Visual letter similarity effects during sentence reading: Evidence from the boundary technique

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ABSTRACT

The study of how the cognitive system encodes letter identities from the visual input has received much attention in models of visual word recognition but it has typically been overlooked in models of eye movement control in reading. Here we examined how visual letter similarity affects early word processing during reading using Rayner's (1975) boundary change technique in which the parafoveal preview of the target word was either identical (e.g., *frito-frito* [*fried*]) or a one-letter-different nonword (e.g., *frjto-frito* vs. *frgto-frito*). Critically, the substituted letter in the nonword was visually similar (based on letter confusability norms) or visually dissimilar. Results showed shorter viewing times on the target word when the parafoveal preview was visually similar than when it was visually dissimilar. Thus, visual letter similarity modulates the integration of parafoveal and foveal information during sentence reading. Future implementations of models of eye movement control in reading should incorporate a more developed orthographic-lexical module to capture these effects.

1. Introduction

When reading, adults show a remarkable ability to access the appropriate lexical entry among thousands of potential competitors—some of them perceptually similar (e.g., compare *moose* vs. *mouse* or *calm* vs. *clam*)—in 150–300 ms (see Rayner, Pollatsek, Ashby, & Clifton, 2012, for review). This process requires a set of highly efficient operations that extract the identity and the order of the letters that compose each word (Grainger, 2018). In hierarchical models of letter/word recognition (e.g., see Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Rey, & Dufau, 2008, for neural models), the visual features of the letters are combined by shape-specific letter detectors (e.g., "a" and "*a*", but not "A", activate the shape-specific letter detector of the letter "a"). These letter detectors are in turn, combined by complex, case-insensitive letter detectors (e.g., "a", "*a*", and "A" would activate the complex letter detector of "a"), which, in turn, drive the process of lexical access. Although a detailed account of the orthographic processes that underlie lexical access is necessary for a full comprehensive model of eye movement control during reading (Reichle, 2015), the most influential models of eye movement control in reading (e.g., E-Z Reader model, Reichle, Pollatsek, Fisher, & Rayner, 1998; SWIFT model, Engbert, Nuthmann, Richter, & Kliegl, 2005) have not yet implemented detailed modules of orthographic and lexical processing.

Prior research using word recognition tasks (e.g., lexical decision,

naming, semantic categorization) has consistently shown that orthographic processing (i.e., letter identity and letter order) is subject to perceptual uncertainty in the early moments of lexical access (e.g., the pseudoword *nevtral* would generate a similar perceptual input as the word *neutral*), which is eventually resolved (see Marcet & Perea, 2018, for review). Using Forster and Davis' (1984) masked priming technique, words with visually similar embedded letter-like digits (e.g., *M473R14L*) are more effective at activating their base words (*MATERIAL*) than visually dissimilar controls (e.g., *M629R32L*) (Perea, Duñabeitia, & Carreiras, 2008). That is, the digit *4* in *M473R14L* activates the letter detector corresponding to the visually similar letter *A*. Furthermore, Marcet and Perea (2017) found that word response times to a target word (e.g., *NEUTRAL*) were faster when the one-letter different prime was visually similar (*nevtral*) than when it was visually dissimilar (*neztral*)—word identification times to *nevtral-NEUTRAL* were only slightly longer than those to *neutral-NEUTRAL* (see also Marcet & Perea, 2018, for evidence with multi-letter homoglyphs [e.g., *docurnent-DOCUMENT* faster than *docusnent-DOCUMENT*]). Taken together, these findings favor the view that in the initial moments of word processing, there is some uncertainty concerning letter identity for highly visually similar letters (e.g., *nevtral* produces a similar perceptual input as *neutral*). In order to shed more light on the time course of the effects of visual letter similarity during word recognition, Gutiérrez-Sigut, Perea, and Marcet (2018) conducted two masked priming

