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Electroencephalographic Investigations of Hemispheric Specialization¹

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In this chapter, we review studies of the electrocortical manifestations of hemispheric specialization in humans – focusing on the relation between linguistic performance and hemispheric activities. In all of the reviewed studies, measures of the human electroencephalogram (EEG) or event-related potentials (ERPs) are used as dependent variables. This is an extensive revision of an earlier review which considered literature published before 1975 [DONCHIN *et al.*, 1977]. In the present review, we have paid closer attention to the correlation between linguistic function and the electrical activity of the brain. Our previous review considered in some detail methodological problems which confront investigators in this area of research. This discussion is not repeated here and interested readers should consult the earlier paper.

Measures of various aspects of human EEG have long been used in clinical neurology [COOPER *et al.*, 1974]. The scalp distribution of the EEG can be used in localizing epileptic foci [GIBBS *et al.*, 1936], tumors [WALTER, 1936], focal lesions [CASE and BUCY, 1938], and other pathologies. Such success derives from the fact that these gross pathologies may be associated with localized electrical dipoles which generate interpretable distributions of activity at the scalp [COOPER *et al.*, 1974]. The principal characteristic of such studies is that differences between activities recorded at different electrodes are used to infer intracranial events. The events of interest have

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well-defined physical properties, such that conclusions about them are usually based on sound physical principles. The papers reviewed here utilize the same logic – the scalp distribution of some EEG parameter is the source of inferences about the differential utilization of distinct cortical regions during the normal processing of information by the brain. The underlying assumption is that certain aspects of scalp-recorded activity are correlated with ‘utilization’. Unfortunately, the physical properties of a ‘utilized’ population of cells are not very well understood and the effects such activities may have on scalp recording is even more in doubt.

The electrophysiological investigation of hemispheric specialization has blossomed with the increasing interest in the study of the complementary specialization of the cerebral hemispheres. Much evidence has accrued during the last two decades, demonstrating that the two hemispheres of the brain are not functionally equivalent. A grossly oversimplified summary of these data would consider the left hemisphere, in dextrals, as supporting verbal, analytic processing, with the right hemisphere specializing in spatial holistic processing. While the association between speech and the left hemisphere has been known at least since the mid-19th century [BROCA, 1861], the more extensive knowledge obtained during the past two decades has derived primarily from research on the small population of commissurotomy patients [GAZZANIGA, 1970; SPERRY, 1974], hemispherectomized, or lesioned patients [MILNER, 1974]. Such data cannot, of course, be readily obtained. Extension of this work depends on complementary and more accessible sources of data.

There is another, perhaps more important, reason for investing effort in the study of hemispheric specialization in the intact subject. It is becoming increasingly evident [GAZZANIGA, 1974] that while the hemispheres may well be subserving specialized functions, the organism has a capacity to integrate them in the service of whichever task is undertaken. There is a danger when focusing on abnormalities that the differentiation of neural subsystems may obscure the basic fact of neural function – namely that all the subsystems are coordinated to produce the smooth, efficient course of behavior. It is necessary therefore to investigate in detail functional differences between the hemispheres in intact subjects, in whom commissural integration is possible, to provide information on the manner in which these functional differences are recruited in the service of behavioral integration. At present, the most successful approach has been through the presentation of lateralized sensory inputs [KIMURA, 1961; BRYDEN, 1965] which allow, through the standard techniques of experimental psychology, an evaluation of differential pro-

cessing [DIMOND and BEAUMONT, 1974]. Lateralization of sensory inputs, however, is not an easy task and imposes numerous restrictions on the range of paradigms in which hemispheric specialization can be studied. It is in this context that electrophysiological techniques are of potential value. If, indeed, it is possible to infer hemispheric utilization from electrophysiological parameters, then a convenient, noninvasive technique will be available to complement the data obtained from commissurotomy patients.

One promising paradigm involves the comparison of the distribution of spectral power in the alpha band at homologous hemispheric locations while subjects are engaged in tasks presumed to differentially engage the hemispheres. This interest derives from the earliest studies of the EEG by BERGER [1930] and ADRIAN and MATTHEWS [1934] which indicated an inverse relationship between alpha presence and 'mental effort'. The assumption is made that hemispheric involvement is indexed by differential suppression of alpha. The hemisphere more engaged in the task would exhibit less alpha activity than the idle hemisphere.

The same logic can be applied in studies which use ERP parameters as dependent variables. The ERP is emerging as a unique and powerful tool for probing physiological and psychological processes in humans [DONCHIN and LINDSLEY, 1969; REGAN, 1972; MCCALLUM and KNOTT, 1973, 1976; DESMEDT, 1977b]. The ERP is not a uniform entity. The data accumulated over the past decade strongly supports the contention that the series of voltage oscillations, lasting several hundred milliseconds after the eliciting event, represents a composite of largely independent components related to successive levels of processing within the nervous system [MCKAY, 1969; DONCHIN and LINDSLEY, 1969]. For example, the auditory ERP has been divided into three subsets of components with increasing latency from the eliciting events [PICTON *et al.*, 1974]. An audible click will elicit a series of 7 wavelets in the first 10 msec following the event which can be recorded from the vertex in man [JEWETT *et al.*, 1970]. Analogous components in the cat have been shown by BUCHWALD and HUANG [1975] to represent successive stages in the transmission of an auditory signal through the afferent pathways from the auditory nerve to the inferior colliculus. If the stimulus is a tone burst instead of a click, a sinusoidal component termed the frequency-following potential or FFP [MARSH and WORDEN, 1968] is elicited with approximately 6 msec latency from the stimulus. The FFP mimics the frequency of the stimulus [MOUSHEGIAN *et al.*, 1973; MARSH *et al.*, 1975]. SMITH *et al.* [1975] believe that the FFP recorded from the human scalp represents the activity of the inferior colliculus. It is notable that the FFP

can be elicited by stimuli whose frequency content lies well within that of human speech [MOUSHEGIAN *et al.*, 1973; MOUSHEGIAN, 1977].

A second group of 5 waves occur within 10–50 msec after a click. The study of these components has been hampered by their temporal proximity to reflexive muscle activity and, as yet, their origin is a matter of speculation. Nevertheless, such components have proved stable enough to be utilized for electrical response audiometry (ERA) [DAVIS, 1976; GOLDSTEIN, 1973].

The third set of components have latencies beyond 80 msec of the stimulus event. For the first 200 msec, the specific configuration of the ERP waveform appears to depend on the modality of the stimulus [GOFF *et al.*, 1969]. These components are sensitive to a wide range of psychophysical variables [MCKAY, 1969; REGAN, 1972], such as repetition rate, intensity, and frequency of the stimulus event, as well as psychological and state variables such as level of arousal and directed attention [HILLYARD and PICTON, 1974]. A number of ERP components with latencies beyond 200 msec are often recorded. These typically display the properties which characterize the endogenous components of the ERP [DONCHIN, 1975]. That is, they can be elicited in the absence of a stimulus and are largely independent of the modality of the eliciting stimulus and its specific physical features. They are, on the other hand, very sensitive to manipulations of task variables. Particularly strong data are available for a component with a latency of at least 300 msec. This component, called P300, is not modality-specific [SQUIRES, *et al.*, 1977] and is not specifically labile to physical stimulus properties [JOHNSON and DONCHIN, 1976]; indeed, this component can be generated when the eliciting event is the absence of a stimulus [SUTTON *et al.*, 1967]. This component is most sensitive to manipulations of complex psychological parameters such as task relevance and expectancy [SQUIRES *et al.*, 1976]. An additional class of endogenous components precede the event of interest. Such components as the contingent negative variation (CNV) and readiness potential (RP) appear to be related to preparation or anticipation for or about the event [WALTER *et al.*, 1964; KORNHUBER and DEECKE, 1965].

It is evident that the ERP represents progressive stages of analysis of the stimulus event. The earliest components appear to faithfully index the quality of the stimulus event and are stable over a range of psychological manipulations; hence their usefulness in ERA and neurological diagnosis [STARR and ACHOR, 1975]. With increasing latency from the event, the ERP components reflect more complex properties of the stimulus in a psychophysical and a psychological sense. Ultimately, the P300 component is independent of stimulus characteristics except in how they affect the psycho-

logical aspects of the event. For the sake of simplicity, we use the heuristic dichotomy of exogenous and endogenous components. Exogenous components are those evoked by the stimulus and thus reflect the quality and modality of the stimulus in their scalp distributions and waveshape. Endogenous components, on the other hand, are elicited by the stimulus event as it contacts information processing activities invoked by task demands and the psychological properties of the event.

