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Electrocortical Indices of Hemispheric Utilization

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It is well known that electroencephalographic (EEG) activity recorded from widely spaced scalp electrodes is quite diverse; at any instant the voltage at any site may be of a different amplitude or polarity than that recorded at other electrodes. When the properties of the EEG as a time series are evaluated over extended epochs, spectra of simultaneously recorded series vary considerably (Walter, Rhodes, Brown, & Adey, 1966). This variability is due to the structural and functional differences between brain sites underlying the electrodes. As brain tissue varies in its activity patterns so do the manifestations of these activities on the scalp.

The scalp distribution of EEG parameters, estimated from appropriately placed electrodes, has long served to support inferences concerning intracranial electrophysiological events. The most notable success and broadest application of these inferential procedures has been in clinical neurology (Cooper, Osselton, & Shaw, 1974). The scalp distribution of the EEG is widely used in localizing epileptic foci (Gibbs, Lennox, & Gibbs, 1936), tumors (Walter, 1936), focal lesions (Case & Bucy, 1938), and other pathologies. The relative success of these procedures has

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derived from the fact that the pathology may create localized electrical activity at the scalp (Cooper *et al.*, 1974). More recent attempts to identify the intracranial locus of the generators of components of time-locked, event-related potentials (ERPs) have also assumed that these generators represent spatially circumscribed entities (Vaughan, 1969, 1974; Goff, Matsumiya, Allison, & Goff, 1969). In the case of events generated early in the afferent sequence (events we shall label *exogenous*), such inferences seem to be well supported (Goff *et al.*, 1969; Jewett, Romano, & Williston, 1970).

This review is concerned with attempts to extend the use of EEG scalp distribution to the assessment of the differential utilization of distinct cortical areas under different circumstance. Our review is restricted to studies that compare the electrical activity recorded from homologous sites on the two hemispheres. The data collected in these studies are normally used to infer which of the two hemispheres is "utilized," or more actively engaged, during the performance of one task or another (cf. Gur & Gur, this volume).

The use of electrophysiological indices of hemispheric utilization has grown with the increasing interest in the study of the complementary specialization of the hemispheres. Much evidence, surveyed in other chapters of this volume, has accrued during the past two decades demonstrating that the two hemispheres are not functionally equivalent. A grossly oversimplified summary of these data would describe the left hemisphere, in dextrals, as supporting verbal, analytic processing, and the right hemisphere as specializing in spatial, holistic processing. Although the association between speech and the left hemisphere has been known since at least the mid-nineteenth century (Broca, 1861), the more extensive knowledge obtained during the past two decades has derived primarily from research on more recent populations of commissurotomy patients (Gazzaniga, 1970; Sperry, 1974), hemispherectomized (Smith, 1972), or lesioned patients (Milner, 1974). Extension of this work depends on complementary and more accessible sources of data. At present the most successful approach has been through the presentation of lateralized sensory inputs (Kimura, 1961; Bryden, 1965; see Berlin; Springer, this volume), which allow, through the use of the standard techniques of experimental psychology, an evaluation of differential hemispheric processing (Diamond & Beaumont, 1974).

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

This chapter is a review of past attempts to realize the

potential contribution of EEG lateralization studies (see also Butler & Glass, 1974). As will become apparent, the literature is replete with uncertain and conflicting results often due to inadequate attention to methodology. The chapter concludes with a description of work conducted in our laboratory.

A SURVEY OF CURRENT STUDIES

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 this paper 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, and all estimate some *parameter* of the process generating the data. Thus, investigators have wide freedom in the choice of parameters. The specific choice they do make is determined by their hypotheses on the nature of the EEG and EEG-behavior relations. The choice, in turn, can determine the import of the results.

The studies can be conveniently classified into two categories according to the dependent variables used. In one category are all studies that focus on the "ongoing" EEG activity and in which frequency-domain parameters of the EEG are estimated (see Gardiner & Walter; Nelsen, Phillips, & Goldstein; Webster, this volume). Such parameters are usually measures of the power or amplitude, of the EEG, integrated over some narrow or broad bandwidth. In the second category fall studies that analyze the EEG in the time domain (see Anderson; Stamm, Rosen, & Gadotti; Thatcher, this volume). These are exclusively concerned with the waveforms of event-related potentials (ERPs) extracted from the EEG by signal averaging. Within these two categories the studies are classified in terms of the independent variables used by the experimenter. An overview of the dependent variables follows.

