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ERP correlates of transposed-letter priming effects: The role of vowels versus consonants

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Abstract

One key issue for any computational model of visual-word recognition is the choice of an input coding scheme for assigning letter position. Recent research has shown that pseudowords created by transposing two letters are very effective at activating the lexical representation of their base words (e.g., *relovution* activates *REVOLUTION*). We report a masked priming lexical decision experiment in which the pseudoword primes were created by transposing/replacing two consonants or two vowels while event-related potentials were recorded. The results showed a modulation of the amplitude at an early window (150–250 ms) and at the N400 component for vowels but not for consonant transpositions. In addition, the peak latencies were faster for transposed than replaced consonants. These results suggest that consonants and vowels play a different role during the process of visual word recognition. We examine the implications for the choice of an input coding scheme in models of visual-word recognition.

Descriptors: Visual-word recognition, Transposed-letters, ERPs, Consonants and vowels, Masked priming

When we read, it is relatively common to misread words like *causal* and *casual*. This misperception is related to a basic issue in reading that can be summarized in the following question: How do we extract the identity and position of the letters in a written word? Recent research has shown that transposed-letter neighbors are perceptually very similar to the target stimulus (*trail* and *trial*, *jugde* and *judge*; e.g., Perea & Lupker, 2003, 2004). For instance, in a masked priming paradigm, a target word is recognized faster when it is preceded by a briefly presented transposed-letter nonword prime (jugde–JUDGE) than when it is preceded by an orthographic control (jupte–JUDGE) (see Forster, Davis, Schoknecht, & Carter, 1987; Perea & Carreiras, 2006a, 2006b; Perea & Lupker, 2003, 2004; Schoonbaert & Grainger, 2005). Furthermore, transposed-letter effects have also been found in normal silent reading when the participants' eye movements are monitored (see Acha & Perea, 2008; Johnson, 2007; Johnson, Perea, & Rayner, 2007; Rayner, White, Johnson, & Liversedge, 2006). Most notably, the presence of transposed-letter similarity effects has critical implications for the choice of a coding scheme in visual word recognition: Most current computational models of visual-word recognition (e.g., Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Paap, Newsome, McDonald, & Schvaneveldt, 1982; Perry, Ziegler, & Zorzi, 2007) assume that each letter is encoded in a different "letter-channel," and hence they cannot accommodate the presence of transposed-letter effects.

A number of input "coding schemes" have recently been proposed that successfully capture the existence of transposed-letter effects (e.g., SERIOL model, Whitney, 2001; SOLAR model, Davis, 1999; open-bigram model, Grainger & van Heuven, 2003; overlap model, Gomez, Ratcliff, & Perea, 2008). Although the basic mechanisms of how letter position is encoded differ across these models (e.g., via the activation of open bigrams in the SERIOL and open-bigram models, via a spatial-coding in the SOLAR model, or via a noisy perceptual input in the overlap model), they all predict that transposed-letter neighbors like *casual* and *causal* are perceptually very similar. There is one caveat, though: These models assume that consonants and vowels are processed in exactly the same way. However, this may not be the case.

Recent research suggests that the processing of vowels and consonants may be different. For instance, vowel information constrains lexical selection less tightly than consonant information (see Cutler, Sebastián-Gallés, Soler-Vilageliu, & van Ooijen, 2000). Cutler et al. showed that, when allowed to change one phoneme to make a word from a pseudoword, participants more often alter a vowel than a consonant. Thus, when presented with a pseudoword like *zobra*, listeners tend to come up with the word *zebra*, rather than with the word *cobra*, showing that a vowel substitution is easier than a consonant substitution—and this is

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so in languages as different and Dutch and Spanish (see also Berent & Perfetti, 1995; Lee, Rayner, & Pollatsek, 2001, 2002, for additional evidence of consonant/vowel differences in visual word recognition). Furthermore, in a lexical decision task in which either two of the constituent vowels or two of the constituent consonants were delayed for 50 ms (e.g., *PRIM V RA–PRIMAVERA* vs. *PRI A ERA-PRIMAVERA*), Carreiras, Gillon-Dowens, Vergara, and Perea (in press) found a difference in sustained negativity in the ERP waves between consonants and vowels; more specifically, this negativity was larger when two consonants were delayed as compared to when two vowels were delayed. Consonant/vowel differences have also been found in auditory word recognition: It is very difficult to use transitional probabilities between successive vowels to find words, whereas this process is much easier for successive consonants (Bonatti, Peña, Nespor, & Mehler, 2004;see also Nespor, Peña, & Mehler, 2003; Peña, Bonatti, Nespor, & Mehler, 2002). Furthermore, a number of neuropsychological studies with patients also suggest that there are processing differences between consonants and vowels (Caramazza, Chialant, Capasso, & Miceli, 2000; Cotelli, Abutalebi, Zorzi, & Cappa, 2003; Cubelli, 1991; Miceli, Capasso, Benvegnu, & Caramazza, 2004; Tainturier & Rapp, 2004). Clearly, these findings offer some neuropsychological "reality" to the functional distinction between vowels and consonants. This was corroborated in a recent study by Carreiras and Price (2008). They used fMRI in lexical decision and naming to investigate whether vowel and consonant processing differences are expressed differently in the neural activation pattern. Vowels and consonants produced different effects on regional brain activation. Changing vowels relative to consonants increased activation in a right middle temporal area previously associated with prosodic processing of speech input. Taken together, these results are consistent with claims that vowels and consonants are processed differently.

