20 The Potentials for Basic Sentence Processing: Differentiating Integrative Processes

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ABSTRACT

We show that analyzing voltage fluctuations known as "event-related brain potentials," or ERPs, recorded from the human scalp can be an effective way of tracking integrative processes in language on-line. This is essential if we are to choose among alternative psychological accounts of language comprehension. We briefly review the data implicating the N400 as an index of semantic integration and describe its use in psycholinguistic research. We then introduce a cognitive neuroscience approach to normal sentence processing, which capitalizes on the ERP's fine temporal resolution as well as its potential linkage to both psychological constructs and activated brain areas. We conclude by describing several reliable ERP effects with different temporal courses, spatial extents, and hypothesized relations to comprehension skill during the reading of simple transitive sentences; these include (1) occipital potentials related to fairly low-level, early visual processing, (2) very slow frontal positive shifts related to high-level integration during construction of a mental model, and (3) various frontotemporal potentials associated with thematic role assignment, clause endings, and manipulating items that are in working memories.

In it comes
out it goes
and in between nobody knows
how flashes of vision
and snippets of sound
get bound to meaning.
From percepts to concepts
seemingly effortless integration
of highly segregated
streams of sensory information
--with experiences past
out of the neural closet
and in use at last.
--M. K.

20.1 INTRODUCTION

Pulling the external world apart and putting the pieces back together internally, differentiating and integrating, assimilating and accommodating to a torrent of information arriving from multiple senses, acting and reacting to a world we both experience and change-these are the sensory, perceptual, and cognitive processes that make our brains among the most metabolically active tissue in the body (Plum 1975). Thus, when we speak of integrative processes, we are clearly talking about processes of perception and of action, multiply instantiated in different brain regions according to the modality of input and level of processing, whose neural connections have been sculpted by the history of the organism and the history of the species (the prewired and the postwired together).

Language comprehension in general, and reading in particular, are good examples of activities involving a wide range of analytic and synthetic operations. In this chapter we will argue that event-related brain potentials (ERPs) can give us insight into the time course and intensity of the integrative processes involved in reading, not merely at the level of the single word, but at the level of whole phrases and clauses as well. Moreover, we will show how judiciously combining electrophysiological data with other functional imaging data can help ground these integrative processes to their neural generators, an essential step in our goal of unifying cognitive theory with biology.

As we are clearly in the first throes of an admittedly ambitious project, this chapter serves primarily to spell out which integrative aspects of language processing might be most amenable to electrophysiological study and to pose hypotheses about the connection between specific ERP features and (chiefly) syntactic features of sentences. We begin with a brief discussion of working memory (WM), which we view as the arena for integrative processing. In particular, we discuss how properties of the WM system might determine the way in which thematic roles (e.g., agent, patient, theme, instrument) are mapped onto the linguistic representation of discourse participants to yield the intended meaning of a clause. Next, we consider what the neuroanatomy of the cortex tells us about the structure of language processing. We suggest that evidence from a functional analysis of language processing and from brain imaging of language processes together have revealed that computations like thematic role assignment are both functionally and anatomically distributed. We briefly introduce the basics of cognitive electrophysiology, including those components of the ERP to words which most directly relate to potential integrative processes. We also discuss the most heavily investigated component of the ERP sensitive to semantic features of words-the N400. We conclude with a description of an experiment involving basic transitive clauses, which we performed in order to see how easily electrophysiological correlates of language processing could be mapped onto linguistic concepts. In summary, we think our results provide preliminary evidence that the ERP approach to sentence processing can help in the examination and analysis of linguistic concepts such as thematic role assignment, thereby deepening our understanding of how discourse representations of clauses are constructed on-line.

20.2 INTEGRATION, ARGUMENT STRUCTURE, AND WORKING MEMORY

Integration in language processing goes beyond simply assigning hierarchical structure to what are essentially one-dimensional strings of linguistic tokens (themselves built up from patterns of light and sound). Full comprehension of a message requires that the comprehender arrive at an interpretation that yields information not already known, causing a change in the comprehender s state of knowledge and possibly also behavior. Precisely how this integration occurs is both unknown and highly controversial. For the purposes of our argument, however, we will assume that the cognitive outcome of integration is a (re)depiction of the activity of various discourse entities as expressed by the speaker in the listeners mind. Creating this mental redepiction presumably entails selecting discourse entities and encoding their interactions within a dynamic mental model that supports the kinds of inferences required to yield new information to the comprehender; this is the discourse level of representation.

In this chapter we will focus on processes that obtain syntactic and thematic role information from word representations and apply it to the construction of temporary syntactic and more long-lived, discourse-level representations. We assume that lexical access, thematic role assignment, and construction of a discourse representation are heavily interleaved, rather than strictly sequential, and that partial information is routinely used as it becomes available. On this assumption, for instance, a reader would form a discourse representation of a noun phrase (NP) such as "the secretary," even though it may subsequently be refined by a prepositional phrase or relative clause (e.g., ,the secretary at the reception desk," "the secretary who typed the memo").[1] We also discuss the interface between working memory and thematic role assignment. Specifically, we outline the proposal that unintegrated syntactic constituents impose a load on working memory until they are integrated by extending Gibson's (1990, 1991) model of syntactic ambiguity resolution to unambiguous sentences.

20.3 WORKING MEMORY

While the concept of working memory (WM) as a constraint to processing has long been a key to psycholinguistic theories, going back at least to the collaboration of Miller and Chomsky (1963), its use has been largely intuitive. There is still no generally agreed-upon mechanistic account of exactly how WM constrains language processing, although no one doubts that it does (but see just and Carpenter 1992 for a promising approach). For instance, despite the universal acceptance of the idea that WM is capacity-limited, rarely is this property defined precisely, presumably due to the difficulties in identifying the relevant "units" of storage in language. At present, it simply is unclear whether working memory is best quantified in terms of discrete, chunklike entities (e.g., Simon 1974), levels of activation within a production system (e.g., Anderson 1983) or across units of a neural network (e.g., St. John and McClelland 1990), or as the products of more specific processes coded as a function of articulatory parameters or visuospatial structure (Baddeley 1986). Although we also provide no definitive answer on this, we suggest that itemlike and patternlike views are in many cases complementary.

Another, perhaps too obvious, characteristic of working memory is that its contents are temporary. Items can only be active, that is, remain a part of working memory, only so long; once activated, they can and often should be suppressed as soon as the computations for which they were needed have run their course. Indeed, it is from the temporal sequencing of computations that a type of self-organization of processing emerges-an organization that enforces some degree of separation between processes that would otherwise lead to confusion and ambiguity. The.active suppression of "irrelevance" in large part serves to guarantee that working memory contains only necessary information, with the practical consequences that processing is simpler, faster, and less error-prone than it might otherwise be.[2] More important for present purposes, we should expect both the capacity limitation and the temporal characteristics of WM to impact language processing inasmuch as we believe WM is needed for successful comprehension.

Comprehension of even the simplest sentences requires successful mapping between representations at different levels. This is not an easy problem. For one thing, linguistic inputs, while perhaps not strictly one-dimensional strings, are undeniably more "linear" than the higher-order representations they must be mapped onto.[3] Moreover, many kinds of natural language structures can be conceived of as requiring multiple arguments to complete their meaning-in other words, of having several "slots" that need to be "filled." Or, from the inverse perspective, some structures can be construed as isolated "chunks" or "fillers" that need to be "connected" or "slotted" to form higher-level units. But given that linguistic input is serial in nature, "fillers" will not necessarily precede their "slots." Accordingly, during the processing of structures requiring multiple arguments, some "slots" may remain unfilled until their expected "fillers" are encountered, leading to the generation of expectancies.[4] Likewise, some "fillers" may remain unattached until their expected "slots" are encountered, requiring active maintenance of the filler. Thus successful comprehension entails storage or *maintenance* of activation,[5] generation of *expectations* for future items, and assignment of fillers to slots or *integration.* These are in fact generally considered to be basic operations of working memory and, as such, would be subject to its capacity limitations and temporal characteristics.

This understanding of the operations on WM is not unique to language processing; such operations would appear instead to be "central" to many different cognitive problems in Fodor's (1983) sense of that term. This perceived centrality notwithstanding, their existence in a cognitive system may be quite specialized in function and distributed in character. In fact, Baddeley's (1986) influential model of WM points toward a degree of specificity in storage components (e.g., phonological store, articulatory loop, visuospatial scratch pad), although it has been criticized primarily for its underspecification of central executive processes. Both psychological and neurophysiological evidence as well as computational arguments now converge to suggest that Baddeley's underspecification of the central executive may reflect a real weakness in the theory, and that the executive may not be as central as originally proposed. For example, recent studies in cognitive neuroscience by Goldman-Rakic (1987) and her colleagues (e.g., Wilson, Scalaidhe, and Goldman-Rakic 1993) suggest that working memory storage systems are so highly fractionated as to render it next to impossible to lesion central "executive" processes while sparing storage, and vice versa. Thus, while the frontal cortex has been implicated in the so-called executive functions, in practice, these have proven intractable to separation from storage components behaviorally (reviewed by Fuster, 1989, 1993); they appear not to be centralized in the sense of being localized to a single, distinct, amodal cortical area (Sereno 1991).

In line with the neuroscience view of working memory, Kimberg and Farah (1993) demonstrated via computer simulations of frontal lobe functioning how the notion of a central executive may be superfluous. Using a model of WM that does not include any central executive module, they were able to simulate both normal and abnormal performance on at least four tasks sometimes impaired by frontal lobe damage. The beauty of their working computer model is that it accounts for abnormal performance in a variety of so-called frontal tasks by changing only a single parameter without recourse to a central executive; the frontal cortex modulates (maintains and controls) the strength of associations among various (broadly defined) elements of different information types. Thus merely weakening associations among elements mimics frontal patients' performance in seemingly disparate areas such as motor sequencing tasks, the Stroop test, the Wisconsin card sorting task, and tests of source memory. In the next section, we argue that at least one prominent aspect of integration in language processing, namely thematic role assignment, can be similarly analyzed.

20.4 THEMATIC ROLES IN PRINCIPLE

The field of syntax has long felt a tension between theoreticians who sought to enforce a strict division of syntactic and semantic processing (e.g., Chomsky 1965) and those who sought to unify the two (e.g., Fillmore 1968). A limited rapprochement between these two positions has occurred over the last decade with the development of Chomsky's "Government and Binding" (GB) framework (1981), which places more emphasis on general principles of language processing (than on highly specific, tightly ordered rules) and on the centrality of semantic argument structure (in the guise of thematic role assignment) in syntactic analysis. Although we do not have space to do this issue justice, we raise it to justify our particular position here: because something akin to thematic role assignment occurs during parsing, it is reasonable to track the progress of processing simple, single clauses by examining thematic roles.

In essence, thematic role assignment expresses 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. Given that much of the information needed to make these participant-action correspondences is carried by verbs, once the possible roles associated with a verb are revealed, we can conceive of a process that maps these thematic roles onto the discourse participants. In other words, information in the verb can be used to map explicit associations between particular, previously unassociated items in working memory. (This characterization might remind some readers of Kimberg and Farah's 1993 theory of the frontal cortex.)

Our position on the relationship between thematic role assignment and working memory owes much to Gibson (1990), who has used (limited) working memory capacity both to sanction and to constrain the pursuit of parallel analyses in cases of syntactic ambiguity. Specifically, Gibson proposed that readers were free to pursue multiple parallel analyses of a temporarily ambiguous syntactic structure with two provisos: first, that the capacity required to maintain multiple parsings did not exceed readers' total WM capacity and, second, that readers be allowed to discard analyses whenever these were significantly more costly to maintain than the "easiest" reading. Gibson proposed that cost (thematic or working memory load) was incurred by NPs temporarily lacking a thematic role and by thematic roles that were momentarily unassignable. Because both these types of load on working memory were presumed to be similar in nature and equal in magnitude, thematic load was calculated as a simple sum of NPs not yet assigned roles and thematic roles not yet assigned to NPs.

Although Gibson's (1990) theory was intended to account for garden path effects, we think it can be extended to language processing in general. For example, Gibson's purposes required only that readings exceeding total WM capacity, or consuming much more memory than a rival reading lead to observable behavioral effects. However, with more sensitive dependent measures even "subcritical" thematic loads might have observable effects. Furthermore, the proposed equality of the two types of thematic loads (NPs without roles, unassigned thematic roles) posited by Gibson was more a matter of convenience than a theoretical necessity. Thus the WM loads induced by NPs without roles and by unassigned thematic roles might be psychologically and physiologically distinguishable, in a way parallel to our previous suggestion for the WM processes required to maintain "passive" memory loads and to project or expect future events. Accordingly, we anticipate that this psychological decomposition of WM operations will have reliable electrophysiological signatures, as will be detailed in our discussion of the brain and its electrophysiological message.

