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Research report

Semantic processing of open- and closed-class words: an event-related potentials study

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Abstract

Previous research on open- and closed-class words has revealed the existence of several differences in the processing of these types of vocabulary. In this paper the processing of open- and closed-class words was compared by means of an early electrical brain response, recognition potential (RP), which indexes semantic processing and originates from basal extrastriate areas. The effects of word frequency on closed-class words were also investigated. For these purposes, open- and closed-class words, among other stimuli, were presented by means of the rapid stream stimulation procedure. Results showed that there were no significant differences when comparing the RP evoked by open- and closed-class words in the left hemisphere. However, in the right hemisphere this situation changed: the RP evoked by open- and closed-class words did differ. Moreover, there were no differences between the RP evoked by closed-class words and pseudowords. These patterns of results suggest that the semantic processing of closed-class words shares some aspects with the processing of open-class words, despite the existence of some differences. Thus, whereas the semantic processing of open-class words recruits brain areas of both hemispheres, the semantic processing of closed-class words is left-lateralized. A second purpose of this work is to study word-frequency effects on closed-class words. Our results show the insensitivity of closed-class words to word-frequency effects.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: Event-related potential; Recognition potential; Open-class word; Closed-class word; Semantic processing

1. Introduction

Linguistics distinguishes basically between two major vocabulary classes, open-class/content and closed-class/function words. The former class refers to all those words that carry the meaning in language, such as nouns, verbs, adjectives, and so on. Open-class words are constantly being increased by the addition of new words. On the other hand, closed-class words include those words preferentially subserving structural functions that provide information on the syntactic relations that exist among open-class words. They are supposed to be relatively devoid of meaning, and new members are rarely incorporated into vocabulary. Typical elements of closed-class vocabulary are prepositions, conjunctions, pronouns, determiners, etc. Roughly speaking, the two vocabulary classes reflect the distinction between semantics and syntax [16].

It is commonly assumed that open- and closed-class words are accessed by different and dissociable mechanisms, and may even belong to separate sub-lexicons [47]. Basically, it has been argued that closed-class words are accessed by a specialized route that is insensitive to meaning because it is only involved in syntactic processes such as the assignment of phrase structure [6]. The main evidence supporting these assertions comes from studies dealing with the effects of word frequency on the process-

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ing of open- and closed-class words. Presenting words in isolation, Bradley et al. [5] reported a frequency effect for open-class words during a lexical decision task, that is, more frequent words were identified quicker, whereas this effect was absent in the case of closed-class words. Similar findings have been reported with Spanish words [14]. However, several authors have failed to replicate this differential sensitivity to word frequency [12,18,28].

The situation is different when open- and closed-class words are presented in the context of a sentence. The results of these experiments are more consistent, and support the existence of processing differences between these two vocabulary types [8,22,23,54]. It has been argued that the contradiction between the results reported in the experiments presenting open- and closed-class words in isolation and those presenting them in a sentence suggests that the effect of vocabulary type is related to the actual functional role of the open- and closed-class words during sentence processing, rather than to a possible difference in the specific retrieval mechanisms associated with the two classes of word [8].

Another source of evidence supporting the word-class distinction is aphasia and dyslexia research, which has demonstrated that the use of open- and closed-class words during language processing can be selectively disrupted. Whereas anomic aphasics are selectively impaired in the production of open-class words, while the production of closed-class words is relatively preserved, agrammatic aphasics show the opposite pattern of a closed-class words deficit [3,11,39,46,52]. Similarly, patients with surface dyslexia have difficulty when reading open-class words, whereas patients with phonological and deep dyslexia show a profound inability to read closed-class words [42,48–50]. All of these findings suggest that different brain structures and mechanisms underlie the processing of open- and closed-class words.

Some event-related potentials (ERPs) investigations have been concerned with the search for brain responses that constitute specific signatures of the processing of either open- or closed-class words, with a view to validating the distinction postulated by psycholinguistics. The results of these studies are controversial. Neville et al. [31] reported a frontal negativity evoked only by closed-class words over left anterior electrode sites that peaked at about 280 ms after stimulus presentation. They took this response as an index of the existence of specific mechanisms dealing with the processing of closed-class words. However, it has been claimed that some variables, such as word frequency or word length, seemed to be confused with word class in Neville et al.'s experiment, as several researchers have found a similar N280-like negativity evoked by open-class words in the time window ranging between 250 and 350 ms [21,33,38,39]. Some differences exist, nevertheless, between the early anterior negativity evoked by open- and closed-class words. Two recent experiments found that this negativity showed a delayed latency in the case of open-class as compared to closed-class words that could not be attributed to frequency or length effects [4,52]. These authors interpreted these differences as a result of the earlier availability of the lexical-categorical information associated with closed-class words.

Several differences between the two vocabulary classes have also been reported in the N400 component, an ERP response related to semantic processing that seems to specifically reflect post-lexical aspects dealing with the integration of word representations in the current context of a sentence [10,37,55]. Closed-class words tend to elicit lower-amplitude N400 as compared to open-class words [15,31,34,38,42,52], though this was not always found to be the case [54].