Frequency-Domain Studies of the EEG

Many investigators have compared the distribution of the spectral power of the EEG at homologous hemispheric locations. Best known are studies focusing on the activity in the 8-12 Hz band (known as *alpha*). The interest in alpha activity derives from the well-known inverse relationship between alpha power and mental effort (Adrian & Matthews, 1934; Berger, 1930). The assump-

tion is made that hemispheric involvement might be indexed by differential suppression of alpha in the two hemispheres (Galin & Ornstein, 1972). More recently, measures of intrahemispheric "coupling" have been used as indices of hemispheric utilization (Callaway & Harris, 1974). The assumption here is that hemispheric involvement leads to a greater degree of interaction between different intrahemispheric sites, which manifests itself in increased intrahemispheric coupling.

Time-Domain Studies of Event-Related Potentials (ERPs)

With few exceptions, students of the ERP report their results in terms of amplitude or latency of the entire ERP waveform, or its features. It is important, however, to distinguish between three classes of ERP studies in terms of the components that are in fact analyzed. The ERP consists of a sequence of positive-negative potentials that either precede or follow the eliciting event. Post stimulus activity tends to subside after about 500 msec, though anticipatory processes are known to operate over several seconds. The early poststimulus components represent stages in the afferent stream (Buchwald & Huang, 1975) and are often referred to as exogenous. Exogenous components can only be recorded in association with some sensory stimulus. Their scalp distribution depends to a considerable extent on the modality of the stimulus (Goff *et al.*, 1969) and their morphology on the physical parameters of the stimulus.

By contrast, the later ERP components, those with latencies exceeding 150 msec, can be elicited in the absence of a stimulus (Sutton, Tueting, Zubin, & John, 1967; Klinke, Fruhstorfer, & Finkenzeller, 1968), are relatively insensitive to stimulus modality (Vaughan, 1969), and are enormously sensitive to task parameters. We believe these components are manifestations of cortical information-processing activities engaged by task demands, and we shall refer to these as *endogenous* components (Donchin, 1975).

There are two classes of endogenous components, those appearing before and those appearing after the eliciting events. Of the postevent components, the best known is P300 (Sutton, Braren, Zubin, & John, 1965). The preevent components, such as the Contingent Negative Variation (CNV) or the Readiness Potential (RP), are apparently related to anticipatory or preparatory activities (Walter, Cooper, Aldridge, McCallum, & Winter, 1964; Kornhuber & Deecke, 1965).

The studies relating ERP components to hemispheric specialization have most often been concerned with endogenous components. However, data on the lateral distribution of exogenous components are available and will be reviewed.

SURVEY OF FREQUENCY-DOMAIN STUDIES

EEG Measures and Handedness

This survey begins with an analysis of the relationship of EEG measures to manual preferences, followed by a discussion of task-induced changes in scalp distribution of EEG parameters.

Early investigators of the EEG, although they noted occasional hemispheric asymmetries, stressed the similarity of EEG tracings recorded from the two hemispheres (Adrian & Matthews, 1934). Large differences between homologous recordings were considered abnormal and were used to localize focal disorders not characterized by obvious dysrhythmias (Aird & Bowditch, 1946; Aird & Zeale, 1951). Much evidence, however, that the alpha rhythm is rarely symmetric in amplitude or in phase has accrued in the past few decades (Raney, 1939; Remond, Leservre, Joseph, Rieger, & Lairy, 1969; Liske, Hughes, & Stowe, 1967; Hoovey, Heinemann, & Creutzfeldt, 1972). These asymmetries have sometimes been related to the subject's lateral preferences. The alpha rhythm in the dominant hemisphere has been found to be of lower amplitude (Cornil & Gastaut, 1947; Raney, 1937), but this relationship is not universally reported (Butler & Glass, 1974a; Glanville & Antonitis, 1955; Liske et al., 1967; Provins & Cunliffe, 1972; Remond et al., 1969). A relationship between interhemispheric EEG phase and laterality preferences has also been reported (Giannitrapani, 1967; Giannitrapani & Darrow, 1963; Giannitrapani, Darrow, & Sorkin, 1964; Giannitrapani, Sorkin, & Ennenstein, 1966). However, the relationship appears to be quite complex and confused, with the direction of the phase asymmetry changing with subject and state variables.

