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The processing of consonants and vowels during letter identity and letter position assignment in visual-word recognition: An ERP study

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ABSTRACT

Recent research suggests that there is a processing distinction between consonants and vowels in visual-word recognition. Here we conjointly examine the time course of consonants and vowels in processes of letter identity and letter position assignment. Event related potentials (ERPs) were recorded while participants read words and pseudowords in a lexical decision task. The stimuli were displayed under different conditions in a masked priming paradigm with a 50-ms SOA: (i) identity/baseline condition e.g., chocolate-CHOCOLATE); (ii) vowels-delayed condition (e.g., choc░l░te-CHOCOLATE); (iii) consonants-delayed condition (cho░o░ate-CHOCOLATE); (iv) consonants-transposed condition (cholocate-CHOCOLATE); (v) vowels-transposed condition (chocalote-CHOCOLATE), and (vi) unrelated condition (editorial-CHOCOLATE). Results showed earlier ERP effects and longer reaction times for the delayed-letter compared to the transposed-letter conditions. Furthermore, at early stages of processing, consonants may play a greater role during letter identity processing. Differences between vowels and consonants regarding letter position assignment are discussed in terms of a later phonological level involved in lexical retrieval.

1. Introduction

One of the critical sub-processes in visual-word recognition involves the mapping of an abstract letter representation onto a whole-word representation. To complete this stage in an alphabetic language, both the identity and the position of the letters have to be computed – if not, one would not be able to distinguish salt and slat, or hat and that. None of the influential computational models of visual-word recognition that employ a slot coding scheme (e.g., interactive activation model, McClelland & Rumelhart, 1981; DRC model, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; MROM model, Grainger & Jacobs, 1996; CDP + model, Perry, Ziegler, & Zorzi, 2007; Bayesian Reader model, Norris, 2006) can accommodate the presence of the effects of transposed-letter priming (e.g., *relovution* primes *RELOVUTION* more than *retosution*; e.g., Perea & Lupker, 2004) and relative position priming (*BLCN* primes *BALCON* more than *CTR;* Grainger, Granier, Farioli, van Heuven, and Van Assche, 2006; Peressotti & Grainger, 1999). This limitation has been overcome by more flexible input coding schemes (e.g., SERIOL model, Whitney, 2001; SOLAR model, Davis, 1999; open-bigram model, Grainger & van Heuven, 2003; and overlap model, Gomez, Ratcliff, & Perea, 2008). One problem here is that vast majority of implementations of these input coding schemes do not specify any processing differences as a function of the letter status (i.e., vowel vs. consonant). The exception is the current version of the SERIOL model (see Whitney & Cornelissen, 2005), in which letter encoding is parsed into a graphosyllabic representation in which vowels and consonants would have separate slots; however, no specific predictions are made in this model for the effects of manipulating consonants vs. vowels. There is growing research, however, that shows that vowels and consonants are not processed in the same way during the processing of written words (e.g., Berent & Marom, 2005; Buchwald & Rapp, 2006; Carreiras, Dunabeitia, & Molinaro, 2009; Cutler, Sebastian-Galles, Soler-Vilageliu, & van Ooijen, 2000; Lee, Rayner, & Pollatsek, 2001; Lee, Rayner, & Pollatsek, 2002; New, Araujo, & Nazzi, 2008; Perea & Lupker, 2004).

One important approach to examining the time course of processing of consonants and vowels is by measuring ERP waves in a visual-word recognition task. In a recent ERP study using a single-presentation lexical decision task, Carreiras, Vergara, and Perea (2007) obtained differences in an early time window (300–500 ms) between the processing of pseudowords created by

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replacing two letters of their base word (e.g., *retosución*; the base word was *REVOLUCIÓN*) and the processing of pseudowords created by transposing two letters (*relovución*), and this occurred for both consonant and vowel-transpositions. However, in a later time window (500–650 ms), they observed different effects for the consonants-transposed pseudowords and for the vowels-transposed pseudowords. More recently, Carreiras, Vergara, and Perea (2009) found this consonant/vowel dissociation in a masked priming experiment in which the primes were pseudowords created by the transposition/replacement of two vowels or two consonants. Finally, Carreiras, Duñabeitia, et al. (2009) showed that the status of letters (consonants vs. vowels) modulated the process of letter position assignment in relative position priming. At 175–250 ms and 350–450 ms time epochs, words preceded by relative position primes composed of consonants (*frl-FAROL*) elicited the same ERP waves as the words preceded by an identity priming condition (*farol-FAROL*), whereas words preceded by a relative position prime composed by vowels (*aeo-ACERO*) showed ERP waves similar to an unrelated priming condition (*iui-ACERO*).

Another paradigm used to analyze the different role of consonants and vowels in visual-word recognition is to delay the presentation of one/two letters (either consonants or vowels) for a short period. Lee et al. (2001, 2002) used a delayed-letter presentation paradigm where the onset of several letters (vowels or consonants) was delayed at the beginning of a word fixation during sentence reading. They showed that delaying a consonant for 30 ms increased gaze durations on the target word relative to delaying a vowel. More interesting for the present purposes, Carreiras, Gillon-Dowens, Vergara, and Perea (2009) employed a similar procedure in a lexical decision task while collecting the ERP waves. Carreiras et al. found larger N250 amplitudes for the consonants-delayed (e.g., *RE O UCION – REVOLUCION*) compared to the identity condition over all scalp areas, while the differences regarding this component between the vowels-delayed and baseline conditions were only observed in posterior scalp areas (*REV L CION – REVOLUCION*).

In addition, there is evidence that strongly suggests that there is a differential role of consonants and vowels in other areas of language processing. Several phonology-related phenomena have the effect of reducing the contrastive power of vowels (e.g., vowel harmony and centralization of unstressed vowels), and this impoverishes their role in distinguishing lexical items (Bonatti, Peña, Nespor, & Mehler, 2005). Indeed, 20-month-old infants can learn two words that differ by only one consonant, but fail when the distinctive phoneme is a vowel (Nazzi, 2005; Nazzi & New, 2007). Furthermore, humans are better at capturing non-adjacent regularities based on consonants than on vowels (Bonatti et al., 2005; Mehler, Peña, Nespor, & Bonatti, 2006). In contrast, vowels are used to extract structural generalizations in artificial languages (Nespor, Peña, & Mehler, 2003; Toro, Nespor, Mehler, & Bonatti, 2008). It has also been suggested that consonants carry lexical information while the main role of vowels is that of allowing the identification of the rhythmic class as well as of specific properties of syntactic structure (see Nespor et al., 2003, for a review). Finally, neuropsychological dissociations show that the processing of these two types of speech segments is dissociable by brain damage (see Caramazza, Chialant, Capasso, and Miceli, 2000).

If consonants are so powerful in terms of quality distinctions among lexical representations, it is important to examine the time course of consonants/vowels during the processes of letter identity and letter position assignment. Note that previous ERP studies examined either letter position processes or letter identity processes, but they have not considered all these conditions in a single experiment; obviously, the lack of a conjoint experiment to examine these issues makes it difficult to meaningfully compare the time course of letter identity/position for vowels and consonants. To this purpose, in the present experiment we will conjointly examine the role of letter identity and position – of vowels and consonants – during visual-word recognition while measuring the ERP waves. We manipulated, on the one hand, the delay of vowels and consonants (REVOLUCION was preceded by either *rev l cion* or *re o ucion*) and, on the other hand, the transposition of vowels vs. consonants (REVOLUCION was preceded by either *revulocion* or *relovucion*).

One novel manipulation was the inclusion of a baseline condition (identity condition). In previous studies (Carreiras et al., 2007; Perea & Lupker, 2004), the control condition was a prime created by substituting the letters (e.g., the orthographic control for *relovución* was *retosución*). In order to measure independent effects for the identity and the position of the letters, a more appropriate baseline should be an identity prime, as it provides an index of how similar the pseudoword prime is to the "best" condition (i.e., the identity condition; see also Carreiras, Gillon-Dowens, et al., 2009).

