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Lexical competition is enhanced in the left hemisphere: Evidence from different types of orthographic neighbors ☆

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Abstract

Two divided visual field lexical decision experiments were conducted to examine the role of the cerebral hemispheres in orthographic neighborhood effects. In Experiment 1, we employed two types of words: words with many substitution neighbors (high-*N*) and words with few substitution neighbors (low-*N*). Results showed a facilitative effect of *N* in the left visual field (i.e., right hemisphere) and an inhibitory effect of *N* in the right visual field (left hemisphere). In Experiment 2, we examined whether the inhibitory effect of the higher frequency neighbors increases in the left hemisphere as compared to the right hemisphere. To go beyond the usual *N*-metrics, we selected words with (or without) higher frequency neighbors (addition, deletion, or transposition neighbors). Results showed that the inhibitory effect of neighborhood frequency is enhanced in the right visual field. We examine the implications of these findings for the orthographic coding schemes employed by the models of visual word recognition.

Keywords: Visual field; Coding scheme; Orthographic neighborhood; Lexical decision; Lexical competition

1. Introduction

In recent decades, a growing body of evidence has shown that during the recognition of a word, not only is the orthographic representation of the stimulus activated, but also the representations of similarly spelled words (or "neighbors"). Therefore, one key issue for any computational model of visual word recognition is the specification of the mechanisms responsible for correct lexical selection among the potential candidates (see Davis & Lupker, 2006; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006). The most popular measurement of orthographic similarity has been "*N*" (Coltheart, Davelaar, Jonasson, & Besner, 1977), which is computed by counting the number of words that can be created by substituting a single letter of the stimulus, keeping constant the letter positions (i.e., the so-called substitution neighbors; Davis & Taft, 2005). For example, the word *timer* has a low density of substitution neighbors ($N = 1$; the word *tiger*), whereas the word *liver* has a high density of substitution neighbors ($N = 11$; the words *diver*, *fiver*, *giver*, *river*, *lever*, *lover*, *lifer*, *liner*, *lived*, *liven*, and *lives*).

What is the role of a word's neighbors in visual word recognition? In lexical decision, Grainger, O'Regan, Jacobs, and Segui (1989, 1992) found that words with higher frequency substitution neighbors (e.g., *spice*; the words *space* and *spite* are its higher frequency substitution neighbors) are responded to more slowly than words with no higher frequency substitution neighbors (e.g., *sauce*). This "neighborhood frequency" effect has also been found in normal sentence reading when the participants' eye

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movements are monitorized (Perea & Pollatsek, 1998; Pollatsek, Perea, & Binder, 1999; Slattery, Pollatsek, & Perea, submitted for publication but see Sears, Campbell, & Lupker, 2006). The presence of an effect of neighborhood frequency makes sense if an important phase of word identification is selection of the actual lexical item from a candidate set because, in a model that uses a competitive selection mechanism (e.g., the interactive activation model, McClelland & Rumelhart, 1981, and its successors, dual-route cascaded model, Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; multiple read-out model, Grainger & Jacobs, 1996), a higher frequency neighbor should compete more actively for final selection than should lower frequency neighbors (see Bowers, Davis, & Hanley, 2004).

However, the story is more complex. Previous research has found a facilitative effect of *N* on words in lexical decision, although the effect seems to be restricted to low-frequency words (see Andrews, 1997, for review). Given that *N* typically correlates positively with the number of higher frequency substitution neighbors, this finding is quite problematic for theoretical accounts based on the principle of lateral inhibition at the lexical level, such as the interactive activation model (see Jacobs & Grainger, 1992, for a failure to simulate the effect of *N*). Nonetheless, these facilitative effects of *N* in lexical decision may be reflections of a response based on the degree of global lexical activation (see Coltheart et al., 2001; Forster & Shen, 1996; Grainger & Jacobs, 1996; Paap & Johansen, 1994; Perea & Rosa, 2000, 2002; Perea, Rosa, & Gómez, 2005). This idea has been implemented in the multiple read-out model (Grainger & Jacobs, 1996; see also Coltheart et al., 2001, for a similar implementation in a dual-route cascaded model): a ‘‘word’’ response in a lexical decision task is generated (read-out) when at least one of the codes that is appropriate for responding in that task reaches a critical activation level. A criterion set on activity in whole-word representations is used to trigger a positive word recognition response: this is the so-called M criterion. Alternatively, participants may make a positive lexical decision response on the basis of global lexical activity before even identifying the letter string as a real word: this is the so-called Σ criterion. In this way, the multiple read-out model captures the fact that the same stimuli may produce a facilitative or an inhibitory effect of *N* in lexical decision, depending on the characteristics of the task (e.g., blocked vs. unblocked presentation, see Johnson & Pugh, 1994; Perea, Carreiras, & Grainger, 2004; or difficult vs. easy nonword foils, see Carreiras, Perea, & Grainger, 1997; Grainger & Jacobs, 1996). However, this idea cannot be the whole story: some contrast manipulation of the letters modulates the effect of *N* in lexical decision (Whitney & Lavidor, 2005). This result is difficult to explain under the assumption that facilitative effects of *N* arise solely at the lexical level, as a result of total lexical activation.

To explore in greater detail the role of a word’s neighbors in lexical access, one useful strategy is to examine the role of the cerebral hemispheres in ‘‘orthographic neighborhood’’ effects by using a divided visual field lexical decision task. Leaving aside the advantage of using a within-item manipulation of orthographic neighborhood (see Forster, 2000, for a cautionary note on between-item comparisons in word recognition experiments), the underlying idea is that in a divided visual field experiment, information to the right of fixation (i.e., right visual hemifield) is initially projected to the visual cortex of the left cerebral hemisphere, and information to the left of fixation (i.e., left visual hemifield) is initially projected to the visual cortex of the right cerebral hemisphere. There is ample empirical evidence that shows a left hemisphere advantage over the right hemisphere when processing linguistic material (e.g., Ellis, Young, & Anderson, 1988; Perea & Fraga, 2006; see also Hunter & Brysbaert, in press, for a recent review on interhemispheric transfer costs in visual word recognition). More specifically, it has been suggested that the left hemisphere produces a more abstract encoding than the right hemisphere, and that the right hemisphere may have a delayed letter-encoding stage (Chiarello, 2003; see also Barca, Cornelissen, Urooj, Simpson, & Ellis, 2007, for MEG evidence). Consequently, stimuli processed initially by the right hemisphere may be more sensitive to orthographic effects (see Lavidor & Ellis, 2001).[1] If this is so, orthographic neighborhood effects should differ in the left and right hemispheres. Two computational models of the letter-encoding process make specific predictions in this respect: the split-fovea model (Shillcock, Ellison, & Monaghan, 2000) and the SERIOL model (Whitney, 2001).

