CHAPTER 4

PSYCHOLINGUISTICS ELECTRIFIED

EVENT-RELATED BRAIN POTENTIAL INVESTIGATIONS

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I. INTRODUCTION

There are those who would argue that there is no more to be learned about mental faculties from monitoring the patterns of electrical activity at the scalp than there was from palpating the various and sundry bumps on skulls of talented individuals or hysterical widows in the heyday of phrenology. But the contributions of various schools of thought often outlast the schools themselves or the techniques that they espoused. For example, the important distinction between perceptual and reflective knowledge, and the idea that cognition can be divided into separable mental faculties-both very much a part of modern-day psychology-were first emphasized by Gall and his followers. The discipline of cognitive electrophysiology seeks to provide a view of various of these perceptual and cognitive processes as they unfold in real time. The brain's electrophysiology can serve as a framework for extending the much sought after links between psychological and neurobiological levels of analysis. Moreover, as neuroscientists begin to appreciate the importance of correlated neuronal activity throughout the central nervous system, there is obviously much to be gained from mapping the regularities in external stimuli or events onto the regularities in brain activity time-locked to those events. Already there is ample evidence showing that these perceptual and cognitive regularities are mirrored, in part, in the modulations of electrical activity referred to as the evoked potential (EP) or event-related brain potential (ERP).

II. GENERAL DESCRIPTION OF THE ELECTROENCEPHALOGRAM AND EVENT-RELATED BRAIN POTENTIALS

A. Electroencephalogram

Given our current state of technology, there are two relatively unobtrusive methods for looking at brain activity associated with both sensory and cognitive functioning. Both of these methods allow measurement of the electrical activity of the brain, taking advantage of the fact that transmission of information in the brain involves the flow of ions. Ion flow across a neuronal membrane produces a voltage field around each active neuron. The activity of a single neuron can be monitored during invasive intracranial recordings, but the electrical fields around neighboring neurons also sum geometrically to produce a field that can be detected as far away as the scalp.

Scalp electrodes can thus be used to record the voltage fluctuations produced by large populations of neurons; the resulting trace of voltage across time is known as the electroencephalogram (EEG). Any given tracing reflects the differences in electric potential (i.e., voltage) between two recording sites. One glimpse at the underlying mental processes is provided by the differential EEG patterns observed while a subject is engaged in various tasks which presumably engage different neural systems (for review, see Butler & Glass, 1976). Such studies typically focus on the relative amount of "alpha"-EEG power in the frequency band between 8 and 12 Hz-although similar analyses can be applied to other frequency bands as well (e.g., beta, gamma, theta, etc).[1] Because high alpha power is generally associated with rest and relaxation, alpha suppression is presumed to reflect increased mental activity. Most EEG studies of language, therefore, have been aimed at showing that during "verbal" tasks there is less alpha over the left but not the right hemisphere and that the converse holds for "nonverbal" tasks (J. Doyle, Ornstein, & Galin, 1974; Ehrlichman & Wiener, 1980; Galin & Ornstein, 1972). Although there has been modest support for this differential-activation hypothesis, many of the studies have been criticized on a number of methodological grounds (Gevins et al., 1979).

B. Event-Related Brain Potentials

The emphasis of the present chapter is on a different aspect of the scalp-recorded electrical activity, namely activity that is time-locked or synchronized to some external event. At any given moment the EEG is likely to reflect the activity of a number of functionally distinct neuronal populations. With the advent of computer averaging, it became possible to obtain an estimate of activity which is time-locked to an arbitrary point, such as the onset of a stimulus. At the scalp an ERP (5-10 μV) is substantially smaller in amplitude than the background EEG (50-100 μV) and must, therefore, be extracted by an averaging procedure. This involves recording ERPs to repeated presentations

[1] There has been a recent upsurge of interest in gamma or 40 Hz band activity, correlated brain activity, and its role in binding the various attributes of a visual stimulus into a coherent object (Engel, Konig, Kreiter, Schillen, & Singer, 1992; Gray, Engel, Konig, & Singer, 1992; Lowel & Singer, 1992; Singer, 1990).

of "similar" stimuli. Voltage fluctuations generated by neurons which are not involved in processing the stimuli of interest will be random with respect to the time of stimulus onset and thus cancel each other, to leave a record of the event-related activity (ERP) that was time-locked to stimulus presentation. Averaging improves the signal-to-noise ratio of the evoked signal in proportion to the square root of the number of responses included. The number of stimuli needed for a reliable (i.e., "clean") average is a function of the amplitude of the ERP component under study. The smaller the component, the more trials are needed to extract it from the "noise" or spontaneous EEG. Which stimuli are defined as "similar" for the purposes of repetition and averaging depends on the goals of the experiment and is established a priori by the experimenter. For example, we could investigate the factor of word frequency by averaging across many different words from each of several different frequency ranges. If some part of the waveform recorded was sensitive to variation in word frequency, the ERP "frequency" effect could then be used to test alternative proposals on the role of frequency in word recognition for words in isolation or in sentence context (see Van Petten & Kutas, 1990, 1991a).

The major statistical assumption in averaging is that the signal is indeed time-locked to the averaging trigger whereas the noise is not. Time-locked noise typically occurs only in the case of electrical artifacts generated by the laboratory equipment which presents the stimulus (e.g., vibration from a headphone speaker or a tactile stimulator). For the early "sensory" portion of the ERP elicited by the stimulus, the time-locking assumption is well supported. In the case of later portions of the ERP which are instead elicited by higher-level "cognitive" analyses of the stimulus, the latency of the signal may not be invariant with regard to stimulus onset. Under these circumstances there are a variety of pattern recognition techniques such as cross-correlation (e.g., Woody adaptive filter) and discriminant analysis that can be used to characterize and re-align the signal for subsequent averaging (for details of these procedures, see Coles, Gratton, Kramer, & Miller, 1986).

1. Peaks and Components

The ERP waveform of voltage plotted against post-stimulus time typically includes a series of positive and negative peaks. In reading a report of an ERP experiment it is essential to note the polarity markings on figures, as some investigators plot positive upward on the page and others "negative up." It is also important to remember that both the amplitude and the polarity of these peaks are relative. Voltage is, by definition, the difference in electrical charge between two spatial locations, whether the two locations are the two poles of a battery or two recording sites on a human head. In ERP recording, one site is typically used as the reference or "inactive" site for all others, so that the choice of reference location will determine both the polarity and amplitude of the recordings. The amplitude/voltage of the peaks in an ERP is relative in a second sense as well. Because our interest is in brain activity elicited by particular stimuli rather than spontaneous activity, we need a comparison with some neutral time period. The ERP average will thus typically include a pre-stimulus baseline, that is a short (100-200 ms) record of activity (or preferably inactivity) immediately preceding each experimental stimulus. Post-stimulus activity is then evaluated relative to the pre-stimulus portion of the recording epoch, so that voltages are only negative or positive with respect to the zero provided by the baseline. Given the relativity of this "zero," ERP researchers are often more concerned with whether a portion of the waveform is "negative-going" or "positive-going" (i.e., becoming more negative or positive with increasing time) than whether it is above or below the baseline pre-stimulus epoch per se.

The peaks of an ERP are typically labeled according to their polarity (negative [N] or positive [P]) and latency in milliseconds relative to stimulus onset (e.g., N100, P230, P300). On occasion, the peaks are designated by their polarity and ordinal position in the waveform (e.g., N1, P1, N2). Sometimes, albeit less often, the labels denote a functional description (e.g., readiness potential, RP; mismatch negativity, MMN) or refer to the brain area which is presumed to be the neural generator of a component (e.g., auditory brainstem response, ABR). Which brings us to the distinction between a peak in a waveform, readily observed by the eye, and the more theoretical concept of a "component" (see also Allison, Wood, & McCarthy, 1986; Donchin, Ritter, & McCallum, 1978).

Asking a group of cognitive psychophysiologists to define "component" may sometimes seem like opening Pandora's box. The basic concept is clear: The processing of any external stimulus occurs over some period of time, so that different parts of the nervous system are invoked at different points and perform different analyses. The ERP is an extended record of this processing, so that different temporal intervals of the waveform will reflect different anatomical locations and different functional processes, although any particular interval may involve more than one temporally overlapping brain region/functional process. Thus, while investigators differ as to the relative importance granted different factors, all use some combination of two sets of factors to identify some portion of an ERP as a unitary component. One set of factors is visible in a single ERP waveform and bears some, although usually unknown, relationship to the anatomy of the underlying neural generators: polarity, latency from stimulus onset, and relative amplitude across a number of scalp locations (i.e., scalp distribution). The second set of factors involves comparisons between two or more experimental conditions to determine what experimental manipulations will influence one temporal region of the waveform.

Susceptibility to SOME experimental manipulation is essential for component identification, making "peak" nonsynonymou with "component." However, the experimental manipulations may take very different forms: (a) varia tions of the physical attributes of the stimuli, such as size, luminance, or color for a visual stimulus; (b) varying the psychological attributes of the stimuli, such as using words which are known or unknown to the subject; (c) varying the physiological state of the subject, by drug administration, selecting a population with a particular type of brain damage, etc.; or (d) varying the psychological state of the subject via task instructions.

The functional characterization offered by the sort of stimulus and task manipulations used by psychologists and the neural characterization that might be offered by a physiologist are thus all part of the definition of an ERP compo nent, under ideal circumstances. However, circumstances are rarely ideal. A functional characterization is most easily carried out via experiments involving large numbers of healthy human subjects, whereas a neural characterization typically requires converging evidence from animal models, neurological patients undergoing invasive clinical procedures, and scalp recordings from patients with defined brain damage (Arezzo, Vaughan, Kraut, Steinschneider, & Legatt, 1986; Buchwald & Squires, 1982; Halgren, 1990; Knight, Scabini, Woods, & Clayworth, 1989; McCarthy, Wood, Williamson, & Spencer, 1989; Pineda, Foote, & Neville, 1989, Pineda, Swick, & Foote, 1991; Smith & Halgren, 1989). In the absence of such converging evidence, only a few general principles of neurophysiology constrain the possible generators of a scalp-recorded component.

It is generally believed that the electrical activity recorded at the scalp is a summation of graded post-synaptic potentials (PSPs) generated by the depolarization and hyperpolarization of brain cells (see Nunez, 1981, 1990; Wood & Allison, 1981). The electrical conductivity of the skull separating the brain from scalp electrodes is low enough that potentials recorded at the scalp must be a reflection of the activity of a relatively large number of neurons, on the order of 103 -104 cells. Pyramidal cells in the cortical layers are likely candidates for most ERP components because they are large and because their dendritic processes are organized in parallel; such an organization leads to the summation of the associated currents, especially when these neurons are synchronously activated in relation to the eliciting event. Negativity or positivity at the scalp reflects the direction of current flow between the active neurons and the recording site. The direction of current flow is determined by a combination of the orientation of the neurons to the recording site, the active areas of the neuronal membrane (basal dendrites, apical dendrites, or cell bodies), and whether the membrane is being excited (depolarized) or inhibited (hyperpolarized). It is thus not possible to equate scalp positivity with neuronal excitation or inhibition unless one has advance knowledge of the other relevant factors.

As a general rule, the amplitudes, latencies, and scalp distributions of the earlier components of the ERP (with latencies of less than 100 ms) are highly reproducible from session to session within an individual (Halliday, 1982). Moreover, systematic variations in the physical parameters of the evoking stimulus (e.g., intensity, frequency, duration) lead to predictable changes in these early components reflecting the altered activation of the sensory pathways. Hence, the earlier evoked components are considered to be "exogenous" or stimulus-bound; they are generally impervious to a subject's state of alertness or attentiveness. It is this invariance in the face of changing psychological states that makes the exogenous components an excellent diagnostic tool for certain sensory and neurologic disorders (Chiappa, 1983; Cracco & Bodis-Wollner, 1986).

For present purposes, however, given our interest in the neural bases of cognition in general, and language in particular, the more informative brain waves are the so-called endogenous components, which may precede or follow a triggering event by many hundreds of milliseconds. An "event" in this case refers to a stimulus, a response, a voluntary movement, or a cognitive operation for which an external timing marker can be specified so that time-locked electrical brain activity (ERP) can be examined. The relative insensitivity of endogenous components to variations in the physical stimulus parameters contrasts with their exquisite responsivity to task demands, instructions, and subjects' intentions, decisions, expectancies, strategies, mend set, and so on. In other words, endogenous ERP components are not "evoked" by a stimulus but are elicited by the perceptual and cognitive operations that are engendered by that stimulus. The same physical stimulus may or may not be followed by a particular endogenous component depending on how the subject chooses to process that stimulus. The term "late" component is often used interchangeably with "endogenous" component because most potentials in this class occur with a latency beyond 100 ms.

2. Recording Parameters

It is important to note that there are well-reasoned rules for determining the characteristics of the amplifiers, bandpass, digital sampling rate, number of stimulus repetitions, time between repetitions, et cetera for the recording of ERPs (see Regan, 1989).[2] No amount of elegance in experimental design or theoretical framework can override an inappropriate recording bandpass or a low signal-to-noise ratio from an insufficient number of trials. A psycholinguist new to ERP research might believe that presenting the same syntactic construction more than 10-20 times will alter the subject's processing strategies and therefore limit the number of trials to five or six. This is clearly too few for any but the largest of electrical signals, but the problem can usually be handled by including a large number of experimental trials supplemented by an even larger number of filler stimuli. Alternatively, some experimenters have chosen to deal with this problem by trading off numbers of trials and subjects (see Garnsey, Tanenhaus, & Chapman, 1989). Fewer than 25-30 trials in an average usually does not provide a good signal-to-noise ratio. Similarly, fewer than 15-20 subjects does not give a true picture of between-subject variability. Moreover, optimal recording parameters will differ depending on whether one is interested in early or late components. This issue is one that may trip up a psycholinguist who teams up with a clinical ERPer or hospital researcher who is accustomed to recording the higher frequency early components and not the lower frequency components and therefore uses a low-pass filter setting of 0.3 Hz instead of 0.01 Hz, or is not sensitive to low-frequency artifacts in the recording.

To date almost all the investigations employing ERPs as indices of language processing have been based on analyses of the voltage waveforms in time. However, in principle there is no reason that such analyses must be restricted to measurements of the voltage waveform. Indeed it may be quite informative to examine the consequences of the experimental manipulations for other estimates of the electrical activity, such as various moments of the voltage field.

Distribution or topography across the scalp recording array has always been one of the criteria for component identification. Because each "active" scalp site is referred to a common reference site, scalp distribution will depend on the location of the reference. An ideal reference site is immune to brain activity (i.e., "inactive") yet is susceptible to the same electrical noise from the external environment as the scalp sites of interest. Reference sites are typically on or close to the head for the latter reason. However, it is also clear

[2] We touch only a few topics in recording procedures here, and briefly at that. The interested reader should consult reference works (Coles et al., 1986; Regan, 1989) for more detailed information.

that none of the more commonly used reference sites, mastoid (bony process right behind the ear), earlobe, chin, nose, vertex, inion, or sternum-vertebra, is completely insulated from brain activity. Until recently the most common reference was linked left and right mastoids. However, Nunez (1981, 1990) showed that linking the mastoids could actually distort the shape of the field at the scalp by forcing the voltage at the two mastoids to be equipotential. Thus, many researchers switched to using an off-line average of the recordings at the two mastoids as a reference. This procedure requires that during the recording session one mastoid be used as a reference for all sites and the other mastoid be included as an active site. The underlying reason for using both mastoids as a reference is, of course, some suspicion that the left and right mastoids may not be equivalent because they pick up more activity from one side of the brain. But if there is good reason to believe that the mastoids are asymmetrically active in a particular paradigm, then it is probably a good idea to use a reference site somewhere along the midline. The best of these is a noncephalic sterno-vertebral reference (Nunez, 1981, 1990; Van Petten & Kutas, 1988).

Recently, much effort has gone into the development of procedures for obtaining reference-free estimates of the ERP. One solution that has been suggested has been to use a so-called average reference together with many electrodes that cover the surface of the head evenly; in this case, the reference for any given site is the average activity across all the other recording sites (Bertrand, Perrin, & Pernier, 1985; Spitzer, Cohen, Fabrikant, & Hallett, 1989). Clearly, the average reference is very sensitive to the total number of electrodes use, as well as to their spatial layout across the head (see Tomberg, Noel, Ozaki, & Desmedt, 1990). The best coverage is afforded by many electrodes (around 26 or more), evenly spaced. The average reference procedure still provides a voltage waveform in time.

Another reference-free procedure provides, instead of the standard voltage measure, an estimate of the instantaneous electrical current flowing into and out of the scalp at each recording site. Current source density (CSD) analysis comes from the second spatial derivative of the voltage surface at the scalp (see Nunez, 1981, 1990; Pernier, Perrin, & Bertrand, 1988). CSD is often used in combination with a spherical spline function to interpolate data recorded from irregularly spaced electrodes and infer current sources and sinks that are not directly beneath a recording site (Perrin, Pernier, Bertrand, Giard, & Echallier, 1987). CSD, like the average reference procedure, requires good spatial sampling of the scalp surface (often 64 sites or more) with precisely defined loci.

3. Measurement and Analysis

There is a sufficiently large number of techniques for data reduction and analysis to make it impossible to cover either all of them or any of them to any depth. Thus what follows is a brief description of the most common ones (but for more details and procedures, see Gevins & Remond, 1987; Lehmann & Skrandies, 1984; Regan, 1989). However, we cannot overemphasize our belief that the choice of analysis method should be motivated as much as possible by some experimental rationale-the nature of the ERP comparisons determined by the questions asked and the hypotheses and predictions which led to the experimental design. As in all other areas, fancy analytic technique cannot make up for poor experimental design.