Finally, closed-class words elicit a broad frontal negativity shift in the time window ranging between 350 and 700 ms that is absent for open-class words [4,21,31,38,52,54]. This negativity might reflect anticipatory processes associated with the role of closed-class words in sentence parsing [54]. Also proposed has been a more general expectation process reflecting the fact that the most likely word to follow a closed-class is an open-class word [4,52]. The existence of differences in the engagement of the left and right hemispheres during the processing of open- and closed-class words is a well-documented finding in ERP research. Pulvermüller and collaborators [42] found that open-class, on comparison with closed-class words, showed a similar response around perisylvian regions of the left hemisphere, whereas the response to each class of words differed in the right hemisphere. Open-class words elicited larger negativities compared to closed-class words in posterior brain areas of the right hemisphere in the time-window ranging from 160 to 300 ms. On the basis of their data and Hebb's concept of cell assemblies [19], these authors have proposed a model of processing for open- and closed-class words. Basically, in their model the processing of open-class words engages neuronal assemblies equally distributed over the two hemispheres, whereas assemblies corresponding to the processing of closed-class words are lateralized to the perisylvian regions of the left hemisphere [39–42]. This model receives some support from recent fMRI data revealing that semantic processing leads to a more bilaterally distributed activation as compared to syntactic processing [32].

In this study we aim to examine the processing of open- and closed-class words by means of an electrophysiological response, recognition potential (RP), that reflects semantic processing [25,26]. RP is a negative response that peaks at around 250 ms after stimulus onset and indexes semantic processing, since it shows a larger amplitude in response to meaningful stimuli as compared to others devoid of meaning, including pseudowords and strings of random letters [25]. RP neural generators are placed within the basal temporal fusiform/lingual cortices [20,26], an area that is particularly involved in the processing of visual-semantic information [30,51,53]. The main purpose of the present experiment is to compare the processing of open- and closed-class words in some of those brain regions involved in the processing of semantic information. We expect to find a notably larger RP response evoked by open-class as compared to closed-class words, since the latter word class is assumed to have less semantic content than the former. A greater involvement of the left hemisphere in the processing of closed-class words might also be hypothesized, as closed-class words are mainly processed by this hemisphere [39–42]. An additional goal of this experiment is to examine how the frequency of word usage affects closed-class words. Most ERP research dealing with word class and frequency effects has demonstrated the sensitivity to word frequency of both open- and closed-class words in some ERP responses such as N280 negativity or N400 [21,38,54]. In the particular case of RP, Rudell [44] demonstrated the sensitivity of RP latency to word frequency in open-class words. He found that more frequently-used open-class words evoked earlier RP latencies. However, the question of whether frequency affects the RP evoked by closed-class words remains unexplored. We aim to clarify this matter by means of comparing the RP evoked by two sets of closed-class words with different levels of word frequency.

2. Methods and materials

2.1. Subjects

Twenty native Spanish speakers (seven women), ranging in age from 20 to 27 (mean 23.7) years, participated in the experiment as volunteers. All were right-handed, with average handedness scores of +0.79, ranging from +0.43 to +0.100 according to the Edinburgh Handedness Inventory [36]. All participants had normal or corrected-to-normal vision. Subjects were paid for their participation in the experiment.

2.2. Stimuli

Blocks of animal names, open-class words, closed-class words, pseudowords, strings of random letters, controls and background stimuli. Each block comprised 20 stimuli, with the exception of the background block, which contained 40 elements.

The animal names block constituted the target stimuli, and was included with the purpose of providing subjects with an active lexical decision task in order to sustain their attention. It contained 15 two- and five three-syllable common Spanish animal names. The open- and closed-class blocks, which constituted the main object of the present experiment, were matched in length and word frequency. The former block comprised 15 two-syllable and five three-syllable Spanish nouns, while the latter included 15 two-syllable and five three-syllable Spanish conjunctions. According to the Alameda and Cuetos [1] dictionary of word frequencies for Spanish, the two blocks were of comparable usage frequency (mean 1314 for open-class words, 1850 for closed-class words, $t_{19}=1.3$, $P>0.1$). We decided to limit our open- and closed-class blocks to nouns and conjunctions, respectively, in order to avoid comparisons within each vocabulary type, since some studies have found subtle differences between certain types of both open-class (e.g. Ref. [40]) and closed-class words (e.g. Ref. [4]). The words included in the animal names, open-class words and closed class-words blocks are shown in Appendix A, together with their English translations.

The closed-class block was further divided into two sub-blocks, with the purpose of studying word-frequency effects on closed-class words. The high-frequency closed-class words sub-block included the ten conjunctions with a frequency above the median, while the low-frequency closed-class words sub-block included the ten conjunctions that were below the frequency median. This resulted in two sub-blocks differing in their mean frequency of usage (frequency means 3075 and 625, respectively, $t_{18}=3.7$, $P<0.005$).