In sum, we will compare the time course of delayed/transposed-letter effects, regarding the different role of vowels and consonants during visual-word recognition. ERPs provide decomposable measures of online processing and enable fine-grained descriptions of processing due to the excellent time resolution of this technique. ERPs are voltage changes recorded from the scalp and extracted from the background electroencephalogram by averaging time-locked responses to stimuli onset. Of specific interest for our study are the following components: N250 and N400. The N250 component has been associated with the degree of prime-target orthographic overlap and phonological overlap in masked priming, suggesting that it is sensitive to processing sub-lexical representations (Grainger, Kiyonaga, & Holcomb, 2006; Holcomb & Grainger, 2006). Furthermore, Carreiras, Gillon-Dowens, et al. (2009) obtained larger N250 amplitudes for the consonants-delayed condition than for the baseline condition using this ERP component.

The N400 component is a negative deflection occurring around 400 ms after word presentation that has been associated with lexical-semantic processing (see Holcomb, Grainger, & O'Rourke, 2002; Kutas & Federmeier, 2000). The amplitude of this negativity is an inverse function of lexical frequency and lexicality (Carreiras, Vergara, & Barber, 2005; Neville, Mills, & Lawson, 1992; see also Barber & Kutas, 2007, for a review). In addition, items from small orthographic/syllabic neighborhoods produce an N400 of smaller amplitude than items from a large orthographic/syllabic neighborhood (Barber, Vergara, & Carreiras, 2004; Holcomb, Grainger, & O'Rourke, 2002). Larger neighborhoods produce higher levels of activation, either at the level of form representation or at the level of semantic representation (Holcomb, Grainger, & O'Rourke, 2002). Carreiras et al. (2007) showed that transposed-letter consonant pseudowords produced a modulation of the amplitude in a late time window (500–650 ms) in the same way as orthographic neighborhoods do. Carreiras et al. concluded that transposed letter-pseudowords created by transposing two consonants activated their corresponding base word to a larger degree than the transposed letter-pseudowords created by transposing two vowels.

If the contribution of consonants and vowels to the letter assignment process is different and has a different time course, we expect our manipulations to have a differential impact on the ERP components described above. Previous research has shown early differences between both vowels- and consonants-delayed conditions, and the identity condition (Carreiras, Gillon-Dowens, et al., 2009), while in another study, Carreiras et al. (2007) found that transposed-letter effects show up later in time relative to a replacement letter condition (Carreiras et al., 2007). If consonants act as "islands of reliability" regarding orthographic processing – and also operate as the basic skeleton of lexical representations, we should expect early differences for consonant and vowel manipulations regarding letter identity, compared to consonant and vowel manipulations regarding letter position. Late differences between the manipulation of consonants and vowels should also be expected in the N400 component: consonants seem to be more constraining in the process of lexical access. Although these hypotheses are consistent with previous results, we will focus on studying the time course of lexical activation (on the basis of consonant/vowel status) over letter identity and position assignment. Finally, comparisons of these manipulations across words and pseudowords will help to disentangle the effect of lexical activation on the computation of consonants compared to vowels.

2. Method

2.1. Participants

Twenty-two (11 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 28 years (mean = 19.9 years). All participants were right-handed, as assessed with an abridged Spanish version of the Edinburgh Handedness Inventory (Oldfield, 1971).

2.2. Materials

We selected 198 Spanish words of seven to eleven letters (mean length: 9.0 letters) with a mean frequency of 23 per million in the LEXESP Spanish database (range: 4–146; Sebastián-Gallés, Martí, Carreiras, & Cuetos, 2000). For each word, we created six experimental conditions: (i) the word was preceded by itself for 50 ms (identity condition; e.g., chocolate-CHOCOLATE); (ii) the word was preceded by itself except that two non-adjacent internal vowels (separated by a consonant) were missing and the symbol "░" occupied the missing slot instead (vowels-delayed condition; choc░l░te-CHOCOLATE); (iii) equal to condition ii, but two internal consonants (separated by a vowel) were missing (vowels-delayed condition; cho░o░ate-CHOCOLATE); (iv) the word was preceded by itself except that two non-adjacent internal vowels (separated by a consonant) were transposed (vowels-transposed condition; chocalote-CHOCOLATE); (v) equal to condition iv, but two internal consonants (separated by a vowel) were transposed (consonants-transposed condition; cholocate-CHOCOLATE); (vi) the word was preceded by an unrelated word, as in editorial-CHOCOLATE. The position of the delayed/transposed letters was around the word center for these conditions (i.e., around position 5 across the delayed/transposed conditions). Across words, the position of the delayed/transposed letters was equated across the vowel (delayed or transposed) and consonant (delayed or transposed) conditions. It is important to mention that, for all words, the target word was the only legal word that could be generated by filling in the missing letter. For instance, from the sequence choc░l░te or from the sequence cho░o░ate, no word other than CHOCOLATE could be generated by filling in the spaces – this was the case for both the delayed and the transposed conditions. These words were extracted from low-density orthographic neighborhoods ($N = 0.8$ in the Spanish database; Davis & Perea, 2005); Coltheart's N (i.e., the number of "orthographic" neighbors; see Coltheart, Davelaar, Jonasson, & Besner, 1977) refers to the number of words that exist in the language by replacing one letter from an existing word in a given position (e.g., *bar*, *can*, and *cap* are orthographic neighbors of *car*).

For the purposes of the lexical decision task, we included a set of 198 orthographically legal pseudowords of seven to eleven letters (mean length: 9.0 letters). These pseudowords had been created by replacing the three initial letters from the experimental words (e.g., the nonword FLICOLATE was created from the word CHOCOLATE), so that a word was not possible even with the missing letters. The manipulation for the nonword stimuli was the same as that for the word stimuli (i.e., identity condition, vowels-delayed condition, consonants-delayed condition, vowels-transposed condition, consonants-transposed condition, and unrelated condition). Six lists of materials were created so that participants saw each target word (or nonword) in only one of the six conditions, and the assignment of the stimuli to conditions was counterbalanced across participants.

2.3. 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. The words were displayed in white lowercase Courier 24 font against a dark-gray background. 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 the left button was assigned the "No" response. For the remaining participants the order was reversed. The sequence of events in each trial is described as follows. First, a fixation point ("+") appeared in the center of the screen for 1200 ms. This fixation point was followed by the prime (always in lowercase) for 50 ms, which was replaced by a word or a pseudoword that remained on the screen for 400 ms (always in uppercase). The trial ended with the participant's response, or 2000 ms after the presentation of the word if the participant had failed to respond. The inter-trial interval varied randomly between 1000 and 1300 ms. The stimuli were presented in different random order for each participant. Twenty-two warm-up trials, which were not further analyzed, were provided at the beginning of the session and were repeated if necessary. Participants were also asked to avoid eye movements and blinks during the interval starting from the fixation point until response was given. Participants were instructed to favor accuracy over speed in their responses.

2.4. EEG recording and analyses

Scalp voltages were collected from 58 Ag/AgCl electrodes which were mounted in an elastic cap (ElectroCap International, Eaton, USA, 10–10 system). Linked earlobes were used as reference (see Fig. 1). Eye movements and blinks were monitored with six further electrodes providing bipolar recordings of the horizontal and vertical electrooculogram (EOG). Inter-electrode impedances were kept below 10 K Ω. EEG was filtered with an analogue bandpass 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 corresponding to 600 ms after word onset presentation were averaged and analyzed. Baseline correction was performed using the average EEG activity in the 200 ms preceding the onset of the prime as a reference signal value. Following baseline correction, epochs with simultaneous artifacts in at least 10 channels were rejected. In addition, trials that were not responded to correctly were not included in the analysis. Due to artifacts and/or wrong response, approximately 13% of the trials were excluded (6.5% of word trials and 6.5% of nonword trials). This means that, in average, the mean voltage was calculated across 28 trials per subject and condition. No statistical difference was observed in the number of rejections across conditions ($F < 1$).