The most common ERP measures within electrified psycholinguistics are the amplitude (in microvolts) and the latency from stimulus onset (in milliseconds) of a peak in the average waveform. Typically, peak identification involves selecting either the largest or smallest voltage within some prespecified time window. The amplitude of the peak is calculated relative to a baseline; the baseline is presumed to be a time of inactivity and has most often been some period (50-200 ms) prior to stimulus onset.[3] Thus, the resulting measure is referred to as base-to-peak measure; in this way, a peak in the ERP is reduced to the amplitude and latency of a single point. This can be constrasted with a peak-to-peak measure taken between successive peaks of opposite polarity rather than from an inactive baseline (see Coles et al., 1986, for a discussion of other techniques for measuring peaks). Peak-to-peak measurements have serious drawbacks (see Regan, 1989), the most obvious being that a difference between two conditions may reflect a change in the positive peak, the negative peak, or both. It is important to note that neither base-to-peak nor peak-to-peak measures confer a privileged psychological or physiological status to a peak relative to other points in the ERP waveform. As points of highest voltage, peaks are convenient landmarks.

Since peak measurements are inaccurate estimates of long-lasting effects in the ERP that may span multiple peaks and are also quite sensitive to residual noise in the average, many researchers use MEAN amplitude measures-the average voltage during some time window which may span several hundred milliseconds. Such area measurements are taken relative to the mean amplitude in a presumably inactive baseline region. Area measures are less affected by noise and latency jitter than peak measures but are equally dependent on the choice of baseline and do not circumvent the problem of component overlap. There are two approaches to choosing the boundaries for areal integration. For previously documented experimental effects, the limits of the window are those used in prior experiments. When characterizing novel experimental effects, or for researchers who find a particular time window too arbitary, area measurements are taken across the entire waveform in successive increments 30-100 ms in duration. If the waveforms to be compared are noisy, it may be as important to say that some time windows are not statistically different as to say that others are.

Both peak and mean amplitude measures are usually subjected to a multivariate analysis of variance or an analysis of variance with repeated measures, in some cases followed up by Tukey or Scheffe contrasts.

The most common multivariate technique for ERP analysis that has been advocated and used by some researchers is principal components analysis (PCA). PCA, which is closely related to factor analysis, is a procedure for

[3] Choosing a good baseline is by no means an easy task, especially in the case of ERPs to words within written text or natural speech, where the interval preceding sentence-intermediate words is clearly not inactive. Whenever the choice of a baseline is uncertain, a safe procedure is to make measurements relative to several and assess the extent to which the interpretation of the effects would be altered by the different choices. Obviously, the best outcome is if the choice of baseline does not alter the conclusions one would draw.

extracting a small number of components from the total variance of the ERP. The variance in most ERP data to date can be accounted for by no more than eight factors. A discussion of the limits of PCA analysis of ERPs can be found in McCarthy and Wood (1985).

Over the past few years, there has been a significant decrease in the cost of computers and graphics programs as well as an increase in the number of electrode locations from which data are recorded. Thus, it has become necessary to develop a variety of techniques to display multichannel data. The choice of procedures for displaying multidimensional data from a round head on a two-dimensional medium is not without its problems and consequences (see Duffy, 1986; Gevins & Bressler, 1988). A variety of such procedures exist, with some clearly better than others. It is critical to note that most of these are means of DISPLAYING data only, and have nothing to do with data ANALYSIS. In fact, there are very few statistical procedures currently available for comparing two or more experimental conditions with multichannel recordings. Within a standard ANOVA, a typical approach is to include electrode site as a multilevel factor or factors.[4] In this case, some correction procedure must be used to compensate for violations of sphericity of variance (see Vasey & Thayer, 1987, for discussion and suggestions).

4. Magnetic Event-Related Fields

Where there are electric currents and electric fields there are also magnetic fields; electric current generates a magnetic field whose field lines follow the "right hand rule."[5] Until recently this knowledge about the relation between electric and magnetic fields was of little use in the neurosciences, but with the recent advances in superconductors-materials that lose all electrical resistance when cooled below a critical temperature-it has become possible to measure the neuronal magnetic fields (the magnetoencephalogram, MEG) in much the same way as the EEG. Measurement of MEG requires a superconducting quantum interference device (SQUID), in conjunction with pickup or detection coils all of which are immersed in a bath of liquid helium. The system works because a magnetic field interferes with the flow of a superconducting current within a SQUID; the stronger the field the larger the interference. Thus, in the same way that it is possible to present stimuli and record the voltage waveforms at various locations over the head, it is possible to record the magnetic fields associated with the active neurons. By recording from many locations over the scalp it is possible to get a spatiotemporal map of the brain's electrical activity associated with an eliciting stimulus.

Although a large population of neurons, organized side by side and firing simultaneously, is a must for both electric and magnetic scalp recordings, the ERP and MEG provide somewhat different views of the underlying brain activity (Hart & Lounasmaa, 1989; Regan, 1989; Williamson & Kaufman, 1987). Mag-

[4] For instance, one might use two factors, one for laterally (left vs. right) and another to represent the anterior/posterior dimension. It is best not to include midline electrodes in ANOVAs using laterality as a factor, since the midline amplitudes are almost always larger than those recorded more laterally.

[5] If the thumb of the right hand is put along the direction of the moving charge of an electric current, then the magnetic field lines fall along the direction of the other fingers of the hand.

netic recordings are relatively more sensitive to neural activity which is close to the surface of the brain because the strength of a magnetic field decreases proportional to the cube of the distance from the current flow, whereas an electrical field decreases only with the square of the distance. This means that pickup coils a few millimeters above the scalp are likely to be sensitive to activity within the cerebral cortex only. Second, SQUID devices detect only magnetic fields produced by current flow oriented tangentially to the skull, not radially. This means that only neurons tangential to the skull, namely those within cortical sulci rather than gyri, will contribute to the magnetic field. Third, the relations between direction of current flow and orientation of the resulting magnetic field suggest that magnetic recording devices are more sensitive to intracellular than extracellular current flow. Given a single active zone in a neuron, say the apical dendrites, intracellular current will flow in only one direction, whereas extracellular "volume" currents will arrive from both ends of the neuron and produce canceling magnetic fields. Finally, the skull and other tissues are completely transparent to magnetic fields, in sharp contrast to the low electrical conductivity of bone. While magnetic recordings are thus limited in scope, it is substantially easier to estimate where a magnetic event-related field (MERF) source is located. This is in contrast to the ERP, which reflects currents both perpendicular and tangential to the skull, is sensitive to variations in skull thickness and electrical conductivity, is distorted by large holes like the eyeball or ear canal, and gets a contribution from volume current. This is at least one reason that it is generally not safe to say that where an ERP component is biggest in amplitude is necessarily the place to look for its generator. In summary, the MEG mostly provides information about the synchronous firing of pyramidal cells located superficially within cortical sulci. The ERP provides a broader picture of underlying neuronal activity, which includes both superficial and deep sources to various orientations relative to the scalp. To date only one study has employed the MEG to localize a component of the ERP elicited in language-processing paradigms (Schmidt, Arthur, Kutas, George, & Flynn, 1989).

III. WHY USE ERPS TO STUDY LANGUAGE?

There are two distinct uses to which ERPs have been put in the study of language. The ERP technique occupies a privileged but precarious position on the boundary between psychology and neuroscience. The ERP is both a correlate of behavior, much like a button-push, and a direct reflection of brain activity, much like a spike in a single-cell recording. On the one hand, electrophysiological measures have been used to address questions specifically related to the structure and processes of language. To this end, investigators have sought various markers of specific linguistic processes and evidence for the existence of different hypothesized levels of linguistic representations. We refer to this as the psycholinguistic ERP approach. On the other hand, however, ERPs are also a physiological measure of mass neuronal activity which can be used to examine the functional organization of the brain for language and language processing. The majority of studies adopting this approach compare not only the ERPs elicited by two different experimental conditions but also how the pattern of differences is altered across the course of normal development or in the face of unusual early experiences such as congenital deafness or bilingualism (see, e.g., Holcomb, Coffey, & Neville, 1992; Neville, Kutas, & Schmidt, 1982).

Before discussing the specific ways in which ERPs have been used, we examine the advantages and disadvantages of using the electrical activity of the brain in investigations of language processing.

A. Advantages

1. Lots of Data

One of the indisputable advantages of the ERP technique is that the EEG/ERP can be recorded in Synchrony with all events of interest. Every word flashed on a CRT or played through a speaker will elicit an ERP, and the response begins within a few milliseconds of the stimulus. The measure is as close to immediate and on-line as is now technically possible. As long as there is a time-locking point, an ERP can be extracted for every event in an experiment. In sentence processing research, this enables the experimenter to track processes throughout the course of a sentence within a Single Subject. It also means that with appropriate stimulus coding, one can examine more than one issue within a Single study. Theoretically, one could investigate Semantic context, word frequency, lexical class, clause boundary, word repetition, and verb subcategorization effects in one grand experiment, although in practice the standard requirements for matching stimuli on extraneous factors would probably preclude looking at more than two issues in a single study (although less pristine pilot data can be gathered on several others as well).

In addition to the Sheer number of ERP averages that can be formed from a single data set divided into different stimulus categories, each averaged waveform is itself a multidimensional measure. An ERP waveform provides informa tion about early sensory and perceptual processes as well as some of the later cognitive processes. Thus, without much additional effort it is possible to guarantee that none of the observed effects are a consequence of abnormal or differential perceptual processes. Insofar as the componential analysis of ERPs is successful and different components are validated against specific linguistic or nonlinguistic operations, an ERP analysis will aid in delineating the different subprocesses engaged during the performance of any given task. There is thus the possibility of monitoring the activity of a specific mental process via an ERP signature across tasks or stimulus configurations with very different characteristics. For instance, the presence of a negativity (N400) whose amplitude is sensitive to semantic relations in both lexical decision and categorization tasks and in both sentences and word lists supports the idea that there is some mechanism of semantic analysis common to sentences and lists which can be tapped into by a variety of tasks.

Of course, there is no free lunch-comparing components across experiments is a difficult matter and sometimes leads to heated discussion among ERP researchers. It is thus important to note that there are ways of analyzing ERPs to yield useful information which do not require a componential analysis. Given a well-characterized problem, it is sometimes theoretically sufficient to determine whether two waveforms elicited in conditions differing in one and only one factor are statistically identical or not. Such an identity /nonidentity strategy is analogous to reaction time (RT) research, wherein milliseconds are not, in and of themselves, an interesting unit of analysis, but similar or different RTs across conditions are. However, a caveat is in order here: It is much safer to conclude that the ERPs associated with two conditions differ than that they are the same. It is possible that adding another recording site or two would reveal a distributional difference that was unobservable with sparser spatial sampling. Thus, statements about ERP identity across conditions are particularly worrisome if they are based on only a few midline sites (such as frontal along nasion-inion line (Fz), central along nasion-inion line (Cz), and parietal along nasion-inion line (Pz)]. Recent work by Nobre and McCarthy (1992) suggests that even 12-16 recording sites may be too few to identify all the different loci of activity in a language processing task. If this finding generalizes, and 50 electrodes are indeed needed to make even identity/nonidentity judgements, we may be well advised to set up regional centers with such facilities, conduct initial experiments at such testing sites, and perform the more restricted follow-up studies at facilities with fewer resources.

Additionally, issues that revolve around questions of timing do not always require the identification of specific ERP components. For example, if one was interested in the relative timing of processes sensitive to word frequency and those sensitive to semantic context, it might be sufficient to ask which effect has the earlier onset latency (see Van Petten & Kutas, 1991 a). However, while it might be valid to ignore the question of whether the two ERP effects surfaced in the same component, this strategy should remain tentative until more information accrues about the temporal relationship between different scalp components and underlying neurophysiological activity. Finally, another experimental strategy requires a componential analysis within a single experiment, but does not require comparisons across experiments. We might call this final strategy "counting the experimental effects." As an illustration, one might find an amplitude difference in Component X as a consequence of manipulating Factor A, but find amplitude differences in Components X and Y as a consequence of manipulating Factor B. No doubt, this pattern of results would stimulate further work on what cognitive processes are reflected in Components X and Y. However, it can also be taken as a hint that Factor B is not unitary but involves distinct subprocesses, at least one of which is shared with Factor A.

2. Freedom from Extraneous Task Demands

Another appealing characteristic of the ERP methodology for language research is that task demands do not need to be imposed on the subject unless they are experimentally interesting. Often in psycholinguistic research, the task assigned to a subject is not an inherent subcomponent of natural language processing (i.e., lexical decision), but is instead necessary as an index of some aspect of natural language processing. Substantial task analysis and numerous experiments are then required to evaluate the relationship between the underlying linguistic process and the experimental index and to determine what aspects of performance variability are specific to the experimental task rather than general to the linguistic process (Balota, 1990; de Groot, 1990). In ERP research, there is still, of course, an inferential chain between data and conclusions, but the chain can be shortened by one link Since responses can be obtained without imposing what is essentially a Secondary task requiring Some motor response. Simply reading or listening for comprehension or memory is sufficient to elicit different ERPs as a consequence of some psycholinguistic manipulation.

For pragmatic reasons, we have sometimes included a Secondary task in many of the experiments wherein subjects' primary task was to read a number of unrelated sentences. Having a button to press every now and then serves to reassure some subjects that they are really participating in an experiment, and the behavioral responses provide the experimenter with an easy way to monitor a subject's alertness during a long session. Such Secondary tasks have included detecting an occasional repeated Sentence, indicating whether or not a subsequent probe word occurred in the preceding Sentence, making a true/ false response to a question about the preceding sentence, and indicating whether or not a particular letter of the alphabet occurred in a probe word following each sentence. These tasks all were constructed in Such a way that subjects were neither required to make overt responses while reading nor, with the exception of the repeated sentence task (wherein the repeated Sentences were excluded from analysis), to recognize task-related Stimuli while reading (in the recognition probe and letter detection tasks, subjects did not know which word or which letter would be their target until Some time after the completion of the sentence and did not know what constituent of a Sentence would be questioned). Thus far there has been little variability in the pattern of ERP results as a function of which secondary task was used. Other investigators have employed Sentence acceptability ratings (Neville, Nicol, Barss, Forster, & Garrett, 1991, Osterhout & Holcomb, 1992) or lexical decisions to the final words (Roesler, Friederici, Puetz, & Hahne, 1992) to similar effect. Thus we think that the ERP results common to all these experiments reflect general mechanisms of word recognition and Sentence comprehension rather than task-specific factors.

The ubiquity of Some ERP results across a range of secondary tasks Should not be taken to suggest that an appropriately designed task cannot be used to augment the ERP data. An experimental condition might be subdivided to reveal different ERPs elicited during trials which received correct or incorrect subsequent responses from a subject. Or, instead of classifying **trials**, one might classify **subjects** according to their accuracy in the experimental task. We have recently observed that an ERP index of the utilization of Sentence context is correlated with how well a Subject does in the task of deciding whether or not a subsequent probe word appeared in an experimental Sentence, suggesting a possible link between the ability to use Sentence context and working memory capacity (Van Petten, in press).

Yet another approach is to include Secondary Stimuli without adding a Secondary task. For example, Papanicolaou (1980) developed an ERP version of the "Secondary probe" reaction time (Posner & Boies, 1971). Photic probe stimuli (i.e., brief light flashes used as processing probes) were presented to Subjects as they processed Speech for acoustic, phonetic, or Semantic targets. Papanicolaou found that the N1 component of the ERP to the visual probe was asymmetric during performance of the phonetic and Semantic but not acoustic tasks. Unlike the RT probe paradigms, the ERP probes are very unobtrusive. It is, however, important to control for interactions between the ERPs to the probes and the ERPs to the Speech across experimental conditions.

3. Modality Neutral

Some experimental tasks in the psycholinguist's battery are tied to a particular input modality. Phoneme monitoring and shadowing, for example, have been useful techniques for investigating spoken word processing (Foss & Ross, 1983; Marslen-Wilson & Tyler, 1980), but it is difficult to say what would constitute analogous results in reading. Because one can use very general tasks such as "read/listen for meaning" in ERP experiments, it is easier to compare results across presentation modalities to determine which processes might indeed be amodal. Although the early sensory components of the waveform are unique to the input modality, the later cognitive components are apparent (although not identical) across stimulus modalities. Below, we briefly review the results of similar paradigms using spoken, written, and signed language.

4. A Link to the Brain

As noted earlier in this chapter, the exact relationship between any scalp-recorded ERP and the neuronal activity which generated it is not obvious from visual inspection of the ERP. A number of laboratories are engaged in defining this relationship for various components of the ERP using intracranial recordings in both humans and animals, correlation of human brain lesions identified in magnetic resonance images with abnormalities in the scalp potentials, animal lesion experiments, and the use of pharmacological agents specific to some neural systems (Buchwald, 1990; Johnson, Rohrbaugh, & Parasuraman, 1987; Knight, 1990; Paller, Zola-Morgan, Squire, & Hillyard, 1988; Pineda et al., 1989, 1991; Williamson & Kaufman, 1987). This research endeavor is far from complete but has met with significant progress over the last 15 years. We will not review these results here since these investigators have only recently turned their attentions to the ERPs elicited in psycholinguistic paradigms.