In part, the confusion derives from difficulty in defining and validating a "resting" state in which to take baseline EEG measures. The wide variations in measurement and analysis techniques also account for some of the confusion in the literature. Mostly, however, 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 the ambidextrous, or in those in whom lateral specialization may be weak, such as stutterers (Travis & Knott, 1937; Lindsley, 1940). Similar asynchronies have also been found in children with disordered verbal-motor development (Lairy, Remond, Rieger, & Leserve, 1969). Amplitude asymmetries, on the other hand, have been reported to be larger in subjects with clearly defined hand preferences (Lairy et al., 1969; see Subirana, 1969). EEG measures may, then, depend on the degree of lateral specialization in individuals rather than on its direction (cf. Collins, this volume). Such considerations must be kept in mind when evaluating the use of EEG measures to index functional asymmetry in the human brain.

Interhemispheric EEG Asymmetries and Hemispheric Specialization

A number of recent studies have claimed that interhemispheric changes in alpha and total EEG power 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. Occipital (Dumas & Morgan, 1975; Morgan, Macdonald, & Hilgard, 1974; Morgan, McDonald, & Macdonald, 1971), temporal and parietal (Doyle, Ornstein, & Galin, 1974; Galin & Ornstein, 1972; McKee, Humphrey, & McAdam, 1973) electrode placements, referenced to the vertex (C_z) position, have been used. Intrahemispheric bipolar linkages have also been employed (Butler & Glass, 1974a).

Tasks presumed to utilize the left hemisphere differentially have included composing letters (Galin & Ornstein, 1972; Doyle *et al.*, 1974), word-search tasks (McKee *et al.*, 1973), mental arithmetic (Morgan *et al.*, 1971, 1974; Dumas & Morgan, 1975; Butler & Glass, 1974a), and verbal listening (Morgan *et al.*, 1971, 1974; Dumas & Morgan, 1975). Right-hemisphere tasks have included modified Kohs Blocks, Seashore tonal memory, and drawing tasks (Galin & Ornstein, 1972; Doyle *et al.*, 1974). They have also included spatial imagery tasks (Morgan *et al.*, 1971, 1974; Dumas & Morgan, 1975) and music listening tests (McKee *et al.*, 1973; Morgan *et al.*, 1971; see Gardiner & Walter, this volume). In addition, occupation (artist versus engineer) and hypnotic susceptibility have been used as independent variables (Morgan *et al.*, 1971, 1974; Dumas & Morgan, 1975).

Data have been analyzed in many different ways. Often, investigators have integrated the raw or filtered EEG (Dumas & Morgan, 1975; Galin & Ornstein, 1972; McKee *et al.*, 1973; Morgan *et al.*, 1971; Nelsen *et al.*; Webster, this volume). Others have computed amplitude histograms of the EEG (Butler & Glass, 1974a) or have used conventional spectral-analysis techniques (Doyle *et al.*, 1974; Gardiner & Walter, this volume). Despite the variety of methods for obtaining estimates of power, most researchers have then expressed their results in terms of right/left or left/right power ratios for homologous electrode sites (Doyle *et al.*, 1974; Galin & Ornstein, 1972; McKee *et al.*, 1973; Nelsen *et al.*; Webster, this volume) or as a laterality score expressing differences in power as a function of total power (Dumas & Morgan, 1975; Morgan *et al.*, 1974; Gardiner & Walter, this volume). 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 implies a lesser degree of hemispheric involvement). Similar results were obtained in studies of activity in the alpha band (Dumas & Morgan, 1975; McKee *et al.*, 1973; Morgan *et al.*, 1971). Butler and Glass (1974a) found left-hemisphere suppression of alpha during mental arithmetic but only in their dextral subjects; unfortunately, no right-hemisphere tasks were used for comparison. A more sophisticated frequency analysis (Doyle *et al.*, 1974) revealed that the main locus of task-dependent distributional changes occurs in the alpha band. They reported minor interhemispheric differences in the beta and theta bands and no changes in the delta band (cf. Gardiner & Walter, this volume).

Although these studies may indicate that there are small task-dependent changes in the EEG spectrum, the implication that selective suppression in the dominant hemisphere for the task is the cause of the ratio changes cannot be supported on the evidence presented. 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 is 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.

Intrahemispheric EEG Measures and Hemispheric Specialization

To date, only one study has employed the intrahemispheric coupling approach to the study of hemispheric specialization (see Livanov, Gavrilova, & Aslanov, 1964, 1973 for related work). Callaway and Harris (1974) reported that appositional or spatial analysis of visual stimuli increases the relative amount of posterior right hemisphere coupling, and propositional examination of visual material (such as reading) increases posterior left hemisphere coupling. As yet unpublished data from the same laboratory tend to confirm and extend these observations (Callaway, personal communication).