Virtually all studies reviewed in this chapter have employed the same general paradigm. The independent variable is always defined in terms of tasks assigned to the subject, some presumably involving the right, others the left hemisphere. The dependent variable is always some parameter of the scalp-recorded EEG activity. The term *parameter* is used in the following sense. The primary data collected in all the reviewed studies consist of the raw EEG recorded in either analog or digital form. Any number of functions can be defined on these raw data. Such statistics as the mean power, the frequency spectrum, the cross-correlation function, or the ensemble average are all functions of the raw data. All estimate some parameter of the process which has generated the data. Thus, investigators have wide freedom in the choice of parameters. The specific choice they make is determined by their hypotheses on the nature of the EEG and EEG-behavior relations.

The studies can be conveniently classified into two categories according to the dependent variables utilized. In one category are all studies which focus on the ongoing EEG and in which, by and large, frequency domain parameters of the EEG are estimated. Such parameters are usually statements about the power or amplitude of the EEG integrated over some narrow or broad bandwidth. In the second category fall studies which analyze the EEG in the time domain. These are concerned with the waveforms of ERPs extracted from the EEG by signal averaging (one exception to this classification scheme is the coherence analysis of ERPs by DAVIS and WADA, 1974, this volume). Within these two categories, the studies are classified in terms of the independent variables used by the experimenter.

Survey of Frequency Domain Studies

Early investigators of the EEG, while noting occasional hemispheric asymmetries, stressed the similarity of EEG tracings recorded from the two hemispheres [ADRIAN and MATTHEWS, 1934]. Large differences between homologous recordings with subjects at rest or during photic driving activa-

tion procedures were considered abnormal and used to localize unilateral focal disorders [AIRD and BOWDITCH, 1946; WALTER and WALTER, 1949; AIRD and ZEALEAR, 1951; KOOI *et al.*, 1957]. Much evidence, however, has accrued in the past few decades that the alpha rhythm is rarely symmetric in amplitude or in phase [RANEY, 1939; RÉMOND *et al.*, 1969; LISKE *et al.*, 1966; HOOVEY *et al.*, 1972]. At times, these asymmetries have been related to the subject's lateral preferences. The alpha rhythm in the dominant hemisphere has been found, by some, to be of lower amplitude [RANEY, 1939; CORNIL and GASTAUT, 1947]. However, LANSING and THOMAS [1964], in a study of predominantly dextral subjects, found a suppression of alpha in the right hemisphere. Others have found no consistent correlation [PLANVILLE and ANTONITIS, 1955; LISKE *et al.*, 1966; RÉMOND *et al.*, 1969; PROVINS and CUNLIFFE, 1972; BUTLER and GLASS, 1974a]. A relationship between inter-hemispheric EEG phase and laterality preferences has also been reported [GIANNITRAPANI and DARROW, 1963; GIANNITRAPANI *et al.*, 1964, 1966; GIANNITRAPANI, 1967]. HOWEVER, the relationship appears to be quite complex and confusing, with the direction of the phase asynchrony changing with subject and state variables.

In part, this derives from difficulty in defining and validating a 'resting' state in which to take baseline EEG measures. Also, the wide variation in measurement and analysis techniques accounts for some of the confusion in the literature. Mostly the relationship between EEG laterality and subjects' lateral preferences is in fact quite complex. Interhemispheric alpha asynchrony has been reported to be more prevalent in subjects with less established lateral preferences, such as ambidextrals, or in those in whom lateral specialization may be weak, such as stutterers [TRAVIS and KNOTT, 1937; LINDSLEY, 1940]. Similar asynchronies have also been found in children with discrepant verbal motor development [LAIRY *et al.*, 1969]. Amplitude asymmetries have been reported to be larger in subjects with clearly defined hand preferences [LAIRY *et al.*, 1969; SUBIRANA, 1969]. EEG measures may, then, depend on the degree of lateral specialization in individuals rather than on its direction. That hemispheric symmetry of electrocortical parameters may index hemispheric integration gains support from the study of the photic driving response in human newborns by CROWELL *et al.* [1973, 1977] who proposed the existence of a developmental sequence of photic driving. In the earliest stage, no driving can be observed. Then unilateral (primarily right hemisphere) driving appears, followed by the bilateral driving pattern observed in adults. Such considerations must be kept in mind when evaluating the use of EEG measures to index functional asymmetry in the human brain.

A number of recent studies have claimed that interhemispheric changes in alpha and total EEG accompany the performance of functionally asymmetric tasks. Such investigations typically employ a paradigm in which a subject performs a task thought to engage primarily one hemisphere while bilateral samples of EEG are taken. Many different recording montages have been used. Occipital [MORGAN *et al.*, 1971, 1974; DUMAS and MORGAN, 1975], temporal and parietal [MCKEE *et al.*, 1973; GALIN and ORNSTEIN, 1972; DOYLE *et al.*, 1974; ROBBINS and MCADAM, 1974], and parietal and central [RUOFF *et al.*, 1976] electrode placements, referenced to the vertex (Cz) position have been used. Interhemispheric [BUTLER and GLASS, 1974a] and intrahemispheric [WARREN *et al.*, 1976] bipolar linkages have also been employed. In one study, bilateral parietal electrodes were referenced to linked mastoids [CHARTOCK *et al.*, 1975].

Some of the tasks presumed to utilize the left hemisphere differentially have included composing letters [GALIN and ORNSTEIN, 1972; DOYLE *et al.*, 1974], word search tasks [MCKEE *et al.*, 1973], mental arithmetic [MORGAN *et al.*, 1971, 1974; DUMAS and MORGAN, 1975; BUTLER and GLASS, 1974a; ROUFF *et al.*, 1976], verbal listening [MORGAN *et al.*, 1971; DUMAS and MORGAN, 1975], and verbal imagery tasks [ROBBINS and MCADAM, 1974; MORGAN *et al.*, 1971, 1974; DUMAS and MORGAN, 1975]. Right hemisphere tasks have included spatial manipulation of blocks, seashore tonal memory, and drawing [GALIN and ORNSTEIN, 1972; DOYLE *et al.*, 1974; ROUFF *et al.*, 1976], spatial imagery [MORGAN *et al.*, 1971, 1974; ROBBINS and MCADAM, 1974; DUMAS and MORGAN, 1975], music listening tests [MCKEE *et al.*, 1973; MORGAN *et al.*, 1971], and affective imagery [DAVIDSON and SCHWARTZ, 1976]. In addition, occupation (artist versus engineer) and hypnotic susceptibility have been used as independent variables [MORGAN *et al.*, 1971, 1974; DUMAS and MORGAN, 1975].

The data were analyzed in many different ways. Often, investigators integrated the raw or filtered EEG [MORGAN *et al.*, 1971; GALIN and ORNSTEIN, 1972; MCKEE *et al.*, 1973; ROBBINS and MCADAM, 1974; DUMAS and MORGAN, 1975]. Others computed amplitude histograms of the EEG [BUTLER and GLASS, 1974a] or used conventional spectral analysis techniques [DOYLE *et al.*, 1974; ROUFF *et al.*, 1976]. Still others have obtained measures of alpha duration over time [CHARTOCK *et al.*, 1975; WARREN *et al.*, 1976]. Most researchers have expressed their results in some transformation of right/left or left/right ratios for homologous electrode sites [GALIN and ORNSTEIN, 1972; MCKEE *et al.*, 1973; DOYLE *et al.*, 1974; ROBBINS and MCADAM, 1974; DAVIDSON and SCHWARTZ, 1976; ROUFF *et al.*, 1976], or as a 'laterality score'

expressing differences in power as a function of total power [MORGAN *et al.*, 1974; DUMAS and MORGAN, 1975; WARREN *et al.*, 1976]. Changes in these ratios are interpreted as evidence for differential hemispheric involvement. For example, GALIN and ORNSTEIN [1972] obtained the power of the total EEG at the right and left parietal electrodes. The right/left power ratio is 1.15 for the 'spatial' Kohs blocks task and 1.30 for the 'verbal' letter-writing task. The increase in the power in the right hemisphere relative to the left hemisphere for the letter-writing task is presumed to reflect the greater involvement of the left hemisphere in that task (recall that increased power implies increased alpha activity and by inference less hemispheric involvement). Similar results were obtained in studies of activity in the alpha band [MORGAN *et al.*, 1971, 1974; MCKEE *et al.*, 1973; DUMAS and MORGAN, 1975]. BUTLER and GLASS [1974a] found left hemisphere suppression of alpha during mental arithmetic but only in their dextral subjects; unfortunately, no right hemisphere task was used for comparison. A more sophisticated frequency analysis [DOYLE *et al.*, 1974] revealed that the main locus of task-dependent distributional changes was in the alpha band. They reported minor hemispheric differences in the beta and theta bands and no changes in the delta band.

