Blackwell.   [CP]

Solomyak, O. & Marantz, A. (2010) Evidence for early morphological decomposition in visual word recognition. *Journal of Cognitive Neuroscience* 22(9):2042–57.   [rRF, MS]

Sproat, R. (2000) *A computational theory of writing systems*. Cambridge University Press.   [MSS]

Stanovich, K. E. & West, R. F. (1989) Exposure to print and orthographic processing. *Reading Research Quarterly* 21:360–407.   [SHD]

Steever, S. B. (1998) An introduction to the Dravidian languages. In: *The Dravidian languages*, ed. S. B. Steever, pp. 1–39. Routledge.   [MELB]

Still, M. L. & Morris, A. L. (2010) Interference from reversed anagram primes. Poster Paper presented at the 51st Annual Meeting of the Psychonomic Society, St. Louis, MO, November 18–21, 2010.   [CW]

Szwed, M., Cohen, L., Qiao, E. & Dehaene, S. (2009) The role of invariant features in object and visual word recognition. *Vision Research* 49:718–25.   [MS]

Szwed, M., Dehaene, S., Kleinschmidt, A., Eger, E., Valabregue, R., Amadon, A. & Cohen, L. (2011) Specialization for written words over objects in the visual cortex. *NeuroImage* 56(1):330–44.   [MS]

Taft, M. & Nillsen, C. (in press) Morphological decomposition and the transposed letter-effect. *Language and Cognitive Processes*.   [rRF]

Tan, L. H., Spinks, J. A., Feng, C. M., Siok, W. T., Perfetti, C. A., Xiong, J., Fox, P. T. & Gao, J. H. (2003) Neural systems of second language reading are shaped by native language. *Human Brain Mapping* 18:155–66.   [rRF]

Thomas, M. S. C. & van Heuven, W. J. B. (2005) Computational models of bilingual comprehension. In: *Handbook of bilingualism: Psycholinguistic approaches*, ed. J. F. Kroll & A. M. B. de Groot, pp. 202–25. Oxford University Press.   [NJP]

Tishby, N., Pereira, F. C. & Bialek, W. (1999) The information bottleneck method. In: *Proceedings of the 37th Annual Allerton Conference on Communication, Control and Computing, Monticello, IL, September 1999*, ed. B. Hajek & R. S. Sreenivas, pp. 368–77. University of Illinois Press.   [aRF]

Tishby, N. & Polani, D. (2010) Information theory of decisions and actions. In: *Perception-reason-action cycle: Models, algorithms and systems*, ed. V. Cutsuridis, A. Hussain & J. G. Taylor, pp. 601–36. Springer.   [aRF]

Tong, X. & McBride-Chang, C. (2010) Developmental models of learning to read Chinese words. *Developmental Psychology* 46:1662–76.   [SHD]

Treiman, R. (1993) *Beginning to spell: A study of first-grade children*. Oxford University Press.   [UG]

Treiman, R., Goswami, U., Tincoff, R. & Leevers, H. (1997) Effects of dialect on American and British children's spelling. *Child Development* 68:229–45.   [UG]

Treiman, R., Mullennix, J., Bijeljac-Babic, R. & Richmond-Welty, E. D. (1995) The special role of rimes in the description use and acquisition of English orthography. *Journal of Experimental Psychology: General* 124:107–36.   [aRF]

Tsai, J. L., Lee, C. Y., Tzeng, O. J. L., Hung, D. L. & Yan, N. S. (2004) Use of phonological codes for Chinese characters: Evidence from processing of parafoveal preview when reading sentences. *Brain and Language* 91:235–44.   [JL]

Tsang, Y.-K. & Chen, H.-C. (2010) Morphemic ambiguity resolution in Chinese: Activation of the subordinate meaning with a prior dominant-biased context. *Psychonomic Bulletin and Review* 17:875–81.   [CMcB-C]

Tydgat, I. & Grainger, J. (2009) Serial position effects in the identification of letters, digits, and symbols. *Journal of Experimental Psychology: Human Perception and Performance* 35(2):480–98. doi:10.1037/a0013027.   [CW]

