Journal of Memory and Language 77 (2014) 40–58

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

What can we learn from learning models about sensitivity to letter-order in visual word recognition?

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ARTICLE INFO

Article history:
Received 23 August 2013
revision received 14 August 2014
Available online 8 October 2014

Keywords:
Connectionist modeling
Fundamentalist modeling
Letter-position coding
Letter-transposition effect
Cross-linguistic differences

ABSTRACT

Recent research on the effects of letter transposition in Indo-European Languages has shown that readers are surprisingly tolerant of these manipulations in a range of tasks. This evidence has motivated the development of new computational models of reading that regard flexibility in positional coding to be a core and universal principle of the reading process. Here we argue that such approach does not capture cross-linguistic differences in transposed-letter effects, nor does it explain them. To address this issue, we investigated how a simple domain-general connectionist architecture performs in tasks such as letter-transposition and letter substitution when it had learned to process words in the context of different linguistic environments. The results show that in spite of the neurobiological noise involved in registering letter-position in all languages, flexibility and inflexibility in coding letter order is also shaped by the statistical orthographic properties of words in a language, such as the relative prevalence of anagrams. Our learning model also generated novel predictions for targeted empirical research, demonstrating a clear advantage of learning models for studying visual word recognition.

Introduction

In the last decade a large number of studies have consistently reported that readers are surprisingly tolerant to letter transpositions. This aspect of visual word recognition, often labeled as "The Cambridge University effect" (an alleged study conducted at Cambridge University showing that readers do not care about the order of letters), has been the focus of extensive research, heated debates, and impressive modeling efforts. Overall, studies that experimentally examined the impact of manipulating letter-order on reading performance have shown a very 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., jugde-JUDGE; Duñabeitia, Perea, & Carreiras, 2007; Johnson, Perea, & Rayner, 2007; Kinoshita & Norris, 2009; Perea & Carreiras, 2006a, 2006b, 2008; Perea & Lupker, 2003, 2004; Rayner, White, Johnson, & Liversedge, 2006; Schoonbaert & Grainger, 2004). Transposed-letter (TL) effects were reported in a variety of European languages such as English (e.g., Perea, 2003), French (Schoonbaert, 2004), and Spanish (Perea & Carreiras, 2006a, 2006b), but also for non-European alphabetic languages such as Basque (Duñabeitia et al., 2007), and Japanese Katakana (Perea & Perez, 2009).

The apparent indifference of readers to letter order converged with experimental findings such as relative

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http://dx.doi.org/10.1016/j.jml.2014.09.002
0749-596X/

position priming (Humphreys et al., 1990), and subset priming (Peressotti & Grainger, 1999), and was consequently taken to be a hallmark of reading. Its implications to modeling visual word recognition resonated with mounting theoretical discussions regarding *the alignment problem* (Davis, 1999), according to which, words are recognized irrespective of the absolute position of their letters (e.g., CAT, TREECAT), so that their letter identification must be context-sensitive and (relatively) position invariant. Because prior computational models of orthographic processing encoded letter positions in rigid and absolute terms (e.g., the Interactive Activation Model, IAM, McClelland & Rumelhart, 1981) and models of orthographic-to-phonological correspondences made similar peripheral assumptions about rigid orthographic coding (e.g., the Dual-Route Cascaded model, DRC, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; the Connectionist Dual Process Model, CDP, Plaut, McClelland, Seidenberg, & Patterson, 1996; Zorzi, Houghton, & Butterworth, 1998), they were taken to miss a critical component of orthographic processing – fuzziness in coding letter-position. This limitation led the way for a new generation of models that focused on producing letter-coding schemes and computational solutions that were non-rigid (e.g., the SERIOL model, Whitney, 2001; the SOLAR model, Davis, 1999; the Spatial Coding model, Davis, 2010; the Bayesian Reader model, Kinoshita & Norris, 2009; the Overlap model, Gomez, Ratcliff, & Perea, 2008).