The pseudowords block included 15 two- and five three-syllable pseudowords selected from a previous study with a Spanish population [14]. They followed Spanish orthographical and phonological rules but were devoid of meaning.

The strings of random letters block also consisted of non-words, but these follow neither orthographic nor phonological Spanish rules. Special care was taken to obtain string lengths resembling those in the closed-class words and open-class words blocks in terms of number of letters. These non-words were created by randomizing the letters of the animal names.

The control stimuli were made by cutting the words included in the animal names block into ‘n’ portions (‘n’ being the number of letters that formed a word, minus one). These portions were repositioned following the same rules every time: the last piece of the word was placed in the first position of the new stimulus, and vice versa; the penultimate portion was placed in the second position, and vice versa; and so on. Each stimulus made by this method had at least two complete letters, but also clearly identifiable non-letters (formed by the fusion of different letter fragments).

Finally, the background stimuli block was composed of the same 20 control stimuli together with a new set of 20 stimuli made in an identical way to the control stimuli, except that portions were replaced randomly. Examples of each type of stimulus are displayed in Fig. 1.

All stimuli were matched in visual aspects. They were 1.3 cm in height and 3.5 cm in width. Subjects’ eyes were 65 cm from the screen. At this distance images were 1.14° high and 3° wide in their visual angle. Stimuli were

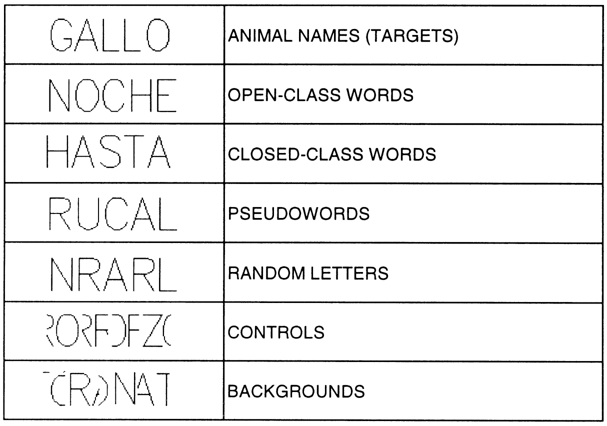

Fig. 1. Examples of the stimuli presented to subjects.

presented white-on-black on an NEC computer MultiSync monitor, controlled by the Gentask module of the STIM package (NeuroScan Inc.).

2.3. Procedure

Stimuli were presented according to the rapid stream stimulation procedure [43] with a stimulus onset asynchrony (SOA) of 257 ms. This procedure greatly attenuates ERP responses other than RP. Stimulation was organized in sequences. In each of these sequences the computer displayed mostly background stimuli, and after six or seven of these stimuli (this number being randomized) a test stimulus was presented. Test stimuli included animal names, open-class words, closed-class words, pseudowords, strings of random letters and controls.

An experimental session consisted of 16 sequences of stimuli with a duration of about 1 min each. Two practice sequences were carried out before the experiment began. A sequence started with six or seven background stimuli, followed by the first test stimulus. A sequence included 30 test stimuli: five animal names, five open-class words, five closed-class words, five pseudowords, five strings of random letters, and five control stimuli, together with the proportional amount of background stimuli. A random process determined the type of test stimuli applied, with the constraint of no more than two of the same type occurring consecutively. Accordingly, each type of test stimulus appeared four times during the experimental session, and was never repeated within the same sequence.

Subjects were instructed to press a button as fast as possible every time they detected an animal name. They were also informed of the payment schedule. A response between 550 and 800 ms after an animal name appeared was considered a hit that earned 5 points. Responses made between 300 and 500 ms were considered fast responses and earned 10 points. A 25-point penalty was imposed for responding to stimuli other than animal names or for premature responses, occurring before 300 ms after an animal name. The points were exchanged for the corresponding amount of money at the end of the session. The payment schedule was intended to encourage a low error rate, produce a high percentage of correctly-detected words, and provide an incentive for rapid responses [25,45]. At the beginning of each sequence subjects had to push the button and a message appeared on the screen telling them they could blink as much as they wanted in order to avoid blinking during stimulus presentation, and to push again to begin the sequence. When a sequence was over, subjects were provided with feedback about their performance.

2.4. Electrophysiological recordings

An electrode cap (electroCap International) with tin electrodes was used for recording Electroencephalographic (EEG) data from a total of 59 scalp locations: Fp1, Fpz, Fp2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FC5, FC3, FC1, FCz, FC2, FC4, FC6, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO3, PO1, POz, PO2, PO4, PO8, O1, Oz, O2 and left mastoid all referred to the right mastoid. These labels correspond to the revised 10/20 International System [2], plus two additional electrodes, PO1 and PO2, located halfway between POz and PO3 and between POz and PO4, respectively. Bipolar horizontal and vertical electrooculogram (EOG) was recorded for artifact rejection purposes. Electrode impedances were kept below 3 kΩ. The signals were recorded continuously with a bandpass between 0.3 and 100 Hz (3 dB points for −6 dB/octave roll-off) and were digitized at a sampling rate of 250 Hz. The buffers were stored in a file along with other relevant information, such as number of trials of each type.

