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Event-Related Potentials and Semantics: An Overview and an Integrative Proposal

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Event-related potentials have shown to be a valuable tool when studying language processing. In this review we focus on the literature that deals with semantic processing. Thus, we review studies concerning the classic semantic-related ERP component, the N400, those concerning the recently described recognition potential (RP), and studies that have attempted to identify brain activations related to semantic processing without focusing on specific ERP components. From the available data we provide an integrative proposal. According to this proposal, ERPs are clear indexes of the three subprocesses presumably involved in semantic comprehension. ERPs would provide, additionally, information about the time course of such subprocesses. © 2001 Academic Press

Key Words: event-related potentials; semantic processing; recognition potential; N400; fusiform gyrus.

INTRODUCTION

The large number of processes underlying language comprehension have been described in a variety of models that attempt to integrate the increasing amount of knowledge on language processing (Altmann & Shillcock, 1993; Grosjean & Frauenfelder, 1997). These models not only aim at identifying and describing the factors involved in the processing of phonological, morphological, syntactic, and semantic information, but also at knowing how these processes occur in a temporal dimension. This is a very important point by considerating the speed at which these processes take place when we read, speak, or just hear speech. However, in order to have a wholly appropriate approach, a detailed description of the relationships between language and brain seems mandatory (Friederici, 1997). Such a description should not include exclusively a list of locations of the different areas involved; it is also important to determinate the moment at which these areas are involved and how they interact across time.

While techniques such as positron emision tomography (PET) or functional magnetic resonace imaging (fMRI) are very effective when localizing brain areas that deal with language processing (Cabeza & Nyberg, 1997; Chee et al., 1999), others seem preferable when describing the temporal course of these processes. These techniques would include electroencephalography (EEG), magnetoencephalography (MEG) (Kuriki et al., 1998), and the recently developed near-infrared optical im-

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aging, which has not been used, to our knowledge, in any language study outside of the neurosurgical operating room. Event-related potentials (ERP) are among those techniques that provide a temporal resolution of milliseconds. ERPs are summed postsynaptical potentials generated by large populations of neurons that reflect the electrical response of the brain time-locked to the presentation of a given event averaged over time. Such a response can be either positive (P) or negative (N) so that components are usually named with a P or a N to reflect their polarity. Components may also differ in latency, usually the moment at which they start to be modulated compared to baseline prestimulus activity or when they reach maximum peak values in relation to stimulus onset. Finally, it must be noted that the electrical response will be larger depending on the brain area involved and the electrode placement.

There are two main approaches when using ERPs in the study of cognitive processes. The first consists of centering attention on a given component (which we will call the ''from ERP to cognition approach''), whereas the second one consists of identifying components related to a given cognitive process (the ''from cognition to ERP'' approach).

In the field of language processing, ERPs have been widely used, almost exclusively, since the early 1980s for studying comprehension, specifically word recognition. This is due to the methodological problems that are implied in the study of language production with ERP. Articulation and muscle activity cause important artifacts that mask brain activity. However, some studies have been performed recently to elucidate the time course of syntactic, phonological, and semantic processes involved in language production (van Turennout et al., 1997, 1998). As these studies are the exceptions, this overview focuses exclusively on language comprehension. Moreover, we restrict our review to semantic processes. This field has been the object of much attention in recent years, resulting in a large amount of reported data that should be reviewed and integrated in order to clarify the state of the question at the present moment. This will also facilitate further research by clarifying the aims and problems that still need to be resolved.

Since its earliest use, most of the ERP research on semantic aspects of language comprehension has mainly followed the ''ERP to cognition'' approach. Hence, studies were mainly devoted to the N400 component. However, in the past few years a new ERP component, the recognition potential (Rudell, 1990; Rudell & Hua, 1997; Rudell & Hu, 2000; Martín-Loeches et al., 1999; Hinojosa et al., in press), has proved to be at least a complement to the N400 in the study of language semantic processing, as is discussed below. Also in very recent years, a number of experiments has been conducted following the ''cognition to ERP'' approach. We review data concerning both approaches.