In addition to the various empirical methods for discovering ERP generators, there has recently been a great deal of interest in analytical techniques for constraining the possible neural generators given the scalp-recorded data (Balish & Muratore, 1990; Dale & Sereno, 1993; van Oosterom, 1991). It is well known that it is not possible to uniquely determine the distribution of current flows inside the head that lead to an external electrical or magnetic field; for any external field, there is more than one intracranial state capable of producing it. However, certain assumptions (some more problematic than others) can reduce the number of possible solutions. Initially, a mathematical model must reduce the activity of millions of individual neurons to a small set of equivalent electrical dipoles. The head is modeled as a set of concentric spherical shells (brain, meninges, skull) of differing electrical conductivity. One can then compare the predictions of a model with particular dipole locations with empirical results. For magnetic ERP data, a topographic map of the magnetic fields around the head can be constructed given enough recording sites. A "perfect" magnetic field distribution corresponding to one intracranial current dipole would have two extrema, where the field enters and leaves the head. From the strength of the field and the separation of the extrema, one can get a first-order approximation of the location of the dipole. Then by tweaking the parameters of the spherical model (including depth, orientation, and strength of the hypothetical dipole) it is possible to see how much error variance remains between the model and the real data. The parameters of this model then become the best guess as to the generator of the field recorded. The hypothesis so generated can then be tested via the empirical methods noted above. To date, much of the work with MERFs has focused on the early sensory components of the ERP for which a general vicinity was already known from anatomical, physiological, and neuropsychological data. The other simplifying factor for the localization of these early components is that a single brain area may dominate activity soon after the stimulus is delivered, so that one dipole may account for most of the scalp field. In the time region that cognitive electrophysiologists are most interested in, hundreds of milliseconds later, information has had time to diverge to a number of brain areas. Thus far, there has been little success at using such models for localizing more than one simultaneous dipole source. But this endeavor is only a few years old, and future prospects look bright.

A similar modeling approach can be taken with maps of electric fields (Berg & Scherg, 1991a, 1991b). This is a more difficult problem because electrical recordings are sensitive to a larger volume of the brain (deep as well as superficial sources) and are also more subject to distortion from the resistivity of intervening tissues.

B. Some Disadvantages and Some Limitations of Current Data

1. Artifacts

As is true of any experimental technique, the ERP technique has some drawbacks. For example, one experimental constraint on the recording of ERPs is a limit on concurrent motor activity that the subject can be allowed to engage in. Eye movements, activity of facial muscles, and tongue movements each produce electrical artifacts which may obscure the record of ongoing EEG (Grozinger, Kornhuber, Kriebel, Szirtes, & Westphal, 1980; Picton & Stuss, 1984; Stuss, Sarazin, Leech, & Picton, 1983). In practice this means that the best ERP recordings are obtained when the subject stays relatively still; this is also the case for magnetic recordings although for different reasons. It follows that it is difficult to record an ERP during natural reading (i.e., in association with saccadic eye movements across text on a page) and during pronunciation tasks. This particular limitation can in principle be overcome by the development of analytic techniques which tease apart the contributions of different electrical generators; in combination with dipole modeling techniques such as Brain Electric Source Analysis (BESA), this is a real possibility (Berg & Scherg, 1991 a, 1991b).

More typically, EEG trials contaminated by biological, but nonneural, electrical activity such as electro-oculographic artifacts from eye movements and blinks, excessive muscle activity, tongue movements, large electrocardiographic potentials, and changes in skin conductance are rejected. Artifact rejection is not a conceptually difficult matter, but it does require a visual distinction between EEG and these other sources of electrical activity. A few examples of artifacts are illustrated in Figure 1. It is best if these distinctions can be made on line so that the problem can be corrected, rather than relying on subsequent computer algorithms to reject contaminated trials. Low-frequency artifacts are of particular concern since most of the energy in the late cognitive

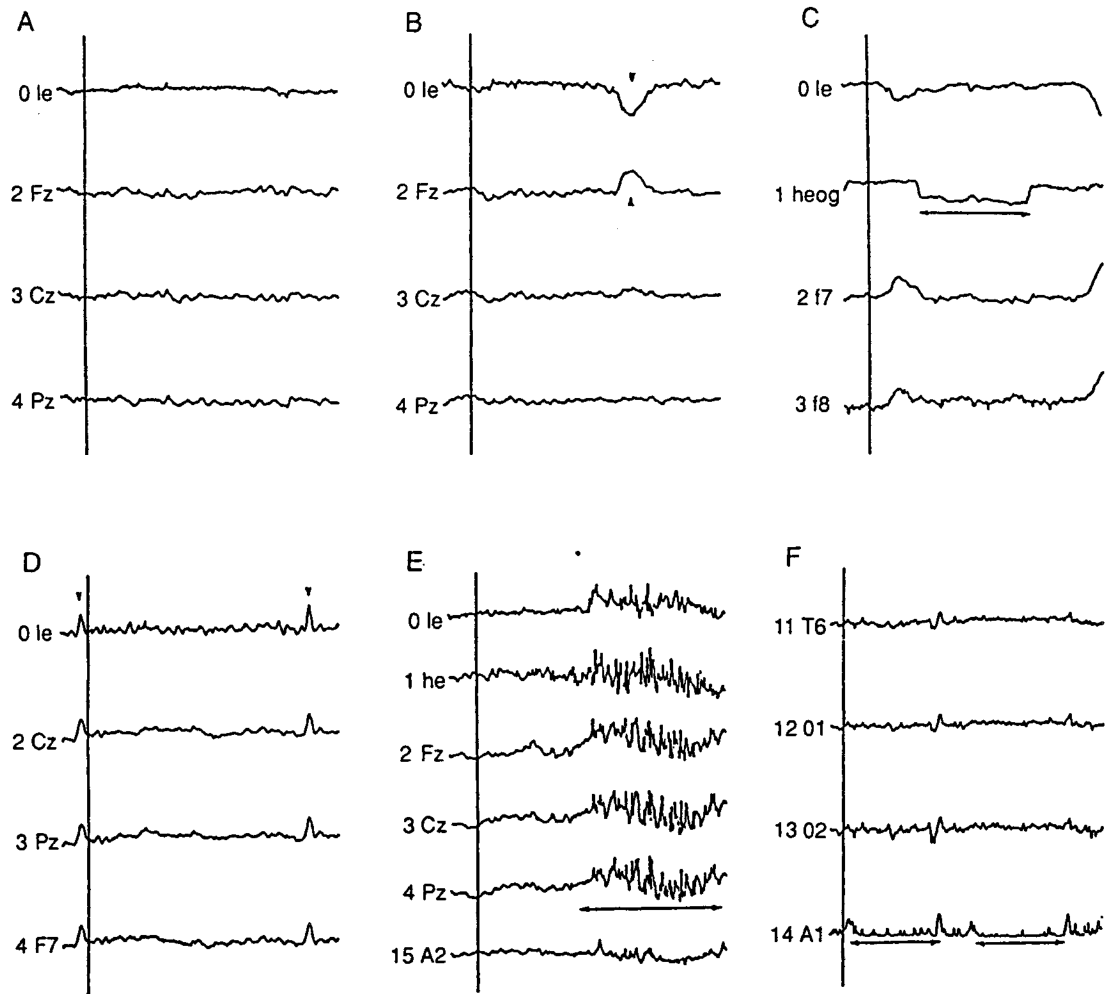

FIG. 1 Six panels representing single-trial EEG. The vertical line in each case represents stimulus onset. (A) clean EEG from below the lower eye and at three midline locations; (B) eye blink marked by an arrow; note the reversal of polarity for the blink above (*frontal site*) and below the eye; (C) lateral eye movement most noticeable in the horizontal electro-oculogram recording; this is a bipolar record between electrodes placed at the left and right external canthus of the eye; includes two sites over left and right frontal sites; (D) heartbeat (arrow) in lower eye record, two midline sites, and left frontal site; (E) excessive muscle (*underlining*) in lower eye, horizontal eye, three midline sites, and at right mastoid; (F) amplifier blocking (*underlining*) in left mastoid recording. Abbreviations: le, below the eye; heog or he, horizontal eye, bipolar left to right canthi recording; F7, frontal left hemisphere; F8, frontal right hemisphere; T6, posterior temporal right hemisphere; O1, occipital left hemisphere; O2, occipital right hemisphere; A2, right mastoid process; A1, left mastoid process.

components of the ERP also tends to be in the low frequencies. Of this category, skin potentials are the most frequent and the most difficult to reject via computer algorithms. Proper electrode application and instruction of subjects can reduce most sources of artifact to near zero. The exception to this rule is eye blinks, where one can only try to set up the experiment so that subjects have predefined intervals (between sentences for example) to blink. A few adaptive filter techniques for subtracting eye artifacts from the EEG have been developed, although no one technique has been widely adopted and there are some good arguments that every filter will be associated with some distortion of the data (O'Toole & Iacono, 1987). Eye movement artifacts are also less of a problem for current Source density (i.e., Second Spatial derivative of potential field) maps.

2. Overlapping Components

In addition to artifacts, ERP interpretation can be complicated by the elicitation of multiple ERP components in the Same latency range. Thus, Some ingenuity in experimental design is called for to circumscribe cognitive activity and avoid overlapping endogenous ERP components. For instance, a well-studied large positive ERP component named the F300 or P3b generally appears in any task in which the Subject is required to make a binary decision, as in go/no-go tasks or cases where the Subject must press one of two buttons (Donchin, 1981; Donchin & Coles, 1988; Johnson, 1988; Kutas & Hillyard, 1989; Pritchard, 1981; Verleger, 1988). Thus, tasks Such as lexical decision which require an on-line decision of this type are likely to yield overlapping P300 and N400 components within the same latency window. Because the latency of the P300 varies with the time required to make the decision, and its amplitude may reflect the subject's confidence in their decision, the P300 elicited across experimental conditions may not be constant. Such variations in P300 latency and/or amplitude can then obscure experimental effects in other components. In a semantic priming paradigm, Bentin and colleagues dealt with this problem by comparing the effect of Semantic relationship in subaverages of the target ERPs Sorted according to lexical decision times (Bentin, McCarthy, & Wood, 1985). They were able to Show an N400 priming effect in all subaverages despite variation in P300 latency. Kutas and colleagues have argued that the difficulties in disentangling these two components can be avoided altogether by eliminating the necessity for a task-related decision within the post-stimulus epoch of interest. Kutas and Hillyard (1989), for instance, showed that it was possible to obtain semantic priming effects on the N400 component of the ERP with no overt behavioral responses required of the Subject. This experiment asked for a decision that both was orthogonal to the priming manipulation and could not be made until after all the Stimuli for a given trial had been given. Specifically, subjects had to indicate whether a letter flashed approximately one Second later had been present in either (or both) words in related and unrelated pairs. Other sets of overlapping components may Still create interpretive difficulties in Some experiments, but the P300 at least can usually be eliminated by Some attention to experimental design.

A problem related to overlapping components elicited by the same stimulus is that of overlapping responses to two or more Stimuli. If a second stimulus is presented before the ERP to a preceding stimulus has played out, the ERP Synchronized to the presentation of either stimulus will contain Some portion of the response to the preceding or following Stimulus. If Stimulus presentation rate is constant, there will be no certain means of uniquely assigning aspects of the ERP within the overlap region to one or the other stimulus (See Woldorff, 1993, for a more detailed analysis of this issue). Most ERP studies of language have been conducted in the visual modality for Stimuli presented at relatively slow rates (e.g., one word every 600-900 ms) in order to reduce the amount of overlap from adjacent responses and isolate the response to a Single word. However, the overlap problem is tractable, Such that recent work has utilized presentation rates of 200-400 ms per word. A generally cautious approach will always be to examine responses from slow presentation rates before turning to faster rates. Figure 2 illustrates an example of this approach.

Aside from the impact of presentation rate, the serial word presentation (SVP) format is itself different from normal self-paced reading. Some investigators have presented frames including two or three words at a time; in this case the ERP is elicited by the combination of words so that responses to single words are not isolable (Fischler, Bloom, Childers, Arroyo, & Perry, 1984). A couple of labs have also worked on multiword presentations using the subjects' saccades as time-lock points for the averaging procedure, rather than the computer's signal of stimulus onset. The data have been very similar to that seen with SVP, suggesting that SVP presentation is not overly disruptive of the normal reading process (Marton & Szirtes, 1988a, 1988b; Marton, Szirtes & Breuer, 1985; Marton, Szirtes, Donauer, & Breuer, 1985).

Besides its potential impact on subjects' reading strategies, we should also remember that SVP presentation with standard averaging procedures provides a restricted window on what we might be able to observe in the ERP. In the most standard situation, one will see one second's worth of ERP time-locked

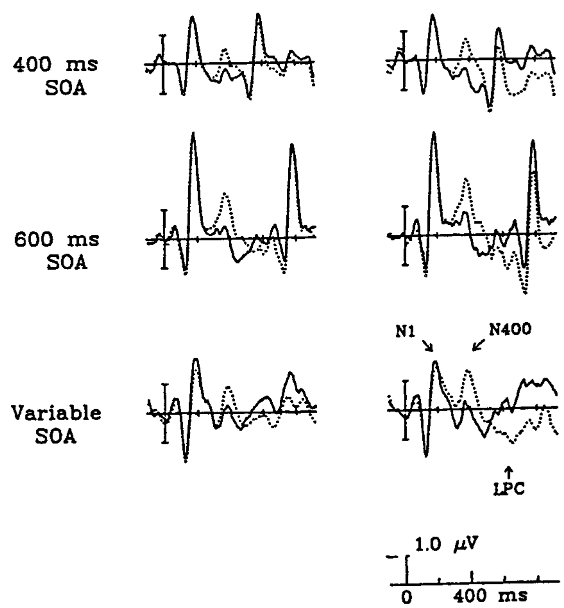

FIG. 2 Word repetition effects at a left parietal-temporal electrode site, at three different stimulus presentation rates. Both high- (left column) and low-frequency (right column) words show a smaller N400 amplitude for repeated (solid line) than new (dotted line) words. Low-frequency words additionally show a reduced late positivity (LPC) upon repetition, beginning about 500 ms post-stimulus. With a 400 ms stimulus-onset asynchrony (SOA), this repetition effect began after the presentation of the next word; note that it begins after the N1 elicited by this next word. With an SOA of 600 ms, the repetition effect still begins at around 500 ms, but it is now clear that the positivity was elicited by the word presented at time 0 and not the subsequent word. In the third row, a variable SOA was used (320-680 ms), so that the ERP to the second word is not time-locked to time 0 in the figure. The similar latency of the LPC repetition effect in this case provides further evidence that it is elicited by the word presented at time 0. Data from Van Petten et al. (1991).

to the onset of each word in a set. It might be difficult to observe, for example, slower processes which occur over the course of an entire sentence if they are not strictly synchronized to any single word. This particular problem can be surmounted by forming long-epoch averages which encompass a larger portion of a sentence, as shown in Figure 3. This figure also illustrates why we believe that it is a good idea to examine such long-epoch averages.

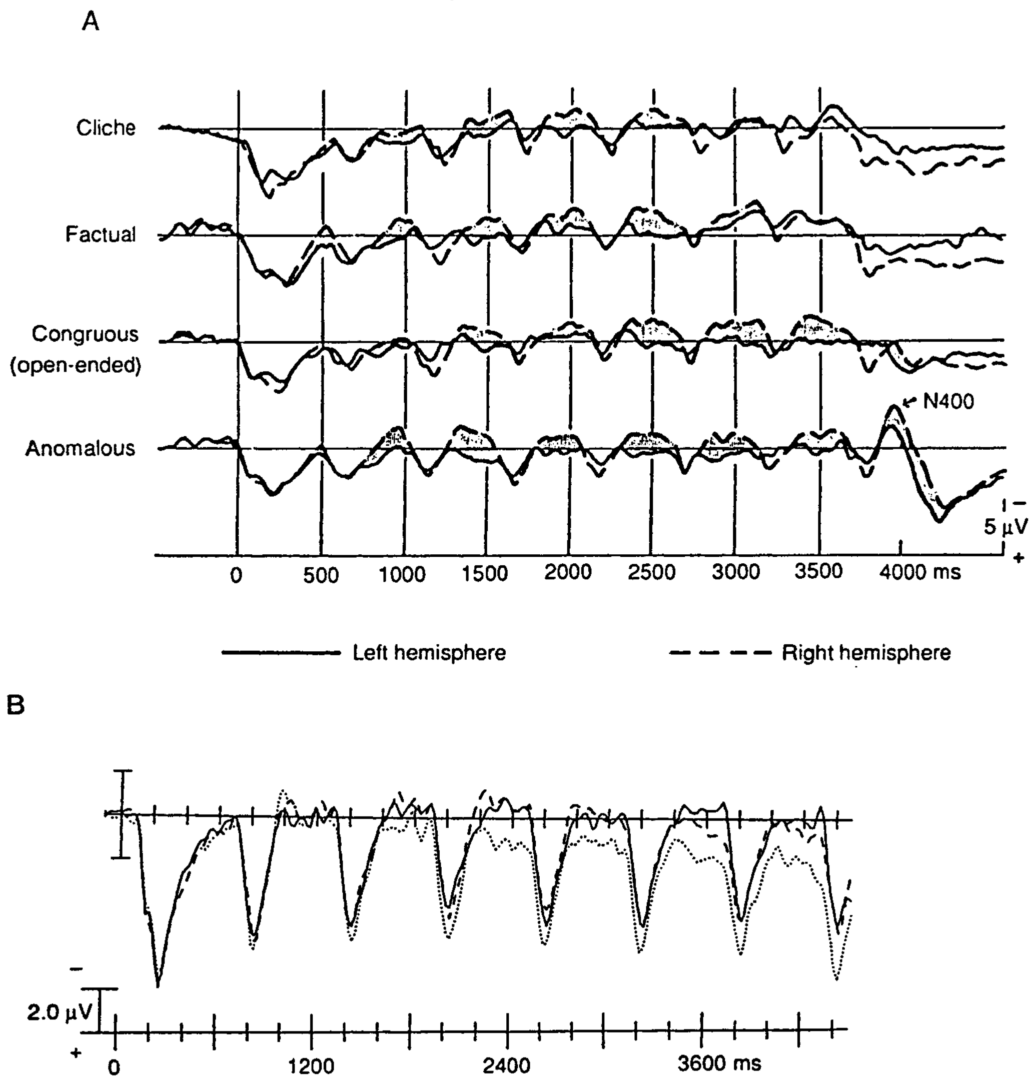

FIG. 3 Long-epoch averages showing the ERPs elicited by sequential words in sentences presented one word at a time. (A) ERPs to seven-word sentences preceded by a stimulus. Recorded at a midline parietal site. Figure from Kutas, Van Petten, and Besson (1988). (B) ERPs to the first seven words of congruent sentences (solid line), syntactically structured but semantically anomalous sentences (dashed line), and random word strings (dotted line). Note the slow positive potential elicited in random word strings which is superimposed on the ERPs elicited by individual words. The slow positive shift was difficult to visualize in shorter recording epochs. Recorded at a left central site (C3); data from Van Petten and Kutas (1991a).

