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Tests of a model of multi-word reading: Effects of parafoveal flanking letters on foveal word recognition

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ABSTRACT

We used the "flanking letters lexical decision" paradigm of Dare and Shillcock (2013) in order to test a model of multi-word reading. In the model, multiple words (on fixation, and to the left and right of fixation) are processed in parallel by a bank of location-specific letter detectors. These letter detectors feed information forward to a "bag of bigrams" that represents location-invariant sublexical orthographic information for all words processed in parallel. Bigrams are only formed within words (i.e., between spaces) but activate all compatible word representations. The model accounts for a finding reported by Dare and Shillcock (2013): Word recognition is facilitated when flanking letter pairs are present in the target (e.g. RO ROCK CK) compared with different letter flankers (ST ROCK EN), but independently of the position of the flanking bigrams (e.g., CK ROCK RO). In the present study we replicate this key finding and show that, as predicted by the model, although bigram position does not matter, within-bigram letter position does. Word recognition is harder when the position of letters within bigram flankers is reversed (e.g., OR ROCK KC/KC ROCK OR), but these conditions still facilitate with respect to a different letter flanker condition.

1. Introduction

In a recent study, Dare and Shillcock (2013) reported what we believe to be a key finding for reading research. This finding was obtained using a novel paradigm, the "flanking-letters lexical-decision" paradigm, where target words and nonwords on which subjects make lexical decisions are flanked by letter pairs located to the left and right of the target and separated from targets by a single space. Dare and Shillcock (2013) found that when flanking letters were present in the target, lexical decisions were facilitated for word stimuli compared with the condition where flanking letters were not present in the target. Most important is that this flanking-letter effect did not depend on the left–right ordering of the letter pairs such that response times (RTs) were the same to the target word "ROCK" when flanked by "RO" to the left and "CK" to the right and when flanked by "CK" to the left and "RO" to the right (0 ms difference between these two conditions for both high-frequency and low-frequency words, see Fig. 3a).

This rather counterintuitive finding fits well with the theoretical framework for multiple-word processing proposed by Mozer (1987) and adapted in the more recent work of Grainger and Van Heuven (2003). Here we describe how a straightforward extension of the Grainger and van Heuven model, that retains many of the key properties of Mozer's Blirnet model, provides a simple account of Dare and Shillcock's results. An informal presentation of the model suffices at present for describing how it accounts for these findings, and how it generates predictions with respect to the new conditions to be tested in the present study. The architecture of the model is shown in Fig. 1. The first layer of the model performs parallel independent letter processing via a horizontally aligned bank of location-specific letter detectors. Two main factors determine activity at this level of processing: acuity and crowding. Bottom-up input to letter detectors drops linearly with increasing eccentricity, but letters at the outer positions of words benefit from reduced crowding. This leads to the typical W-shaped serial position function for letter identification accuracy with centrally fixated strings (e.g., Tydgat & Grainger, 2009). The second layer of the model is a "bag of bigrams" representing an unordered set of ordered letter combinations. Following Grainger and Van Heuven (2003) we use an open-bigram scheme such that the letter combinations include contiguous and non-contiguous sequences of two letters. Following Hannagan and Grainger (2012) we include the space character (#) along with the 26 letters of the alphabet when generating bigrams, such that information about single letters is also encoded.[1] The third and final layer of the model is a set of whole-word orthographic representations that relays information onto semantic representations.

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[1] As noted by Hannagan and Grainger (2012), the addition of a space character in a bigram coding scheme corresponds to "both edges" coding (Fischer-Baum, McCloskey, & Rapp, 2010), provided that information about the distance between the space and the letter is also available. This enables an implementation of both coarse-grained and fine-grained orthographic codes, as defined by Grainger and Ziegler (2011), within a single representational scheme.

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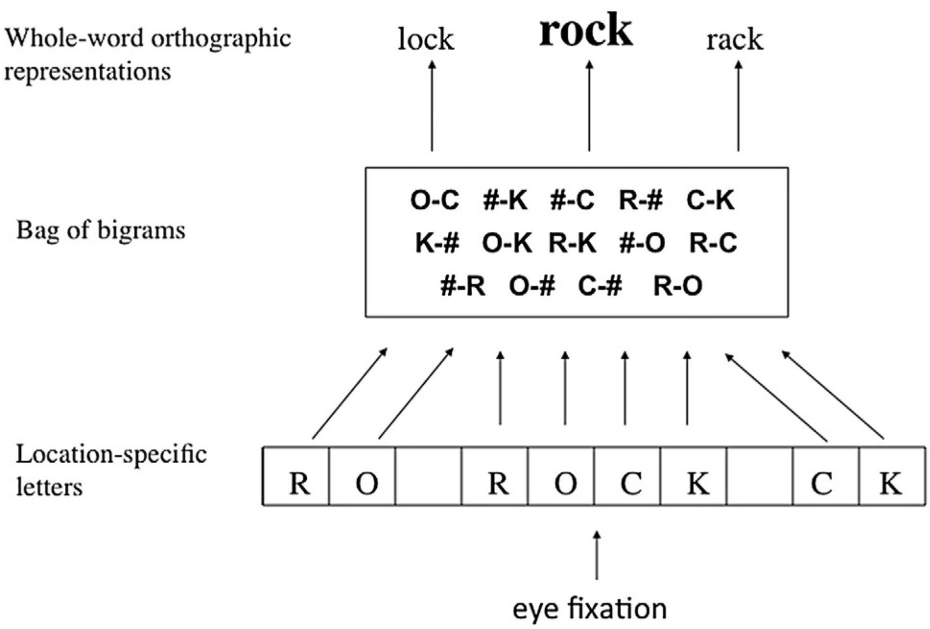