SURVEY OF TIME-DOMAIN STUDIES

In this section we report on studies of event-related potentials (ERPs) extracted by signal averaging from the ongoing EEG. All the studies reviewed compared ERPs recorded at homologous hemispheric sites. As in the frequency-domain studies discussed in the previous section, the ERP investigators endeavored to demonstrate that task variables determine the relative amplitude of ERPs over the hemispheres. These differences were sometimes evaluated in terms of subjects' handedness and cerebral dominance.

Studies of Exogenous Components

Very few of the studies reviewed in this section were motivated

by an interest 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 data were often 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 such lateralization, such biases must be considered when testing hypotheses about hemispheric specialization. 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.

Somatosensory ERPs

The data are scant. The consensus seems to be that the largest somatosensory responses are recorded from the scalp overlying the parietal cortex contralateral to the stimulation site (Calmes & Cracco, 1971; Goff, Rosner, & Allison, 1962; Manil, Desmedt, Debecker, & Chorazyna, 1967).

Auditory ERPs

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 (see Anderson; Berlin; Springer, this volume) 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. Most reports maintain that there is a general predominance of the contralateral response; some find differences in terms of a shorter latency response (Majkowski, Bochenek, Bochenek, Knapik-Fijalkowska, & Kopec, 1971), others in terms of a larger amplitude response (Andreassi, De Simone, Friend, & Grotta, 1975; Peronnet, Michel, Echallier, & Girod, 1974; Price, Rosenblut, Goldstein, & Shepherd, 1966; Ruhm, 1971; Vaughan & Ritter, 1970), and a few in terms of both these measures (Butler, Keidel, & Spreng, 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 (Peronnet *et al.*, 1974; Ruhm, 1971) report that the right-hemisphere response is consistently larger only for left-ear stimulation. Peters and Mendel (1974) failed to find such a consistent relationship between the ear stimulated and the latency and amplitude of early (less than 70 msec) ERP components. 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.

Visual ERPs

Similar inconsistencies appear in studies of the laterality of visual ERPs. Studies of interhemispheric 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. Whereas it has been well established that stimulation of different visual half-fields elicits different scalp distributions (see MacKay, 1969; Regan, 1972), the comparison of the hemispheric distributions of visual ERPs is not as straightforward. Several investigators (Kooi, Guvener, & Bagchi, 1965; Vaughan, Katzman, & Taylor, 1963; Harmony, Ricardo, Fernandez, & Valdes, 1973) have reported that visual ERPs recorded over homologous regions in normal subjects are symmetric. Other researchers, however, have maintained that visual ERPs recorded from the right hemisphere are larger than those recorded from the left hemisphere (Perry & Childers, 1969; Rhodes, Dustman, & Beck, 1969; Rhodes, Obitz, & Creel, 1975; Richlin, Weisinger, Weinstein, Giannini, & Morganstern, 1971; Schenkenberg & Dustman, 1970; Butler & Glass, 1972). A more recent report has indicated that retinal site of stimulation may induce latency asymmetries in ERP components (Andreassi, Okamura & Stern, 1975).

The few investigations (Culver, Tanley, & Eason, 1970; Eason, Groves, White, & Oden, 1967; Gott & Boyarsky, 1972) concerned with the relations between handedness, cerebral dominance, eye dominance, and visual ERPs have yielded ambiguous results. Eason et al. (1967) originally reported that the 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 that 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 effects of sex and handedness (cf. Gur & Gur, this volume). Gott and Boyarsky (1972) reported that left-handers produced larger visual ERPs over the left hemisphere and that direct stimulation of the dominant hemisphere (generally right for sinistrals and left for dextrals) elicited ERPs with shorter latency than those elicited by stimulation of the opposite, nondominant hemisphere.

A report by Galin and Ellis (1975) indicates 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 inducing hemispheric asymmetries in alpha power were also asymmetric as determined by measures of

peak-to-trough amplitude and power. Such results are provocative and suggest that baseline symmetry in ERPs may depend on variability in ongoing EEG activity, which may in turn depend on subject state variables.

Studies of Endogenous Components

Asymmetries in Movement-Related Potentials

The most consistent observations of functionally interpretable lateralization have been obtained for slow potentials that are apparently associated with the control or the monitoring of movement.

