OXFORD UNIVERSITY PRESS Cerebral Cortex

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Journal:	*Cerebral Cortex*
Manuscript ID:	CerCor-2008-00575.R2
Manuscript Type:	Original Articles
Date Submitted by the Author:	30-Jan-2009
Complete List of Authors:	Carreiras, Manuel; Universidad de La Laguna, Psicologia Cognitiva Duñabeitia, Jon Andoni; Universidad de La Laguna, Psicologia Cognitiva Molinaro, Nicola; Universidad de La Laguna, Psicología Cognitiva
Keywords:	visual word recognition, ERPs, consonants and vowels, letter processing, relative position priming

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Consonants and vowels contribute differently to visual word recognition: ERPs of relative position priming.

Manuel Carreiras[1,2], Jon Andoni Duñabeitia[2], and Nicola Molinaro[2]

[1] *Basque Center on Cognition, Brain and Language. Donostia. Spain*

[2] *Instituto de Tecnologías Biomédicas. Universidad de La Laguna. Spain*

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Keywords: Visual Word-Recognition. ERPs, Relative Position Coding, Consonants and Vowels

Correspondence:

Manuel Carreiras

Basque Center on Cognition, Brain and Language

Paseo Mikeletegi, 53

20009- Donostia-San Sebastián, SPAIN.

email: m.carreiras@bcbl.eu; mcarreir@ull.es

Abstract

This paper shows that the nature of letters –consonant vs. vowel– modulates the process of letter position assignment during visual word recognition. We recorded Event Related Potentials (ERPs) while participants read words in a masked priming semantic categorization task. Half of the words included a vowel as initial, third and fifth letters (e.g., acero [steel]). The other half included a consonant as initial, third and fifth (e.g., farol, [lantern]). Targets could be preceded 1) by the initial, third and fifth letters (relative position; e.g., aeo - acero and frl - farol), 2) by three consonants or vowels that did not appear in the target word (control; e.g., iui - acero and tsb - farol), or 3) by the same words (identity: acero-acero, farol-farol). The results showed modulation in two time windows (175-250 and 350-450 ms). Relative position primes composed of consonants produced similar effects to the identity condition. These two differed from the unrelated control condition, which showed a larger negativity. In contrast, relative position primes composed of vowels produced similar effects to the unrelated control condition and these two showed larger negativities as compared to the identity condition. This finding has important consequences for cracking the orthographic code and developing computational models of visual word recognition.

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Printed word recognition is a key process for reading. Whether or not words are recognized visually as a whole via their constituent letters has been debated for more than a century. Although early research suggested that words could be identified by the use of word shape (see Cattell, 1886) and some investigators still argue that supra-letter features such as word shape play a role in visual word recognition (e.g., Allen, Wallace, & Weber, 1995; Healy & Cunningham, 1992; Healy, Oliver, & McNamara, 1987), most theorists currently support the idea that words are initially formed from component letters (analytical models; e.g., the search model, Forster, 1976; the multiple read-out model, Grainger & Jacobs, 1996; the interactive-activation model, McClelland & Rumelhart, 1981; the activation-verification model, Paap, Newsome, McDonald, & Schvaneveldt, 1982). Recent research has shown that words in alphabetic languages are processed via their constituent letters (see Pelli, Farell, & Moore, 2003). However, the process of coding for letters (i.e. how letters are assigned within words, including their identity and position), remains poorly understood. To recognize a printed word, we need to process the identity and position of its letters, hence distinguishing between trail and trial, but not between tABLe and TabLE, or chair and CHAIR. Thus, one critical issue for understanding visual word recognition is the nature and functioning of the orthographic input code to the system. Recently, a neurobiological model has been proposed (the local combination detector or LCD model; Dehaene et al., 2005; see also Vinckier et al, 2007) as a new attempt to crack the orthographic code. One important aspect of the LCD model is that it distinguishes between letter identity and letter order processes, taking into account neurobiological constraints and the development of new coding schemes for computational models of visual word recognition. According to the Dehaene et al. proposal, the brain decodes words through a hierarchy of local combination detectors in the occipito-infero-temporal pathway which are sensitive to increasingly larger fragments of words. In particular, they tentatively propose detectors for letter shapes in V4, abstract letter detectors in

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V8, which represent letters denoting their identities but abstracted from their visual appearance (e.g., CaSe, font, size), and detectors for letter strings in the left fusiform gyrus (LFG). However, as with current computational models, this proposal assumes that the process of assigning letters within words is similar for both consonant and vowels. Here, we present evidence from event related potentials (ERPs) that challenges this assumption.

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) have assumed that letter position coding was "channel-specific". That is, letters are assumed to be tagged to their positions in the orthographic representation of the word presented when the identities of the letters have been encoded. However, two recent findings have challenged this assumption: the transposed letter effect and the relative position priming effect.

The transposed-letter priming effect refers to the fact that nonword primes created by transposing two letters from a real word produce form-priming effects, relative to the orthographic control creating by replacing letters (e.g., jugde-JUDGE vs. jupte-JUDGE; Perea & Lupker, 2003, 2004; see also Duñabeitia, Perea, & Carreiras, 2007; Perea & Carreiras, 2006a, 2006b, 2006c, 2008; Perea, Duñabeitia & Carreiras, 2008). The relative position priming effect has been defined as a "variety of orthographic priming that involves a change in length across prime and target such that shared letters can have the same order without being matched in terms of absolute, length-dependent position" (Grainger, 2008, page 16). Target words like BALCON preceded by nonword primes created by replacing some letters with hyphen marks (e.g., B-LC-N; the absolute position condition) or with the same letters without the hyphens (e.g., BLCN; the relative position condition) are recognized faster than when preceded by nonsense symbol strings (e.g., %%%%%), or than when preceded by unrelated control strings (e.g., CRTR) (see also Humphreys et al., 1990). Importantly,

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the size of the effect is the same for the absolute and the relative position conditions. In addition, the effects are cancelled when relative position is violated (e.g., BCLN instead of BLCN) (Grainger et al, 2006; Peressotti & Grainger, 1999); that is, when the same letters as those used as relative position primes are presented in a partially scrambled order. This condition produces similar reaction times as those to the unrelated primes. The relative position priming effect also vanishes at long prime durations (approximately 80 ms) (Grainger, Granier et al, 2006). Thus, because these effects are short-lived and similar for absolute and relative position primes, the findings suggest that the orthographic information extracted at early stages of processing is letter identity and the relative ordering of letters in the input string, with no specific encoding of the absolute position of each letter.

The transposed letter effect and the relative position priming effect generate serious problems for standard computational models (e.g., McClelland & Rumelhart, 1981; Coltheart et al, 2001; Grainger & Jacobs, 1996) because none of them can account for either of these two effects: (1) transposed-letter neighbors are more similar to target words than replaced-letter neighbors and (2) two strings that differ in length and therefore in the absolute position of the letters but that do not differ in the relative order/position of the letters activate each other to a great extent. However, a number of input "coding schemes" have recently been proposed that successfully capture the existence of these effects (e.g., SERIOL model, Whitney, 2001; SOLAR model, Davis, 1999; open-bigram model, Grainger & van Heuven, 2003; Overlap Open Bigram model Grainger, Granier et al, 2006; overlap model, Gomez, Ratcliff, & Perea, 2007), 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). Interestingly, these input schemes are favored in the LCD model. There is one caveat, however: these models assume that

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consonants and vowels are processed in exactly the same way, but this does not seem to be the case.

Recent transposed-letter experiments (e.g., Perea & Lupker, 2004; see also Carreiras, Vergara, & Perea, 2007, 2009; Perea & Carreiras, 2006a) have found a differential role of consonants and vowels in transposed-letter similarity effects. For instance, Perea and Lupker (2004) obtained a masked priming effect for consonant transpositions (relovución-REVOLUCIÓN vs. the replaced letter control condition (retosución-REVOLUCIÓN), but not for vowel transpositions (reluvoción-REVOLUCIÓN vs. relavición-REVOLUCIÓN) (see Duñabeitia, Perea & Carreiras, in press for the suitability of this control). There are specific hypotheses suggesting that the consonant-vowel structure is determined and coded very early in word processing (e.g., Berent & Perfetti, 1995). Furthermore, recent research with other paradigms and methodologies (e.g., reaction time ERPs, fMRI) in auditory and visual word recognition suggests that the processing of vowels and consonants may be different. For instance, adults are more likely to replace vowels than consonants when instructed to change one phoneme from a nonword to make it a word (*kebra* becomes *cobra* rather than *zebra*) (Cutler, Sebastián-Gallés, Soler-Vilageliu, & van Ooijen, 2000; Van Ooijen, 1996). Moreover, participants find it very difficult to use transitional probabilities between successive vowels when presented with an auditory string of artificial speech and later on are asked to identify possible words, while this process is much easier for successive consonants, demonstrating the greater importance of consonants for word identification than of vowels (Bonatti Peña, Nespor, & Mehler, 2005; Peña, Bonatti, Nespor, & Mehler, 2002). Vowels and consonants produce different effects on regional brain activation when participants are engaged in a lexical decision task with pseudowords created by changing two consonants or two vowels (Carreiras & Price, 2008). Readers find more difficulty in recognising a word when two consonants as compared to two vowels are slightly delayed during the presentation of the word (Carreiras, Gillon-Dowens, Vergara, & Perea, 2009; Lee, Rayner, & Pollatsek, 2001).

