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On the contribution of ERPs to the study of language comprehension[1]

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Abstract

La compréhension du langage nécessite l'intégration de nombreuses informations à différents niveaux linguistiques. Grâce à une des techniques d'imagerie cérébrale, les potentiels évoqués (ou ERPs, pour Event-related potentials) il est possible d'évaluer *comment* et *quand* les lecteurs utilisent les informations linguistiques lors de l'interprétation d'une phrase. Après une introduction à la technique des ERPs et une revue de la littérature sur les composantes sensibles au processus linguistique (la N400, la ELAN et la P600) nous discutons d'un point de vue méthodologique les analyses réalisées sur ce type de données, analyses en terme de composantes et analyses en terme de topographie. Pour finir nous présentons une analyse préliminaire sur la compréhension du langage lors de la présentation de violation sémantique et syntaxique. Les résultats sont analysés à l'aide de la méthode de segmentation en micro-état des ERPs et sont visualisés en terme de carte topographique des composantes.

1. Introduction

Understanding the relation between brain structure and brain function constitutes a major objective of neuropsychology. Although research on this relation in the area of language has been pursued for more than a century, progress has been relatively slow in part due to our ignorance of the biochemical and physiological properties of the brain. Moreover, for obvious ethical reasons, the investigation of the representation of language and its processing in the brain has until recently been limited largely to inferences made from the observations of abnormal behavior in aphasic patients.

This approach of correlating the location and the size of lesions in post-mortem analyses with observed behavioral patterns has contributed substantially to our understanding of the relation of language processing and brain, but clearly has its limits. These relate to the variability in this relation across patients and the adaptability of the system after damage, both of which complicate drawing conclusions about normal functioning.

The introduction in the early 1970's of powerful non-invasive brain monitoring techniques has dramatically modified our approach to these problems. It has allowed us to collect large amounts of novel data about how our

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brain processes information and produces different types of human behavior. This enterprise is gaining increasing sophistication and now provides an important complement to these traditional methods of studying the relation between brain and language behavior. In addition these techniques have also been used to examine aphasic patients in order to better understand the relation between normal and pathological function.

This brief contribution presents some of the recent language-related research and situates our own efforts in this area. We first summarize some of the major theoretical issues confronted in the investigation of language comprehension, our research focus. We subsequently introduce experimental procedures based on the measurement of event-related brain potentials (ERPs), and we review some select ERP results obtained during different stages of language comprehension. Finally, we describe our current research on the processing of syntactic and semantic information in reading sentences.

2. Language comprehension

Models of language comprehension attempt to provide an account of the information processing that allows the listener to go from the sensory input to a discourse interpretation. The specific components of language comprehension can be summarized as follows: 1) speech processing, the segmentation and classification of the incoming sensory input, 2) lexical processing, the recognition of individual words and the access to the different types of information associated with them, 3) sentential processing, the extraction and combination of syntactic information of individual words and their order to construct a syntactic representation and the integration of this representation with meaning information and world knowledge to arrive at a sentence interpretation, 4) discourse processing, the integration of the interpretation of successive sentences to create a discourse representation. We will examine briefly each of these components below.

During speech perception the sensory input is classified to construct a series of successively more abstract (auditory, phonetic, phonological) representations (SAWUSCH, 1986). Although the speech signal that reaches the ears of a listener is continuous and variable, it is nonetheless perceived as being made up of discrete and distinct units. A central objective in the investigation of speech processing is to determine which units are computed and how this computation takes place.

During lexical processing, the representation computed during speech processing, the so-called "input representation", makes contact with the internally stored lexical representations. Thus, this input representation is matched with the lexical representations to select that lexical representation which best corresponds to the received input. This selection process involves the activation of a set of matching lexical candidates and the selection of the target word from amongst this activated set (MARSLEN-WILSON, 1990). Once the correct lexical entry has been located, the semantic and syntactic information associated with that word becomes available.

Sentence comprehension can be broken down into several component parts: extracting the syntactic structure and the semantic representation of a sentence, interpreting these representations in light of the preceding linguistic context, and retaining the relevant information in permanent memory. Syntactic parsing (FRAZIER, 1987) refers to the process of constructing an internal representation of the sentence on the basis of the information provided essentially by the morphosyntactic specifications associated with each word - especially the closed class or function words and their order. The mental computation of a sentence also includes the construction of a logical form expressing those aspects of meaning which are determined by sentence grammar. Syntactic parsing and its relation to semantic interpretation are topics that have received considerable attention in the psycholinguistic literature (MITCHELL, 1994).