In the split-fovea model (Shillcock et al., 2000), the right hemisphere is assumed to have a coarser encoding of letters than the left hemisphere (which is more fine-grained; see also Beeman, 1998; Beeman, Friedman, Grafman, & Perez, 1994). As a result, the right hemisphere is more sensitive to multi-letter representations. This difference stems from the assumption that the information projected in one hemisphere continues to be processed by that hemisphere until the point of lexical access (but see Barber & Kutas, 2007). In the split-fovea model, the right hemisphere deals with greater orthographic density than the left hemisphere because the letters appearing at the beginning of words (left visual field, right hemisphere) are more varied that the ones appearing at the end (see Monaghan, Shillcock, & McDonald, 2004). Therefore, it is more efficient for the right hemisphere to rely on representations larger than letters (such as bigrams or even larger units), whereas it is more efficient for the left hemisphere to operate on single letters. That is, all information (unigrams, bigrams, trigrams, etc.) is available throughout the system, but the reliance on different levels varies according to usefulness. In sum, the split-fovea

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[1] One reason why the facilitative effect of *N* has an orthographic locus is that Paap and Johansen (1994) and Pollatsek et al. (1999) found that the facilitative effect of *N* was due essentially to the lower frequency substitution neighbors, and not the higher frequency substitution neighbors.

model assumes that it is easier to find effects of units larger than letters in the right hemisphere rather than in the left hemisphere. This implies that the effect of *N* should be sensitive to visual field, with more facilitative effects of *N* in the right hemisphere than in the left hemisphere (see Lavidor, Hayes, Shillcock, & Ellis, 2004; Monaghan et al., 2004).

Alternatively, in the SERIOL model (Whitney, 2001; Whitney, 2004; Whitney & Lavidor, 2005), the differences in processing across hemispheres occur at a pre-lexical level, but not at the lexical level. More specifically, information in the right hemisphere is transferred to the left hemisphere at the letter level, in line with the proposal that there is a specific (word form) area in the left cerebral hemisphere where orthographic information is initially analyzed (see Barber & Kutas, 2007, for a recent review of computational models and cognitive electrophysiology). The left and the right hemispheres differ in the slope of letter-encoding activity at the feature level, with reduced bottom-up activation in the right hemisphere. Although the SERIOL model focuses on bottom-up processing, it also allows top-down activation; indeed, the model predicts that it is top-down input that is mainly responsible for the facilitative effect of *N*. The SERIOL model assumes that hemispheric differences arise from the formation of the spatial gradient, coupled with the processing which converts the spatial gradient into a serial firing pattern. Due to these dynamics, increased top-down input to the letter level (from words with many neighbors) has a facilitative effect in left visual field presentation, but not in right visual field presentation (see Whitney, 2004). Interestingly, Whitney and Lavidor (2005) showed that specific contrast manipulations can reverse the usual pattern of data with a visual field paradigm, and this is consistent with the assertion that visual field effects arise from the quality of orthographic encoding.

Several studies using English stimuli have found an interaction between *N* and visual field in lexical decision. Lavidor and Ellis (2002; see also Ellis, 2004; Lavidor & Ellis, 2001; Whitney, 2004) found a facilitative effect of *N* when the words were presented to the left visual field (right hemisphere), but not to the right visual field (left hemisphere). (The mean *N* values were 6.2 and 17.0 in the Lavidor & Ellis, 2002, study, and 1.0 vs. 9.5 in the Lavidor & Ellis, 2001, study.) Nonetheless, an unpublished study by Fiset and Arguin (1999), using French stimuli, failed to find a significant interaction between *N* and visual field in lexical decision.

Given that the interaction between *N* and visual field is a strong (and testable) prediction from two recently proposed models of letter encoding (split-fovea model and SERIOL model), Experiment 1 is designed to replicate the reliability of the interaction between *N* and visual field in a language with shallow orthography (Spanish). The reason why we chose Spanish is that the magnitude of the facilitative effect of *N* in lexical decision tends to be smaller than in English (see Carreiras et al., 1997). For instance, Carreiras et al. (1997) failed to find an effect of *N* in lexical decision on (centrally presented) words when the set of nonwords was wordlike—they only found a facilitative effect of *N* when the set of nonwords was not wordlike. As indicated by Whitney and Lavidor (2005) in the context of a lexical decision task, spelling in a shallow language may depend more on phonology-to-orthography than on word-to-orthography connections; if this is so and top-down connections are weaker, then the activation from high-*N* words should be less in Spanish than in English (i.e., the facilitative effect of *N* would be reduced in a shallow language). Furthermore, as noted by Whitney and Lavidor (2005), unlike Spanish, most substitution neighbors in English tend to occur in the initial letter position. Thus, a replication of the interaction between visual field and *N* with Spanish stimuli would imply that the English findings are not specific to this language. To anticipate the results, Experiment 1 showed the expected *N* by visual field interaction: there was a facilitative effect of *N* in the left visual field (right hemisphere) and an inhibitory effect of *N* in the right visual field (left hemisphere). The goal of Experiment 2 was to further examine whether the effects of lexical competition among word units are enhanced in the right visual field (i.e., left hemisphere). More specifically, we employed a visual field manipulation in which participants were presented with words with higher frequency neighbors and with words without higher frequency neighbors (i.e., a "neighborhood frequency" manipulation; see Grainger, O'Regan, Jacobs, & Segui, 1989). To generalize our findings beyond substitution neighbors, in Experiment 2 we employed three types of orthographic neighbors that have shown to be perceptually similar to a given stimulus item (see Davis & Taft, 2005; de Moor & Brysbaert, 2000; Perea & Lupker, 2003): transposition neighbors (e.g., *causal–CASUAL*), addition neighbors (e.g., *drive–DIVE*), and deletion neighbors (*drive–DRIVEL*).