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Infants fail to discriminate vowels in a lexical acquisition task, whereas they do discriminate between consonants (Nazzi, 2005). Finally, a number of neuropsychological studies have found a double dissociation, so that some patients find vowels more difficult to produce than consonants while others show the reverse pattern (e.g., Caramazza, Chialant, Capasso, & Miceli, 2000).

One potential target area for identifying differences between consonants and vowels is the letter assignment process in visual word recognition. If differences are found here, the effect will have very important theoretical consequences for the development of computational models of word recognition and letter identification, as well as for the LCD model, which assumes that some of the new coding schemes have neurobiological plausibility, but does not make any distinction between consonants and vowels in the letter assignment process. To investigate this possibility, we will measure ERPs on the relative position priming effect. Previous behavioral research (Duñabeitia & Carreiras, submitted) has already shown that the relative position priming effect vanishes when the letters manipulated are vowels, while it is preserved when the letters are consonants (e.g., csn-CASINO vs. aia-ANIMAL). In addition, these authors showed that the relative position that only holds for consonants cannot be accounted for just by the frequency of letters: When they presented primes that contained only vowels, only high frequency consonants or only low frequency consonants, they found a significant relative position priming effect of the same size for the two consonant conditions, but no effects for vowel primes. Thus, despite the fact that vowels are typically of higher frequency than consonants, Duñabeitia and Carreiras showed that the frequency of the letters by itself is not the factor responsible for the vanishing of the relative position priming effect (note that, otherwise, high frequency consonants should have produced reduced priming effects as compared to low frequency consonants). Finally, they also showed that the inclusion of repeated letters in the primes did not have an impact on the relative position priming and type of letter (consonant, vowel) interaction (e.g., lbl-GLOBAL and cbr-ICEBERG vs. iia-DIGITAL and iea-MINERAL).

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However, to claim that the consonant/vowel difference is influencing the letter position assignment process it is critical to show that it is affecting the very early moments of visual word recognition. So far, some previous attempts to show early consonant/vowel effects using transposed-letter stimuli either showed late effects more related with response bias than with perceptual encoding (e.g., Carreiras, Vergara & Perea, 2007), or only early effects for vowels (Carreiras, Vergara & Perea, 2009). This paper investigates in detail the time course of the processing of vowels and consonants during letter position assignment in visual word recognition, using the relative position priming paradigm combined with the recording of Event Related Potentials.

Event Related Potentials (ERPs) are functionally decomposable to a greater extent than behavioural data, thus enabling conclusions not only about the existence of processing differences between vowels and consonants, but also about the level of processing at which these differences occur. 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. Of specific interest for our study are three components: N/P150, N250, and N400. The N/P150 component has a posterior scalp distribution focused over right occipital scalp sites and is larger (i.e., more positive) to target words that are repetitions of a prior masked prime word compared to targets that are unrelated to their corresponding masked prime (Holcomb & Grainger, 2006). In addition, the N/P150 component has been found with the masked priming paradigm using single letters as primes and targets (Petit et al., 2006). They found that the P150 was significantly larger to mismatches between prime and target letter case, but more so when the features of the lower and upper case version of the letters were physically different compared to when they were physically similar (e.g. A-A compared to a-A vs. C-C compared to c-C). Thus, this component seems to be sensitive to processing at the level of visual features. Recent research has shown that this early ERP component can take the form of a bipolar effect across frontal and occipital electrodes (e.g., Chauncey et al., 2008), so that while it is more

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positive over occipital areas, it is more negative over frontal areas of the scalp. The N250 component has been associated with the degree of prime-target orthographic overlap and phonological overlap in masked priming, suggesting that is sensitive to processing sublexical representations (Grainger, Kiyonaga, & Holcomb, 2006; Holcomb & Grainger, 2006; Carreiras et al, 2009, Carreiras, Perea et al, in press), at least when the prime strings do not constitute real words (Duñabeitia, Molinaro, Laka, Estévez & Carreiras, in press). The N250 has a more widespread scalp distribution than the N/P150. Two windows can be isolated in the N250, the first window being more sensitive to orthographic processing and the second to phonological processing (see Grainger, Kiyonaga et al., 2006; Carreiras et al., 2009, Carreiras, Perea et al, in press). 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; Müller et al., submitted). Specifically, the amplitude of this negativity is an inverse function of lexical frequency, of lexicality (e.g, Neville, Mills, & Lawson, 1992; see also Barber & Kutas, 2007; Carreiras, Vergara, & Barber, 2005). In addition, items from small orthographic or syllabic neighborhoods produce an N400 of smaller amplitude than items form a large orthographic or syllabic neighborhood (Holcomb, Grainger & O'Rourke, 2002; Barber, Vergara & Carreiras, 2004).

In particular, we asked: i) whether consonants and vowels have a differential influence on the letter assignment process in visual word recognition, for which the relative position priming was manipulated for vowels and consonants, and ii) whether the time course for consonants and vowels in the letter assignment process differs, since it has been shown to be different in letter identification (Carreiras, Gillon-Dowens et.al., 2009). To this end, we sought differences in the relative position priming effects between strings that share only consonants (e.g., *frl* priming *farol*, the Spanish for *bluff* and *lantern*), or that share only vowels (e.g., *aeo* priming *acero*, the Spanish for *steel*).

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We also included an identity condition (e.g., *farol* priming *farol* and *acero* priming *acero*), and an unrelated condition (e.g., *tsb* and *iui*) as control conditions.

If the contribution of consonants and vowels to the letter assignment process is different and has a different time course, we expect our manipulation to have a differential impact on the ERP components described above. More specifically, for both consonant and vowels we expect a difference in early perceptual components between the identity and the other two conditions, reflected in the N/P150 component, the reason being that there is a lower perceptual change in the identity condition.

Differences between relative position priming for consonants and vowels are expected in the N250 component (i.e., a component which has been posited to be sensitive to orthographic overlap), assuming that there is differential orthographic processing of these two types of letters in the initial stages of visual word recognition. The reason for this expectancy relies on the tight link between consonants, orthographic processing and lexical selection processes, and the importance of vowels in orthographic encoding, since the role of vowels is more related to rhythmic and syntactic patterns, as proposed by Nespor, Peña and Mehler (2003; see also Carreiras & Price, 2008) Finally, late differences between the manipulation of consonants and vowels should also be noticeable in the N400 component, according to the lexical constraint hypothesis: Vowel primes and consonant primes may trigger different patterns of activation in the lexicon, and more critically, different numbers of lexical candidates. Consonant primes are much more constraining than vowel primes, because there are far fewer words consistent with the consonant primes than with the vowel primes. Hence, vowel primes activate many lexical units and therefore produce more dispersion of the activation and probably more competition during the lexical selection processes.

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Method

Participants.

27 undergraduate students (16 women) from the University of La Laguna 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. All participants were right-handed, as assessed with an abridged Spanish version of the Edinburgh Handedness Inventory (Oldfield, 1971).

Materials.

A total of 258 words were selected from the Spanish LEXESP database (Sebastián-Gallés, Martí, Carreiras, & Cuetos, 2000) and analyzed with the B-PAL software (Davis & Perea, 2005). All of the words were five or six letters long (mean: 5.47). Half of these words (namely 129) included a vowel as first, third and fifth letters (e.g., acero [steel]). The mean frequency of these words was 14.23 appearances per million (range: 0.18-204.46), the mean length was 5.57 letters, and the mean number of orthographic neighbors was 1.51 (range: 0-8). The other half (the remaining 129 words) was composed of words that included a consonant as first, third and fifth letters (e.g., farol, [lantern]). These words were matched to the previous ones in frequency (mean: 17.97; range 0.18-201.07), length (mean: 5.36), and number of orthographic neighbors (mean: 2.20; range: 0-11) in a pairwise manner using the Match software (van Casteren & Davis, 2007). See Table 1 for a summary of the characteristics of the materials. These words could be preceded 1) by the first, third and fifth letters (relative position priming condition; e.g., aeo - acero and frl - farol), 2) by three consonants or vowels that did not appear in the target word (control priming condition; e.g., iui - acero and tsb - farol), and 3) by the same word (identity priming condition; e.g., acero - acero and farol – farol) as an extra control condition. Three lists of materials were created, so

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that each target appeared once in each, but each time in a different priming condition. Different participants were assigned to each of the lists.

<Insert Table 1 around here>

In order to make the go/no-go semantic categorization possible, we included a set of 40 animal names in the item set of each list (e.g., erizo [hedgehog], lince [linx]) of similar length, frequency and structure to the critical words (targets: mean length 5.60; mean frequency 5.54 and number of orthographic neighbors 2.05; primes: mean length 5.55, mean frequency 9.78 and number of orthographic neighbors 2.07).These words were primed by a new set of 40 unrelated non-animal prime words. A prime visibility test was also included in order to check for conscious identification of the masked primes. To this end, the 40 animal names were presented as primes and followed by 40 unrelated non-animal target words. Thus, each list contained 338 trials of which 258 were experimental trials, 40 were trials with animal names for the go/no-go semantic categorization task, 12% of the total amount of trials, and finally 40 were trials for the prime visibility test, 12% of the total amount of trials.