The final step in deriving the speaker's communicative intentions involves discourse processing. Listeners are assumed to use a variety of strategies to understand the incoming discourse. The result of the application of these strategies is a representation of the discourse in memory in a hierarchical form with both higher and lower level propositions. In the process of understanding discourse, the listener is constantly drawing inferences to increase the coherence and the completeness of the message (SINGER, 1994).

3. ERPs and language processing

Over the last two decades, functional brain-imaging techniques have been increasingly used to examine both language production and comprehension. Many of these techniques, like positron emission tomography (PET) or functional magnetic resonance imaging (fMRI), provide precise information concerning the location of brain activity during language processing. Although the spatial resolution of these techniques is very high, their temporal resolution is not. However, recording electrical activity of the brain (electroencephalogram, EEG) or magnetic activity (magnetoencephalogram, MEG) provides excellent temporal resolution that can reveal the successive steps of processing in the brain. In this paper we will only discuss methodology and results of one of these techniques: Event-related potentials.

3.1 ERPs and how they are analyzed

Electrodes placed upon the scalp measure the voltage fluctuations that are produced by a large population of neurons. The resultant electroencephalogram (EEG) reflects the spontaneous electrical activity of the brain across time. In contrast, ERPs represent the electrical activity related to specific sensory, motor or cognitive events (HILLYARD & PICTON, 1987) that are triggered by the presentation of synchronized and repeated stimuli. Since the ERP signal is weak (5-10 mV) and confounded with the stronger but noisy EEG signal (50-100 mV), it is necessary to extract the former from the latter. To do so, averaging techniques combine the EEGs that are obtained from multiple trials and are time-locked with the onset of the critical stimulus. Through such analysis techniques, the spontaneous activity is basically eliminated and the activity resulting from the processing of the stimulus remains. As more trials are included in the analysis, the ERP signal becomes better.

ERPs are most commonly represented in terms of three different parameters: the amplitude of the average waveform (in microvolts), the latency (delay from stimulus onset) and the polarity (positive or negative). The amplitude is calculated with respect to some reference base-line of non-activity. Finding an appropriate reference is not a trivial matter. Typically the maximum or minimum value within a given time-window is taken to identify a peak. Peaks are thus generally labeled in terms of their polarity (P or N) and their latency (400 or 600 ms).

On the basis of an analysis of the peaks and their relation to specific electrode sites, it is possible to identify different components. These are taken to correspond to the processing of a specific type of information by a particular part of the brain. Components can be defined in terms of constant relations between systematic variations in the external stimuli and both the properties of the peak and of the activated scalp region. We will examine several components related to language processing in the following section.

Since the latency ranges during which certain components emerge have now begun to be established, researchers often concentrate their analyses upon the appropriate temporal windows and attempt to discover which external factors produce and modulate the components at these specific latencies. Fluctuations in the polarity, the amplitude, the latency of the peaks and the topography of the potential on the scalp are all subject to analysis.

A topographic map allows the researcher to visualize the distribution of the electric field generated by the ensemble of neurons firing in the brain. Although the same surface topography observed on the scalp could be generated by two different populations of neurons, two different surface topographies are most likely produced by different sets of neural generators (SKRANDIES, 1986; FENDER, 1987). Thus, significant differences in two topographic maps suggest that the underlying neuronal activity is not the same. If we accept that a cognitive function can be defined by specific neuronal activity, we can conclude that different configurations of electric potential reflect different psychological processes.

The study of the topography of the components makes it possible to obtain some information concerning the localization of the neural generators activated during the task. However, the problem of drawing inferences concerning the localization of these generators on the basis of scalp topography, the so-called inverse problem is very difficult – although many efforts are currently being made to find the appropriate algorithms and to test these solutions.

3.2 Advantages of ERP studies.

Language comprehension has been studied experimentally in recent years with on-line measures of mental chronometry based on reaction times (RTs). In comparison with mental chronometry, ERP presents a number of potential advantages. First, the data are collected continuously and generate a measure for every processing moment rather than only a single measure per trial like for RTs. A further advantage of ERPs is that participants are not required to engage in a secondary task, as is the case in psycholinguistic experiments on comprehension. For example, with the ERP method they can be instructed to simply read or listen to sentences without making any conscious decision or response. However, to ensure that the participants are actually following instructions and understanding the sentences that they are receiving, some additional test of comprehension is often included in the experiment. Finally, unlike many on-line experimental techniques (e.g., phoneme monitoring) ERP experiments can be conducted in both the visual and the auditory modality.