2. Experiment 1 ($N \times$ Visual field)

2.1. Method

2.1.1. Participants

Thirty (23 women) undergraduate students from the University of Santiago de Compostela received course credit for participating in the experiment. All of them either had normal or corrected-to-normal vision and were native speakers of Spanish. Ages ranged from 21 to 25 years (mean = 22.7 years). All subjects were right-handed, with scores of at least 80 in the Edinburgh Handedness inventory (Oldfield, 1971).

2.1.2. Materials

For the word trials, we selected a set of 120 two-syllable words of five letters from the Spanish database (Davis & Perea, 2005). Sixty of these words had very few substitution neighbors (mean $N = 0.3$, range 0–1). The other 60 words had many substitution neighbors (mean $N = 8.4$, range 7–12) (see the Appendix for a complete list of stimuli). Factors like written word frequency and syllable frequency of the initial syllable (Perea & Carreiras, 1998) were con-

Table 1
Characteristics of the words in Experiment 1

	High-*N* words	Low-*N* words
Word Freq	5	5
Word length	5	5
# Syllables	2	2
Mean BF	2.8	2.2
Syll.Freq (1st)	163	170
Syll.Freq (2nd)	1535	80

Note: Word Freq = mean word frequency per million words; word length = number of letters; *N* = number of substitution neighbors; mean BF = mean (log) bigram frequency; Syll.Freq (1st or 2nd) = median syllable frequency.

trolled (see Table 1). For the high-*N* words, the number of letter positions with substitution neighbors was 3.7 (range: 3–5).[2] For the purposes of the lexical decision task, 120 two-syllable nonword targets of five letters were created; 60 had no substitution neighbors and 60 had two substitution neighbors.

2.1.3. Procedure

Participants were tested individually in a quiet room. Presentation of the stimuli and recording of response times were controlled by SuperLab on a PC compatible computer. Participants sat at a viewing distance of 50 cm, with the head positioned in a chin rest. On each trial, a fixation point ("X") was presented at the center of the screen for 400 ms. Then, a target item was briefly presented (150 ms) to the left or to the right of the fixation point. The letter strings were presented at a displacement of 2.5° from the fixation point to the center of the word or nonword. The displacement (in the case of left/right presentations) was to the left or to the right of a central focus point (left visual field and right visual field, respectively). Participants were instructed to press one of two buttons on the keyboard to indicate—as quickly and as accurately as possible—whether the letter string was a legitimate Spanish word or not ("-" for word and "Z" for nonword"; for half of the participants the response keys were reversed—note that in a Spanish keyboard "-" is bottom right and "Z" is bottom left). Participants were instructed to keep their eyes on the central fixation point. Each participant received a different order of trials. The stimuli were presented on 28 pt. lowercase Tahoma. The letters appeared in black on a white background. Each participant received a total of 24 practice trials prior to the 240 experimental trials. The whole session lasted approximately 11 min.

2.2. Results and discussion

Incorrect responses and reaction times less than 250 ms or greater than 1500 ms (less than 1%) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 2. For word targets, ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (*N*: low, high) × 3 (Visual field: left, center, right) × 3 (List: list 1, list 2, list 3) design. The factor List was included as a dummy variable to extract the variance due to the error associated with the lists (see Pollatsek & Well, 1995). For nonword targets, ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (*N*: low, medium) × 3 (Visual field: left, center, right) × 3 (List: list 1, list 2, list 3) design.

2.2.1. Word targets

The ANOVA on the latency data showed a main effect of visual field, $F1(2,54) = 45.23$, $MSE = 2665.3$, $p < .001$; $F2(2, 228) = 87.72$, $MSE = 3010.2$, $p < .001$, while there were no signs of a main effect of *N*, both *F*s < 1. More important, the interaction between *N* and visual field was significant, $F1(2, 54) = 10.02$, $MSE = 978.2$, $p < .001$; $F2(2, 228) = 5.98$, $MSE = 3010.2$, $p < .003$. This interaction reflected that, in the left visual field, words with many substitution neighbors were responded to 23 ms *more rapidly* than words with few substitution neighbors, $F1(1, 27) = 4.64$, $MSE = 1718.6$, $p < .041$; $F2(1, 114) = 4.86$, $MSE = 4521.4$, $p < .03$; in contrast, in the right visual field, words with many substitution neighbors were responded to 28 ms *more slowly* than words with few substitution neighbors, $F1(1, 27) = 7.55$, $MSE = 1534.1$, $p < .011$; $F2(1, 114) = 5.07$, $MSE = 3723.8$, $p < .03$; in the central visual field, there were no signs of an effect of *N*, both *F*s < 1.

The ANOVA on the error data only showed a main effect of visual field, $F1(2, 54) = 12.07$, $MSE = 276.5$, $p < .001$, $F2(2, 228) = 51.75$, $MSE = 3010.2$, $p < .001$: post hoc Tukey comparisons (all *p*s < .05) showed that words presented in the left visual field yielded more errors than words presented in the right visual field (25 vs. 18%, respectively), and in the central visual field (10.4%).

2.2.2. Nonword targets

The ANOVA on the latency data showed a main effect of visual field, $F1(2, 54) = 20.85$, $MSE = 2606.1$, $p < .001$; $F2(2, 228) = 45.46$, $MSE = 2563.0$, $p < .001$: post hoc Tukey comparisons (all *p*s < .05) showed that nonwords presented in the left visual field were responded to 14 ms slower than nonwords presented in the right visual field, and 58 ms slower than nonwords presented in the central visual field. In addition, nonwords with two substitution neighbors were responded 34 ms slower than nonwords without substitution neighbors, $F1(1, 27) = 40.76$, $MSE = 1269.5$, $p < .001$; $F2(1, 114) = 14.09$, $MSE = 7233.1$,

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[2] Previous research with the lexical decision task has found no direct relationship between bigram frequency and response time (see Andrews, 1992). In Spanish, the syllable frequency of the initial syllable is the key sublexical variable in lexical decision and naming tasks (see Carreiras & Perea, 2004; Perea & Carreiras, 1998), and this variable was controlled in the experiment.