FROM ERP TO COGNITION

The N400 Component

The so-called N400 was originally described by Kutas and Hillyard in 1980. They visually presented seven-word sentences to their subjects. Words were presented singly every 700 ms until the sentence was completed. Some of these sentences (75%) were correctly constructed, whereas the remaining 25% ended with a word that was incongruent with the semantic context of the sentence. Sentences that ended this way evoked a posterior negative wave between 300 and 600 ms after the onset of the last word. Several posterior findings have clearly demonstrated that N400 amplitude varies as a function of how easily a word is integrated within a sentence context (King & Kutas, 1995; Kutas, 1997). Hence, it is important to note that the N400 amplitude would not therefore index word anomaly, but instead the absence of contextual support for that word (Van Petten et al., 1999).

Although this component has been mainly related to sentence comprehension (Brandeis et al., 1995), it has also been found when pairs of words were presented, with the N400 displaying larger amplitudes when the second word has no semantic relationship with the first one (Holcomb & Neville, 1990; Kiefer et al., 1998; Silva-Pereyra et al., 1999). Even presenting isolated words has elicited an N400 (Nobre, Allison, & McCarthy, 1994).

N400 responses have been reported in several languages (Friederici, 1997) and with both visual and auditory stimulation. Whereas in the visual modality the N400 displays its maximum over right centroparietal areas, in the auditory modality it shows a more symmetric distribution and it can even display a certain degree of left lateralization. Moreover, as Holcomb and Neville reported (1990, 1991), the N400 has a longer duration and an early onset with auditory presentation, probably due to coarticulaton processes and to the fact that most words can be identified before their acoustic offset is completed, as postulated by models that propose that a set of lexical candidates is actived by incomplete auditory input (Marsel-Wilson, 1987; Norris, 1994).

Several task manipulations affect the N400. Increase the rate of word presentation delays N400 latency and cause it to display a more frontal distribution (Kutas, 1987), which probably reflects an increase in the difficulty of word comprehension as the speed at which a word has to be processed increases. Word repetition leads to an attenuation of the N400 component, but only in those cases in which first presentations were attended (Okita & Jibu, 1998). Finally, words that occur in late-sentence positions elicit smaller N400s than the words situated in earlier positions because the former ones can take advantage from a larger exposure to the ongoing sentence context (Van Petten, 1995).

A great number of experiments have been performed concerning priming effects on N400. Both its latency and its amplitude diminish with semantic and phonological priming (Nobre, Allison, & McCarthy, 1994; Radeau et al., 1998), this reduction being more remarkable in the first case. However, interposing an unrelated word between primes and targets disrupts amplitude and latency effects of priming N400 (Deacon et al., 1998). These findings were taken by the authors as a tentative evidence that semantic information is represented in a distributed fashion rather than locally. A recent study attempted to find out differences between verb and noun processing based on N400 amplitude and latency when a semantic priming task was presented to subjects (Gomes et al., 1997). Results showed differences in the N400 latencies between both kinds of words, indicating functional differences in the processing of nouns and verbs, although no topographic differences were found. However a recent study conducted by Sitnikova and Holcomb (1999) reported a more anterior N400-like component distribution for verbs than for nouns, which would reflect not only functional differences in the processing of verbs and words as proposed by Gomes et al. (1997), but also that these types of words are processed in different brain regions. Whatever the case one should be cautious when interpreting these data, since they refer to regional distribution on the scalp and not to the location of the source.