4. Major findings on language comprehension

So many language-related studies with ERPs have been conducted in the last two decades that it is beyond the scope of the present article to give them complete coverage. Rather, in what follows we restrict ourselves to some of the major findings of this research on the different linguistic levels of processing and their associated components. Different components reflect specific activation of neuronal network and define distinct stages in the linguistic processing of the semantic properties of words or the syntactic category of words.

4.1 Semantic processing and N400 component

The development of ERP language research began with the seminal study by KUTAS & HILLYARD (1980) on the semantic processing of written sentences. These authors examined the ERPs produced when participants read sentences which ended either with a semantically congruent or incongruent word. They observed an endogenous component that peaked about 400 milliseconds (ms.) after the onset of the incongruent word. This so-called N400 is a broad, posteriorly distributed, negative wave.

There are several factors that affect the amplitude of this component including: the critical word's cloze probability, larger N400 amplitude for less predictable lexical items compared to more predictable ones (KUTAS & HILLYARD, 1984); word frequency, larger N400 amplitude for low frequency compared to high frequency words (VAN PETTEN & KUTAS, 1990, RUGG, 1990); word concreteness, larger N400 for abstract compared to concrete words (PALLER, KUTAS, SHIMAMURA & SQUIRE, 1987); word class, larger N400 component for content compared to function words (BESSON, KUTAS & VAN PETTEN, 1992); semantic relation between words, larger N400 for unprimed compared to primed word (BENTIN, MCCARTHY & WOOD, 1985); and word repetition, larger N400 for first presentation compared to the second one (BESSON, KUTAS & VAN PETTEN, 1992). To conclude, the amplitude of the N400 component provides a measure of the difficulty encountered by the reader in integrating the lexical element in the preceding context.

The N400 component has been observed under a wide range of conditions: in different languages including English, Dutch, German, French, in different modalities including visual, auditory and even sign language, and with different experimental procedures (for a review see KUTAS & VAN PETTEN, 1994).

It is not yet known precisely which processing stages are reflected by the N400 component. One possible answer comes from research using masked semantic primes on word pair trials. The size of both semantic (BROWN & HAGOORT, 1993) and phonological (CONNOLLY, PHILLIPS, STEWART & BRAKE, 1992) priming effects as reflected by N400 amplitude were considerably reduced when the primes were masked. These data suggest that N400 effects are obtained when participants consciously perceive the stimuli and that the N400 is dependent on postlexical integration processes.

4.2 Syntactic processing and P600 and ELAN components

Attempts to find ERP components specific to other linguistic levels of processing have obtained some success. For example, the presentation of syntactic violations like verb subcategorization violations (OSTERHOUT & SWINNEY, 1989; OSTERHOUT & HOLCOMB, 1990) did not produce a N400 component, but rather an increase in the positivity with a biparietal distribution, several hundred milliseconds later. This effect has been called a P600 (OSTERHOUT & HOLCOMB, 1992) or a late positive syntactic shift (HAGOORT, BROWN & GROOTHUSEN, 1993).

Certain researchers have claimed that the P600 component is not specifically linguistic, but belongs to the family of P300 effects, often observed after the reception of any unexpected stimuli. At present, the discussion as to whether the P600 is specifically a linguistic component is still on-going. But, OSTERHOUT, HOLCOMB & SWINNEY (1994) have claimed that the amplitude of the late positive peak is correlated with the "cost of processing". An alternative possibility is that the latency in the onset of this peak reflects the amount of reanalysis required to recover from an erroneous analysis of a garden-path sentence (FRIEDERICI & MECKLINGER, 1996).

Experiments have subsequently compared more varied types of syntactic violations, and a P600 has generally been recorded for all types of syntactic violations presented. It is interesting to note that certain studies have obtained an earlier effect, which is violation-specific. In particular, FRIEDERICI, PFEIFER & HAHNE (1993) have observed an early component with an "early left anterior negativity" (ELAN) between 200 and 400 ms. after the onset of the word violating the basic phrase structure of the language. For both a visual (OSTERHOUT & HOLCOMB, 1992) and an auditory mode of presentation (FRIEDERICI, PFEIFER & HAHNE, 1993), a word having an inappropriate syntactic category elicited this ERP pattern. It appears thus that the processing of syntactic category information of a word precedes the processing of its lexical-semantic information (N400).

In summary, two ERP components, the ELAN and the P600, have been observed in the presence of syntactic violations. The P600 component is associated with aspects of structural reanalysis and repair, including those required to deal with ungrammatical sentences. In contrast, the early negativity ELAN appears to reflect a first-pass parsing stage responsible for the building of local phrase structure.

