UC Berkeley
UC Berkeley Previously Published Works

Title
Theories of reading should predict reading speed

Permalink
https://escholarship.org/uc/item/71h303td

Journal
Behavioral and Brain Sciences, 35(5)

ISSN
0140-525X

Authors
Pelli, Denis G
Chung, Susana TL
Legge, Gordon E

Publication Date
2012-10-01

DOI
10.1017/s0140525x12000325

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

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

doi:10.1017/S0140525X12000325

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

doi:10.1017/S0140525X12000118

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