20.5 LIMITATIONS OF THE CORTEX: SIZE MATTERS

Our brief discussion of thematic role assignment suggests how one might begin to map highly complex linguistic concepts onto simpler psychological primitives. We will motivate our mapping of the interactions among these same psychological primitives onto electrophysiological effects at the scalp by pointing out some neuroanatomical constraints on processing. That is, we will detail the manner in which neural circuitry in general might delimit the ways that language and working memory processes (and the associated ERPs) could and could not work. Our conclusions support the idea that there are multiple "language areas," that these areas subserve both language-specific and non-language-specific subprocesses, and that they are widely but not randomly distributed in the brain.

Textbook models of language imply the existence of specifically linguistic processes instantiated in a neural system that includes a single pair of interconnected cortical areas, namely Broca's area in frontal cortex, and Wernicke's area in the temporal lobe near its junction with the parietal lobe. This anatomically bipartite language-processing model has suggested a number of ways to construe language as a dichotomous entity. As mood or fashion suits us, we see various dichotomous pairings of production versus comprehension, of syntax versus semantics, of grammar versus lexicon, and of regularity versus exception, with one term of each pair assigned to Broca's area and the other to Wernicke's area, respectively. Indeed, this is more than just idle theorizing; neuropsychologists working with both normal and aphasic populations do find evidence in favor of such dichotomies (see, for example, Caplan 1994). However, it has proven exceedingly difficult to move beyond descriptions of aphasic symptomatology and to reify these dichotomies in a satisfying model of what is processed in, say, Broca's area.

Moreover, the anatomical definition of cortical language areas has tended to be surprisingly loose; rarely are their size, shape, or evolutionary history relative to adjoining areas of cortex discussed in any detail (but see Deacon 1992). Some of this looseness might be ascribed to a sort of (wishful?) thinking that because these areas are supposed to be highly flexible, higher-order association cortex, they should be more variable (than, say, primary sensory areas). Recent work, however, has cast doubt in particular on the very existence of purely "associative" brain areas of any sizable extent (e.g., Sereno 1991). This leads us to reconsider some basic questions: how many language areas are there, where are they located, what are their particular functions, how are they connected to each other in time and space, and is there any principled order to their activity? Before we address these questions directly, we outline the logic behind a reliably informative, if uncommon, approach to cortical organization that uses information about the size, number, and connectivity of individual areas to appreciate the integrative problems they help to solve.

In an average person, the cortical surface area of a single hemisphere measures approximately 80,000 mm^2 (e.g., Cherniak 1994)[7] which Brodmann's (1909) influential work divided into 47 architectonically distinct brain areas. It is now dear this was a conservative parcellation, although it was in fact less conservative than other contemporary schemes. To cite a clear example of a likely undercount, Brodmann defined only 6 areas in what is now considered the hurnan visual cortex; this is 4 times less than the current estimate of the number of cortical visual areas (about 25) found in a visually sophisticated primate like the macaque (Felleman and Van Essen 1991). Furthermore, many of the visual areas that Brodmann missed were far from exotic, including such well-established areas as MT (responsible for processing motion) and V4 (responsible for processing color and other higher-order features). While we would hesitate to suggest that this factor-of-4 difference would apply to Brodmann's total, we can with high confidence add to his 47 areas the number of "extra" areas so far demonstrated in visual, auditory, and somatosensory cortex (as briefly reviewed by Felleman and Van Essen 1991) and suggest there are at least 80 human cortical brain areas, defined cytoarchitectonically and by patterns of interareal connections. Thus the "average" brain area even in the human brain would at best cover about 1,000 mm^2 of the cortex, which is only slightly larger than two ordinary postage stamps. Even primary visual cortex (VI) measures only approximately 2,500 mm^2 (Horton and Hoyt 1991), and can be further divided into upper and lower visual field "subareas" on the basis of separate connections to higher visual areas (Felleman and Van Essen 1991).

The point of this exercise was to give us a ballpark estimate of the size of an average cortical area and see how the so-called language areas measure up. The size and location of Broca's area, as usually depicted, varies substantially from source to source, but certain "minimal" areas are universally included; namely, a substantial amount of the cortex along the inferior frontal gyrus, almost all of the pars opercularis and pars triangularis, and also parts of the more anterior pars orbitalis (e.g., Penfield and jasper 1954; Ojemann 1991). The pars triangularis alone, at approximately 3,500 mm^2 is 40 percent larger than V1, and over three times the size of the average brain area.[8] Similar rough estimates of several different "textbook" depictions of Broca's area yield similar results.[9]

All in all, these depictions of Broca's area (even in the more advanced texts cited here, which show relatively "punctate" areas) would appear to make it by far the largest known cortical brain area in the human. In our opinion, this is highly unlikely. Even Brodmann divided this region into two areas, and we might expect four or more to be found, based on the size of the "average" brain area (also see Deacon 1992). A similar argument can be made concerning Wernicke's area, which is more variable in its size and placement than Broca's (see, for example, Sereno 1991).[10]

We have argued that the number of distinct brain areas within the classical language regions is larger than previously supposed. Accordingly, it is not surprising that the correlation between damage to Broca's and Wernicke's areas and aphasic symptomatology is so low (Willmes and Poeck 1993). As suggested by Alexander, Naeser, and Palumbo (1990), ;a larger number of brain areas would suggest more principled reasons for the variability of damage to language processing following lesions to Broca's area. Some of the more selective cases reported in the literature may in fact reflect selective damage to particular cortical fields within the anterior language-processing region, or the disconnection of these areas from each other or from posterior areas. This would also be consistent with the remarkable variability across positron-emission tomography (PET) studies of exactly which areas appear to change their activity during supposedly "language"-processing tasks (e.g., Roland 1993).

If there actually are many cortical language areas, as we have argued, we would also expect a *decrease* in the relative degree of interconnectivity among them, especially between those not adjacent on the cortical sheet (Cherniak 1990, 1994).[11] The important point is that, even if there were only two language *regions* comprising a larger number of language subareas, limitations on their interconnectivity should not be underestimated. Yet a further wrinkle in the cortical language area story has been added by the discovery of a *third* language area on the bottom of the temporal lobe, called the "basal temporal language area" (Luders et al. 1986). In summary, if language regions are mosaics of subareas, the functional and electrical responses from, say, left anterior brain areas would be expected to generate multiple observable activity patterns that we could associate with distinct processing factors. In general, the pattern of electrical activity over the scalp during the processing of a sentence should be quite complex. We now turn to a discussion of the electrophysiological pattern actually observed.

20.6 BRIEF INTRODUCTION TO ERPS

Ever since Berger's (1929) discovery that brain electrical activity can be measured at the human scalp, the electroencephalogram (EEG) has been used as a research tool to investigate the functioning of the central nervous system in both mental and physical terms. The EEG can be used in a variety of ways as a dependent measure of changes either in its frequency content or in the brain activity triggered (evoked) by some transient event. We will briefly sketch these two approaches, and then introduce the ERP components most commonly associated with reading.

The spectral analysis of resting EEG is widely known because of its clinical applications (see, for example, Spehlmann 1981). Of greater relevance to our research are recent efforts that correlate regionalized alterations in the spectral (frequency) composition of the EEG with differences in cognitive tasks (e.g., Klimesch, Schimke, and Pfurtscheller 1993). The typical measure is an attenuation in the amount of power within specific frequency bands, mostly alpha (10 Hz) but also beta (20-50 Hz) and others in association with the processing of some event, hence, the term *event-related desynchronization.*[12] These techniques are less commonly known to most cognitive psychologists, but we mention them here because recently they have been applied to investigations of "intensive" dimensions of processing and working memory use (Pfurtscheller and Klimesch 1990; see also Gevins and Cutillo 1993 for a related approach).

The other common use of EEG information as a dependent measure is based on the concept of evoked potentials, whereby it is assumed that some triggering event causes a change in the brain's response in a way that can be related to its content and/or context. The most common way to analyze such data is to form averages from the EEG of many individual trials, time-locked to the trigger (generally an external stimulus or a subject-generated movement). The assumption behind this approach is that transient activity not specific and therefore not synchronized to the triggering event is random and will average out over the course of many repetitions, leavifig an event-related potential (ERP) signal that presumably reflects activity causally time-locked to the event.[13] Brain activity measured in this way is an extremely sensitive index of changes in brain state or operations, as a function of the environment or otherwise (reviewed extensively by Regan 1989).

Given what is known about the organization and activation of the neural circuitry necessary to generate a sizable ERP at the scalp, the best candidate generator for most of what is seen are the pyramidal cells in the cortical layers. Calculating from this potential distribution at the scalp exactly which generators are active is known as the "inverse problem." The general inverse problem is, in principle, insoluble (no matter how dense the recording electrode array) because there are infinitely many combinations of neural generators that could yield the same distribution of electrical activity at the scalp (Nunez 1981). This is why merely locating the largest peak amplitude at some point over the scalp *cannot* be given as sole evidence that the generator is located in the cortical patch right beneath that electrode, or that what looks like a local tangential dipole is such. Sometimes that it true, but sometimes it is not. Fortunately, as Dale and Sereno (1993) have suggested, adding a few constraints (i.e., external structure or more information) to the problem renders it soluble in practice.14

While the mapping of generators onto mental functions is not straightforward (as the mapping may be other than one to one), knowing the minimum number of possible generators can give us a starting point for hypothesizing about the minimum number of mental processes necessary to explain performance in some task. The ERP provides a good link between the physical and mental world because it is brain activity whose parameters are sensitive to manipulations of psychological variables.

An important division in the study of ERPs is usually made between "fast" activity, which generates most of the response we see to single words,

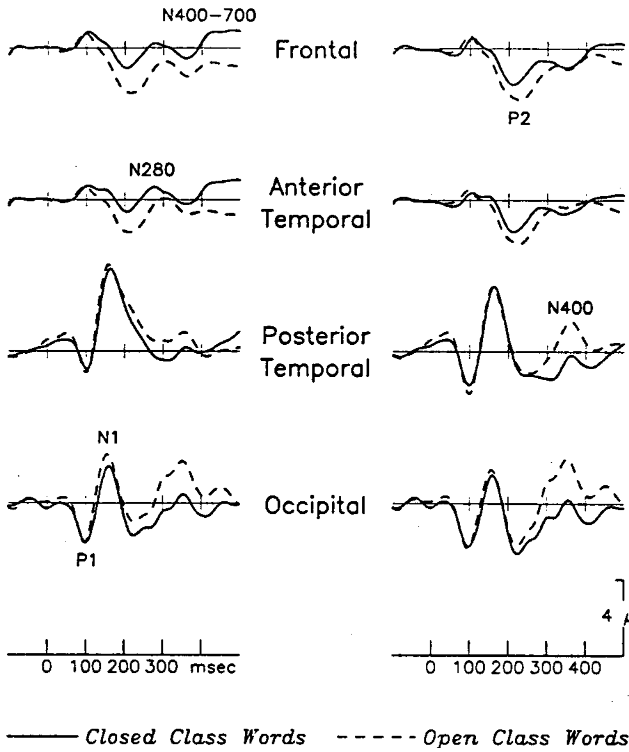

Figure 20.1 Grand average ERPs (N = 24) from 8 representative electrode sites for open-class (solid line) and closed-class (dashed line) words from recent ERP language study (King and Kutas 1995). Left hemisphere is plotted on left, and in this and all subsequent figures, negative voltages are plotted up. ERP features labeled on this figure are mentioned in text.

and "slow" activity in very low frequency bands of the ERP (less than 1 Hz). Both fast and slow potentials can be characterized in terms of their morphology (waveshape), latency and/or time course, amplitude, and distribution across the scalp. We recommend that duration be added, at least until it is shown to be uninformative. To date, virtually all of the research on the ERPs related to language processing has focused on the faster, transient responses triggered by individual words; these include the P1, N1, P2, N2, N280 or lexical processing negativity (LPN),[15] P300, N400, and N400-700 (see fig. 20.1 for illustration; Hillyard and Picton 1987 and Kutas and Van Petten 1994 for reviews).[16] A thumbnail sketch of the relation between psychological processes and these ERP components, in our opinion, would link the earliest components (P1, N1) to early visual processing-(e.g., feature extraction) and attentional modulations thereof; the LPN to lexical access; the P2 and the family of P3-like components" to encoding and memory storage-related operations; the N400 to aspects of semantic analyses; and the N400-700 to anticipatory processes. In addition, these faster responses are superimposed on much slower (lower-frequency) voltage modulations.

Until relatively recently, cognition-related modulations of very slow cortical potentials (SCPs) have been explored primarily in the realm of memory (especially working memory) and vigilance research (for review, see McCallum and Curry 1993; Ruchkin et al. 1988; Rosler and Heil 1991). We will not summarize this work here, but merely emphasize for present purposes that the slow cortical potentials are not simply a sum of overlapping transient ERP components but a reflection of brain activity in their own right.

Previously, we reviewed evidence demonstrating that language processing is widely distributed in the brain. We now turn to the question of what implications this distribution might have for our ability to record electrical activity specific to language processing. Insofar as the various cortical language areas are in close proximity to each other and do cooperate to process the same kinds of information, we might expect them to be extensive enough to have distinct electrophysiological signatures even with a modest number of sensors. Moreover, if there are three (or more) language regions as well as other brain regions playing a supporting role in language processing, we should be able to see multiple and differentiable ERP effects caused by differences in linguistic input or differences in the performance of the subjects. We start our discussion of language-related ERPs by reviewing the work on the N400 and its use in psycholinguistic research.