An interesting variant of the basic paradigm reviewed above has been used by SCHWARTZ *et al.* [1976] who trained subjects to produce interhemispheric asymmetries using biofeedback techniques and assessed the cognitive strategies employed by their subjects to create them: a right greater than left asymmetry in alpha was associated with more verbal cognitions while the reverse pattern was associated with more visual cognitions. These results are reminiscent of the early reports that persistent alpha production was associated with verbal imagery and alpha suppression with visual imagery [GOLLA *et al.*, 1943].

Measures of ongoing EEG other than alpha magnitude have been used as dependent variables during the execution of functionally asymmetric tasks. One such measure is the cortical coupling index developed by CALLAWAY and HARRIS [1974] and extended by YAGI *et al.* [1976]. The technique attempts to assess the degree of correlation or 'coupling' between pairs of electrodes, assuming that changes in such measures represent the degree of intracortical functional communication. For related material, see LIVANOV *et al.* [1964]. Interhemispheric comparisons of coupling measures derived from intrahemispheric pairs showed tasks requiring verbal-propositional processing (such as reading or mentally composing a letter) were reported to increase relative left hemisphere coupling and visual-appositional tasks (listening to

music, examining pictures) to increase relative right hemisphere coupling [CALLAWAY and HARRIS, 1974; YINGLING, this volume].

Another dependent variable examined is the period of the EEG using the central-moments technique applied by SURWILLO [1975, 1976] to verbal (digit recall) and nonverbal (simple reaction time) tasks; he found no differences in central tendency, dispersion, skewness, and kurtosis in the distribution of EEG period between the left and right hemisphere (parietal-occipital derivations) during the verbal task. During the reaction time (RT) task, however, a small (0.4 Hz) but significant reduction in mean period occurred over the left hemisphere.

While these studies may indicate that there are small task-dependent changes in the EEG spectrum, the implication that selective suppression in the alpha rhythm of the dominant hemisphere for the task is the cause of the ratio changes cannot be supported on the evidence presented (unless accompanied by raw measures from each hemisphere as in ROBBINS and McADAM [1974]). It is not possible to tell if a ratio has been modified by changing the numerator, the denominator, or both when only the ratio figure has been presented. Note also that in most of these studies the experimentally induced differences are superimposed upon a constant right/left hemisphere asymmetry and do not represent shifts from a symmetric baseline. Equal increments or decrements to both the numerator and denominator of an asymmetric ratio is manifested as a change in the ratio. This point is especially important as the amount of power present may relate to the load imposed on the subject by each task.

This last point is illustrated by data collected in our laboratory. Spectral power measures were taken from subjects engaged in a visual matching task [McCARTHY and DONCHIN, 1976; an earlier version of this study based on five different subjects was reported by DONCHIN *et al.*, 1977]. Visual stimuli, consisting of three line drawings each, were presented for short durations (50 msec) to ten subjects (all dextral without sinistral relatives). Two of the figures looked alike (structurally matched), while two of the figures were conceptually related (functionally matched). One figure was common to both pairs. The subjects were instructed to match figures on the basis of structure or function. On different experimental trials, one or the other match was required depending on the instructions. The subjects reported which of the three figures matched by pressing a single button coded for their positions (three possible responses for each slide). The reaction time as well as the accuracy of the response was measured. A tone preceded each slide by 1,000 msec. In 'fixed matching' conditions, this tone was always of one fre-

quency and served only to warn of the slide's arrival – the subject making the same class of matches (structural or functional) for every trial. In 'mixed matching', the tone frequency randomly varied between two possibilities; each cued a different match type. During mixed mode, the subject did not know which of the two match types would be required for each individual trial until he heard the warning tone. Additional trials in which the subjects were required to respond rapidly to a neutral slide stimulus (RT control) and also trials in which no stimuli were presented at all (rest control) were used.

The performance data clearly indicated that structural and functional matching differed in difficulty regardless of the mode of presentation. Structural matching was completed more rapidly and with fewer errors than functional matching (950 versus 1,469 msec for mean RT, 93 versus 75% accuracy for structural and functional matching, respectively). The EEG spectra were measured over an epoch lasting 2,200 msec, beginning at the warning tone and lasting until 1,200 msec following the slide. Power measures were obtained for six lateral electrode sites (F3, F4, C3, C4, P3, P4) referenced to linked mastoids. In figure 1, the power in the alpha band is shown for structural and functional matching as well as for the RT and rest control conditions. The measures for structural and functional matching are pooled over fixed and mixed mode as the mode of presentation had no effect on the data.

Match type, however, had significant effects on the absolute levels of alpha. Less alpha was associated with functional than with structural matching. In addition, both control conditions were associated with more alpha than either matching task. No task dependent lateralities in alpha power were observed, implying that task difficulty was the significant factor for these data.

The generality of this interpretation might be questioned as the design of our experiment differs from others reviewed here and because the epoch analyzed for power changes included a 1,000-msec preparatory interval. However, our interpretation is strengthened by the data of CHARTOCK *et al.*, [1975] who examined alpha power at P3 and P4 (referenced to linked mastoids) for verbal and visuospatial paired-associates tasks. These investigators found no task specific lateral differences in alpha power although, as in our study, the total alpha power present varied with some behavioral performance measure; in this case, the rate of learning for the tasks.

These data argue strongly that measures of performance should be obtained to evaluate and quantify the load the tasks impose upon the sub-

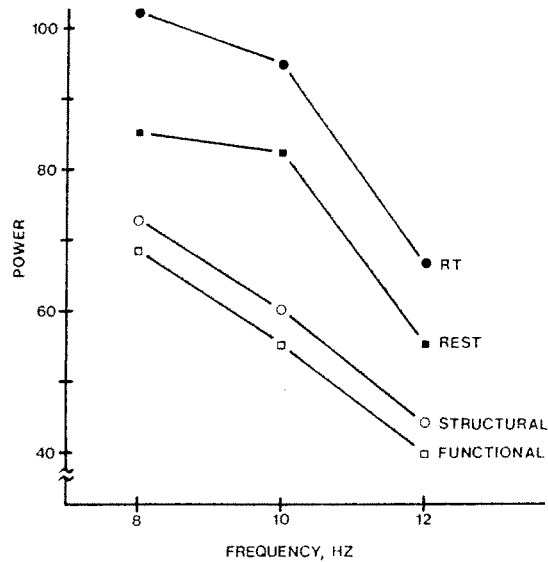


Fig. 1. Spectral power (in arbitrary units) is plotted for the alpha band for each experimental task. The values for structural and functional match conditions have been pooled over fixed and mixed presentation mode as the mode had no significant effect on alpha magnitude. The main effect of match type is significant ($p < 0.05$) at each frequency plotted.

jects. As these effects may be present, ratio measures are not valid dependent variables for evaluating hemispheric shifts in alpha power. It is interesting to note that both MCCARTHY and DONCHIN [1976] and CHARTOCK *et al.* [1975] used a reference not on the scalp for recording the EEG. It is regrettable that in most of the studies presented in this section, the vertex electrode was used as the reference. Such a choice of reference clearly confounds alpha amplitude with interhemispheric phase relationships.

Survey of Time Domain Studies

In this section, we report on studies of ERPs extracted by signal averaging from the ongoing EEG. Many of the studies compared ERPs recorded at homologous hemispheric sites although some investigated only the vertex or midline positions, in order to find out whether task variables determine the relative amplitude and latency of the ERP components at the hemi-

spheres. These differences were sometimes evaluated in terms of subjects' handedness and cerebral dominance.

1. Studies of Exogenous Components

Very few of the studies reviewed in this section were motivated by an interest in the linguistic-nonlinguistic distinction or in hemispheric specialization. Rather, the investigators were seeking information on the scalp distribution of sensory evoked potentials. Their goal has usually been the elucidation of the intracranial sources of these exogenous components. Yet often the data were collected from homologous hemispheric sites. These provide valuable baseline data on hemispheric asymmetries. Clearly, if ERPs associated with a given modality are asymmetric in the absence of any task inducement for lateralization, such biases must be considered when testing hypotheses about hemispheric specialization and the effect of linguistic or semantic analyses. The results on hand, however, are equivocal. It would be difficult to develop, on the basis of the available literature, a specification of the lateralization biases for different stimulus modalities.