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Procedure.

Participants were individually tested in a well-lit soundproof room. The presentation of the stimuli and recording of the responses was carried out using Presentation software on a computer associated to a CRT monitor. All stimuli were presented on a high-resolution monitor that was positioned at eye level 80 cm in front of the participant. Each trial consisted in the presentation of a forward mask created by hash mark symbols for 500 ms, followed by the displaying of the prime for 50 ms, and immediately followed by the presentation of the target. Primes and targets were presented in lowercase following previous work on the relative position priming effect (e.g., Grainger, Granier et al., 2006; Peressotti & Grainger, 1999) in which primes and targets were also presented in the same case. Primes and targets were presented in Courier New font. In order to minimize physical overlap between primes and targets, different font sizes were used for these strings. Each character of the prime strings had a width of 0.12 inches, while each character of the targets had a width of 0.16 inches (note that Courier New font is a non-proportional font in which all letters occupy the same amount of space). Under these conditions, no saccades were required during reading of each stimulus, since the strings filled less than 1.5 degrees of the visual field. Target items remained on the screen for 500 ms. The inter-trial interval varied randomly between 700 and 900 ms. After this interval, an asterisk was presented for 1000 ms in order to allow participants' blinks (see Figure 1 for and schematic representation of each trial). All items were presented in a different random order for each participant. Participants performed a go/no-go semantic categorization task: they were instructed to press the spacebar on the keyboard only when the letter string displayed referred to an animal name. Twenty warm-up trials, containing different stimuli from those used in the experimental trials, were provided at the beginning of the session. Participants were asked to avoid eye movements and blinks during the interval when the row of hash marks or the asterisk were not present. Each session lasted approximately one hour and fifteen minutes.

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EEG recording and analyses.

Scalp voltages were collected using a BrainAmp recording system from 32 Ag/AgCl electrodes which were mounted in an elastic cap (ElectroCap International, Eaton, USA, 10-10 system). Figure 2 shows the schematic distribution of the recording sites. Linked earlobes were used as reference. Eye movements and blinks were monitored with four further electrodes providing bipolar recordings of the horizontal (Heog-, Heog+) and vertical (Veog-, Veog+) electro-oculogram. Inter-electrode impedances were kept below 10 KΩ. EEG was filtered with an analogue band-pass filter of 0.01-100 Hz and a digital 30 Hz low-pass filter was applied before analysis. The signals were sampled continuously throughout the experiment with a sampling rate of 256 Hz.

<Insert Figure 2 about here>

As in prior research with the masked priming technique, the focus was on the word targets. Only trials free of ocular artifacts (blinks and eye movements) and muscular artifacts were averaged and analyzed (more than 95% of the trials). Epochs of the EEG up to 550 ms after the onset of the target word (i.e. 50 ms after the target word disappeared from the monitor) were the primary data. The baseline correction was performed using the average EEG activity in the 200 ms preceding the onset of the target as a reference signal value – we also visually examined ERPs using baselines calculated during the 100 ms before the target and the 100 ms immediately preceding prime and the outcome was the same as the one presented here. Separate ERPs were formed for each of the experimental conditions, each of the subjects, and each of the electrode sites (see electrode numbers in Figure 2).

We planned two analysis strategies: a “local” one in the occipital electrodes and a “distributed” one to evaluate effects evident all over the scalp.

As demonstrated in recent studies by Holcomb and Grainger (2008) masked priming studies show the earliest effects around 100-150 ms in the occipital electrodes. We evaluated these effects through the “local” analysis considering only the occipital (O1, O2) and temporal-occipital electrodes (PO7/PO8). For each time window of interest we ran a four-way ANOVA with Electrode (O1/O2, PO7/PO8), Hemisphere (Left, Right), Letter (Vowel, Consonant) and Condition (Identity, Relative, Control) as factors

The “distributed” analysis consisted initially in separate ANOVAs on four groups of electrodes (Figure 2, see also Neville et al., 1992, Holcomb & Grainger, 2006 for similar analysis patterns) considering all the six conditions. In the Midline (electrodes linked by thick solid lines) we ran a three-way analysis of variance considering the

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Electrode factor (5 levels: Fpz, Fz, Cz, Pz, Oz), the type of Letter (2 levels: Vowels, Consonants) and the Condition (3 levels: Identity, Relative, Control). The effects at the electrodes of the Column 1 group (electrodes linked by thin solid lines) were initially evaluated by means of a four-way ANOVA crossing the Letter and Condition factors with the Electrode factor (three levels: FC1/FC2, C3/C4, CP1/CP2) and with the Hemisphere (2 levels: Left, Right). The Column 2 electrodes (electrodes linked by thin dotted lines) were analyzed crossing the same Letter, Condition and Hemisphere factors with a four level Electrode factor (F3/F4, FC5/FC6, CP5/CP6, P3/P4). Finally, the Column 3 electrodes (electrodes linked by thin dashed lines) were analyzed crossing Letter, Condition and Hemisphere with a six-level Electrode factor (Fp1/Fp2, F7/F8, T3/T4, T5/T6, PO7/PO8, O1/O2). In order to evaluate the contrasts between conditions we ran pairwise comparisons for each group of electrodes with the same spatial factors (Electrode and Hemisphere) with a two-level Condition factor (Identity vs. Relative, Identity vs. Control, Relative vs. Control). When appropriate, p-values are reported using the Greenhouse-Geisser (1959) correction.

Mean amplitudes were obtained for different time windows. A first “local” analysis was performed on the 100-250 ms time window for the N/P150 and the N250 effects that could emerge in the occipital electrodes. The N250 was analyzed using the “distributed” analysis in the 150-250 ms time window. This time window has been shown to elicit orthographic effects in previous ERP studies (Grainger, Kiyonaga et al., 2006). A further “distributed” analysis was performed for the N400 (350-450 ms) component.

Results

<u>Behavioral measures.</u>

Participants correctly categorized 97.3% (SD=0.8) of the animal names when these words were presented as targets. None of the participants made more than 5% of errors in the categorization task.

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When the animal names were presented as masked primes, participants only identified them in 0.5% (SD=0.5) of the trials. In fact, none of the participants identified the masked animal names in more than 5% of the cases. This result confirms that the participants were mostly unaware of the existence of the masked primes, and even where they did perceive something, they were not able to consciously recognize the briefly presented word.

Electrophysiological measures

ERP grand averages time-locked to the onset of the target words are represented in Figure 3. The upper panel of Figure 3 shows the contrasts between the identity, unrelated and relative position priming conditions for consonants, whereas the lower panel of Figure 3 shows the same conditions for vowels. Visual inspection of Figure 3 reveals differences in amplitude for the experimental conditions. In this first time window, which corresponds to the deflection starting around 100 ms, and lasting until 250 ms, there is a clear positive deflection in the anterior areas of the scalp and a corresponding negative deflection in the posterior areas. This first component appears to be bimodal in the posterior areas with an initial negative peak around 150 ms and a second peak of similar amplitude around 200 ms. The grand average showed different initial trends between Consonants and Vowels. Considering the three Vowel conditions, both in the anterior and posterior electrodes the Relative position and Control conditions are more negative compared to the Identity condition. On the other hand, comparing the three Consonant conditions, the Control condition is more negative compared to the Identity and Relative position conditions. Interestingly, in the posterior electrodes (O1, O2, Oz, PO7, PO8), the above-described dissociation for the N250 among consonants and vowels is preceded by an earlier negativity for the Identity condition. We consider this negativity as reflecting the N/P150 elicited by the prime-

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target physical overlap. For both consonants and vowels, the peak is more negative for the Identity compared to the other two conditions.

<Insert Figure 3 about here>

100-250 ms window (N/P150 and occipital N250)

The effects identified by visual inspection are supported by the overall ANOVA for each group in the 100-250 ms time window. We ran a “local” ANOVA on the occipital electrodes to analyze the bimodal waveform evident in the grand average (see electrode O2 in Figure 4).

<Insert Figure 4 about here>

For both the Vowel and the Consonant manipulation, the early negative peak (around 150 ms) showed a more negative trend for the Identity condition compared to the other two conditions. The second negative peak (around 200 ms) showed an opposite trend: the Control condition is more negative compared to the Identity, while the Relative position condition is similar to the Control for the Vowel manipulation, and more similar to the Identity for the Consonant manipulation. These occipital effects were evaluated splitting the whole time window into two parts. In fact, we divided the 100-250 ms time window into two consecutive time windows of 75 ms each. Our expectation was to replicate the Letter by Condition interaction in the late time window, but not in the early window. This is exactly what happened: in the early time window only the main effect of Condition emerged ($F(2,52)=11.531$, $p<0.001$); in the late time window we found both a main effect of Condition ($F(2,52)=4.144$, $p<0.05$) and an interaction Letter with Condition ($F(2,52)=3.227$, $p<0.05$). When we included the time Window (Early, Late) as a factor in the ANOVA, a strong interaction of Window by Condition emerged ($F(2,52)=14.599$, $p<0.001$), thus confirming the trend evident in the grand average. To examine this effect, we ran two-way ANOVAs with Electrode (5

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levels: PO7, O1, Oz, O2, PO8) and Condition (two levels) as factors in each time window, comparing in a pairwise manner the conditions for the Consonant and Vowel manipulation (Table 2).