20.7 ELECTROPHYSIOLOGY OF SEMANTIC PROCESSING: THE N400

The event-related potential technique has been used for over thirty years in investigations of cognition. And, over this period, we have discovered facts about phonological, lexical, semantic and syntactic analyses (see the special issue of *Language and Cognitive Processes* edited by Garnsey, vol. 8, no. 4, 1993). We begin with a very brief review of the work related to semantic processing and then describe a new way of using ERPs to study reading (and ultimately speech comprehension).

Much of the early work in the electrophysiology of language capitalized on the sensitivity of the ERP to violations of semantic expectancies-failures of integration at the level of meaning. A larger percentage of the more recent work has focused on violations of various syntactic rules or constraints, with the aim of determining the extent to which there exist separate semantic and syntactic levels of representation (e.g., Neville et al. 1991; Osterhout and Holcomb 1992; Munte, Heinze, and Mangun 1993; Rosler et al. 1993; Hagoort, Brown, and Groothusen 1993). Such studies rest on the assumption that if semantic and syntactic processing and violations thereof yield qualitatively different patterns of brain activity, then they must be subserved by different brain systems whose very existence is proof of their separate identities. And, indeed, the results to date show that semantic violations on the whole differ from syntactic ones in some way, although the story is clearly more complicated because the brain's responses to various syntactic violations also differ from one another in ways that are still poorly understood (e.g., Neville et al. 1991). For the moment, we cannot be certain that it is always syntax which has been violated. But, rather than dwelling on this issue, let us briefly review what has been learned from the ERP investigations of a class of semantic violations.

The ERP to a word that is semantically anomalous within a sentence is characterized by a negative-going wave between 200 and 600 ms, peaking around 400 ms, with a somewhat posterior, slightly right-hemisphere amplitude maximum; this is the so-called N400. The N400 elicited by a semantic violation is large and remarkably similar (albeit not identical) in its distribution whether the violation occurs in sentences being read (e.g., Kutas and Hillyard 1980), listened to (e.g., McCallum, Farmer, and Pocock 1984), or interpreted from hand shapes and movements of American Sign Language (e.g., Kutas, Neville, and Holcomb 1987). Moreover, the amplitude of the N400 effect (the difference between responses to anomalous and congruent words) appears to be similarly sensitive to a number of factors including semantic relationship whether the sentences are presented visually one word at a time at relatively slow rates (e.g., one word every 700 to 1,100 ms), as was frequently done in early work, or at somewhat faster rates (e.g., between 250 and 500 ms), as is more typical today (e.g., Gunter, Jackson, and Mulder 1992; Kutas 1993).

The ERP to a clear-cut semantic violation has the largest N400. However, fifteen years of research has revealed that the ERPs to all words contain some N400 activity whose amplitude is determined by a variety of factors (for review, see Kutas and Van Petten 1994). Chief among these is how expected or predictable a word is, given its *current context.* We take current context to include not only sentential contexts but also paragraphs and texts, on the one hand, and word pairs and lists on the other, as we shall describe. Further, the N400 effect is not strictly limited to real words because large N400s also characterize the ERPs to pseudowords-letter strings that both look and sound as though they could be words, and give a reader the sense that they ought to have meaning. Pseudoword N400 effects occur both in the context of word-nonword pairs and in lists of words (e.g., Bentin, McCarthy, and Wood 1985; Holcomb 1993; Holcomb and Anderson 1993; Holcomb and Neville 1990; Rugg, Doyle, and Melan 1993). By contrast, the ERPs to *nonwords* (orthographically illegal combinations of unpronounceable letter strings) do not seem to show any N400 activity (Holcomb and Neville 1990; Nobre and McCarthy 1994) Thus the extremes in the distribution of N400 amplitudes elicited by single-word stimuli are marked by pseudowords at one end and nonwords at the other. The amplitudes of the N400s to all other words fall somewhere in between, with the exact distribution being determined by a combination of different factors as detailed below.

The reality that multiple factors affect N400 amplitude is made especially salient when we seek to explain the modulation of an N400 due to the lexical class of the eliciting word. Thus, while we see larger N400s to open-class or content words (e.g., nouns, verbs, adjectives and -ly adverbs) than to closed-class or function words (Kutas and Van Petten 1994; Neville, Mills, and Lawson 1992), some or all of this difference may be caused by factors such as word frequency, abstractness, and repetition that are correlated with, but distinct from, lexical class. In experiments using lists of unrelated words, one sees larger N400s elicited by lower frequency words than by high-frequency words (e.g., Rugg 1990), larger N400s to concrete words than to abstract words (e.g., Kounios and Holcomb 1992) and larger N400s to the first occurrences of words in a session than to subsequent occurrences of the same word in both word lists and in text (Rugg 1985; Karayanidis et al. 1991; Van Petten et al. 1991). Notice that each of the simple effects of frequency, abstractness, and repetition alone could account for the larger N400s in open-class than in closed-class words, without the need to resort to the possible interactions among them.[18]

The factors described above have effects on the N400 *independent* of context, but many other factors are richly *dependent* on context, especially the semantic and pragmatic context. Thus in list contexts we find N400s to words preceded by an associatively or semantically related word are smaller than those to words preceded by an unrelated word (e.g., Bentin, McCarthy, and Wood 1985; Kutas and Hillyard 1989; Holcomb 1988; Holcomb and Neville 1990). Although this effect could be explained in terms of item-to-item priming alone, such an explanation seems less plausible when we consider the effects of sentence contexts, where we find smaller N400s to words that are more semantically constrained by their context (Van Petten and Kutas 1991) even when there is little direct semantic association between the eliciting word and other words in the sentence. Also note that the type of constraint effective in dampening the N400 effect is far from general; accumulating syntactic constraints by themselves do *not* reduce N400 amplitude (Van Petten and Kutas 1991).

Overall, the N400 is very sensitive to many of the factors shown to have behavioral effects in studies of word recognition. Moreover, it appears that these factors can interact to influence the amplitude of the N400. For instance, the N400 frequency effect is reduced as a function of accumulating semantic constraints; clear frequency effects are seen on the N400 to the first few open-class words in a sentence, but none are seen on the N400 to congruent open-class words late in a sentence (Van Petten and Kutas 1991). Another robust finding is that the N400 congruity effect is reduced by repetition (Kutas, Van Petten, and Besson 1988; Besson and Kutas 1993; Mitchell, Andrews, and Ward 1993), although the precise pattern of effects is complex.[19]

In our opinion, one of the most important consequences of this research has been the suggestion that the way the brain deals with semantic violations is not *qualitatively* different from the semantic analyses it routinely carries out during reading or speech comprehension in the absence of obvious violations. Thus we view the apparent failures of semantic integration that people experience when a "real" violation occurs as merely an end point on a continuum of processing for meaning. This realization was brought home by the data showing different amplitude N400s to the final words of the following two sentences:

(1) The bill was due at the end of the hour.

(2) She locked the valuables in the safe.

These are both perfectly normal, comprehensible sentences, and yet the N400 to "hour" was significantly larger than that to "safe." In fact, Kutas and Hillyard (1984) found that the amplitude of the N400 was inversely correlated ($r = -.9$) with the cloze probability of the eliciting word.[20] This correlation has led to the hypothesis that N400 amplitude may merely index a word's predictability (subjective conditional probability). If these were the only data available, this would be a viable hypothesis. However, in the same paper as well as others since (e.g., Kutas 1993), it was demonstrated that words with equivalent predictability (i.e., identical cloze probabilities) were nonetheless associated with N400s of different amplitudes. In other words, when cloze probability was held constant, N400 amplitude was a function of the semantic or associative relation between the expected word and the word actually presented.[21] For instance, if the sentence fragment "The better students thought the test was too" were completed not by the expected word "easy" but by one of two words with equally low subjective conditional probability ($p < .03$) such as "simple" or "short," the ERP to both of these would contain a sizable N400; however, the N400 to the word "simple" would be smaller, presumably because of its closer semantic tie to "easy." A similar effect has been observed for outright semantic incongruities (Kutas, Lindamood, and Hillyard 1984). Thus N400 amplitude goes beyond sheer indexing of subjective conditional probability.[22]

Our knowledge of what factors do and do not modulate the amplitude of the N400 has allowed us to address some specific questions within psycholinguistics. For example, Garnsey, Tanenhaus, and Chapman (1989) used the fact that N400s are reliably elicited by semantic anomalies to evaluate two alternative hypotheses about the strategies that guide parsing sentences when there is a momentary ambiguity about their syntactic structure. The strategy used in the study was to construct sentences that were semantically anomalous, but where the anomaly would become obvious at different points in the sentence depending upon which parsing strategy was followed. Consider the following *wh-* question:

(3) What bread did he read at the library?

This sentence is clearly anomalous, and our knowledge of the N400 congruity effect predicts a clear N400 difference between some word in (3) and an appropriate control sentence. The relevant and controversial issue, however, is where in the course of this question the N400 would be elicited. From a "first resort strategy" (Frazier and Fodor 1978), it follows that the N400 would be elicited at the first location where one could assign a thematic role to the filler NP (e.g., "what bread," which fills the gap following "read"). In (3) this would be at the word "read" because books, newspapers, and maybe even palms can be read but "bread" cannot; the N400 would thus reflect the unsuitability of "bread" as an object of "read." An alternative strategy, which can be called the "last resort strategy," predicts that the language system waits until the last possible gap could have occurred, and only then attempts to perform the thematic role assignment. On this view, one can argue that an N400 would not be elicited at "read" but rather at "library," when the end of the sentence precludes the possibility of finding a second possible gap, and the sentence is without doubt anomalous. Some version of the last resort strategy would clearly be more effective in the case where the question presented turned out to be not (3) but (4):

(4) What bread did he read about at the library?

Here, attempting to fill the first possible gap at "read" would lead to an immediate semantic anomaly, while the very next word would have allowed the parser to posit a second, more semantically plausible gap, thereby disambiguating the structure. Garnsey, Tanenhaus, and Chapman (1989) found an N400 at the earliest possible point in the sentence time-locked to the word "read," and took this as evidence for the "first resort strategy." Because this is a psycholinguistics experiment touching on fairly subtle issues, there are other viable interpretations for this outcome. These issues, however, are not unique to this study, nor are they raised by the use of the N400 as an electrophysiological index of anomaly processing. Accordingly, we offer it as an illustration of how the N400 in particular and ERPs in general can be used in psycholinguistic research to limit the number of possible explanations for certain phenomena.

Another application of the N400 is as an index of the integrity of certain normal functions in special populations. For example, Kutas, Hillyard, and Gazzaniga (1988) used the fact that semantic anomalies elicit N400s to assess the sentence-processing capabilities of the, right hemisphere of split-brain patients. ERPs were recorded to very brief flashes of bilateral presentations of two words each of which was either congruent or incongruent with a preceding spoken sentence frame. Briefly, Kutas, Hillyard, and Gazzaniga (1988) found that all patients produced N400s when the semantic violation was presented to the left hemisphere, but only the two patients whose right hemispheres showed a capacity for controlling speech output also generated N400s when the anomalous word was flashed to the right hemisphere. Thus Kutas and colleagues speculated that the proposed semantic organization of the lexicon may be more a consequence of the need for speeded output from a concept to actual words (i.e., for speech production) than the more standard view, which emphasizes this organization for comprehension.

Another result of this experiment was that the distribution of the N400 in these split-brain patients was most consistent with a deep neural generator.

Recently, evidence for just such a generator was reported by McCarthy and his collaborators (McCarthy et al. 1995; Nobre, Allison, and McCarthy 1994) based on depth recordings from patients with intractable epilepsy undergoing evaluation for possible surgical treatment. Specifically, they found a component in their depth recordings that behaved like a surface N400 in many of the ways listed above, that was quite focal, and that was electrophysiologically most consistent with a source in the anterior fusiform gyrus on the underside of the temporal lobe.[25] This is apparently the same region of the fusiform gyrus that Luders has shown includes a previously unknown "language area"--a patch of cortex that, when stimulated electrically, hinders a patient's ability to name objects or, in some cases, to speak at all (Luders et al. 1986). Surgical resection of this area is associated with aphasia, which does, however, usually fully resolve (Luders et al. 1991).

20.8 THE ELECTROPHYSIOLOGY OF BASIC SENTENCE PROCESSING

Unspoken in this story of the N400 is an implicit assumption about what kinds of processes are likely to trigger language ERP components, namely the sensory registration, encoding, and interpretation of individual words. We would expect to see these reflected in transient ERP components such as the P1, N1, P2, LPN, P3, and N400 to varying degrees. But as we noted in the introduction, this is not the complete story of language processing, which also entails the computation of the syntactic, semantic, and thematic relationships among single words. Thus, in addition to attentional focusing, visual feature extraction, lexical access, and activation of semantic memory, which are triggered by each lexical item with a certain urgency, the activated words and concepts must somehow be functionally linked so as to support a discourse representation and the inferences it affords. Aspects of these latter processes are by their nature cumulative, integrative, and more variable in their time course relative to individual words; thus we might expect to see them reflected in brain potential activity that is less reliably time-locked (than transient ERPs) to any given word with a time course that is slower and in some cases also either continuous or cumulative.