The goal of the present experiment is to examine the effects of transposed-letter priming on lexical access, with specific attention to the role of consonants and vowels, by using electrophysiological measures. Note that response times may not be the best method to directly tap into the time course of processing, because they give the researcher only one data point at the end of processing. Event-related potentials (ERPs) are voltage changes recorded from the scalp and extracted from the background electroencephalogram by averaging time-locked responses to stimuli onset. ERPs are functionally decomposable to a greater extent than behavioral data, thus enabling us to draw conclusions not only about the existence of processing differences between vowels and consonants, but more importantly, about the level of processing at which these differences occur. Of specific interest for our study is the N400 component, a negative deflection occurring around 400 ms after a word presentation that has been associated with lexical-semantic processing (see Holcomb, Grainger, & O'Rourke, 2002; Kutas & Federmeier, 2000). In particular, for the present purposes, the amplitude of this negativity is an inverse function of orthographic neighborhood size (Holcomb et al., 2002). Words embedded in a large neighborhood (in terms of "one-letter different" neighbors; see Carreiras, Perea, & Grainger, 1997; Perea & Rosa, 2000) generate a larger N400 component than words embedded in a sparse neighborhood. In addition, transposed-letter pseudowords generate more lexical activity than replacement-letter pseudowords, either at the level of form representations or at the level of semantic representation (see Holcomb et al., 2002), as deduced from the high rate of false positives in the lexical decision task (Carreiras, Vergara, & Perea, 2007; see also Perea & Lupker, 2004)—note that this is particularly the case when the transposed letters are consonants (Carreiras et al., 2007). Therefore, using transposed-letter pseudowords as masked primes should attenuate the amplitude of the N400 component relative to replacement-letter pseudowords. Finally, we examine the P3 component, because this component is usually present in priming experiments using word pairs that require an immediate response (e.g., Bentin, McCarthy, & Wood, 1985) in binary-type decision tasks (Donchin & Coles, 1988).

A number of studies have recorded electrophysiological measures with a masked priming paradigm (e.g., Deacon, Hewitt, Yang, & Nagata, 2000; Grossi, 2006; Holcomb, Reder, Misra, & Grainger, 2005; Kiefer, 2002; Kiefer & Spitzer, 2000; Misra & Holcomb, 2003; Schnyer, Allen, & Forster, 1997). Of special relevance for the present study is the experiment reported by Grainger, Kiyonaga, and Holcomb (2006), which (to our knowledge) is the only previous work that has examined the time course of transposed-letter priming (e.g., *barin-BRAIN* vs. *bosin-BRAIN*) using ERPs. More specifically, Grainger et al. found that transposed-letter primes modulated the ERP signal in a window between 150 and 250 ms after stimuli presentation. Replaced letter controls produced a larger amplitude in the 150–250-ms window than transposed letter primes. They interpreted this pattern as reflecting orthographic sublexical processes. In addition, other studies have found a modulation of early ERP components by sublexical variables in similar time windows (Carreiras, Vergara, & Barber, 2005; see Barber & Kutas, 2007, for a review of ERP effects in visual-word recognition). Therefore, the combination of masked priming with ERPs seems to be the appropriate combination to capture early differential effects of processing vowels versus consonants.

One potential limitation of the Grainger et al. (2006) transposed-letter experiment is that consonant/vowel status was not controlled. As reviewed earlier, consonants and vowels seem to be processed differently in a number of visual-word paradigms, and transposed-letter priming may not be an exception: Behavioral masked transposed-letter priming experiments have shown some dissociation between consonant and vowel transpositions. For instance, in a masked priming lexical decision experiment, Perea and Lupker (2004) obtained a priming effect for consonant transpositions (*relovución-REVOLUCIÓN* vs. the control *retosución-REVOLUCIÓN*), but not for vowel transpositions (*reluvoción-REVOLUCIÓN* vs. *revalición-REVOLUCIÓN*; see Lupker, Perea, & Davis, 2008, for a replication in English). (Note that in a single-presentation technique, transposed-letter pseudowords produce slower responses times and more error rates than replacement-letter pseudowords, and again this effect is greater for consonant than for vowel transpositions; Perea & Lupker, 2004; see also Carreiras et al., 2007; Lupker et al., 2008; Perea & Carreiras, 2006c). Perea and Lupker (2004) argued that these results were consistent with claims that there may be some basic processing differences between vowels and consonants in the process of lexical access.