<Insert Table 2 around here>

150-250 ms window (N250)

The N250 effects identified by visual inspection are supported by the “distributed” ANOVA considering all the six condition in the 150-250 ms time window. A main effect of Condition was found (Midline: $F(2,52)=5.020$, $p<0.05$; Column 1: $F(2,52)=4.411$, $p<0.05$; Column 2: $F(2,52)=3.867$, $p<0.05$). Moreover, a significant interaction of Electrode and Condition emerged (Midline: $F(8,208)=5.939$, $p<0.01$; Column 1: $F(4,104)=6.263$, $p<0.01$; Column 2: $F(6,156)=8.94$, $p<0.01$; Column 3: $F(10,260)=7.368$, $p<0.01$). Finally, more crucial for our manipulation, Letter and Condition interacted significantly in all groups (Midline: $F(2,52)=3.764$, $p<0.05$; Column 1: $F(2,52)=3.360$, $p<0.05$; Column 2: $F(2,52)=5.038$, $p<0.05$; Column 3: $F(2,52)=5.249$, $p<0.01$).

Separate planned comparisons for vowels and consonants confirmed the visual inspection evaluation. The Vowel conditions revealed statistical differences between the Identity and the Relative position condition: an effect of Condition was significant in the central areas (Midline: $F(1,26)=7.478$, $p<0.05$; Column 1: $F(1,26)=7.714$, $p<0.05$; Column 2: $F(1,26)=7.217$, $p<0.05$;) and the interaction Electrode with Condition emerged for the more lateral electrodes (Column 2: $F(3,78)=5,138$, $p<0.05$; Column 3: $F(5,130)=4.131$, $p<0.05$). This last interaction is probably due to the more posterior effect for the Identity condition compared to the Relative position condition (see topography of the ERP differences in Figure 5, upper panel).

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<Insert Figure 5 around here>

Also the Identity and the Control conditions differed, as shown by main effect of Condition (Midline: F(1,26)=5.452, p<0.05; Column 1: F(1,26)=4.889, p<0.05) and the interaction Electrode by Condition (Midline: F(4,104)=5.484, p<0.01; Column 1: F(2,52)=5.834, p<0.01; Column 2: F(3,78)=7.596, p<0.01; Column 3: F(5,130)=5.359, p<0.05) that confirms the more anterior effect between these two conditions evident in the grand-average. The Relative position and the Control conditions were not statistically different for the Vowel manipulation (see Figure 5, upper panel).

The Consonant conditions showed statistical differences between the Identity and the Control conditions: a main effect of Condition emerged in the central areas (Midline: F(1,26)=6.376, p<0.05; Column 1: F(1,26)=5.29, p<0.05; Column 2: F(1,26)=5.256, p<0.05), but the interaction Electrode by Condition showed that the effect is mainly posterior (Midline: F(4,104)=5.134, p<0.05; Column 1: F(2,52)=5.891, p<0.05; Column 2: F(3,78)=5.467, p<0.01; Column 3: F(5,130)=7.665, p<0.01) (maps in Figure 5). Comparing the Relative position and the Control conditions a main effect of Condition emerged (Midline: F(1,26)=9.761, p<0.01; Column 1: F(1,26)=6.516, p<0.01; Column 2: F(1,26)=11.386, p<0.01; Column 3: F(1,26)=11.717, p<0.01). The Identity and the Relative position conditions did not statistically differ for the Consonant manipulation.

350-450 Window

Finally, the 350-450 ms time window was selected to evaluate the N400 modulation. The grand average concerning the Vowel manipulation shows a more pronounced negativity both for the Relative position and the Control condition. Interestingly, the visual inspection of the grand average for the Consonant manipulation shows that the N400 for the Relative position condition is markedly reduced, being similar to the Identity condition, particularly at the anterior electrodes (see Figures 3,

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upper panel, and 5, lower panel). The Control condition remains more negative than the Identity.

The overall ANOVAs showed a main effect of Condition (Midline: $F(2,52)=5.205$, $p<0.05$; Column 1: $F(2,52)=7.856$, $p<0.01$; Column 2: $F(2,52)=7.101$, $p<0.01$; Column 3: $F(2,52)=3.892$, $p<0.05$), an interaction Electrode by Condition (Midline: $F(8,208)=2.972$, $p<0.05$; Column 2: $F(6,156)=3.495$, $p<0.05$; Column 3: $F(10,260)=3.466$, $p<0.05$). Moreover, the interaction Letter by Condition (Midline: $F(2,52)=4.374$, $p<0.05$; Column 1: $F(2,52)=4.551$, $p<0.05$; Column 2: $F(2,52)=4.455$, $p<0.05$; Column 3: $F(2,52)=4.201$, $p<0.05$) confirmed the trend evident in the previous time windows.

Planned comparisons for the Vowel manipulation showed a main effect of Condition for the comparison between the Identity and the Relative position conditions (Midline: $F(1,26)=6.580$, $p<0.05$; Column 1: $F(1,26)=9.482$, $p<0.01$; Column 2: $F(1,26)=10.296$, $p<0.01$; Column 3: $F(1,26)=5.922$, $p<0.05$). The comparison between the Identity and Control conditions showed the following interactions: Electrode by Condition (Midline: $F(4,104)=3.84$, $p<0.05$; Column 2: $F(3,78)=5.79$, $p<0.05$; Column 3: $F(5,130)=5.36$, $p<0.05$), Hemisphere by Condition (Column 2: $F(1,26)=4.841$, $p<0.05$) and Electrode by Hemisphere by Condition (Column 3: $F(5,130)=5.097$, $p<0.01$) in the more lateral electrodes. These effects are due to the slightly left-anterior distribution of the N400 (see Identity effect for vowels in Figure 5, lower panel). No reliable effects emerged from the comparison between the Relative position and Control conditions.

The Consonant manipulation in the N400 time window showed a main effect of Condition between the Identity and the Control for all groups (Midline: $F(1,26)=9.273$, $p<0.01$; Column 1: $F(1,26)=12.266$, $p<0.01$; Column 2: $F(1,26)=11.090$, $p<0.01$; Column 3: $F(1,26)=6.986$, $p<0.05$). Similarly, the analyses comparing the Relative position and Control conditions also showed a main effect of Condition for the more central electrodes (Midline: $F(1,26)=5.311$, $p<0.05$; Column 1: $F(1,26)=7.263$, $p<0.05$; Column 2: $F(1,26)=4.589$, $p<0.05$) (see topography of the consonant effects in Figure

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5, lower panel). The analyses comparing the Identity and the Relative position conditions did not show any statistically reliable effects.

Discussion

The present experiment has demonstrated clear evidence of differential processing of consonants and vowels during visual word recognition by showing that the consonant-vowel status of shared letters critically modulates the relative position priming. Overall, we found a very consistent pattern in the data. In the first window (100-175) we found that the identity condition differed from the other two conditions – relative position and unrelated priming conditions– both for consonants and vowels. This result is consistent with previous findings showing that the N/P150 is sensitive to processing at the level of visual features, probably reflecting the mapping of visual features onto letter-level representations (e.g., Carreiras, Gillon-Dowens et al., 2009; Chauncey et al, 2008; Holcomb & Grainger, 2006; Petit et al, 2006). In addition, we found that the N250 (175-250) was sensitive to the consonant-vowel distinction. In this window the amplitude of the relative position priming conditions was similar to the identity condition for consonants and to the unrelated condition for vowels. The two identity conditions also differed from the two unrelated conditions[i]. It seems that from a very early moment of word processing the brain establishes differences between consonants and vowels. Previous results have related the N250 component to orthographic processing (Carreiras et al, 2009; Carreiras, Perea et al, in press; Grainger, Kiyonaga et al, 2006). Thus, these results also provide converging evidence that the N250 reflects processing at the level of form representations. Strikingly, the relative position priming condition for consonants parallels the effects of the identity condition, which seems to suggest that consonants are the main driving force in the process of visual word recognition. Finally, similar effects were again obtained in the N400 component. For consonants, the control condition is more negative than the relative position and the identity conditions; for vowels, the control and the relative position conditions are more negative than the identity condition. Later effects on the N400 are likely to reflect lexical competition processes and/or the mapping of whole-word representations onto semantics (see, Barber, Vergara & Carreiras, 2004; Holcomb & Grainger, 2006; Muller, Duñabeitia & Carreiras, submitted; Carreiras, Vergara & Barber, 2005).