experiments while measuring event-related potentials—they used the same materials as Marcet and Perea (2017). Gutiérrez-Sigut et al. found that, at an early time-window associated with orthographic processing (N250; see Grainger & Holcomb, 2009, for review), the ERP waves for the identity condition (e.g., *neutral-NEUTRAL*) and the visually similar condition (*nevtral-NEUTRAL*) behaved similarly, while the visually dissimilar condition (*neztral-NEUTRAL*) produced a larger negativity. This is consistent with the idea of an early perceptual uncertainty concerning letter identity for visually similar letters. In addition, at a later time-window associated to lexico-semantic component (N400), the visually similar condition (*nevtral-NEUTRAL*) produced a larger negativity than the identity condition. This latter finding suggests that the uncertainty concerning letter identity is resolved over time.

The issue under scrutiny in the current experiment is whether these visual letter similarity effects that have been found in word identification tasks with the masked priming technique can be generalized to normal reading. When we read text, we extract information not only from the fixated word, but also from the following word/s in the parafovea (see Rayner et al., 2012, for review). Importantly, information in the parafovea has shown to impact the processing of the word once it is fixated in the fovea, hence this allows for an ecological scenario to examine visual letter similarity effects during the early stages of word processing. An excellent technique to tap these early word identification processes during text reading is Rayner's (1975) gaze-contingent boundary change paradigm. Rayner's boundary change technique allows for the manipulation of parafoveal information that is available to the reader before the foveal processing of a target word (see Fig. 1 for a depiction of the technique). Importantly, although the text may be altered, readers are typically unaware of these changes. Similarly to the masked priming technique, the boundary technique examines the relationship between a prime stimulus and a target stimulus (e.g., the parafoveal previews *nevtral* or *neztral* and the target word *neutral*). Results from this paradigm have revealed that the nature of the codes integrated across fixations is orthographic (or phonological) rather than visual. As found by McConkie and Zola (1979) and Rayner, McConkie, and Zola (1980), changing the case of words from fixation to fixation (e.g., *cHaIr → ChAiR*) does not interfere with reading. Likewise, in a
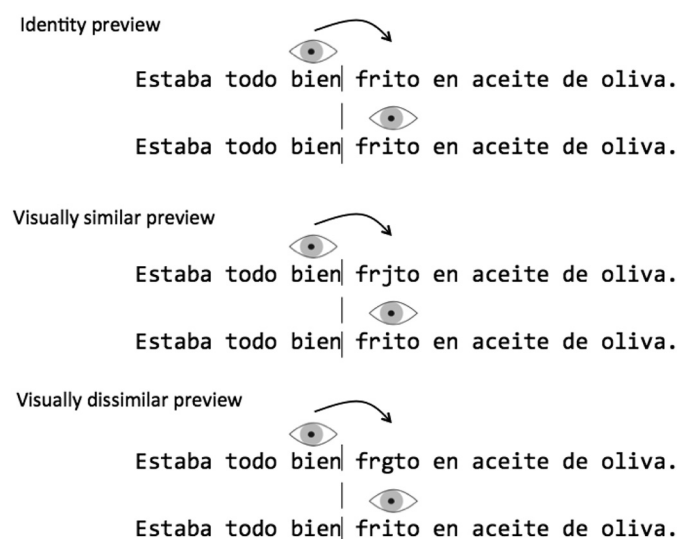
change detection paradigm, Slattery, Angele, and Rayner (2011) found that the probability of detecting a display change from the parafoveal preview to the target was higher when there was a change in letter identities (*jNxVa → gReEn*) than when there was a change in letter case (*gReEn → GrEeN*) (see also Angele, Slattery, & Rayner, 2016, for discussion). Finally, recent research has shown that readers may also extract semantic and higher-order contextual information from the parafoveal previews (e.g., see Hohenstein & Kliegl, 2014, to cite one recent example).