1. *Readiness Potential.* There is now a general consensus that the slow negative shift preceding voluntary arm and hand movements, variously called the readiness potential (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, Vaughan, & Costa, 1966; Kutas & Donchin, 1974a, 1974b; Vaughan, Costa, & Ritter, 1968). Kornhuber and his co-workers (Deecke, Scheid, & Kornhuber, 1969; Kornhuber & Deecke, 1965) maintain that this contralateral dominance is restricted to the abrupt negativity just preceding the movement, but Kutas and Donchin (1974a, 1974b) demonstrated that the hemispheric asymmetry can be observed hundreds of milliseconds prior to the response. The exact timing of the components of the motor potential immediately preceding the movement is, however, controversial. Gerbrandt, Goff, and Smith (1973) claimed that this negativity occurs after movement; Vaughan *et al.* (1968) found that the RP has a somatotopic distribution and clearly occurs prior to movement. Two reports (Gerbrandt *et al.*, 1973; Wilke & Lansing, 1973) reject the notion that these premovement potentials are associated with a motor command and claim that the potentials are manifestations of the activity of postresponse proprioceptive mechanisms. However this issue is resolved, there is no question that N1 precedes the movement. Thus, our demonstration that the N1 component 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 & Donchin, 1974a).

The absolute amplitude of the motor potentials depends on a number of variables such as force (Kutas & Donchin, 1974a, 1974b; Wilke & Lansing, 1973) and motivation (McAdam & Seales, 1969). The relevant parameters affecting the degree of N1 asymmetry, other than subject handedness and responding hand, have yet to be determined. A promising source of data is intracerebral recording from human patients (see McCallum & Papakostopoulos, 1974). These preliminary data suggest that subtle changes in timing and asymmetry of the RP may be obscured in scalp recordings.

2. *Response Variables and the Contingent Negative Variation.*

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 (Cohen, 1969; Low, Borda, Frost, & Kellaway, 1966) demonstrated that the CNV preceding a motor response in an RT paradigm is 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 & Leifer, 1973). Syndulko (1972) reported that this response-related lateral asymmetry was specific to central as opposed to frontal, parietal, or occipital locations and developed only preceding unimanual response preparation. Otto and Leifer (1973), on the other hand, noted that a CNV laterality was statistically significant only when the data were pooled across their response and feedback conditions. It has been well established that CNVs can be generated in the absence of a motor response (Cohen & Walter, 1966; Donchin, Gerbrandt, Leifer, & Tucker, 1972; Donchin, Kubovy, Kutas, Johnson, & Herning, 1973; Low et al., 1966) 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 by Hillyard (1973; see also Gazzaniga & Hillyard, 1973). In one of our studies (Donchin, Kutas, & McCarthy, 1974, discussed in more detail later in this chapter), we were able to elicit in rapid succession a lateralized motor potential followed by a bilateral anticipatory potential. (See also Stamm et al., this volume.)

ERP asymmetries Associated with Cognitive Functions

Very few studies have been designed specifically to seek concomitants of lateralized perceptual or cognitive functioning in such endogenous ERP 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) originally 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 had only one left-hander against whom to compare the data of their right-handed subjects. The fact that in their "control" condition large asymmetric CNVs were also generated makes the results still more difficult to interpret. Care must in general be exercised in the choice of stimulus modalities and response requirements in designing such studies, as CNVs in different paradigms have distinct anterior-posterior scalp distributions, a central dominant CNV preceding tasks requiring motor readiness (Jarvilehto & Fruhstorfer, 1970; Syndulko, 1972; Poon, Thompson, Williams, & Marsh, 1975), a frontal dominant CNV accompanying auditory discrimination (Jarvilehto & Fruhstorfer, 1970; Syndulko, 1972), and a parietal dominant CNV accompanying similar visual tasks (Cohen, 1973; Syndulko, 1972). 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 using ERP methods to investigate differences between the dominant and nondominant hemispheres, but progress has been slow and somewhat hampered by inadequate experimental design and analysis procedures.

ERP Asymmetries in Linguistic Processing

In this section we will review studies of the ERP relating hemispheric asymmetries to linguistic functions. Given the abundant evidence that verbal information is processed more efficiently by the left hemisphere, the search for ERP correlates of linguistic processing has become increasingly energetic in the past decade.

1. *Asymmetries 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 are reflected in the ERP (see Thatcher, this volume). Buchsbaum and Fedio (1969) have 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 foveally presented verbal and nonverbal stimuli elicit waveforms that are more differentiable when recorded at the left than when recorded at the right hemisphere. They have 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 & 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 identify their stimuli verbally. During the anticipation of flashed word symmetric CNVs were generated at the midtemporal and angular

gyrus placements. Preliminary data obtained when the two experimental conditions (verbal and nonverbal) were intermixed 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 that 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. 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, Simson, Ritter, & Rapin, 1975). Friedman and his associates present a trenchant critique of the studies reviewed in this section.

