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Higher-order activity beyond the word level: Cortical dynamics of simple transitive sentence comprehension

Manuel Martín-Loeches[a,*], Pilar Casado[a], José A. Hinojosa[b], Luis Carretié[c], Francisco Muñoz[a], Miguel A. Pozo[b]

[a] *Cognitive Neuroscience Unit, Center for Human Evolution and Behavior, UCM-ISCIII, Madrid, Spain*
[b] *Brain Mapping Unit, Universidad Complutense, Madrid, Spain*
[c] *Dpto. de Psicología Biológica y de la Salud, Universidad Autónoma de Madrid, Spain*

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Abstract

Slow electrophysiological effects, which fluctuate throughout the course of a sentence, independent of transient responses to individual words, have been reported. However, this type of activity has scarcely been studied, and with only limited use of electrophysiological information, so that the brain areas in which these variations originate have not been clearly identified. To improve this state of affairs, a principal component analysis and a modern source analysis algorithm (LORETA) were applied to the slow activity underlying transitive sentence reading. Four components explained 97.3% of the variance. Of key interest was a slow variation that occurred throughout the entire sentence but peaked with the appearance of the verb. The main solution for this component was localized in prefrontal and temporal regions presumably involved in semantic sentence processing. This constitutes empirical evidence for cortical activity—related to semantic processes thought to be involved in thematic role assignment—developing throughout the sentence but presenting a conspicuous maximum with the appearance of the verb. This finding also highlights the central role of verb information in the understanding of transitive sentences.

Keywords: Event-related potentials; Language; Sentence processing; Thematic role assignment; PCA; LORETA

1. Introduction

Understanding a sentence is a complex process that requires not only comprehension of the meaning of its constituent individual words, but also the assignment of the structural relationships between those words. Thereafter, sentence processing allows the reader or listener to determine "who did what and to whom," based upon structural (syntactic) and meaning (semantic) features.

Current linguistic frameworks stress the existence of general principles of language processing (rather than highly specific ordered rules) and the centrality of semantic argument structure in syntactic analysis (Chomsky, 1981, 1995; Jackendoff, 1997).

This view of language processing entails, therefore, a central role for processes such as thematic role assignment during sentence comprehension. Thematic role assignment (θ-roles) refers to the implicit syntactic arguments a verb may convey, based on our intuitive semantic knowledge of the verb's meaning (Dowty, 1988). As Kutas and King (1996) have lucidly pointed out, thematic role assignment would express "*the creation of a bridge between the linguistic representation of a participant in a discourse and the specific role the participant is expected to take*" (Kutas & King, 1996, p. 506). Hence, and following these authors, information in the

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[*] Corresponding author. Fax: +34 91 387 75 48.
E-mail address: mmartinloeches@isciii.es (M. Martín-Loeches).

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verb can be used to map thematic roles onto the discourse participants, that is, to map explicit associations between particular, previously unassociated items in working memory.

Accordingly, in order to know "who did what and to whom," thematic role assignment would be a core operation. However, sentence processing could not be reduced to verb processing alone. Rather, noun phrases provide important thematic information about players and their roles. This information is necessary to complete the actions provided by the verb. Consequently, the process of determining "who did what and to whom" would be a process occurring throughout the whole sentence, even if crucial milestones, such as verb information, may be found at certain prominent moments. In other words, all available information must be integrated within working memory to form a coherent mental model of the state of affairs to which the sentence refers. At different time points during the sequential presentation of information in a sentence, different aspects of information previously presented in the sentence take on a greater relative importance in the construction of this mental model.

Event-related potentials (ERPs) have been used as a source of evidence for psycholinguistics in recent years. ERPs are known to offer millisecond temporal resolution, thus permitting measurement of electrical brain activity as language processes take place over time. ERPs would therefore confer an obvious advantage for studying these processes in comparison to other brain-imaging techniques, even taking into account the possibilities of event-related functional magnetic resonance imaging (fMRI).

Most of the ERP literature in relation to language processing, however, is based on an indirect measure of how the processing of an entire sentence is performed, as most studies are based on ERP time-locked to the onset of one word in the sentence. Notably, left anterior negativities, roughly at between 200 and 500 ms, appear to syntactic and morphosyntactic violations, and may reflect early syntactic processing (Münte, Heinze, Matzke, Wieringa, & Johannes, 1998) or working memory aspects of language (Kluender & Kutas, 1993). In contrast, pure lexical access to semantic content may be reflected by a left occipito-temporal potential peaking at about 250–300 ms (the Recognition Potential), which has been reported as context-responsive during sentence processing (Dien, Frishkoff, Cerbone, & Tucker, 2003; Martín-Loeches, Hinojosa, Gómez-Jarabo, & Rubia, 2001). One of the most well known language-related ERPs is a centro-parietally distributed negativity around 400 ms, the N400 component (e.g., Kutas, 1997), which may reflect postlexical processes involved in semantic integration (Brown & Hagoort, 1993; Holcomb, 1993). Finally, when an unsuccessful match occurs and a reanalysis or repair becomes necessary, a late centro-parietally distributed positivity, the P600 or SPS, can be observed (Osterhout & Holcomb, 1992).

Sentence comprehension, however, and as mentioned above, would actually imply essential and specific processes taking place throughout sentence reading, since understanding a sentence depends on structural relationships within a sentence, and not only to information provided by an isolated word. Although information provided by certain isolated words should certainly interact with these lengthier processes (this being the case especially in relation to certain significant landmarks, such as verbs), cross-sentence brain activity must be studied if we are to fully understand sentence processing. ERPs are highly suited to the study of temporally extended brain processes occurring when a sentence is heard or read.

Surprisingly, only a very small number of studies have directly attempted to study ERPs throughout sentence comprehension, even though such study might actually shed some new light on the processes involved in sentence processing. These studies have been performed by Kutas and collaborators (King & Kutas, 1995; Kutas & King, 1996; Mueller, King, & Kutas, 1997). These authors apply a low-frequency low-pass digital filter to the ERPs elicited by transitive clauses, obtaining several slow effects that show systematic variation both in time across the sentence and in space across the scalp. According to Kutas' team (Kutas & King, 1996), four effects would characterize these cross-clause slow potentials: (1) A positivity over temporal sites coinciding with the appearance of the verb that could reflect thematic role assignment; (2) A temporal negativity indicating clause ending (called clause ending negativity, or CEN) that peaks at the final word of the clause, and may be related to demands on working memory processes at clause boundaries; (3) A very slow frontal positivity that may reflect the building of a schema of the sentence from an integration of items in working memory with representations in long-term memory; and (4) A sustained negative shift over occipital sites reflecting early visual processing that begins with the first word and is sustained at a steady level throughout the entire clause.

Quite recently, and as a complement to these findings, Steinhauer and co-workers (Steinhauer & Friederici, 2001; Steinhauer, Alter, & Friederici, 1999) have also reported an effect that partly resembles the CEN (though with positive polarity) in the study of slow potentials related to speech processing and the reading of prosodic cues, but which would be in line with positivities related to the feature of "gap duration" in auditorily presented sentences reported by Mueller et al. (1997). Furthermore, Matzke, Mai, Nager, Rüsseler, and Münte (2002) have reported an extended negative shift over anterior scalp regions for sentences beginning unambiguously with a non-canonical word order, and which presumably reflects working memory operations, while Rösler, Pechmann, Streb, Röder, and Henninghausen (1998) have also reported diverse effects for the processing of words at terminal positions in sentences with non-canonical order.

Probably the most remarkable of these reported effects would be the positivity coinciding with the appearance of the verb. The hypothesis of Kutas and colleagues (Kutas & King, 1996) is that this positivity actually reflects some aspects of thematic role assignment that are based upon information contained in the lexical representation of the verb. In this regard, it could reflect operations within working memory such as uncovering argument structure information from a verb and making preliminary role assignments to the subject noun phrase. If this were the case, it would constitute a crucial component in sentence analysis. Indeed, the identification of this component as related to the verb is not a secondary finding, and several authors maintain that the more frequent thematic structure of a verb phrase determines the initial syntactic analysis of the whole sentence (Trueswell, Tanenhaus, & Kello, 1993).

On the other hand, the very slow frontal positivity that could reflect working memory integration may also constitute an important activity for sentence comprehension, as it might be reflecting the construction of a sentence-level schema within working memory (Kutas & King, 1996). Similarly, it could be interpreted as the frontal negativity reported by Matzke et al. (2002), despite its opposite polarity, which might be explained by the use of non-canonical materials and, therefore, the involvement of more complex operations. Kutas and King (1996) indicated nonetheless that the involvement of the processes reflected by this long-lasting frontal activity would be greatly reduced for basic material, such as simple transitive constructions.