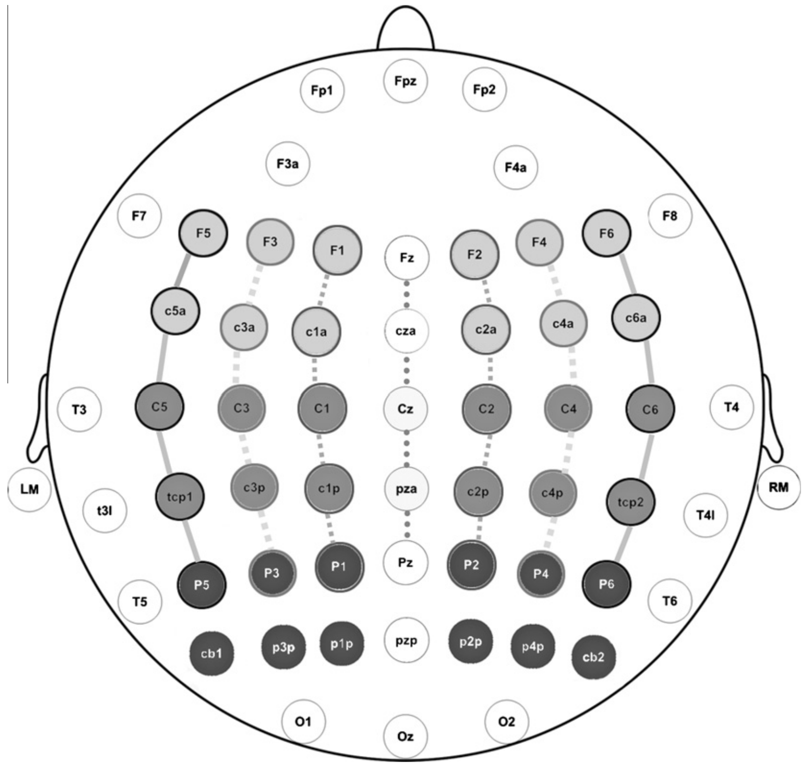

Fig. 1. Schematic flat representation of the 58 electrode positions from which EEG activity was recorded (the front of the head is at the top). The different styled lines represent the columns' distributed analysis.

Separate ERPs were formed for each of the experimental conditions, each of the subjects and each of the electrode sites.

The effects of letter delay and letter-transposition were analyzed separately. Mean amplitudes were obtained for different time windows. For each time window, separate repeated-measures ANOVAs were performed on four column groups of electrodes (see Fig. 1 for the description of each column; Holcomb & Grainger, 2006, for a similar analysis). The ANOVAs ran over columns 1 to 3 included (for the letter delay comparison): *delay* (identity/baseline, vowel-delay, consonant-delay) as main factor, *hemisphere* (left/right), and *electrode* factor (five locations). For the letter-transposition comparison: *transposition* (identity/baseline, vowel-transposition, consonant-transposition), *hemisphere* (left/right), *electrode* factor (five locations). The ANOVAS ran over column 4 (middle line) did not include the factor *hemisphere*. This approach to ERP data analysis has been applied in a number of previous studies (Grainger et al., 2006; Holcomb & Grainger, 2006; Neville et al., 1992) as a solution when a full description of the distribution of the effects has to be combined with the simplicity of design.

Where appropriate, critical values were adjusted using the Greenhouse and Geisser (1959) correction for violation of the assumption of sphericity. In addition, post hoc Sidak contrasts were performed after interactions or main effects of *delay* to control for type I error in multiple comparisons. Effects for the *electrode* factor or for the *hemisphere* factor will only be reported when they interact with the experimental manipulations.

3. Results

3.1. Behavioral measures

Incorrect responses (4.1% of the data for word targets) and reaction times less than 250 ms or greater than 1500 ms (fewer than 2% of the responses to word targets) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 1. To parallel the statistical analysis of the ERP waves, a repeated-measures ANOVA on the response times (and error rates) for words was performed including (for the letter delay comparison) delay (identity/baseline, vowel-delay, consonant-delay) as a factor. Likewise, for the letter-transposition comparison, a repeated-measures ANOVA was performed including transposition (identity/baseline, vowel-transposition, consonant-transposition) as factor. The data from nonwords did not produce any significant effects and will not be considered further.

3.2. Letter delay

The ANOVA on the response times showed a significant effect of letter delay, $F_{2,42} = 15.50$, $p < .001$, MSE = 341: this reflected substantially faster RTs for the identity condition than for the letter delay conditions (both $p < .005$), while there were no significant differences between the two letter delay conditions. The ANOVA on the error rates also showed a significant effect of letter delay, $F_{2,42} = 5.37$, $p < .01$, MSE = 9.6: this reflected less errors for the identity condition than for the letter delay conditions (both $p < .05$), while there were no significant differences between the two letter delay conditions.

3.3. Letter-transposition

The ANOVA on the response times showed a significant effect of letter-transposition, $F_{2,42} = 11.54$, $p < .001$, MSE = 414: this reflected substantially faster RTs for the identity condition than for the transposed-letter conditions (both $p < .05$), while there were no significant differences between the two letter-transposition

Table 1
Mean lexical decision times (in ms) and percentage of errors (in parentheses) for word and nonword targets in the experiment.

	Type of prime					
	Identity	Delay-V	Delay-C	TL-V	TL-C	Unrelated
Words	590 (2.3)	615 (5.4)	619 (4.3)	608 (3.6)	616 (3.2)	661 (5.6)
Nonwords	712 (6.7)	708 (5.6)	716 (5.1)	714 (5.6)	719 (6.2)	726 (5.8)

conditions. The ANOVA on the error rates failed to show a significant effect of letter-transposition ($F < 1$).

3.4. ERP results

ERP grand averages time-locked to the onset of the target words for the delay and the transposed comparisons are represented in Figs. 2 and 3 respectively (Figs. 4 and 5 show the ERP waves for pseudowords), over 15 recording sites. Figs. 2 (words) and 4 (pseudowords) show three conditions: baseline/identity, consonants-delayed, and vowels-delayed. Figs. 3 (words) and 5 (pseudowords) show baseline/identity, consonants-transposed, and vowels-transposed.

Baseline and transposed-letter conditions (for both words and pseudowords) follow a similar pattern of peaks which consists of a negative potential peaking around 100 ms followed by a bipolar component peaking positive around 200 ms over frontal regions while it peaks negative over posterior regions. Following these peaks, a negativity around 350 ms (N400) post-stimuli is observed in central and posterior electrodes, which is followed by a long lasting positivity peaking around 550 ms.

Visual inspection of Figs. 2 and 4 (letter delay manipulation) show larger negative amplitudes for the delayed-letter conditions compared to the baseline condition over frontal and central areas between 200 and 300 ms. Regarding words, this difference is also present over posterior areas between 300 and 400 ms, with the largest difference for the consonants-delayed compared to the vowels-delayed. By 400 ms, this last pattern is mostly distributed over central scalp areas. Regarding pseudowords, by 350–600 ms post-stimuli, larger negativities are observed for the baseline condition compared to the delayed conditions, while no difference is observed between the consonants- and vowels-delayed conditions.

Concerning letter-transposition, Figs. 3 and 5 do not show amplitude differences for the transposed compared to the baseline conditions until around 400 ms post-stimuli. Regarding word targets, larger negativities are observed for transposed compared to baseline condition over frontal areas. However, in the case of pseudoword targets, Fig. 5 shows larger negative amplitudes for the baseline compared to the transposed conditions. More specifically, this difference is located over frontal areas, and it is larger between the baseline condition and the consonants-transposed condition.