A few number of studies have reported how the N400 varies with age. Its latency diminishes as age increases, probably due to facilitation of lexical access and semantic integration processes (Gunter et al., 1992). However, N400 latency increases again in the elderly (Gunter et al., 1996; Kutas & Iragui, 1998), in this case probably due to impairment of language-related capacities. The amplitude is also reduced in elderly people. Kutas and Iragui (1998) recorded ERPs from individuals between 20 and 80 years of age and found a linear decrease in amplitude and an increase in latency with age. These authors attributed their results to quantitative rather than qualitative changes in semantic processing. Functional changes in semantic processing with aging, such as larger semantic networks and diffuse semantic activation, have been also suggested as explaining this reduction (Miyamoto et al., 1998). Finally a study in which preschool children had to discriminate between speech and nonspeech auditory materials revealed that the N400 amplitude over the right temporal cortex reflects stimuli discrimination at this age (Molfese & Molfese, 1988).

Several points of view have been developed to attempt to explain the role played in language comprehension by the processes the N400 reflects. The N400 was initially related to lexical access or to semantic representation of a word (Kutas & Van Petten, 1988). More recently, however, it has been suggested that the N400 component mainly reflects postlexical processes related to semantic integration (Friederici, 1997). However, Kluender (1991), has reported an N400 even in response to close class words, which would support previous assertions. In this sense, the N400 would be therefore reflecting semantic expectancy relative to word integration in addition to associative postlexical processes that integrate word representations with current context (Holcomb, 1993; Chwilla et al., 1995; Federmeier & Kutas, 1999; Weckerly & Kutas, 1999). Finally, another point of view considers that the N400 component reflects the inhibition of incompatible knowledge (Debruille, 1998).

Regarding the neural generators of the N400 component, it must be said that intracranial recordings suggest that they are placed in the neocortex, near the collateral sulcus, including anterior fusiform and possibly parahippocampal gyri (Nobre, Allison, & McCarthy, 1994; McCarthy et al., 1995). These findings have been recently corroborated by studies using high-density mapping (Johnson & Hamm, 2000).

Recognition Potential

The recognition potential (RP) is an electrical brain response evoked when subjects watch recognizable word images (Rudell et al., 1993; Rudell & Hua, 1997; Rudell & Hu, 2001; Martín-Loeches et al., 1999; Hinojosa et al., 2000). It was originally described by Rudell (1990), who presented English and Chinese words to subjects who could not speak Chinese. He found a positivity with a peak latency in the 200- to 250-ms interval in occipital regions in response to English words but not to Chinese ones. Similarly, when subjects were Chinese speakers an RP response was evoked by Chinese words, while no response was evoked by English words. In further experiments (Rudell, 1992) developed a stimulus presentation procedure named ‘‘rapid stream stimulation’’ that basically consists in presenting either recognizable or nonrecognizable stimuli being presented at a high rate of stimulation (between 4 and 10 Hz).

Several task manipulations affect its latency, such as degrading image quality (Rudell, 1991; Rudell & Hua, 1995; Martín-Loeches et al., 1999) or increasing word difficulty (Rudell & Hua, 1997; Rudell, 1999); both increase RP latency. On the other hand, presenting a prime stimulus decreases RP latency (Rudell & Hua, 1996a).

Selective attention and conscious awareness play an important role when evoking the RP. Rudell and Hua (1996b) presented superimposed Chinese and English words to subjects who spoke both languages. The task consisted of selectively response to words of only one target language. The main finding was that the RP was evoked only by attended language.

The RP is a good index of reading skills. In this sense, subjects with greater scores in the Graduate Record Examination Verbal showed a shorter RP latency (Rudell & Hua, 1997). From these results, authors concluded that this component might be reflecting the speed at which words are perceived.

Rudell and Hua (1997) raised the possibility of the RP being sensitive to semantic processing. This assertion was recently supported in an experiment in which words, pseudowords, strings of letters, and word fragments were presented to subjects. The major finding was that RP amplitude increased progressively and significantly as the level of linguistic analysis increased, showing the highest amplitudes in the case of words (Martín-Loeches et al., 1999). Moreover, in a different experiment the RP showed larger amplitudes when stimuli belong to a specific semantic category (animals) compared to an heterogeneous pool of words, indicating that the RP is sensitive not only to the presence of semantic aspects but also to the specific semantic content (Martín-Loeches et al., 2001). This leads us to conclude that the RP does not reflect all-or-nothing processes, but a gradual response to the different psycholinguistic levels.