Spoken language brings its own complications for establishing a time-lock point to synchronize the ERP averaging process. In connected speech, there are rarely silent pauses between words. Only in the last few years have there been many studies using words or sentences rather than single phonemes or syllables (D. L. Molfese, 1980; Wood, 1975). One technique has been to perform minor editing of the stimulus set so that each word has an easily defined onset point (Holcomb & Neville, 1991). Even more recent work has suggested that ERPs to natural unedited speech can be reliable; these will be a very effective way of studying the breakdown of language in aphasics and other patient populations (P. Hagoort, personal communication).

IV. OVERVIEW OF LANGUAGE-SENSITIVE COMPONENTS

An exhaustive review of ERP studies relevant to language research would occupy more space than available. We aspire only to give the reader some background, a flavor of active research topics, and enough citations to search for relevant information. We begin with an overview of potentially useful ERP components and the impact of general cognitive factors on these components. Because the concept of "component" is intimately tied to the demonstration of one or more experimental effects, any such lists of components will need to be constantly updated. We focus first and foremost on those that are fairly well characterized and clearly relevant to the study of language processing, with other components which have been less well characterized described in subsequent sections. This general background section is followed by summaries of the impact of some biological and psycholinguistic factors on particular components.

A. N400

The N400 was first described in an experiment contrasting semantically predictable with semantically incongruent sentence completions (Kutas & Hillyard, 1980c). Subjects in this experiment (as in most of those described here) silently read sentences presented one word at a time on a CRT. Incongruous final words elicited a negative wave which was largest over posterior scalp locations and somewhat larger over the right than the left hemisphere. Congruous endings elicited a positive-going wave instead. The separation between the congruous and incongruous waveforms occurred at about 200 ms after the onset of the visual word; the difference peaked at about 400 ms post-stimulus, as shown in Figure 4 (Kutas & Hillyard, 1980a, 19806, 1980c, 1982; Kutas, Van Petten, & Besson, 1988). Since the initial experiment, it has become clear that the positivity elicited by a wholly predictable word is the exceptional case; most words elicit an N400 whose amplitude and latency vary with experimental manipulation.

The largest and most robust N400 is elicited by an open-class word that is semantically anomalous within its context and not associated with any task-related decision. This general finding holds whether the anomalous word occurs at the end or in the middle of a sentence (see Fig. 5; Kutas & Hillyard, 1983). In both cases, the anomalous word elicits a significantly larger negativity which

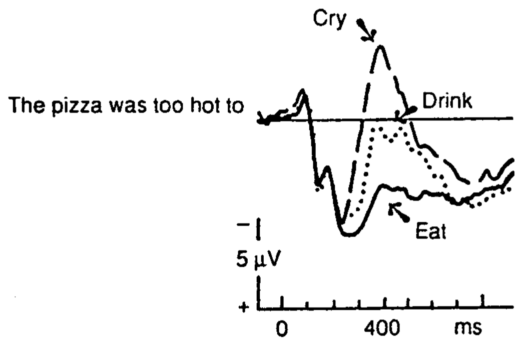

FIG. 4 ERPs elicited by sentence-final words at a midline central site. showing the positivity *(solid line)* for a predictable word. N400 elicited by an incongruous word *(dashed line).* When the final word is semantically incongruent but related to the expected final word *(dotted line),* it elicits a smaller N400 than an unrelated incongruity. Sample endings are for illustrative purposes only. since the same sentence frames were never repeated in this experiment. Figure from Kutas et al. (1984). Copyright Raven Press. Reprinted with permission.

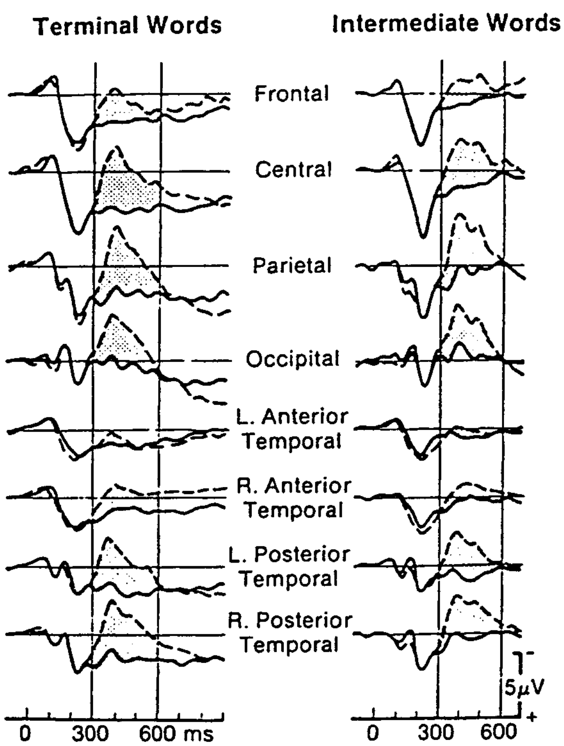

FIG. 5 ERPs to semantically incongruous words at intermediate and terminal positions of sentences *(dashed lines).* The superimposed waveforms *(solid lines)* are ERPs to semantically congruent words at corresponding positions. From Kutas and Hillyard (1983). Copyright 1983 by the Psychonomic Society. Reprinted by permission.

diverges from the response to a semantically appropriate word in the same ordinal position at about 200 ms, peaks between 350 and 400 ms, and in the averaged waveform, has a duration of 300-400 ms. It is unknown whether this relatively long duration in the average is a consequence of the averaging procedure, or whether each single-trial N400 also has a long duration. Analytic procedures for extracting single-trial ERPs are difficult even for ERP components with very large amplitudes (15 µV), and the N400 is not one of these (most N400s are in the 5-8 µV range). N400 amplitude differences between conditions are of shorter duration for some experimental contrasts than others, suggesting that "the" N400 may be composed of overlapping subcomponents whose characterization will require further research.

The fact that an N400 effect is apparent shortly after the appearance of an anomalous /congruent word, regardless of its ordinal position in a sentence, is most consistent with those models of sentence processing that emphasize the immediate and on-line nature of comprehension (Gernsbacher & Hargreaves, 1988; Just & Carpenter, 1980).[6] The sentence N400 data do not support models in which information is largely buffered for inferential and elaborative processing at clause or sentence boundaries. This is not to deny that there is substantial interpretation and integration at the ends of sentences and probably other syntactic boundaries as well. Indeed it is likely that most structural boundaries are regions of higher than average processing load. Eye-movement data, click displacement studies, and ERP data all attest to the sense of such a view (Fodor & Bever, 1965; Garrett, Bever, & Fodor, 1966; Just & Carpenter, 1980; D. C. Mitchell & Green, 1978). The nature and timing of processes at clause boundaries is ripe for good ERP research. The late positive wave elicited by terminal words at sentence boundaries is invariably larger and more prolonged than that elicited by intermediate words. The long duration of this positivity is one reason that we generally provide subjects with an interval between sentences that is three or four times as long as that between words. The additional time between sentences also gives subjects enough time to blink without contaminating the data-it usually requires some instruction and feedback to encourage subjects to delay blinking for close to a second after the final word of a sentence.

While the initial discovery of the N400 was during sentence processing, our current understanding is most consistent with the idea that it is the default response to words (see Section IV,A,4 for the exceptions). When letter strings are presented in lists or pairs rather than sentences, the following pattern of results has emerged: words which are unrepeated and semantically unrelated to previous words elicit the largest N400; orthographically legal, pronounceable nonwords (pseudowords) also elicit large N400s; and unpronounceable nonwords elicit little or no N400 activity (Bentin, 1987; Bentin et al., 1985; Holcomb, 1988; Rugg & Nagy, 1987; Smith & Halgren, 1987). In various studies using different materials, the pseudoword N400 has been either somewhat larger or

[6] An N400 or any ERP component is most obvious in a contrast between two waveforms where one has a small amplitude component and the other a large one. It is important however, to maintain a distinction between the component per se, and the EFFECT, or amplitude difference between two waveforms.

somewhat smaller than that elicited by real words. It is not yet clear how the amplitude of the pseudoword N400 will compare to that of the largest possible N400 elicited by real words, namely that to a set of words which are unrepeated, unrelated to previous words, and low in frequency of usage. In any case, the difference between pseudowords and nonwords gives a starting point for thinking about the fundamental process reflected in the N400. If the component were produced only after the meaning of a word had been accessed, there should be no N400 for pseudowords. On the other hand, if N400 amplitude reflected simply the "wrongness" of a letter string, there should be a sizable N400 for illegal nonwords. The results for the two classes of nonwords thus is more consistent with the view that the N400 reflects some of the earlier processes in word recognition,. wherein illegal nonwords can be quickly rejected, but pseudowords require some additional processing to determine that they are not, in fact, words and therefore do not fit with their present context.

1. Scalp Distribution

The prototypic N400 semantic incongruity effect is broadly distributed across the scalp but is larger over parietal, posterior temporal, and occipital sites than frontal sites. It is also larger over the right than the left hemisphere. The hemispheric asymmetry is not a strong effect, but clearly a real one. A survey of 30+ experiments shows perhaps 60% with statistically significant right-greater-than-left asymmetries, a number with insignificant tendencies in the same direction, some bilaterally symmetrical N400 effects, and a very small number of left-greater-than-right asymmetries (Kutas & Hillyard, 1982; Kutas, Van Petten, & Besson, 1988; M. Kutas, unpublished observations). Typically, the responses to both congruent and incongruent words are asymmetric as well, although both the size and the direction of the asymmetry vary considerably across subjects. Thus, the N400 elicited by incongruous words is often but not always larger over the right hemisphere sites. Perhaps the degree of asymmetry is task-dependent, although this observation has not been investigated systematically. Additionally, the positivity elicited by highly predictable sentence-final words is usually larger over the right when linked or averaged mastoids are used as the reference.

We should note that "right hemisphere distribution" does not imply "right hemisphere generation"; in fact the weight of evidence favors a left hemisphere generator (see Section V,A). A posterior right hemisphere distribution characterizes the N400 elicited by printed words delivered at a relatively slow rate. A smaller number of observations have consistently indicated that when the SOA between words drops below 400 ms, the N400 effect shows a more frontal distribution than at slower rates (Kutas, 1987; Van Petten & Kutas, 1987; M. Kutas, unpublished observations). Similarly, the distribution of the N400 elicited by spoken words may be distinct from the visual topography (see Section IV,A,3).

2. Latency

Although the N400 (difference) is elicited in close synchrony with an anomalous word, the peak latency is slightly later (by about 30 ms) for semantic anomalies occurring in the middle rather than at the ends of sentences. We take this as an indication that intermediate anomalies are appreciated more slowly than terminal anomalies. A similar but larger delay has been observed when sentences are presented at the rapid rate of 10 words per second (Kutas, 1987; see also Gunter, Jackson, & Mulder, 1992). In contrast to slower rates (1-4 words per second), these N400s both begin and peak 50-100 ms later. Because the same subjects and the same stimuli (counterbalanced) were included in the ERPs obtained at different rates, we are confident in labeling all the incongruity effects as N400 effects despite the change in scalp distribution with the rate manipulation. The general waveshape, duration, and lateral distribution of the incohgruity effects were unchanged by rate, but this still presents a case of conflict between a top-down functional aefinition of a component and a bottom-up data-driven definition. The change in scalp distribution with rate may reflect the overlap of an additional process needed to read material presented at faster than normal reading rates. It clearly underscores our need to know more about what changes in cellular physiology can produce such a shift in scalp distribution. Nonetheless, the similarity of results across rates suggests that it is reasonable to draw inferences about normal reading processes from slower than normal presentation speeds. The advantage of allowing more time between words is that it is possible to visualize the entire sequence of ERP components elicited by single words without overlapping responses from previous and subsequent words.

While we refer to the N400 (and other ERP components) in terms of its peak latency, this should be taken as an easy reference point rather than as an indication that 400 ms is a critical processing point. In most experiments, N400 amplitude differences are apparent by 200 ms post-stimulus. At present, neither the cellular events underlying word processing nor those underlying the N400 are known. It is possible, for instance, that the N400 is elicited at the offset of the relevant process(es), thereby reflecting activity which began earlier than either the peak or the onset. Because the physiology of the cortex is marked by interactions between cell types in each lamina, feedback between laminae within a single cortical area, and feedback between areas, neural activity continues well beyond what one might think of as the "important" processing done by any particular subpopulation of cells. In the retina, a more peripheral and thus better understood neural system, delays between "critical" cellular events and evoked potentials have been better characterized. The earliest (0.1-30 ms) components of the electroretinogram (ERG, the ERP of the retina) are generated by the photoreceptors after they absorb light. A larger later component, the B-wave, is generated not by neurons, but rather by current flowing along Mueller (glial) cells in response to the release of potassium by active neurons upstream from the photoreceptors. The amplitude of the B-wave is thus tied to the initial event in the retina, light striking photoreceptors, without receiving any direct contribution from those cells. Later yet, changes in the distribution of potassium ions cause the hyperpolarization of the pigment epithelium at the back of the eye; this event generates the C-wave of the ERG, which can last for 5 s (Berson, 1981; Kline, Ripps, & Dowling, 1978). Similarly, we suspect that the relevant cognitive operations precede the N400 rather than being coincident with it. In any case, N400 is a convenient label rather than a specific moment of recognition, comprehension, or integration (assuming that such events occur at moments rather than across intervals of time).

3. Modality of Presentation

N400 effects have been observed in the visual modality in a variety of languages including English (see Kutas & Van Petten, 1988, for a previous review), Dutch (Gunter et al., 1992), French (Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Besson & Macar, 1987; Spanish (Kutas, Bates, Kluender, Van Petten, Clark, & Blesch, in preparation) and Japanese (Koyama et al., 1991). In the auditory modality, N400 effects appear both in comparisons of congruous versus incongruous sentence terminations, and for semantically related versus unrelated words in lists (Bentin, Kutas, & Hillyard, 1993; Connolly, Stewart, & Phillips, 1990; Herning, Jones, & Hunt, 1987; Holcomb & Neville, 1990, 1991; McCallum, Farmer, & Pocock, 1984; O'Halloran, Isenhart, Sandman, & Larkey, 1988). Both the initial auditory experiment of McCallum et al. and the recent thorough investigations of Holcomb and Neville hint at differences between the auditory and visual N400. The data suggest that the auditory N400 effect begins earlier and is longer in duration. Additionally, the auditory N400 seems to be larger over the left than the right hemisphere, and more frontally distributed than the analogous visual effects. Each of these are issues which need to be systematically investigated. Given our previous statement that the N400 belongs to the class of late/cognitive/endogenous ERP components rather than the early/sensory/exogenous class, it may seem surprising to find differences contingent on the modality of input. However, the extraction of linguistic information from a printed word is likely to exhibit a very different time course than for a spoken word: A printed word can usually be captured in one visual fixation whereas an auditory signal is extended in time. Moreover, a reader can control the rate of stimulus input via longer or shorter gaze durations whereas a listener is obliged to keep up with the speaker. Given these disparities, the similarities between auditory and visual N400s are more striking than the differences.

Another example of the relative independence of the N400 from surface form comes from the work of Neville and colleagues with congenitally deaf adults (Kutas, Neville, & Holcomb, 1987; Neville, 1985). Her studies yield clear N400s in response to semantic incongruities in American Sign Language (ASL). Such data show that the N400 effect reflects a level of analysis beyond the individual letters in a written word, the phonemes or syllables in a spoken word, or the handshapes and movements in a signed word.