Given the empirical evidence on processing differences between vowels and consonants, it is of particular interest to reexamine in depth (via ERPs) the time course of transposed-letter priming for consonant versus vowel transpositions. Thus, in the present study, we wished to examine the scope of transposed-letter effects on electrophysiological measures. More specifically, we asked which transposed-letter similarity differences in the ERPs occur for target words (e.g., *REVOLUCIÓN*) preceded by transposed-letter pseudowords created by transposing two nonadjacent consonants (e.g., *relovución*) and two nonadjacent vowels (e.g., *reluvoción*). In all cases, these effects were evaluated relative to the appropriate orthographic controls (i.e., replacement-letter pseudowords as primes, as in *retonución* and *revalición*). It is important to mention that the assumption of a differential role for consonants and vowels in letter position coding has recently been challenged. In a recent eye-movement study, Johnson (2007) failed to obtain any signs of dissociation between consonant-consonant (C-C) and vowel-vowel (V-V) transpositions in the parafovea when the participants' eye movements were monitored. Specifically, she found that reading times to words (e.g., *forest*) were faster when they had been preceded by a transposed-letter parafoveal preview (*fosert*) than by a replacement-letter parafoveal preview (*fonewt*): This transposed-letter priming effect was approximately the same size for C-C transpositions (e.g., *fosert-forest* vs. *fonewt-forest*) and for V-V transpositions (e.g., *flewor-flower* vs. *flawur-flower*). Johnson suggested that parafoveal effects would reflect low-level processing that may occur before the encoding of a vowel/consonant label and the phonological attachment of letters to sounds. Furthermore, in a recent masked priming lexical decision experiment, Perea and Acha (2008) found that the transposed-letter priming effect to target words occurred for C-C transpositions, but not for V-V transpositions—as in the experiments of Perea and Lupker (2004; Lupker et al., 2008). However, when the same materials were used in a low-level perceptual task (a same–different task), the transposed-letter priming effect for word stimuli was essentially of the same magnitude for C-C and V-V transpositions. Thus, Perea and Acha extended Johnson's observation to a foveal presentation (via masked primes) and a low-level perceptual task: the same–different task. Thus, it seems of particular importance to revisit the transposed-letter priming effect with consonant–consonant and vowel–vowel transpositions by examining in detail the *timing* of these priming effects in the lexical decision task, via ERPs.

In sum, by using primes created by transposing two consonants or two vowels versus replacing two consonants or two vowels we expect an attenuation of the N400 amplitude, an attenuation of the amplitude in an early window (150–250 ms) that was previously found to be sensitive to orthographic processes (Grainger et al., 2006). Furthermore, in the lexical decision times, we predict faster latencies to words preceded by a transposed-letter prime (relative to a replacement-letter prime), as in previous behavioral studies (e.g., Perea & Carreiras, 2006a, 2006b; Perea & Lupker, 2004). Finally, if there are processing differences for consonants and vowels during the time course of visual word recognition, differences in the ERP signal should be observed when comparing masked transposed-letter priming effects for consonants versus vowels, such as the P3 component—note that the P3 latency varies as a function of the difficulty of the stimulus evaluation (Kutas, McCarthy, & Donchin, 1977).

Method

Participants

Forty-two (22 women) undergraduate students participated in the experiment in exchange for course credit. All of them were native Spanish speakers, with no history of neurological or psychiatric impairment, and with normal or corrected-to-normal vision. Ages ranged from 18 to 26 years (mean = 23.2 years). All participants were right-handed, as assessed with an abridged Spanish version of the Edinburgh Handedness Inventory (Oldfield, 1971).

Materials

The targets were 240 Spanish words that were 7 to 11 letters long (mean word frequency per one million words in the count by Sebastián-Gallés, Martí, Cuetos, & Carreiras, 2000: 23, range: 1–147; mean number of one-letter different neighbors (Coltheart's *N*): 0.5, range: 0–5; mean length in letters: 8.9, range: 7–11, in the B-Pal database, Davis & Perea, 2005). The targets were presented in uppercase and were preceded by pseudoword primes in lowercase that were (1) the same except for a transposition of two internal consonants, *relovución-REVOLUCIÓN* (transposed-letter consonant condition); (2) the same except for the substitution of the corresponding internal consonants, *retosución-REVOLUCIÓN* (replacement-letter consonant condition); (3) the same except for a transposition of two internal vowels, *revuloción-REVOLUCIÓN* (transposed-letter vowel condition); or (4) the same except for the substitution of the corresponding internal vowels, *revalición-REVOLUCIÓN* (replacement-letter vowel condition). Primes were always pseudowords. The transposed-letter pseudowords and their orthographic controls both had, on average, 0.075 one-letter different neighbors (range 0–1) (note that all these neighbors were always very-low-frequency words, with a frequency no higher than 3 per million). The bigram frequency was similar for the transposed and replacement letter nonwrod primes, $p > .50$. In all cases, the first syllable of the base word remained unchanged. An additional set of 240 target pseudowords that were 7 to 11 letters long was included for the purposes of the lexical decision task. The manipulation of the pseudoword trials was the same as that for the word trials. To counterbalance the materials, four lists were constructed so that each target appeared once in each list, but each time in a different priming condition (see Pollatsek & Well, 1995). Different groups of participants were assigned to each list.