As the RP amplitude is maximal at occipital areas, Rudell and collaborators speculated with the possibility that its origin is in extrastriate occipital cortex, where neural activity related to words and symbols has shown to originate in the 150- to 300-ms interval (Kuriki et al., 1998). Recently, two experiments have been performed by our research group in order to determine the possible neural generators of the RP applying the Brain Electrical Source Analysis (BESA) algorithm (Scherg, 1990, 1992). The results of applying this procedure showed that neural generators of the RP are located in medial parts of the lingual/fusiform gyri (Hinojosa et al., 2000; Martín-Loeches et al., 2001). Both the lingual and fusiform gyri seem to play important roles in semantic processing, although their specific involvement on these processes is still unclear (Büchel et al., 1998; Hagoort et al., 1999).

On the basis of all these findings the RP, a component that has received as much attention as the N400, seems a valuable and promising tool for the study of semantic processing with ERP.

FROM COGNITION TO ERPS

A certain number of studies reflect a variety of findings related to different aspects of semantic processing. These findings appear difficult to integrate due to the disparity of results obtained, although many of the differences might probably be related to theoretical and methodological divergences in the procedures of stimulus selection and presentation. Several findings, nevertheless, reveal important aspects that should be taken into consideration and should stimulate further research. These findings are summarized below.

There is some evidence of ERP modulations related to semantic features at very early latencies. For example, a recent study using the semantic differential technique revealed ERP responses that were sensitive to connotative semantic aspects as early as 80 and 265 ms after stimulus presentation without hemispheric differences in scalp topography (Skrandies, 1998). Similar early activations related to semantic factors have been reported by other studies. For instance, Nobre and collaborators found an activation in posterior fusiform gyrus peaking around 150 ms after the presentation of the stimulus that was selectively elicited by words but not by faces or other nonlinguistic visual stimuli (Nobre et al., 1994; Allison et al., 1994). Compton et al. (1991) presented words and random nonwords in a passive viewing task to their subjects, reporting a left lateralized ERP difference between words and nonwords over posterior temporal areas starting at about 125 ms poststimulus onset. Schendan et al. (1998) also found that responses that originated in the posterior fusiform gyrus for printed words started to diverge from other objects at 90 ms and were maximal around 150 ms after stimulus onset. Finally, Sereno et al. (1998) described how ERPs to words diverged from those to pseudowords and consonant strings in a lexical decision experiment at 100 ms over posterior parietal scalp sites. Taken together, these indicate that brain activity is modulated by the meaning of the stimuli even at early processing stages.

Another group of studies, however, suggest later influences of semantic processing. Khated et al. (1999) used a pair matching paradigm where subjects had to decide whether the second word of a pair is semantically related to the first one. In this study the authors tried to figure out when semantic and phonological word processing start to differ. The major finding was that these processes do not differ in the 280 ms following word presentation and after that latency, differences last for only 100 ms. Ziegler et al. (1997) used a letter search task and a categorization task in which subjects had to decide whether the target stimulus belonged to a prime category. Target stimuli included words that could belong to a particular category and pseudowords. Differences between words and pseudowords started around 300 ms, although several differences could be found as early as 100 ms on certain electrodes. The effects mainly consisted of an overall increase of a negativity to pseudowords probably related to an increment in processing difficulties.

In another study, a negative potential peaking at about 450 ms was reported by Bentin et al. (1999). These authors presented abstract and concrete words, pseudowords and strings of consonants while subjects had to keep a silent count of the abstract words. This negative potential was maximal at anterior-temporal and left fronto-central sites and was associated with semantic processing, as it was evoked by words but not by pseudowords or strings of consonants. These authors dissociated this negative potential from other N400-like responses, as it did not display a similar distribution. Moreover, its latency was larger; this longer latency is probably attributable to stimulation procedures, as stimuli were presented at a lower rate and with longer duration than other ERP components paradigms.