Also in line with this general view are data comparing semantic incongruities in the form of line drawings versus words. Figure 6 shows the ERPs elicited by words and line drawings completing written sentences in a congruous or incongruous way (Kutas & Van Petten, 1990). In this experiment, subjects saw 160 sentences one word at a time; their task was to attend for a subsequent recognition memory test. One-fourth of the sentences were completed by a line drawing, half of which were semantically incongruent. The remaining sentences were terminated by words, one-sixth of which were incongruent. Despite the differences in waveforms elicited by words and drawings, there is a remarkable similarity in the relative difference between congruent and incongruent stimuli. In this data set, the congruity effect at the parietal site peaked earlier for line drawings than words. Perhaps this finding argues that drawings provide a faster route to meaning than written words. However it is that our semantic concepts

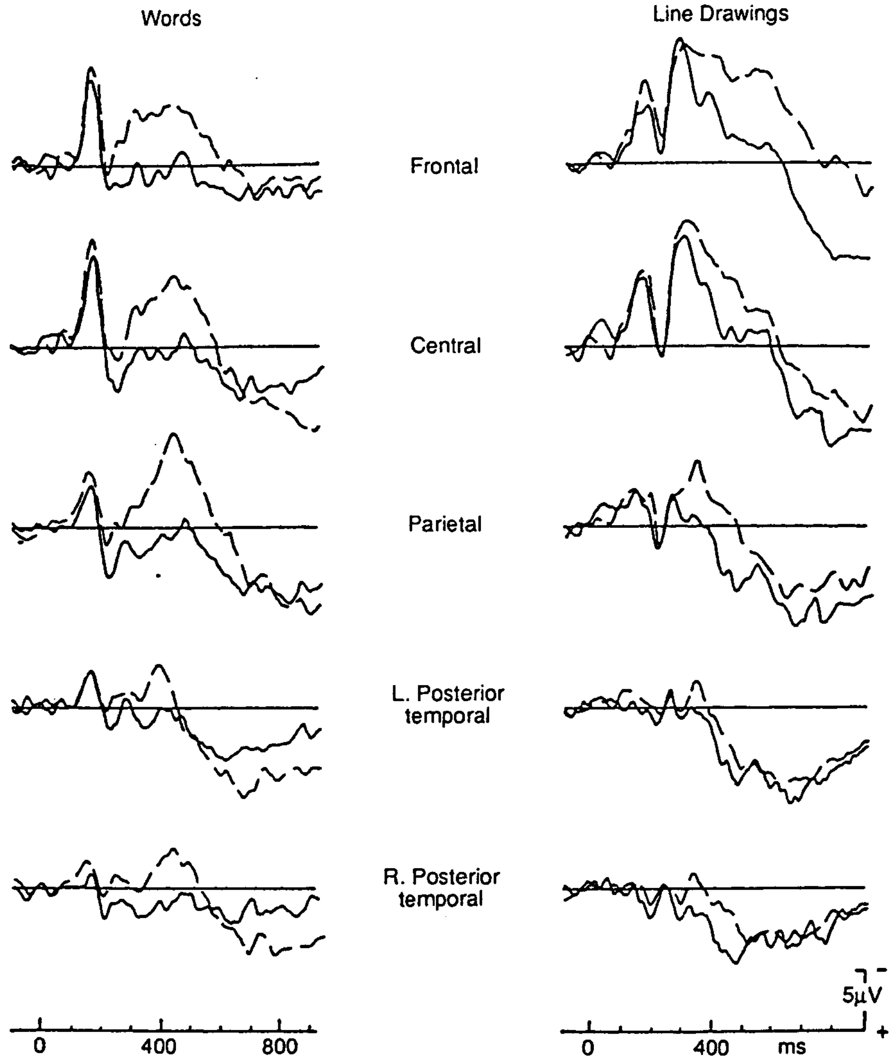

FIG. 6 ERPs elicited by semantically congruent (*solid lines*) and incongruent (*dashed lines*) sentence terminal words are shown in the left column. On the right are ERPs to line drawings which completed sentence fragments in a congruous or incongruous way. Copyright 1990 by Elsevier Science Publishers. Reprinted by permission.

develop, they are based more on objects in the visual world than on decoding orthography. But the present data are not clean enough to allow such interpretations. For one thing, the concepts represented in the words versus drawings were not matched for imageability; while those depicted by the drawings were imageable by definition, those represented by words may not all have been. Also, because the majority of sentences ended with words, pictures (regardless of their congruity) were relatively unexpected; this difference might be manifest in the large frontal negativity and/or P3-like components seen in the ERPs to pictures. Experiments of this sort, properly done, would contribute to our understanding of whether words and visual objects are represented via a common conceptual System or Separate systems (Glucksberg, 1984; Kolers & Brison, 1984; Kroll & Potter, 1984; Paivio, 1991; Pylyshyn, 1973). There has been amazingly little ERP research directed at this question (but See a recent study by Nigam, Hoffman, & Simons, 1992).

4. Task Sensitivity

As noted above, Sentence incongruity effects have been obtained across a range of tasks, none of which conflicted with subjects' primary instructions to read for comprehension (see Section III,A). Semantic relationship effects have also been observed in N400s collected in word list or pair experiments using lexical decision, Semantic categorization, Semantic rating, or letter Search tasks (Bentin et al., 1985; Holcomb, 1986; Holcomb & Neville, 1990; Kutas & Hillyard, 1989; McCallum et al., 1984; Rugg, 1985b, 1987). However, in list/pair experiments, the degree to which the assigned task encourages Semantic analysis has a clear impact on the ERPs. Kutas and Hillyard manipulated this factor by contrasting a letter Search task with one where subjects rated the strength of each pair's semantic relationship. Holcomb (1986) varied the proportion of related pairs in a lexical decision task together with instructions which alerted Subjects to the semantic relationships in the high-proportion condition (See Kutas & Van Petten, 1988, for review). In these cases, additional attention to Semantic relationships had little impact on the amplitude of the N400 elicited by the unrelated words, but the positivity elicited by related words was enhanced and thus So was the N400 effect, or difference between related and unrelated words. This sort of data has led us to consider the N400 as the standard response to words, whereas the relative lack of an N400 is reflective of contextual constraint.

The differing task Sensitivity of the N400 effect in Sentence and word list paradigms is probably best explained by common sense. When instructed to sit quietly in a sound-attenuated chamber which is relatively featureless except for the presence of a CRT displaying sentences, Subjects spontaneously read for comprehension, which entails a fairly detailed level of semantic analysis for each incoming word. The Secondary tasks assigned thus far have not been so demanding as to interfere with this tendency. Word lists or pairs do not naturally engender as high a level of Semantic analysis, so that it is only under tasks which enforce this strategy that the list/pair effects begin to approach the sentence effects in amplitude.

More recently, investigators have begun to examine more extreme attentional manipulations than those utilized by Kutas and Holcomb, such as presenting words outside the spatial focus of attention in the visual modality (Nobre & McCarthy, 1987, 1992, personal communication; Otten, Rugg, & Doyle, in press), or in an unattended ear in the auditory modality (Bentin, Kutas, & Hillyard, 1993). In these situations, the Subject is actively prevented from analysis of these words due to the demands of attending to other words which are within the focus of attention. In these situations, the typical N400 Semantic effects are absent. A more thorough review of this interesting research domain will have to wait a few years; at present we can only suggest that Semantic effects on N400 amplitude are present under a wide variety of conditions but do demand attentional processing (see Kutas, 1993, for an expanded discussion of this topic).

Two studies have investigated the impact of visual masking in a word pair priming paradigm (Brown & Hagoort, 1993; Neville, Pratarelli, & Forster, 1989). In these experiments, related and unrelated word pairs were used, but the first (prime) word was masked to a level which precluded better than chance performance in forced choice identification. Both studies yielded no sign of the typical centro-parietal N400 difference between related and unrelated second words, although Neville et al. observed a small effect at frontal sites. Under the same masking conditions, small priming effects were found in lexical decision times, whereas larger reaction time effects (12 vs. 70 ms in Brown and Hagoort, 12 vs. 90 ms in Neville et al.) and typical N400 effects were observed under unmasked conditions. These data suggest that obtaining an N400 effect requires conscious perception of the stimuli. At face value, the dissociation between reaction time and ERP measures would indicate that lexical decision indexes some priming process(es) that the N400 does not. One caveat is in order here, however. There has been little work explicitly comparing the signal-to-noise ratio of ERP and behavioral measures of the same process. In any psychological experiment, one includes multiple trials in each condition to overcome random variability or "noise" in the data. It is not clear how to compare the sources of variability in reaction time to those in an ERP measure. We do know, however, that it typically requires more trials to obtain a clean ERP average than a reliable RT, perhaps because some of the spontaneous EEG that must be averaged out has no correlate in reaction time. Additionally, "outlying" reaction times are typically trimmed before calculating a mean RT, and there is no similar procedure in common use before forming an average ERP. If indeed the signal-to-noise ratio is lower for the ERP than for RTs, it will be difficult to determine whether or not processes that result in very small RT differences also influence ERPs.

B. The Contingent Negative Variation and the Readiness Potential

The contingent negative variation (CNV) is a slow, negative potential that develops on the scalp when a person prepares to process sensory information or take a motor action (Donchin, Gerbrandt, Leifer, & Tucker, 1972; Hillyard, 1973; Irwin, Knott, McAdam, & Rebert, 1966; McAdam, Irwin, Rebert, & Knott, 1966; Rohrbaugh & Gaillard, 1983; Walter, Cooper, Aldridge, McCallum, & Winter, 1964). It was first described as the negativity between a warning stimulus and a later imperative stimulus requiring a motor response. Subsequently, it was observed that the CNV could be elicited prior to perceptual judgments as well as motor acts, although its amplitude is generally larger when overt movements are involved. In fact, it is probably most accurate to regard the classic CNV paradigm as one which elicits at least two components that overlap and sum to yield the CNV: a negativity before an anticipated stimulus or the CNV per se, and a second negativity related to planning a movement. The second negativity has been labeled the readiness potential or Bereitschafts-potential. The readiness potential is clearly related to preparation to act, as it is apparent before muscle activity in self-paced movement paradigms where there is neither a warning nor an imperative stimulus, and it has a scalp distribution consistent with the organization of motor cortex. Thus, most formulations of the cognitive events underlying the CNV characterize them as anticipation or preparation to process incoming information, whereas the RP is an index of the preparation of specific muscle groups which will be called on to make a response.

The RP[7] has been put to good use in a variety of paradigms to track the time course of stimulus analysis (de Jong, Coles, Logan, & Gratton, 1990; Gratton et al., 1990; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Miller & Hackley, 1992; Osman, Bashore, Coles, Donchin & Meyer, 1992). The most useful attributes of the RP for a cognitive psychologist are that it indexes motor preparation rather than the final command to contract a muscle and is larger over the hemisphere contralateral to the responding hand. If different categories of stimuli are assigned responses from different hands, one can then observe preparation of one response hand, whether or not this preparation culminates in an actual movemeht. RP investigators have thus been able to track subjects' partial or interim analyses of stimuli prior to their settling on a final decision which manifests in an overt movement. The recording of RPs is both technically demanding and requires experimental design and analyses distinct from those of the other ERPs discussed here. To date, the "partial-information" paradigm has thus been used primarily with stimulus arrays involving geometrical shapes or letters of the alphabet. We can hope, however, that further development of RP paradigms will allow their application to psycholinguistic issues. What if one could actually monitor which parse of a garden-path sentence a subject was following at various points in the sentence?

The CNV, like the RP, is clearly not specific to language processing. However, it has been used to investigate differential preparation of the two hemispheres for either receptive processing or language production (Butler, Glass, & Heffner, 1981; Donchin, Kutas, & McCarthy, 1977; Donchin, McCarthy, & Kutas, 1977; Picton & Stuss, 1984). The design of these experiments is very similar to those using alpha power in the EEG to assess differential hemispheric activation.

C. P300

The P300 falls somewhere between the N400 and the CNV as far as the generality of the cognitive process(es) it reflects. There is an enormous literature concerning the P300 family of potentials, so we will include here only the most basic of descriptions (for reviews, see Donchin, 1981; Donchin & Coles, 1988, Donchin et al., 1978; Johnson, 1988; Pritchard, 1981; Verleger, 1988). P300s are elicited by any stimuli requiring a binary decision (yes/no, go/no-go, left-button/right-button, etc.). The decision need not involve an overt motor response; for instance, maintaining a silent count of target stimuli presented among nontargets is sufficient to elicit a large centro-parietal positive wave. The P300 is thus sensitive to the "task-relevance" of a stimulus. The amplitude of the P300 is also sensitive to the degree of confidence a subject has in his or her classification of the stimuli.

[7] Actually, most of the psychological work has focused on that part of the readiness potential that is asymmetric-the so-called lateralized readiness potential (LRP), although we use the term RP to encompass all RP-related studies.

While a binary decision between two equiprobable events is sufficient to elicit a P300, its amplitude is particularly sensitive to fluctuations in stimulus probability (at least at interstimulus stimulus intervals of <3 s). For exam ple, increasing the proportion of randomly occurring deviations within a Bernoulli sequence has been shown to yield P300s of linearly decreasing amplitude (Duncan-Johnson & Donchin, 1977). Indeed, one of the more influential views of the P300 component, the expectancy model, is based on the relation between P300 amplitude and subjective probability (Squires, Wickens, Squires. & Donchin, 1976). In many experiments, it appears that subjects spontaneously take note of stimulus probability, so that low-frequency events elicit larger P300s even if no experimental task is assigned. Like the N400, the P300 is modality-neutral, so that either a red light among a series of blue lights or a high-pitched tone occurring unpredictably among a sequence of low-pitched tones will yield a larger P300 than the standard stimuli, although P300s in different modalities have slightly different scalp distributions and developmental timecourses (G. Barrett, Neshige, & Shibasaki, 1987; Johnson, 1989a, 1989b; Simson, Vaughan, & Ritter, 1977; Snyder, Hillyard, & Galambos, 1980).

Like its amplitude, the latency of the P300 has been found to be highly but systematically variable. The more complex the stimulus evaluation phase of the decision process leading to the P300, the longer is its measured peak latency, which can vary from 300 to 1000+ ms (Donchin et al., 1978; Kutas, McCarthy, & Donchin, 1977; Magliero, Bashore, Coles, & Donchin, 1984; McCarthy & Donchin, 1981; Ritter, Simson, & Vaughan, 1972).

The P300 is not language-specific, but since its amplitude and latency are reflective of some general process(es) of stimulus evaluation and classification (see Donchin & Coles, 1988; Verleger, 1988), it can be harnessed to the study of psycholinguistic issues (see, e.g., Polich, McCarthy, Kramer, Wang, & Donchin, 1983).

There are, however, some disjunctions between the general conditions which elicit P300s and the outcome of psycholinguistic paradigms. The most obvious example of this occurred in the first N400 experiment of Kutas and Hillyard (1980c). Given the database described above, these researchers reasoned that unpredictable sentence endings embedded in a series of meaningful sentences would be low-probability events, and if the subjects were reading for comprehension, they would also be task-relevant events-a perfect recipe for a P300 to semantically incongruent words. This, of course, is not how the experiment turned out, since the incongruities elicited N400s instead. Surprises such as this illustrate that while our ability to predict stimulus and task configurations that will elicit P300s is generally quite good, our concepts are still somewhat inadequate.

The P300 has thus far not proved useful in sentence processing paradigms (but see Section VI,B), but a psycholinguist needs to be aware of the general circumstances which will yield P300s and cognizant that they may appear in situations where they serve as confounds in data interpretation. P300s will be apparent in any task requiring a binary decision, with a latency corresponding to the time at which the decision is made. Such task-induced P300s of variable latency may overlap other components which are sensitive to the psycholinguistic manipulations of interest. The probability sensitivity of the P300 also suggests that the occurrence of stimuli in one or another experimental condition be made as equiprobable as possible.

D. Very Slow Potentials

Over the past five years or so, there has been a resurgence of interest in the use of direct current (DC) recording in investigations of various cognitive phenomena.[8] This revived interest is based on the belief that measurement of DC shifts provides one of the best means for online monitoring of relatively long lasting, sustained cognitive processes, as in learning and memory. Negative DC shifts on the scalp have been shown to covary with potentials recorded at the cortical surface and with the firing patterns of cortical single neurons (e.g., Caspers, Speckmann, & Lehmenkuhler, 1980). In addition, it has been shown that those cortical areas which exhibit an increase in regional cerebral blood flow also give rise to an increase in DC shifts (Goldenberg et al., 1989; Uhl, Goldenberg et al., 1990). Thus, it is assumed that these scalp-recorded DC shifts can be used to assess varying cerebral activation patterns. The majority of these studies have focused on learning and memory in general rather than language processes per se (Lang et al., 1988; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992; Uhl, Franzen et al., 1990; Uhl, Lang, Lindinger, & Deecke, 1990; Uhl, Lang, Spieth, & Deecke, 1990). However, it has consistently been observed that learning and memory tasks involving verbal materials, as opposed to nonverbal materials such as faces or music, are characterized by negative DC potential shifts that are largest over left frontal areas. This left lateralization is evident during both acquisition and retrieval phases of these experiments. The processing of nonlinguistic stimuli also leads to steady potential shifts but with a different topographical profile (e.g., Ruchkin et al., 1992). Indeed, Ruchkin and his colleagues have been using these slow potential shifts to evaluate the neurological reality of the hypothesized subsystems within working memory such as visuospatial scratch pad, phonological buffer, and so on. Although there are clear benefits to DC recording, it is appreciably more difficult than most AC recordings and should, therefore, be undertaken only if the psycholinguistic question requires it (see Rugg, Kok, Barrett, & Fischler, 1986).

V. BIOLOGICAL FACTORS

A. Handedness and Lateralization for Language

Although it leaves much to be desired as a description of the neural substrates for language processing, an asymmetric cortical organization for many language processing abilities has been well documented. In right-handers (or in subject groups unselected for handedness and thus dominated by right-handers), several components of the ERP including the N400, CNV, and P300 have shown amplitude asymmetries in language processing studies (Butler et al., 1981; Kutas, Van Petten, & Besson, 1988; Neville, 1974, 1980; Neville, Mills, & Lawson, 1992). The CNV and P300 are larger at recording sites over the left hemisphere, while the N400 is larger over the right hemisphere. The asymmetry of the N400 might be regarded as paradoxical until one remembers that scalp distribution is determined by the orientation of neuronal current flow and not by the location

[8] Note that the majority of work discussed so far has been recorded with alternating current (AC) amplifiers with time constants ranging from 3 to 10 s. DC amplifiers have an infinite time constant.

of neurons per se. Such "paradoxical lateralization" has been observed in an early component of the visual pattern-reversal ERP: This P1 is larger over the hemisphere ipsilateral to stimulus presentation, in contrast to the known projections of the right and left visual fields onto contralateral visual cortex. This pattern of results has been explained as a consequence of the generating neurons being close to the medial surface of the hemisphere and oriented such that their dipoles point toward the scalp overlying the opposite hemisphere (G. Barrett, Blumhardt, Halliday, Halliday, & Kriss, 1976). A similar line of reasoning has been used to explain the paradoxical lateralization of the readiness potential prior to foot movements (Brunia, 1984).