We take the continued activation, suppression, reactivation, and interaction of elements of these representations during sentence comprehension to be the province of working memory. Moreover, we presume that such links and integrative processes constitute the various temporary representations in phrases and clauses as well as in discourse. The basic building blocks for representations at the level of clauses (e.g., NPs and VPs) and at the level of discourse (e.g., actions and entities) are provided by linguistic theories; previously, we proposed an account of how these might rely on WM operation. Because various WM functions have different expected time courses and different relations to lexical items and sentence-level processes, we might expect them to be reflected in ERP effects with different time courses and distributions at the scalp. Specifically, (1) articles at the beginning of a noun phrase can reliably be used to anticipate the impending arrival and storage of a noun phrase (as reflected in the N400-700, which would resolve); (2) noun phrases can be assigned to a thematic role if one is unfilled and the link is obvious, or must be maintained for future use if it is not; (3) verbs can be used to delimit the possible thematic roles and make assignments to actors that are available in WM; and (4) clause endings can provide a good opportunity to perform WM operations before the next lexical onslaught. Thus we might expect different ERP patterns loosely time-locked to articles, nouns, verbs, and clause endings.

Theoretically, components that index integration should be present during the processing of virtually any kind of sentence, possibly modulated by a host of structural factors. There is, however, a great attraction to simplicity. Thus, for the following ERP. analysis during reading, we concentrate on processing very simple transitive clauses (subject, verb, object) throughout their extent. This analysis reveals four potentially critical ERP effects, reflecting aspects of lexical access, the addition of noun phrases into working memory, thematic role assignment, and high (discourse) level integration; these effects have different time courses, distinct spatial distributions across the scalp, and are differentially affected by a number of within and between subject variables. A glimpse of ERP records to more complex sentence structures is also presented as an additional test of the hypothesized link between the various ERP effects and the underlying cognitive operations.

Our approach was to record the ERPs from a number of sites spread evenly across the scalp as subjects read 256 sentences, which included our critical materials, namely, multiclausal sentences that began with simple transitive clauses and continued with a causative conjunction, such as:

(5)	The	secretary	answered	the	phone	because ...
	[article]	[noun]	[verb]	[article]	[noun]	[conjunction]

There are several advantages to using such simple materials. First, it is easy to construct vast numbers of these syntactically simple sentences so as to obtain good signal-to-noise ratios even for single subjects. Second, unlike some special syntactic constructions, such sentences do not draw attention to themselves and yet still require orthographic, lexical, semantic, syntactic, and pragmatic analyses. Likewise, they must also tap limited working memory resources and long-term memory for ultimate comprehension even if they are not taxing. That is, these materials are essentially nonreactive when compared with sentences including more complex clauses (e.g., "The boat sailed down the river sank"; "The German people hated was Hitler; "The cat the dog the boy kicked chased died") or outright anomalies (" I like coffee with cream and dog"; "The broker persuaded to sell the stock"; "She was happy to get himself a drink"; "They was not pleased by the outcome"; 'The scientist criticized the of proof the theorem."). Clearly, such sentences do draw attention to themselves by virtue of their incomprehensibility, strangeness or ungrammaticality and thus elicit ERPs that may reflect this aspect of the stimuli. By contrast, we think the ERP waveforms elicited by simple transitive clauses are unlikely to reflect the output of any specialized or abnormal processing strategies.

We expect that, just as the value of the N400 as an index of semantic analysis rose when it was shown to be characteristic of the ERP to every word,[26] so the utility of other language-related potentials will increase insofar as they are shown not to be processing violations per se. Finally, simple transitives might be less controversially used as a benchmark for sentence-processing investigations with special populations (e.g., nonfluent aphasics, patients suffering from various types of dementia, etc.) than other sentence types.

Method

Eighteen right-handed, monolingual English speakers (nine women, all between 18 and 29 years of age) were paid for their participation. Six of these participants reported having at least one left-handed family member, a factor known to influence ERPs to language stimuli, and particularly the laterality of the N400 (Kutas, Van Petten, and Besson 1988). None of the subjects reported any history of reading problems or any neurological disorder, and all had normal or corrected-to-normal vision.

Participants were asked to read sentences presented one word at a time (200 ms duration, with a 500 ms word onset asynchrony) for comprehension. There were a total of 256 sentences ranging between 12 and 18 words in length. Of these, 72 were the critical materials, namely multiclausal sentences beginning with a pure transitive clause followed by a causative conjunction. The remaining 184 sentences were fillers including 20 sentences whose first clauses contained a complex complement object (detailed below). It should be noted that just over half of the total sentences in this experiment began with the category sequence [det]-[N]-[V], which made our critical materials all the more unexceptional by comparison. Comprehension was tested on a random 50 percent of the sentences by having subjects respond to true/false probes querying the sentence material; 24 critical and 104 filler sentences were so probed. The true/false comprehension probe appeared 1,500 ms after the sentence-final word and remained on the screen for 2,500 ms, during which eye movements were explicitly allowed. A half-second fixation interval then preceded the next trial.

Recordings were made with 26 geodesically arranged electrode sites on a standard electrocap (see fig. 20.2) and from electrodes over both mastoid processes. In addition, electrodes placed at the outer canthi and under both eyes were used to record eye movements and blinks. All recordings were taken relative to a noncephalic reference, that is, a cardiac artifact-adjusted average of electrodes placed at the sternoclavicular junction and on top of the seventh cervical vertebra.

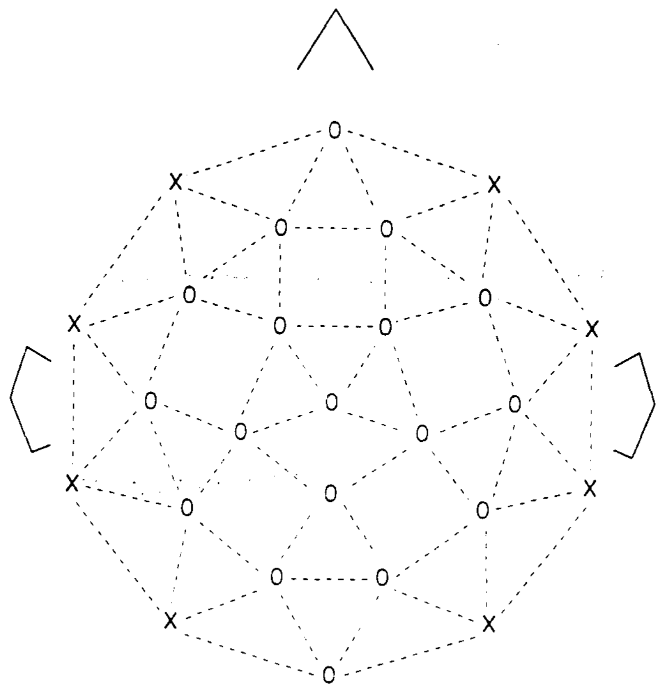

Figure 20.2 Schematic representation of location of each of 26 recording sites on scalp. In this and in all subsequent 26-electrode figures, nose is pointing toward top of page and topmost electrode is in center of forehead. Four'lateral pairs of electrodes used in analyses that follow (frontal, anterior temporal, posterior temporal, and occipital) are shown as Xs.

The electroencephalographic and electro-oculographic recordings were analog-filtered between .01 and 100 Hz (TC ~ 8 sec), digitized at a sampling rate of 250 Hz, and decimated[27] to 83.3 Hz prior to averaging over the longer epochs reported in this chapter. Epochs with blinks, eye movements and other artifacts such as amplifier blocking were rejected off-line before averaging (approximately 39 percent of all trials); epochs with correctable blinks (i.e., without amplifier blocking) were corrected using an adaptive filtering algorithm developed by Dale (1994) and included in the relevant ERP averages.

Results and Discussion

Comprehension Performance As expected, subjects had little difficulty comprehending the sentences that these transitive clauses initiated. Average comprehension rates were over 95 percent; however, six subjects did show comprehension rates markedly lower than 90 percent, which is rather striking for sentences of this nature. Hereafter we refer to these six subjects as "poor comprehenders" (relative to the twelve so-called good comprehenders.)[28]

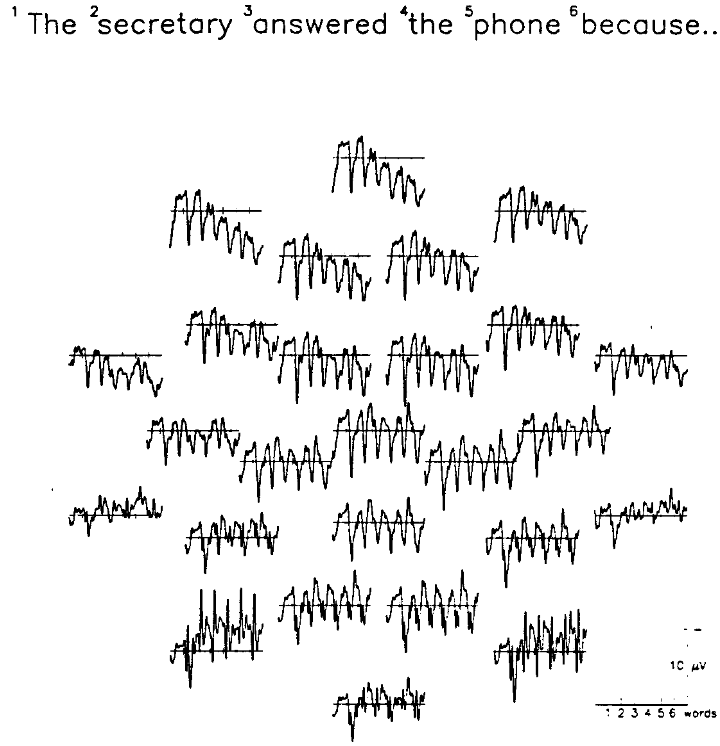

Figure 20.3 Grand average (N = 18) ERPs across simple transitive clause (i.e., first five words) and following word at all 26 scalp recording sites. Superscripts in example sentence refer to serial position indicated in calibration legend.

Event-related Brain Potentials (ERPs) ERP waveforms to simple transitive clauses were derived from an average of 44 blink-corrected trials per subject (range: 28 to 58) with an epoch length of 3,500 ms, including a 500 ms presentence baseline. This epoch included all five words in the initial transitive clause and the following causative conjunction (e.g., "because"). Thus the contribution of any given lexical item to the average at each position was reduced while at the same time the lexical class and functional similarities among words at each position were highlighted.

Typically, such data are examined by averaging the ERP to each word in a sentence, forming subaverages as a function of experimental conditions, and measuring the amplitudes of peaks (or over some longer range) and latencies of the positive and negative peaks and troughs in the various waveforms. However, because our focus here is on processes that go beyond the single-word level, we will concentrate on measures of clause-length ERPs. The resultant grand average ERPs (N = 18) across the entire clause at all 26 electrode locations are shown in figure 20.3. Although this display highlights the regularity of the ERP response to each word and shows how it varies with scalp location to some degree, it does not easily yield to a visual

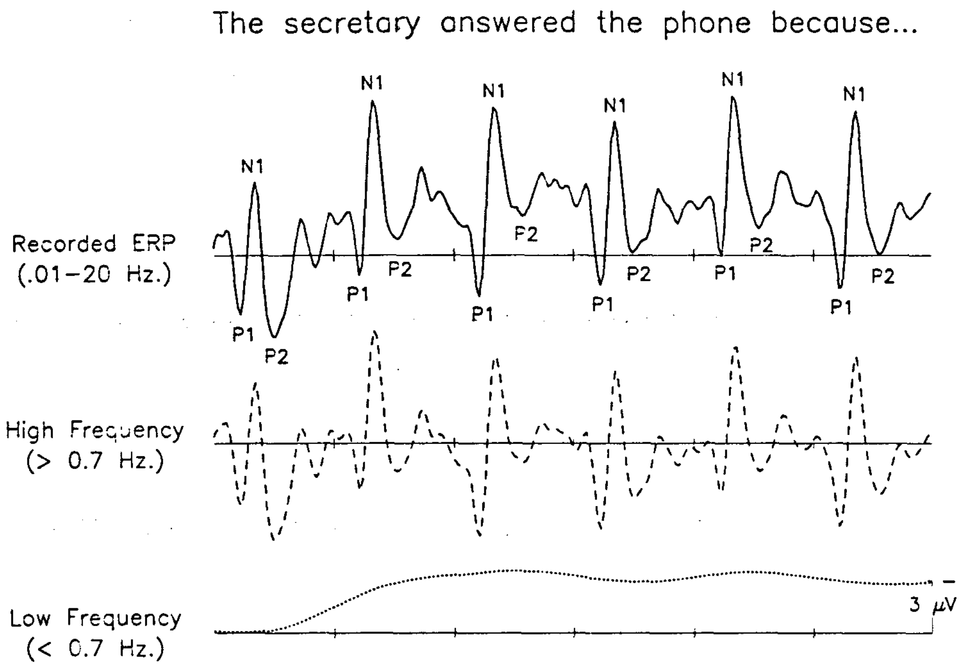

Figure 20.4 Cross-clause grand average ERP from left occipitotemporal site showing originally recorded and averaged data in first row (solid line), digitally high-pass filtered data in second row (> 0,7 Hz, dashed line), and digitally low-pass filtered data in third row (< 0.7 Hz, dotted line).

analysis of topographical distinctions. In order to tease apart the relatively punctate processes from those with a more prolonged and/or cumulative time course, we digitally filtered the recorded waveforms with a low-pass filter (<.7 Hz). Figure 20.4 shows the consequences of such digital filtering in separating the high- and low-frequency components of the recorded ERP for a single site (left occipitotemporal). Clearly, there is substantial slow activity across the course of the sentence that is independent of the transient P1-N1-P2 components triggered by each incoming word (see fig. 20.4, third row).