The data are rather scant for the somatosensory ERPs, although it is agreed that they are largest at the scalp electrodes overlying the parietal cortex contralateral to the stimulation [GOFF *et al.*, 1962; DESMEDT, 1971; CALMES and CRACCO, 1971; DESMEDT *et al.*, 1976, 1977]. For the auditory modality, considerable controversy exists regarding the lateral distribution of the various components of auditory ERPs. The maximal contralateral projection to the auditory cortex as well as the oft observed dominance of one ear over the other in dichotic listening tasks suggest that, at least under certain conditions, different auditory ERPs should be recorded over the two hemispheres. Most investigators concur that right and left ear stimulation generate different scalp distributions, but there is no agreement on the specifics of these distributions. The majority of reports maintain that there is a general predominance of the contralateral response, either as a shorter latency [MAJKOWSKI *et al.*, 1971] or as larger amplitude response [PRICE *et al.*, 1966; VAUGHAN and RITTER, 1970; RUHM, 1971; PERONNET *et al.*, 1974; ANDREASSI *et al.*, 1975a], and a few in both of these measures of contralateral response [BUTLER *et al.*, 1969]. VAUGHAN and RITTER [1970] reported a small but consistent tendency for larger responses to appear contralateral to the stimulated ear, but the effect was greater over the left hemisphere in response to right ear stimulation. Other researchers [RUHM, 1971; PERONNET *et al.*, 1974] reported that the right hemisphere response is consistently larger only for left ear stimulation. PETERS and MENDEL [1974] failed to find such a con-

sistent relationship between the ear stimulated and the latency and amplitude of ERP components with latency shorter than 70 msec. Given these contradictions, there seems to be little basis yet in trying to relate the lateral asymmetry of auditory ERPs to handedness, cerebral dominance or ear preference.

Similar inconsistencies appear in studies of the laterality of visual ERPs. Studies of hemispheric differences in visual ERPs have been particularly hampered by the need to assure that the ERP elicited by stimulation of a retinal half field is generated entirely within a single hemisphere. To direct stimuli at a lateral hemi-retina, the subject's fixation must be known. It is, of course, possible to instruct subjects to fixate, but it is quite difficult to be sure that they do so. The electrooculogram (EOG) can be used as a check but, without DC recording, it does not assure that the subject is in fact fixating such a point. Behavioral techniques for monitoring fixation are available. KRYNICKI [1976] provides a fine example. Whereas it has been well established that stimulation of different visual half fields elicits different scalp distribution [MCKAY, 1969; REGAN, 1972; DESMEDT, 1977a], the comparison of the hemispheric distributions of visual ERPs is not as straightforward. Several investigators [KOOI *et al.*, 1965; VAUGHAN *et al.*, 1963; HARMONY *et al.*, 1973] have reported that visual ERPs recorded over homologous regions in normal subjects are symmetric. Others, however, have maintained that visual ERPs recorded from the right hemisphere are larger than those recorded from the left hemisphere [PERRY and CHILDERS, 1969; RHODES *et al.*, 1969; SCHENKENBERG and DUSTMAN, 1970; RICHLIN *et al.*, 1971, 1976; VELLA *et al.*, 1972; RHODES *et al.*, 1975]. BECK *et al.* [1975] report that the increased amplitude of the response of the right hemisphere following blank flashes is absent (or much reduced) in sinistrals, mongoloids, and children with low IQs. This may allow for the use of the asymmetry in the visual ERP as a metric for neurological organization and development. Latency asymmetries in the ERP have also been observed. ANDREASSI *et al.* [1975b], for example, reported observing latency asymmetries in ERP components as a function of retinal site of stimulation.

The few investigations [EASON *et al.*, 1967; CULVER *et al.*, 1970; GOTT and BOYARSKY, 1972; BECK *et al.*, 1975] concerned with the relations between handedness, cerebral dominance, eye dominance, and visual ERPs have yielded ambiguous results. EASON *et al.* [1967] originally reported that visual ERPs were larger over the right than the left hemisphere for left-handers only. However, a subsequent report from the same laboratory [CULVER *et al.*, 1970] failed to confirm this finding. Rather, CULVER *et al.* reported visual ERP amplitudes were larger over the right than the left

occipital lobe in response to left but not right visual field stimulation. This failure to replicate previous results is attributed by CULVER to confounding sex with handedness. GOTT and BOYARSKY [1972] reported that left-handers produced larger visual ERPs in the left hemisphere and that direct stimulation of the dominant hemisphere elicited ERPs with shorter latency than that elicited by stimulation of the opposite hemisphere.

2. Studies of Endogenous Components

a) *Asymmetries in movement-related potentials.* Little is known about the manner in which the left hemisphere is involved in linguistic function. There is, however, an aspect of brain function which is not only patently lateralized but for which the nature of lateralization is fairly well understood. This is the control of motor function. It is well known that the movements of the left side are 'controlled' from the right hemisphere and vice versa. Clearly, if hemispheric utilization has electrocortical manifestations, these should appear in association with motor function. The degree of lateral asymmetry in this context can serve as a measure of the base level of laterality. It is therefore of interest that the most consistent observations of functionally interpretable lateralization have been obtained for slow potentials which are apparently associated with the control or the monitoring of movement.

There is now a consensus that the slow negative shift preceding voluntary arm and hand movements, variously called the RP, Bereitschaftspotential (BSP), or N1 of the motor potential (MP), is a few microvolts larger over the pre-Rolandic area on the scalp contralateral to the responding limb [GILDEN *et al.*, 1966; VAUGHAN *et al.*, 1968; KUTAS and DONCHIN, 1974]. KORNHUBER and DEECKE [1965]. DEECKE *et al.* [1969, 1976], and DEECKE and KORNHUBER [1977] maintain that this contralateral dominance is restricted to the abrupt negativity just preceding the movement, but KUTAS and DONCHIN [1977] demonstrated that the hemispheric asymmetry can be observed hundreds of milliseconds prior to the response. The exact timing of the components of the MP immediately preceding the movement is, however, controversial. GERBRANDT *et al.* [1973] claimed this negativity to be post-movement while VAUGHAN *et al.* [1968] found that the MP has a somatotopic distribution and view the potentials as clearly pre-movement. Two reports [GERBRANDT *et al.*, 1973; WILKE and LANSING, 1973] reject the notion that these pre-movement potentials are associated with a motor command, and claim that these potentials are manifestations of the activity of post-response proprioceptive mechanisms. However this issue is resolved there is no question that N1 precedes the movement. Thus, our demonstration that the N1 com-

ponent of the MP is larger contralateral to the responding hand is a clear illustration of the manner in which EEG scalp distributions reflect hemispheric utilization [KUTAS and DONCHIN, 1974, 1977].

These observations have recently been extended in a detailed examination by KUTAS [in preparation] of the lateral asymmetry of response-related potentials under different response conditions. In figure 2 are shown some of the results. Each pair of traces is the difference between C3' and C4' recorded when the subject responded with his right (solid line) or his left hand (dashed line) in one of the five experimental conditions described in the legend to figure 2. Increasing amplitude of these difference curves is a measure of hemispheric asymmetry, while the degree to which the curves in a pair are out of phase reflects the extent to which the direction of asymmetry depends upon the responding hand. Under all response regimes, a degree of response-related asymmetry is clearly evident, its initiation seemingly dependent upon the time at which the response selection becomes definite. The implication of these data to the study of electrocortical manifestations of linguistic function is that when clear differences in hemispheric utilization exist, they are measurable. Possibly, the relation between processing mode and the hemispheres is somewhat less definite than that between the hemispheres and motor activities.

The absolute amplitude of the MPs depends on a number of variables such as force [WILKE and LANSING, 1973; KUTAS and DONCHIN, 1974, 1977] and motivation [MCADAM and SEALES, 1969]. The relevant parameters affecting the degree of NI asymmetry, other than subject handedness and responding hand, have yet to be determined. A promising source of data is intracerebral recording from human patients [MCCALLUM and PAPA-KOSTOPOULOS, 1974]. These preliminary data suggest that subtle changes in timing and asymmetry of the RP are obscured in scalp recordings.