Several of these studies made an effort to attempt to integrate word comprehension aspects and those related to more complex linguistic units such as sentences. Posner and Pavese (1998) presented two kind of tasks to their subjects. In the first one they presented a sentence with an omitted word, followed by an isolated word; subjects had to judge whether the word was appropriate to the sentence context. In a second task, subjects had to ignore the sentence and perform a lexical decision concerning whether the isolated word was a natural or a manufactured object. Results indicated that the second task activates left anterior-frontal areas around 200 ms after the presentation of the stimuli. These authors related these findings to the search of word meaning in working memory. In relation to the first task, an activation over left posterior Wernicke areas was reported, peaking at around 600 ms after stimulus onset. Such activation would be related to the role that these posterior areas play in integrating word meanings in order to constitute the meaning of the sentence taken as a whole. In a different experiment conducted by Abdullaev and Posner (1998), two tasks were again presented to the subjects. The first one consisted in reading words aloud, whereas in the second one the same words were presented to subjects but they were instructed to give a use for each of the words. Authors found a pattern of activations similar to that reported by Posner and Pavese, together with activation of the anterior part of the cingulus around 170 ms after stimulus presentation. On the basis of these results, these authors outlined a model in which the semantic processing of visually presented words activates on a first stage (around 150 ms after the word is presented) an anterior region of the cingulus related to processes that tend to direct attention to the most appropriate word meanings. The access to the meanings would take place later, at around 200–250 ms, as reflected by the activation of the left anterior cortex. On a final step, Wernicke’s area activation at around 600 ms after stimulus presentation would be related to comprehension of the propositions that include several words (Abdullaev & Posner, 1998; Posner & Abdullaev, 1999).

Finally, we consider a few number of studies that directly deal with sentence comprehension. Of the highest interest are the studies developed by Kutas and King (1995, 1996), who searched for ERPs that might reflect the hierarchical relationships between words in sentence processing. They presented simple transitive sentences that included a subject, a verb, and an object. These sentences were presented visually word by word, and a word was displayed every 500 ms. They found several ERP responses to different linguistic aspects such as a left occipital negativity that was associated to the processing of the visual input, or a clause-ending negativity related to working memory processes concerning sentence closure. More interestingly, they reported a positivity over anterior temporal regions evoked by verbs that authors related to thematic role assignment based on the information included in the lexical representation of the verb (Kutas & King, 1996).

The main criticism that these studies might receive is that words were presented at a rate that does not correspond to the rate at which natural speech is perceived, which is about three words per second (Levelt, 1989). Mueller et al. (1997) replicated these results but using recorded (more natural) sentences. Their results were identical to those obtained by King and Kutas with the exception that the topographic distribution of the electrical activity was more right lateralized in the case of auditory presentations.

DISCUSSING AND INTEGRATING DATA

We have reviewed a large amount of data concerning semantic language processing that would be reflected by the activation of several brain areas at the time that these processes occur. Regarding sentence comprehension, conclusions should be only tentative, as only a few studies have been devoted to this feature. On the basis of available data, nothing but the time at which thematic role assignment occurs according to the semantic information provided by the verb can be well established. More studies need to be made in order to validate current psycholinguistic modular and interactive models. In the case of word comprehension, however, the situation changes dramatically due to the numerous studies performed, so that an integrative proposal, including the time course of the processes implied, could be outlined on the basis of ERP.

Semantic processing mainly consists of three basic subprocesses. First, named lexical access, a kind of presemantic analysis, is performed; the initial input activates a subset of compatible entries in the mental lexicon. Later, and during lexical selection, the best of these candidates is chosen among others as the preferred one. In a final step, the selected lexical item is integrated into a higher order representation as specified by the semantic and syntactic constraints of the context provided by sentences. The studies reviewed here would support the idea proposed by Marslen-Wilson (1989) and Friederici and collaborators (1999).