Ullman, S. (2007) Object recognition and segmentation by a fragment-based hierarchy. *Trends in Cognitive Sciences* 11(2):58–64.   [MS]

Uriagereka J. (1998) *Rhyme and reason: An introduction to minimalist syntax*. MIT Press.   [CB]

Vaid, J. & Gupta, A. (2002) Exploring word recognition in a semi-alphabetic script: The case of Devanagari. *Brain and Language* 81:679–90.   [CR]

Vallar, G., Burani, C. & Arduino, L. S. (2010) Neglect dyslexia: A review of the neuropsychological literature. *Experimental Brain Research* 206: 219–35.   [NF]

Van Assche, E. & Grainger, J. (2006) A study of relative-position priming with superset primes. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 32:399–415.   [aRF]

van Heuven, W. J. B. & Conklin, K. (2007) Effects of cross-linguistic orthographic and phonological similarity in Chinese–English bilinguals. Paper presented at the 15th Meeting of the European Society for Cognitive Psychology, Marseille, France, August 29–September 1, 2007. Abstract available at: http://sites.univ-provence.fr/wlpc/escop07_2/proceedings_ESCOP2007.pdf.   [NJP]

Van Orden, G. C. (1987) A ROWS is a ROSE: Spelling, sound, and reading. *Memory and Cognition* 15:181–98.   [JL]

Velan, H., Deutsch, A. & Frost, R. (in press) The flexibility of letter-position flexibility: evidence from eye-movements in reading Hebrew.   [rRF]

Velan, H. & Frost, R. (2007) Cambridge University vs. Hebrew University: The impact of letter transposition on reading English and Hebrew. *Psychonomic Bulletin and Review* 14(5):913–18.   [aRF, KK]

Velan, H. & Frost, R. (2009) Letter-transposition effects are not universal: The impact of transposing letters in Hebrew. *Journal of Memory and Language* 61:285–320.   [CJD, aRF]

Velan, H. & Frost, R. (2011) Words with and without internal structure: What determines the nature of orthographic and morphological processing? *Cognition* 118:141–56.   [arRF, PG, MP, DCP]

Velan, H., Frost, R., Deutsch, A. & Plaut, D. (2005) The processing of root morphemes in Hebrew: Contrasting localist and distributed accounts. *Language and Cognitive Processes* 29:169–206.   [aRF]

Vinckier, F., Dehaene, S., Jobert, A., Dubus, J. P., Sigman, M. & Cohen, L. (2007) Hierarchical coding of letter strings in the ventral stream: Dissecting the inner organization of the visual word form system. *Neuron* 55:143–56.   [MS]

Wagner, R. K. & Barker, T. A. (1994) The development of orthographic processing ability. In: *The varieties of orthographic knowledge: Theoretical and developmental issues*, ed. V. W. Berninger, pp. 243–76. Kluwer Academic.   [SHD]

Wang, C. & Peng D. (2000) 重复启动作业中词的语义透明度的作用 [The role of semantic transparencies in the processing of compound words]. *Acta Psychologica Sinica* 32:127–32.   [NJP]

Wang, F., Tsai, Y. & Wang, W. S.-Y. (2009) Chinese literacy. In: *Cambridge handbook on literacy*, ed. D. Olson & N. Torrance, pp. 386–417. Cambridge University Press.   [aRF]

Wang, W. S.-Y. (1981) Language structure and optimal orthography. In: *Perception of print: Reading research in experimental psychology*, ed. O. J. L. Tzeng & H. Singer, pp. 223–36. Erlbaum.   [aRF]

Webb, T. M., Beech, J. R., Mayall, K. M. & Andrews, A. S. (2006) It's what's on the outside that matters: An advantage for external features in children's word recognition. *Journal of Experimental Child Psychology* 94:163–81.   [NJP]

White, S. J, Bertram, R & Hyönä, J. (2008) Semantic processing of previews within compound words. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 34:988–93.   [JL]