As can be seen in figure 20.5, even a cursory examination of the electrical signatures of these slow components of whole-clause averages reveals a rich landscape of differentiable potentials. The most remarkable aspect of these potentials is their systematic inhomogeneity over the scalp, with both anterior-posterior and left-right differences in polarity, time course, and amplitude. Presumably these electrical patterns were sculpted by the various nontransient demands of visual sentence processing, with their richness paralleling the complexity and multitude of the underlying neural processes.

The diversity of the whole-clause ERPs is especially striking when one compares analogous locations over the left and right hemispheres at the most lateral recording sites, that is, the outermost ring going from the front (top) to the back (bottom) of the head.[29] Ideally, we would employ statistical

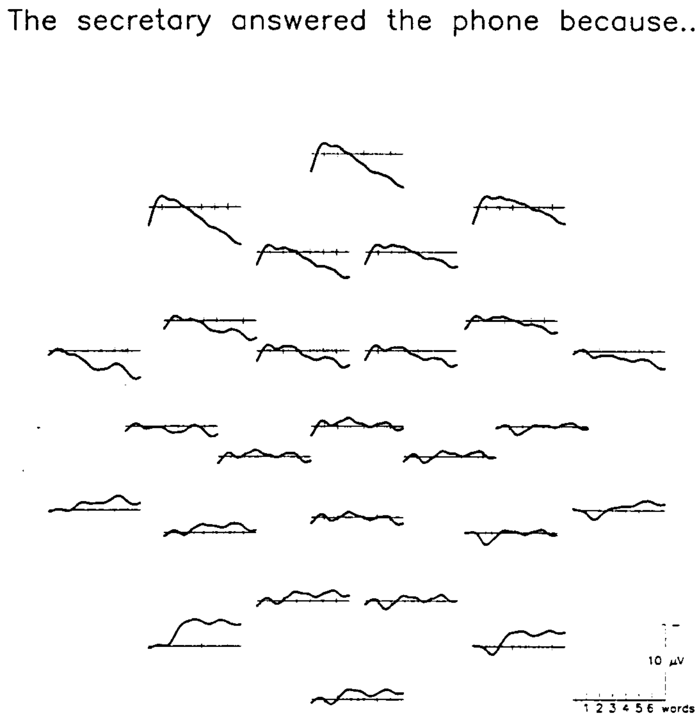

Figure 20.5 Same data as in figure 20.3 subjected to low-pass filtering at 0.7 Hz, resulting in emphasis of slow potential activity across transitive clause.

procedures tailored for making inferences about maps with rich spatiotemporal structure, but the commonly accepted and available methods are far from ideal, especially from the point of view of statistical power. For this chapter, we restrict our analysis to well-known factorial analyses of variance (ANOVAs) with repeated measures performed on the four pairs of most lateral electrodes, with the factors being hemisphere (left, right) and electrodes (four levels as described above). Individual analyses of pairs of sites were then performed after the omnibus ANOVA as indicated. All analyses, unless otherwise noted, were performed on the mean amplitude of the region between 2000 and 2500 ms post sentence onset, that is, on the clause-ending word.

Overall, the strong visual impression of voltage differences along an anterior-posterior axis that are shaped by laterally asymmetric factors is confirmed by the omnibus ANOVA (main effect of electrodes: $F(3,51) = 5.19$, $p < .001$; interaction of electrodes and hemisphere: $F(3,51) = 8.28$, $p < .001$). Over the front of the head, the slow potential is negative for the first two words but thereafter slowly becomes more and more positive over the course of the clause; this positive drift is significantly larger over left- than right-hemisphere sites by the end of the clause at prefrontal sites ($F(1,17) = 7.92$; $p < .05$). At anterior temporal sites, superimposed on a subtle version of this slow positivity there is a more phasic positive change coincident with the appearance of the verb, and maximal in the range of 1300 to 1800 ms. This positivity is in turn followed by a negative-going wave that peaks at the clause-final word. Both the positivity and the subsequent negativity are better articulated over the left- than the right-hemisphere sites. Thus, for the verb-related positivity, we have a main effect of hemisphere at anterior temporal sites in the region between 1300 and 1800 ms, with the left hemisphere being more positive ($F(1, 17) = 6.45$; $p < .02$). For the clause-ending negativity at anterior temporal sites, we take the clause ending effect as the difference between the mean voltage at the end of the clause and the mean voltage on the following word, where we find a similar effect of hemisphere, with the left-hemisphere effect being larger ($F(1,17) = 11.02$; $p < .01$).

Turning our attention to sites over the back of the head, the most obvious change is in the overall polarity of the ERP from positive-going over the front of the head to negative-going over the back; this effect is more pronounced over the left hemisphere. Thus, if we add an additional factor, grouping electrodes into anterior and posterior sets, we find a significant main effect of this anterior-posterior factor ($F(1,17) = 9.00$; $p < .01$), and an interaction of this factor with hemisphere ($F(1,17) = 14.64$; $p < .01$). At the posterior temporal sites (third pair of most lateral sites from front to back), this negativity builds slowly from the second word of the sentence to a peak around the clause ending, similar to that at anterior temporal sites. More prominent is the slow negative potential over the occipitotemporal sites that begins with the first word and is sustained at a steady level across the entire clause; this negative shift is also reliably larger over the left than the right hemisphere by the end of the clause ($F(1,17) = 7.50$; $p < .02$). In summary, the slow components visible at frontal, anterior temporal, posterior temporal, and occipitotemporal sites show a left-right asymmetry consistent with the specialized role in language processing ascribed to the left hemisphere in the standard teachings of neuropsychology. It is important to note, however, that these data do not rule out involvement of the right hemisphere.[30]

20.9 PARSING THE ERP BY LOCATION AND FUNCTION

But what is the brain doing? What is the mind doing? We start our explanation with a discussion of the sensory, perceptual, and cognitive processes we know from behavioral, psychological, and psycholinguistic studies of word recognition and reading. We combine this with the spatial and temporal information provided by the patterns of the electrical activity at the scalp, and integrate this knowledge with data from other neuroscience studies to put forward some testable working hypotheses. Clearly, the first thing that subjects must do in this reading task is to process the words as visual input, analyzing the relevant visual features and forming representations at the word-form level sufficient to support the phenomena described by lexical access. By lexical access, we mean activation that leads to the availability of the syntactic specifications (e.g., word class, arguments, etc.) and core semantic attributes associated with each letter string.

Visual Processing and Occipitotemporal Cortex

A good place to start, therefore, is over the visual areas, the occipital cortex, because anatomical and neurophysiological research on visual processing has demonstrated that it is these areas which perform the initial visual analyses to provide the language system with input for further processing. It is here that the ERPs show the earliest time-locked activity following each word, namely, the P1 component of the visual evoked potential (EP). As seen in figure 20.6, the ERP to each word is characterized by the P1, N1, and P2 components (also see fig. 20.4). The earliest component, P1, occurs between 70 to 100 ms post word onset. The P1 and N1 have together been implicated in early sensory visual and vision-related attentional processing (reviewed by Hillyard and Picton 1987). Both have been found to vary in amplitude with manipulations in the physical parameters of visual stimuli as well as with attention, especially when attentional allocation is based on spatial location.

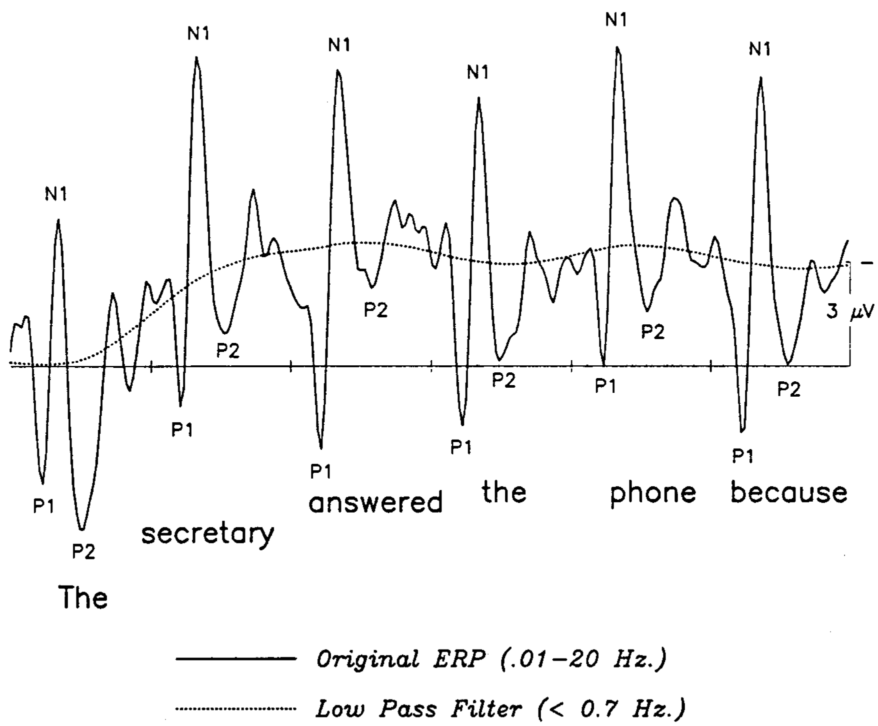

Figure 20.6 Cross-clause grand average ERP from left occipitotemporal site as originally recorded and averaged (solid line), and after application of a low-pass (<0.7 Hz) digital filter that emphasizes slow activity (dotted line). Early, visually specific P1, N1, and P2 components elicited by each word are labeled throughout clause.

For example, the amplitude of the P1 over the right occipital area is enhanced when attention (but not the eyes) is directed to a specific location to the left of fixation, and the opposite pattern holds when attention is focused to the left of fixation. Indeed, the behavior of the P1 component in a variety of visuospatial selective attention tasks has led Hillyard and his collaborators to propose that the P1 reflects the activity of a sensory gate mechanism that modulates the beam width of the attentional "spotlight" (Mangun, Hillyard, and Luck 1993). Recently, Mangun et al. (1993) combined individual subject magnetic resonance images (MRIs), brain electrical source localization (BESA), and current source density analysis (CSD) to localize the PI generator to the extrastriate cortex contralateral to the visual field stimulated. While there is likely to be a family of P1s with slightly different functions and localizations, the class of P1 potentials is a good candidate for an early sensory potential that reflects decoding of visual input such as the letter strings subjects were asked-to read in this experiment.

A good functional account of the next positive component, the P2, is lacking, but it is known that its amplitude is sensitive to pattern in the visual input. Thus, for example, the P2 is larger for patterned visual stimuli than for unstructured light flashes and larger when the visual features are coherent, as in a real face, than when all the facial features are present but scrambled (Jeffreys and Tukmachi 1992). All in all, it is reasonable to assume that the Pi, N1, and P2 components of the visual EP reflect neural activity involved in early sensory analyses including visual feature extraction and its modulation by attention.

Consistent with previous reports, both the P1 and the P2 components to each word were asymmetric in amplitude, being larger over the right hemisphere (e.g., Kutas, Van Petten, and Besson 1988; Compton et al. 1991). If we are justified in assuming that these Pis are generated in the extrastriate cortex as per Mangun, Hillyard, and Luck's (1993) analysis, then this component falls close to the region identified by Petersen et al. (1990) via positron-emission tomography (PET) as specialized for processing the attributes of visually presented wordlike stimuli. Specifically, across a number of studies, Petersen and his colleagues found increased blood flow in this region of the extrastriate cortex when subjects viewed real words, nonsense strings, and so-called false fonts (i.e., stimuli that looked like words comprising fragments that looked somewhat like letters) but not when they listened to spoken words. Moreover, this is essentially the same area where Squire et al. (1992) observed significant decreases in blood flow when words were repeated within an experimental session (in an implicit priming task), presumably because aspects of visual feature extraction were facilitated (primed) by exposure during a prior study episode.