The new models of reading naturally differ in their initial aims and in the scope of phenomena they describe. However, recent discussions regarding their *descriptive adequacy* have centered to a large extent on their relative ability to reproduce and fit the growing body of empirical data regarding readers' resiliency to letter-jumbling, given different types of distortion in the sequence of letters. While this approach has advanced us in outlining the possible constraints imposed on the front-end of the reading system, it also had a critical disadvantage. From an empirical perspective, consistent findings have shown that TL priming effects are not universal but restricted to a family of languages (Frost, 2012a). For example, reading in Semitic languages such as Hebrew and Arabic is characterized by extreme letter-coding precision (Perea, abu Mallouh, & Carreiras, 2010; Velan & Frost, 2007, 2009, 2011).[1] Thus, transposing the prime's letters in Hebrew or Arabic does not yield a strong facilitation of target recognition as in Indo-European languages, and sometimes even hinders it (Velan & Frost, 2009, 2011).[2] Similarly, presenting sentences that contain TL words in rapid serial visual presentation results in strikingly poor reading performance in Hebrew but not in English (Velan & Frost, 2007). Recent studies from Korean (Lee & Taft, 2009, 2011) also indicate that letter-transposition effects are not obtained in the alphabetic Korean Hangul as they are in European languages. These cross-linguistic differences regarding the impact of letter-transpositions are critical for understanding visual word recognition and should be taken as important constraints while modeling it. Because most recent models of reading have exclusively focused on languages that show insensitivity to transposed letter effects, they miss the well-established cross-linguistic variability in positional encoding necessary in a general account. More important, from a theoretical perspective, understanding *the source* of differences in sensitivity to letter-position is critical for assessing the explanatory adequacy of any model of reading (see Frost, 2012a for an extensive discussion).

In the case of TL effects, the debate has centered on what it is that determines (or allows for the emergence of) insensitivity to letter order. For many recent modelers of visual word recognition the working hypothesis was that this reflects a hardwired neurobiological constraints in coding position of sequentially aligned visual stimuli given the inherent noise characteristic of the visual processing system (see Grainger, Dufau, Montant, Ziegler, & Fagot, 2012; Norris & Kinoshita, 2012; Szwed, Vinckier, Cohen, & Dehaene, 2012). For example, in open-bigram models (e.g., Whitney, 2001), it is claimed that the brain encodes words based on the presence of all ordered combinations of two letters appearing in a given word (e.g., encoding the word 'form' as the collective bigrams 'fo', 'or', 'rm', 'fr', 'om', and 'fm'). By this view, TL priming effects mirror the way in which the human brain encodes the position of letters in printed words in any language (e.g., Grainger & Whitney, 2004; Whitney, 2001; Dehaene, Cohen, Sigman, & Vinckier, 2005), where letters are often taken as two-dimensional objects processed by the visual system (e.g., Grainger et al., 2012; Norris & Kinoshita, 2012). In contrast, in a recent review of TL effects across writing systems, Frost (2012a) has argued that the overall findings regarding letter-position insensitivity cannot be described and explained simply by assuming a predetermined characteristic of the brain's neurocircuitry that processes orthographic information. Rather, it is an emergent particular consequence of the neural system's interaction with the *linguistic* properties of European languages, reflecting an efficient optimization of encoding resources. By this account, in European languages printed words generally (albeit with some exceptions) differ by the *identity* of their constituent letters, so that different sets of letters are assigned to different words. Consequently, printed words can still be easily recognized even when their letters are transposed. In contrast, in Semitic languages, words are formed by inserting a tri-consonantal root into fixed phonological word-patterns (see Frost, Forster, & Deutsch, 1997, for a detailed description), and the root letters are the initial target of orthographic processing (e.g., Frost, Kugler, Deutsch, & Forster, 2005). Because many roots share a subset of three letters but in a different order, words often differ by the *order* of these letters rather than by their mere identity. This cross-linguistic difference is reflected by the differential prevalence of anagrams in European versus Semitic languages: Whereas in English, French, or Spanish anagrams are mostly incidental exceptions, in Hebrew or Arabic anagrams are very common (Velan & Frost, 2011).

[1] Here we emphasize that letter-coding precision in Semitic languages is characteristic of lexical and reading tasks. Non-lexical tasks such as the same-different tasks do show fuzzy-letter coding in Hebrew as well (Kinoshita, Norris, & Siegelman, 2012).

[2] TL effects for Semitic words range from −11 ms to +8 ms depending on prime condition. TL effects for Hebrew non-Semitic words yield facilitation of 20 ms, similar to that of European languages (Velan & Frost, 2009, 2011).