Many investigators have noted the similarity of the CNV and N1. The suggestion that these two waveforms might represent identical processes is derived partly from the fact that most CNV studies have required a motor response to the imperative stimulus. Early mapping studies [LOW *et al.*, 1966; COHEN, 1969] demonstrated that the CNV preceding a motor response in an RT paradigm was symmetrically distributed over the two hemispheres. Within the past few years, it has been asserted that slightly larger CNVs appear over the hemisphere contralateral to the hand used for the response [SYNDULKO, 1969, 1972; OTTO and LEIFER, 1973]. SYNDULKO [1972] and SYNDULKO and LINDSLEY [1977] found that response-related lateral asymmetry was specific to central as opposed to frontal, parietal or occipital

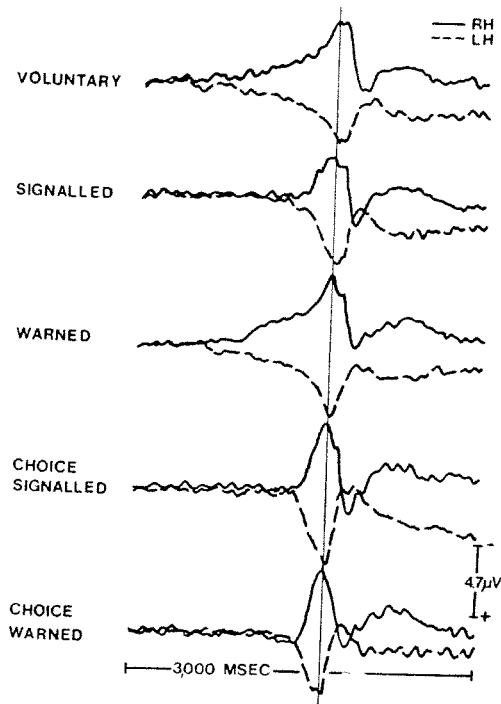


Fig. 2. Each curve represents the difference between the ERPs recorded at C3' and C4' calculated for each subject and averaged over the subjects for the five experimental conditions: (1) voluntary – subjects made self-paced movements; (2) signalled – subjects squeezed a dynamometer in response to a randomly occurring tone; (3) warned – subjects responded to the second of two tones 1,000 msec apart; (4) choice signalled – subjects made a right or left hand response cued by the frequency of an irregularly occurring tone; (5) choice warned – subjects responded to the second of two tones with the right or left hand depending upon the frequency of the second tone. All waveforms shown in this figure were obtained by point-to-point subtraction of the ERPs recorded at the left central electrode (C3', 4 cm lateral to midline) from the ERPs recorded at the right central electrode (C4', 4 cm lateral to midline). The response-locked averages obtained when subjects were squeezing a dynamometer with the right (solid line) and left hands (dashed line) are superimposed for each of the five experimental conditions. Each waveform (over 10 SS) represents an average of approximately 800–1,000 trials. The vertical line separates pre- from post-squeeze activity.

locations and developed only preceding unimanual response preparation. OTTO and LEIFER [1973], on the other hand, noted that CNV laterality was statistically significant only when the data were pooled across their 'response' and 'feedback' conditions. In both cases, only stimulus-locked activity was examined. It has been well established that CNVs can be generated in the absence of a motor response [COHEN and WALTER, 1966; LOW *et al.*, 1966; DONCHIN *et al.*, 1972, 1973] and must therefore represent more than mere motor preparation. The weak laterality of the slow negative wave in response-oriented CNV paradigms suggests that the negativity is multiply determined. It is conceivable that both a response-related lateralized negativity and a 'cognitive' bilateral negativity are generated in the classical CNV paradigms. Such a two-component hypothesis has been suggested [HILLYARD, 1973; GAZZANIGA and HILLYARD, 1973] and observed in a number of studies using long interstimulus intervals (ISIs) [WEERTS and LANG, 1973; LOVELESS and SANFORD, 1974, 1975; ROHRBAUGH *et al.*, 1976]. Recent work in our laboratory demonstrates that with the use of proper distributional techniques, long ISIs are unnecessary for dissociation of the different CNV components [McCARTHY and DONCHIN, 1976].

Figure 3 presents data obtained in the study of functional versus structural matching described previously. We superimpose ERPs (averaged over all subjects) at each of three electrode sites (Fz, Cz, Pz) for each of the experimental conditions. Thus, there are data for structural and functional matches in fixed and mixed modes, as well as for the simple reaction time condition. It will be noted that the potentials recorded immediately after the tone have a different scalp distribution than those just preceding the slide. As we reported previously [DONCHIN *et al.*, 1977], there is a clear dissociation between these two subepochs even with a warning period as short as 1,000 msec. Moreover, a principal components analysis of these data revealed the existence of two components within the epoch; one affected mostly by the presentation mode, the other largely by the match type. A more detailed description of these data will be presented by McCARTHY and DONCHIN [in preparation].

Another consideration which is often ignored in evaluation of ERP data is that when the experimental task induces much variability in the subject's reaction time, there may be a substantial difference between response-locked and stimulus-locked averages. In fact, preliminary results in our laboratory suggest that a lateralization evident in response-locked averages is obscured in stimulus-locked averages, especially in subjects with slow and highly variable reaction times.

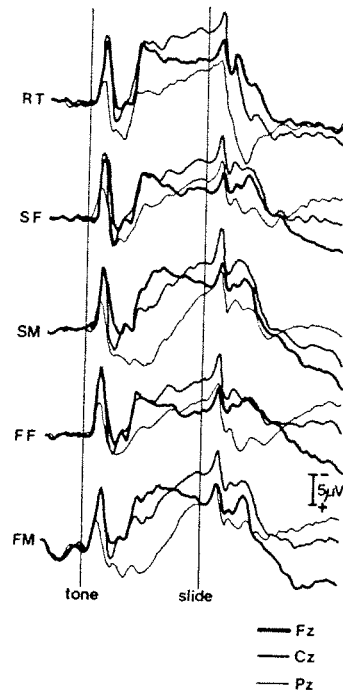


Fig. 3. ERP waveforms averaged over subjects are displayed for the RT control condition (RT), structural fixed mode (SF), structural mixed mode (SM), functional fixed mode (FF), and functional mixed mode (FM) matching conditions. Waveforms from Fz (thick line), Cz (medium line), and Pz (thin line) are overlapped. The tone preceded the slide by 1,000 msec.

Figure 4 presents individual subjects' average ERP waveforms recorded at C3' and C4' during a simple warned reaction in which the subject squeezed a dynamometer with the right hand. A comparison of the response-locked (middle column) and stimulus-locked averages (right column) reveals that the similarity between the two waveforms depends on the variability in reaction time. Response-related laterality is visible in stimulus-locked CNVs associated with low RT variability. No such laterality is observed in the stimulus-locked CNVs associated with high RT variability. The laterality is evident in response-locked averages of the same data. In another study [DONCHIN *et al.*, 1974, 1977], we have been able to elicit in rapid succession a lateralized MP and a bilateral symmetric anticipatory potential.

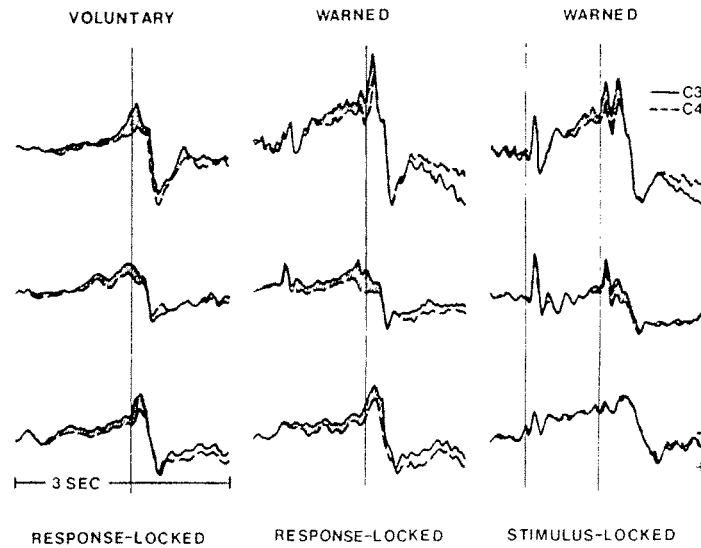


Fig. 4. A comparison of event-related potentials recorded at electrodes placed at left central (C3, solid line) and right central (C4, dashed line) loci during two experimental conditions. The ERPs in columns 1 and 2 are response-locked averages obtained when subjects were squeezing a dynamometer with the right hand in a self-paced and warned situation, respectively. The vertical line represents the onset of dynamometer movement. The ERPs in the third column are stimulus-locked versions of the data shown in column 2. The two vertical lines delineate the 1,000-msec warning interval. The mean reaction times for the three SS in the warned condition from top to bottom are: 206 (SD = 42); 336 (SD = 119), and 350 (SD = 130).

b) ERP distributions and asymmetries associated with cognitive functions.