Taken together, these scarce and highly valuable studies constitute the foundations of significant and pioneering work demonstrating that slow cortical potentials are a promising tool in the study of language processing dynamics at the sentence level. Currently, however, not only is there a remarkable scarcity of this type of whole-sentence ERP study, but the studies that there are have employed a limited number of electrodes, with no thorough analysis about the neural origins of the different effects observed during sentence comprehension. This is a situation that must be rectified.

As the dynamics of sentence comprehension processes elude the temporal resolution of techniques with a higher spatial resolution, there is a need for exhaustive research ERP findings on sentence processing using modern source analysis algorithms. Indeed, the validity of these algorithms with regard to the spatial localization of electrophysiological activity is a topical issue. Former problems of source analysis algorithms have to a large extent been overcome by algorithms now available. It has recently been asserted that current source analysis implementations can be safely assumed to have a localization accuracy of the order of several millimetres or, at worst, a few centimetres (Pascual-Marqui, 1999). Although the inverse problem has not been totally overcome and the reliance on these algorithms should not be blind, this suitable accuracy combines with anatomical and physiological plausibility to largely substantiate the reliability of the solutions provided by these algorithms.

The current methodological development of source analysis algorithms, coupled with the dearth of such studies in the literature, vindicated ERP measurement of slow waves elicited by the processing of simple transitive sentences. The present study aimed at obtaining electrophysiological activity beyond the word level and exhaustively analyzing ERP data obtained from a large array of cephalic electrodes. Exhaustive analyses included the search for components explaining most variance extracted by means of temporal principal component analysis (tPCA). This technique has been repeatedly recommended for the detection and quantification of components, since the exclusive use of the traditional visual inspection of grand averages may lead to several types of misinterpretation (Chapman & McCrary, 1995; Coles, Gratton, Kramer, & Mille, 1986; Donchin & Heffley, 1978; Fabiani, Gratton, Karis, & Donchin, 1987; McGillem & Aunon, 1987), and this may even be aggravated when long epochs are considered. Subsequently, tPCA-extracted components were submitted to a 3D, discrete linear solution for the EEG inverse problem. Thus, an analysis was performed to determine the possible neural generators of the ERP variations related to sentence processing. These procedures greatly enhance the objectivity of a visual inspection of grand averages and source analyses, and have been successfully applied by the authors elsewhere (Carretié, Martín-Loeches, Hinojosa, & Mercado, 2001).

The data obtained with these procedures were directly contrasted with data obtained from the literature using hemodynamic techniques (PET and fMRI) on language processing. These data served to establish whether the generating areas for the slow fluctuation were specialized in a particular type of processing and, therefore, how the different stages in sentence processing were involved. Furthermore, this type of data acted as an independent verification of the anatomical plausibility of the algorithms obtained with source analysis, thus further offsetting any possible limitation in these procedures.

However, the material studied in present research differed slightly from that used by Kutas and colleagues, in that single-clause sentences were used here, rather than phrases embedded within multi-clause sentences. Since the present study constituted a first approach on the neural generators involved in sentence processing as revealed by ERPs, it was decided to use the simplest sentence material.

2. Materials and methods

2.1. Participants

Twenty native Spanish speakers (11 females), ranging in age from 20 to 29 years (mean = 21.4 years), participated as volunteers in the experiment. All of them had normal or corrected-to-normal vision and were right-handed, with average handedness scores (Oldfield, 1971) of +82, ranging from +57 to +100. Participants were paid for participating in this experiment.

2.2. Stimuli

The materials consisted of a set of 50 Spanish transitive sentences with 5 words each. In addition to the set of experimental items, a set of 50 filler items (intransitive sentences with 6 words each) was constructed. The transitive–intransitive dimension of the sentences was determined not only by phrase structure but also by the use of transitive or intransitive verbs, respectively. Accordingly, transitivity or intransitivity of the sentences was first of all and primarily determined by type of verb. In this regard, intransitive verbs can never work as transitive, and transitive verbs only very rarely appear as intransitive in Spanish (Fernández & Anula, 1995).

All sentences presented the same structure: a noun phrase followed by a verb, with the category sequence [det]-[N]-[V], and finally, a complement. This complement was always a direct object in the case of the transitive sentences, e.g., *"La niña abrió la puerta" (The girl opened the door)*, and a prepositional phrase in the intransitive (filler) sentences, e.g., *"El ladrón luchó con la policía" (The thief fought with the police)*, with one of two possibilities: having an adverbial role (58%) or representing an indirect object (42%). Also, 96% of subject nouns referred to animate entities in transitive sentences, while this figure was 68% for intransitive sentences.

The verbs—the main items in the present experiment—were equal in length and frequency of use. Both pools (transitive and intransitive) comprised 44 two-syllable and 6 three-syllable verbs each. According to the Alameda and Cuetos (1995) dictionary of frequencies for Spanish, the two pools were of comparable familiarity (mean 33.42 for transitive verbs, 38.74 for intransitive verbs; $t_{49} = -0.381$, $p > .1$).

Expectancies for verbs after subject nouns were measured in a sample of 30 participants not involved in the present study. We measured the extent to which a particular verb was expected during both types of sentence after the appearance of subject nouns. The results were 26.9% for transitive and 25% for intransitive sentences. That is, a particular verb was to some extent expected in both types of sentence after the appearance of subject nouns, and a similar degree of expectancy was present in the two. However, the verbs actually presented during the ERP recordings were not necessarily those expected, since the probability for the presented materials was 4.2 and 4.8% for transitive and intransitive verbs, respectively.[1] In any case, the verbs used here did not differ with regard to expected probability. As regards expectancies for sentence-ending words, these were 55.3% for transitive and 53.1% for intransitive sentences, the final words used here being mostly the expected words (48.6 and 41.5% for transitive and intransitive sentences, respectively).

All stimuli were equated in visual aspects. Participants' eyes were 65 cm from the screen. At that distance, a word made up of 5 letters was 1.14° high and 3° wide. Stimuli were presented white-on-black on an NEC computer MultiSync monitor, controlled by the Gentask module of the STIM package (NeuroScan).

2.3. Procedure

An experimental session consisted of 100 sentences. Participants were also given a short training run, consisting of ten practice sentences. None of the sentences used in the training were experimental sentences.

All 100 sentences appeared word-by-word in the centre of a computer screen while the electroencephalogram was recorded. Each sentence was presented in the same form: the first word began with a capital letter and the last word was presented with a full-stop to mark the end. Words were presented with a duration of 500 ms, with an inter-stimulus interval of 200 ms. Fig. 1 illustrates the stimulation paradigm.

Participants were instructed to read each word and try to link them together in their mind to produce a comprehensible sentence, knowing that they were to be questioned after a number of sentences. After a random number of 4–6 sentences, a YES/NO comprehension question appeared in the centre of the screen, 1500 ms after the onset of the last word of the immediately preceding sentence. Questions appeared in full on the screen, and referred to the just-finished sentence. Half of the questions had an affirmative response and the remainder had a negative response. These questions were included to motivate participants to be attentive

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[1] This difference between the expected and actually presented verbs was fortuitous and unintentional. Starting from a list of transitive and intransitive verbs, sentences were constructed from these lists without paying special attention to the actual noun subjects employed, except with regard to frequency of use, which was equated in the two types of sentence (mean 426.9 for transitive sentences, 423.6 for intransitive sentences; $t_{49} = 0.024$, $p > .1$).

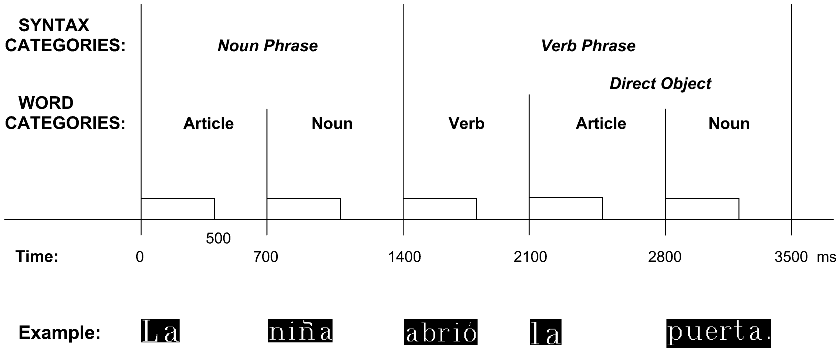


Fig. 1. Examples of the stimuli presented to participants, together with a schematic representation of the stimulation procedures.

to the sentences. Participants were encouraged to minimize blinking during sentence presentation and to confine blinks and movements to these question sessions. A total of twenty comprehension questions were asked, half of them following transitive sentences.