The best evidence to date on the hemisphere responsible for the generation of scalp-recorded N400s comes from a study including commissurotimized ("split-brain") subjects (Kutas, Hillyard, & Gazzaniga, 1988). While subjects who have their corpus callosum (and often anterior commissure) severed for relief of epilepsy can never be regarded as equivalent to normal subjects, divided visual field studies in such patients provide a relatively unambiguous technique for restricting stimuli to one or the other hemisphere. In this experiment, sentence fragments (omitting the final 'word) were presented aurally so that both hemispheres had access to the context, but the final words were presented in the visual half-fields to limit access to a single hemisphere. There were four conditions: (a) congruent final word displayed in both left (LVF) and right visual field (RVF); (b) incongruent final word to LVF and RVF; and (c) and (d) congruent word to one visual field, incongruent word to the opposite visual field. The critical comparison is thus between the last two conditions: Only a hemisphere receiving an incongruent word should generate an N400, IF that hemisphere has the capability. The five split-brain subjects all showed some degree of receptive language ability in both hemispheres. In a pre-test, they were able to judge with greater than 70% accuracy whether or not a word presented to the LVF (right hemisphere) formed a sensible completion to the auditory sentence, and of course showed higher accuracies for the RVF. However, while all five of the left hemispheres generated N400s when presented with incongruous words, only two of the right hemispheres did so. The critical distinction between the two groups of subjects proved to be right hemisphere control of expressive language. At the time of testing, one of the two subjects with right hemisphere N400s could control overt speech with that hemisphere, whereas the other subject showed a high degree of generative capacity with respect to written output. Some six months after the ERP experiment, this subject began to show a right hemisphere speech capability which was fully developed two years later. While this study raises interesting questions about the role of speech capability in hemispheric specialization for language (discussed in the original report), it also suggests that only a hemisphere with full language capability will generate an N400. Thus, the typical right-greater-than-left asymmetry of the N400 should probably be taken as reflective of the dipole orientation of a left hemisphere generator.

The relationship between handedness and asymmetric organization for language has received a fair amount of attention in anatomical and behavioral studies, with the general conclusion that some 60-80% of left-handers show a left hemisphere dominance equivalent to that of right-handers, but a substantial minority show a reversed asymmetry or a greater degree of bilaterality (for reviews, see Bradshaw & Nettleton, 1981; Kolb & Whishaw, 1990; Perecman, 1983). Relatively few ERP studies using words or sentences as stimuli have contrasted left- and right-handed groups of subjects to see if they yield opposing patterns of asymmetry. S. E. Barrett and Rugg (1989) examined handedness and phonological priming but found no group difference.

In work with both healthy and brain-damaged subjects, family history of left-handedness has sometimes proved as important as the handedness of the subjects themselves, so that right-handers with left-handed family members appear to have a more bilateral language representation than those without (Bever, Carrithers, Cowart, & Townsend, 1989; Bradshaw & Nettleton. 1981; Hardyck & Petrinovich, 1977; but see also Orsini, Satz, Soper, & Light, 1985). There are slightly more ERP data in this domain, as it takes little additional effort to query one's subjects about family handedness in the regular course of an experiment. We have consistently observed that the typical right-greater-than-left asymmetry of the visual N400 is absent or reduced in right-handers with left-handed family members. This is true not only for the N400 incongruity effect, but also for the smaller N400 elicited by congruent, intermediate sentence words (Kutas & Hillyard, 1980b; Kutas, Van Petten, & Besson, 1988). Whether the laterality of the auditory N400 is also sensitive to familial left-handedness is unknown. It would also be interesting to find out if the reduced asymmetry associated with familial sinistrality holds equally for young children, or in ASL.

B. Development and Aging

Babies and children are likely to be less compliant than adults to standard instructions to sit still, pay attention, and refrain from eye movements, so that obtaining clean ERPs from these populations requires a patient and ingenious experimenter. On the other hand, as ERPs do not require an overt response, many of the problems inherent in the more traditional assessments of a child's language capabilities are bypassed. Electrophysiological data related to language processing have begun to appear only over the last few years (although see Kurtzberg, 1985, for a description of ERPs to stop-consonant CV syllables in infants up to 24 months old). For example, Mills, Coffey, and Neville (1993) collected ERPs from 20 month old infants as they listened to sets of words including ten whose meaning they knew, ten whose meaning they did not know, plus ten words played backward in time (also see Molfese, 1989, 1990). Two aspects of the procedure helped increase the amount of artifact-free data. First, the words were presented from a speaker located behind a moving puppet in a puppet theater, although the movements of the puppet's mouth were not synchronized to the word presentation. Moreover, after the child sat still for approximately ten trials, a battery-operated toy attached to the puppet theater was activated as the experimenter praised the child. This procedure led to a major reduction in the percentage of trials lost due to artifacts. Different patterns of ERPs were elicited by the three types of stimuli. Specifically, two negative peaks (N200 and N350) were elicited primarily by normally spoken and not by backward words (which do not conform to the articulatory/phonological constraints of English; this is probably true of most languages). The amplitude of N200 further distinguished the known and unknown words, especially over temporal-parietal regions of the left hemisphere.

Neville's laboratory has also studied older children in various language tasks. For example, Holcomb et al. (1992) studied children and young adults aged 5-26 years as they heard or read sentences that ended with either a highly expected ending or a semantically anomalous word (in the reading version, the minimum age was 7). They found that a host of early and late components of the ERP decreased in amplitude and latency with age. More relevant for present purposes, they observed that while all age groups showed an N400 effect in both modalities, the size of the effect was inversely correlated with age. The results were interpreted as consistent with other reports showing that children rely less on semantic context as they acquire good language skills. It should be noted, however, that with more complex language materials than predictable versus incongruous sentences, we have observed that some N400 effects are positively correlated with language skills (Van Petten, in press).

Although outside the domain of this chapter, the reader should note that there exist ERP data on language and non-language tasks from a number of different populations of children characterized by their abnormal language skills, such as those with Williams syndrome and language-impaired children (Neville, Coffey, Holcomb, & Tallal, 1993: Neville, Mills, & Bellugi, in press).

In experiments contrasting congruous and incongruous sentence completions, or related and unrelated words in lists, young adults generate larger, more peaked, and shorter peak latency N400s in the visual modality than do elderly adults (Gunter et al., 1992; Hamberger & Friedman, 1989; Harbin, Marsh, & Harvey, 1984). Pooling the developmental data with the aging data shows that there is a linear reduction in the amplitude of the N400 incongruity effect from 5 years (or earlier) to 80 years of age (Holcomb et al., 1992; Kutas, Mitchiner, & Iragui-Madoz, 1992). It will be interesting to see if all N400 effects exhibit a similar linear decline. Preliminary evidence suggests that N400s elicited by spoken words may not reflect aging processes as directly (P. Hagoort, C. Brown, & T. Swaab, personal communication).

C. Deafness and Language History

Congenitally deaf individuals who learn ASL as their first language have been something of a proving ground for theories about the abilities of the two hemispheres underlying the left dominance for language. Since the right hemisphere is generally superior in visuospatial abilities and both lexical and syntactic information is conveyed by modulations of handshape, location, and motion in ASL, one might think that native signers would show a right hemisphere dominance for language. However, studies of brain-damaged signers have shown that it is left hemisphere damage which is most likely to lead to aphasia and that the syndromes are remarkably similar to spoken language aphasias (Bellugi, Klima, & Poizner, 1988; Poizner, Bellugi, & Klima, 1991).

The work of Neville and colleagues with healthy signers has complemented the sign aphasia studies by showing that the N400 sentence incongruity effect shows the typical right-greater-than-left asymmetry in congenitally deaf individ uals tested in either ASL or written English (Kutas et al., 1987; Neville, 1991; Neville et al., 1992). For English sentences, however, deaf and hearing native-speaking subjects do not exhibit identical ERPs (Neville et al., 1992). The basic N400 to congruent open-class words in intermediate sentence positions is larger over the right only at occipital sites in the deaf subjects, as opposed to the more widespread asymmetry in the hearing subjects. Similarly, the typical asymmetries observed at frontal sites for closed-class words are reduced in the deaf subjects. The deaf ERPs to both classes of words are also marked by a large positive offset beginning about 100 ms after stimulus onset. At present, it is difficult to determine if the other apparent differences are due to the presence of this overlapping positivity or independent from it. In either case, preliminary evidence suggests that these deaf/hearing differences may have little to do with deafness per se, or the fact that ASL and English are learned in different modalities. This is because English is the second language of these subjects, and they are often not fully fluent in written English. Deaf Subjects who perform the best on tests of English grammar show a pattern of ERPs and ERP asymmetries more like native English speakers (Neville, 1991).

However, Neville et al. have found that the acquisition of acoustic versus Spatial language does have some consequences for the asymmetry of cortical organization (Neville & Lawson, 1987a, 1987b, 1987c). In a nonlinguistic visuo Spatial task requiring the detection of motion and directionality in the periphery, native English speakers are more accurate for stimuli in the left visual field, whereas deaf signers Show the reverse asymmetry. This reversed asymmetry can be attributed to the acquisition of ASL (rather than auditory deprivation), since hearing children of deaf parents Show the same pattern. So, rather than the visuospatial superiority of the right hemisphere engendering right hemisphere language, acquisition of a visuospatial language seems to have improved some aspects of the left hemisphere's performance in this domain. The ERPs collected during the motion detection task also Showed differences in scalp distributions (in both the lateral and the anterior-posterior dimensions), some of which could be attributed to auditory deprivation, and others to the acquisition of ASL.

While native signers are a unique population, Neville's results have hinted that some of the hearing/deaf differences in language processing experiments reflect the difference between a first and second language. In studies including spoken language bilinguals, it is clear that the N400 Sentence incongruity effect peaks later in the less fluent language (Ardal et al., 1990; Kutas et al., in preparation; Neville et al., 1992). The effects of experimental manipulations which are more syntactic in nature show qualitative differences depending not only the fluency of the Subject in that language, but the particular language being tested. Both Syntactic manipulations and inter-language comparisons are relatively recent trends in psycholinguistic ERP research; we note some of those results below.

VI. PSYCHOLINGUISTIC FACTORS

A. Lexical and Semantic Manipulations

1. Isolated Words

Isolated words can be sorted on a number of dimensions to determine whether or not these have ERP signatures. Orthographic and phonological characteristics are two obvious dimensions which have received little attention. For instance, we do not know if there is any difference between regularly and irregularly pronounced words. Such a comparison might Shed light on the relative timings and obligatory/optional status of various routes by which a word can be retrieved. Similarly, number of orthographic neighbors influences pronunciation time for words, rejection times for nonwords, and masked priming effects for words (Coltheart, Davelaar, Jonasson, & Besner, 1977; Forster, 1987; Patterson & Coltheart, 1987). We do not know if there is an ERP correlate which can be used to further understand neighborhood effects, although this is a topic under investigation (P. Michie & M. Coltheart, personal communication). Finally, the impact of a word's inflectional status has not been investigated in lists of unrelated words, although we have compared inflected to uninflected words in text, and other investigators have investigated priming between forms of the same word (M. C. Doyle & Rugg, 1991; C. Van Petten, R. Kluender, & M. Kutas, unpublished).

The dimension of concreteness has been given a modicum of attention. Paller and colleagues found that concrete words elicited more negative ERPs than abstract words from about 300 to 900 ms (Palter, Kutas, Shimamura, & Squire, 1987). However, the dimension of concreteness was incidental to the design of this memory experiment; a rating of concreteness was the task assigned to subjects during the study phase of the experiment as a prelude to subsequent tests of recall and priming. The difference between concrete and abstract words may then have been a consequence of how subjects construed the task; for instance they may have considered abstract words to be the "targets." Smith and Halgren (1987) used a lexical decision task in which the concreteness of the words was irrelevant to the task and observed no ERP difference between abstract and concrete words. In contrast, Kounios and Holcomb (in press) found that concrete words elicited more negativity between 300 and 500 ms than did abstract words with the difference being more pronounced over the right than the left hemisphere. Since this concreteness effect was smaller during lexical decision than during an abstract/concrete judgment, the three studies do seem to form a consistent pattern. Kounious and Holcomb also noted different ERP repetition effects for the two word types and interpreted their overall findings as converging evidence of the dual coding theory's structural account of concreteness effects in semantic processing. In a subsequent study, these investigators used concrete and abstract words to complete sentences (Holcomb, Kounious, & Anderson, submitted). They found no difference when the words were predictable, high cloze probability completions eliciting little N400 activity. As low cloze endings however, concrete words elicited larger N400s than abstract words. The factor of concreteness/abstractness is thus one where a few more experiments may present a clear picture.

Frequency of usage is a lexical factor which has been examined in priming paradigms using lists of words, in sentences, and in text. We thus devote a separate section to it below, together with the related phenomena of word repetition effects.

2. Sentences

Thus far, we have mentioned only the most basic of N400 effects obtained in sentences, the difference between congruent and incongruent words. The amplitude of the N400 elicited by words in a sentence reflects finer gradations of the semantic constraints placed on that word. One a priori metric of the amount of semantic constraint imposed on a terminal word by the preceding sentence fragment can be obtained via the off-line technique of cloze probability, e.g., what proportion of subjects will fill in a particular word as being the most likely completion of a sentence fragment (Taylor, 1953). Cloze probability proportions and N400 amplitude have been shown to be inversely correlated at a level above 90%. It is important to note, however, the subtle distinction between the cloze probability of a terminal word and the contextual constraint of the sentence fragment per se. For example, the fragment *The bill was due at the end of the . . .* is of high contextual constraint in that most people will fill in *month,* while *He was soothed by the gentle . . .* is of low contextual constraint because there are a number of acceptable endings, no one of which is clearly preferred over the others (Bloom & Fischler, 1980). But both fragments can be completed by words of equal (low) cloze probability as in *The bill was due at the end of the hour* and *He was soothed by the gentle wind.* The results of experiments which crossed several levels of contextual constraint with several levels of cloze probability showed that N400 amplitude was correlated with the Coze probability of the final word but generally independent of the contextual constraint of the preceding sentence fragment (Kutas & Hillyard, 1984; Kutas, Lindamood, & Hillyard, 1984). This result was critical in establishing that N400 amplitude does not index the violation of previously established expectancies for a particular word which was not presented, but rather is sensitive to the degree to which the sentence fragment prepared the way for the word which actually followed. Note, however, that in the absence of an explicit attempt to dissociate cloze probability and contextual constraint, the two factors are generally correlated. In what follows we use the term "contextual constraint" in reference to this more typical situation.

Given the Coze probability results for sentence-final words, we wanted to determine if N400 amplitude also reflected gradations of semantic constraint for intermediate words. One can use the cloze probability for intermediate words, but obtaining useful measures for relatively unconstrained intermediate words requires an enormous number of subjects. We used a pragmatic shortcut instead. With a set of unrelated stimulus sentences, the subject/reader must begin each sentence with no information concerning the topic, but as it progresses he or she should begin building a mental model of the concept expressed by the sentence and have more available information concerning what sorts of words might occur next. The strength of the correlation between degree of semantic constraint and word position will naturally vary from sentence to sentence, but an average across a large number of sentences (100-240 in these experiments) should reveal the correlation. Intermediate words sorted according to sentence position yielded a linear decrement in N400 amplitude with increasing position (Kutas, Van Petten, & Besson, 1988). We subsequently verified that the decrement was due to a sentence-level factor via the observation that it did not occur in random word strings of equal length, and we have replicated the effect for congruent sentences in several other data sets (Van Petten & Kutas, 1990, 1991a, 1991b, unpublished observations). The correlation between N400 amplitude and sentence position holds only for the open-class words of a sentence; while closed-class words elicit N400s, these are not sensitive to overall sentence position. Although the hypothesis has not been explicitly tested, it seems likely that the constraints on closed-class words do not develop over an entire sentence but are instead more local and bound within a single phrase or clause.

3. Semantic Relationships in Lists or Pairs of Words

Studies using lexical decision, letter search, and category judgment tasks have shown that words elicit smaller N400s if semantically related to the previous word than if not (Bentin et al., 1985; Boddy, 1981; Boddy & Weinberg, 1981; Harbin et al., 1984; Holcomb & Neville, 1990; Kutas, in press; Polich, Vanasse, & Donchin, 1981; Rugg, 1985b, 1987). In many of the studies using semantic categories as stimuli, these were a convenient means of defining "related" and "unrelated" words *a priori,* and it was found that an out-of-category word following several from the same category elicited a larger N400 than another word from the established category. Other studies have used phrases or sentence fragments to establish a semantic category (e.g., *a type of fish,* or *an apple is a . . .*). These have similarly observed that words which do not fit the category elicit larger N400s than those which do (Fischler, Bloom, Childers, Roucos, & Perry, 1983; Neville, Kutas, Chesney, & Schmidt, 1986).

Recent work has shown that among words which fit an established category, atypical members *(a type of bird: ostrich*) elicit larger N400s than typical members (Heinze, Muente, & Kutas, 1993; M. Kutas, unpublished observations; Stuss, Picton, & Cerri, 1988). The ERP categorization and typicality effects are immune to larger list-context effects observed in reaction time measures of category judgments. For instance, the use of false but related trials such as *a fish: whale* or *a bird: bat* produces slower reaction times for the true trials than when the false trials are unrelated (*a fish: window*). The impact of the related lures is more pronounced for atypical category judgments than typical. The N400 measure, however, shows no effect of list context, and no interaction between list context and typicality, suggesting that the list-context effect may be due to decision-related processes occurring subsequent to those indexed by the N400 (Heinze et al., 1993).

The typicality effect might be considered one manifestation of contextual constraint, so that the size of the N400 is dependent on how predictable the target word is. Kounios and Holcomb (1992) have noted that it matters whether a categorial statement begins with the superordinate *(Some fruits are apples*) or the subordinate term (*All apples are fruits*). Words at the end of a superordinate sentence elicited larger N400s, perhaps because the terminal word was less predictable given the one-to-many mapping between a category name and its exemplars. Kutas and her colleagues have also found that the size and the latency of the N400 effect are influenced by whether the prime consists of a category or an antonym. Across a series of experiments they used statements like *The opposite of black* and A *type of animal* as primes and found that the N400 difference between words that matched or did not match the prime was larger, more peaked, and of earlier peak latency in the antonym than in the category conditions. As can be seen in Figure 7, this effect is due to an earlier and larger positivity to congruent words, and a slightly earlier rise and peak of the N400 is due to incongruent words in the antonym condition. In fact, the typicality effect on the N400 appears to fall on the continuum from the early positivity for the highly predictable, congruent exemplars primed by a small category (antonyms) to the large N400 elicited by unpredictable, incongruent nonmembers primed by a larger category.