Figure 20.6 also shows that at the occipitotemporal sites, these transient sensory responses are superimposed on a sustained negativity. This standing negativity took approximately one second to reach its eventual plateau of approximately -3 uV. Thus, at this site, the nature of the visual processing was insensitive to lexical class (e.g., open or closed class) and was laterally asymmetric, being larger over the left than the right hemisphere. As a working hypothesis, we suggest that this negative shift reflects processing and integration of the visual features necessary to activate a word-form representation. If so it may be related to the activation in the ventral occipital areas proposed by Petersen et al. (1990) to be involved in processing word forms. Fiez and Petersen (1993) described a region in the lower side of the occipital lobe that showed increased blood flow both following visually presented words and orthographically regular pseudowords but not 'following either so-called false fonts or unpronounceable consonant strings. Because Fiez and Petersen did not use very familiar visual patterns such as pictures of objects or faces as a control, their identification of this area as specific to word form may be premature.[31] Nonetheless, the general region undoubtedly has a role in early visual processing.

The time course of the slow negativity fits with the proposal that it mirrors the use of resources dedicated to the continued processing of visual features, or the continuous activation of word-form representations supporting higher-level computations. A further testable hypothesis is that the asymmetry in this component may reflect lexical processes; it would thus be informative to determine whether a similar negativity would distinguish the processing of lists of pseudowords (where it would be expected) from lists of nonwords (where it would not). Moreover, examining the elicitation of this negativity during extended presentations of complex visual scenes, faces, or real pictures would further test its specificity to lexical level analysis. Finally, if the negativity is uniquely tied to lexical-level processes, then we might expect a similarly prolonged potential during speech reflecting acoustic-phonetic analyses and segmentation. Based on the available neuropsychological, neurophysiological, and neuroimaging data, these operations would most likely be carried out in the superior temporal gyrus and nearby brain regions, thereby resulting in a more central scalp distribution typical of that obtained for early sensory auditory components (Naatanen 1992).

A somewhat surprising aspect of these occipital potentials is highlighted in the comparison between good and poor comprehenders in figure 20.7. Because the absolute level of performance was relatively high (over 80 percent for all subjects), and the differences between good and poor comprehenders were therefore relatively small, we were surprised to find that the ERPs from the two groups differed in several respects. First, the sensory components were on the whole larger peak-to-peak (e.g., P1-N1, N1-P2) for the poor than good comprehenders. Second, both the amplitudes of the sensory components and the slow negativity exhibited greater hemispheric asymmetry in the poor comprehenders (for the slow negativity at occipitotemporal sites, $F(1,16) = 5.31$; $p < .05$). In a previous report, we have suggested that the larger visual EPs in the poorer comprehenders might indicate that they allocated more attentional resources to fairly low-level visual processing of the words (feature extraction) than the better comprehenders (King and Kutas

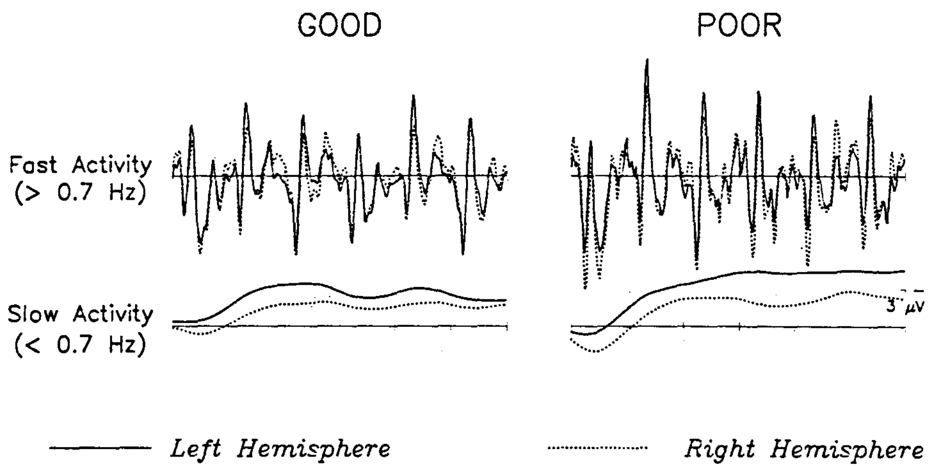

Figure 20.7 Comparison of lateral distribution of cross-clause ERPs from over occipito-temporal sites for good (N = 12, left column) and poor comprehenders (N = 6, right column). Left (solid line) and right (dotted line) hemispheres are shown superimposed in top row after high-pass digital filtering and in bottom row after low-pass digital filtering.

1995a). The present data are in line with this suggestion, perhaps indicating that the poorer comprehenders also devoted more processing resources to the integration of the visual features into a representation (word form) that could be used to access a word's syntactic specifications and semantic attributes.

As mentioned previously, these occipital potentials were not especially sensitive to lexical class or word meaning. Typically, ERPs over more anterior regions are more sensitive indices of lexical class and semantic relationships both at the word and sentence levels. The factors that influence this N400 potential were noted in the introduction. As we did not explicitly manipulate the amplitude of the N400 in this study, we merely point out its presence as an index of semantic analysis at the interface between lexical and sentential levels.

Semantic and Syntactic Processing: Frontal and Temporal Electrode Sites

By contrast to the early feature extraction that takes place transiently between 80 and 100 ms post stimulus onset, the effects of semantic and structural variables tend to be reflected transiently in the ERP almost 100 ms later between 200 and 600 ms post word onset. We think that it is at this time that the specific word meanings derived from an interplay between the "core" characteristics of a word and the context in which it is currently embedded emerge. Thus at the same time as the visual areas are engaged with early visual processing functions, accessing visual word forms, and keeping these word forms active for further processing, frontal and temporal regions are

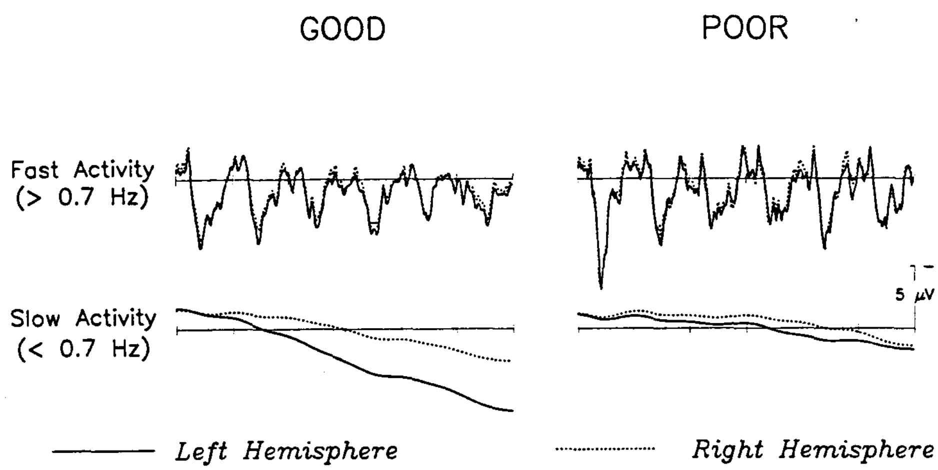

Figure 20.8 Comparison of lateral distribution of the cross-clause ERPs from over the prefrontal sites for good (*N* = 12, left column) and poor comprehenders (*N* = 6, right column). Left (solid line) and right (dotted line) hemispheres are shown superimposed in top row after high-pass digital filtering and in bottom row after low-pass digital filtering. Note that ultraslow positive drift is almost twice as large over left hemisphere, while faster potentials are almost identical over two hemispheres.

involved in analyzing word meanings and the sentence constituents, setting up a mental model of the situation or delimiting a mental space (Johnson-Laird 1983; Fauconnier 1985), and keeping all of these information sources active as working memory. Noun phrases and verbs are presumed to be especially important here in that they provide the players, the roles, and the actions-who did what to whom (when and where).

We now turn to the slow activity at the most frontal recording sites,[32] where we found that reading the transitive clauses was associated with a slow-growing, cumulative positivity; this positive drift was almost twice as large over the left than the right frontal sites (see also fig. 20.9). By contrast, the transient EPs at these same frontal sites were bilaterally symmetric. The frontal maximum of these potentials taken together with the known role of the frontal lobes in the "executive" functions of working memory suggest that they reflect integration between items in WM with information from long-term memory to form a coherent mental model essential both to understanding and to the laying down of a retrievable memory trace.

Just as with the posterior slow potential effects, the good and poor comprehenders could be differentiated on the basis of the amplitude and asymmetry of this frontal positivity (see fig. 20.8). It was much larger for the good than the poor comprehenders; the difference being mostly due to its absence in the left-hemisphere ERPs of the poor comprehenders, causing a reliable interaction of comprehension skill and hemisphere at the frontal lateral sites ($F(1,16) = 5.06$; $p < .05$). Note that this is exactly the opposite of the pattern we observed for the occipital negativity, where poorer comprehenders

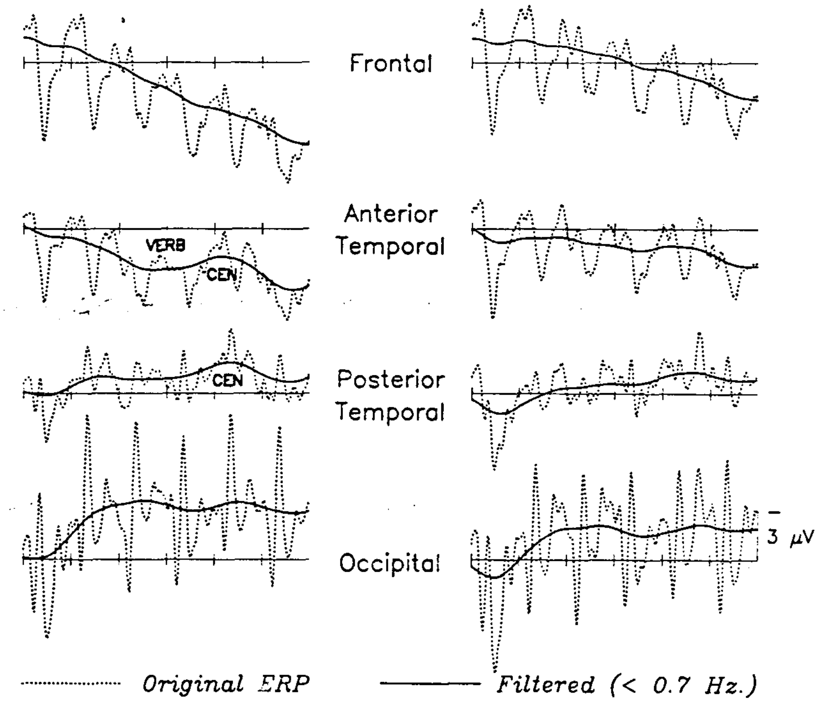

Figure 20.9 Superimposed are originally recorded cross-clause grand average ($N = 18$) ERPs and the slow activity only (low-pass-filtered at 0.7 Hz) for 4 pairs of sites going from front to back of head over left and right hemispheres, separately. Note phasic positivity at left anterior temporal sites that. peaks just following the verb and is itself immediately followed by negativity at clause ending (i.e., clause-ending negativity or CEN).

showed larger effects. We take this pattern as indicative of a possible trade-off in the poor comprehenders between resources devoted to early visual processing and those devoted to higher-level integrative processing (e.g., Perfetti and Lesgold 1977); one might expect such a trade-off to be imposed by the time constraints of working memory operations. Although we did not test their memory for the experimental materials, we would expect poor comprehenders to perform worse on recognition memory or recall tests for these sentences if less time was devoted to "deeper" processing. Of some interest to this reciprocity hypothesis is what would happen in the poor comprehenders if the sentences were spoken instead of read. Insofar as their comprehension problem is solely a consequence of impaired early visual processing, poor comprehenders should show normal ERPs during speech processing, assuming that their early auditory processing is within normal limits. Of course, it is also possible that the early processing difficulties are due to a fault in a domain-general operation such as temporal synchrony or sequencing, and would therefore be manifest in both reading and speech processing (see, for example, Tallal, Miller, and Fitch 1993).

The extreme slowness of the frontal activity is very striking. Indeed, its time course is more in line with that of neuromodulatory, metabolic, or blood flow processes than postsynaptic activity. One obvious temptation is to seek some connection of these slower frontal potentials and the activity of a neuromodulatory neurotransmitter known to impact working memory performance, namely, dopamine. There is substantial evidence that both the frontal lobes and its dopamine innervations are critical for proper execution of WM functions (e.g., Sawaguchi and Goldman-Rakic 1991). In short, both the frontal region and dopamine appear to be necessary to allow humans to stop and think without always reacting in a reflexive fashion-to determine what is relevant and requires attentional resources, and what is immaterial, given the current situation. Certainly part of the frontal lobe must be involved in maintaining the frontal attentional system (Posner and Petersen 1990) and in holding onto the sense of continuity that characterizes most immediate thought.[33] We should also note the possibility that this slow scalp-positive shift could be due to a cortical surface negative shift within a deep convolution of the frontal cortex or along a medial surface such as the anterior cingulate, which would reverse in polarity over the ipsilateral scalp.34

In either case, our working hypothesis is that this growing anterior positivity is a cumulative index of the construction of a coherent sentence-level schema of the delimitation of a mental space (e.g., Fauconnier 1985). Clearly, this integrative process would be most easily achieved and most readily completed for simple transitive constructions and would be more difficult for sentences with embedded clauses (which we will discuss later). Insofar as such integration is difficult, the slow frontal positivity should grow less rapidly. In general, we have found that loading unassigned noun phrases into working memory and possibly holding onto thematic role placeholders in working memory were associated with negative-going potentials superimposed on this slow frontal shift (King and Kutas 1995a). On the other hand, operations within working memory, such as uncovering argument structure information from a verb and making preliminary role assignments to the subject NP, seem to be associated with a positive-going potential. This phasic positivity is superimposed on the slower, more anterior positivity; thus, coincident with the verb there was a phasic positivity more prominent over left temporal sites (see fig. 20.9). Also at the left anterior temporal recording site, this phasic positivity was almost immediately followed by a negativity that appeared time-locked to the end of the clause (we will dub this the "CEN" for clause-ending negativity). The CEN also was most prominent at temporal sites over, the left hemisphere.