Procedure

Participants were seated comfortably in a darkened, sound-attenuated chamber. All stimuli were presented on a high-resolution monitor that was positioned at eye level 80–90 cm in front of the participant. All targets were displayed in white uppercase Arial 24 point font against a dark gray background. Primes were displayed in lowercase. Participants performed a lexical decision task: They were instructed to press one of two buttons on the response pad to indicate whether the letter string was a legitimate Spanish word or not. A response button was positioned beneath each thumb. For half of the participants the right button was used to signal the "yes" response and left button was assigned the "no" response. For the remaining participants the assignment was reversed. Each trial began with a row of hash marks ("##########"), which appeared in the center of the screen and remained there for 500 ms. A prime word displayed for 44 ms followed, and then the target item was displayed for 400 ms. The trial ended with the participant's response or 2000 ms after the presentation of the word if the participant failed to respond. The intertrial interval varied randomly between 1000 and 1300 ms. Participants reported no awareness of the lowercase stimuli when asked after the experiment. All items were presented in a different random order for each participant in six

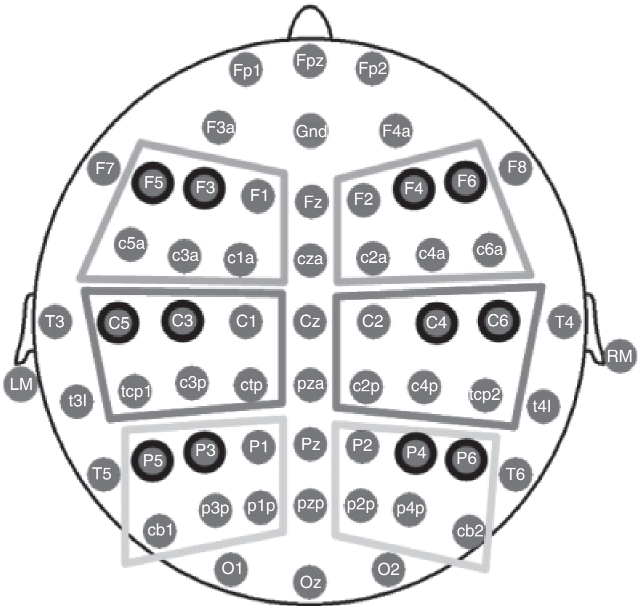

Figure 1. Schematic flat representation of the 58 electrode positions from which EEG activity was recorded (front of head is at top). Approximate international 10-20 system localizations are marked. The electrodes were grouped and analyzed in the six critical regions, as shown in the figure.

different blocks, with a break of few minutes between blocks in which the participant could rest and the impedances were checked.

Sixteen different warm-up trials, containing different stimuli from those used in the experimental trials, were provided at the beginning of the session and were repeated if necessary. Participants were asked to avoid eye movements and blinks during the interval when the row of hash marks was not present, and they were directed to favor accuracy over speed in their responses. Each session lasted approximately 1 h 15 min.

EEG Recording and Analyses

Scalp voltages were collected from 58 Ag/AgCl electrodes that were mounted in an elastic cap (ElectroCap International, Eaton, USA; 10-10 system). Figure 1 shows the schematic distribution of the recording sites. Linked earlobes were used as reference. Eye movements and blinks were monitored with six further electrodes providing bipolar recordings of the horizontal and vertical electro-oculogram (EOG). Interelectrode impedances were kept below 10 KΩ. EEG was filtered with an analogue band-pass filter of 0.01–100 Hz, and a digital 20 Hz low-pass filter was applied before analysis. The signals were sampled continuously throughout the experiment with a sampling rate of 250 Hz.

Epochs of the EEG up to 700 ms after word onset presentation, corresponding to correct responses and free of ocular (blinks and movements) and muscular artifacts, were averaged and analyzed (more than 94% of trials). The baseline correction was performed using the average EEG activity in the 100 ms preceding the onset of the prime pseudoword as a reference signal value. (The results of the analyses were similar when a baseline correction of 100 ms before the target was used.) Separate ERPs were formed for each of the experimental conditions, each of the subjects, and each of the electrode sites. Six regions of interest were computed out of the 58 electrodes, each containing the mean of a group of electrodes. The regions were (see electrode numbers in Figure 1) left-anterior (F1, F3, F5, C1A, C3A, C5A), left-central (C1, C3, C5, C1P, C3P, TCP1), left-posterior (P1, P3, P5, P1P, P3P, CB1), right-anterior (F2, F4, F6, C2A, C4A, C6A), right-central (C2, C4, C6, C2P, C4P, TCP2), and right-posterior (P2, P4, P6, P2P, P4P, CB2).