Very few studies have been designed specifically to seek ERP concomitants of lateralized perceptual or cognitive functioning with the use of such endogenous components as P300 and CNV. It has been claimed that the lateral distribution of the CNV changes with task demands, but there is no consensus as to whether the engaged hemisphere has the larger or smaller CNV. MARSH and THOMPSON [1973] observed a symmetric CNV during preparation for a visuospatial discrimination, presumably a right hemisphere task. When this nonverbal task was randomly interspersed among verbal stimuli and required a pointing, rather than a verbal response, the hemisphere primary for that task had the smaller amplitude CNV. In contrast, BUTLER and

GLASS [1974b] found a larger CNV over the 'dominant' hemisphere during a warning interval in which subjects awaited numerical information. The CNV asymmetries took the form of an earlier onset and greater amplitude potential over the hemisphere contralateral to the preferred hand. Unfortunately, they only had one left-hander against which to compare the data of their right-handed subjects. Large asymmetric CNVs were also generated in the 'control' condition. Care must always be exercised in the choice of stimulus modalities and response requirements in designing these studies as CNVs in different paradigms may have different anterior-posterior scalp distributions [WEINBERG and PAKOSTOPOLOS, 1975]; a central dominant CNV preceding tasks requiring motor readiness [JARVILEHTO and FRUHSTORFER, 1970; SYNDULKO, 1972; POON *et al.*, 1974], a frontal dominant CNV accompanying auditory discrimination [JARVILEHTO and FRUHSTORFER, 1972; SYNDULKO, 1972], and a parietal dominant CNV accompanying similar visual tasks [SYNDULKO, 1972; COHEN, 1973]. No definite conclusions can be drawn at this time as to how CNV distribution is related to cerebral dominance.

In summary, a start has been made toward utilizing ERP methods to investigate differences between the hemispheres, but progress has been slow and somewhat hampered by inadequate experimental design and analysis procedures.

c) ERPs in language reception: visual modality. Results based on multiple electrode recordings have led to the claim that asymmetric cerebral functions underlying evaluation of visual stimuli and processes related to linguistic analysis are reflected in the ERP. BUCHSBAUM and FEDIO [1969] presented different visual stimuli (words, dots or designs) in a random sequence. They reported that ERPs elicited by words can be differentiated from ERPs elicited by nonlinguistic patterned stimuli. They also claimed that verbal and nonverbal stimuli presented foveally elicit waveforms which are more differentiable when recorded at the left than at the right hemisphere. They reported similar results in a study investigating interhemispheric differences in ERPs related to the perception of verbal and nonverbal stimuli flashed to the left or right visual fields [BUCHSBAUM and FEDIO, 1970].

MARSH and THOMPSON [1973] investigated the possibility that verbal sets would lead to differential right and left hemisphere amplitudes of slow negative shifts by asking subjects to verbally identify their stimuli. During the anticipation of flashed words, symmetric CNVs were generated at the 'midtemporal' and 'angular gyrus' placements. Preliminary data obtained when the two experimental conditions (verbal and nonverbal) were inter-

mixed yielded asymmetries in the temporal and parietal sites. Other studies dealing with visually presented words have noted a striking lack of hemispheric asymmetry. SHELBURNE [1972, 1973] recorded visual evoked potentials to three individually flashed letters which comprised either a real or a nonsense word. A comparison of the responses elicited by these two different linguistic stimuli revealed no consistent differences between the visual ERPs to the words and to the nonsense syllables in either the left or right, parietal or occipital leads. SHELBURNE's study is designed quite differently from the other studies reviewed in this section. SHELBURNE utilized a paradigm in which the last of a triplet of letters presented to a subject delivered task relevant information. This is typical of paradigms in which P300 is elicited and the waveforms published by SHELBURNE are indeed characterized by a P300 component. What distinguishes SHELBURNE's data from other P300 experiments is that the task in which P300 is elicited can be performed only by linguistically competent subjects. Thus, the extent to which the P300 is elicited can serve as an index of linguistic competence, even if no laterality is observed. In a similar paradigm, in which subjects were asked to report the key word in a visually presented sentence, no asymmetries in any of the components of the ERPs associated with words could be seen [FRIEDMAN *et al.*, 1975, this volume].

An interesting study has been conducted by KRYNICKI [1976]. What singles out KRYNICKI's study is that he preceded his electrophysiological investigation with a detailed behavioral analysis of his tasks in intact persons. Subjects were presented with 16-sided randomly shaped polygons. After each presentation, the subject had to identify the polygon by pointing to one of several in a response panel. The stimulus polygons were presented to either half of the visual field; extraordinary care was taken to assure that the subjects fixated properly. The hemispheres were shown to be differentially engaged by one aspect of the task, namely the orientation of the polygons displayed on the response panel. When the stimulus and the response figure were of the same orientation, stimulating the left hemisphere led to improved task performance; the right hemisphere was superior when the response figures were rotated. Thus, when the subject was required to perform a mental rotation of the stimulus figure to match it with a response figure, the task was performed better when the figure was presented to the left half field. KRYNICKI provides ample behavioral data in support of this assertion. The corresponding electrophysiological data are striking. The ERP elicited by the stimulus figure in the preferred hemisphere was large and elaborate. Several distinct components were clearly apparent in the right or left hemi-

sphere ERP, depending on the subject's task. The ERPs recorded simultaneously from the other hemisphere were dramatically different in that they were characterized by a large slow component. In fact, no other study, even those making the strongest claims for electrophysiological lateralization, has reported differences of this magnitude.

An altogether different approach has been taken by CHAPMAN *et al.* [this volume] who attempt to relate aspects of processing to the waveform of the ERP. CHAPMAN's independent variable, rather than assaying a linguistic-nonlinguistic dimension, focuses on variations presumed to be inherent to language; specifically on OSGOOD's demonstration that the affective meaning of words can be described within a three-dimensional coordinate system [OSGOOD *et al.*, 1957]. CHAPMAN reports that ERPs elicited by words with extreme locations in OSGOOD's space are different than the ERPs elicited by words located in the other extreme. These intriguing results should be cautiously interpreted. The differences that CHAPMAN observed were minute (less than $1 \mu\text{V}$); careful replication and further controls in other laboratories are clearly necessary. It is worth mentioning a potential source of experimental control that is neglected. We refer to the multiplicity of languages. It would be useful to know, for example, the electrophysiological response of bilingual speakers to CHAPMAN's word stimuli, when presented in their native and second languages. If CHAPMAN is right, there ought to be no difference between the ERPs elicited by words from the same locus in OSGOOD's space no matter in which language they were presented. Also, presenting words in a language foreign to a subject and comparing his response to that of native speakers should reveal if it is the affective meaning or the physical features of the stimuli which determines the response.

d) ERPs in language reception: auditory modality. Although no lateralized component specific to either linguistic or non-linguistic stimuli has been identified reliably, it has been amply demonstrated that such stimuli yield ERPs with distinct features when presented visually. On the other hand, investigators have been unable to differentiate consistently between ERP waveforms to aurally presented linguistic and non-linguistic stimuli. Vertex ERPs time-locked to the first syllable of sentences which had to be identified in the presence of interfering messages and under conditions of distortion were found to be very similar to tone ERPs [FELDMAN and GOLDSTEIN, 1967]. Furthermore, while the ERP waveforms in this task varied as a function of signal level, they were not influenced by sentence intelligibility. ROTH *et al.* [1970] could easily classify the responses to the beginnings of sentences as a

function of task, whether sentences were attended to or ignored, but could not distinguish between the ERPs to the different syllables in the sentences. They were also unable to discriminate ERPs to real words from those to nonsense syllables. The presentation of stimuli, however, in a story form with nonsense syllables interspersed required linguistic analysis of each of the monosyllables independent of semantic value. RATLIFF and GREENBERG [1972] – employing various tones, words, and noise envelopes – obtained differences in the latency and polarity of the ERP components between linguistic and non-linguistic stimuli, being longer for nonlinguistic than linguistic stimuli. GREENBERG and METTING [1974] further noted that while normal subjects display different ERPs to speech and non-speech stimuli, aphasics generate abnormal and inconsistent responses to all stimuli.