Table 2
Mean lexical decision times in milliseconds and percentage of errors (in parentheses) for words and nonwords in Experiment 1

	Words			Nonwords		
	LVF	CVF	RVF	LVF	CVF	RVF
High N	557 (25.0)	479 (10.2)	549 (18.5)	609 (15.0)	541 (12.2)	591 (14.6)
Low N	580 (25.7)	481 (10.7)	521 (17.0)	566 (13.8)	518 (5.7)	555 (6.8)
N effect	−23 (−0.7)	−2 (−0.5)	28 (1.5)	43 (1.2)	23 (6.5)	36 (7.2)

Note: LVF, CVF, and RVF refer to left, central, and right visual field, respectively.

$p < .001$. The interaction between the two factors did not approach significance, both $ps > .15$.

The ANOVA on the error data showed a main effect of visual field, $F1(2, 54) = 9.70$, $MSE = 50.01$, $p < .001$; $F2(2, 228) = 8.16$, $MSE = 118.82$, $p < .001$. In addition, nonwords with several substitution neighbors showed a higher error rate than nonwords with no substitution neighbors (13.7% and 8.8%, respectively), $F1(1, 27) = 27.64$, $MSE = 39.8$, $p < .001$; $F2(1, 114) = 9.00$, $MSE = 244.5$, $p < .001$. The interaction between N and visual field was significant in the analysis by subjects, $F1(2, 54) = 3.18$, $MSE = 51.0$, $p < .05$; $F2(2, 228) = 2.73$, $MSE = 118.8$, $p = .067$. This interaction reflected an inhibitory effect of N in the right and central visual fields (12.2% for nonwords with several neighbors and 5.7% for nonwords with no neighbors in central visual field, 14.6% for nonwords with several neighbors and 6.8% for nonwords with no neighbors in the right visual field), $F1(1, 27) = 15.19$, $MSE = 41.7$, $p < .05$; $F2(1, 114) = 9.36$, $MSE = 164.7$, $p < .05$, and $F(1, 27) = 13.20$, $MSE = 58.4$, $p < .05$; $F2(1, 114) = 13.60$, $MSE = 93.2$, $p < .05$, but not in the left visual field, both $ps > .15$.

In sum, in the present experiment we found a right visual field advantage in response times and error rates for words—relative to the left visual field.[3] But the most remarkable finding is the interaction between N and visual field: there was a facilitative effect of N in the left visual field (i.e., right hemisphere) and an inhibitory effect of N in the right visual field (i.e., left hemisphere). In addition, there was a null effect of N for central presentations, replicating the null effect of N reported by Carreiras et al. (1997) in Spanish. There were no trends towards a speed/accuracy trade-off: the same pattern occurred for both response times and error rates. It is important to note that this pattern occurred in a language (Spanish) in which, unlike English, substitution neighbors tend to be more equally distributed across letter positions.

Thus, the presence of an interaction between N and visual field confirms a key prediction from the SERIOL and split-fovea models. Furthermore, the present findings replicate and extend previous research by Lavidor and Ellis (2002), who found a facilitative effect of N in the right hemisphere (left visual field) and a null effect of N in the left hemisphere (right visual field). In the present experiment, we found a facilitative effect of N in the left visual field and an inhibitory effect of N in the right visual field—we also found a null effect of N for central presentations (see also Carreiras et al., 1997).

Interestingly, the observed interaction between N and visual field may be taken to suggest an enhanced lexical competition among word units when the words are presented in the right visual field (i.e., there was an inhibitory effect of N). Or, alternatively, in terms of a multiple read-out model (Grainger & Jacobs, 1996), one could argue that, because of increased processing efficiency in orthographic encoding, responses in the right visual field (left hemisphere) were mainly driven by the unique-word identification (M) criterion, while responses in the left visual field (right hemisphere) were partly driven by global activation in the lexicon (Σ criterion).

One way to test the generality of the above-mentioned hypothesis is to employ a visual field manipulation in which participants are presented with words with higher frequency neighbors and with words without higher frequency neighbors (i.e., a "neighborhood frequency" manipulation; see Grainger et al., 1989). To generalize our findings beyond the N metric, in Experiment 2 we employ several types of orthographic neighbors, the reason being that it has become increasingly clear that the N metric is just an approximate measure of the size of a word's neighborhood. It seems possible that this measure has now outlived its usefulness, and that a more comprehensive measure of "orthographic neighborhood" is required (Davis & Perea, 2005; Davis & Perea, submitted for publication). More specifically, in Experiment 2, we examine three types of "neighbors": (i) *transposition neighbors*

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[3] We believe that it is important to discard the influence of two potential confounding variables—bigram frequency and the frequency of the second syllable– which could not be tightly controlled in the experiment. Although there is no reliable evidence of an effect of bigram frequency on word latencies (see Andrews, 1992), we conducted a post hoc analysis to determine whether bigram frequency could have influenced the observed data. When the effect of N was partialed out, the Pearson correlation coefficient between the response times to words and (log of) bigram frequency did not approach significance in any of the visual field conditions (the r values were .09, −.14, and −.08 for the left, central, and right visual field, respectively, all $ps > .10$). Likewise, it could be argued that some of the obtained effects could have been due to an uncontrolled effect from the frequency of the second syllable. Consistent with prior research that had failed to show any effects of the frequency of the second syllable (e.g., see Carreiras & Perea, 2004; Perea & Carreiras, 1998), the Pearson correlation coefficient between the response times to words and (log of) the frequency of the second syllable did not approach significance in any of the visual field conditions (the r values were .15, .02, and −.04 for the left, central, and right visual field, respectively, all $ps > .10$).

(i.e., pairs of letter strings that are identical save for the transposition of two adjacent letters; for example, the word *trail* is a transposition neighbor of the word *trial*), (ii) *addition neighbors* (i.e., an addition neighbor of a word involves the addition of a single letter—in any position—to that word; i.e., the word *derive* is an addition neighbor of *drive*), and (iii) *deletion neighbor*s (a deletion neighbor of a word differs from that word by the deletion of a single letter; e.g., the word *dive* is a deletion neighbor of the word *drive*).