To explain how orthographic information from the parafoveal previews is integrated across saccades in the word recognition stream, Rayner et al. (1978; see also Rayner et al., 2012) proposed the "preliminary letter identification" hypothesis. The rationale of this account is that while the eye is fixating on word *n*, factors such as visual acuity and lateral masking would hinder the identification and relative order of the letters in word *n + 1*. Hence, orthographic processing in the parafovea would be subject to letter confusability, particularly for those letters that share many visual features (e.g., *b* and *h*). Support for the preliminary letter identification hypothesis comes from the boundary experiments reported by Rayner and colleagues (Rayner, 1975; Rayner et al., 1978; Rayner, Well, Pollatsek, & Bertera, 1982). In a sentence reading experiment, Rayner (1975) included an identity preview (e.g., *tested*), a visually similar nonword preview (e.g., *tcrted*) and a visually dissimilar nonword preview (e.g., *tflmed*). Rayner (1975) found shorter viewing times for the target words when the preview was a visually similar nonword than when the preview was a visually dissimilar preview—this was accompanied by briefer viewing times in the identity condition than in the visually similar preview condition. In the Rayner et al. (1978) experiments, readers looked at a dot in the center of the screen while a word or nonword appeared in the parafovea. When the participants moved their eyes toward the letter string, the word/nonword was replaced by a target word that the participant had to read aloud. The parafoveal preview conditions comprised: 1) a visually similar word (*police-palace*); 2) a visually similar replaced-letter nonword (*pcluce-palace*); and 3) a visually dissimilar replaced-letter nonword (*pyltce-palace*). Rayner et al. (1978) found longer naming times for those words that were preceded by a visually dissimilar preview than by a visually similar preview, which in turn produced longer naming times than the identity preview condition (see also Rayner et al., 1982, for converging evidence). Similarly, other boundary change experiments only found slightly faster viewing times on a target word in the identity condition than in a visually similar preview condition (e.g., *song-song* vs. *sorp-song*) (e.g., Altarriba, Kambe, Pollatsek, & Rayner, 2001; Balota, Pollatsek, & Rayner, 1985; Pollatsek, Rayner, & Balota, 1986; see also Cutter, Drieghe, & Liversedge, 2015, and Hyönä, Bertram, & Pollatsek, 2004, for reviews).[1]

Taken together, the above-cited experiments suggest that visual letter similarity plays a role in the initial moments of processing during normal reading. However, a limitation of these experiments is that visual letter similarity was merely operationalized in terms of letter shape. For instance, when creating the stimuli in the visually similar condition, Rayner et al. (1982) indicated that "every ascender was replaced by an ascender, every descender was replaced by a descender, and letters that did not extend above or below the line of print were replaced by other similar nonascending or nondescending letters" whereas in the visually dissimilar letter condition, "every letter was replaced by a dissimilar letter, with ascenders replaced by descenders or letters that did not extend above or below the line" (p. 542). That is, visual letter similarity was simplified to three categories of letter shape:

Identity preview

Estaba todo bien| frito en aceite de oliva.

Estaba todo bien| frito en aceite de oliva.

Visually similar preview

Estaba todo bien| frjto en aceite de oliva.

Estaba todo bien| frito en aceite de oliva.

Visually dissimilar preview

Estaba todo bien| frgto en aceite de oliva.

Estaba todo bien| frito en aceite de oliva.

Fig. 1. Description of an eye movement contingent display-change trial with the three experimental conditions (identity preview, visually similar preview, visually dissimilar preview). The eye symbol represents where the reader is fixating, and the arrow represents the saccade crossing the invisible boundary (the dashed vertical line) preceding the target word. Before crossing the boundary, the sentence is presented with the identity, visually similar or dissimilar previews. When the eyes cross the boundary, the parafoveal preview is replaced by the target word.

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[1] Pollatsek, Lesch, Morris, and Rayner (1992) found a sizeable advantage of the identity condition over a visually similar condition (around 25 ms in the first fixation on the target word), but this difference occurred primarily when the visually similar preview did not share the initial letter with the target word (e.g., *aerial-cereal*).