Fig. 1. Extension of Grainger and Van Heuven's (2003) model of orthographic processing to the case of multiple words (strings separated by spaces). Location-specific letter detectors operate in parallel across multiple words, signaling the evidence that a given letter identity or inter-word space is present at a given location relative to eye fixation. This information is used to activate ordered pairs of contiguous and non-contiguous character combinations (26 letters augmented with the space character—#) stored as an unordered set of open-bigrams (a bag of bigrams). Bigrams then activate whole-word orthographic representations for unique word identification (winner-take-all).

During fixation within a given word, location-specific letter detectors process visual information about the fixated word as well as information to the left and right of that word, within the limits imposed by acuity, crowding, and spatial attention (e.g., Marzouki, Meeter, & Grainger, 2013). All activated letter detectors send activation on to all compatible bigram representations in the bag of bigrams. The only additional constraint within this single-channel approach to multiple-word reading is that bigrams are only formed within words and not between words. That is, when reading the phrase "gray mouse", bigrams "g-r" and "g-y" but not "y-m" are activated. This constraint is essential for implementing parallel processing of sublexical orthographic information across several words while limiting the generation of illusory words formed by combinations of letters from different words. It points to a key role for inter-word spaces in orthographic processing in general, as already revealed in prior research (e.g., Morris, Rayner, & Pollatsek, 1990; Rayner, Fischer, & Pollatsek, 1998; Winskel, Radach, & Lukaneeyanawin, 2009).

Once location-specific letter detectors begin to activate bigram representations, activity in these bigram detectors is then fed-forward to whole-word orthographic representations, which compete with each other for unique word identification via lateral inhibition. Once a word is identified, activity in the corresponding whole-word orthographic representation is suppressed in order to remove interference during processing of the subsequently fixated word. This model therefore enables parallel processing of orthographic information spanning several words while ensuring that only one word is identified at a time.

The model accounts for the results of Dare and Shillcock (2013) because flanking letter pairs will generate activation in bigram representations independently of whether they appear to the left or to the right of fixation. The model predicts, however, that reversing the order of letters within the flanking letter pairs (e.g., 21 1234 43)[2] should make target word recognition harder than when the order is not reversed (12 1234 34). Priming will, however, still arise in the reversed letter condition relative to a different letter condition (dd 1234 dd) because of the "single letter" bigrams (bigrams formed by combining the space character and a letter). The model therefore predicts no difference between conditions 12 1234 34 and 34 1234 12, but both should facilitate target word recognition relative to conditions 21 1234 43 and 43 1234 21, which in turn should facilitate target word recognition relative to the different letter condition dd 1234 dd.

In sum, we will use the flanking-letters lexical-decision paradigm in order to i) replicate the key finding of Dare and Shillcock (2013), and ii) test a key prediction of our model of multiple-word reading. The flanking-letter conditions to be tested are:

12 1234 34; 34 1234 12; 21 1234 43; 43 1234 21; dd 1234 dd.

We use these conditions to provide pairwise estimates of flanking letter effects relative to a different-letter condition, plus an analysis of letter order and bigram order in a 2 × 2 factorial design (without the different-letter condition). We expect all conditions where flankers contain letters in the target to facilitate word recognition compared with different-letter flankers. We also expect to replicate the absence of an effect of bigram order reported by Dare and Shillcock, such that conditions 12 1234 34 and 21 1234 43 are the same as conditions 34 1234 12 and 43 1234 21. We also expect to observe an effect of letter order such that conditions 12 1234 34 and 34 1234 12 will improve target word recognition compared with conditions 21 1234 43 and 43 1234 21.

2. Method

2.1. Participants and apparatus

Twenty students from Aix-Marseille University participated in the experiment, and received €3 or course credit for their participation. All participants reported normal or corrected vision and were native French speakers. The experiment was conducted on a 19″ TFT monitor with a resolution of 1280 × 1024 pixels and a refresh rate of 60 Hz. Stimulus presentation was controlled using OpenSesame (Mathôt, Schreij, & Theeuwes, 2012).

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[2] Following the notation used to describe experimental conditions in research on orthographic priming, flanking letter conditions are described by using numbers to indicate the position of a flanking letter in the target when the letter is present in the target, and using the letter "d" (different letter) otherwise.