After responding to each comprehension question, a message appeared on the screen informing participants that they should blink as much as they wanted, and asking them to push a button to start a new block of sentences.

2.4. Electrophysiological recordings

An electrode cap (ElectroCap International) with tin electrodes was used for recording Electroencephalographic (EEG) data from a total of 58 scalp locations (Fig. 2), and left mastoid (M1), each referred to the right mastoid (M2). The labels correspond to the revised 10/20 International System (American Electroencephalographic Society, 1991) plus two additional electrodes, PO1 and PO2, located halfway between POz and PO3 and between POz and PO4, respectively. The electrooculogram (EOG) was obtained from below versus above the left eye (vertical EOG) and the left versus right lateral orbital rim (horizontal EOG). Electrode impedances were kept below 3 kΩ. The signals were recorded continuously with a bandpass between DC and 100 Hz (3 dB points for −6 dB/octave roll-off), and were digitized at a sampling rate of 250 Hz.

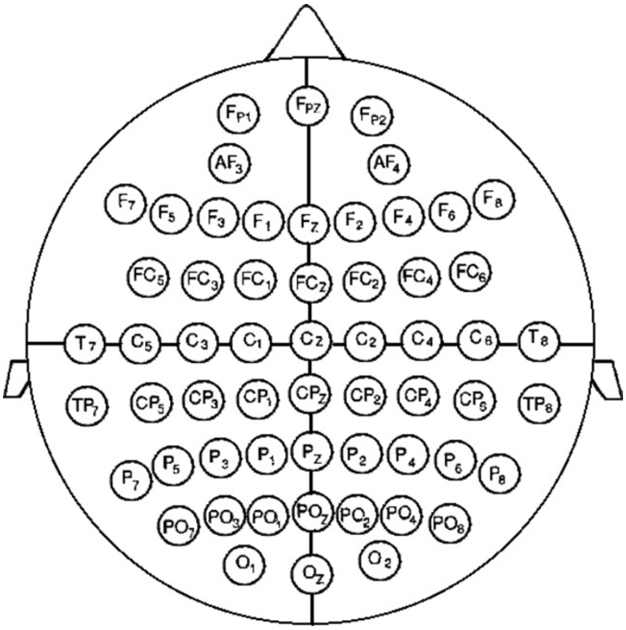


Fig. 2. Electrodes used in the present experiment. Electrode locations on the scalp follow the proposal by the American Electroencephalographic Society (1991).

2.5. Data analysis

ERP waveforms to the experimental materials were derived from an average with an epoch length of 4000 ms, including a 500 ms pre-sentence onset baseline. This epoch included all five words in the transitive sentences.

Artifacts were automatically rejected by eliminating those epochs that exceeded ±65 μV. Additionally, a visual inspection was performed in order to eliminate epochs with too many blinks, excessive muscle activity or other artifacts. Off-line correction of smaller eye movement artifacts was also made, using the method described by Semlitsch, Anderer, Schuster, and Preelich (1986). For the whole sample of cephalic electrodes, originally M2-referenced data were algebraically re-referenced off-line using the averaged mastoids as reference.

The waveforms were digitally filtered with a low-pass filter of 0.7 Hz, with the intention of obtaining the low-frequency components of the recorded ERPs. Clearly, there is substantial slow activity across the course of the sentence that is independent of the transient components triggered by each incoming word, as can be seen by comparing Figs. 3 and 4.

Components explaining most variance across electrodes and throughout the full-sentence period were extracted through temporal principal components analysis (tPCA) The decision on the number of components to select was based on the scree test (Cliff, 1987), and the

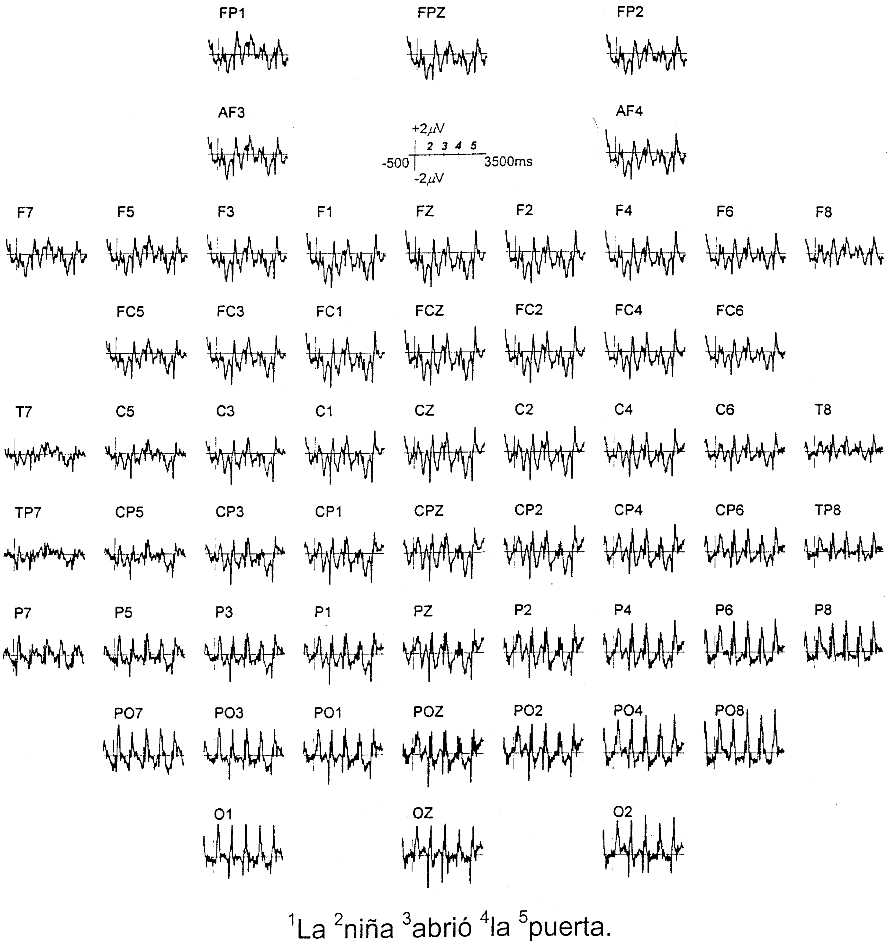


Fig. 3. Grand average unfiltered ERP across simple transitive sentences at all 58 scalp-recording sites. Superscripts in example sentence refer to serial position indicated in calibration legend. Translation for this example sentence: *^{1}The ^{2}girl ^{3}opened ^{4}the ^{5}door.*

extracted components were then submitted to varimax rotation.

Finally, low-resolution brain electromagnetic tomography (LORETA) (Pascual-Marqui, 1999; Pascual-Marqui, Michel, & Lehmann, 1994) was applied, a 3D, discrete linear solution for the EEG inverse problem. LORETA refers to a three-shell spherical model registered to the Talairach human brain atlas (Talairach & Tournoux, 1988), yielding solutions as in *XYZ* coordinates. Registration between the spherical and realistic head model in which solutions are given by LORETA used EEG electrode coordinates reported by Towle et al. (1993). From a physiological point of view, the solution provided by LORETA takes into account that neighboring neurons are most likely to be active synchronously and simultaneously (with similar orientation and strength) than grid points that are distant from one another (Pascual-Marqui et al., 1994). In mathematical terms, the task of this algorithm is to find the smoothest of all possible solutions. The characteristic feature of this solution is, therefore, its relatively low-spatial resolution, which is a direct consequence of the smoothness constraint. Even so, solutions are complemented by centroids that can be safely assumed to have a localization accuracy in the order of 14 mm at worst, with as few as 16 electrodes (Pascual-Marqui, 1999). It has recently been demonstrated that the localization of intracerebral generators of EEG using this technique correlates with spatial indices of glucose metabolism measured with FDG-PET (Dierks et al., 2000).

Apart from these analyses, an additional exploration of our data was performed, though subsidiary to the purposes of the present study. As a control for the main results of the present study, tPCA and LORETA analyses were also carried out for the intransitive (filler) sentences. For these purposes, the procedures followed were exactly the same as those for transitive (experimental) sentences, with the exception that analyzed epochs were of 4700 ms, including a 500-ms pre-sentence onset baseline, since intransitive sentences were one word longer than transitive ones.