While the N/P150 effect was restricted to the occipital areas, the N250 effect was a more widely-spread distributed ERP negativity. Differences in the topographical distribution add more evidence to the idea that these two components are tapping into two different processes of visual word recognition. While effects in the N/P150 seem to be related to early perceptual processes, effects in the N250 seem to be related to orthographic processes. In fact, Grainger, Kiyonaga et al. (2006) found that transposed-letter primes modulated the ERP signal in a window between 150 and 250 ms after stimuli presentation. More specifically, they presented targets preceded by transposed letter primes (e.g., barin-BRAIN) and their controls (e.g., bosin-BRAIN). Replaced letter controls produced larger amplitude in the 150-250 ms window than transposed letter primes (see also Carreiras et al., 2009; Duñabeitia, et al., in press). Furthermore, one recent study has found evidence for a dissociation in the processing of vowels and consonants in the N250 (Carreiras, Gillon-Dowens, Vergara, & Perea, 2009). In the Carreiras et al. study, an anterior N250 effect was found when manipulating consonants (in a delayed letter paradigm), whereas a posterior effect was found when manipulating vowels. Thus, the differences in the 175-250ms window may reflect a genuine differential computation of consonants and vowels as different objects with different linguistic properties. In fact, some theoretical proposals acknowledge that while the role of consonants is specifically linked to lexical selection, the role of vowels is more related to rhythmic and syntactic patterns (Nespor, Peña & Mehler, 2003; see also, Bonati et al, 2005; 2007). In addition, there is a computational model, the CDP+ model (Perry, Ziegler & Zorzi, 2007), which makes an early distinction between

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consonants and vowels in the input representation to align graphemes to a graphosyllabic template with onset, vowel and coda constituents. Thus, the N250 could be tapping this early processing of consonants and vowels as two different entities, which will have differential influence on later computations during the stream of word processing.

On the other hand, the pattern of data obtained in the N400 window may be a consequence of the differential lexical activation produced by consonants and vowels. Vowel and consonant relative position primes create different lexical activation patterns according to the view that consonant primes are much more constraining than vowel primes. That is, there are far fewer words consistent with the consonant relative position skeleton than with the vowel relative position skeleton, as a consequence of the fact that most languages have a higher number of consonants than vowels. Thus, the observed effect in the N400 component may well be reflecting the lexical constraint provided by the relative position primes. More concretely, consonant relative position primes activate few lexical units, since that consonantal pattern does not match with too many word forms. Importantly, the target word will be one of these candidates, and therefore it is expected that the consonant relative position priming condition activates the target word to a similar extent to the identity priming condition, due to the reduced number of competing lexical representations. For instance, consider the example *farol* used in our experiment; In the Spanish corpus, only 4 different words coincide with the consonantal pattern -f-r-l- (the target *farol*, and the competing lexical representations *farola*, *foral* and *férula*). In contrast, vowel relative position primes activate many lexical units and, once those lexical units start competing with one another, there is little priming effect to be had on the actual target recognition. For instance, taking the word *acero* as an example, the pattern -a-e-o- is found to be present in more than 150 Spanish words (the target *acero*, but also *asesor*, *cajero*, *alero*, *casero*, *granero*, …), thus yielding higher values of global lexical activation and competition than the consonantal patterns. Therefore, the results of the low constraint and/or high

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competition of the relative position priming for vowels do not favor the recognition of the target, as happens with the vowel unrelated condition.

Thus, from a very early moment in the process of visual word recognition the brain uses a system that allows for coding the relative position of letters which is mainly based on consonants, since this code is good enough to trigger the whole word representation. It seems to be as good for consonants as the complete string of letters. However, this is not the case for vowels. The information contained in vowels is not as valuable as that contained in consonants in accessing words, considering the high lexical activation dispersion that vowel-based skeletons lead to. These results challenge one important assumption of most models of visual word recognition in alphabetic orthographies about how the human processing system encodes letter positions when creating internal orthographic representations, that is, that all letters are encoded in a similar fashion at early stages of orthographic processing, independently of their consonant-vowel status. The basic conclusion from this study is that not only are the identity and position of a character in a string of letters different perceptual dimensions, but consonants and vowels are also two different objects with differentiated roles in the processes of visual word recognition. Present models of orthographic encoding are unable to explain these findings in their current form. None of the "classical" computational models of visual word recognition or the "recent" ones that incorporate a difference between letter position and letter identity (e.g., Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Davis, 1999; Dehaene, Cohen, Sigman, & Vinckier, 2005; Gomez, Ratcliff, & Perea, 2007; Grainger & Jacobs, 1996; Grainger & van Heuven, 2003; McClelland & Rumelhart, 1981; Whitney, 2001) can account for differential processing of consonants and vowels. One noticeable exception, however, is the recent CDP+ model (Perry, Ziegler & Zorzi, 2007), which makes an early distinction between consonants and vowel in the input representation to align graphemes to a graphosyllabic template with onset, vowel and coda constituents. Hence, in the CDP+ model the consonant-vowel differentiation is a basic assumption

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that underlies the ortho-phonological encoding of the input units. However, it has to be mentioned that this model in its current version has not been tested with a large pool of masked priming lexical decision data, since its major focus is on reading aloud. Future research should be aimed at exploring the validity of this model in terms of the most influential orthographic effects (e.g., form priming, transposed-letter priming or relative position priming, among others).

It could be argued, however, that the differences reported between vowels and consonants in relative position priming effects do not pose a problem for the computational models, because the reason for the difference could simply be letter frequency: vowels are more frequent than consonants. Much evidence supports the idea that perceptual systems become selectively efficient at processing input that is encountered frequently. Thus, if the consonant/vowels processing difference could be accounted for by just letter frequency, any of the current models could easily account for the present results. However, Duñabeitia and Carreiras (submitted) tested whether the consonant-vowel differentiation could be a consequence of the frequencies of the letters and ruled out a purely frequency account. When they presented primes that contained only vowels, only high frequency consonant or only low frequency consonants, they found a significant relative position priming effect of the same size for the two consonant conditions but no effects for vowel primes. Thus, it is quite unlikely that the differences observed in the present experiment which mirrors the pattern obtained by Duñabeitia and Carreiras (submitted) could be reduced to a letter frequency effect. However, it remains to be seen whether other frequency accounts such as the co-occurrence of letters can account for the observed differences between consonants and vowels. In any case, we should also acknowledged that a complete reduction of processing differences between consonants and vowels to computation of statistical regularities has been advocated as quite unlikely in speech segmentation (Bonatti et al, 2007). While consonants have a prominent role in word identification, vowels have a prominent role in rule extraction. Using artificial speech streams in which

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words and rules were implemented over either consonants or vowels, Toro et al (2008) showed that participants identified words by computing statistical dependencies among consonants, but failed to do so when vowels carried the same dependencies. In contrast, participants extracted simple structural generalizations when vowels instantiate them, but failed to do so when they were instantiated by consonants.

Finally, one important finding that deserves attention is the null difference found between the consonant relative position priming condition and the identity priming condition (namely, the similar ERP effects in the N250 and N400 components for frl-farol and farol-farol). Consonant relative position primes elicited an N250 and N400 of similar amplitude to the identity condition, while vowel relative position primes produced an N250 and N400 effects of similar amplitude to the unrelated condition. In spite of the undeniable importance of the consonant-vowel distinction in the relative position priming effect for current models of word recognition and orthographic encoding, the negligible difference between the consonant relative position and identity conditions provides interesting insights about the way in which the visual word recognition system extracts the key information of words (i.e., letter identities). The most plausible interpretation of these findings derives from the lexical constraint imposed by consonants. Considering that consonants are much more constraining than vowels for word recognition (due to the higher number of consonants as compared to the typically limited number of vowels), and according to the view that consonants have a more marked role in orthographic processing that vowels, it could be assumed that when a string is briefly presented (for around 50 ms), the visual word recognition system only extracts basic features of this string to be processed, mainly focusing on consonants. If this is so, it is feasible to assume that for both identical (farol) and relative position consonant primes (frl), the orthographic processor might be fired, extracting the same amount of information (f-r-l and frl, respectively). In the case of identity primes in the vowel condition (acero), the same mechanism would only lead to the identification of the consonants from the identity condition (-c-r-). However, in the case of the vowel

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relative position priming there is no consonantal information to be extracted from the input. Therefore, a much larger number of possible candidates compatible with the three vowels (aeo) input will be activated. Accordingly, a reasonable number of possible lexical candidates that fit with these extracted patterns would then be activated only in the case of the two identity conditions and the consonant relative position condition and the appearance of the target words would fire a matching procedure, based on classical candidate suppression mechanisms (e.g., lateral inhibition processes), that would finally lead to the correct lexical candidate selection. Such a mechanism of orthographic processing based on consonant detection would account for both for the null difference between absolute and relative position priming conditions (f-r-l and frl from farol) that has previously been reported (Grainger, Granier et al., 2006) and for the effects observed in the present study. This mechanism predicts no differences between the consonant relative position and identity priming conditions, while clear differences are to be expected between vowel relative position and identity priming conditions, both at early orthographic encoding stages (reflected in the N250 component) and in later lexico-semantic processing stages (as shown in the N400 component).