2. *Asymmetries in Language Reception: Auditory Modality.* Although still contradictory and inconsistent, somewhat more promising results have been obtained with auditory stimuli (Brown, Marsh, & Smith, 1973; Cohn, 1971; Matsumiya, Tagliasco, Lombroso, & Goodglass, 1972; Molfese, Freeman, & Palermo, 1975; Morrell & Salamy, 1971; Neville, 1973; Teyler, Harrison, Roemer, & Thompson, 1973; Wood, Goff, & Day, 1971; Anderson, this volume). A number of studies have in fact supported the view that linguistic analysis occurs primarily in the left hemisphere. 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 the N100 component elicited by nonsense words larger over the left than the right temporoparietal area. It is difficult to interpret their results, as they failed to use a nonlanguage 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 ascribe 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 that appeared in the N100-P200 component, depending on whether the subject was required to perform a linguistic or an acoustic analysis of the stimulus (cf. Anderson, this volume). Molfese et al. (1975) found a similar enhancement in the amplitude of the N1-P2 component of the ERP in the left relative to the right hemisphere for speech stimuli, even when the subject's task was merely to listen. On the other hand, nonspeech acoustic stimuli were found to produce larger amplitude responses in the right hemisphere. Although Molfese et al. found asymmetries in the auditory ERPs from infants, children, and adults, they noted that the lateral differences to both types of stimuli decreased with age. Neville (1974) reported lateral ERP amplitude and

latency differences elicited by digits but not by clicks in a dichotic listening paradigm.

Several investigators have attempted to evaluate the influence of linguistic meaning on scalp ERPs. Teyler *et al.* (1973) reported that different ERPs could be recorded 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 a particular word differed according to its contextual meaning and (2) that these differences were significantly greater for left- than for right-hemisphere loci. It seems then that different investigators find in a variety of ERP parameters greater variability over the left than over the right hemisphere.

3. *Slow-Potential Asymmetries Preceding Language Production.* Whereas the studies just reviewed were primarily concerned with demonstrating different degrees of hemispheric asymmetry in response to verbal and nonverbal stimuli, others have tried to find the ERP concomitants of speech production. McAdam and Whitaker (1971) 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. 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 claim that when movement artifacts were monitored and the same measurements were made for all waveforms, no hemispheric asymmetries consistent with localization over Broca's area could be found (cf. Anderson, this volume). McAdam and Whitaker's findings, on the other hand, have been essentially confirmed by Low, Wada, and Fox (1974, 1976) who, in addition, found 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 supports 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 existing in many of the studies cited render any decision about the efficacy of ERPs as indices of linguistic processing inconclusive.

METHODOLOGICAL CRITIQUE OF LATERALIZATION STUDIES

One need not be overly critical to conclude from the preceding review that it is premature to advocate the use of the EEG and ERP parameters as indices of hemispheric utilization; similar conclusions have recently been adumbrated by Friedman *et al.* (1975) and by Galambos, Benson, Smith, Schulman-Galambos, and Osier (1975). Yet, within the welter of conflicting claims and apparent inconsistencies there is a thread of positive results that indicates the promise of the approach. The expectation that differential hemispheric utilization will manifest itself in scalp-recorded electrical activity is plausible. Why then is the literature so confused? There are two related answers. The functional significance of electrocortical "macro" potentials is, as yet, obscure. Although the evidence is strong that the EEG is a manifestation of "real" brain events, neither its general role nor the role of its many different parameters has been clarified. It is, therefore, the case that the studies reviewed earlier, as well as our own studies, are not guided by a specific theoretical view of the EEG. On the whole, investigators do not have *a priori* expectations regarding the direction of the differences they will observe. Until neurophysiologists supply a coherent view of the EEG, an empirical approach must predominate in this research. As long as it does, a measure of uncertainty will naturally pervade the literature.

The uncertainties and confusions deriving from our meager understanding of the EEG are exacerbated by inattention to proper methodology. Even within the constraints discussed previously, the issues could be clarified, were investigators to attend more carefully to methodological considerations. The following is a review of some of the more important points that should be considered in designing, conducting, and analyzing experiments in this field.