Mean amplitude values were calculated over three windows of analysis which were selected according to visual inspection. The onset of these time windows were statistically determined around the first latency at which the difference between waveforms was significant using a series of point-by-point t-tests (N250: 200–300 ms; N400: 300–400 ms and 450–525 ms). A summary of the

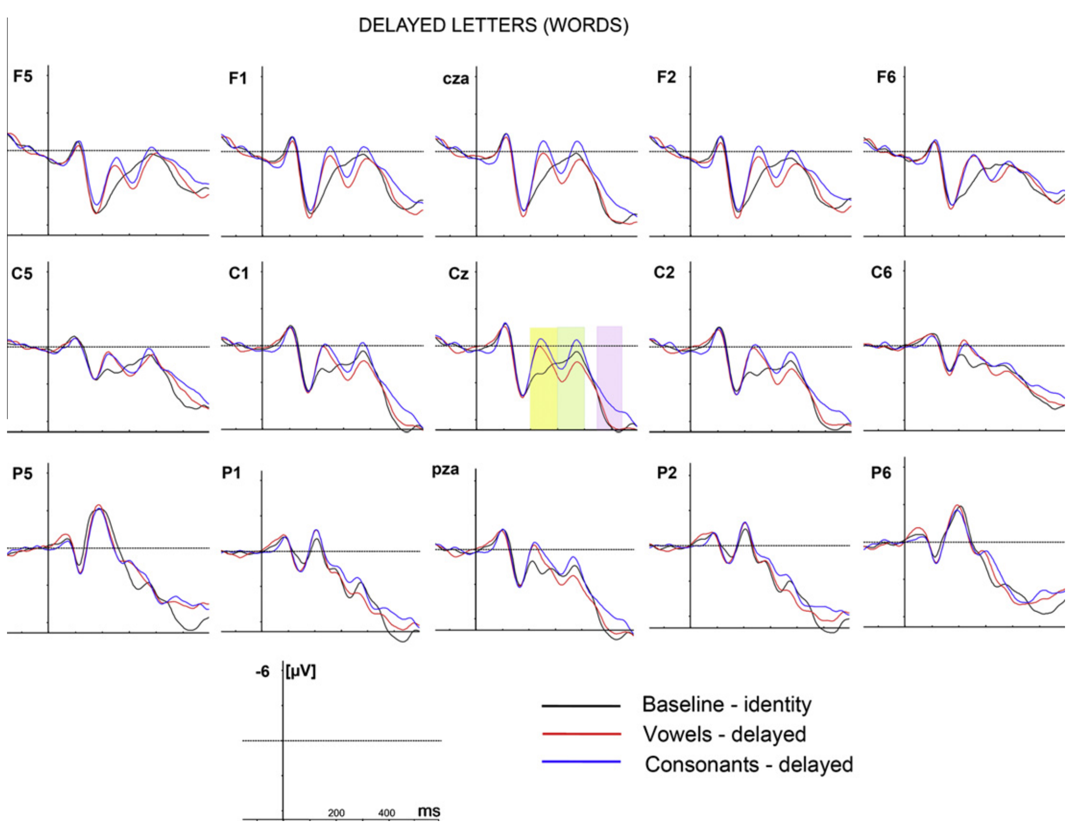

Fig. 2. Grand average ERPs to the target words in three different conditions (baseline/identity, vowels-delayed, and consonants-delayed condition) in representative electrodes of each column of analysis. The three windows of analysis (200–300, 300–400 and 450–525 ms) are highlighted by the vertical colored bars.

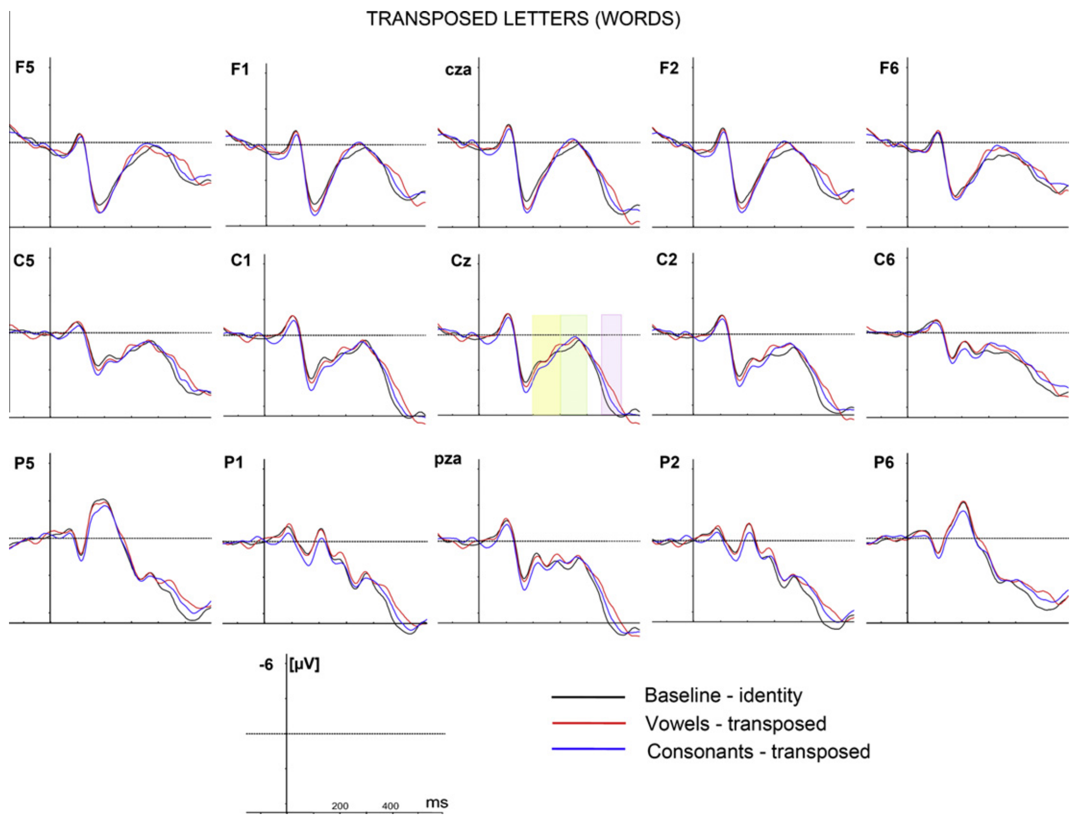

Fig. 3. Grand average ERPs to the target words in three different conditions (baseline/identity, vowels-transposed, and consonants-transposed condition) in representative electrodes of each column of analysis. The three windows of analysis (200–300, 300–400 and 450–525 ms) are highlighted by the vertical colored bars.

simple comparisons within *delay* and *transposition* factors across the three epochs is shown in Table 2 (words) and in Table 3 (pseudowords).

4. Words

4.1. Delay effects

4.1.1. 200–300 epoch

The ANOVAs over columns 1 to 4 on the average voltage values showed interaction of *delay* and *electrode factor* on columns 1 and 2. Columns 3 and 4 showed main effects of *delay*. Within-factor comparisons showed significant differences between the baseline and both vowels- and consonants-delayed conditions. This effect was observed in frontal and central electrode positions as simple comparisons shown in Table 2. Nonetheless, direct comparisons between vowels- and consonants-delayed conditions showed no significant effects.

4.1.2. 300–400 epoch

Although a main effect of delay was not observed when including the factor *delay* with three levels (baseline, vowels-delayed, consonants-delayed), planned comparisons between the two delayed conditions revealed significant differences in columns 3 and 4 (marginally significant differences were also observed on column 2).

4.1.3. 450–525 epoch

The ANOVAs over columns 1–4 on the average voltage values showed a main effect of *delay*. Simple comparisons revealed significant differences between the baseline and the consonants-delayed condition across all columns. In columns 3 and 4 (midline), both baseline and vowels-delayed conditions differed from the consonants-delayed condition (see Table 2 for a summary of the effects).

4.2. Transposition effects

4.2.1. 200–300 and 300–400 epochs

No significant differences were obtained in these epochs.

4.2.2. 450–525 epoch

The ANOVAs over columns 1, 3 and 4 on the average voltage values showed a main effect of *transposition* (a marginally significant effect of *transposition* was obtained in column 2). Simple comparisons revealed significant differences between the baseline and the vowels-transposed condition across all columns (see Table 2 for a summary of the effects).

5. Pseudowords

5.1. Delay effects

5.1.1. 200–300 epoch

The ANOVA over column 1 showed an interaction of *delay* and *electrode*. This interaction reflected differences between the baseline and the two delayed conditions over most anterior electrodes. The ANOVAs over columns 2 and 3 showed main effects of delay and interaction of *delay* and *hemisphere*. Differences between the baseline and the two delayed conditions were statistically significant over the right hemisphere. The ANOVA over column 4 showed main effects of delay. Direct comparisons between vowels- and consonants-delayed conditions showed no significant effects (see Table 3 for a summary of the effects).