2.5. Data analysis

The continuous recording was divided into 1024-ms epochs beginning from the onset of each type of test stimulus. Artifacts were automatically rejected by eliminating those epochs that exceeded ±65 μV. Additionally, a visual inspection was performed, and trials in which there were no motor responses to target stimuli or that contained false alarms were excluded. Trials in which RT was not between 300 and 800 ms were also excluded. ERP averages were categorized according to each type of test stimulus.

For the entire sample of scalp electrodes, originally M2-referenced data were algebraically re-referenced off-line using the averaged reference method [24]. This has proved to be the best way to obtain RP [26]. Both latency and amplitude, together with the topography of the RP, were measured from average waveforms in the interval 160–417 ms after test stimulus onset, following criteria outlined elsewhere [45].

3. Results

3.1. Performance

There were 9600 epochs (80 averages per each one of the six stimulus types in 20 subjects), and 1.2% were rejected because of eye blinks. Also excluded were those trials with omission, false alarms, and premature or late responses, which represented 1.4%, 0.86%, and 0.25%, respectively. Mean reaction time was 533.2 ms.

3.2. Electrophysiology

The activity evoked by control stimuli was subtracted from the waveforms evoked by the other stimulus types in order to enhance language-related factors. Figs. 2 and 3 display unsubtracted and difference waveforms, respectively, for all types of stimuli. A negative component, RP, was obtained for each type of stimulus peaking maximally at the PO7 electrode in the left and at the PO8 in the right hemisphere. Table 1 summarizes amplitude and latency values for all types of stimulus at the PO7 and PO8 electrodes.

An ANOVA was conducted in order to determine whether the latency of the RP component observed at the PO7 and PO8 electrodes differed across types of stimulus. This yielded non-significant results ($F_{4,76}$=2.08; P>0.1, at PO7 electrode; $F_{4,76}$=2.15; P>0.1, at PO8 electrode). Therefore, the same peak latency could be assumed for all types of stimulus. Moreover, in both electrodes the overall mean latency was around 260 ms. Therefore, the area within a single time-window was calculated for topographical maps and statistical analyses on RP amplitude. This window ranged from 232 to 288 ms (around latency mean±28 ms) after stimulus presentation.

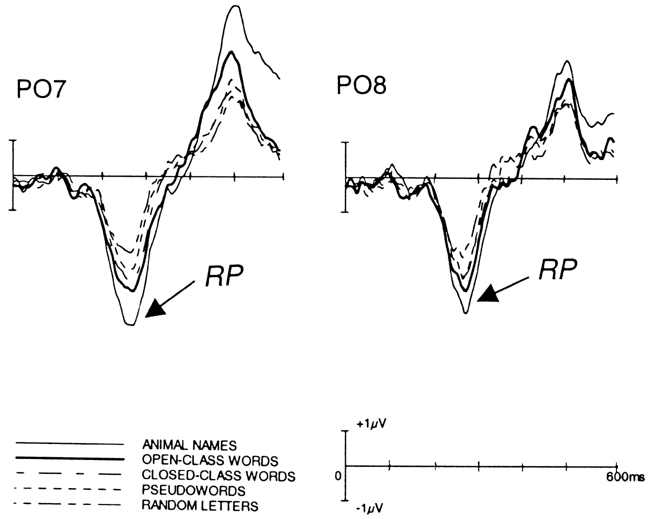

Fig. 3. Absolute grand mean averages at the PO7 and PO8 electrodes after subtracting control trials from each of the waveforms corresponding to each type of stimulus. The recognition potential amplitude was similar for open- and closed-class words at the PO7 electrode. However, open-class words evoked a larger amplitude compared to closed-class words at the PO8 electrode. At this electrode closed-class words and pseudowords displayed the same amplitude. Recognition potential latency was around 260 ms.

The maps in the 232–288 ms period are displayed in Fig. 4. Again, activity evoked by control stimuli have been subtracted from each of the waveforms. All maps show a similar topography, which consisted in a bilateral inferior-parietal negativity, with a positive counterpart of smaller amplitude over frontal and frontopolar regions.

Statistical analyses on RP amplitude were performed on a selected sample of 30 of the total 60 electrodes with the aim of avoiding an unacceptable level of loss of statistical power due to the use of a high number of electrodes [35]. These 30 electrodes were: Fp1, Fp2, AF3, AF4, F5, F1, F2,