Finally, and despite overall differences between transitive and intransitive sentences, brain slow electrical potentials (that is, before submitting the waveforms to tPCA) obtained for transitive sentences and intransitive sentences for the 1450–2810 ms period after onset of the

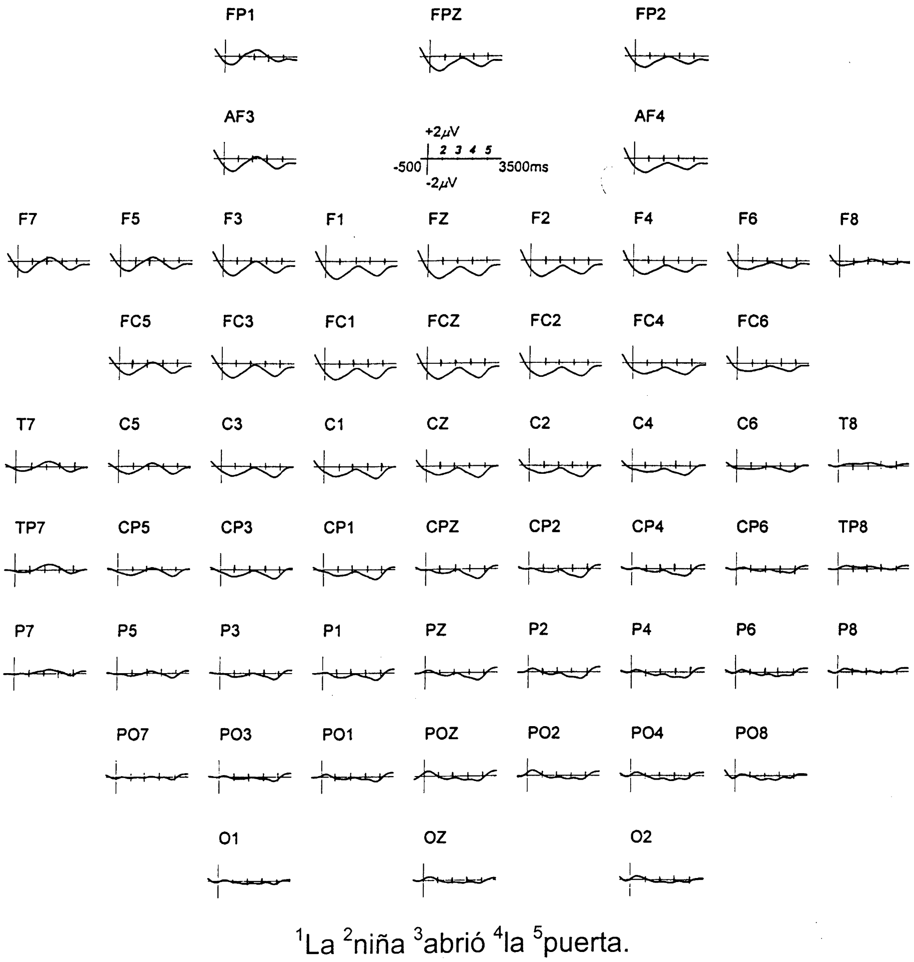


Fig. 4. Same data as in Fig. 3 subjected to low-pass filtering at 0.7 Hz, which emphasizes slow potential activity across transitive sentence.

first word in the sentence were compared. With the aim of avoiding an unacceptable loss of statistical power due to the high number of electrodes used, statistical analyses on amplitude were planned and carried out on a selected sample of 38 of the total 58 cephalic electrodes. These 38 selected electrodes were: Fp1, Fpz, Fp2, AF3, AF4, F5, F1, Fz, F2, F6, FC5, FC1, FCz, FC2, FC6, C5, C1, Cz, C2, C6, CP5, CP1, CPz, CP2, CP6, P5, P1, Pz, P2, P6, PO7, PO1, POz, PO2, PO8, O1, Oz, and O2. ANOVAs were performed with Type of Verb (transitive versus intransitive) and Electrode (38 levels) as repeated-measures factors for each of the thirty-four 40-ms wide windows covering the period analyzed.

3. Results

3.1. Behavioral data

As expected, participants had no difficulty responding to the 20 probe questions presented. The average comprehension rate was more than 95%, indicating that the main objective of presenting/displaying these questions, i.e., to maintain participants' attention, was achieved. On splitting comprehension rates as a function of sentence type, these were found to be 98% for transitive and 95.5% for intransitive sentences. This indicates that, although in general intransitive materials may be slightly more difficult than transitive materials, they were nevertheless also highly comprehensible.

3.2. Electrophysiological data

The data collected were analyzed in four ways. First, averaging the artifact-free EEG over full sentence-length epochs (3500 + 500 ms previous to the first word-stimulus, as a baseline) of the critical materials as described below, and following procedures outlined elsewhere (Kutas & King, 1996). A digitally filtered wave (with a low-pass filter <.7 Hz) was obtained. Fig. 3 displays raw (unfiltered) ERP data across the entire sentences in the 58 cephalic electrodes used in the electroencephalographic recording, while Fig. 4 shows the slow waves across the entire sentences in the same electrodes.

Second, on the basis of these data, filtered ERP waveforms were submitted to a principal components analysis (PCA) followed by varimax rotation, to determine the sources of variance in these ERP waveforms. Components explaining most ERP variance were extracted through temporal principal component analysis (tPCA). A covariance-matrix-based tPCA was carried out. Since the original number of cases (58 channels × 20 participants) and the number of variables (1000 digitized points) were excessive for computations, an operation for data reduction, maintaining the relevant ERP information, was carried out. Accordingly, in order to reduce the amount of data we averaged each four adjacent digitized points for each ERP (each four adjacent points represent 16 ms). The decision on the number of components to select was based on the scree test (see, e.g., Cliff, 1987; for a description). Extracted components were then submitted to varimax rotation.

Third, topographic maps of the selected components were drawn up in order to determine their scalp distribution. Factors scores resulting from tPCA were computed, yielding a single value for each component at each electrode separately.

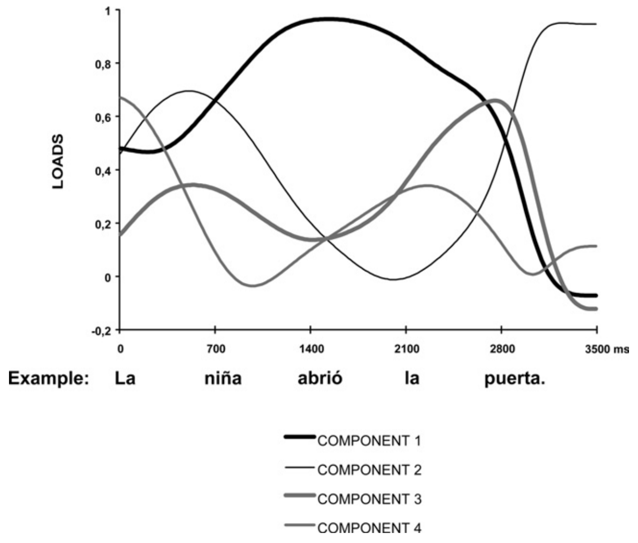


Fig. 5. PCA analysis: factor loadings after varimax rotation. Each word in the example sentence (same as for Fig. 3) is located under the corresponding milliseconds tick mark indicating its onset.

Fourth, in order to calculate the possible neural origin of these components through inverse solutions, low-resolution brain electromagnetic tomography (LORETA) was applied: a 3D, discrete linear solution for the EEG inverse problem (Pascual-Marqui, 1999; Pascual-Marqui et al., 1994). In its current version, LORETA refers to a three-shell spherical model registered to the Talairach human brain atlas (Talairach & Tournoux, 1988). A solution is given, therefore, as centroids in three coordinates: '*x*' is the distance in millimetres to the right (+) or left (−) of midline, '*y*' is the distance anterior (+) or posterior (−) to the anterior commissure, and '*z*' is the distance superior (+) or inferior (−) to a horizontal plane through the anterior and posterior commissures.

Following selection criteria, four components or factors were extracted from ERPs. Fig. 5 shows the rotated loadings plotted over time for the four components, which accounted for 97.3% of the variance. Maximum-latencies of the PCA components and their distribution across time can be observed. Fig. 6 displays the topographic maps illustrating the mean factor scores for scalp locations, while Fig. 7 illustrates the sources of activity for the four components as calculated by LORETA. Source analyses were carried out on factor scores resulting from tPCA analysis.