There is some evidence using the lexical decision task that shows an inhibitory effect of having addition neighbors of higher frequency (Davis & Perea, submitted for publication; see also Bowers et al., 2004, for evidence using a semantic categorization task), of having deletion neighbors of higher frequency (Davis & Taft, 2005), and of having transposition neighbors of higher frequency (Andrews, 1996). One important reason for being interested in the perceptual similarity of these three types of neighbors is that this is a critical issue for the choice of an input coding scheme of computational models of visual-word recognition. Evidence supporting the perceptual similarity of transposition, addition, and deletion neighbors would make it necessary to use a different type of coding scheme other than the "slot" coding scheme employed in many computational models of word recognition (e.g., the interactive activation model, McClelland & Rumelhart, 1981, and its successors; e.g., Coltheart et al., 2001; Grainger & Jacobs, 1996). Interestingly, a high degree of perceptual similarity between transposition neighbors, addition neighbors, and deletion neighbors is a natural consequence of the input coding scheme of the split-fovea and SERIOL models (Monaghan et al., 2004; Whitney, 2001; a similar argument applies to the SOLAR model, Davis, 1999, 2006). (We defer a discussion of this issue until the Section 4.)

3. Experiment 2 (neighborhood frequency × Visual field)

Experiment 2 is aimed at examining the "neighborhood frequency" effect on words with deletion, addition, or transposition neighbors of higher frequency, and whether this neighborhood frequency effect is modulated by visual field. Because of the limited number of word stimuli, and to achieve enough experimental power to detect the critical effects/interactions, words were presented either in the left or right visual field—but not in the central visual field.

3.1. Methods

3.1.1. Participants

Forty-four (38 women) undergraduate students from the University of Santiago de Compostela received course credit for participating in the experiment. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish. Ages ranged from 20 to 27 years (mean = 23.1 years). All participants were right-handed, with scores of at least 80 in the Edinburgh Handedness Inventory (Oldfield, 1971). None of them had taken part in Experiment 1.

3.1.2. Materials

The experimental stimuli consisted of 224 items: 112 low-frequency words (mean frequency = 4.7 per million in the Spanish database, Davis & Perea, 2005) and 112 nonwords. All stimuli contained between six and nine letters (mean number of letters = 6.2). We had three sets of words (words with higher frequency deletion neighbors, words with higher frequency addition neighbors, and words with higher frequency transposition neighbors, and their corresponding controls) (see the Appendix for a complete list of stimuli). Firstly, we selected 20 word stimuli (mean word frequency = 4.3 per million, mean word length = 6.8 letters) that had deletion neighbors that were of higher frequency than the stimulus word (mean frequency = 27 per million). The position of the letter removed to create the deletion neighbor word was always an internal letter position, around the word center (e.g., the Spanish word *obseso* has the higher frequency deletion neighbor *obeso*). Each of the critical words was paired with a control word that did not possess a deletion neighbor. Experimental and control words were matched with respect to length, number of syllables, *N*, bigram frequency, and word frequency (see Table 3). None of these words had any higher frequency substitution neighbors, any transposition neighbors, or any addition neighbors. Secondly, we selected 18 word stimuli (mean word frequency = 4.5 per million, mean word length = 6.3 letters) that possessed addition neighbors that were of higher frequency than the stimulus word (mean frequency = 25 per million). The position of the addition neighbor word was always an internal letter position, around the word center (e.g., *pasaje* has the higher frequency addition neighbor *paisaje*). Each of the critical words was paired with a control word that did not have an addition neighbor. Experimental and control words were matched with respect to word length, number of syllables, *N*, bigram frequency and word frequency (see Table 3). None of these words had any higher frequency substitution neighbors, any transposition neighbors, or any deletion neighbors. Thirdly, we selected 18 word stimuli (mean word fre-

Table 3
Characteristics of the words in Experiment 2

	DN		AN		TLN	
	Exper	Cont	Exper	Cont	Exper	Cont
Word Freq	4.3	4.5	5.1	4.3	4.5	5.3
Word length	6.8	6.3	5.9	6.8	6.3	5.9
# Syllables	2.8	2.8	2.8	2.8	2.8	2.8
N	0.3	1.1	2.6	0.2	0.7	2.4
Mean BF	2.4	2.5	2.5	2.3	2.2	2.6

Note: DN = words with a higher frequency deletion neighbor; AN = words with a higher frequency addition neighbor; TLN = words with a higher frequency transposition neighbor; *N* = number of substitution neighbors; BF = mean (log) bigram frequency.

quency = 5.2, mean word length = 5.9) that possessed transposition neighbors that were of higher frequency than the stimulus word (mean frequency = 47 per million). The position of the transposition neighbor always occurred at an internal letter position, around the word center (e.g., the Spanish word *guarida* has the higher frequency transposition neighbor *guardia*). Each of the critical words was paired with a control word that did not have a transposition neighbor. Experimental and control words were matched with respect to word length, number of syllables, *N*, bigram frequency and word frequency (see Table 3). Because of the small number of transposition neighbors in Spanish, some of them had addition/deletion neighbors and/or higher frequency substitution neighbors; to control for these variables, the experimental and control words were matched with respect to the number of addition neighbors, deletion neighbors, and the number of higher frequency substitution neighbors. We also employed 112 orthographically legal nonwords—with the same length and syllabic structure as the experimental/control words—for the purposes of the lexical decision task. Two lists of materials were constructed to counterbalance the items across visual field (left, right). Different groups of participants were used for each list.

3.1.3. Procedure

This was the same as in Experiment 1, except that we did not include a "central visual field" condition.

3.2. Results and discussion

Incorrect responses and reaction times less than 250 ms or greater than 1500 ms (less than 1%) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 4. For word targets, ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (neighborhood frequency: words with higher frequency neighbors, words with no higher frequency neighbors) × 3 (Type of target: deletion, addition, transposition) × 2 (Visual field: left, right) × 2 (List: list 1, list 2) design. For nonword targets, ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (Visual field: left, right) × 2 (List: list 1, list 2) design.