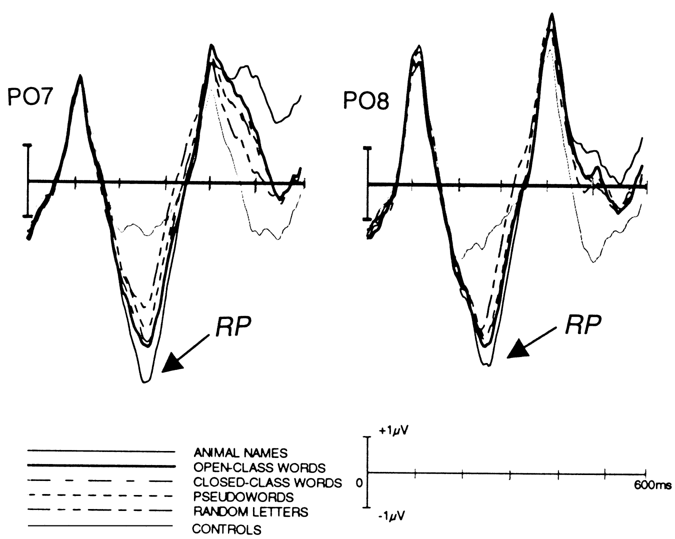

Fig. 2. Unsubtracted absolute grand mean averages at the PO7 and PO8 electrodes corresponding to each type of stimulus. All of them evoked recognition potential, with the exception of control stimuli, which evoked a drive rhythm.

Table 1
Amplitude and latency values for the recognition potential (RP) evoked by the different types of stimulus at electrodes that showed the maximal RP responses

	PO7		PO8	
	Amplitude (μV)	Latency (ms)	Amplitude (μV)	Latency (ms)
Animal names	−4.3	260	−3.9	264
Open-class words	−3.3	264	−3.3	264
Closed-class words	−3.1	260	−2.9	260
Pseudowords	−2.7	264	−2.9	264
Random letters	−2.2	260	−2.3	260

F6, FC5, FC1, FC2, FC6, C5, C1, C2, C6, CP5, CP1, CP2, CP6, P5, P1, P2, P6, PO7, PO1, PO2, PO8, O1, and O2. An ANOVA was performed on the mean amplitude of the 232–288 ms window with the following repeated measures factors: Type of stimulus (six levels: animal names, open-class words, closed-class words, pseudowords, strings of random letters and controls); Electrode (15 levels); and Hemisphere (two levels).

We obtained significant results for Type of stimulus, Electrode, Hemisphere, and the interactions Type of

