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

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**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

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**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