Results

Electrophysiological Measures

The ERP grand averages, time-locked to the onset of the target words are represented in Figure 2 over six recording sites. Figure 2a,b shows the words preceded by the four types of primes: transposed consonants and replaced consonants (Figure 2a) and transposed vowels and replaced vowels (Figure 2b). Visual inspection of Figure 2a,b reveals clear differences between consonant and vowel transpositions/replacements. The effect of transposed versus replaced letters for vowels—attenuation of the amplitude for the transposed-letter condition—starts at the 150–250-ms window, and it is maintained up to 550 ms. No amplitude differences can be seen for consonants, although peak latencies are shorter for transposed than replaced consonants in a late window (500–600 ms). Mean amplitude values were calculated over two windows of analysis according to visual inspection and following the previous work by Grainger et al. (2006). Grainger et al. analyzed three windows (150–250, 250–350, 350–550 ms); however, given the similar pattern of data in the last two windows, and for the sake of simplicity, we decided to use only one early and one late window (150–250 and 250–550 ms). A peak-latency analysis according to visual inspection was also applied over a late window (500–600 ms). Note that in the present experiment, there were no amplitude differences in the P3, although the corresponding peak latency varied according to the lexical decision times. The peaks within this window were calculated as the maximum positive averaged values across each group of six electrodes corresponding to each region of interest. For these specific analysis, the ERPs were filtered with a digital 5-Hz low-pass filter in order to select one only value within this large epoch.

For each window, a repeated-measures ANOVA was performed, including *electrode regions* (anterior, central, and posterior), *hemisphere* (left/right), and the experimental variables as factors. These variables were *type of similarity* of the prime (transposed vs. replaced) and *type of letters* changed in the prime (consonants vs. vowels). Where appropriate, critical values were adjusted using the correction of Greenhouse and Geisser (1959) for violation of the assumption of sphericity. Effects for the *electrode region* factor or for the *hemisphere* factor will only be reported when they interact with the experimental manipulations.

150–250-mSegment

The ANOVA on the average values of the 150–250-ms time epoch showed a marginally significant effect of type of similarity, $F(1,41) = 3.7$, $p = .06$] and an interaction of Type of Similarity × Type of Letter × Hemisphere, $F(1,41) = 11.4$, $p < .01$. Simple test comparisons showed that the effect of type of transposed-letter similarity occurred in vowels to a larger degree in the right hemisphere, $F(1,41) = 9.5$, $p < .005$, whereas differences in the left hemisphere for vowels were only marginally significant, $F(1,41) = 3.2$, $p = .07$. The transposed-vowel priming condition was more positive-going than the replaced-vowel priming condition. In contrast, no effects were observed for consonants, $F\text{s} < 1$.