Clause boundaries are known to be loci where changes related to language processing have large effects on working memory. For example, clause boundaries and sentence-final words are typically associated with increases in reading times measured via button presses and eye movements (Just and Carpenter 1980; Aaronson and Ferres 1986). Further, Levin and Kaplan (1970) reported that the eye-voice span became shorter at clause boundaries, in agreement with other results indicating that secondary task performance suffers insofar as it competes with clause closure processes. Without additional manipulations, we cannot be certain whether the CEN reflects successful wrap-up of the clause or processes that detect would-be clause endings based on structural considerations. In other words, we cannot distinguish theories that posit specialized wrap-up or integrative processes at clause boundaries from those that argue against any special or additional processing at a clause boundary. In this latter view, clause boundary effects would simply reflect the frequent coincidental co-occurrence of clause endings and finalizing multiple thematic role assignments.

Comparing Simple with Embedded Clauses

In other recent work (King and Kutas 1995a), we proposed that updating one's mental model by adding elements and/or forming functional links between them in WM were manifest in ERP modulations over frontal and temporal regions, especially in the left hemisphere. In that study we examined WM operations during reading by comparing sentences that contained embedded relative clauses. The critical materials were closely matched pairs of sentences both of which contained a relative clause modifying the main clause subject but differing in the role that the subject of the main clause played in the relative clause:

(6) a. The reporter who harshly attacked the senator admitted the error.
    b. The reporter who the senator harshly attacked admitted the error.

In (6a) "the reporter" is also the agent-subject of the relative clause, and the sentence is referred to as a "subject subject (SS) relative." By contrast, in (6b) "the reporter" is the object of the relative clause verb and the sentence is referred to as a "subject object (SO) relative." Neither of these sentence types is ambiguous, but they do differ in processing difficulty, with the object relative (SO) causing greater difficulty. Participants tend to be slower when reading object relatives and also make more comprehension errors when questioned on who did what to whom. The difficulty is seemingly concentrated on the verbs of the relative clause and main clause ("attacked" and "admitted") (e.g., King and just 1991). These processing differences have been attributed to the greater working memory load imposed by object relative sentences, wherein not all information can be used as immediately upon occurrence, as it can in the subject relative sentences.

Our ERP data corroborated these behavioral findings in revealing large ERP differences (i.e., a left anterior negativity, or LAN effect; see also Kluender and Kutas, 1993a, 1993b) where the greatest processing times are typically reported for both word-by-word reading time (Ford 1983; King and just 1991) and eye fixation studies (Holmes and O'Regan 1981), namely, at the main verb just following the relative clause. Our linking of modulations in this negativity with WM load is supported by the data in figure 20.10,

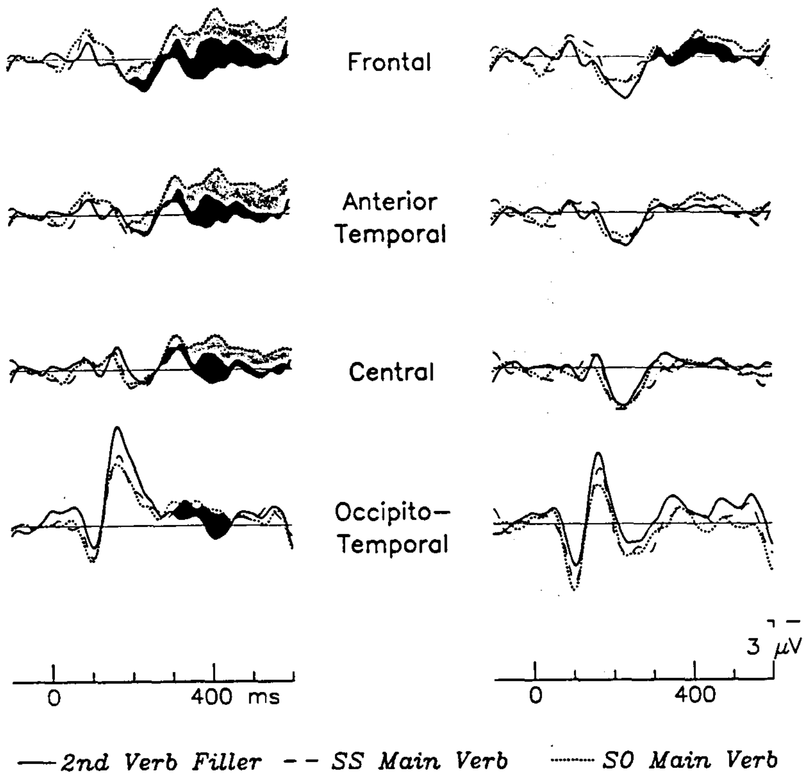

Figure 20.10 Grand average (N = 24) ERPs to main clause verb from subject relative (SS) and object relative (SO) sentences contrasted with the ERPs to second verbs in multiclausal sentence without any embeddings (e.g., 'The secretary answered the phone and scribbled a message on the legal paper"). This difference in relative negativity over left frontal sites is known as "left anterior negativity" (LAN) effect. Data from King and Kutas (1995a).

showing the greatest LAN for the verbs in the more difficult SO sentences, the least negativity for the second verb in sentences without any embedded clauses, and a negativity of intermediate amplitude for the main verb of SS sentences. Further evidence for this position is given in Kluender and Kutas (1993a). More important, however, across-sentence ERP averages unambiguously demonstrated that the brain deals with subject and object relative sentences differently, well before the verbs (see figure 20.11). That is, we observed significant differences between the two sentence types much earlier than typical reading time effects.

One striking ERP feature distinguishing SS from SO sentences was the relatively larger slow frontal positive shift in SS sentences; in this case, the ERPs to the two sentence types diverged as soon as the reader was obliged to add a second noun phrase (NP) to working memory in object relative sentences. This frontal shift grew over the course of these sentences most quickly for the structurally simpler sentence type (e.g., the first clause of coordinate transitive clauses similar to the ones we discussed previously) and

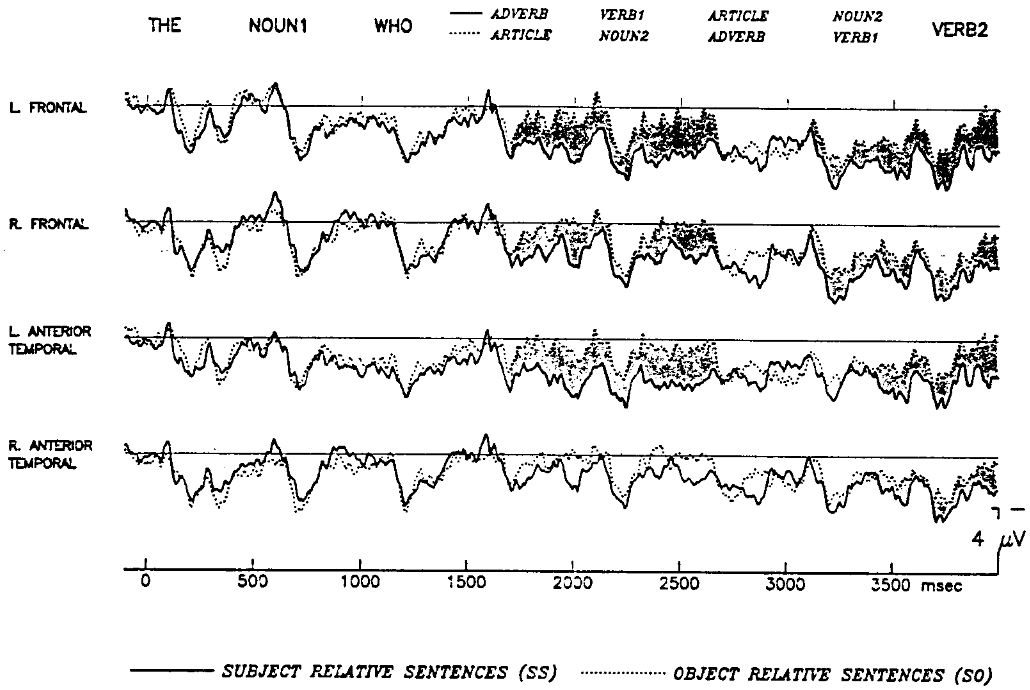

Figure 20.11 Comparison of grand average ($N = 24$) ERPs elicited by subject (SS) and object (SO) relative sentences at four anterior recording sites. Recordings span first two words of the main clause, the embedded clause; and next few words of main clause. Difference between two ERPs is shaded for emphasis. Data taken from King and Kutas (1995).

least quickly for the structurally more complex sentence type, reaching the smallest amplitude offset for the most difficult (SO) sentence type. As mentioned earlier, we linked this slow frontal positive drift with sentence level integration and hypothesized that negative-going deflections from it occurred with each additional demand on working memory: the heavier the load, the more negative (i.e., less positive) the slow potential shift. Note that at the end of the SS relative clause we see a phasic negativity, which we take to be the CEN for the relative clause. The CEN for the SO clause is not apparent, but, then again, neither is the actual end of the relative clause, which ends with a gap. One interesting possibility is that the left frontal negativity we observe following the relative clause is primarily an enlarged CEN, possibly prolonged through time, as also suggested by Kluender and Kutas (1993b). This pattern of effects is reasonable not only because the detection of the gap in the relative clause may not be closely time-locked to any word onset, but also because clause-ending processes in SO sentences may take longer, as has been suggested by reaction time and eye movement data (e.g., King and Just 1991; Ford 1983; Holmes and O'Regan 1981).

We observed a similar effect in the present data when comparing the simple transitive clauses with more complex sentence types; loading items into WM was associated with enhanced frontotemporal negativities. Note

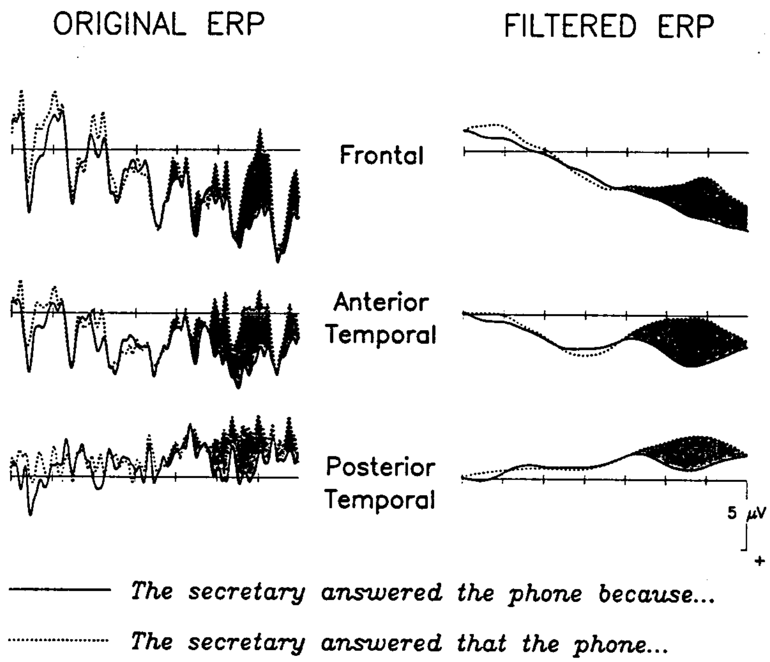

Figure 20.12 Grand average ERPs to simple transitive clauses plotted against clauses where object is complex complement structure (i.e., embedded sentence). Note that shaded difference between two sentence types becomes substantial after point at which it is clear that object of verb in nonsimple case is complex complement.

that this WM-related negativity is different from the CEN. This contrast is depicted in figure 20.12, where the ERPs to simple transitives are overlaid with those to clauses whose object is a complex complement. The ERP difference between these two sentence types becomes substantial after the point at which it is obvious that the object of the verb in the nonsimple case is an embedded sentence. Thus, in the case of the simple transitives, the clause ending is demarcated by a negativity with a left temporal focus. By contrast, in the case of the more complex sentence type, the waveform also goes more negative as information is loaded into WM, although this negativity seems to include both a prolongation of the CEN and a more frontal component reflecting the additional WM load.