3.2.1. Word targets

The ANOVA on the latency data showed that words with higher frequency neighbors were responded to 15 ms more slowly than their corresponding control words, $F1(1, 42) = 9.77$, $MSE = 4676$, $p < .001$; $F2(1, 50) = 4.47$, $MSE = 2781$, $p < .04$; and that words presented in the left visual field were responded to 48 ms more slowly than words presented in the right visual field, $F1(1, 42) = 36.09$, $MSE = 8363$, $p < .001$; $F2(1, 50) = 98.21$, $MSE = 1568$, $p < .001$. More important, there was a significant interaction between neighborhood frequency and visual field, $F1(1, 42) = 5.28$, $MSE = 3862$, $p < .03$; $F2(1, 50) = 2.86$, $MSE = 1507$, $p < .098$: in the right visual field, words with higher frequency neighbors were responded to 31 ms more slowly than their controls, $F1(1, 42) = 19.62$, $MSE = 3241$, $p < .001$; $F2(1, 50) = 7.10$, $MSE = 2211$, $p < .011$; in contrast, this difference vanished (it was only 6 ms) in the left visual field, both $ps > .15$. In addition, there was a significant interaction between type of target and neighborhood frequency in the analysis by participants, $F1(1, 42) = 8.50$, $MSE = 2912$, $p < .001$; $F2(1, 50) = 1.39$, $MSE = 2781$, $p > .15$: words with higher frequency addition neighbors were responded to 44 ms more slowly than their controls, $F1(1, 42) = 28.48$, $MSE = 2988$, $p < .001$; $F2(1, 16) = 5.32$, $MSE = 3493$, $p < .035$; words with higher frequency deletion neighbors were responded to 15 ms more slowly than their controls, $F1(1, 42) = 3.73$, $MSE = 2606.4$, $p = .06$; $F2 < 1$; whereas the difference between the words with higher frequency transposition neighbors and their controls was only 3 ms, both $ps > .15$. Finally, the interaction between type of target and visual field approached significance in the analysis by participants, $F1(1, 42) = 3.47$, $MSE = 3683$, $p = .069$; $F2 < 1$: the effect of visual field (i.e., the difference in response time between the right and left visual fields) was smaller for words with higher frequency addition neighbors (28 ms) than for words with higher frequency deletion neighbors (59 ms) or words with higher frequency transposition neighbors (56 ms). The other effects were not significant (all $ps > .15$).

The ANOVA on the error data showed that words presented in the left visual field yielded more errors than the words presented in the right visual field (35.7 vs. 16.9%, respectively), $F1(1, 42) = 61.67$, $MSE = 749$, $p < .001$; $F2(1, 50) = 159.62$, $MSE = 123$, $p < .001$. In addition, type

Table 4
Mean lexical decision times in ms and percentage of errors (in parentheses) for words in Experiment 2

	Left visual field			Right visual field		
	HFN	No HFN	NF effect	HFN	No HFN	NF effect
AN	600 (36.6)	575 (31.8)	25 (4.8)	591 (19.2)	528 (12.4)	63 (6.8)
DN	600 (31.4)	596 (36.1)	4 (−4.7)	551 (16.1)	526 (18.6)	25 (−2.5)
TLN	600 (37.9)	611 (40.2)	−11 (−2.3)	552 (17.7)	548 (17.7)	4 (0.0)

Note: HFN = words with a higher frequency neighbor; no HFN = words without higher frequency neighbors; AN = words with a higher frequency addition neighbor; DN = words with a higher frequency deletion neighbor; TLN = words with a higher frequency transposition neighbor.
The mean response time and percent error (in parentheses) for the nonwords were 617 ms (11.7%) and 595 ms (10.3%) for the left and right visual fields, respectively.

of word interacted with the word having a higher frequency neighbor in the analysis by participants, $F1(1, 42) = 5.08$, $MSE = 179$, $p < .03$; $F2(1, 50) = 1.70$, $MSE = 263$, $p > .15$: participants made less errors to words with higher frequency addition neighbors than to their corresponding controls (4.8 vs. 6.8% respectively), $F1(1, 42) = 7.52$, $MSE = 197$, $p < .009$; $F2(1, 16) = 2.59$, $MSE = 235$, $p = .12$, whereas the difference between words with higher frequency deletion or transposition neighbors and their corresponding controls was not significant. The other effects did not approach significance (all ps > .15).

3.2.2. Nonword targets

The ANOVA on the latency data only showed that nonwords in the left visual field were responded to 23 ms more slowly than the nonwords presented in the right visual field, $F1(1, 42) = 10.04$, $MSE = 1111$, $p < .001$; $F2(1, 110) = 22.24$, $MSE = 1450$, $p < .001$. The ANOVA on the error data did not reveal any significant effects (all ps > .15).

The results of Experiment 2 are straightforward: we found a right visual field advantage and an inhibitory effect of neighborhood frequency—this time for deletion/addition/transposition neighbors. But the most remarkable finding is the interaction between visual field and neighborhood frequency: the inhibitory effect of neighborhood frequency occurs in the right visual field (i.e., left hemisphere) rather than in the left visual field (right hemisphere). Finally, the inhibitory effect of neighborhood frequency differs across type of words: having a higher frequency addition neighbor produces a stronger inhibitory effect than having a deletion or a transposition neighbor of higher frequency.

4. General discussion

The main findings of the present experiments can be summarized as follows: (i) as usual, we found a right visual field advantage in response times and error percentage (relative to the left visual field), (ii) the effect of number of substitution neighbors (or *N*) interacted with visual field: the effect of *N* was facilitative in the left visual field (right hemisphere), while it was inhibitory in the right visual field (left hemisphere), (iii) the inhibitory effect of neighborhood frequency is enhanced in the right visual field (left hemisphere) relative to the right visual field (left hemisphere), and (iv) this pattern of lexical competition was obtained with addition, deletion, and transposition neighbors. Taken together, these findings have clear implications for the input coding schemes employed by models of visual word recognition.

Experiment 1 showed that the facilitative effect of the number of substitution neighbors (*N*) that occurred in the left visual field (i.e., initially projected to the right hemisphere) was inhibitory when the words were presented in the right visual field (left hemisphere). Clearly, orthographic neighbors can have both an inhibitory effect (from lexical competition) and a facilitative effect (most likely due to top-down orthographic activation), and the present findings show that the relative strength of these effects varies with the visual field presentation. As Lavidor and Ellis (2002) suggested, there is more "widespread orthographic activation" in the right hemisphere than in the left hemisphere. This interpretation is reinforced by the findings from Experiment 2. In Experiment 2, we examined the effect of neighborhood frequency in a visual field paradigm by using words with higher frequency addition, deletion, or transposition neighbors relative to carefully matched control words. An inhibitory effect of neighborhood frequency (i.e., a sign of lexical competition) was found in the right visual field (left hemisphere), but not in the left visual field (right hemisphere). Taken together, these results support the view that there is a different pattern of orthographic encoding for words presented in the left and right visual fields (e.g., see Chiarello, 2003; Crossman & Polich, 1988; Lavidor & Ellis, 2001; Lavidor & Ellis, 2002; Perea & Fraga, 2006; Whitney & Lavidor, 2005).