Component 1 explained 82.76% of total variance (50.12% after rotation), and displayed its maximum at about 1550 ms, which coincides fairly closely with the appearance of the verb (1400 ms). It must be noted, however, that maximum-latencies should not be understood as the only conspicuous moments at which each component is involved. Rather, loadings for each component are also apparent at other time points, and may present noticeable values throughout extended time periods, as is especially the case for Component 1. The map of this component shows a left frontal positivity, though a counterpart of slightly smaller amplitude was also observed over inferior parietal regions. The main solution provided by LORETA for Component 1 consisted in a prefrontal focus corresponding to Talairach's coordinates [$x = -3$, $y = 52$, and $z = 1$]. The medial frontal gyrus (BA 10, $d \leqslant 1$ mm) is the particular area for this focus, though a close but notably less active focus is located at the inferior frontal gyrus (BA 44,

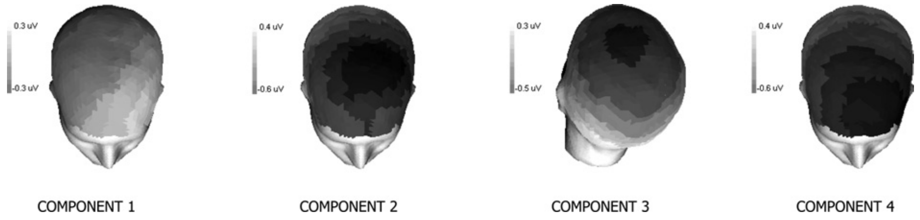
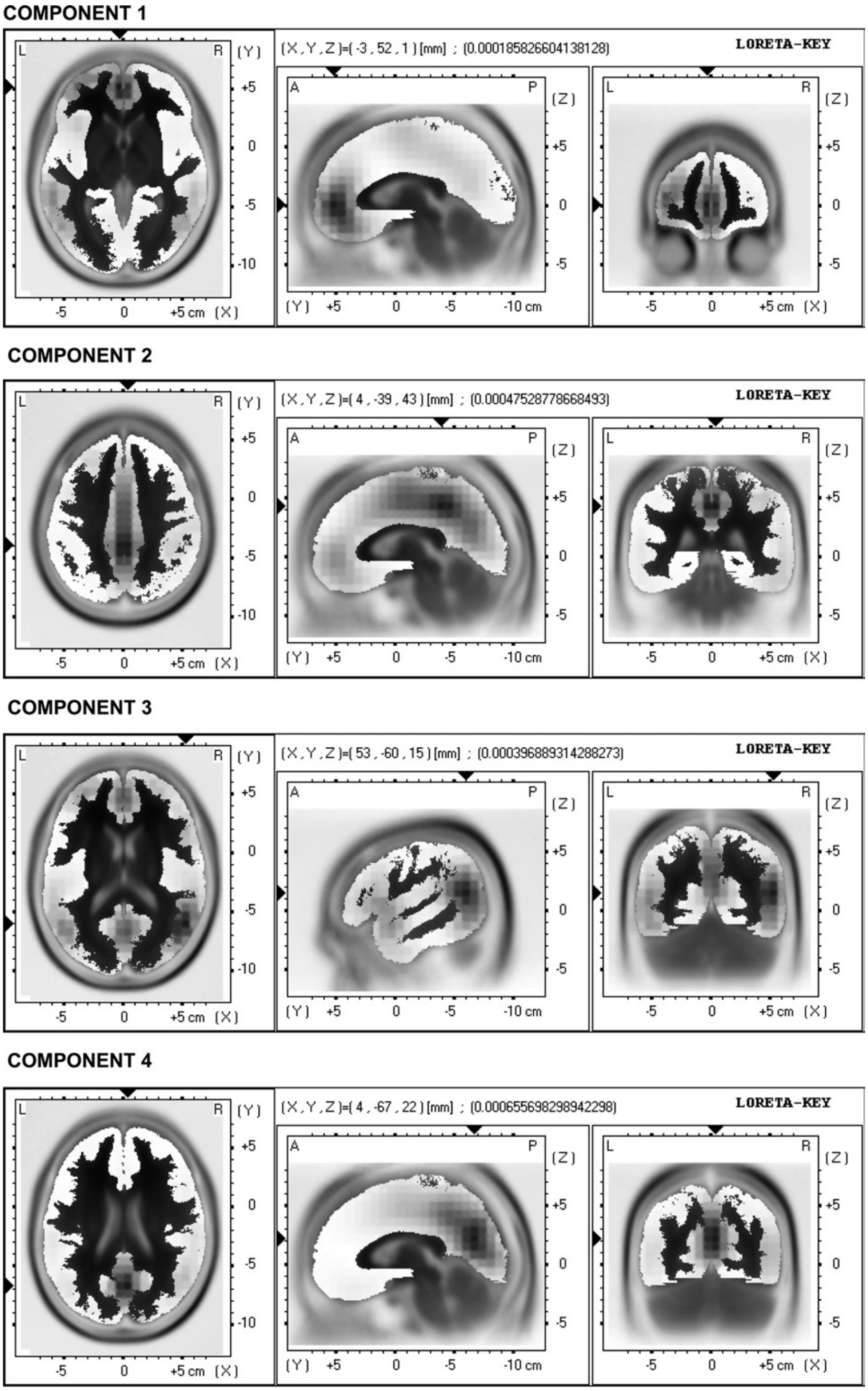


Fig. 6. Topographic maps corresponding to the four components of PCA distribution across the total array of 58 scalp electrodes. They represent mean values for the time period described in the text for each component.



COMPONENT 1

COMPONENT 2

COMPONENT 3

COMPONENT 4

Fig. 7. Images of neuronal electric activity computed with LORETA for each component of PCA. Images were scaled to the maximum activity in the total grey matter volume (more intense red indicates greater activity). Figures display transaxial (left columns), sagittal (middle columns), and coronal (right columns) slices in Tailarach space for the estimated source distributions of the components.

$d \leqslant 2$ mm). Interestingly, another secondary (but noticeably activated) focus for Component 1 was the inferior and medial temporal gyri, bilaterally (BA 22, $d \leqslant 1$ mm; BA 21, $d \leqslant 2$ mm; and BA 37 $d \leqslant 2$ mm).

Component 2 explained 10.32% of the total variance (27.57% after rotation), and its maximum appeared at about 3280 ms, which coincided fairly closely with the end of the sentence. The map for this component displays a central negativity with a counterpart of slightly lower amplitude over superior parietal regions, while the focus provided as a solution by LORETA corresponds to Tailarach's coordinates [$x = 4$, $y = -39$, and

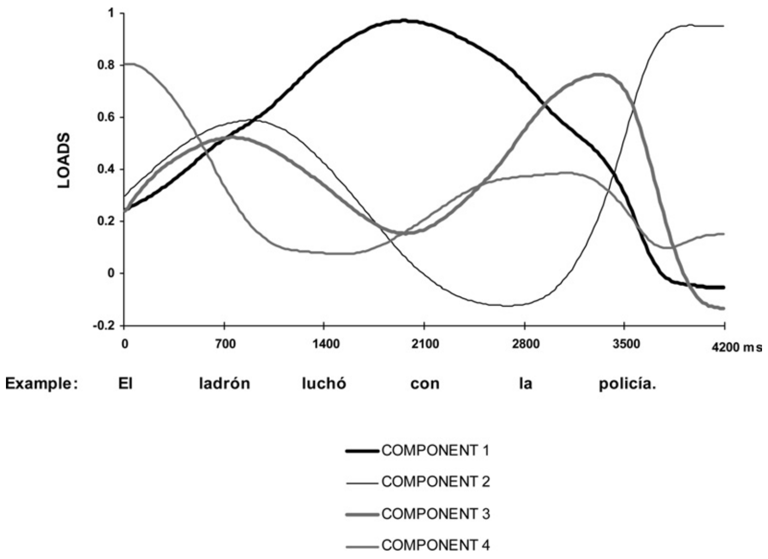


Fig. 8. PCA analysis for intransitive (filler) sentences: factor loadings after varimax rotation. Each word in the example sentence is located under the corresponding milliseconds tick mark indicating its onset. Translation for the example: *The thief fought with the police*.

$z = 43$]. The closest areas for this source are the precuneus (BA 7, $d \leqslant 2$ mm) and the cingulate gyrus (BA 31, $d \leqslant 3$ mm).

Component 3 explained 3.90% of the total variance (12.37% after rotation), and was maximal at about 2800 ms. This component also displayed a central, though narrower negativity, with a positive counterpart of smaller amplitude over occipital regions, bilaterally. According to the solution provided by LORETA, it is associated with a focus in Tailarach's coordinates [$x = 53$, $y = -60$, and $z = 15$], the superior temporal gyrus, bilaterally (BA 22, $d \leqslant 3$ mm), being the closest region for this solution. Secondary, though noticeable activations were observed for Component 3 at the middle frontal gyrus (BA 10, $d \leqslant 2$ mm and BA 9, $d \leqslant 3$ mm) and at posterior cingulated regions (BA 31, $d \leqslant 2$ mm).