5. Language-related ERPs research in Geneva

This research is the fruit of a collaboration with the cartographic laboratory of the Cantonal hospital of Geneva where the analysis techniques of topographical mapping were developed.

5.1 Mapping and segmenting ERPs

To restrict the ambiguity of analyses based on the amplitude of specific components, analyses based upon the spatial configuration of the electric field have been proposed, including one by LEHMANN (1971). This latter technique involves the analysis of the topographic distribution of the electric field configuration. The interest of such spatio-temporal analyses of ERP lies in the fact that all of the electrical activity measured by the electrodes is included in the analysis. Thus, the components are analyzed in terms of the distribution of both positive and negative polarity across the scalp at any given moment in time.

The main objective of the spatio-temporal analyses (LEHMANN & SKRANDIES, 1980) is to identify and characterize the changes in the electrical configurations on the scalp. These configurations remain constant over a certain period of time, and change into the next state relatively rapidly. Thus, it is possible to identify periods during which the topographic maps are stable and only the power varies. Such periods are called micro-states, functional/physiological states of the brain, characterized as a fixed spatial distribution of active neural generators. According to LEHMANN & SKRANDIES (1980), cognitive activities of the brain can be represented as a series of non-overlapping micro-states across time. The sequence of micro-states can thus be associated with functional stages of information processing that take place during language comprehension (BRANDEIS, LEHMANN, MICHEL & MINGRONE, 1995).

5.2 Our experiment

Objectives

We are interested in examining the processing of different types of grammatical violations in sentences by means of this segmentation technique (BRANDEIS & LEHMANN, 1986; LEHMANN, 1987). Our objective is to use topographic analysis to characterize successive segments or micro-states in the reading of sentences. By presenting different kinds of violations we intend to identify the diverse segments which vary on scalp topography.

Procedure and material

Stimuli were presented in French. The violations were of four different types: semantic violations (restrictions of selection), and morphosyntactic violations of person and number agreement, and of tense.

Examples:

Semantic	Après-demain les lettres *mangeront* un sandwich.
Number agreement	En été l'herbe *pousseront* facilement.
Person agreement	Dans un an les travailleurs *gagnerez* de l'argent.
Tense	Demain l'étudiant *lisait* le livre.

Participants were required to read sentences presented one word at a time on a computer screen. Each word was displayed for 200 ms. with an SOA (stimuli onset asynchrony) of 500 ms.. In addition, participants had to indicate by means of a delayed manual response whether the sentence was grammatical or not.

We recorded the ERPs with 41 multi-channel electrodes placed on the scalp, and we synchronized these recordings with the onset of the violations.

Results

Preliminary results are shown in Figure 1.