Although still contradictory and inconsistent, more promising results relating ERP lateralization to linguistic or semantic processing have been obtained with auditory stimuli [GREENBERG and GRAHAM, 1970; COHN, 1971; MORRELL and SALAMY, 1971; WOOD *et al.*, 1971; MATSUMIYA *et al.*, 1972; TEYLER *et al.*, 1973; BROWN *et al.*, 1973, 1976; HAALAND, 1974; NEVILLE, 1974; MOLFESE *et al.*, 1975; WOOD, 1975]. A number of studies in which various combinations of phonemes, words, and sentences were used to elicit ERPs have supported the view that linguistic analysis occurs primarily in the left hemisphere while processing of nonverbal stimuli, such as musical chords, takes place in the right hemisphere [TAUB *et al.*, 1976]. GREENBERG and GRAHAM [1970] investigated the EEG correlates of verbal learning through an analysis of spectral components of AEPs to various consonant-vowel-consonant combinations (CVC) and piano notes. They found a left hemisphere dominance of the activity in all frequencies during speech learning and a trend toward a shift from left to right hemisphere dominance in the frequency components considered to reflect overall ERP amplitude for the notes. TAUB *et al.* [1976] in fact demonstrated that the averaged response evoked by monaurally presented nonverbal sounds, such as major, minor, and diminished musical chords, are larger over the right than over the left auditory cortex. In a brief report, COHN [1971] tells of a prominent, positive-going peak with a 14-msec latency elicited in the right hemisphere by click stimuli but not by single syllable words. MORRELL and SALAMY [1971] found that the N100 component elicited by nonsense words was larger over the left than right temporoparietal electrode. It is difficult to interpret their results as they failed to use a non-language control. MATSUMIYA *et al.* [1972] reported a hemispheric asymmetry in a 'W-wave' (a positive

response recorded bipolarly, peaking at 100 msec) elicited by real words and environmental sounds. They ascribed this hemispheric asymmetry to the significance of the auditory stimuli for the subject rather than to the linguistic features of the stimulus. WOOD *et al.* [1971] reported differences in the ERPs recorded over the left hemisphere which appeared in the N100-P200 component, depending on whether the subject was required to perform a linguistic or an acoustic analysis of the stimulus. These results were essentially replicated by WOOD [1975, this volume] in experiments comparing the processing of two different dimensions (auditory and phonetic) of the same CV syllables. Distinct ERPs were obtained to stimuli along phonetic and auditory dimensions but not to two stimuli along the auditory dimension or different acoustic components of the phonetic dimension. MOLFESE *et al.* [1975] found a similar enhancement in the amplitude of the N100-P200 component of the ERP in the left relative to the right hemisphere for speech stimuli even when the subjects' task was merely to listen. On the other hand, nonspeech acoustic stimuli were found to produce larger amplitude responses in the right hemisphere. The lateral differences to both types of stimuli decreased with age from infants to adults [MOLFESE, this volume]. GALAMBOS *et al.* [1975] failed to find hemispheric differences in the P300 component elicited by target stimuli although they did note that the P300 to speech stimuli were of longer latency than those to clicks. NEVILLE [1974] reported lateral ERP amplitude and latency differences elicited by digits but not by clicks in a dichotic listening paradigm. During a comparison of the effects of different forms of verbal input (monaural, dichotic and diotic) on inter- and intrahemispheric ERP distributions, HAALAND [1974] found that the P(160-306) component was greater over the right than the left hemisphere in all presentation modes.

Several investigators have attempted to evaluate the influence of linguistic meaning on scalp ERPs. TEYLER *et al.* [1973, this volume] recorded different ERPs from the same electrode site to the same click stimulus depending on the meaning of the verbal context (noun-verb) to which the stimulus was temporally related. Linguistic stimuli elicited responses of greater magnitude in the dominant hemisphere. In a similar study, BROWN *et al.* [1973] recorded ERPs to the actual words rather than to coincidental clicks. The words they used were ambiguous and were disambiguated by their context. They reported (1) that the waveform of the ERPs evoked by the same word differed according to its contextual meaning, and (2) that these differences were significantly greater for left than right hemisphere loci. Similar results were obtained by BROWN *et al.* [1976] in a study

using the stimulus homophone 'led' or 'lead' in the ambiguous phrase 'it was /led/'. The ERPs elicited by the homophone differed as a function of the subjects' set to perceive a particular meaning of the phrase only in the left hemisphere, primarily over Broca's area. It seems, then, in general, that different investigators find in a variety of ERP parameters greater variability over the left than the right hemisphere.

Two strategies are available for revealing the effects of hemispheric specialization on ERP components. Both strategies challenge the subjects with tasks presumed to engage selectively one of the hemispheres. One, however, investigates the ERPs elicited by stimuli integral to the challenging task. This has been the strategy adopted by the studies reviewed above. An alternate strategy would probe the subject with stimuli unrelated to the task. If the hemispheres are differentially engaged, the response evoked by such probe stimuli may well be different. The more direct strategy adopted by most investigators is somewhat weak because the choice of differential tasks is dictated by the requirement that they provide distinct stimuli for eliciting ERPs. The probe strategy permits the choice of tasks which are continuous in time and with a potential for substantially loading the hemispheres. The ERP to the probes during task performance could be compared to the response to the same probes in the absence of a task.

This approach has been used rather infrequently. A report by GALIN and ELLIS [1975] indicated that the symmetry of the visual ERP is influenced by the spectral characteristics of the EEG at the time of stimulus presentation. They found that ERPs elicited during tasks which induced hemispheric asymmetries in alpha power were also asymmetric as determined by measures of peak-to-trough amplitude and power. A sophisticated application of the probe strategy has been reported by SHUCARD *et al.* [1976], who demonstrated that lateralization of brain functioning can be indexed by task-irrelevant tone pairs which were presented while subjects were either detecting a melody in a Bach fugue or listening for a phrase in a spoken passage. They report that the probe ERPs were of higher amplitude in the hemisphere hypothesized to be most engaged by the primary task (the right for musical task and left for verbal task). The effect was most pronounced for the second of the paired tones. Unfortunately, as SHUCARD *et al.* [1976] recorded T4-Cz and T3-Cz, it is difficult to determine if their results are due to shifts in hemispheric balance or in the intrahemispheric distribution of the potentials. Such results are provocative and suggest that baseline symmetry in ERPs may depend upon variability in ongoing EEG activity which may, in turn, depend upon subject state variables.

e) Slow potentials preceding speech production. Although some questions were raised as to the replicability and exact nature of the reported ERP differences associated with speech perception, no doubts were cast as to the cerebral origin of these potentials. In contrast, the interpretation of scalp-recorded activity associated with speech production present difficulties in differentiating between cerebral potentials and interfering neuromuscular and respiratory artifacts. This possible confound has led to controversy concerning the origin, topographical distribution and hemispheric asymmetry of these potentials and their relationship to cerebral dominance.

A number of bioelectric sources of artifact such as eye movements, GSR, head movements, muscle tension, respiratory waves, and lip and tongue movements can influence asymmetrically speech-related electrical potentials [KLASS and BICKFORD, 1960; MORRELL and HUNTINGTON, 1971, 1972; GRABOW and ELLIOTT, 1973, 1974; GRÖZINGER *et al.*, 1973, 1975, this volume]. KLASS and BICKFORD [1960] were the first to note that movements of the tongue, the tip of which is negatively charged in relation to the body, gave rise to 1–6/sec rhythmic waves in the EEG of 5% of their patient and subject samples during speaking and reading aloud. The prominence of this artifact, labelled the glossokinetic potential, appeared to be a function of ‘... (1) the degree of tongue movement with speech; (2) the cranial topography of the tongue relative to the scalp, and (3) the electrical charge on the tongue...’. Since then GRABOW and ELLIOTT [1973, 1974] found that hemispheric asymmetries in the EEG could be produced by directing the tongue toward either the right or left side of the mouth. GRÖZINGER *et al.* [1973, 1975] further noted that articulation and speech can be preceded by slow periodic brain potentials (R waves) correlated with respiration which also seem to have a lateralized distribution, the more active hemisphere showing slightly smaller potentials [GRÖZINGER *et al.*, this volume].

Few studies, however, have acknowledged the possible presence of artifacts from lateral eye movements (not blinks) which themselves have been accepted as reflective of functional hemispheric asymmetry. Shifts to the right have been associated with left hemisphere processing while shifts to the left are taken as indicators of right hemisphere engagement [KINSBOURNE, 1973, 1974; GUR *et al.*, 1975].