It would help to discuss first the formal structure of the experiments reviewed and to identify within that structure the major loci of methodological difficulty. The dependent variable in the reviewed literature is always the difference between a pair of values of some EEG or ERP parameter recorded at homologous bilateral sites. The independent variables are most often discussed in terms of the tasks the investigator has imposed on the subject. A class of tasks that is presumed, on previous data or intuitive grounds, to engage differentially one hemisphere or the other, is usually selected. The experimental conclusions can invariably be stated as a functional relationship between the sign and magnitude of the EEG parameter and task variables, which are in turn presumed to reflect basic features of human information processing.

Assume, for the sake of argument, that there really is a difference of the type sought. If the various experimental statements are in conflict or are not very convincing, any or all of

the following reasons might be the cause:

1. The experimental design is not sufficiently sensitive to allow detection of the differences or is inadequate to support the conclusions.
2. The tasks assigned the subject may not in fact differentially engage the hemispheres.
3. The effects are range-restricted and the values of the independent variables are out of the relevant range.
4. Subject individual-difference variables are not considered.
5. The parameters of the EEG used as dependent variables were unwisely selected.
6. The measurement techniques used to obtain the parameters are inappropriate.
7. The data are improperly quantified and were inappropriately or insufficiently analyzed.

Design and analysis problems in recording scalp electrical activity in humans have been the topic of many comprehensive reviews (Donchin, 1973, 1975; Donchin & Lindsley, 1969; Thompson & Patterson, 1974). Our discussion is therefore limited to those problems specific to the use of the distribution of scalp potentials as an index of hemispheric functioning.

SURVEY OF METHODOLOGICAL PROBLEMS

Design Problems

If one point emerges with clarity from the studies reviewed, it is this: If there are any differences between the electrocortical activity of the two hemispheres, they will be minute. This implies that to reveal lateral dominance for study one must use techniques with the required high resolving power. The subtlety of the differences sought dictates the use of experimental designs of great sensitivity. Real but minute differences should not be ignored (type II errors), but at the same time artifactual sources of interhemispheric differences that may lead to type I errors should be avoided. The designs should minimize the chances of both types of errors. All too often the designs used in the reviewed studies were far from optimal.

In virtually all the reviewed studies, data were obtained from all subjects under all experimental conditions. For example, all subjects were challenged with spatial and verbal tasks. The investigators then chose between pooling the subjects' data, comparing group means, or using a repeated measurements design (with each subject serving as his own control). The last procedure is customarily preferred when large individual differences are expected in the data. The increased power of within-group designs aids in uncovering small-magnitude changes that would otherwise be obscured in between-group variance. Repeated-

measures designs are common in ERP work, but many of the widely cited studies of frequency-domain parameters contain data that were averaged over groups of subjects.

It is, of course, crucial to ensure that all experimental designs include proper control procedures. When lateral asymmetry is attributed to the specific effects of a task, it is incumbent upon the experimenter to demonstrate that the same parameter, when estimated during some neutral task, does not display a similar asymmetry (see Thatcher, this volume). At the least, the investigator should demonstrate that the lateral asymmetry can be reversed or modulated with appropriate changes in the task ("double dissociation"); thus investigators should include tasks designed to engage each hemisphere differentially. Unfortunately, many investigators fail to include such elementary controls. It is sometimes difficult to determine whether asymmetries observed in the control conditions are a function of such variables as handedness, cerebral dominance, ill-balanced electrode placements, or skull thickness. Again, this problem is especially severe in studies of EEG spectra, although large CNV asymmetries too have been reported in a presumably neutral task (Butler & Glass, 1974b). More extensive baseline data should be collected.

Validation of Task Variables

Common to a number of studies reviewed is the lack of attention directed toward the definition and validation of the task variables presumed to be the independent variables. Too many investigators (Brown et al., 1973; Doyle et al., 1974; Galin & Ornstein, 1972; Morgan et al., 1971) merely ask their subjects to imagine relationships or to perform mental operations without objectively verifying that the subjects are in fact following instructions. Even when measurable responses are required of the subject, no systematic presentation or analysis of these behavioral measures is made (see for example Butler & Glass, 1974a; McKee et al., 1973). Many studies leave the reader to wonder whether the subject complied with task demands and, if so, to what degree. The possible influence of task difficulty on these results has often been ignored. The subjective estimates of task difficulty that have been used are difficult to interpret without performance measures (Dumas & Morgan, 1975; McKee et al., 1973; Morgan et al., 1974).