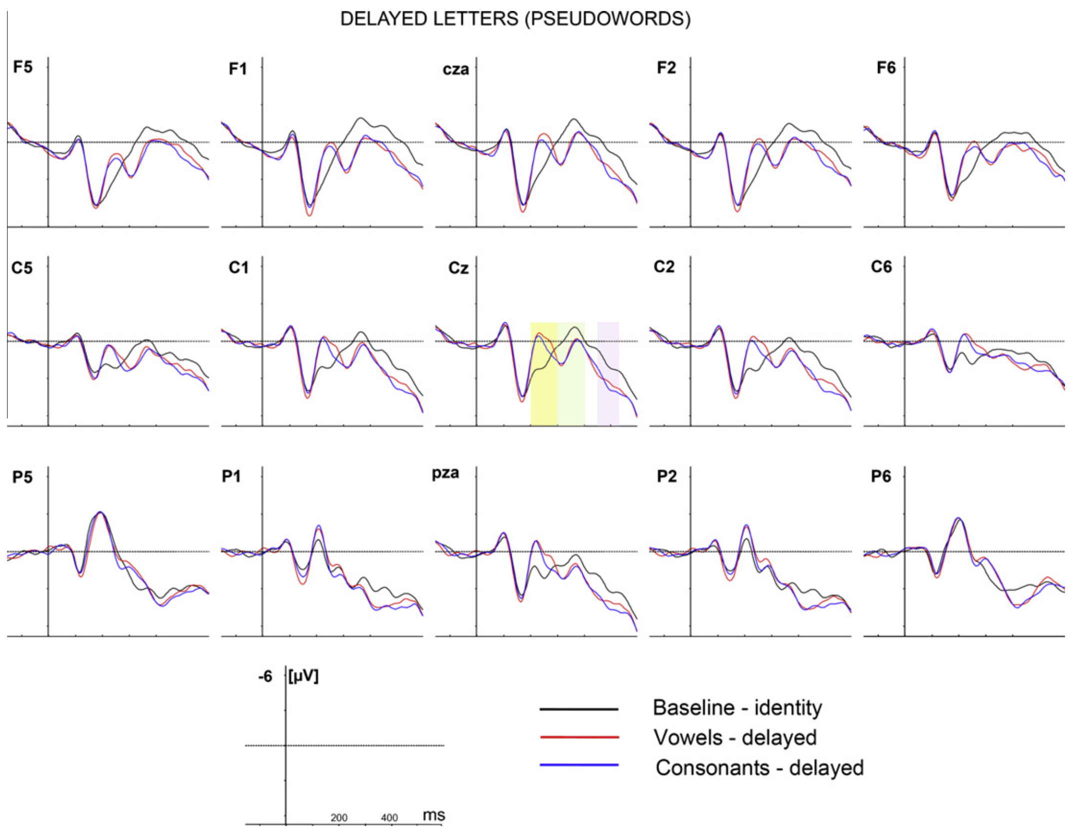

Fig. 4. Grand average ERPs to the target pseudowords in three different conditions (baseline/identity, vowels-delayed, and consonants-delayed condition) in representative electrodes of each column of analysis. The three windows of analysis (200–300, 300–400 and 450–525 ms) are highlighted by the vertical colored bars.

5.1.2. 300–400 epoch

The ANOVAs over columns 1–4 on the average voltage values showed significant interaction of *delay* and electrode. Planned comparisons showed that statistically significant differences were present between the baseline and the two delayed conditions over most anterior/frontal electrodes.

5.1.3. 450–525 epoch

The ANOVAs over columns 1–4 on the average voltage values showed significant effect of *delay*. Planned comparisons showed significant differences between the baseline and the two delayed conditions. Direct comparisons between vowels- and consonants-delayed conditions showed no significant effects.

5.2. Transposition effects

5.2.1. 200–300 and 300–400 ms epochs

No significant differences were obtained in these epochs.

5.2.2. 450–525 ms epoch

The ANOVAs over columns 2–4 on the average voltage values showed a significant main effect of *transposition*. Simple comparisons revealed significant differences between the baseline and the two transposed conditions. Direct comparisons between vowels- and consonants-delayed conditions showed no significant effects.

6. Summary of the ERP results

6.1. Delayed-letter manipulation

At early stages of processing (200–300 ms), targets preceded by a delayed-letter prime showed significant differences compared to the baseline. We found no differences between vowels-delayed and consonants-delayed conditions at this stage, and the pattern of results was similar for words and pseudowords. Between 300–400 ms, a different pattern arises regarding vowels and consonants. For words, the consonants-delayed stimuli elicited larger negativities than the vowels-delayed condition. However, the pattern for pseudowords resembles that obtained for the previous time window: both vowels-delayed and consonants-delayed conditions differ from the identity condition. Between 450–525 ms, and for words, the consonants-delayed condition elicited larger negativities relative to both the identity and the vowels-delayed conditions, whereas the differences between the vowels-delayed and the identity conditions were not significant. In contrast, for pseudowords, both delayed-letter conditions showed smaller negativities compared to the baseline.

6.2. Transposed-letter manipulation

We failed to find any significant effects at two initial time windows (200–300 and 300–400 ms) either for words or pseudowords. In the 450–525 ms window, for words, larger negativities were observed for vowels-transposed compared to baseline. For pseudowords, a larger negativity was observed for the baseline compared to the two transposed conditions.

Delayed-letter effects were similar for words and pseudowords on the first time window of analysis. However, the effect of consonants-delay differed from the vowels-delay during the processing of words in the 300–400 and in the 450–525 ms time windows, while no differences between the two delayed conditions were observed at all in the processing of pseudowords (neither in the delayed nor in the transposed manipulation). Interestingly, at the last time window of analysis, the largest difference was obtained

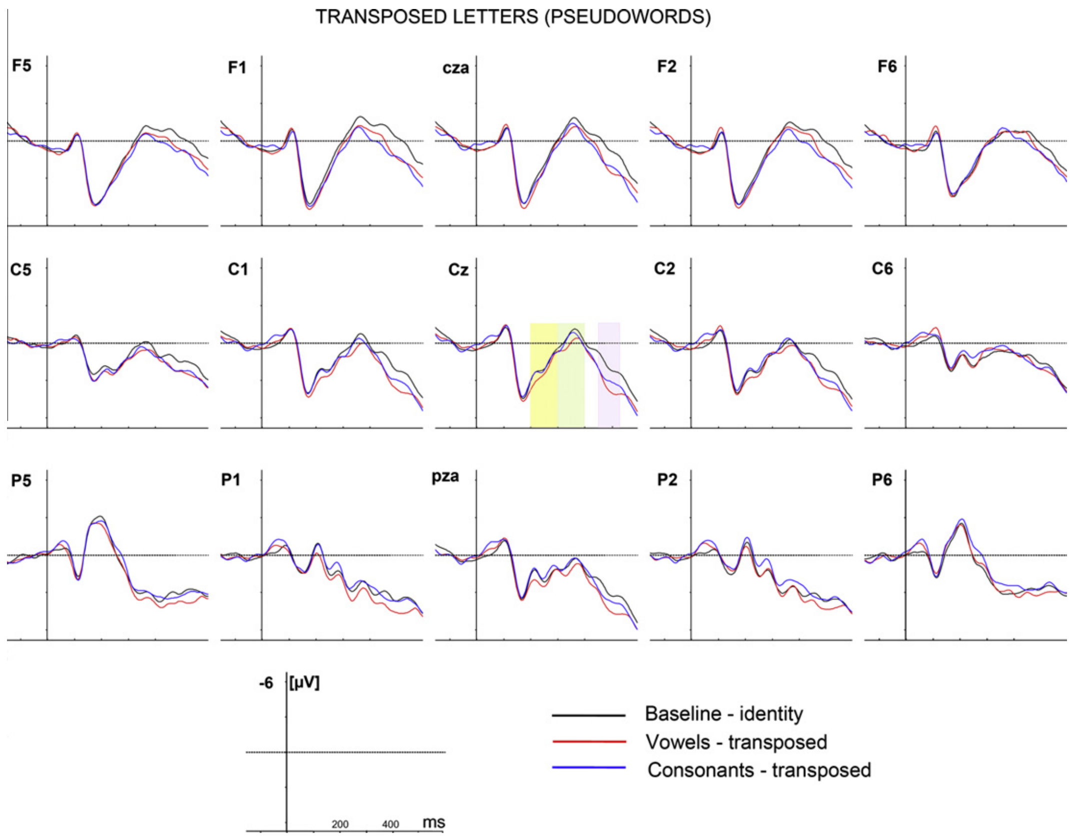

Fig. 5. Grand average ERPs to the target pseudowords in three different conditions (baseline/identity, vowels-transposed, and consonants-transposed condition) in representative electrodes of each column of analysis. The three windows of analysis (200–300, 300–400 and 450–525 ms) are highlighted by the vertical colored bars.