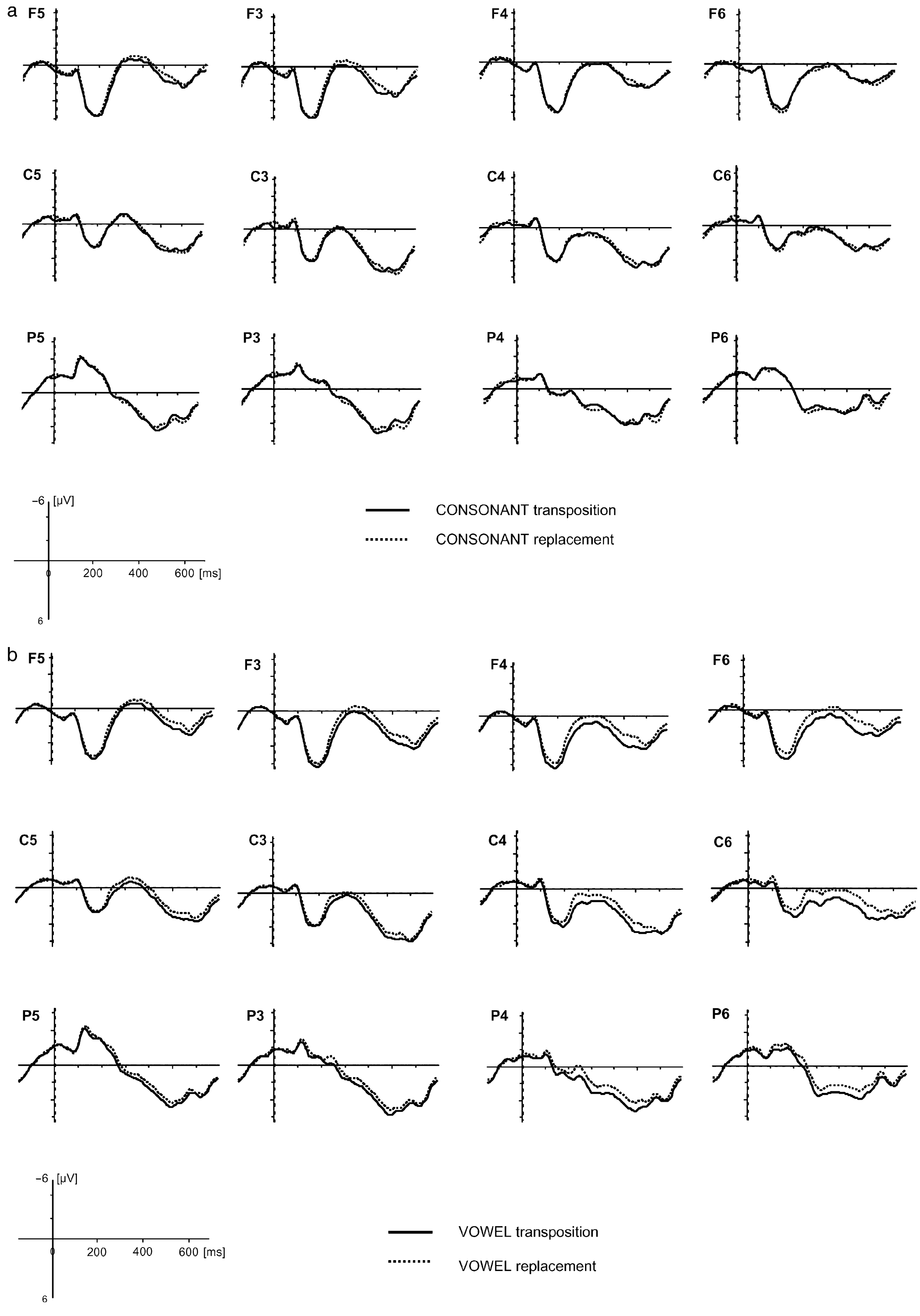

Figure 2. ERP waves to the target words preceded by the two prime conditions where consonants or vowels were manipulated: transposed consonants and replaced consonants (a) and transposed vowels and replaced vowels (b). Negative amplitude is plotted upward. Each tick mark represents 100 ms.

250–550-mSegment

The ANOVA on the average values of the 250–550-ms time epoch showed an effect of type of similarity, $F(1,41) = 9.1$, $p < .01$, an interaction of Type of Similarity × Type of letter, $F(1,41) = 5$, $p < .05$, and of Type of Similarity × Type of Letter × Hemisphere, $F(1,41) = 15$, $p < .001$. Simple test comparisons showed that the effect of type of similarity for vowels was larger in the right than in the left hemisphere: right hemisphere, $F(1,41) = 15.8$, $p < .001$; left hemisphere, $F(1,41) = 7.1$, $p < .05$. The transposed-vowel priming condition was more positive-going than the replaced-vowel priming condition. No effects were observed for consonants, *F*s < 1.

Peak Latency Analysis: 500–600 ms

The peaks within the 500–600-ms window were calculated as the maximum positive averaged values across each group of six electrodes corresponding to each region of interest. The ANOVA on the latency values showed a main effect of similarity, $F(1,41) = 15.2$, $p < .001$. Although the *F* ratio of the interaction did not reach significance, $F(1,41) = 1.5$, $p = .21$, planned comparisons were conducted to examine the transposed-letter priming effect for consonants and vowels. These comparisons showed that words preceded by a transposed-letter consonant prime peaked 14 ms earlier than the words preceded by a replacement-letter consonant prime (543 vs. 557 ms), $F(1,41) = 8.5$, $p < .01$, whereas the parallel effect for vowels produced a nonsignificant 6-ms advantage (544 vs. 550 ms), $F(1,41) = 3.5$, $p = 06$.

Behavioral Measures

Reaction times and error rates were also analyzed. Incorrect responses (2.6%) were excluded from the latency analysis. In addition, to avoid the influence of outliers, reaction times less than 300 ms or greater than 1500 ms (less than 0.3% of the data) were excluded. The mean latencies for correct responses and error rates of word targets are presented in Table 1. The statistical analyses showed that words preceded by a transposed-letter prime were responded to faster than those preceded by a replacement-letter prime, $F(1,41) = 6.01$, $p < .02$, whereas there were no differences between words preceded by a consonant versus vowel transposed-letter/replaced-letter prime, $F(1,41) < 1$. Although the *F* ratio of the interaction between the two factors did not reach significance, $F(1,41) = 0.9$, $p > .20$, planned comparisons were conducted to examine the transposed-letter priming effect for consonants and for vowels: Words preceded by a transposed-letter consonant prime were responded to faster than the words preceded by a replacement-letter consonant prime (694 vs. 704 ms), $F(1,41) = 5.88$, $p = .02$, whereas the masked transposed-letter priming effect for vowels did not approach significance (696 vs. 699 ms), $F < 1$. Thus, the behavioral data replicate the findings of Perea and Lupker (2004; Lupker et al., 2008). Finally, note that the error rates were very low (2.6%) and did not reveal any significant effects, all *F*s < 1.