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Conclusion

The empirical data on two phenomena –transposed-letter and relative position priming– have given rise to the general consensus that there is a level of orthographic processing where some form of approximate, flexible coding of letter positions operates. How is letter position information coded during the earliest phases of visual word recognition? It is assumed that individual letters are the key elements for orthographic processing and that the mechanism used to code for the positions of these letters is what critically determines the nature of the orthographic code. Here we show that letter position assignment is modulated by whether the letter is a consonant or a vowel. The results reported here for ERPs, which are very sensitive to the time course of early processing in the visual word recognition system, suggest that consonants seem to trigger the coding, but vowels do not, or at least not to the same extent. Consonant and vowels seem to be distinctive elements in the initial stages of visual word recognition and they seem to trigger different patterns of activation in the lexicon, as shown by their differential effects on a series of ERP components which reflect a cascade of processes triggered on presentation of a printed word and which are sensitive to form representations (N250) and lexico-semantic representations (N400). These results challenge one important assumption of most models of visual word recognition in alphabetic orthographies about how the human processing system encodes letter positions when creating internal orthographic representations. These consonant/vowel differences should be taken into consideration when developing computational models of visual word recognition.

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References

Allen P A, Wallace B, & Weber T A. 1995. Influence of case type, word frequency, and exposure duration on visual word recognition. J. Exp. Psych: Hum. Percep. Perform. 21, 914-934.

Barber H, Kutas M. 2007. Interplay between computational models and cognitive electrophysiology in visual word recognition. Brain Res. Rev. 53, 98-123

Barber H, Vergara M, Carreiras M. 2004. Syllable-frequency effects in visual word recognition: evidence from ERPs, Neuroreport, 15, 545-548

Berent I, Perfetti CA. 1995. A rose is a REEZ: The two cycles model of phonology assembly in reading English. Psychol Rev 102, 146-184.

Bonatti L L, Peña M, Nespor M, Mehler J. 2005. Linguistic constraints on statistical computations: The role of consonants and vowels in continuous speech processing. Psychol. Science, 16, 451-459

Bonatti LL, Peña M, Nespor M, Mehler J. 2007. On consonants, vowels, chickens, and eggs. Psychol. Science, 18, 924–925.

Caramazza A, Chialant D, Capasso D, Miceli G. 2000. Separable processing of consonants and vowels. Nature, 403, 428-430.

Carreiras M, Gillon-Dowens M, Vergara M, Perea M. 2009. Are vowels and consonants processed differently? ERP evidence with a delayed letter paradigm. J. Cogn. Neurosc. 21, 275-288.

Carreiras M, Price C J. 2008. Brain activation for consonants and vowels. Cer. Cortex, 18, 1727-1735.

Carreiras M, Vergara M, Barber H. 2005. Early ERP effects of syllabic processing during visual word recognition. J. Cogn. Neurosc. 17, 1803-1817.

Carreiras M, Vergara M, Perea M. 2007. ERP correlates of transposed-letter similarity effects: Are consonants processed differently from vowels? Neurosc. Letters, 419, 219-224.

Carreiras M, Vergara M, Perea M. 2009. ERP correlates of transposed-letter priming effects: The role of vowels vs. consonants. Psychophysiology,46, 34-42. DOI: 10.1111/j.1469-8986.2008.00725.x

Carreiras M, Perea M, Vergara M, Pollatsek A. In press. The time course of orthography and phonology: ERP correlates of masked priming effects in Spanish.

Cattell J M. 1886. The time taken by cerebral operations. Mind. 11, 220-242.

Chauncey K. Holcomb P J, Grainger J. 2008. Effects of stimulus font and size on masked repetition priming: An ERP investigation. Lang. Cogn. Proc. 23, 183-200.

Coltheart M, Rastle K, Perry C, Ziegler J, Langdon R. 2001. DRC: A Dual-Route Cascaded model of visual word recognition and reading aloud. Psychol.Rev. 108, 204-256.

Cutler A, Sebastián-Gallés N, Soler-Vilageliu O, van Ooijen B. 2000. Constraints of vowels and consonants on lexical selection: Cross-linguistic comparisons. Mem. Cogn. 28, 746-755.

Davis C J. 1999. The Self-Organising Lexical Acquisition and Recognition (SOLAR) model of visual word recognition. Unpublished doctoral dissertation, University of New South Wales.

Davis C J, Perea M. 2005. BuscaPalabras: A program for deriving orthographic and phonological neighborhood statistics and other psycholinguistic indices in Spanish. Beh. Res. Methods, 37, 665-671.

Dehaene S, Cohen L, Sigman M, Vinckier, F. (2005). The neural code for written words: a proposal. Trends Cogn. Scien., 9, 335-341.

Duñabeitia J A, Carreiras M. Submitted. The relative position priming effect depends on whether letters are vowels or consonants.

Duñabeitia J A, Perea M, Carreiras M. 2007. Do transposed-letter similarity effects occur at a morpheme level? Evidence for morpho-orthographic decomposition. Cognition, 105(3), 691-703.

Duñabeitia JA, Molinaro N, Laka I, Estévez A, & Carreiras M. (in press). N250 effects for letter transpositions depend on lexicality: Casual or causal? NeuroReport

Forster K I. 1976. Acessing the mental lexicon. In RJ Wales & EW Walker (Eds.) New approaches to language mechanisms (pp.257-287). Amsterdam. North Holland.

Gomez P, Ratcliff R, Perea M. In press. The overlap model: A model of letter position coding. Psychol. Rev.

Grainger J. 2008. Cracking the orthographic code: An introduction. Lang. Cogn. Proces. 23(1), 1-35.

Grainger J, Jacobs A M. 1996 Orthographic processing in visual word recognition: A multiple read-out model. Psychol. Rev. 103, 518-565.

Grainger J, Kiyonaga K, Holcomb P J. 2006. The time-course of orthographic and phonological code activation. Psychol. Science, 17, 1021-1026.

Grainger J, Granier J P, Farioli F, Van Assche E, van Heuven W. 2006. Letter position information and printed word perception: The relative-position priming constraint. J. Exp. Psychol: Hum. Percep. Perform. 32, 865-884.

Grainger J, van Heuven W J B. 2003. Modeling setter position coding in printed word perception. In P. Bonin (Ed.), The mental lexicon (pp. 1–23). New York: Nova Science.

For Peer Review

Greenhouse S, Geisser S. 1959. On methods in the analysis of profile data. Psychometrica, 24, 94-112.

Healy A F, & Cunningham T F. 1992. A developmental evaluation of the role of word shape in word recognition. Mem. Cog. 20, 141-150.

Healy A F, Oliver W L, & McNamara T P. 1987. Detecting letters in continuous text: Effects of display size. J. Exp. Psych.: Hum. Percept. Perform. 13, 279-290.

Holcomb P J, Grainger J. 2006. On the time course of visual word recognition: an event-related potential investigation using masked repetition priming. J. Cogn. Neurosc. 18, 1631–1643.

Holcomb P J, Grainger J, O'Rourke T. 2002. An Electrophysiological study of the effects of orthographic neighborhood size on printed word perception. J. Cogn. Neurosc. 14, 938-950

Humphreys G W, Evett L J, Quinlan P T. 1990. Orthographic processing in visual word identification. Cogn. Psychol. 22, 517-560.

Kutas M, Federmeier K. 2000. Electrophysiology reveals semantic memory use in language comprehension. Trends in Cogn. Scienc. 4, 463-470.

Lee H-W, Rayner K, Pollatsek A. 2002. The processing of consonants and vowels in reading: Evidence from the fast priming paradigm. Psych. Bull. Rev. 9, 766-772.

McClelland J L, Rumelhart D E. 1981. An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. Psychol. Rev. 88, 375-407.

Muller O, Duñabeitia J A, Carreiras M. Submitted. Orthographic and associative neighborhood density effects: What is shared, what is different?

Nazzi T. 2005. Use of phonetic specificity during the acquisition of new words: differences between consonants and vowels. Cognition, 98, 13-30.

Nespor M, Peña M, Mehler J. 2003. On the different roles of vowels and consonants in speech processing and language acquisition. Lingue e Linguaggio, 2, 221–247.

Neville H J, Mills D L, Lawson D S. 1992. Fractionating language: different neural subsystems with different sensitive periods. Cer. Cortex, 2, 244–258.

Oldfield R C. 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia, 9, 97-113.

Paap K R, Newsome S L, McDonald J E, Schvaneveldt R W. 1982. An activation-verification model for letter and word recognition: The word superiority effect. Psychol. Rev. 89, 573-594.

Pelli D G, Farell B, Moore D C. 2003. The remarkable inefficiency of word recognition. Nature, 423, 752-756.

For Peer Review

Peña M, Bonatti L L, Nespor M, Mehler J. 2002. Signal-driven computations in speech processing. Science, 298, 604–607.

Perea M, Carreiras M. 2006a. Do transposed-letter similarity effects occur at a syllable level? Exp. Psychol. 53, 308-315.

Perea M, Carreiras M. 2006b. Do transposed-letter effects occur across lexeme boundaries? Psych. Bull. Rev. 13, 418-422.

Perea M, Carreiras M. 2006c. Do transposed-letter similarity effects occur at a prelexical phonological level? Quart. J. Exp. Psychol, 59, 1600-1613

Perea M, Carreiras M. 2008. Do orthotactics and phonology constrain the transposed-letter effect? Lang. Cogn. Proc. 23, 69-92.

Perea M, Duñabeitia J A, Carreiras M. 2008. Transposed-letter priming effects for close versus distant transpositions. Exp. Psychol. 55, 397-406.

