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Orthographic units in the absence of visual processing: Evidence from sublexical structure in braille

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ABSTRACT

Reading relies on the recognition of units larger than single letters and smaller than whole words. Previous research has linked sublexical structures in reading to properties of the visual system, specifically on the parallel processing of letters that the visual system enables. But whether the visual system is essential for this to happen, or whether the recognition of sublexical structures may emerge by other means, is an open question. To address this question, we investigate braille, a writing system that relies exclusively on the tactile rather than the visual modality. We provide experimental evidence demonstrating that adult readers of (English) braille are sensitive to sublexical units. Contrary to prior assumptions in the braille research literature, we find strong evidence that braille readers do indeed access sublexical structure, namely the processing of multi-cell contractions as single orthographic units and the recognition of morphemes within morphologically-complex words. Therefore, we conclude that the recognition of sublexical structure is not exclusively tied to the visual system. However, our findings also suggest that there are aspects of morphological processing on which braille and print readers differ, and that these differences may, crucially, be related to reading using the tactile rather than the visual sensory modality.

1. Introduction

Written language is a relatively recent cultural invention that lies at the intersection of spoken language and vision. Given its recent emergence in human evolution, the neural substrates of written language cannot possibly be predetermined by the genetic code. Rather, learning to read and write is based on facility with spoken language (Goswami & Bryant, 1990; Mattingly, 1972; Melby-Lervåg, Lyster, & Hulme, 2012; Treiman & Baron, 1981; Wagner & Torgesen, 1987); and word recognition is based in domain-general characteristics of the visual system such as feature identification, pattern recognition, and object perception (Behrmann & Plaut, 2015; Malach, Levy, & Hasson, 2002; Nestor, Behrmann, & Plaut, 2012; Wandell, 2011). In addition to its general role in facilitating word recognition, several lines of research suggest that properties of the visual system may actually motivate and constrain the structure of orthographic representations (Changizi, Zhang, Ye, & Shimojo, 2006): (1) There are systematic commonalities in the shapes that make up orthographic characters across languages that have been linked to the kinds of shapes the visual system has evolved to perceive (Changizi et al., 2006). (2) The visual system is capable of parallel processing (Cave & Wolfe, 1990), and most theories of visual word reading assume that letters are processed in parallel in at least some parts of the reading system (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Davis, 2010; Harm & Seidenberg, 1999; McClelland & Rumelhart, 1981; Perry, Ziegler, & Zorzi, 2007; Reichle, Rayner, & Pollatsek, 2003, cf. Whitney, 2008). There is increasing evidence that in the literate adult brain, written language depends on richly structured orthographic representations that are largely independent of the spoken language that they represent (Caramazza & Miceli, 1990; Fischer-Baum & Rapp, 2014; Rapp, Fischer-Baum, & Miozzo, 2015). In the writing systems of many languages, including English, orthographic representations make use of rich sublexical structure, such as digraphs and morphemes, the recognition of which has also been shown to have a strong basis in the visual system (Doignon & Zagar, 2005; Prinzmetal, 1990; Prinzmetal, Hoffman, & Vest, 1991; Prinzmetal, Treiman, & Rho, 1986; Rapp, 1992). As previous research has overwhelmingly demonstrated that the visual system plays a central role in facilitating reading and shaping orthographic representation, this paper seeks to explore the nature of this relationship by addressing a basic ontological question: is visual processing a strict prerequisite for the recognition of sublexical structure in reading? This paper seeks to answer this question by presenting evidence from two experiments with proficient adult

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readers of English braille, a writing system that relies on the tactile rather than the visual modality.

Braille provides a potentially fruitful area of exploration for reading researchers in at least three respects. First, understanding the perceptual and cognitive mechanisms underlying tactile reading offers insights into alternative pathways by which reading may take place, and broadens our understanding of what 'reading' must be understood to be – in the same way that our knowledge of reading is informed and enriched by the diverse types of writing systems found in the world's languages (logographic, syllabic, alphabetic, etc.), and by the diversity of languages themselves in terms of syntax, morphology, phonology, and the orthographic depth of their writing systems. Secondly, an examination of reading in the absence of the visual system may contribute to a more nuanced understanding of how visual reading works, and therefore indirectly contribute to the refinement of theories of visual reading. Thirdly, braille may provide insight regarding the influence of sensory modality on orthographic representation (Carreiras & Alvarez, 1999; Perea, García-Chamorro, Martín-Suesta, & Gómez, 2012; Perea, Jiménez, Martín-Suesta, & Gómez, 2015; Reich, Szwed, Cohen, & Amedi, 2011). We take this third approach as our point of departure for this paper, presenting two lines of experimental evidence examining whether adult readers of (English) braille are sensitive to sublexical units. We compare this evidence with evidence for these same types of sublexical units as typically reported for adult readers of (English) print.

1.1. Background

Broadly speaking, proposals for sublexical structure can be divided into two types. The first is the identification of multi-letter substrings that are processed as single units, like digraphs – multi-letter combinations that are associated with a single phoneme, for example the SH in FISH. The second involves the parsing of a whole string into meaningful subunits, like recognizing that the word RERUN is composed of the prefix RE and the stem RUN. Both types of sublexical structure play a crucial role in print reading, but there has been a lack of systematic research to investigate what role, if any, these sublexical structures play in braille reading. We examine both types of sublexical structure in braille readers.