Component 4 explained 1.56% of the total variance (7.24% after rotation), and is associated with early processes, since it displayed its maximum over the first 200 ms. The map of Component 4 shows a frontal negativity. The LORETA solution refers to Tailarach's coordinates [$x = 4$, $y = -67$, and $z = 22$]. The precuneus (BA31, $d \leqslant 3$ mm and BA23, $d \leqslant 6$ mm) in the occipital lobe is the nearest match for this source.

Additional analyses of our data were performed using the intransitive (filler) sentences. These analyses were subsidiary to our main aims in the present study, and should be considered as providing additional information that can be explored here, but bearing in mind that the distribution of brain activity is clearly highly sensitive to subtle differences in the linguistic material presented. However, the benefit of analyzing filler materials clearly balances its shortcomings, as the main results of the present study were reinforced and modulated by these analyses. It should also be mentioned that whereas the paradigmatic situation for transitive sentences has been used here (a transitive verb followed by a direct object), this has not been the case for intransitive (filler) sentences. In this regard, intransitive sentences can occur in a wider variety of situations, of which only two (prepositional phrases with either an adverbial role or representing an indirect object) have been employed here, and the two were analyzed together, that is, without disentangling the extent to which each one is contributing separately to the results. Accordingly, whereas the results of the present study may be universally applicable to understanding the processes underlying transitive sentences, this would not be the case for intransitive sentences.

Again, and following selection criteria, four components were extracted from intransitive sentence ERPs. Fig. 8 shows the rotated loadings plotted over time for the four components, which accounted for 98.37% of the variance. Fig. 9 illustrates the sources of activity for the four components in the intransitive sentences as calculated by LORETA.

Component 1 explained 79.68% of the total variance (59.18% after rotation) and displayed its maximum at about 1960 ms. The main solution provided by LORETA consisted of an inferior-temporal focus corresponding to Talairach's coordinates [$x = 53$, $y = -60$, and $z = -61$]. Inferior temporal gyrus (BA 37, $d \leqslant 3$ mm), bilaterally though slightly right, is the particular area for this focus. Another secondary but noticeable focus for Component 1 for intransitive sentences was the medial frontal gyrus (BA 10, $d \leqslant 2$ mm).

Component 2 explained 11.64% of the total variance (14.1% after rotation). The maximum appeared at about 3960 ms, which coincided fairly closely with the end of the sentence. The focus provided as solution for

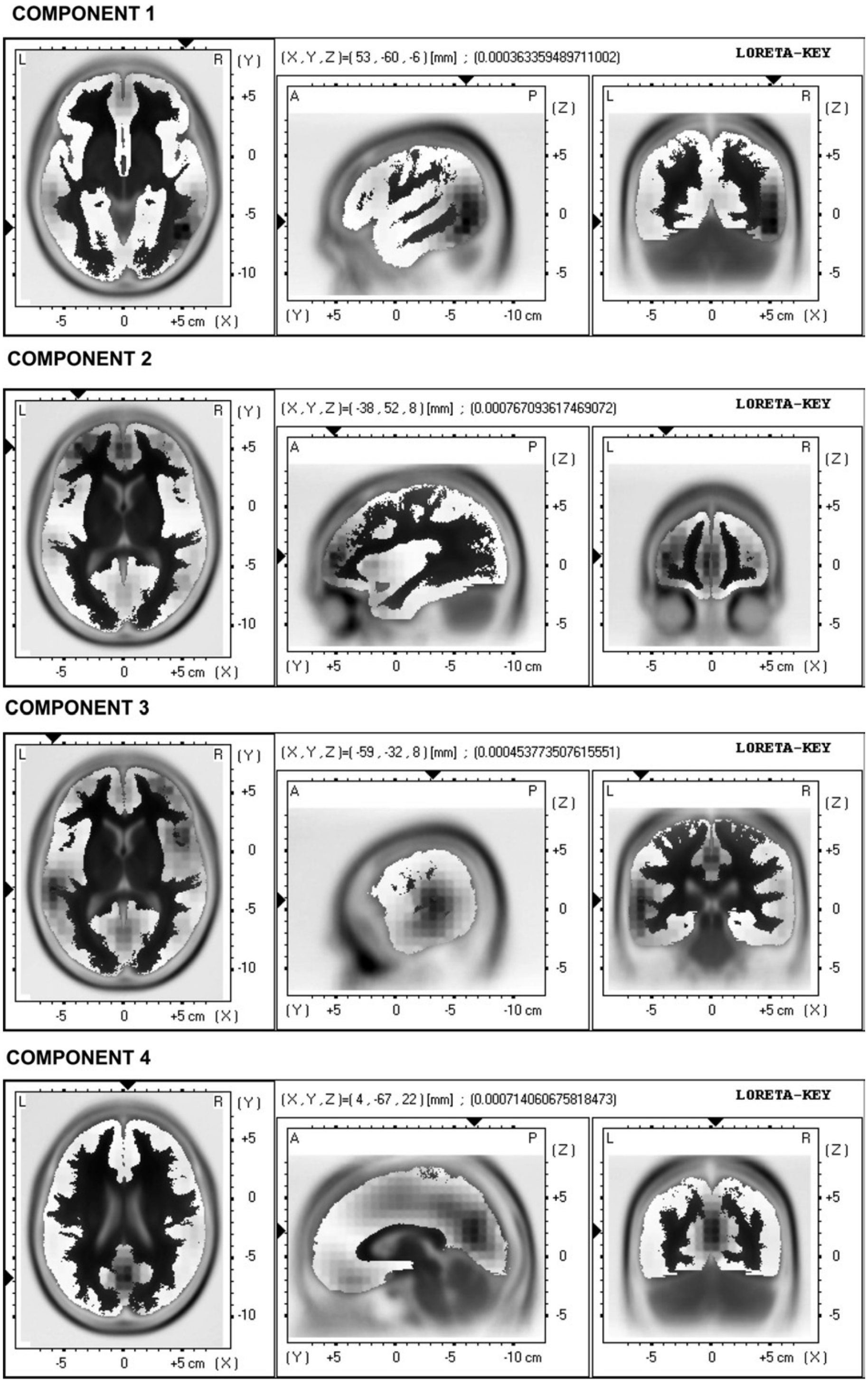


Fig. 9. Images of neuronal electric activity computed with LORETA for each component of PCA for intransitive (filler) sentences. Images were scaled to the maximum activity in the total grey matter volume (more intense red indicates higher activity). Figures display transaxial (left columns), sagittal (middle columns), and coronal (right columns) slices in Tailarach space for the estimated source distributions of the components.

Component 2 corresponds to Tailarach's coordinates [$x = -38$ $y = 52$, and $z = 8$]. The closest area for this source is the middle frontal gyrus (BA 10, $d \leqslant 4$mm). However, additional foci can be observed at the inferior temporal gyrus (BA 37, $d \leqslant 2$mm) and at posterior cingulated regions (BA 31, $d \leqslant 2$mm).

Component 3 explained 5.54% of the total variance (16.55% after rotation), and was maximal at about 3320ms. This component is associated with a main focus in Tailarach's coordinates [$x = -59$, $y = -32$, and $z = 8$], the superior temporal gyrus (BA 22, $d \leqslant 2$mm), mainly left, being the closest region for this solution. Secondary,

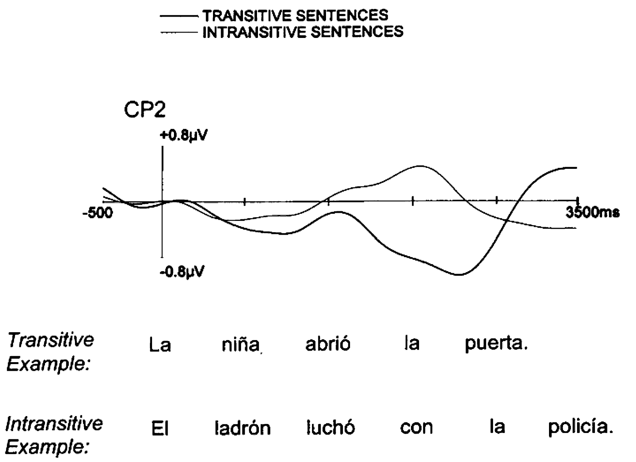


Fig. 10. ERP voltage recorded at CP2 electrode, directly comparing slow activity (low-pass filtering at 0.7 Hz) during the processing of a transitive sentence (solid) and an intransitive sentence (thin). Transitive example is the same as in Fig. 3. Intransitive example is the same as in Fig. 8. Each word in the example sentences is located under the corresponding milliseconds tick mark indicating its onset.

though noticeable activations were observed for Component 3 at the middle frontal gyrus (BA 10, $d \leqslant 2$ mm), at the precentral gyrus (BA 44, $d \leqslant 4$ mm) and at posterior cingulated regions (BA 31, $d \leqslant 2$ mm).