Table 2
Statistics of the main contrasts (vowels vs. consonants; baseline vs. vowels; baseline vs. consonants) of the significant interactions obtained in the delay and transposition manipulations for **words** at three different time epochs across the four columns of electrodes (C1–C4).

Delay							Transposition				
200–300		*F*	Elect.	V<>C	Bs<>V	BS<>C					
C1	Delay × elect.	10.44***	F5, F6	<1	16.53***	8.22**			–		
			C5a, C6a	<1	12.03***	5.63*			–		
C2	Delay × elect.	4.22*	F3, F4	<1	7.51**	6.90*			–		
			C3a, C4a	<1	7.77**	5.26*			–		
C3	Delay	3.85*		<1	4.89*	4.41*			–		
C4	Delay	5.22*		2.13	5.25*	6.24*			–		
300–400											
C2	Delay		–	3.68	–	–	–		–		
C3	Delay		–	6.16*	–	–	–		–		
C4	Delay		–	8.36**	–	–	–		–		
450–525				V<>C	Bs<>V	BS<>C		*F*	V<>C	Bs<>V	Bs<>C
C1	Delay	6.86**	–	1.66	5.65*	15.24***	Trans.	3.47*	1.43	8.33**	1.75
C2	Delay	6.56**	–	2.97	3.11	15.78***	Trans.	3.21	1.29	7.28**	1.74
C3	Delay	7.40**	–	4.94*	1.89	15.91***	Trans.	3.37*	1.43	8.26**	1.69
C4	Delay	8**	–	5.74*	1.45	18.13***	Trans.	3.49*	1.8	8.58**	1.40

Bs: baseline; V: vowels-delayed; C: consonants-delayed; delay × elect. df: 2,24; delay df: 2,42; trans. df: 2,42.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

between the baseline and the consonant-delayed condition, and between the baseline and the vowels-transposed condition. As shown by the ERP waves, the consonants-delayed condition differs clearly from the baseline. Taking into account the previous findings, the larger negativities observed around 400 ms regarding the consonants-delayed manipulation seem to reflect a larger impact of consonants delay on lexical retrieval during the process of visual-word recognition. In order to assess the impact of our experimental manipulations on the time course of lexical access, we conducted a different analysis on the latency of the lexicality effect (i.e., the difference between the response to words and pseudowords). Orthographically legal, pronounceable pseudo-

Table 3
Statistics of the main contrasts (Vowels vs. Consonants; Baseline vs. Vowels; Baseline vs. Consonants) of the significant interactions obtained in the Delay and Transposition manipulations for **pseudowords** at three different time epochs across the 4 columns of electrodes (C1, C2, C3 and C4).

Delay								Transposition
200–300		df	*F*	Contrast	V<>C	Bs<>V	BS<>C	
C1	Delay × elect.	8,168	6.48***	F5, F6	<1	8.93**	6.85**	–
				C5a, C6a	<1	6.27*	5.31*	–
				C5, C6	<1	7.36**	5.10*	–
C2	Delay	2,42	3.44*					–
	Delay × hem	2,42	4.19*	Right H.	<1	7.52*	4.46*	–
C3	Delay	2,42	4.03*					–
	Delay × hem	2,42	4.83*	Right H.	<1	9.17**	4.19*	–
C4	Delay	2,42	4.67*		<1	9.04**	4.46*	–
300–400								
C1	Delay × elect.	8,168	15.13***	F5, F6	<1	9.29**	11.42**	–
				C5a, C6a	<1	9.26**	12.91***	–
C2	Delay × elect.	8,168	7.69***	F3, F4	<1	9.78**	11.26**	–
				C3a, C4a	<1	6.73**	7.18**	–
C3	Delay × elect.	8,168	7.16***	F1, F2	<1	10.78**	10.77**	–
				C1a, C2a	<1	6.67*	9.02**	–
C4	Delay × elect.	8,168	5.54**	Fz	<1	11.20**	13.17**	–
				Cza	<1	6.71*	7.92**	–
				Cz	<1	4.68*	5.67*	–

Delay						Transposition				
450–525		*F*	V<>C	Bs<>V	BS<>C		*F*	V<>C	Bs<>V	Bs<>C
C1	Delay	4.79*	<1	4.31*	9.46**		–	–	–	–
C2	Delay	5.45*	<1	6.02*	9.36**	Trans.	3.43*	<1	6.13*	4
C3	Delay	5.83**	<1	6.74*	9.24**	Trans.	4.14*	<1	7.54*	4.42*
C4	Delay	5.76*	<1	7.53*	8.53*	Trans.	4.19*	<1	7.74*	4.34*

Bs: baseline; V: vowels-delayed; C: consonants-delayed.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

words elicit ERPs qualitatively similar to words, although amplitudes differ. That is, the N400 component would reflect the activation of language based processes that may include orthographic, phonological and semantic components. Larger N400 amplitudes for pseudowords would be associated with failure in finding a semantic match in memory.

The time course of lexical information retrieval would be reflected in the latency of the N400 effect in the baseline comparison. This latency will be the reference so as to measure whether the delay/transposition of vowels/consonants interferes in the standard retrieval of lexical representations. We computed the lexicality effect across the five manipulations (identity-baseline, vowel-delay, consonant-delay, vowel-transposition, consonant-transposition) and across two different time windows (250–400 ms; 400–550 ms), according to visual inspection of our ERP results.

7. Lexicality effect

The comparison of the lexicality effect across each main manipulation (baseline; delayed-letters: vowels and consonants; transposed-letters: vowels and consonants) comprised several repeated-measures ANOVAs which were ran over columns 1–3, and included *lexicality* (word, nonword) *hemisphere* (left, right) and *electrode* (five locations) as factors. The ANOVA on column 4 (middle line) did not include the *hemisphere* factor. Each ANOVA was applied along two separate time epochs (250–400 ms, 400–550 ms). Table 4 shows a summary of the statistical analysis, while the scalp distribution of the lexicality effect across time and in the five manipulations is shown in Fig. 6.

7.1. 250–400 ms epoch

On baseline condition, the ANOVAs on columns 1–4 showed main effects of *lexicality* (in column 1, this effect was modulated by an interaction between *lexicality* and *electrode*: lexicality effects were observed over most anterior electrodes). A main effect of *lexicality* was also observed in the vowels-delayed condition across columns 2–4 (it was marginally significant over column 1). No effects were observed in the consonants-delayed condition nor in the vowels-transposed condition. However, an interaction of *lexicality* and hemisphere was observed in the consonants-transposed over column 1, where simple comparisons showed lexicality effects over the right hemisphere.

7.2. 400–550 ms epoch

At this time window, the ANOVAs on columns 1–4 across the five comparisons showed main effects of *lexicality*.

Our results on the latency of the lexicality effect showed that, by 300 ms (250–400 ms epoch), differences between words and pseudowords were present when the manipulations were identity, vowels-delay and consonants-transposition. At this time window, no differences between words and pseudowords were observed when the manipulation involved consonants-delayed, or when it involved the transposition of two vowels. By 400 ms, the lexicality effect was statistically significant across the five manipulations. This suggests that by 300 ms, delaying the presentation of vowels does not have any impact on the retrieval of the lexical word form, as the time course of lexicality effect under this manipulation is comparable to that of the identity priming manipulation. However, delaying the presentation of consonants seems to delay the access to the word-form retrieval: lexicality effects under this manipulation start up by 400 ms.

8. Discussion

The present experiment was designed to shed some light on the timing of the processing of letter identity and letter position for

Table 4
Statistics of the **Lexicality** effect (words vs. pseudowords) obtained within each one of the five conditions, and across two different time epochs.