As would be predicted from a variety of working memory-based theories of comprehension, the ERP slow potential differences between subject and object relative sentences were correlated with comprehension. Unlike good comprehenders (87 percent accuracy), the poorer comprehenders (68 percent accuracy) showed the positive shift *only* for simple transitive clauses and not for the subject relative sentences. Moreover, poor comprehenders showed relatively little difference in their ERPs to subject and object relative sentences (see fig. 20.13). They appeared to be loaded down simply in comprehending sentences with embedded clauses per se, without much regard for the additional demand the SO sentences made on WM resources. Note that

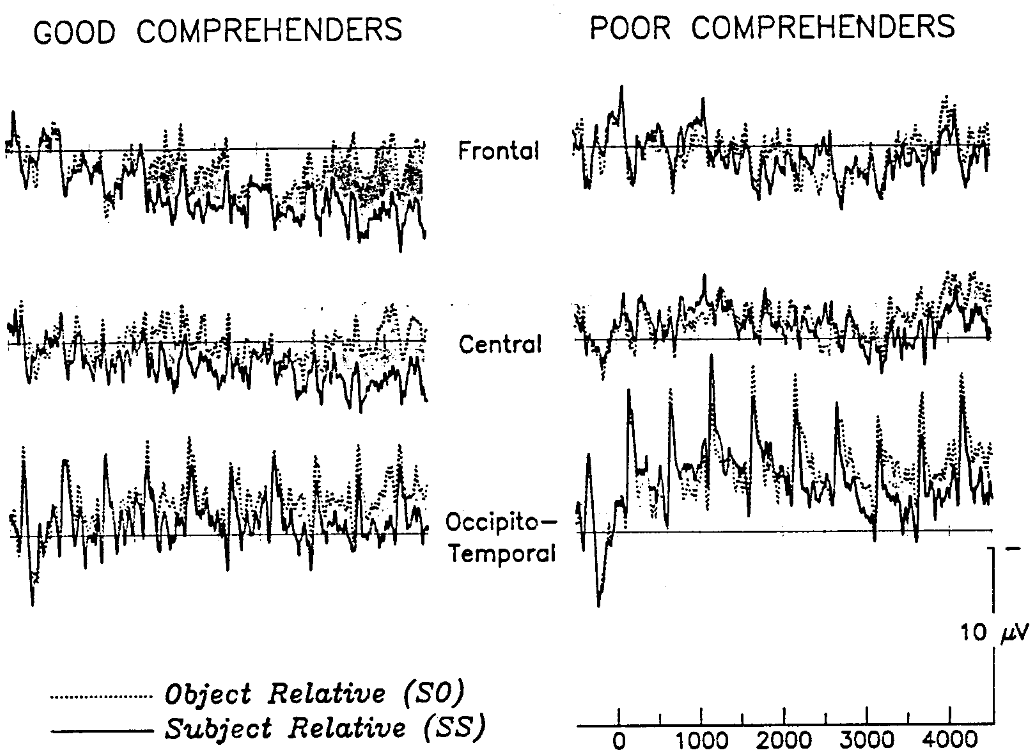

Figure 20.13 Comparison of the cross-clause ERPs from the SS versus SO sentences in good (N = 12, left column) and poor (N = 12, right column) comprehenders at three left-hemisphere sites. Data taken King and Kutas (1995).

the ERPs from the occipital leads also show the previously discussed differences in the visual EPs of good versus poor comprehenders; both the sensory EPs and the slow negativity were larger and more asymmetric in the poor than in the good comprehenders.

20.10 SUMMARY

In this this chapter we have described the patterns of electrical activity recorded from the subjects' scalp as they read through the initial transitive clause in a series of thematically unrelated, multiclausal sentences. We linked the electrical activity to phenomena within the psycholinguistic literature on sentence processing as well as to brain areas defined by research on nonhuman animals, brain-damaged individuals, and various human brain-imaging techniques. We proposed electrophysiological markers for relatively early, low-level processes such as visual feature extraction and integration into a word form, as well as for later processes such as thematic role assignment, clause closure, and the construction and integration of a more complete discourse model. We also presented evidence for an ERP index of maintaining items in working memory. Throughout, we highlighted the differences in these processes as they related to comprehension skill, suggesting a possible trade-off between resources for low-level visual analysis versus higher-level integration. Although our results must be regarded as preliminary, they have suggested to us several working hypotheses that seek to unify concepts in the cognitive and biological studies of language processing, and offer the prospect of achieving a true cognitive neuroscience integration.

ACKNOWLEDGMENTS

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NOTES

1. Because they do not arise in the simple materials used in the present experiment, we will not discuss the complexities of establishing that a particular noun phrase or pronoun actually refers to an antecedent. Nevertheless, these issues are clearly very important in language processing and elegantly underscore the need for a flexible model of working memory.

2. This account has the added benefits of explicit computational modularity (Fodor 1983) without actually encapsulating functional subsystems.

3. This is true whether we prefer to think of linguistic inputs in terms of highly distributed neural networks, explicit tree structures or something in between.

4. Within English, which has too few case markings to indicate case roles for nouns, multiple-slot structures like verbs tend to have greater control over the eventual meaning of their fillers than the reverse, thereby establishing specific "expectations" concerning their fillers even in the absence of much pragmatic information.

5. That is, with respect to fillers or open slots, whether achieved via an articulatory loop or by passive spreading of activation.

6. Note that this characterization of WM is simultaneously at variance with functionally modular models of processing like Fodor's (1983) as well as those that attempt to make all processing dependent on a unified working memory like Newell's SOAR (1990). Fodor's hypothesis depends critically on central processes (e.g., general WM) to digest the output of its perceptual and linguistic modules, while Newell's depends on a universally convertible working memory to feed its more specialized problem spaces that control processing.

7. While 80,000 mm^2 is by no means small, it is actually smaller than even many neuroscientists have guessed in the past (Chemiak 1990).

8. We estimated the area of the pars triangularis by measuring its lateral extent from an actual size figure of the brain printed in DeArmond, Fusco, and Dewey's (1989) atlas and correcting for the amount of folding in this region of the cortex (estimated as a factor of almost 3 from an

inspection of the horizontal sections through this region, and by data presented in Dale and Sereno 1993).

9. The version of Broca's area appearing in Kandel, Schwartz, and Jessel 1991 on page 10 would appear to be over 4,000 mm^2, while the one on page 844 would be perhaps slightly larger. The version of Broca's area shown in Kolb and Whishaw 1990 on page 570 is slightly smaller, although it hardly overlaps those depicted in Kandel, Schwartz, and Jessel 1991.

10. In fact, Wernicke's account of his eponymous brain area shows it as occupying the cortex on the superior temporal gyrus anterior rather than posterior to the primary auditory cortex; see, for example, de Bleser, Cubelli, and Luzzatti 1993 for a facsimile of Wemicke's original figure and a discussion of his work.

11. Cherniak's (1990) work on quantitative neuroanatomy shows, for example, that long fiber connections between ipsilateral brain areas must be relatively scarce, or at best less dense than generally assumed, because there is simply not enough physical (actual) space within the white matter to allow them to be more common or to support them. A somewhat less stringent constraint also applies to the connectional budget between adjacent areas.

12. The use of the term *desynrchronization* in these techniques may be misleading because it is not clear how or to what extent alpha activity (for example) is synchronized in the cortex, or what its desynchronization means.

13. We must assume when we use the average ERP approach that the response function to the trigger is stationary and that the "random" activity is completely uncorrelated with the true response. These strong assumptions are at best only partially fulfilled but do not vitiate the entire approach, judging by the number and variety of highly replicable effects in the field.

14. While an infinite number of configurations of a variable number of neural generators may account for any given pattern of electrical activity at the scalp, only some combinations are actually likely if we assume that the potential at the scalp is a sum of the excitatory postsynaptic potentials (EPSPs) and inhibitory postsynaptic potentials (IPSPs) from cortical pyramidal cells firing in synchrony. Moreover, because for the purposes of this analysis brain waves are just (no more than) electrical signals within a physical system; they can be deciphered in terms of the laws of physics. There are proven mathematical techniques available for determining the minimum number of separate generators needed to explain the pattern of electrical activity at the scalp at any given moment, and certainly at moments correlated in time. Thus, while certain assumptions must be made, they seem eminently reasonable. Still further constraints to delimit the solution space (i.e., the number of possible solutions) are available if findings from depth recordings are added. In all cases, the more electrodes, the better (although point sources would be preferable to large cup electrodes) because until at least the number of underlying generators is known (unless the minimum number of generators is considerable), high spatial sampling is needed to get localization precision. The number of recording electrodes should exceed at minimum (preferably, by a factor of 4) the number of generators assumed to be active. For one thing, you do not want to distort the signal; for another, it would be nice if you could still tell what color hair someone had (if any).

15. The LPN refers to the lexical processing negativity which King and Kutas (1995b) have proposed as an alternative to the N280 (Neville et al. 1992) because its latency varies systematically as a function of the length and frequency of the eliciting word. The LPN thus is an ERP component elicited by a word that marks the upper limit by which lexical access must have occurred.

16. Note that not all and perhaps none of these potentials are language-specific.

17. The P2 and P3-like components are often considered as part of the late positive complex (LPC), which includes both a preceding negativity (N2) and a subsequent slow wave (SW) that is negative frontally and positive posteriorly.

18. Although in fact it may be necessary to resort to such interactions to account for all of the ERP differences between open- and closed-class words. Thus, while not all the relevant analyses have been done, Neville, Mills, and Lawson (1992) used median splits of the open-class ERPs on length and frequency of usage to argue that neither one nor both of these factors were sufficient to account for the observed N400 differences between the two lexical classes.

19. Complicating factors include the nature of the stimuli, repetition lag, subject's task, and number of repetitions.

20. Cloze probability refers to the probability that a given word will be used by a subject to "fill in the blank," given a context with a missing word. We find it more than a little reassuring that probabilistic approaches to on-line parsing have recently enjoyed greater popularity both practically and theoretically (see, for example, MacDonald 1994 and chap. 17, this volume).

21. Of course it is possible that our estimates of cloze probability based on the doze procedure are less sensitive than the brain's on-line estimates of a word's predictability.

22. The sensitivity of N400 amplitude to repetition also suggests that it is more than a measure of subjective conditional probability.

23. See, for example, Fodor (1989) for a thorough review of the issues involved in processing empty categories. More recent work has favored models where the parser maintains parallel syntactic analyses in certain situations (e.g., Gibson 1990). Moreover, MacDonald, Just, and Carpenter (1992) provide evidence that there are WM-related individual differences in the computation of such multiple analyses, thereby muddying the interpretation of Garnsey, Tanenhaus, and Chapman's (1989) data. If subjects were maintaining multiple syntactic analyses, the N400 observed may simply have meant that the "first resort" was one analysis being pursued. In this case, it would be informative to see if manipulating the content of the filler NP to change the plausibility of its filling the first gap affected N400 amplitude (e.g., "What bread" versus "What variety of bread" versus "What breads").

24. Thus there were four conditions: two where the words in the two visual fields were identical (one congruous and one incongruous) and two where the words in the two visual fields were different (one congruous and the other incongruous).

25. The component was a positivity on the cortex surface, but reversed in polarity and presumably would generate a negativity at the scalp surface.

26. With an amplitude determined by the extent to which the word was expected given the context.

27. In this context, decimation refers to a reduction in the EEG sampling rate between the time of acquisition and the time of analysis; for the integral decimation factor in this case, this corresponds to taking every third point of the data collected at 250 Hz.

28. It may be worth noting that four of these six poor comprehenders had at least one left-hander in their immediate family. We have observed group differences related to family history of left-handedness in previous language studies (e.g., Kutas, Van Petten, and Besson 1988; Kluender and Kutas 1993), and work by Bever and his colleagues (Bever, Carrithers, Cowart, and Townsend 1989) suggests that family sinistrality may be a biological factor reflecting a real aspect of the subject's language processing capabilities.

29. Note that these homologous sites are the farthest away from each other in the two hemispheres and therefore least susceptible to contamination by,volume conduction from activity in the other hemisphere.

30. By way of contrast, the more medial recording sites (i.e., those nearer the vertex or center electrode) show much less left-right differentiation from each other. This overall pattern suggests that the generators underlying these slow potentials may be arranged asymmetrically.

Without additional evidence, however, we cannot be sure whether the asymmetry is due to a difference in dipole strength between the right and left hemisphere or to differences in dipole orientation between the two sides.

31. In particular, extremely recent functional magnetic resonance imagery (fMRI) work by Sereno and collaborators (personal communication) and other groups should greatly enrich our knowledge of these early visual areas.

32. Note that these most frontal recording sites have typically not been included in most ERP studies of language processing.

33. We reiterate our caution in inferring the underlying generators from maxima in the potentials at the scalp; we offer these primarily as working hypotheses for the moment.

34. Interestingly, Grossman et al. (1992) have provided PET evidence in favor of a role for the anterior cingulate in sentence processing; they suggest that processing deficits in this brain region play an important role in the (subtle) sentence-processing deficits seen in patients suffering from Parkinson's Disease.

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