A
Segment N400: 389-456 ms

B
Segment P600: 649-716 ms

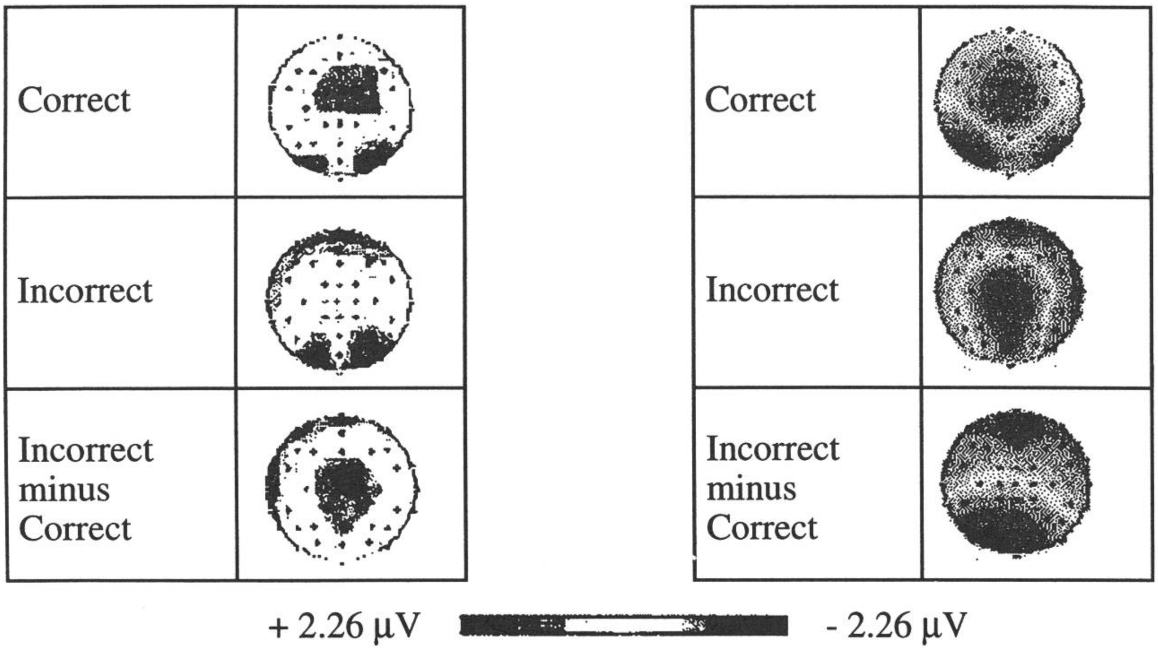

Figure 1: The average reference grand average maps (N=17) are presented for the N400 micro-state (A; 389-456 ms) and the P600 micro-state (B; 649-716 ms). A, incorrect corresponds to the presentation of a semantic violation, B incorrect corresponds to the presentation of a number agreement violation. Correct endings on the top row, incorrect endings on the second row, and segment difference maps (incorrect minus correct) on the third row. Maps are linearly interpolated from the 41 electrodes, left on the head is shown on the left, right on the right.

For the semantic selectional restriction violations, the results of the reading of the anomalous and matching correct sentences differed in only a single segment. The segment maps in Figure 1-A show the full N400 topography and confirm that the spatial feature analysis captures the effects on map topography very well. The difference maps (obtained by subtracting incorrect from correct ERP maps) showed clear centro-anterior minima and a left prefrontal maximum in the N400 segment (386-456 ms).

Violations of person and number agreement produced differences on more segments as compared with the normal sentences than did the semantic violations. In a first latency range, (from 289 to 556 ms., 4 segments) we recorded a negative component in the posterior sites (not shown here) whereas for the later latencies (649 to 748 ms., 2 segments) we observed a positive component situated in a more posterior sites with an amplitude minima in frontal sites (see Figure 1-B). This latter component appears to correspond to the P600 described above.

Finally, violations of tense produced differences later than in the semantic violation condition, and more restricted in time than agreement violations (number or person). Results showed the occurrence of a negativity located in the posterior sites and a positivity located in the frontal site, in only one segment (457 to 556 ms.).

6. Discussion and conclusion

Our results replicate and extend the findings found in the literature, a N400 component for the semantic violation and a P600 pattern for the violations of agreement. Interestingly, the tense violations produce a different pattern than those obtained for the agreement violations (number and person), both of which behaved roughly in the same manner. Of interest for the linguistic analysis of the relevant constructions is the fact that subject-verb mismatch in person or number features and adverb-verb mismatch in tense features produce clearly distinct electrophysiological response. This is expected under current approaches postulating different structural positions and licensing procedures for the two kinds of agreement phenomena (POLLOCK, 1989; CHOMSKY, 1995).

The adaptive segmentation and topographic analysis used here have demonstrated that the N400 and the P600 effects are not only restricted to negative and positive peaks, respectively, as they have been described traditionally. The present findings suggest that the negativity of the N400 is more anterior, and that this component also manifests itself as an increase of positivity in frontal sites. The topography of the P600 component is commonly described as bilateral posterior positivity. Our topographical analysis has shown that the P600 effect is associated with an increase of positivity in the posterior sites but also with an increase of negativity in the frontal sites. In sum, these analyses provide a more complete picture of the electric activity across the entire scalp rather than the activity from a few select electrodes.

The sequence of micro-states reflects the timing, the strength and the spatial pattern of neural activity that presumably corresponds to specific cognitive events. Several micro-state segments have been identified in our topographic analysis. Although we have not yet been able to associate each of these segments with specific psycholinguistic parsing operations, this is the clear objective for our future research.

The study of language knowledge and language use in theoretical linguistics and experimental psycholinguistics is likely to interact more and more tightly with the study of ERP in the near future. Thanks to their excellent temporal resolution, ERP techniques offer a highly promising testing ground for hypothesis on the mental organization and access of linguistic knowledge. It is to be expected that more and more subtle distinctions predicted by sophisticated linguistic models will be tested with ERP techniques, which could thus provide new, crucial evidence bearing on the mental representation of language.

Functional neuro-imaging research is rapidly developing with large technical advances in the performance of scanning machines over the last 15 years and with new techniques and analysis procedures being introduced. We expect that the results from ERP technique with its temporal resolution can be combined with other techniques like fMRI with their more precise localization of cognitive function. Ultimately, it may well be possible to produce a film that shows the progression of brain activity in reading or listening across time from the moment that the signal entries the sensory system until a full interpretation has been constructed.

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