What are the implications of the present findings for models of visual word recognition? Only the split-fovea and SERIOL models predict a dissociating effect of orthographic neighborhood in the left and right visual fields. The split-fovea model (Shillcock et al., 2001; see also Lavidor et al., 2004; Monaghan et al., 2004) assumes that the right hemisphere is more sensitive to multi-letter representations. Words with many neighbors (or words with higher frequency neighbors) involve a higher level of bottom-up activation, but also a higher degree of lateral inhibition. In the right hemisphere, this activity occurs across bigrams and trigrams, whereas in the left hemisphere it occurs across letters. As a result, large orthographic representations are overlapped in the right hemisphere, involving a coarser coding and a facilitative effect of *N*. A similar argument would apply to the dissociating effect of neighborhood frequency across visual field: unlike the more efficient (fine-grained) processing in the left hemisphere, the orthographic representations in the right hemisphere are less fine-tuned. This would prevent lexical inhibition from a word's higher frequency neighbors in the right hemisphere.

The SERIOL model (Whitney, 2001; Whitney, 2004; Whitney & Lavidor, 2005) correctly predicts a facilitative effect of words with high-*N* words in the left visual field in terms of lateral inhibition activity induced by the high top-down activation of the acuity gradient—that is, the facilitative effect of *N* would occur at the letter level. The idea here is that orthographic neighbors can have both an inhibitory effect (from lexical competition) and a facilitative effect (e.g., due to top-down orthographic activation). The relative strength of these effects varies with visual field presentation. In the SERIOL model, the most facilitative effect of *N* occurs in the left visual field because here orthographic encoding is relatively poor, so top-down orthographic facilitation can make up for poorer encoding, allowing the facilitative effect to dominate. This activation implies an increased lateral inhibition activity and an effortful balance of activation weights in the right hemisphere, with low bottom-up activation from the letter to the word level. Unlike the facilitative effect of *N*, which is assumed to occur at the letter level (via top-down input to letter nodes on the basis of global activation in the lexicon), the inhibitory effect of neighborhood frequency would occur at the word level (via lateral inhibition). In the SERIOL model, the degree of lexical inhibition would interact with visual field because the relative activation levels of the stimulus item and its competitors vary with visual field since the quality of orthographic encoding varies with visual field. Although Whitney and Lavidor (2005) did not include any specific simulations of the neighborhood frequency effect across visual field, they did indicate that, in a central presentation, the inhibitory effect from a word's neighbors would be enhanced when the mismatching letter lies in the right visual field (i.e., left hemisphere). Thus, the SERIOL model could, in principle, capture the observed neighborhood frequency effect in the right visual field.

There is alternative explanation for the interaction between *N* (or neighborhood frequency) and visual field in the framework of the multiple read-out model. Because of differential processing efficiency in orthographic encoding across hemispheres, responses in the left and right hemispheres could have a different origin. More specifically, the more efficient processing in the left hemisphere (right visual field) may lead to a lexically-based response, via the use of a unique-word identification criterion (the M criterion). (Note that if most responses are generated via the M criterion, the multiple read-out model predicts an inhibitory effect of *N* and an inhibitory effect of neighborhood frequency, as actually occurs in the experiments.) In contrast, the less efficient processing in the right hemisphere (left visual field) may lead to the use of a global lexical activation criterion (the Σ criterion). (Note that the frequent use of the Σ criterion leads to a facilitative effect of *N* and a null/facilitative effect of neighborhood frequency in lexical decision, as actually occurs.) In any case, what we should also note is that this explanation in terms of different response criteria complements rather than competes with the previously examined models.

Leaving aside the issue of the interaction between visual field and neighborhood frequency in Experiment 2, another remarkable finding is the presence of an effect of neighborhood frequency for several types of neighbors—not just substitution neighbors. The inhibitory effect of having a higher frequency neighbor was particularly strong for addition neighbors (*tail–TRAIL*), it was weaker for deletion neighbors (*tribal–TRIAL*), while the effect of having a higher frequency transposition neighbor was almost negligible (*trial–TRAIL*). This finding implies that perceptual similarity is not length dependent (see also De Moor & Brysbaert, 2000; Grainger et al., 2006; Perea & Carreiras, 1998). Clearly, this effect of neighborhood frequency for addition/deletion neighbors cannot be captured by the (channel-specific) input coding scheme of the interactive activation model (McClelland & Rumelhart, 1981) or its successors (dual-route cascaded model, Coltheart et al., 2001; multiple read-out model, Grainger & Jacobs, 1996): *tribal* and *trial* would not be perceptually similar in a channel-specific coding scheme.

Interestingly, the SERIOL model can readily explain the presence of neighborhood frequency effects with addition, deletion, and transposition neighbors. For example, the word *TRIBAL* in the SERIOL model would be coded by the set {*tr*, *ti*, *ta*, *tl*, *ri*, *ra*, *rl*, *ia*, *il*, *al*}, and is therefore relatively similar to the higher frequency deletion neighbor word *trial*, which is coded by the set {*tr*, *ti*, *tb*, *ta*, *tl*, *ri*, *rb*, *ra*, *rl*, *ib*, *ia*, *il*, *ba*, *bl*, *al*} (i.e., the two words share ten out of fifteen open-bigrams). This type of coding can also explain the perceptual similarity of transposed-letter pairs (e.g., *trial* shares eight of its nine open-bigrams with *trail*). Another recently proposed input coding scheme is the SOLAR model (Davis, 1999; Davis, 2006). According to the SOLAR model, transposition, addition, and deletion neighbors are coded by similar patterns of activity across the same set of letter units (see Davis, 2006). Interestingly, the SOLAR model supports the role of lexical inhibition in lexical selection, and therefore can readily capture the inhibitory effect of neighborhood frequency found in Experiment 2 (see also Davis & Perea, submitted for publication).