Perea M, Lupker S J. 2003. Does jugde activate COURT? Transposed-letter similarity effects in masked associative priming. Mem. Cogn. 31, 829-841.

Perea M, Lupker S J. 2004. Can *CANISO* activate *CASINO*? Transposed-letter similarity effects with nonadjacent letter positions. J. Mem. Lang. 51, 231-246.

Peressotti F, Grainger J. 1999. Letter position coding in random consonant arrays. Percep. Psychoph. 57, 875-890.

Perry C, Ziegler J C, Zorzi M. 2007. Nested incremental modeling in the development of computational theories: the CDP+ model of reading aloud. Psychol. Rev. 114, 273-315.

Petit J P, Midgley K J, Holcomb P J, & Grainger J. 2006. On the time course of letter perception: A masked priming ERP investigation. Psychonomic Bulletin & Review. 13, 674-681

Sebastián-Gallés N, Martí M A, Carreiras M, Cuetos F. 2000. Lexesp: una base de datos informatizada del español. Universitat de Barcelona, Spain.

Toro JM, Nepor M, Mehler J, Bonatti L L. 2008. Finding words and rules in a speech stream. Psychol. Science, 19, 137-144

van Casteren M, Davis M H. 2007. Match: a program to assist in matching the conditions of factorial experiments. Beh. Res. Methods, 39(4), 973-978.

van Ooijen B. 1996. Vowel mutability and lexical selection in English: Evidence from a word reconstruction task. Mem Cogn 24: 573–583.

Vinckier F, Dehaene S, Jobert A, Dubus J P, Sigman M, Cohen L. 2007. Hierarchical coding of letter strings in the ventral stream: dissecting the inner organization of the visual word-form system. Neuron, 55, 143-156.

Whitney C. 2001. How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. Psycho. Bull. Rev. 8, 221-243.

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Author's notes

This research was partially supported by grants from the Spanish Ministry of Education and Science SEJ2006-09238 and CONSOLIDER-INGENIO 2010 (CSD2008-00048).

Correspondence concerning this paper should be sent to Manuel Carreiras. Basque Center on Cognition Brain and Language. Paseo Mikeletegi 53. 20009-Donostia-San Sebastián. (Spain) (e-mail: m.carreiras@bcbl.eu; mcarreir@ull.es) (url: www.bcbl.eu; www.neurocog.ull.es)

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Table 1. Characteristics of the materials used in the experiment. Mean (M) frequency, length and N values are provided with the standard deviation (SD, within parentheses) and ranges.

	Frequency		**Length**		**N**	
	Mean (SD)	Range	Mean(SD)	Range	Mean(SD)	Range
Consonants *(farol)*	17.97 (28.84)	0-201	5.36 (0.48)	5-6	2.27 (2.15)	0-8
Vowels *(acero)*	14.23 (29.24)	0-204	5.57 (0.50)	5-6	1.51 (1.66)	0-11

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Table 2. F values for the Condition factor (two levels, see Comparison column) and the Electrode (five levels: PO7, O1, Oz, O2, PO8) by Condition interaction for the ANOVA performed in the occipital electrodes in the early (100-175 ms) and late (175-250 ms) time windows corresponding to the negative deflection evident on the posterior electrodes in the grand-average.

Manipulation	***Time window (milliseconds)***	***Comparison***	***Condition df (1,26)***	***Electrode x Condition df (4,104)***
Vowel	100-175	Identity vs. Relative	6.164*	5.409**
		Identity vs. Control	12.485**	2.499#
		Relative vs. Control	1.548ns	1.626ns
	175-250	Identity vs. Relative	4.004*	0.454ns
		Identity vs. Control	3.573*	1.217ns
		Relative vs. Control	0.100ns	0.383ns
Consonant	100-175	Identity vs. Relative	14.045**	5.487*
		Identity vs. Control	5.568*	6.717**
		Relative vs. Control	1.096ns	0.527ns
	175-250	Identity vs. Relative	0.218ns	0.348ns
		Identity vs. Control	4.919*	0.522ns
		Relative vs. Control	9.071**	0.333ns

*ns not significant; # (p<0.1); * (p<0.05); ** (p<0.01)*

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Figure captions

Figure 1. Schematic representation of each experimental trial.

Figure 2. Schematic flat representation of the 32 electrode positions from which EEG activity was recorded (front of head is at top). Scheme of the "distributed" analysis is expressed here by different styled lines.

Figure 3. ERP waves corresponding to the identity, relative position and unrelated conditions for consonants (upper panel) and vowels (lower panel). Negative voltages are plotted up.

Figure 4. ERP effects in the electrode O2 for the consonant (upper panel) and vowel (lower panel) manipulation. The N/P150 and the N250 modulations visible in the occipital electrodes are evident here.

Figure 5. Topographical maps of both the N250 (upper panel) and the N400 (lower panel) effects elicited by the identity (control-identity) and relative position (control-relative) conditions compared to the control condition for the consonants and vowels manipulations. Differential effects are calculated between 200 and 230 msfor the N250 and between 350 and 450 for the N400, i.e. at the peak of the effect.

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Footnotes

[i] The identity and the control conditions did not contain the same number of letters in the present experiment, since identity was designed as a control condition. This fact, together with important differences in the experimental procedures (e.g., the use/absence of a backward mask, different size of prime and target stimuli) may account for the slightly different results obtained in Holcomb and Grainger (2006) and in the present experiment when contrasting identity and control conditions. The effects are more limited in spatial extent and arise slightly earlier in the present experiment.

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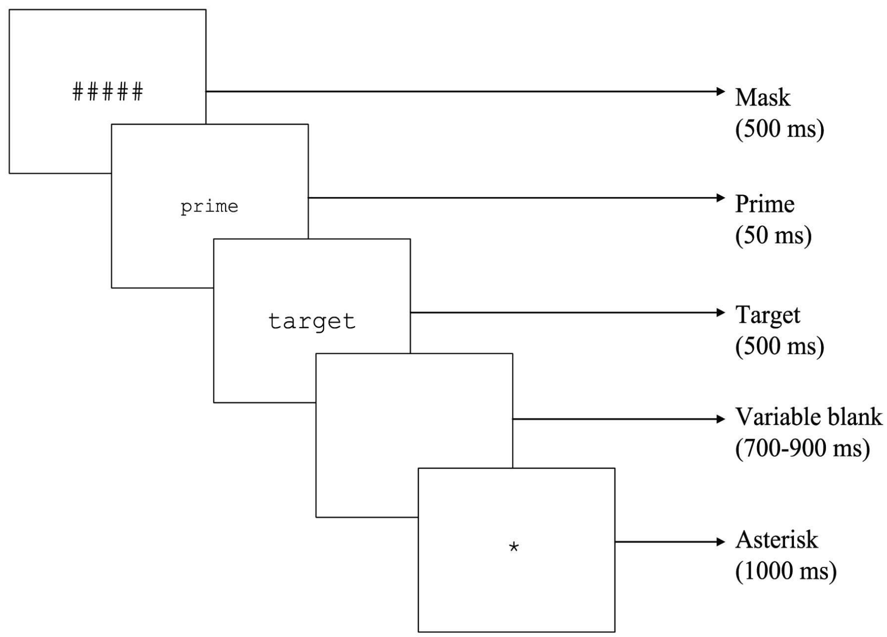

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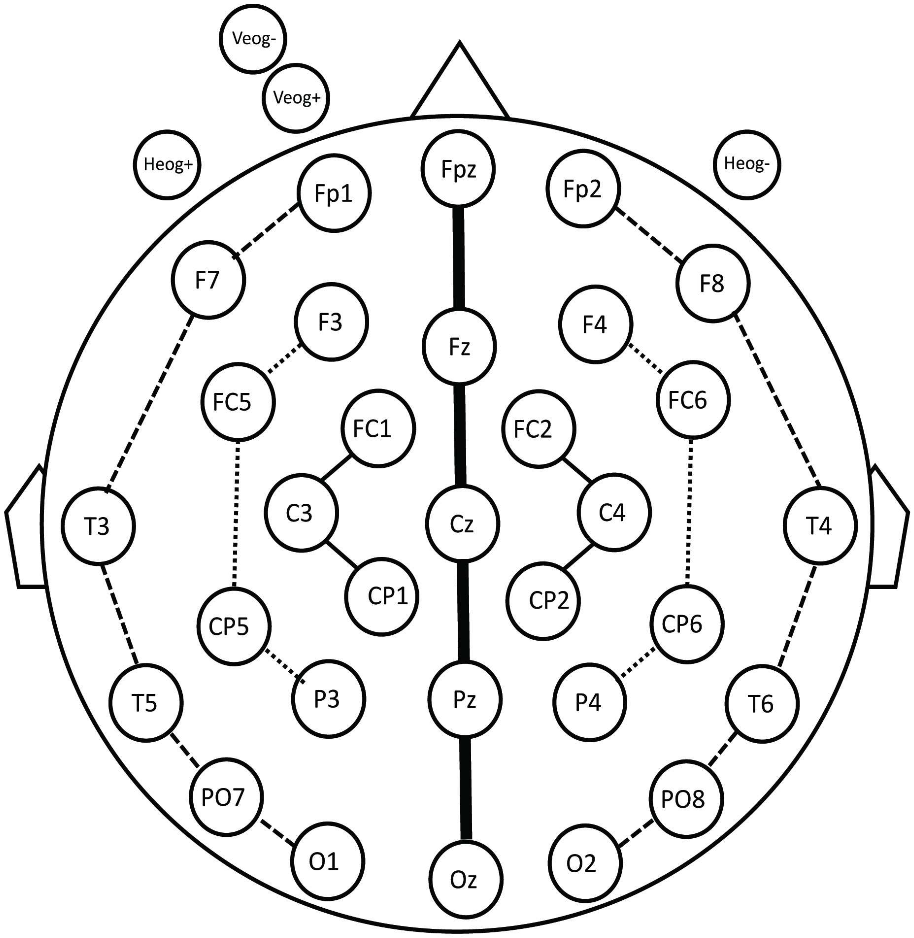