Digraphs – multi-letter combinations that are associated with a single phoneme – have been argued to function as perceptual units in reading, such that the six letter string *wreath* is parsed into three digraph units, one representing [WR], one [EA] and one [TH] (Perry, Ziegler, & Zorzi, 2010; cf. Lupker, Acha, Davis, & Perea, 2012). Evidence for orthographic chunking of letter combinations associated with a specific phoneme comes from a variety of sources. Rey, Ziegler, and Jacobs (2000) report more difficulty in identifying a single letter in a written word when it occurs within a digraph – the letter O in *boat* – compared to when it does not – the letter O in *host* (see also Rey & Schiller, 2005). Martensen, Maris, and Dijkstra (2003; Experiment 1) demonstrate that words are more difficult to recognize if they are presented with visual "violations" of digraph structure (e.g. *wre//ath* is harder to recognize than *wr//eath* or *wrea//th*, see also Dickerson, 1999; Joubert & Lecours, 2000; Pring, 1981). In visual word recognition, it has been argued that multi-letter strings can operate as single units in the orthographic representation (see also Fischer-Baum & Rapp, 2014 for a similar argument in written production).

Morphemes – minimal units of meaning or grammatical function – are the basic semantic building blocks of words. English morphemes can be classified into two broad types: stems (the core meaning of the word) and affixes (prefixes or suffixes that lend derivational or inflectional meaning to the stem). The morphologically complex English word RUNNERS, for example, consists of the stem RUN, the derivational agentive suffix -ER, and the inflectional plural suffix -S. Morphological Awareness is an essential component of the reading process (e.g. Berko, 1958; Nagy, Berninger, & Abbott, 2006; Treiman, Cassar, & Zukowski, 1994). The unconscious recognition of morphemes in orthography enables regular and rapid segmentation of morphologically complex words and access to their meanings. Morphological structure is represented at many levels of the language system; at a syntactic level, morphological structure plays a critical role in making words fit into sentences grammatically (e.g. "The man is catch<u>ing</u> a fish" is grammatical while *"The man is catch<u>es</u> a fish" is ungrammatical). At a semantic level, morphological structure allows for the comprehension of compositional meanings and novel forms (e.g. I may have never heard the word PRERUN before, but I could guess that it means something that you do prior to the act of running). Many theories of visual word recognition posit orthography-specific morphological mechanisms that identify the set of orthographic morphological constituents that form the letter string (e.g., Rastle & Davis, 2008). Unlike digraphs, however, which can be immediately recognized when two letters co-occur, morphological sublexical structure requires access to the entire string of letters first, before a word can be parsed into morphemes. RETRY can be parsed into a prefix and a stem, while RETCH cannot; although the same two letters (RE) appear in both words, TRY is a stem but TCH is not. In other words, in order to recognize RE- as a prefix in RETRY but not in RETCH, the reader must have access to (most of) the remaining letters in the word beyond RE, and a number of experimental results have demonstrated that this parsing happens early in word-recognition and is based solely on visual form—a process referred to as morpho-orthographic decomposition.

Evidence for morpho-orthographic decomposition comes primarily from the effect of pseudomorphological and morphologically-opaque words in masked priming experiments (for a thorough overview, see Rastle & Davis, 2008). Such words are monomorphemic stems whose surface orthography falsely suggests they comprise multiple morphemes, such as BROTHER or CORNER. Orthographically, these two words appear to consist of the suffix -ER attached to the stems BROTH and CORN respectively; but they are actually monomorphemic stems and are not decomposable into smaller units of meaning (a BROTHER is not someone who 'broths', and a CORNER has nothing to do with 'corn'). The key findings in the masked priming studies are that pseudomorphological and morphologically-opaque words prime their (false) stems just like semantically-transparent morphologically complex words do. In other words CORNER primes CORN just like DARKNESS primes DARK. These results suggest that morpho-orthographic decomposition cannot be based in the semantics of a form-meaning pairing, since the (false) stems are not a component of the word's meaning. Furthermore, orthographically similar words like BROTHEL, which have no surface morphology (-EL is not analyzable as a suffix), do not prime their (false) stems; in other words, BROTHER primes BROTH but BROTHEL does not. Therefore, this result must be due to morphological processes and not orthographic similarity, as it is only observed when words can be parsed into multiple surface morphemes (Allen & Badecker, 1999; Diependaele, Sandra, & Grainger, 2005; Fiorentino & Fund-Reznicek, 2009; Longtin, Segui, & Halle, 2003; McCormick, Rastle, & Davis, 2008; Rastle, Davis, & New, 2004). Thus, the weight of the evidence shows that rapid decomposition of morphemically-complex words begins solely based on orthography, early in the process of visual-word recognition, which suggests, again, that the visual system is central in the detection of sublexical structure.

Many lines of research have highlighted the ways in which print words are read not as simply a linear string of letters, but through processes that rely on rich sublexical structure. Less attention has been paid to the question of where this type of sublexical structure comes from. It is typically assumed that the segmentation of written words into sublexical structures depends on properties of the visual system, specifically the parallel processing of letters. Whether the