250–400		Baseline			Delayed				Transposition				
					Vowels	Consonants			Vowels	Consonants			
		F	Contrast	Lex	*F*	*F*	Contrast	*F*	*F*		*F*	Contrast	Lex
C1	*L* × elect.	6**	F5, F6 C5a, C6a C5, C6	8.87** 5.38* 4.74*	3.58	–	–		–	*L* × hem	7.4*	RH	4.12*
C2		5.85*			5.85*		–	–		–	–		
C3		5.96*			9.64**		–	–		–	–		
C4		7.13*			9.7**		–	–		–	–		
400–550													
C1		43.8***		14.15***	*L* × hem	4.63*	HD	9.38**	10.55**		12.28**		
C2		46.19***		17.15***		5.46*			9.95**		13.7***		
C3		42.21***		25.42***		4.57*			11.05**		15.72***		
C4		46.41***		25.47***		5.08*			4.85*		14.64***		

L × elect. df: 4, 84; *L* × hem df: 1, 21; simple contrast df: 1, 21.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

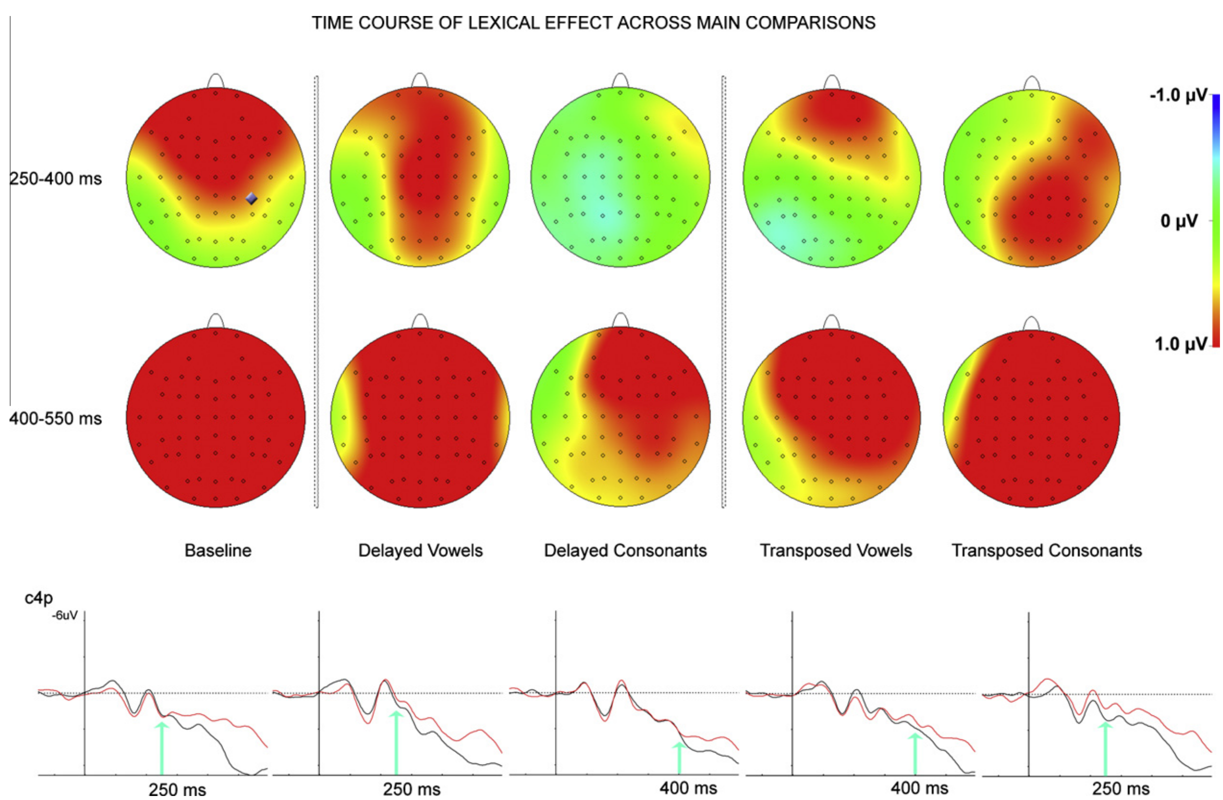

Fig. 6. Topographical distribution of the lexical effect calculated as the difference in voltage amplitude between the ERP response for words vs. pseudowords, under each one of the five main manipulations, and across two time epochs. ERPs for words (black line) and pseudowords (red line) are also shown on electrode C4p.

vowels and consonants by measuring ERP waves. We did so by delaying the presentation of two consonants/vowels and by transposing two consonants/vowels in a masked priming lexical decision experiment. The RTs showed that delaying or transposing two letters had an inhibitory effect on the response – relative to an identity (baseline) condition; indeed, the effect of letter delay was larger than the effect of letter-transposition. However, RT measures were not sensitive enough to reveal any differences between vowels and consonants. It is important to note that previous studies on the transposed-letter priming effect (e.g., Perea & Acha, 2009; Perea & Lupker, 2004) included a replacement condition (where consonants or vowels were replaced with different consonants or vowels) as the control condition in order to measure the priming effect from the transposed-letter conditions; that is, they did not directly compare the transpositions of vowels vs. consonants. In contrast, our ERP results showed that the delay effect for word stimuli was due to differences between consonants- and vowels-delayed (starting around 300 ms), while the transposed-letter effect was (mostly) due to differences between the vowels-transposed and baseline conditions (450–525 ms window). Besides, the ERP analysis on the latency of the lexicality effect showed that delaying two consonants or transposing two vowels shifted the time course of the lexicality effect by about 150 ms later than the baseline condition.

8.1. Delayed-letter effects

First, the delayed-letter manipulation for vowels and consonants had the same impact on early stages of processing for words and pseudowords – as deduced from the ERP waves: the present experiment showed delayed-letter effects for both vowels and consonants at the 200–300 ms epoch. This pattern of results apparently differs from previous evidence (Carreiras, Gillon-Dowens, et al., 2009), where the dissociation between consonants and vowels-delayed conditions (compared to the baseline) was already evident at the 200–300 ms epoch. However, the present paradigm differs from that employed by Carreiras and colleagues. Firstly, the case between prime and target in the present experiment was changed in order to avoid any effects of physical overlap. Secondly, the missing slots in the delayed-letter primes were replaced by the symbol "░" to minimize potential luminance changes from prime to target. In any case, in the present experiment and in the Carreiras et al. experiment, early ERP effects were observed for both words and pseudowords: the conditions with delayed-letters differed from the baseline without a consonant/vowel distinction.

Importantly, after 300 ms of target offset, differences between the consonants- and the vowels-delayed condition are present in the processing of words – but not in the processing of pseudowords. This strongly suggests that, by this time, lexical retrieval is (more) disrupted by the delay of consonants. Furthermore, regarding the lexicality effect, our results showed that the impact of delaying vowels is less pervasive than delaying consonants on lexical information retrieval. In addition, and regarding pseudowords, a larger negativity was observed over frontal areas for the baseline compared to the delayed conditions. Usually, larger N400 amplitudes obtained for pseudowords are interpreted as an index of lexical search processes in which an orthographical and pronounceable nonword is compared to possible lexical candidates in order to find associated lexical-semantic information in long-term memory (Ziegler, Besson, Jacobs, Nazir, & Carr, 1997). For instance, Bentin, Mouchetant-Rostaing, Giard, Echallier, et al., (1999) found that unpronounceable consonant letter strings produced a positivity compared to pronounceable pseudowords – which produced negativity. According to Bentin et al., this difference is showing early lexical or prelexical processes of grapheme-to-phoneme translation. Therefore, our results suggest that pseudoword primes lacking two non-adjacent vowels or consonants interfere equally in this process: smaller N400 amplitudes are shown for both vowel- and consonants-delayed conditions. No differences between vowel/consonant-delay conditions (with respect to the baseline) are observed in pseudowords. Taken together, these findings suggest that the early superiority of consonant vs. vowel identity coding is determined lexically.