Component 4 explained 1.49% of the total variance (8.54% after rotation), and is again associated with early processes, since it displayed its maximum over the first 100 ms. The LORETA solution for this component corresponds Tailarach's coordinates [$x = 4$, $y = -67$, and $z = 22$]. The precuneus (BA 31, $d \leqslant 3$ mm and BA 23, $d \leqslant 6$ mm) in the occipital lobe is the nearest match for this source.

The differences between the two types of sentence were not evident to participants until after the appearance of the verb. For this reason, an exploration of the data was performed, in statistical terms, starting shortly after verb onset, on the brain slow electrical potentials (before submitting the waveforms to tPCA). Considering that the verb appeared at 1400 ms, the 1450–2810 ms period plainly covers any possible slow activity differences due to the appearance of either type of verb. The data indicated significant results for the factor Type of Verb from the 1770 to 1810 ms window to the last window explored (2770–2810 ms). $F_{1,19}$ values ranged between 4.73 and 23.822, while p values ranged between .042 and .0001. There were F value increases (and, consequently, p value decreases) from 1770 to 2450 ms, and F value decreases from then on. The highest F value corresponded to the 2410–2450 window. There were also significant effects of the Type of Verb by Electrode interaction from the 2090 to 2130 ms window to the 2570–2610 ms window. $F_{1,37}$ values ranged between 2.84 and 3.272, while p values ranged between 0.049 and 0.025. There were F value increases from 2090 to 2330 ms; the highest F values were observed for the three windows comprising 2330 and 2450 ms, and F values decreased after that point. Fig. 10 shows a direct comparison between transitive and intransitive verbs at the electrode with the highest differences (CP2). In fact, this absolute or raw difference between sentences displayed a central distribution, slightly right. Although in this comparison it is difficult to see the components extracted by means of tPCA (mainly because they overlap here), it can be appreciated in this figure that there are fluctuations to the positive roughly coinciding in time with Component 1 in both sentences, and that the fluctuation for intransitive material is delayed with respect to that for transitive sentences.

4. Discussion

The results showed that we were able to attain slow waves related to sentence processing in our laboratory, finding four electrophysiological components underlying these slow potentials. For the discussion, we shall group components in two broad categories according to the processes assumed to be reflected by them, based on their time course and on the comparison of their proposed neural generators with data from hemodynamic studies. Therefore, their interpretation should be seen as representing tentative though plausible hypotheses that must nevertheless be confirmed by studying different types of sentence structures and materials using the present methodology. On the one hand, replicated components (Components 1 and 3) appeared as related to particular language processes; on the other, Components 2 and 4 appeared as less specifically related to language processing.

4.1. Components 1 and 3: Thematic role assignment and sentence wrap-up processes

Component 1 exhibited a maximum at 1550 ms after the onset of the first word in the sentence, a time point that clearly coincides with the appearance of the verb. Even so, the activity of this component is not limited to the central presence of the verb. Rather, it begins the sentence with moderate load values, increasing them smoothly and progressively until the appearance of the verb. Thereafter, load values decrease again smoothly until a noticeable decay appears evident by the appearance of the last word. Accordingly, the involvement of this component covers most of the sentence, with enhanced participation upon the appearance of the verb. This Component 1 is the most relevant, as it explained significantly more variance than the others (50.12% after rotation).

The LORETA provided several foci of activity contributing to this component, the medial frontal gyrus

(BA 10) being the main one, accompanied by activations in the inferior and medial temporal gyri (BA 22, BA 21, and BA 37). A minor involvement of the inferior frontal gyrus (BA 44) was also found. Our Component 1 could therefore be described as the involvement of the medial frontal gyrus together with the medial and inferior temporal gyri, working jointly to yield an activity that appears throughout the whole sentence but displays its highest level of involvement with the appearance of the verb.

Though this component displayed mainly a frontal distribution, it seems entirely plausible that it could be identified as the anterior temporal positivity coincident with the appearance of the verb reported by Kutas and colleagues. Differences in topography have already been discussed, though the important source of activity for this component at inferior and medial temporal gyri should be accounted for. Accordingly, the use of the methodology employed here yielded an improved description of the temporal course and of the probable neural generators of this activity.

Given its coincidence with the verb, Kutas and King (1996) interpreted this activity as reflecting preliminary thematic role assignment based on verb information. The maximum value for our Component 1 was at about 1550 ms after first stimulus onset in transitive sentences, which corresponds to about 150 ms after verb onset. In our opinion, an analysis of certain aspects of verb information around that time can be accounted for (Sereno, Rayner, & Posner, 1998), which would be compatible with the assumption that Component 1 refers to thematic role assignment ascribed to the verb. Interestingly, there was a certain delay of the maximum value observed for this component during intransitive (filler) sentences (560 ms after verb onset), which might be related to the fact that prepositions, appearing subsequent to the verb during intransitive sentences, are also a relevant element in thematic role assignment (Chomsky, 1981). The proposed neural generators of Component 1 for intransitive sentences (medial frontal and inferior temporal gyri) largely coincided with those for transitive sentences, their time courses also being quite comparable. Accordingly, Component 1 could plausibly be equivalent in either type of sentence, and the processes reflected by this component could quite possibly relate to thematic role assignment.

This assumption also appears conceivable when considering the proposed neural generators for this component. Hemodynamic data indicate that prefrontal cortical regions, including BA 10 and 44, in consonance with medial and temporal gyri, including BA 22, BA 21, and BA 37, are involved in retrieval of information from semantic memory (e.g., Martin & Chao, 1999; Martin, Wiggs, Ungerleider, & Haxby, 1996; see also Cabeza & Nyberg, 2000 for a review). Medial and inferior temporal gyri are usually related to the semantic processing of verbal material during the comprehension of sentences (e.g., Cooke et al., 2001; Keller, Carpenter, & Just, 2001; Sakai, Hashimoto, & Homae, 2001) and isolated words (e.g., Beauregard et al., 1997; Price, 2000). On the other hand, recent data also reveal that BA 10/9 may be involved in local coherence processing during text comprehension (Ferstl & von Cramon, 2001). The coherence of a representation results from the semantic relations that interconnect its elements (Van den Broek, 1994).

Consequently, semantic operations seem to be attributable to the areas presumably generating Component 1. Although the issue may still be open to discussion, the preeminence and centrality of semantic information in thematic role assignment is currently being highlighted (Ferretti, McRae, & Hatherell, 2001; Saffran & Schwartz, 1998). Hence, considering both its proposed neural generators and the time point at which it displays its maximum values, it appears entirely plausible that Component 1 is reflecting thematic role assignment, or at least a crucial process necessary for this operation.

However, Component 1 cannot be restricted to either verb or prepositions for either transitive or intransitive sentences. Rather, Component 1 has a time course that operates throughout the sentence. Accordingly, if thematic role assignments were accepted as the main processes reflected by Component 1, its time course would rather be reflecting the attempt to assign thematic roles from the beginning of the sentence. This would be compatible with sentence processing models in which the thrust is to assign meaning as quickly as possible, the parser exploiting extrasyntactic information from every new input word, as far as possible without unnecessary delay (Marslen-Wilson, 1975; Marslen-Wilson & Tyler, 1980), which implies a continuum across sentence processing of semantic effects on thematic assignment (Carlson & Tannenhaus, 1988; Saffran & Schwartz, 1998; Tabossi, Spivey-Knowlton, McRae, & Tannenhaus, 1994).

Accordingly, our working hypothesis is that our Component 1 constitutes empirical evidence for a cortical activity that develops throughout the whole sentence and is related to semantic processes presumably involved in thematic role assignment.