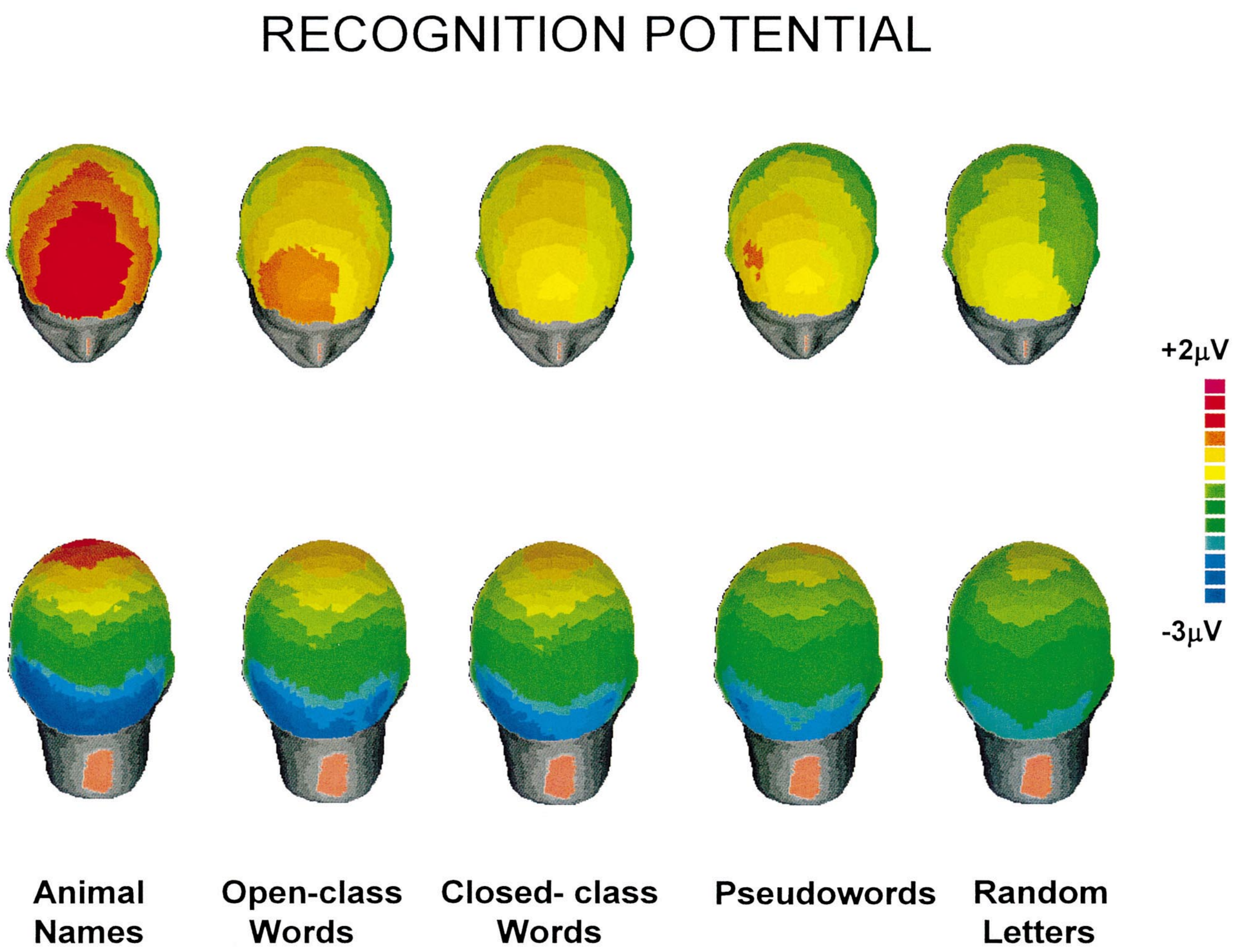

Fig. 4. Topographic maps corresponding to the recognition potential distribution across the total array of 60 scalp electrodes. They represent mean values for the time period ranging between 232 and 288 ms. Activity evoked by control stimuli has been subtracted from the waveforms corresponding to each type of stimulus to make the maps. All the maps display a similar topography, consisting of a bilateral parieto-occipital negativity. Activity in the right hemisphere is stronger for animal names and open-class words compared to the rest of the stimuli. A lower positivity over frontal regions can also be observed.

Table 2
Results of the analysis of variance (ANOVA) conducted in the latency range 232–288 that corresponds to the period of time in which recognition potential occurs[a]

Source	Latency range 232–288 ms	
	df	F
COND	5,95	3.22*
ELECT	14,266	102.06***
HEMIS	1,19	5.60*
COND×ELECT	70,1330	18.98***
COND×HEMIS	5,95	3.25*
ELECT×HEMIS	14,266	0.99
COND×ELECT×HEMIS	70,1330	2.31*

[a] COND, condition; ELECT, electrode; HEMIS, hemisphere. *$P<0.05$, **$P<0.01$, ***$P<0.001$.

stimulus by Electrode, Type of stimulus by Hemisphere, and Type of stimulus by Electrode by Hemisphere. The ANOVA results are summarized in Table 2.

Post hoc analyses with the Bonferroni correction were performed, applying the constraint of using only those electrodes that showed the higher RP values across types of stimulus, that is, PO7 and its contralateral PO8. The results at the PO7 electrode showed that types of stimulus differed significantly when compared with one another ($F_{1,19}$=4.9–211.6; $P<0.0001$ in all cases, except open-class words vs. pseudowords and pseudowords vs. strings of random letters; $P<0.005$; and closed-class words vs. pseudowords; $P<0.05$), with the exception of the comparison between open- and closed-class words, which did not reach significance ($F_{1,19}=1.5$; $P>0.1$). Therefore, statistical analyses supported the existence of amplitude differences across types of stimulus at the PO7 electrode with the exception of open- compared to closed-class words. Also, types of stimulus were significantly different when compared to one another at the PO8 electrode ($F_{1,19}$=4.5–59.4; $P<0.0001$ in all cases, except animal names vs. open-class words, open-class words vs. closed-class words, open-class words vs. pseudowords, closed-class words vs. strings of random letters, and pseudowords vs. strings of random letters; $P<0.05$), with the exception of the comparison between closed-class words and pseudowords, which did not differ ($F_{1,19}=1.4$; $P>0.1$). Thus, according to statistical analyses all types of stimuli differ from one another except in the case of closed-class words compared to pseudowords.

Further statistical analyses were applied to the closed-class words block at the PO7 and PO8 electrodes after it had been divided into the high-frequency and low-frequency blocks. Amplitudes and latencies were -3.2 μV and 256 ms at the PO7 electrode and -3.1 μV and 260 ms at the PO8 electrode for the high-frequency block. In the case of the low-frequency block, amplitude and latency values were -3 μV and 260 ms at the PO7 electrode and -2.9 μV and 268 ms at the PO8 electrode. There were no latency differences between high- and low-frequency blocks at either the PO7 ($F_{1,19}=0.005$; $P>0.1$) or PO8 ($F_{1,19}=3.27$; $P=0.9$) electrodes according to an ANOVA with Type of stimulus as a repeated-measures factor, although a weak statistical trend was observed at the PO8 electrode. Once again, amplitude was measured in the 232–288 ms interval for statistical purposes. An ANOVA comparing the amplitude evoked by high- and low-frequency blocks at both the PO7 ($F_{1,19}=0.9$; $P>0.1$) and PO8 ($F_{1,19}=1.5$; $P>0.1$) electrodes determined that there were no amplitude differences between these blocks of stimuli.