The delayed-letter effects in the present experiment are parallel to those obtained by Carreiras, Duñabeitia, et al. (2009) in a recent experiment on relative position priming. In the Carreiras et al. study, the N250 component was sensitive to the consonant–vowel distinction. The amplitude of the relative position priming condition (consonants: frl-farol; vowels: aeo–acero) was similar to the identity condition for consonant strings, and to the unrelated condition for vowel strings. That is, the sequence of consonants facilitated the processing of the target to the same extent as the identity prime did; in contrast, the vowel-sequence prime was as inefficient as an unrelated prime. Taken together, these findings suggest that the code based on relative position of consonants is as good as the complete string of letters; in contrast, vowels may not provide as valuable information as consonants do in retrieving word forms. One plausible explanation for this phenomenon is that a string of vowels may yield higher values of global lexical activation and competition that consonantal patterns do (e.g., the vocalic sequence "aeo" is present in more than 150 Spanish words). However, in our delayed-letter manipulation, all letters remained as primes except two non-adjacent vowels (or consonants) in up to nine letter-long words. Furthermore, the target words were the only lexical representations that could be pre-activated by prime presentation. In this case, an explanation based on "high lexical dispersion of vowel-based skeletons" (Carreiras, Vergara, et al., 2009, p. 9) does not seem to explain our results. We should consider, instead, that at a very early processing level, only the identity of consonants is taken into account. Under these circumstances, larger negativities (N400: 300–525 ms) for the consonant-delayed condition might reflect the difference in preactivation of the lexical representation triggered by this type of prime compared to the vowels-delayed condition.

Finally, the analysis of the latency of the lexicality effect showed that the lexicality effect (computed as the difference between the words and pseudowords' ERP voltage amplitude) had a longer latency for the consonants-delayed condition (400–550 ms) compared to both the baseline and the vowels-delayed condition (250–400 ms). This suggests that, by 300 ms after target presentation, the activation of the lexical word form triggered by the presentation of the consonants-delayed prime was not high enough (compared to both the baseline and the vowels-delayed condition). Delaying vowels did not interfere as much as delaying consonants in lexical retrieval. This type of results adds more evidence to the key role of consonants during word-form retrieval.

8.2. Transposed-letter effects

Primes created by the transposition of consonants or vowels did not have any significant effects on target processing until 400 ms – relative to the (baseline) identity primes. This clearly implies that letter position assignment takes time to encode. Furthermore, the absence of effects in the initial two windows of analyses occurs for both words and pseudowords. Interestingly, no differences are observed between targets preceded by the baseline primes or the consonants-transposed primes, while the vowels-transposed primes elicited larger negativities than the baseline primes. That is, according to ERP responses, transposing vowels had a larger interfering effect than transposing consonants. Again, the analysis on the latency of the lexicality effect showed that the lexicality effect had a longer latency for the vowels-transposed condition (400–550 ms) compared to both the baseline and the consonants-transposed conditions (250–400 ms). In other words, transposing consonants did not interfere as much as transposing vowels in lexical retrieval. This pattern of results goes in the same direction as previous findings obtained by Perea and Lupker (2004) and Carreiras et al. (2007). In these experiments, highly wordlike pseudowords created by the transposition of vowels and consonants were found to activate their lexical representation at a higher degree than orthographic controls (vowels-transposed: *revuloción*; control: *revileción*; target: REVOLUCION; consonant-transposed: *relovución*; control: *retosución*; target: REVOLUCION; see Perea & Lupker, 2004).

The asymmetry between transposed-letter effects regarding vowels and consonants emerges in a late epoch of the N400 ms time window – relative to the baseline condition, so it is difficult to (exclusively) propose an orthographic locus of the consonant/vowel position coding differences, at least in tasks such as lexical decision, where later stages of word processing are tapped into. Importantly, the asymmetry between transposed-letter effects for vowels and consonants does not occur in tasks that allegedly tap very early processes in visual-word recognition. For example, Johnson (2007) employed a parafoveal transposed-letter priming procedure in the context of normal silent reading while the participants' eye movements were monitored. Her results did not show a dissociation between C–C and V–V transpositions. That is, transposition effects were approximately the same size for both C–C and V–V manipulations. Likewise, Perea and Acha (2009) examined whether the modulation of the transposed-letter priming effect in response times by consonant/vowel status was task-specific by using the same material across a masked priming paradigm with lexical decision task and the cross-case same-different task. This latter task presumably taps low level processing: a probe is presented before a target stimulus (which is presented in different case) and subjects have to judge whether probe and target are the same or not. Parallel to Johnson's (2007) parafoveal priming task, the masked priming same-different task reflects quite early stages of visual processing (Norris & Kinoshita, 2008). Perea and Acha (2009) found a larger masked transposed-letter priming effect for consonants over vowels in the lexical decision task, whereas the same-different task did not show differences between consonants/vowels manipulations. The presence of similar masked transposed-letter priming effects for C–C and V–V transpositions in low-level perceptual tasks suggests that letter position coding occurs before the consonant–vowels distinction is functionally relevant.

What would be the locus of the consonant/vowel dissociation obtained in masked priming lexical decision? One might argue that this difference arises at a sub-lexical phonological level. Note here that 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 consonants-transposed pseudoword RELOVUCIÓN to its base word, REVOLUCIÓN, in contrast to the vowels-transposed pseudoword REVULOCIÓN; see Perea & Lupker, 2004). According to this interpretation, a consonants-transposed prime is more effective than a vowels-transposed prime because the prosodic pattern (intonation and rhythm are determined by the vocalic sequence within a word) is preserved and retrieved in the first case. Conversely, because of a lack of any lexical representation in memory, responses for pseudoword targets would be based more on an analysis of the orthographic structure of the letter string, and hence the consonant/vowel transposed effect asymmetry would be attenuated for pseudowords. In this direction, our ERP results showed that the effect of transposing letters (whether vowels or consonants) had a similar impact on the processing of pseudowords.

8.3. Letter identity, letter position, and consonant/vowel status

The more constraining function of consonants at activating lexical representations may be supported by the critical importance of consonants (compared to vowels) at making quality distinctions. Consonants are, across languages, more numerous than vowels – and this is partly due to the anatomy of the speech tract (Nespor et al., 2003). Consonants tend to disharmonize within a word. Apart from reduplications, consonants, unlike vowels tend not to persevere across a word (Nespor et al., 2003). At some level, the cognitive system specialized for visual-word recognition may have adjusted its parameters to the functional differences of vowels and consonants. Regarding letter position, the difference between vowels and consonants may raise at a later phonological level mostly involved in the lexical form retrieval. As different studies have shown (Perea & Lupker, 2004; see also Carreiras et al., 2007; Carreiras, Gillon-Dowens, et al., 2009; Carreiras, Vergara, Perea, et al., 2009) what is (early in time) mainly coded is the identity of consonants. The situation is different for vowels. There are fewer vowels than consonants, their frequency is larger and they persevere more frequently than consonants across a word. Since the relative position of vowels provides the prosodic pattern of a word, the relative position of vowels seems relevant in activating a lexical candidate. As Perea and Lupker (2004) indicated, the present findings seem to show that, in Spanish, establishing the exact position of vowels may be more relevant for a word's identification that establishing the exact position of consonants. This may be in contradiction with the findings of Berent and Perfetti (1995) on the faster coding for consonants compared to vowels. However, the time course of vowels/consonant processing may vary as a function of the characteristics of each language (see Colombo, Zorzi, Cubelli, & Brivio, 2003, for evidence in Italian). In English, the grapheme–phoneme relationship for consonants is much more consistent than it is for vowels (Brown & Besner, 1987; Carr & Pollatsek, 1985). However, Spanish shows a grapheme–phoneme relationship for vowels as consistent as that for consonants. These findings suggest that the orthographic info extracted at early stages of processing is letter identity, while information on letter order is not as accurately encoded. At later processing stages, vowels and consonants may play different roles in lexical access. The observed differences between consonants and vowels were small and appear relatively late (300 ms). This is in line with the claim that the earliest phase of orthographic processing is insensitive to consonant/vowel status, and these differences emerge later either via the intervention of phonology or via differences in lexical constraint (e.g., as proposed by the dual-route model of orthographic processing, see Grainger & Dufau, 2011). Further research across languages differing in orthographic transparency is necessary to understand and implement the different roles of vowels and consonants on the (presumably) phonological processing involved in visual-word recognition.

9. Conclusions

The effects of transposed-letter priming and relative position priming reflect that, while any input coding scheme must be order sensitive, at some level of word processing letter position coding is rather flexible. Here we have shown converging evidence, using ERP waves, that this flexibility may differ regarding the letter status (whether a vowel or a consonant). At present, none of the computational models that can capture transposed-letter and relative position priming effects make any distinctions between the processing of vowels and consonants – note that phonological processing in these models is not (fully) developed. Further empirical and simulation work is needed to shed more light on the intricacies of vowel/consonant differences in visual-word recognition.

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