The differences found between transitive and intransitive sentences when comparing brain slow electrical potentials (that is, before submitting the waveforms to tPCA) for the 1450–2810 ms period after onset of first word in the sentence can be discussed here. Although this comparison was somewhat secondary here, and differences in the materials other than the transitive–intransitive dimension might be considered, it can provide supplementary information of some interest. Differences between the two types of sentence in ERP slow waves were observed mainly over central regions, slightly to the right, and covering a time range from about 1770ms. after the first word in the sentence (370ms after verb onset) to about one second later. This is taking place clearly after the intervention of the verb-related activity or Component 1, and could therefore be related to the identification by the language processor of important differences in the implications by either type of verb. It seems interesting to point out that the timing and topography of the differences between transitive and intransitive verbs in these slow waves roughly coincided with the traditional values for the N400 component (Kutas, Federmeier, Coulson, King, & Münte, 2000). Despite the conventional view of this component as reflecting purely semantic processes, recent reports suggest that the N400 might actually reflect processes of lexical-semantic and structural information integration, consistent with operations involved in thematic role assignment (Friederici & Frisch, 2000; Gunter & Friederici, 1999). This activity, however, could not be identified with our Component 1, as both the timing and distribution are dissimilar. What these findings would therefore point to is that sentence comprehension is a complex process in which overall sentence-level dynamics and a word-by-word processing co-occur in order to achieve an understanding of linguistic information.

Component 3 displayed its maximum at about 2800ms after onset of the first word in the sentence, roughly coinciding with the end of the experimental sentences, as this occurs after the appearance of their last word. According to the solutions given by LORETA, the main origin for this component would be in the superior temporal gyrus (BA 22), with an additional noticeable activation of the middle frontal gyrus (BA 9 and 10) and of the posterior cingulated region (BA 31). Interestingly, this activation largely overlaps with that for Component 1. Indeed, the superior temporal gyrus has also been related to the semantic processing of sentences (e.g., Sakai et al., 2001). Therefore, additional activation of distributed semantic representations might be assumed to occur at the end of the sentence. Components 1 and 3 might then reflect the activity of functionally related processes, involving largely overlapping or similar brain regions, but whereas the activity reflected by Component 1 develops over the entire sentence, that reflected by Component 3 calls for the information obtained at the end of the sentence.

We believe this Component 3 might be identified as the temporal negativity indicating clause ending (called clause ending negativity, or CEN), reported by Kutas and collaborators. These authors proposed that the CEN would be reflecting working memory operations at clause boundaries (Kutas, 1997). Alternative or complementary to this explanation, a plausible process reflected by the CEN and our Component 3 would rather relate to sentence wrap-up, an additional processing in which readers engage when they reach the end of a sentence or a clause, as no further information is necessary to complete the sentence (Mitchell & Green, 1978; Rayner, Kambe, & Duffy, 2000). In a similar line might also be interpreted the additional activation of posterior cingulated regions observed for Component 3. There is indeed a possible relationship between this activity and the attentional processes presumably reflected by Components 2 and 4.

Finally, it must be mentioned that tPCA and LORETA analyses for intransitive sentences largely replicated this Component 3, with the exception that an involvement of right BA 44 was now observed and that temporal involvement, although again bilateral, was mainly left. Common elements are, therefore, the frontal and the temporal activations, together with posterior cingulated region activation.

4.2. Components 2 and 4: Attentional processes

Components 2 and 4 were considered as less specific to language processing, mainly because their neural generators (according to the solutions given by LORETA) appear as less consistently related to language processes (e.g., Price, 2000; but see Ferstl & von Cramon, 2001). These solutions have been precuneus and posterior cingulated gyrus (BA 7 and BA 31) for Component 2, and, again, the precuneus (BA 31/23) for Component 4.

Interestingly, these two components displayed their maximum values at the very first (Component 4) and the very last (Component 2) moments in the course of the sentence, though their time courses cannot be limited exclusively to these times for either component (especially Component 2). The two also originated from adjacent or similar areas. Indeed, the precuneus may be the shared origin for these two components. It has been reported that these areas constitute an element of the visual attention system, the 'foveal fixation system' (Petit et al., 1999), related to the linking of current visual information with prior perceptual knowledge (Maguire, Frith, & Morris, 1999). Accordingly, it appears plausible that our Components 2 and 4 reflect overall attentional processes occurring at sentence onset and at sentence end. Hence, whereas Component 4 might be reflecting a re-allocation of attentional resources for a new incoming sentence, Component 2, at the end of the sentence, may reflect a closure of the attentional processes.

However, although Component 4 was plainly replicated when tPCA analyses were performed for intransitive sentences, this was not the case for Component 2. Component 2 for intransitive sentences also displayed its maximum at the very end of the sentence, but appeared to largely involve the same areas as those implicated in Components 1 and 3. It would be worthwhile, therefore, to elucidate whether the activity of those areas at such a time is a feature of intransitive sentences, though this goes beyond the scope of the present study.

4.3. Differences between present and previous studies

The effects reported here do not exactly match those reported by Kutas and collaborators. We have been able to replicate the slow activity related to the verb and, presumably, the clause ending negativity (CEN), but not the very low-frontal positivity, nor the sustained occipital negative shift reported by Kutas' team. Also, the topography of the replicated activities does not exactly coincide with that previously reported—especially in the case of the slow activity related to the verb.

Indeed, there were certain differences in the methodological approaches between the present study and those of Kutas and collaborators that might explain, at least to some extent, these discrepancies. First, differences in topography could be due to differences in the references used for EEG recordings. In this regard, whereas Kutas and collaborators have mainly used a non-cephalic reference, in the present study a digital re-reference to linked mastoids was used from an original right mastoid reference. This is a more conventional procedure, which appeared preferable in order to detect laterality effects (Fisch, 1999). Nonetheless, differences in the reference employed cannot account for the failure in replicating the very slow frontal positivity, though the failure to replicate the sustained occipital negative shift related to visual processing might be explained, at least partially, by this procedure, given the proximity of the mastoids to this region.

A second difference between previous methodological approaches and the present one concerns the selection by Kutas and collaborators of the slow components and their distributions by means of a visual examination of the electrical signatures. In our study, the principal components analysis (PCA) was deliberately employed to select underlying ERP factors, since it has been considered that this method describes more objectively and efficiently than conventional analyses the variance contributions of temporally and spatially overlapping ERP components (i.e., the mean amplitude in a latency window) (Chapman & McCrary, 1995).

Another source of differences between the present study and previous work would relate to the type of material. Whereas Kutas and collaborators (Kutas & King, 1996) have mainly used multi-clause sentences that begin with transitive clauses and continue with a causative conjunction, we used single transitive sentences. This difference might explain the absence in the present results of the previously reported very slow frontal positivity that presumably reflects certain aspects of working memory processes, namely executive working memory functions (Kutas, 1997). Indeed, differences in working memory load between the two types of material appear clearly plausible at this level. Kutas and King (1996) already mentioned that the processes reflected by this long-lasting frontal activity would be most easily achieved and more readily completed for simple transitive constructions (i.e., the material in the present study) than for sentences with embedded clauses (the material used when this shift has been observed). This constitutes, in our opinion, the simplest explanation for our failing to detect this frontal slow positivity.

An additional difference between studies is that word onset asynchrony in the present study has been 700 ms, whereas it was 500 in the studies by Kutas and collaborators. This modification was introduced with the intention of better separating the temporal courses of different sentence-processing operations. However, it was made on the assumption that essential processes implied during sentence comprehension processes should remain the same in the present study as in previous ones. Nevertheless, it is true that this variation may have had some partial effect on working memory processes.

Finally, another source of differences between studies is the use in the present one of Spanish sentences, whereas previous studies have employed English sentences. Differences across languages may affect parsing processes (Cuetos & Mitchell, 1996), with important implications for certain working memory processes. Hence, this difference in the language of the material used emerges as an alternative and even complementary explanation for some of the differences between the present study and previous work.

Accordingly, we have two replicated ERP components and two new ERP components of slow activity obtained during sentence processing. Future research is necessary to further elucidate the contribution to these dissimilar results of the differences in either the material studied or the methodology applied. Whatever the case, much can be said on the basis of the present results about the temporal dynamics of simple transitive sentence processing.

5. Conclusion

Exhaustive data analyses of ERP data, by means of tPCA and 3D neural source analyses, lead to some consistent conclusions about the dynamic processes that may occur during simple transitive sentence comprehension at both the cognitive and neural levels. Furthermore, the validation (across languages and laboratories) of a procedure for studying the time course of language processing beyond the word level has been achieved. It is important to stress that the information provided by these procedures goes far beyond the possibilities of other modern brain-imaging techniques (including event-related fMRI) as regards the temporal dimension, while the spatial dimension was, to some extent, suitably approached by the application of current source analysis algorithms.

Component 1 should be highlighted as the central finding of this study. It has been interpreted here as reflecting semantic processes taking place throughout the entire sentence, presumably essential for thematic role assignment, and therefore probably reflecting a fundamental process in relation to sentence processing.

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