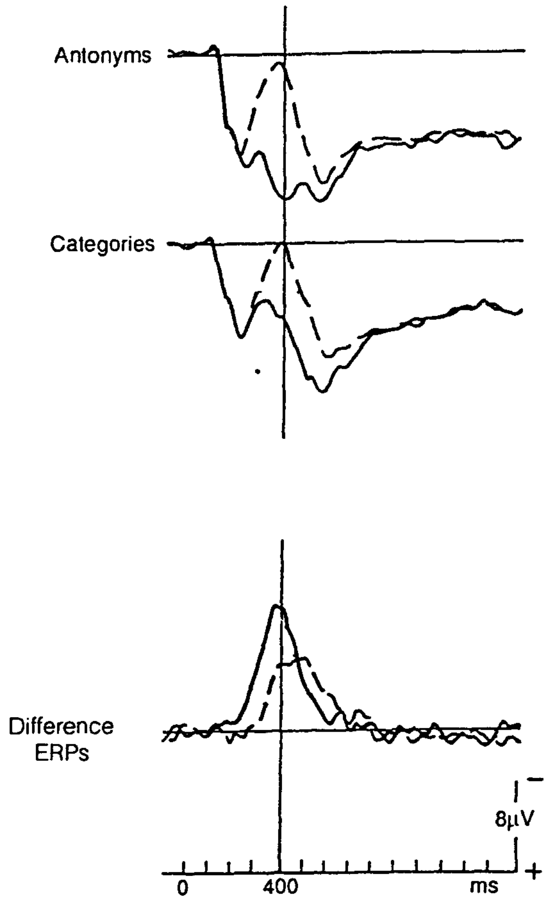

FIG. 7 Grand average ERPs elicited by positive (*solid line*) and negative (*dashed line*) instances of antonym and category conditions. The bottom half shows the difference ERPs derived from a point-by-point subtraction of the positive from negative instance ERP for the antonym (*solid line*) and category (*dashed line*) conditions, respectively, overlapped (M. Kutas, unpublished data).

4. Associative versus Sentence-Level Semantics

When the stimuli for these category experiments have been in the form of sentences, there has been a dissociation between the truth or falsity of the sentence and the semantic relationship between the content words of the sentence. Fischler and colleagues (1983) found that *An apple is a* ***weapon*** elicited the same N400 as *An apple is not a* ***weapon***, both of which were smaller than *An apple is/* ***is not*** *a fruit*. Kounios and Holcomb (1992) similarly observed an effect of relatedness on N400 amplitude, but no effect of whether the quantifier made the sentence true or false: *fruits* elicited the same size N400 in *All apples are fruits* and *No apples are fruits*.

The absence of a sentence validity effect in category experiments may seem to be in conflict with the evidence tying the N400 to sentence-level context effects (see above), unless one considers that these equation-like statements probably do not fully engage the same sentence-processing mechanisms used in normal discourse. We have recently contrasted lexical /associative semantic relationships to sentence-level semantic relationships and observed that both independently influence N400 amplitude (Kutas. in press; Van Petten, in press; Van Petten & Kutas, 1991a; see also Fischler, Boaz, Childers, & Perry, 1985, for a similar conclusion).

A somewhat different paradigm for comparing lexical and sentence-level semantic context is one of the traditional paradigms for examining lexical ambiguity. In this type of study, an ambiguous word is placed at the end of a sentence which clearly disambiguates it. The ambiguous word is then followed by one of three types of probe words which are related to the sententially appropriate sense of the ambiguity, the inappropriate sense, or neither. We have replicated the standard reaction time result in this paradigm to find that both of the related probes elicit faster responses than the unrelated word. However, on the basis of a large latency difference between the N400 priming effect for contextually appropriate and inappropriate probe words, we have argued that sentential context guides the initial interpretation of words which are ambiguous in isolation. These results are detailed elsewhere (Van Petten & Kutas, 1987, 1991a).

5. Nonsemantic Relationships in Word Pairs

We have seen that semantic relationships influence N400 amplitude under a variety of experimental tasks, probably because semantic processing is the default mode for analyzing relationships between items. A handful of studies have shown that if subjects are assigned a rhyme judgment task, then nonrhyming words elicit larger N400s than rhyming (Rugg, 1984, 1985a; Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980). In Rugg's studies, most of the rhyming pairs were orthographically dissimilar (e.g., *moose-juice),* so that the reduced N400 could be attributed to the phonemic similarity. Polich and colleagues investigated the interactions between phonemic and orthographic similarity by crossing these two factors to yield four types of word pairs, and varying the task between rhyme and visual similarity judgments (Polich et al., 1983; see also the discussion of this study in Kutas and Van Petten 1988). For rhyme judgments, they found that both phonemic and orthographic similarity influenced the amplitude of the N400 elicited by second word. For visual similarity judgments, orthographic but not phonemic similarity influenced N400 amplitude. These data thus indicate that phonemic priming effects on the N400 occur only when the task demands this sort of analysis and are also consistent with behavioral reports that subjects are unable to ignore orthographic information during a rhyme judgment task (Seidenberg & Tanenhaus, 1979).

6. Word Frequency and Repetition

Frequency and repetition are logically related, but one refers to a subject's life history of encounters with a particular word (necessarily estimated from normative frequency counts), and the other to the frequency of a word within a particular experiment. Both factors have been part of active research programs, some of which are primarily concerned with memory rather than language processing. For these reasons, we will not be able to review all the frequency/ repetition studies in great detail here (for more extensive reviews, see Besson, Kutas, & Van Petten, 1992; P. F. Mitchell, Andrews, & Ward, 1993; Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991). Both frequency and repetition influence multiple components of the ERP, some of which are affected by both factors.

Repeating a word in a list or in text, or repeating an entire sentence, yields a smaller amplitude N400 for the second than the first presentation of open-class words (Besson et al., 1992; Karayanadis, Andrews, Ward, & McConaghy, 1991; Nagy & Rugg, 1989; Rugg, 1985b, 1987, 1990; Rugg, Furda, & Lorist, 1988; Rugg & Nagy, 1987, 1989; Smith & Halgren, 1987; Van Petten et al., 1991). This repetition effect occurs both within and across the visual and auditory modalities (Feldstein, Smith, & Halgren, 1987; Rugg, 1992). Rugg's work suggests, however, that there is a latency difference for cross-modal repetition depending on whether the spoken word occurs first or second. The N400 repetition effect is also sensitive to the lag between occurrences of the word. The influence of lag time has been fairly well characterized in word lists, where the repetition effect is not apparent beyond about 45 minutes (see citations above, and Fischler, Boaz, McGovern, & Ransdell, 1987). In sentences or text, a limit has not yeti been established. The N400 repetition effect seems fairly impervious to experimental task, provided that both presentations are within the focus of attention.[9]

Analogously to the repetition effect, high-frequency words tend to elicit smaller N400s than low-frequency words. The frequency effect on N400 amplitude is, however, qualified by interactions with both repetition and semantic constraint. When words are repeated in lists, or when entire sentences are repeated, the frequency effect disappears for the second presentation (Besson et al., 1992; Rugg, 1990; Smith & Halgren, 1987). In other words, low-frequency words show a disproportionate repetition effect so that N400 amplitude is equalized by repetition. Sentence and text processing experiments show that semantic context is also capable of wiping out the N400 frequency effect. Above, we described the decrement in N400 amplitude with increasing sentence position. These experiments also show that low-frequency words elicit larger N400s than high-frequency words early in a sentence, but later there is no such difference, as shown in Figure 8. Like the basic word position effect, the position by frequency interaction is due to semantic factors, since it is not apparent either in random word strings or in syntactically legal but semantically anomalous sentences (Van Petten & Kutas, 1990, 1991a, 1991b). In contrast to the independent sentences used in these experiments, semantic constraints in connected discourse span sentences; in text we observe little sign of any N400 frequency effect (Van Petten et al., 1991).

The N400 effects are thus fairly well characterized and orderly: We have seen that amplitude is influenced by frequency, repetition, and semantic constraints, and all three factors interact as if operating through a common mecha nism (see also Kotz, Holcomb, & Kounios, 1992). The two(?) other ERP components sensitive to repetition and frequency are less well understood at present. There have been some reports of a repetition effect preceding the N400, in the

[9] We refer to selective attention paradigms where multiple words are presented simultaneously, or words arc presented individually at a very high rate, and subjects are instructed to attend only to words in one spatial location or one color. As described earlier, these manipulations yield different patterns of effects than the standard situation where the subject has no conflicting attentional demands.

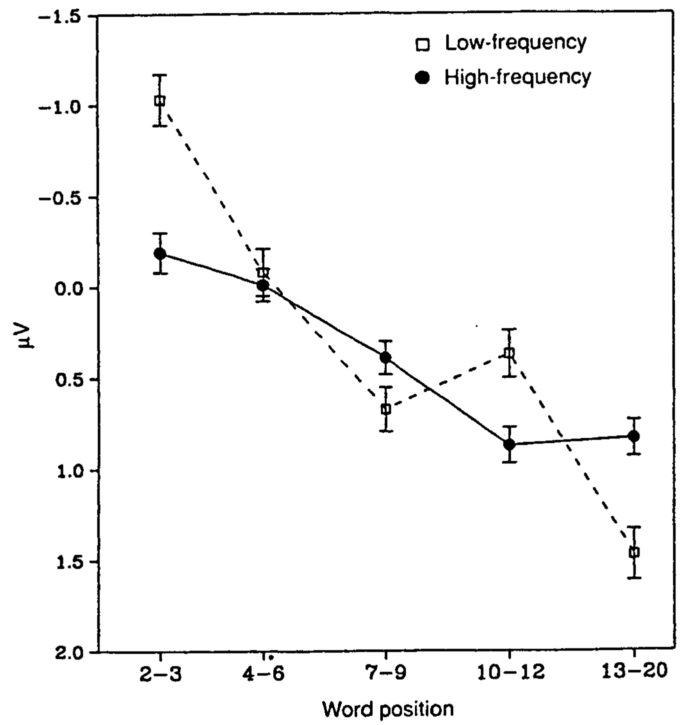

FIG. 8 Amplitude of the N400 elicited by intermediate open-class words in different ordinal positions of congruent sentences, averaged across electrode sites. Data from Van Petten (in press).

latency range of the P2 (200-250 ms, primarily at frontal scalp sites; Rugg, 1987; Van Petten et al., 1991; Young & Rugg, 1992). However, this early effect has been ephemeral, visible or not visible in apparently similar experimental designs (Bentin & Peled, 1990; Karayanadis et al., 1991; Nagy & Rugg, 1989; Rugg et al., 1988; Rugg & Nagy, 1987, 1989). Moreover, the direction of the repetition effect has been variable, sometimes an apparent enhancement of the P2 with repetition, sometimes an apparent diminution. The P2 effect has appeared often enough to suggest that it is a real phenomenon, but obviously we do not have a grasp of it at present.

The third repetition-sensitive component of the ERP is a late positivity. In word lists, this LPC is larger for the second than the first presentation of a word, and further is specific to low- rather than high-frequency words (Rugg, 1990; Rugg & Doyle, 1992; Young & Rugg, 1992). However, when we have compared initial versus subsequent presentations of words in connected discourse, we have observed that the late positivity is decreased rather than enhanced by repetition (Van Petten et al., 1991). The list and text effects are likely to be the same phemomenon, since both are most evident for low-frequency words, larger over the left than the right hemisphere, and have a latency range of 500-900 ms post-stimulus. Like the N400, the LPC is thus sensitive to both frequency and repetition. Finally, when entire sentences are repeated, the LPC repetition effect is most prominent for incongruous rather than congruous sentence completions (Besson et al., 1992). We have speculated that the LPC frequency/repetition effect reflects the retrieval of episodic information, but this is clearly a complex pattern of results calling for further research (for further discussion, see Besson et al., 1992; P. F. Mitchell et al., 1993; Van Petten et al., 1991).

7. Vocabulary Class

Kutas and Hillyard (1983) first noted that open-class or "content" words (nouns, verbs, most adjectives, -ly adverbs) elicited different ERPs than closed-class or "function" words (pronouns, articles, conjunctions, prepositions, etc.) in sentences. However, they did not attempt to determine which aspects of the vocabulary distinction (word length, frequency of usage, repetition, contextual constraint, abstractness of meaning, referentiality, syntactic role, etc.) were responsible for the ERP differences. The difference between open- and closed-class words is highly replicable (see Fig. 9 for a representative example) but

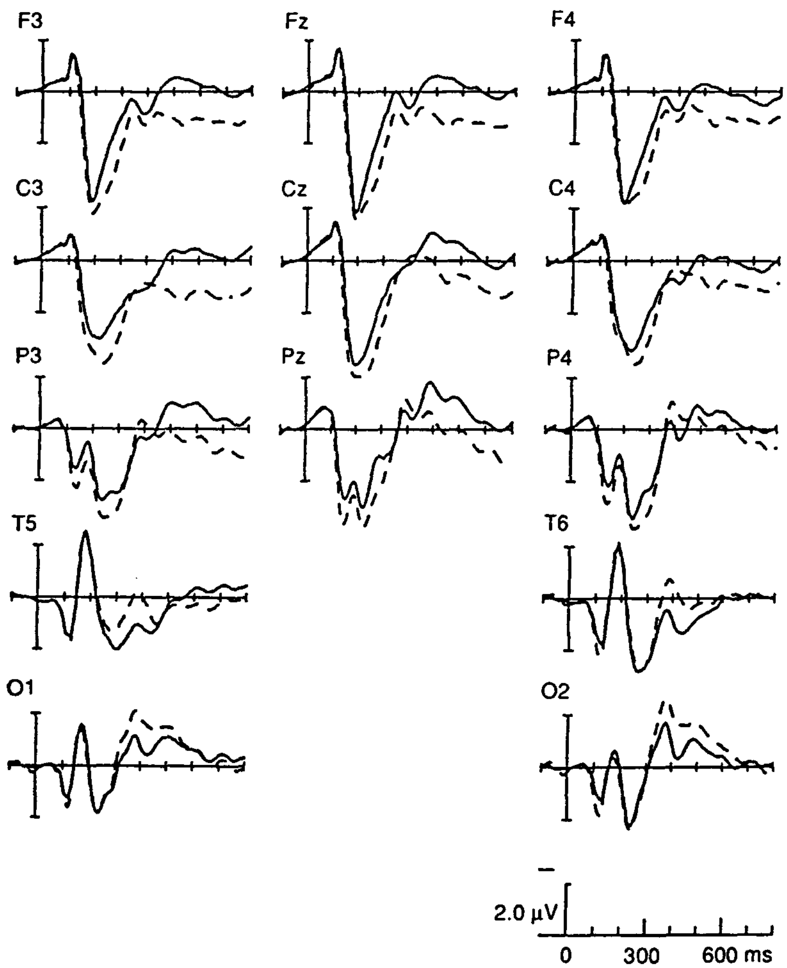

FIG. 9 ERPs elicited by open (*dashed lines*) and closed (*solid lines*) class words in sentences, excluding the initial and final words. F, frontal; C, central; P, parietal; T, temporal; O, occipital. Odd numbers denote sites over the left hemisphere; even numbers, sites over the right hemisphere. Data from Van Petten and Kutas (1990).

probably consists of variance due to more than one of the possible factors mentioned above. Closed-class words in sentences invariably elicit smaller N400s than open-class words. Van Petten and Kutas (1991b) suggested that this is due to the converging influences of higher frequency of usage, higher repetition rate, and greater predictability of closed class items in sentences.

A second difference between open- and closed-class words is a late ramp-shaped negativity over frontal scalp sites, dubbed the N400-700 (see Fig. 9, and Neville et al., 1992). Van Petten and Kutas observed variability in this component when comparing closed-class words in random word strings, syntactically legal but semantically anomalous sentences, and congruent sentences as in (1)-(3).

(1) *To prided the bury she room she of peanut the had china.*
(2) *He ran the half white car even though he couldn't name the raise.*
(3) *He was so wrapped tip in the past that he never thought about the present.*

The frontal N400-700 proved sensitive to both sentence type and word position, as shown in Figure 10. Early in a sentence, the N400-700 was essentially absent in all three conditions but developed in amplitude over the course of congruent sentences. The N400-700 also seems to be absent when open- and closed-class words are presented in a list format for lexical decision (Garnsey, 1985). This finding suggests that the N400-700 does not distinguish between open- and closed-class words *per se* but is instead tied to the development of a coherent sentence structure. This together with other characteristics of the N400-700 effect is consistent with its being a member of the CNV family of potentials (Van Petten & Kutas, 1991b).