4. Discussion

The animal names showed the highest RP amplitude as compared to the rest of the stimuli, including the open-class words block. This difference is not crucial for the purpose of our experiment, however, since the target block was included in order to provide a lexical decision task for maintaining subjects' attention. Previous research on RP has demonstrated that target status has no effect on RP amplitude [27]. Accordingly, we must disregard the possibility of this difference being due to the target effect. A plausible explanation for this result is related to the use of animal names as targets and concreteness effects. Concreteness affects RP [27] in such a way that concrete words show larger RP amplitudes than abstract words, which supports the implication of the areas generating RP in the processing of visual-semantic information. Animal names are among the best examples of concrete nouns. In contrast, the open-class words block used here was composed of heterogeneous nouns, including an considerable proportion of abstract nouns, such as *vida* (life), *pasado* (past), *tiempo* (time), etc. (see Appendix A). This situation, therefore, might have led to the reduced RP response to open-class words as compared to animal names.

In the left hemisphere, closed-class words elicited an RP response similar to that evoked by open-class words, both word classes generating significantly larger RP than the non-meaningful stimuli (pseudowords and strings of random letters). As RP is an electrical brain response sensitive to the semantic content of stimuli [20,25–27], this result indicates that closed-class words are not totally free of semantic content, and are affected at least to some extent by semantic processing. Results reported with the N400, another ERP response related to semantic processing, resembled the results obtained here, that is, the absence of amplitude differences between open- and closed-class words [54], though this has not been a common finding. Again, a possible explanation for this absence of amplitude differences in the present experiment is linked to the already-mentioned reduced RP response to open-class words due to their low level of concreteness.

Whatever the reason, even though the RP amplitude to open-class words was larger than to closed-class words, the most striking finding is the activation of some of the brain regions involved in semantic processing by closed-class words, as demonstrated by the larger RP amplitude to these items when compared to pseudowords or strings of random letters. In line with our findings, Small et al. [49] reported data from a patient with phonological dyslexia who was impaired for reading non-words and closed-class words. After therapy, she recovered the ability to read closed-class words, and fMRI revealed activation of the left lingual gyrus when reading non-words and closed-class words, the lingual gyrus being one of the regions presumably generating RP [20,26]. This means that the left lingual gyrus plays a substantial role in the processing of closed-class words [49], and present data support the proposal of such involvement. Closed-class words have traditionally been considered to be less involved in semantic processing, or indeed to be totally free of semantic content [4,6,34,38]. According to this view, closed-class words are processed on the basis of their syntactic function. However, this is a matter of debate, as some authors have argued that the distinction between open- and closed-class words depends on the amount of semantic information carried by a particular element, attributing a referential meaning to closed-class words [11,13]. Our data clearly show that closed-class words are affected by semantic processing. Closed-class words usually appear among open-class words in natural discourse, which might result in some kind of semantic association between closed- and open-class words, therefore providing closed-class words with some semantic content. This situation may lead the semantic system to analyze closed-class words with the purpose of determining their amount of semantic content, though in a different way than is the case with open-class words, as will be discussed later.

In the right hemisphere however, closed-class words showed a reduced RP amplitude as compared to open-class words. Moreover, closed-class words evoked a similar activity to that evoked by pseudowords. This indicates that those right hemisphere regions generating RP do not participate in the semantic processing of closed-class words to the same extent as they do in the processing of open-class words. This is in consonance with previous research on ERPs, which has reported several differences in the brain responses evoked by open- and closed-class words, consisting primarily in a left-lateralization of those components related to the processing of closed-class words [17,31,33,41,42]. Moreover, some data from lateralized tachistoscopic presentation experiments have revealed a similar pattern of lateralization in the processing of open- and closed-class words. These experiments reveal that the recognition of closed-class words benefits from right visual field presentations, whereas there is no effect of the visual field for open-class words [7,29]. Our data are thus in agreement with results from these experiments and with Pulvermüller et al.'s model of a differential engagement of the two hemispheres in the processing of open- and closed-class words. Moreover, they confirm some of the predictions of Pulvermüller et al.'s model. As Pulvermüller [40] indicates, open- and closed-class words differ in many aspects, including phonological structure, syntactic category or meaning, with any of these aspects constituting a possible explanation of the differences in lateralization during the processing of these two classes of words. Although previous data from Pulvermüller's research group [42] did not allow us to draw any conclusions regarding these explanations, they suggested that semantic properties were the most likely explanation for such differences. The different roles of the left and right hemispheres in the generation of the RP evoked by open- and closed-class words confirms Pulvermüller's prediction about the importance of semantic aspects for explaining differences in lateralization, since RP has repeatedly been shown to index semantic processing [20,25,26].