Whitney, C. (2001) How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin and Review* 8(2):221–43.   [JSB, arRF, JG, CW]

Whitney, C. (2008) Supporting the serial in the SERIOL model. *Language and Cognitive Processes* 23(6):824–65.   [aRF, CW]

Whitney, C. (2011) Location, location, location: How it affects the neighborhood (effect). *Brain and Language* 118(3):90–104. doi:10.1016/j.bandl.2011.03.001.   [CW]

Whitney, C. & Cornelissen, P. (2005) Letter-position encoding and dyslexia. *Journal of Research in Reading* 28(3):274–301.   [aRF, CW]

Whitney, C. & Cornelissen, P. (2008) SERIOL reading. *Language and Cognitive Processes* 23(1):143–64. doi:10.1080/01690960701579771.   [arRF, CW]

Wimmer, H. & Goswami, U. (1994) The influence of orthographic consistency on reading development: Word recognition in English and German children. *Cognition* 51:91–103.   [JL]

Winkler, I., Denham, S. L. & Nelken, I. (2009) Modeling the auditory scene: Predictive regularity representations and perceptual objects. *Trends in Cognitive Science* 13:532–40. [rRF]

Wittgenstein, L. (1953) *Philosophical Investigations*, trans. G. E. M. Anscombe. Basil Blackwell. [rRF]

Wong, A. W. K. & Chen, H.-C. (in press) Is syntactic-category processing obligatory in visual word recognition? Evidence from Chinese. *Language and Cognitive Processes*. doi:10.1080/01690965.2011.603931. [CMcB-C]

Woodworth, R. S. (1938) *Experimental psychology*. Holt. [DGP]

Wydell, T. N. & Kondo, T. (2003) Phonological deficit and the reliance on orthographic approximation for reading: A follow-up study on an English–Japanese bilingual with monolingual dyslexia. *Journal of Research in Reading* 26:33–48. [aRF]

Yamada, J. & Banks, A. (1994) Evidence for and characteristics of dyslexia among Japanese children. *Annals of Dyslexia* 44:105–19. [aRF]

Yan, M., Richter, E. M., Shu, H. & Kliegl, R. (2009) Chinese readers extract semantic information from parafoveal words during reading. *Psychonomic Bulletin & Review* 16:561–66. [JL]

Yan, M., Zhou, W., Shu, H. & Kliegl, R. (in press) Lexical and sub-lexical semantic preview benefits in Chinese reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. doi:10.1037/a0026935. Available at: http://psycnet.apa.org/psycinfo/2012-05107-001/. [JL]

Yap, M. J., Balota, D. A., Sibley, D. E. & Ratcliff, R. (2012) Individual differences in visual word recognition: Insights from the English Lexicon Project. *Journal of Experimental Psychology: Human Perception and Performance* 38:53–79. [JGR]

Yen, M. H., Tsai, J. L., Tzeng, O. J. & Hung, D. L. (2008) Eye movements and parafoveal word processing in reading Chinese. *Memory and Cognition* 36:1033–45. [JL]

Zhang, T., van Heuven, W. J. B. & Conklin, K. (2011) Fast automatic translation and morphological decomposition in Chinese–English bilinguals. *Psychological Science* 22:1237–42. [NJP]

Zhou, X. & Marslen-Wilson, W. (2000) The relative time course of semantic and phonological activation in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 26:1245–65. [JL]

Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faísca, L., Saine, N., Lyytinen, H., Vaessen, A. & Blomert, L. (2010) Orthographic depth and its impact on universal predictors of reading: A cross-language investigation. *Psychological Science* 21(4):551–59. [aRF]

Ziegler, J. C. & Goswami, U. (2005) Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin* 131:3–29. [aRF, JGR]

Zorzi, M., Houghton, G. & Butterworth, B. (1998) Two routes or one in reading aloud? A connectionist dual-process model. *Journal of Experimental Psychology: Human Perception and Performance* 24:1131–61. [aRF]