Table 1. *Mean Lexical Decision Times (in Milliseconds), Percentage of Errors (in Parentheses) and Standard Deviations (in Italics) on Word Targets*

	Type of prime		
	Transposed letter	Replacement letter	Priming
Consonants	694 (2.9)	704 (2.7)	10 (0.2)
	113 (2.6)	*114 (2.7)*	
Vowels	696 (2.3)	699 (2.5)	3 (0.2)
	115 (3.0)	*115 (2.5)*	

Note. Priming refers to the difference between the replacement-letter condition and the transposed-letter condition.

Discussion

As expected, masked transposed-letter priming effects were observed in the ERP waves, replicating and extending the findings reported by Grainger et al. (2006). Effects of amplitude were observed mostly for vowel transpositions in two early windows (150–250 and 250–550 ms). In addition, we found transposed-letter priming effects of peak latency in a late window (500–600 ms), in particular for consonants—with shorter peak latencies for words preceded by a transposed-letter prime than for words preceded by a replacement-letter prime (as in the lexical decision times; see also Perea & Lupker, 2004).

Interestingly, the effects of transposing two vowels modulated the ERP signal in the same window (150–250 ms) in which Grainger et al. (2006) reported a masked transposed-letter priming effect—and others reported effects of sublexical variables, such as syllabic congruency (e.g., Carreiras et al., 2005). Although the topographic distribution of the effects is different from the effects reported by Grainger et al. and Carreiras et al., these results strongly suggest that consonants and vowels are processed differently during the early stages of visual-word recognition. Nonetheless, one could argue that the present findings do not agree with those found by Grainger et al. because the ERP effects were only found in vowels. However, leaving aside the procedural differences between the two studies (e.g., Grainger et al. employed shorter words [five-letter words] and a backward mask of seven random consonants [e.g., CFTRPQB] that immediately replaced the prime and lasted for 17 ms), this does not seem to be the case. We must keep in mind that the transposed-letter manipulation in the Grainger et al. experiment involved *both* consonants and vowels. If we consider together consonants and vowels, the two studies show a similar pattern: We found a similar transposed-letter effect to that reported by Grainger et al. in the 150–250 ms window. The difference is that Grainger et al. reported this effect to occur in posterior areas of the brain, whereas in the present experiment, the effect is more spread out and does not interact with electrode. Thus, the present data replicate the effects obtained by Grainger et al. and also extend them, by showing that masked-transposed-letter priming effects are qualified by the type of letter (consonant vs. vowel) that is manipulated.

The N400 component also showed a significant effect of transposed-letter priming. This finding is in line with the claim that the N400 component is not only sensitive to semantic and repetition priming (e.g., Deacon et al., 2000; Grossi, 2006; Holcomb et al., 2005; Kiefer, 2002; Kiefer & Spitzer, 2000; Misra & Holcomb, 2003; Schnyer et al., 1997), but it is also sensitive to orthographic relationships (see Holcomb & Grainger, 2006). Thus, the presence of a transposed-letter priming effect in the N400 component replicates and extends previous work by Grainger et al. (2006), as in the present experiment we directly manipulated the consonant/vowel status of the transposed/replaced letters. Interestingly, we found a remarkable dissociation between the transposed-letter priming effect for consonant and vowel transpositions. The transposed-letter priming effect was restricted to vowels, and it was larger in the right hemisphere.

(Note, however, that because we used linked ears as reference, lateral asymmetries should be treated with caution.) In contrast, no priming effects were found in the amplitude of the ERP waves for consonants. More specifically, the amplitude of the N400 component for target words was attenuated when primes were transposed-vowel pseudowords as compared to replacement-vowel pseudowords.

However, no differences in N400 amplitude were observed for consonants. As indicated in the Introduction, previous research using behavioral measures has suggested that transposing consonants induce more lexical similarity (i.e., they are more ''wordlike'') than replaced-consonant pseudowords (Carreiras et al., 2007; Lupker et al., 2008; Perea & Carreiras, 2006c; Perea & Lupker, 2004). For instance, the number of false positives in a single-presentation lexical decision task is higher to the TL-consonant nonword *PRIVAMERA* than to the RL-consonant nonword *PRICATERA* (e.g., see Perea & Lupker, 2004). Furthermore, at a subjective, phonological level, the transposition of two consonants appears to preserve more of the sound of the original word than the transposition of two vowels (e.g., compare the TL-consonant nonword PRIVAMERA to its base word, PRIMAVERA, in contrast to the TL-vowel nonword PRIMEVARA). However, this was not reflected in differences in the amplitude in the present set of ERP data. This was not due to lack of statistical power, as the same number of stimuli produced an effect when transposing/replacing vowels, or when these nonwords primes were presented as pseudoword targets in a single-presentation lexical decision task (as in the experiment of Carreiras et al.). Instead the masked transposed-letter priming effect for consonants was reflected in the peak latencies of the P300 component, in the 500–600-ms window—as well as in the lexical decision times. Note that even though the classic effect of the P3 component has been located around after 300 ms of target onset, several studies have shown that this latency can be retarded depending on the complexity of the stimulus or the categorization difficulty that the participant must confront (see Kutas et al., 1977). In the absence of earlier N250 and N400 effects, this suggests that masked transposed-letter priming effects for consonants are likely to be located in late decision (i.e., postlexical) processes. That is, we believe that the transposed-letter priming effect for consonant transpositions on lexical decision times may be reflecting processes that are posterior to lexical analysis and word integration. Keep in mind that the presence of early effects for vowel transpositions is consistent with the data from two procedures that tap very early processes in visual-word recognition: the eye-movement data (via a parafoveal priming manipulation) from Johnson (2007) and with the masked priming data with a same–different task from Perea and Acha (2008). So it seems that part of the lack of transposed-letter priming effect for vowel transpositions when the lexical decision time is the dependent variable is task dependent. Clearly, modeling the dissociation between consonant and vowels in transposed-letter effects across different paradigms and procedures is an important issue for further research.