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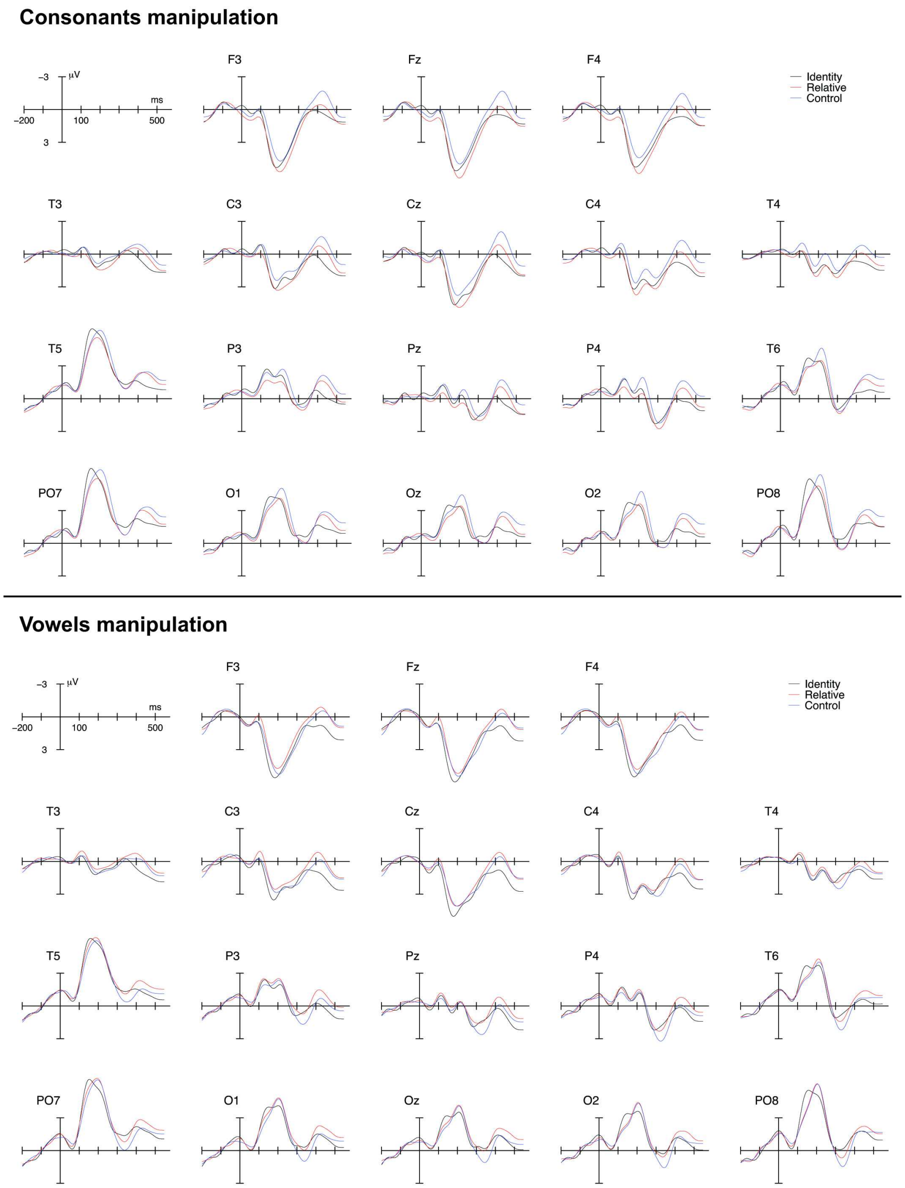

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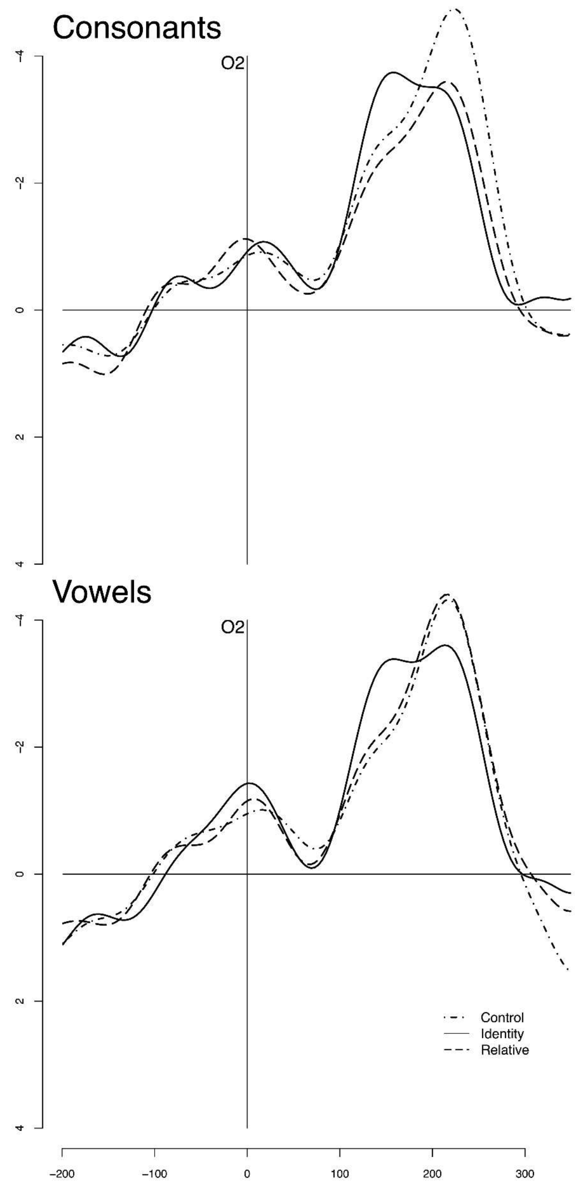

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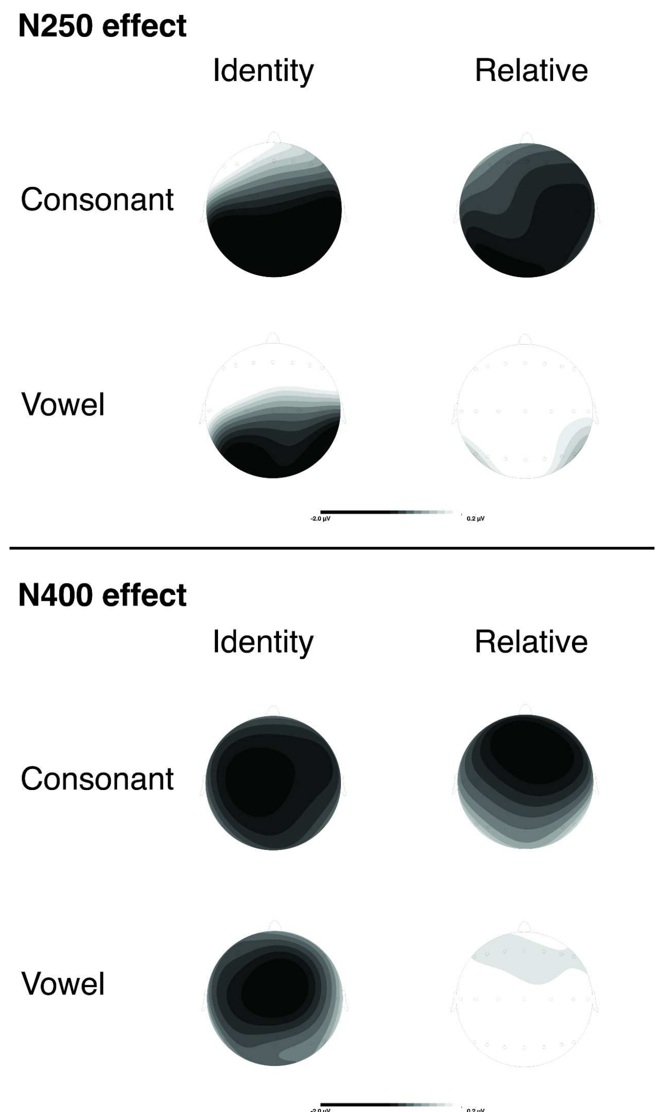

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