A secondary aim of this study was to determine the effects of word frequency on closed-class words by means of RP. With regard to this question, neither the latency nor the amplitude of the RP evoked by the two blocks of closed-class words appear to differ as a consequence of their different frequency, though a weak statistical trend was found when comparing latencies at the PO8 electrode. Therefore, it seems that the processes reflected by the RP evoked by closed-class words are insensitive to frequency effects. This result contrasts with the findings of previous research on RP with open-class words. Rudell [44] found that RP peak latency strongly differed between high- and low-frequency open-class words. Our results concur with those reported in other studies of early ERP responses that found word frequency not to affect the amplitude of the components evoked by closed-class words [4,52], though several authors have reported contrary evidence [21,38]. We should be cautious, however, when comparing these studies with ours, since there are several points that prevent a direct comparison. Firstly, all previous studies about frequency effects on closed-class words referred mainly to the early anterior negativity or N280, a component with a substantially different scalp distribution to that of RP, and which indexes different processes from those reflected by RP. For instance, King and Kutas [21] found that the mean peak latencies of the early left-frontal negativity could be predicted from word frequency in the case of both open- and closed-class words, more frequent words resulting in shorter latencies. A second point concerns the existence of fundamental differences in the methodology and statistical analyses used in different studies (see Ref. [4] for a detailed description of these differences). Here, we compared waveforms that were averaged as a function of two different frequency ranges of the stimuli, a similar approach to that used in the study by Brown et al. [4], who also failed to find frequency effects on closed-class words in the early left anterior negativity.

Taken together, our data suggest the existence of some differences in the semantic processing of open- and closed-class words. Even though the left hemisphere is closely involved in the processing of both vocabulary types, the proposal of differences is supported by the differential involvement of the right hemisphere in the processing of open- and closed-class words, and by the insensitivity of closed-class words to frequency effects as compared to the sensitivity showed by open-class words. Our data do not support a total identification of open-class words with semantics and closed-class words with syntax, since closed-class words participate to some extent in semantic processing, as revealed by left-hemisphere RP activity. The lack of identification of closed-class words with syntax has already been demonstrated by previous research. The N280 response was considered to constitute a specific electrophysiological marker of the processing of closed-class words, and thus to constitute an index of syntactic processing [31]. Neuroimaging data suggest that several areas of the left frontal and prefrontal cortices subserve phonological and syntactic processing, particularly some portions of Broca's areas, such as the pars opercularis [9,13,32]. Processes reflected by the N280 are likely to be generated in some of these areas, and thus to be related to syntactic processing. However, N280-like responses are not specific markers of closed-class word processing, since similar responses have recently been reported for open-class words in several studies [4,21,52]. Nevertheless, the existence of latency differences, that is, shorter latencies for closed-class words, seems to suggest earlier access of closed-class words to the brain areas involved in syntactic processing.

Hence, the existence of differences in the way open- and closed-class words participate in semantic and syntactic processes, proposed by some authors, appears to have empirical support [39], though the view postulating a total segregation in the processing of these two vocabulary types — and even the existence of different sub-lexicons [6] — seems to lack support. Syntactic information would appear to be processed in anterior brain regions, and not to be available at the same moment in time during on-line word processing for closed- and open-class words, the former class being favored. In the case of semantic word processing, which seems to take place mainly in left posterior brain regions, differences indicate a greater participation of the right-hemisphere in the case of open-class words, with processing of closed-class words being limited to left hemispheric areas. It should also be noted that the early electrophysiological signals reflecting syntactic and semantic processing display quite similar latencies. This fits more closely with the proposal of multiple and parallel processing streams within the language system, rather than with that of hierarchical dependence between syntax and semantics, at least in the case of the processing of isolated words.

Finally, it should be mentioned that all of the assumptions made in the discussion about the processing of open- and closed-class words are based on the comparison of a particular type of each of these vocabulary classes (nouns vs. conjunctions). The reasons for selecting these types of words are explained in the methods and materials section. Future research could include other types of open- and closed-class words in order to facilitate the extrapolation of these results to all possible words in the open and closed classes.

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Appendix A

Animal names, open-class and closed-class words presented as stimuli are listed, including their English translation. It should be noted that the translation of the closed-class words is approximate, due to the differences between English and Spanish, particularly in the case of closed-class words.

ANIMAL NAMES	OPEN-CLASS WORDS	CLOSED-CLASS WORDS
Águila (Eagle)	Casa (House)	Acaso (Perhaps)
Avispa (Wasp)	Cuerpo (Body)	Adonde (To where)
Burro (Donkey)	Día (Day)	Ahora (Now)
Caballo (Horse)	Estado (State)	Antes (Before)
Cabra (Goat)	Forma (Form)	Apenas (No sooner)
Cerdo (Pig)	Hombre (Man)	Así (Thus)
Conejo (Rabbit)	Nada (Nothing)	Conque (So that)
Delfín (Dolphin)	Noche (Night)	Cuando (When)
Gallo (Cock)	Madre (Mother)	Cuanto (How much)
Gato (Cat)	Manera (Manner)	Cuyo (Whose)
Gorila (Gorilla)	Mano (Hand)	Después (After)
Mosca (Fly)	Mañana (Tomorrow)	Donde (Where)
Pato (Duck)	Mundo (World)	Hasta (Until)
Perro (Dog)	Parte (Part)	Incluso (Even)
Rana (Frog)	Pasado (Past)	Luego (Them)
Ratón (Mouse)	Tarde (Afternoon)	Menos (Less)
Salmón (Salmon)	Tiempo (Time)	Pero (But)

Tigre (Tiger)	Trabajo (Work)	Porque (Because)
Zorro (Fox)	Vida (Life)	Según (Depending)

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