In sum, the present experiment strongly suggests that each letter (consonant vs. vowel) does not make an equally salient contribution to visual-word recognition. As indicated in the Introduction, it has been claimed that consonants and vowels differ in how rapidly or effectively they constrain lexical recognition (Berent & Perfetti, 1995; but see Perry & Ziegler, 2002). Vowel information appears to constrain lexical selection less tightly (allow more potential ''word'' candidates) than does consonant information, independent of the language-specific phoneme repertoire and of the relative distinctiveness of vowels (see Cutler et al., 2000). The present data also converge with the data obtained by Caramazza et al. (2000) showing a dissociation between consonants and vowels. These data also agree with the greater activation found in the right superior temporal sulcus for vowels as compared to consonants with a single-presentation paradigm (using both lexical decision and naming) in fMRI (Carreiras & Price, 2008).

It is clear that vowels and consonants play qualitatively different roles in the structure of printed words; however, they also differ in a few other ways. One of the basic differences is in terms of frequency: Vowels are more frequent than consonants. This is an important factor to be taken into consideration, given the results reported recently by Lupker et al. (2008). Lupker and colleagues (2008) found a greater transposed-letter priming advantage when the transposed consonants were of low frequency than when the transposed consonants were of high frequency. This finding may be taken to suggest that letter position coding does not differ between consonants and vowels, but rather between high-frequency and low-frequency letters. Thus, it is important to discard an explanation of the present findings in terms of the frequency of the transposed letters. Lupker, Perea, and Davis (2005) reported a robust effect for C-V transpositions in a masked priming lexical decision task. This priming effect for C-V transpositions was numerically greater than that for C-C transpositions. This finding imposes some limits on the generality of the letter frequency account: A letter frequency account would predict stronger priming for C-C than for C-V transpositions. Furthermore, in a single-presentation lexical decision task in which either two of the constituent vowels or two of the constituent consonants were delayed for 50 ms, Carreiras et al. (in press) found a difference in sustained negativity between consonants and vowels, which was restricted to word stimuli. If letter frequency—rather than differences in consonant/vowel status—were the factor responsible, this sustained negativity should have occurred for both word and pseudoword stimuli. Indeed, as Lupker et al. (2008) indicated, their results ''do not prove that the difference between transposed-letter effects for C-C primes versus V-V primes in [their] experiments is completely due to the frequency difference between consonants and vowels'' (p. 106).

What are the implications of the present findings for the ''front end'' of the recently proposed input coding schemes? As we stated in the Introduction, the presence of transposed-letter priming effects is consistent with the predictions of the SERIOL, SOLAR, open-bigram, and overlap models. However, transposed-letter priming effects were different when the transposed letters were consonants than when they were vowels. In the above-cited models there is no difference between vowel and consonant processing, and hence, transposed-letter effects are posited to be of similar magnitude for vowel and consonant transpositions. Nonetheless, it is possible that by tweaking with the parameters, these models could capture the observed effects. For instance, in the overlap model (Gomez et al., 2008), the positions of the letters is assumed to be distributed over position. For instance, if the string of letters is the word *TRIAL*, the letter *I* will be associated with position 3, but also, to a lesser degree, with positions 2 and 4, and even with positions 1 and 5. Each letter position has a different standard deviation that is treated as a free parameter in the model. Although the present implementation of the model does not assume any differences between consonant/vowel processing, it is possible to assume that the "perceptual noise" (i.e., a parameter in the model) of vowels is less than that of consonants.

In sum, the reported experiment has shown a significant masked transposed-letter priming effect in behavioral and electrophysiological measures, which differed depending on whether the transposition of letters involved two consonants or two vowels. Therefore, the data from patients, fMRI, and the present ERP data converge on the idea that there may be some basic processing differences between vowels and consonants. These consonant/vowel differences should be taken into consideration when developing computational models of visual-word recognition. Further empirical and theoretical work is needed to shed more light on this important issue.

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