Investigating cortical activity time-locked to speech onset, SCHAFFER and ERTL [SCHAFFER, 1967; ERTL and SCHAFFER, 1967] maintained that reliable potential changes free of muscle and movement artifact occur over the right sensorimotor and left temporal speech association areas following and preceding speech. Using himself as a subject in 15 different experiments,

SCHAFFER [1967] found that these cortical command potentials time-locked to voice activation were characteristic of each of the spoken stimuli including the letters T, O, and P, the numbers two and ten, and the words yes and no. SCHAFFER tentatively suggested that the early pre-speech components might correspond to the acts of word selection and the decision to speak while the later pre-speech components might reflect the initiation of pyramidal tract firing which controls the vocal musculature specific to a particular word. ERTL and SCHAFFER [1967] extended these findings for the right sensorimotor area in five additional subjects during a comparison of potentials preceding speech and those preceding fist contractions. Interpretations of the cortical command potential described by ERTL and SCHAFFER are limited by their use of time constants too short to allow the emergence of activity with frequency in the RP range. However, VAUGHAN *et al.* [1968] reported that MPs associated with facial and tongue contractions were similar in form to those obtained with limb movements. A subsequent finding that simultaneous recording from the upper lip muscles resulted in an averaged waveform of similar time course to that recorded from the scalp electrodes led ERTL and SCHAFFER [1967] to suggest lip movement as a possible source of the potentials.

The first extensive study of the relationship between cortical activity and the generation of a variety of speech and non-speech sounds was carried out by MCADAM and WHITAKER [1971]. They observed a small increase in the negativity over Broca's area (in the left hemisphere) preceding spontaneous spoken words but not preceding simple oral gestures such as spitting and coughing. This report, however, has been attacked by MORRELL and HUNTINGTON [1971] on several grounds. They questioned MCADAM and WHITAKER's procedures, analyses, and conclusions. MORRELL and HUNTINGTON claimed that when the articulatory muscles were monitored and the same measurements were made for all waveforms, no hemispheric asymmetries consistent with localization over Broca's area could be found. In a subsequent study, however, MORRELL and HUNTINGTON [1972] reported that even after the contaminating effects of lip muscle activity were removed, there remained cortical potentials of cerebral origin time-locked to speech production.

Other examinations of the contamination by artifacts of brain potentials preceding speech production have led to conflicting conclusions. In another attempted replication of MCADAM and WHITAKER [1971], GRABOW and ELLIOTT [1973, 1974] found no consistent hemispheric electropotential lateralization before, during or after verbalization. GRABOW and ELLIOTT

emphasized the possible contamination by the glossokinetic potential as well as the hemispheric asymmetries in the EEG which could be produced by tongue movement. They concluded that there was insufficient evidence relating the average ERP to coding for language production in either hemisphere. On the basis of topographic analysis of speech-related potentials, SZIRTES and VAUGHAN [1973] similarly concluded 'the cortical potentials associated with muscle innervation and possibly with reauditorization of speech sounds overshadow neural activity within the dominant hemisphere related to the programming of speech'.

On the other hand, a number of investigators [Low *et al.*, 1973, 1976, this volume; GRÖZINGER *et al.*, 1973, 1975, this volume] concurred with the statement that the distribution of the pre-speech cortical potentials obtained after elimination of possible artifacts is consistent with an intracranial source reflecting preparation for speech production and the known asymmetries between the hemispheres for linguistic processing. Low *et al.* [1973] have provided further support for such conclusions by finding a significant correlation between hemispheric dominance as determined by the Wada sodium amytal test and dominance derived from the relative CNV amplitudes in the left and right motor speech area. ZIMMERMAN and KNOTT [1974] applied similar procedures to an investigation of the physiological basis of stuttering. A comparison of CNVs in stutterers and normal speakers during speech and nonspeech tasks revealed that only 22% of the stutterers showed a left greater than right asymmetry as opposed to 80% of the normal speakers.

Thus, although a substantial amount of clinical data support the theory of left hemisphere superiority in language reception and production, the ERP data regarding this functional asymmetry are far from consistent. The methodological and statistical shortcomings which exist in some of the studies cited along with inconsistencies in the others render any decision about the efficacy of ERPs as indices of linguistic processing inconclusive.

Concluding Remarks

Much of the research reviewed in this chapter can be described as a search for the electrocortical manifestations of the activity of a left hemisphere language processor. The assumption is made that tasks which require the extraction of linguistic meaning from auditory or visual signals will activate a unique population of neurons charged with such an analysis.

The activation of the linguistic processor will, in turn, produce an interpretable pattern of electrical potentials at the scalp. This same logic applies to the activity of that other impalpable processor, presumably located in the right hemisphere, which is charged with spatial or wholistic processing of stimuli. The crux in both cases is the selection of a task which will activate the appropriate processor.

Unfortunately, the selection of tasks often proceeds on intuitive grounds using the most general statements concerning hemispheric specialization. A severe problem confronting investigators is the lack of a clear consensual theory which could be used to determine which tasks should have what effects on the electrophysiological measures. It is, therefore, no surprise that much of the research is descriptive. In essence, the study of language and the brain and hemispheric specialization was founded on a collection of observations of clinical cases. What theory there is has accumulated over time as the data base expanded and was systematized. Nevertheless, if electrophysiological measures are to add to the study of such complex processes of the brain (rather than merely to reaffirm current knowledge), then tasks must be chosen with reference to existing theoretical frameworks. This, combined with validating behavioral measures, insures that electrophysiological changes, if found, will illuminate rather than obfuscate.

Problems in evaluating many of the studies are compounded by the lack of consistency in the data concerning the baseline symmetry of electroencephalographic parameters. However, asymmetry in baseline conditions does not immediately imply poor electrode placement or asymmetries in subject's skull thickness. Considerable data exists [BECK *et al.* 1975; CROWELL *et al.*, 1973; LAIRY *et al.*, 1969; LINDSLEY, 1940; TRAVIS and KNOTT, 1937], suggesting that the symmetry of electrophysiological measures may vary across individuals as a function of the degree of hemispheric differentiation and its development. Experimenters are therefore faced with the necessity of accounting for a large range of subtle subject factors in their experimental designs. While it is common to treat hemispheric specialization as a polarized process, the behavioral evidence argues for gradients of differentiation in the 'normal' population [SHANKWEILER and STUDDERT-KENNEDY, 1975]. Thus, intuitive task selection based on the most general statements of hemispheric specialization will no longer bring a good return in knowledge with respect to experimental investment.

It may be more profitable to develop experimental paradigms in which ERPs are mobilized to search for answers to questions of linguistic relevance. Language is a form of information processing. There is considerable

evidence that the ERP, in particular the endogenous components, are valuable indices of various aspects of human information processing. It would seem of value to structure experiments not around a search for lateralization *per se*, but on a correlation between linguistically determined aspects of information processing and ERP parameters. Consider for example the issues reviewed by WANNER *et al.* [this volume]. Of particular import is the sequential nature of sentence processing. Is a sentence perceived as a unit or is it processed sequentially? This issue may be tractable to an ERP approach. FRIEDMAN *et al.* [1975] have shown that distinct words in a sentence elicit P300 components and that their amplitudes vary with the degree to which each word is crucial to the meaning of the sentence. Several studies from this laboratory have shown that the amplitude of P300 varies with the expectancy of a stimulus and that the expectancy is determined by the fine structure of events immediately preceding that stimulus [SQUIRES *et al.*, 1976; DUNCAN-JOHNSON and DONCHIN, 1976]. This work suggests that it is possible to evaluate the sequential dependencies within linguistic structures by a study of their ERP concomitants. This is all the more possible if advanced statistical procedures, which are commensurate with the complex nature of ERP data, are used. The dissociation of ERP components with the use of principal components analysis [DONCHIN, 1966, 1969] and the ability to study ERPs associated with single events [SQUIRES and DONCHIN, 1976] allows for a variety of experimental designs.

Another useful variable is the latency of ERP components. While ERP amplitude has been the dependent variable in most ERP studies, the latency of some components, particularly the P300, can be a rich source of information about the manner in which subjects process stimuli. SQUIRES *et al.* [1977] have shown that the latency of P300 depends on the duration of stimulus evaluation. KUTAS and DONCHIN [in press] recorded the P300 elicited when the subject was required to semantically categorize words. The more complex the semantic categorization, the longer the latency of P300. Moreover, in KUTAS *et al.* [1977], a procedure is described for measuring the latency of P300 on individual trials. When this procedure is applied to the semantic categorization data, we find that the latency of P300 reflects, on a trial-by-trial basis, the time required by the subject to categorize the stimulus. Given these data, it is possible to use P300 as an indicator response in psycholinguistic studies where it can augment traditional reaction time measures [cf. also RUCHKIN and SUTTON, 1978].

Our intent is not to detract from studies searching for electrocortical manifestations of verbal and spatial processing, but rather to direct atten-

tion to the many contributions which ERP studies can make to the understanding of human information processing beyond the reaffirmation of hemispheric specialization. We are convinced that these approaches are complementary and necessary.