As we have previously mentioned, several studies reported early brain responses that could be related to the first presemantic analysis. Hence, at this stage and with a time occurrence ranging between 80 and 200 ms after the presentation of the stimuli, processes such as visual perceptual categorization based on long-term experience and the visual recognition of words would occur. Early effects reported by Skrandies (1998), Sereno et al. (1998), and others would confirm this assertion. Interestingly, most of these studies revealed that brain activations reflected by ERP were located over posterior brain areas, more specifically over posterior parts of the fusiform gyrus (Skrandies et al., 1998; Schedan et al., 1998).

Lexical selection seems to be reflected by later ERP responses around 200–300 ms following stimulus presentation; the RP seems an appropriate candidate for reflecting this stage of conceptual access. Its latency coincides with some eye movement studies that reported fixation periods on a given word following saccades that lasted for about 250 ms (Just & Carpenter, 1980; Posner & Abdullaev, 1999). The location of the neural generators of this component within the medial parts of the lingual/fusiform gyrus, a very close anatomical position to that where lexical access takes place (posterior parts of the fusiform gyrus), would point the possibility that a sequential activation of different subdivisions of the fusiform gyrus takes place during word semantic processing. The implication of the fusiform gyrus in semantic processing has been validated in a larger number of studies using neuroimaging techniques than other ERP, such as PET or fMRI (e.g., Price, 1997; Murtha et al., 1999; Büchel et al., 1998). Moreover, the fusiform gyrus appears to be the most consistently activated area in semantic processing research (Murtha et al., 1999).

Effects with a similar latency to that displayed by the RP also have been reported in other studies using the ''cognition to ERP'' approach. For instance, in Khated et al. (1999), semantic processing could co-occur with phonological processing at an early stage, but started to diverge at 280 ms, the moment at which specific semantic analysis was postulated to occur by these authors. On the other hand, Abdullaev and Posner (1998) also postulated that access to meaning would occur around 250 ms, although in the left anterior cortex. Though the proposed time course clearly matches previous findings on access to meaning, the topographical distribution makes it unlikely to be reflecting such processes. Actually it would appear more plausible to assume that lexical selection does occur in a location closer to that where lexical access takes place. Frontal areas traditionally have been considered as subserving memory, control, and executive functions (Fuster, 1997). It has been proposed that the activation in anterior brain areas reported in some language comprehension studies reflects the activity of a part of a conceptual semantic memory system that may overlap to some extent with a word meaning network (Bentin et al., 1999).

The last stage in word comprehension deals with postlexical integration processes. Such processes, as reflected by the N400, would take place 300–500 ms after stimulus onset, therefore providing an index of the integration of word representations in current context. Once again, the fusiform gyrus plays an important role, more precisely its anterior part, since the neural generators of the N400 seem to be placed there (McCarthy et al., 1995). It appears, therefore, that the fusiform gyrus would be implicated at all semantic processing stages, with different subdivisions of this structure sequentially involved at different stages.

A final aspect should be taken into consideration. There is controversy concerning the extent to which the activation needed for semantic processing is automatic and stimulus-driven or task-dependent (Ziegler et al., 1997). On the one hand, the studies reviewed here suggest that the presence of semantic processing is strongly dependent on the type of processes required by the task. On the other hand, some degree of automatic semantic processing should not be discarded since results with different task procedures have yielded a high number of similarities. Studying the influence of task requirements and how they modulate semantic processing seems, therefore, of the highest interest.

From all the above reviewed data it can be concluded that the relationship that exists between brain and language is more complex than was first thought. The classic dichotomy between Wernicke's area for language comprehension and Broca's area for language production seems now obsolete and insufficient. We have seen how the fusiform gyrus is implicated in all semantic processing stages. It appears, therefore, that the development of sophisticated techniques in the neuroscience field have led to the emergence of a different group of brain areas, the so-called ‘‘third language areas’’ (Lüders et al., 1991), implicated in the diverse processes of language comprehension.

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