The N400 and N400-700 effects probably do not exhaust the ways that

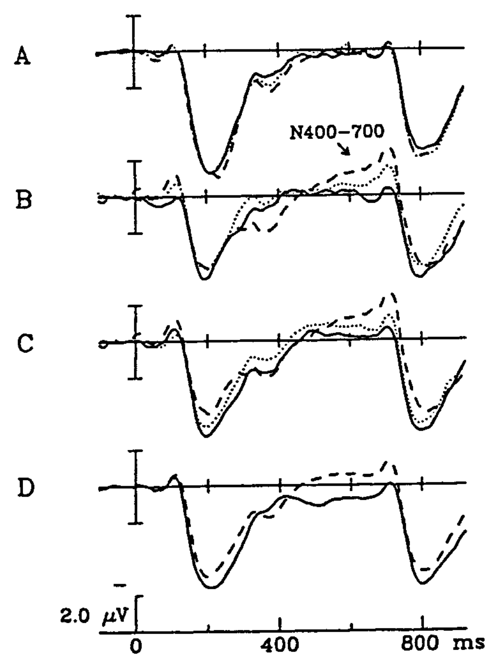

FIG. 10 (A) ERPs to closed-class words in the first and second ordinal positions of congruent sentences (*solid line*), syntactically structured but semantically anomalous sentences (*dotted line*), and random word strings (*dashed line*). (B) ERPs to closed-class words in the ninth and tenth positions of the same three conditions. showing the larger N400-700 in Congruent sentences. The Syntactic sentences appear to fall midway between the Congruent and Random conditions. but they were not statistically different from Random. (C) Closed-class words in the 3rd and 4th (*solid line*), 5th and 6th (*dotted line*), and 9th and 10th (*dashed line*) positions of Congruent sentences, showing the development of the N400-700 across the course of a sentence. (D) ERPs to all intermediate open (*solid line*) and closed (*dashed line*) class words from the congruent sentences. Data from Van Petten and Kutas (1991a).

open and closed ERPs differ. Indeed, the ERP correlates of vocabulary class and variability within each class are being actively pursued in several laboratories (Garnsey, 1985; Kluender & Kutas, 1993, in press; Neville et al., 1992; Van Petten & Kutas, 1991b).

B. Syntactic Manipulations

The history of N400 research demonstrates that VIOLATIONS have been a good way of eliciting large and robust ERP effects. However, the fact that this is the case does not imply that ERP components are specific or unique reflections of any given linguistic violation. For example, the N400 was originally viewed as a Semantic violation detector, but numerous studies Since have demonstrated that a violation is neither necessary nor Sufficient to yield an N400 component. Instead, the Semantic anomalies which elicit the largest N400 effects have proved to be derivable from an interaction of lexical properties (such as frequency of occurrence and vocabulary class) with contextual constraints at the sentence and discourse levels. ERP research on syntactic processing is only a few years old and has been focused on violations of Syntactic Structure as a first-pass Strategy for obtaining ERP effects. As this research matures, it may prove possible to characterize many of the "Syntactic" ERP effects as more general reflections of language processing rather than responses specific to linguistic errors (See Kutas & Kluender, in press, for a more extended discussion of the role of violations in ERP research).

Garnsey and colleagues constructed their stimulus sentences so that the presence or absence of an ERP violation response would provide the answer to the question of whether or not subjects use verb argument preferences as an on-line aid to Sentence parsing (Garnsey et al., 1989). They used sentences with embedded questions to determine when subjects would assign a questioned item (i.e., filler) to a possible gap, as in (4)-(7).

(4) *The babysitter didn't know which **door** the child PUSHED ______ carelessly at the store.*
(5) *The babysitter didn't know which **name** the child PUSHED ______ carelessly at the store.*
(6) *The tour operator wondered which **visitor** the guide WALKED ______ briskly down the hall.*
(7) *The tour operator wondered which **topic** the guide WALKED ______ briskly down the hall.*

Because *push* usually takes a direct object, both a flexible parsing strategy based on verb argument preferences and an inflexible "first resort" strategy would assign *door* and *name* to the first possible gap location after the verb. Either strategy would thus result in a Semantic incongruity at *pushed* in (5), as indexed by a large N400 relative to the control Sentence (4). However, the two strategies predict different outcomes when the verb does not preferentially take an object, as in (6) and (7). Strict adherence to a "first resort strategy" would result in a large N400 following the verb *walked* in (7) but not in (6). On the other hand, if the parser was sensitive to verb argument preference, then neither (6) nor (7) would be anomalous at the verb and no N400 effect would be observed. This is indeed what the results showed.

Garnsey used the N400 semantic incongruity effect as a vehicle for examining questions about syntactic processing. Other studies have been more directly aimed at determining whether or not there is any ERP reflection of a syntactic violation *per se*. The first of these was performed by Kutas and Hillyard (1983), who incorporated morphological violations of verb number, noun number, and verb tense in written text. These morphological violations did not yield an N400 with the same amplitude and distribution as that elicited by semantic violations in the same texts, but there was nonetheless an enhanced negativity in the 300-500 ms range relative to control words. Additionally, there was a hint of an enhanced late positivity following the violaton (see Fig. 11).

This positivity was late enough to appear mostly in the recording epoch for the subsequent word in the sentence and so was not noted in the original report. A replication with another group of monolingual English speakers has shown that both the enhanced negativity and positivity were real effects, and that the different morphological violations are associated with different ERP changes (Kutas et al., in preparation). Comparisons with bilingual Spanish/English speakers reading the same materials and analogous materials in Spanish showed that the exact pattern of negative and positive ERP violation effects was dependent both on the stimulus language and the subject's language history; for example, bilinguals who learned English relatively late (after 8 years) showed the largest late positivities to verb tense violations (see Fig. 12). Hagoort, Brown, and Groothusen (in press) have likewise observed an enlarged positivity in response to agreement errors in Dutch.

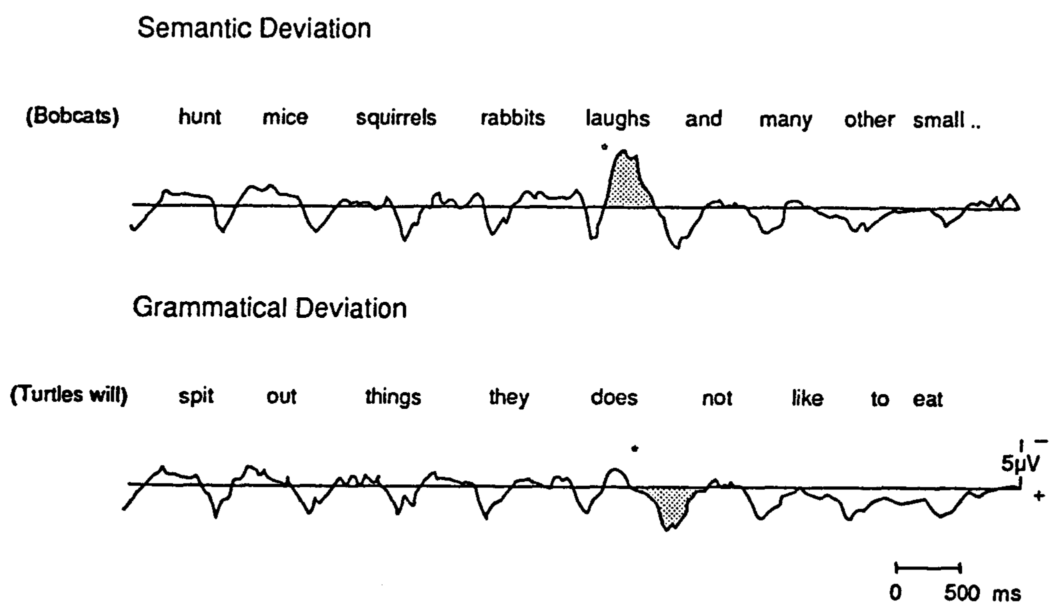

FIG. 11 Grand average ERPs to semantic violations and grammatical (morphological) violations embedded in text. Recordings are from a midline parietal site. Data from Kutas and Hillyard (1983).

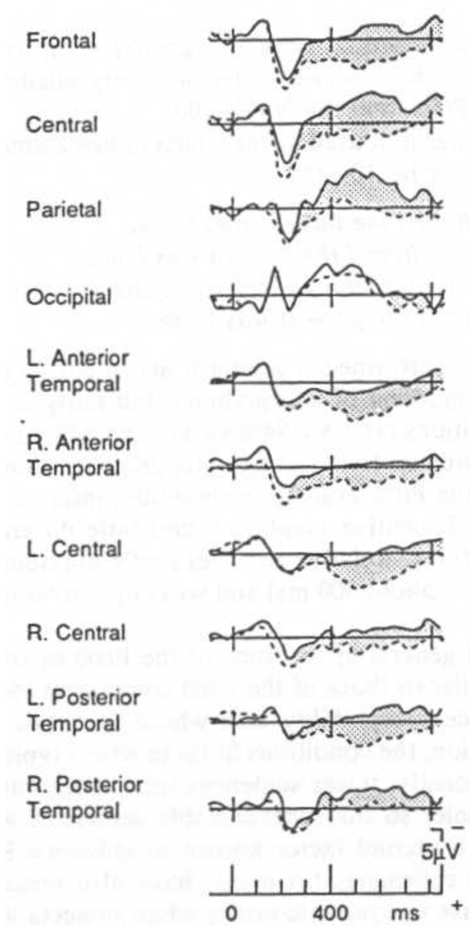

FIG. 12 Grand average ERPs elicited by verb tense violations (dashed lines) and control words (*solid lines*) embedded in Spanish text from Spanish-speaking individuals who had learned English after the age of eight. Data from Kutas et al. (in preparation).

Osterhout (1990; Osterhout & Holcomb, 1992) sought an ERP sign of syntactic violations by manipulating verb argument structure in a manner similar to Garnsey's work. In one experiment, he contrasted sentences like (8)-(9).

(8) *The broker hoped to sell the stock*.
(9) *The broker persuaded to sell the stock*.

Since *persuaded* in its active form requires an object, (9) becomes an unusual sentence construction at the word *to*, whereas (8) continues to be a common construction.[10] Osterhout observed that between 300 and 900 ms after the onset of the word *to*, the ERP in (9) was more positive, primarily over the frontal sites; the response was dubbed P600. The similarity between this P600 and the late positivity elicited by agreement violations is worth noting (Kutas et al., in preparation; Kutas & Hillyard, 1983), as is its possible relation to the N400-

[10] Note that (9) is not ungrammatical at *to*, as the sentence could continue *The broker persuaded to sell the stock was sent to jail*. Osterhout investigated this condition in a subsequent experiment.

700 effect described above.[11] More recording sites and greater scrutiny will be required to ascertain the relationships between the positivity elicited by agreement violations, Osterhout's P600, and the N400-700.

In a subsequent experiment, Osterhout used verbs which follow a gradient in the preference to take an object, as in (10)-(13).

(10) Pure intransitive: *The doctor hoped the patient was lying.*
(1l) Biased intransitive: *The doctor believed the patient was lying.*
(12) Biased transitive: *The doctor charged the patient was lying.*
(13) Pure transitive: *The doctor forced the patient was lying.*

As in the first experiment, subjects performed a sentence acceptability task. The four sentence types showed a gradient of acceptability, but fairly similar ratings for the two intransitive conditions (91 % vs. 84% vs. 66% vs. 4%, respectively). The ERPs elicited by the word *was* followed a similar gradient, showing the highest amplitude positivity in the Pure Transitive condition, intermediate amplitude positivity in the Biased Transitive condition, and little difference between the two intransitive conditions. Relative to Osterhout's previous report, this P600 began somewhat later (about 500 ms) and was larger over more posterior recording sites.

Both the scalp distribution and general appearance of the P600 in Osterhout's second experiment.[12] are similar to those of the P300 component. Since subjects were performing a sentence-acceptability task where the word was delivered the task-relevant information, the conditions fit those which typically elicit decision-related P300s. Additionally, fewer sentences were judged unacceptable (about 40%) than acceptable, so that unacceptable sentences were lower in experimental probability, a second factor known to influence P300 amplitude. However, Hagoort and colleagues (in press) have also obtained centro-parietal positivities in response to syntactic errors when subjects were only asked to read for comprehension. One could still contend that language is so over-learned that the experimenter does not have control over what a subject considers "task-relevant," and that across a subject's life history with his or her language, an error is always a low-frequency event. However, it still remains to be sorted out why some "errors" elicit parietal P3-like positivities, some frontal positivities, and others N400s. Only after we understand this variability can a viable functional characterization of the processing systems handling various aspects of sentence structure be developed. We believe this will be one of the major challenges of psycholinguistic research using ERPs in the next decade. Whatever the ultimate solution, it is clear that comparisons among experiments conducted in different laboratories will be greatly facilitated if the contribution of specific experimental tasks, and the P300s likely to be elicited by those tasks, can be adequately controlled.

[11] The absence of the normal N400-700 would manifest as a relative positivity with a frontal distribution. If the P600 and N400-700 did prove to be the presence/absence of the same ERP component, it would suggest a link between normal sentence processing and the collapse of such processing in the face of certain types of ungrammatical sentences.

[12] We have described only two of six experiments in Osterhout's dissertation. See Osterhout (1990) for a more complete discussion.

Neville and colleagues (1991) also investigated a variety of syntactic errors in sentences. One condition included phrase structure violations which can be viewed as violations of normal word order. Subjects were asked to make grammaticality judgments on sentences like (14)-(15).

(14) *The scientist criticized a proof of the theorem.*
(15) *The scientist criticized Max's of proof the theorem.*

The erroneous word *of* in (15) was associated with a number of ERP effects relative to (14), including a pronounced negativity between 300 and 500 ms over temporal regions of the left hemisphere, and a bilaterally distributed late positivity.

In another condition, the "specified subject constraint" (Chomsky, 1973; Fiengo & Higginbotham, 1981; Huang, 1982) was violated, rendering questions like (17) ungrammatical.

(16) *The scientist criticized Max's proof of the theorem.*
(17) *What did the scientist criticize Max's proof of?*

Over left anterior sites in particular, the ERP to the word *proof* in (17) showed a sustained negativity relative to the control sentence. The earliest portion of this effect (starting at word onset) is too early to reflect differential processing of the word *proof* and must instead be a remnant of differential processing of the previous word. Given the high correlation in the stimulus set between (a) a question's eventual ungrammaticality and (b) the presence of a proper name in a question, the subjects may have begun differential processing before the occurrence of the word that actually rendered the question ungrammatical. Although the negative difference recorded at *proof* did begin early, the 300-500 ms latency band showed the largest amplitude, suggesting that this portion of the effect may indeed have been elicited by the ungrammatical word.

Kluender and Kutas (in press) have also reported negativities in the 300-500 ms latency band which are most prominent over left anterior regions (LAN). However, these were recorded at a number of word positions in questions that were unequivocally grammatical. ERPs were recorded as subjects read a variety of yes/no and *wh*- questions. Comparisons made at various points in the questions suggested that words elicited an enhanced LAN whenever there was an unresolved filler-gap dependency, so that the same lexical items in different question types, or at different points within the same question, would elicit LANs of different amplitudes. The LAN seemed to reflect the presence of an unassigned filler (presumably held in working memory) regardless of whether or not the filler-gap dependency was a grammatical one. Kluender and Kutas (1993) also found that the amplitude of the LAN was modulated by lexical factors at some locations within the questions. They have hypothesized that the amplitude of this left anterior negativity indexes the use of working memory during sentence comprehension. In this scheme, the LAN is most prominent during difficult-to-process or flat-out ungrammatical questions when a working memory system becomes overburdened from trying to maintain both lexical and filler-gap information simultaneously.

The application of ERPs to the study of sentence parsing and various syntactic structures is a field in its infancy. There are other very recent studies that we have not reviewed here (Hagoort et al., in press; King & Kutas, 1992;

Roesler et al., 1992), but those we discussed have been sufficient to illustrate the diversity of ERP effects elicited by syntactic manipulations. There is clearly ERP variability associated with syntactic variability, so that investigators have something to work with, a first step in any scientific endeavor. Moreover, there is an obvious difference between N400 effects which have been associated with semantic processing, word frequency, and repetition, and many of the other effects evident in studies of syntactic processing. We believe that a clear picture of the ERP concomitants of syntactic analysis will emerge as comparisons are made across a large number of studies from different labs, conducted in different languages, given some sensitivity to the following design considerations.

1. *Stimulus repetition.* Word repetition can elicit N400 and/or late positive ERP differences depending on the frequency of the eliciting word, the type of context, and the temporal interval since the last occurrence of the word. Repetition is thus best avoided unless it is the topic of interest.
2. *Task relevance.* Information concerning the subjects' assigned task will elicit P300s whose amplitude and latency will vary with the difficulty of the judgment and the confidence level associated with the decision. Unless this is a desired factor in the design, task-related decisions should be eliminated, postponed until after the recording epoch, or made orthogonal to the linguistic variables of interest.[13]
3. *Correlations between experimental conditions and incidental aspects of the stimulus set* may induce special strategies specific to the stimulus set.
4. *Pre-stimulus baselines for comparing two ERPs.* Activity from the preceding word may spill over into the recording epoch for the current word, so that the preceding words in different conditions should be as similar as possible.
5. *Ordinal position of the critical words in a sentence.* We have seen that the ERPs to both open and closed class words vary systematically (but differently) as a function of the position of the words in sentences, suggesting that this factor should be equated if it is not of interest. The differences between immediately adjacent words are, however, small in amplitude, so that contrasting words in slightly different positions may not have great impact on the data. However, the ERPs to initial and final words in sentences differ dramatically from one another, and from the ERPs elicited by intermediate words, so that it will never be reasonable to conduct comparisons across initial, intermediate, and final words.

VII. CONCLUSIONS

This chapter has been a review of the methods and data in the domain of the electrophysiology of psycholinguistics. It is aimed at the psycholinguist who wants to better understand experimental reports in which ERPs are the primary dependent measure and/or the brave souls who may wish to use ERPs to address certain psycholinguistic questions. Almost any question is game-all

[13] For example, Roesler and colleagues used a lexical decision task in a study comparing the ERPs to syntactically correct and incorrect sentences (Roesler et al., 1992). Although this yielded P300s, there was no reason to believe that their amplitudes or latencies would vary across the experimental conditions.

that is required is a good experimental design and a knowledge of the strengths and weaknesses of the ERP methodology, While we chose to organize the chapter around the methods and measures rather than the issues, it is the desire to answer the various questions concerned with the representation and timing of language processes at both psychological and physiological levels that has yielded the data that were reviewed and will no doubt drive the researchers of tomorrow farther into the wavy frontiers of comprehension and perhaps where almost no electrophysiologist has yet dared to venture-production.

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