There is one caveat, though: in the SOLAR and SERIOL models, transposition neighbors tend to be more perceptually similar than addition/deletion neighbors. However, the results from Experiment 2 suggest that, unlike having higher frequency addition/deletion neighbors, having higher frequency transposition neighbors does not seem to interfere with word processing. The lack of a neighborhood frequency effect with transposition neighbors may not be a type II error. Transposed-letter effects are robust for nonword stimuli (e.g., *cholocate* pronounced as *chocolate*; see Perea & Estévez, in press), but the empirical evidence is scarce for word stimuli. Recently, in a series of masked priming and eye-movement experiments, Duñabeitia, Perea, and Carreiras (submitted for publication) also failed to obtain an effect of neighborhood frequency with transposition neighbors for low-frequency words. What we should also note is that the inhibitory effect of neighborhood frequency reported by Andrews (1992) was restricted to high-frequency words with transposition neighbors—whereas the stimuli of our Experiment 2 were low-frequency words. For instance, one could argue that there might be a very strong inhibitory connection from a low-frequency word unit to a high-frequency transposition neighbor—the strength of this inhibition would be greater than the usual general effect of lateral inhibition.[4] Thus, when the stimulus item corresponds to a low-frequency word, this allows a slightly better orthographic match to the low-frequency word to beat/rule out the strongly-activated high-frequency transposition neighbor. Note that without such strong inhibition, it might not be possible

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[4] We thank Carol Whitney for suggesting this possibility.

for the low-frequency word to win, and this explanation would be consistent with the reported inhibitory effect of lower frequency transposition neighbors on high-frequency words. Instead, for addition or deletion neighbors, general lateral inhibition may allow a low-frequency word to win because the orthographic match to these neighbors would not be as strong as for transposition neighbors—that is, there is no specific strong inhibition between a low-frequency word and its corresponding high-frequency addition or deletion neighbors. In this case, a general effect of lateral inhibition would emerge when a higher frequency neighbor exists, as actually occurs in Experiment 2. Clearly, further experimentation on the dynamics of transposition, substitution, addition, and deletion neighbors during lexical access is necessary to help understand the way the brain encodes letter position in words.

One important question for future experiments is to examine whether the effects of letter position encoding and lexical inhibition have a different impact across languages. As stated in Section 1, the facilitative effect of *N* tends to be greater in English than in Spanish. Although the interaction between *N* and visual field is a robust finding in English and Spanish, the pattern is not exactly the same (e.g., the effect of *N* in the left hemisphere is inhibitory in Spanish, while it is negligible in English). Thus, the question is how a single model might account for the obtained cross-linguistic data. As indicated above, this probably could come from a differential impact of top-down influences vs. bottom-up influences (i.e., orthographic neighbors can have both an inhibitory effect—from lexical competition—and a facilitative effect—from top-down orthographic activation). Alternatively, differences between languages may emerge from the statistical distributions of letters (see Tamariz, 2005, for comparative analyses of entropy for English and Spanish words).

In sum, the present experiments provide compelling evidence for a dissociating role of the cerebral hemispheres in orthographic neighborhood effects: lexical competition across similarly spelled words is enhanced when the words are initially projected to the visual cortex of the left cerebral hemisphere. The present data are consistent with a set of models that postulate hemispheric differences in the involvement of the lexicon (e.g., SERIOL model, split-fovea model). Another important result is that addition and deletion neighbors also form part of a word's orthographic neighborhood—perhaps to a greater degree than transposition neighbors. Taken together, these findings pose important constraints for recent models of visual word recognition.

Appendix A. Words used in Experiment 1

Low-N words. tigre, crema, revés, hábil, mamut, naipe, tecla, ancla, herir, lejía, freír, furor, diván, trufa, ostra, vejez, molde, dátil, bidón, puñal, tilde, tifus, sidra, lonja, flúor, rural, pugna, fósil, esquí, debut, fugaz, tribu, matiz, flujo, globo, nevar, rehén, garbo, bambú, gaita, lápiz, logro, fémur, móvil, bedel, robot, tenaz, rapto, tarot, himno, cisne, fobia, viudo, gripe, audaz, relax, dócil, boina, coñac, momia.

High-N words. tarro, plana, caldo, sarro, parto, gramo, torta, manto, burra, brava, resta, tinta, calco, tallo, rosco, brasa, barca, palmo, pecar, sonda, bruta, dólar, gorra, pollo, manso, grato, pinar, pasto, pegar, grano, menta, porro, pilar, talón, morro, garra, cobra, terso, carpa, casar, callo, braga, valla, trama, trazo, sueco, panal, polar, recta, manco, sorda, hacha, costo, cesta, tazón, graso, zorra, chato, pisar, polio.

Appendix B. Words used in Experiment 2

B.1. Addition neighbors set

Words with higher frequency neighbors. violeta, eslavo, menaje, cocción, planear, conejo, cliente, sobrio, pasaje, visera, alcázar, inmoral, senado, babero, fiado, realzar, pródigo, mítica.

Words with no higher frequency neighbors. insecto, roedor, orfeón, soprano, asustar, arroyo, castigo, jazmín, butaca, fabada, cepillo, gaviota, escudo, nuboso, trufa, embalse, enchufe, cohete.

B.2. Deletion neighbors set

Words with higher frequency neighbors. indicio, camisón, juzgar, trauma, asfalto, desatino, madrina, carnal, fractura, constar, obseso, hervida, estigma, alternar, étnica, absorto, cósmico, granuja, flecha, oregano.

Words with no higher frequency neighbors. limosna, esgrima, vestir, jazmín, lateral, sinagoga, padrino, franja, diagonal, sembrar, bufete, tatuaje, sortija, colmillo, enfado, pupitre, rústico, cotorra, nervio, amuleto.

B.3. Transposition neighbors set

Words with higher frequency neighbors. odio, prejuicio, clamar, estriada, causal, cuneta, clavo, cedro, alergia, hornada, guarida, trío, prado, tarta, tronar, persa, truco, alienar.

Words with no higher frequency neighbors. isla, privación, termal, senadora, trazar, pésimo, tripa, tazón, ofrenda, trapera, cúspide, yema, multa, barca, turbar, sonda, pugna, aturdir.

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