Although negative results are notoriously difficult to interpret, confusion is compounded when EEG data are based on intuitively chosen tasks that have not been validated. Some advantages may be gained by selecting standard neuropsychological paradigms for which differential hemispheric engagement has been assessed (Neville, 1974). It is also important to avoid confounding psychological variables with varying physical parameters of the task-related stimuli. Ample evidence in the literature demonstrates that the characteristics of ERPs are grossly

affected by physical stimulus properties (see Regan, 1972). Several investigators have devised clever strategies for holding the physical parameters of the stimuli constant while varying task variables (for examples, see Brown *et al.*, 1973; Wood *et al.* 1971).

Range of Operation of the Independent Variables

The subject's tasks are usually chosen with the assumption that the manipulation of the independent variable will engage one hemisphere or the other. If no interhemispheric differences are found, the investigators tend to deduce that electrocortical activity is not related to hemispheric utilization. This may be a rash deduction. It is, in fact, possible for the independent variable to have a strong effect on the laterality of the EEG for values of the independent variable other than those selected for study. Consider, for example, the assertion that the N1 of the MP displays no lateral asymmetry. This is in fact the case when the subject merely presses a switch or makes a light movement with his finger. If, however, the response requires a considerable degree of muscular involvement, lateral asymmetries appear (Kutas & Donchin, 1974a). Similar results were obtained by McCallum and Papakostopoulos (1974) with intracerebral recording.

We describe, later, data that suggest that increasing cognitive demands likewise accentuate the lateral asymmetries in the CNV. Within the same context, it is important to note that cognitive sets induced by the order in which experimental conditions are presented can influence the range and direction of functional asymmetries (for behavioral data, see Kimura & Durnford, 1974; Kinsbourne, 1973; for application to ERP work, see Marsh & Thompson, 1973).

Subject Variables

It is a truism that one should know as much as is relevant about the present state and past history of the subject. Yet, such variables as age, sex, prior drug ingestion, and amount of sleep, although known to alter the characteristics of brain activity (Perry & Childers, 1969; Shagass, 1972; Regan, 1972), are sometimes ignored in EEG and ERP studies. Of critical importance in investigations of hemispheric specialization is the subject's history of handedness. Many reports concur that sinistrals differ from dextrals in their response to and recovery from cortical damage and in their performance in a variety of behavioral tasks (Hécaen & Ajuriaguerra, 1964; Levy, 1974). Subject performance is affected not only by handedness but also by familial history of handedness (for references see Levy, 1974). Apparently, the functional asymmetry in the recognition of tachistoscopic material (Bryden, 1965; Springer, this volume) and in dichotic listening (Zurif & Bryden, 1969; Berlin, this

volume) is appreciably smaller for individuals with left-handed relatives. Surprisingly, a number of studies of lateralization have failed to consider this aspect of the subjects' handedness (see Levy, this volume).

Assessing subjects' handedness should be the *sine qua non* of all investigations of laterality. However, subjective self-classification of handedness is inadequate as it correlates poorly with questionnaires and motor performance (Provins & Cunliffe, 1972; Satz, Achenbach, & Fennell, 1967). This is especially true for left-handers, who tend to form quite a heterogeneous population and often yield highly variable test results. Our own experience (Kutas, McCarthy, & Donchin, 1975) has been that handedness is difficult to classify and that, as a minimum requirement, self-reports should be supplemented with questionnaires.

Parameters of the Dependent Variable

Of critical importance is the selection of the proper parameters of EEG or ERP activity for the evaluation of task-induced changes. This is partly an empirical process as many parameters may need evaluation. These task-dependent changes may not always reveal themselves in gross measures of overall ERP amplitude or length, or in total EEG power spectra. They often, in fact, appear as small but consistent modulations of specific ERP components or EEG bandwidths (see Gardiner & Walter, this volume). It cannot be overemphasized that the ERP is not a unitary phenomenon, it is, rather, a sequence of independent components that react differentially to experimental variables (Donchin, 1969).

Care must be exercised in creating composite dependent variables based on various measures of EEG or ERP data. For example, interhemispheric ratios or laterality scores derived from power density spectra can provide a good summary statement descriptive of bilateral power relationships, but such ratios can be misused and are often misleading. Ratios presented independently of the data on which they are based (Doyle et al., 1974; Galin & Ornstein, 1972; McKee et al., 1973) leave the reader uncertain whether the changes are caused by differential engagement of the hemispheres by the tasks consistent with the functional asymmetry of the brain, or are due merely to changes in one hemisphere, perhaps reflecting task difficulty. Reassuring statements about the specific locus of change cannot be taken seriously unless supported by data from each hemisphere.

Data Measurement

Whatever the procedure for measuring the parameters of the dependent variable, no interpretable results can be obtained if data are improperly recorded from the scalp. The necessity for a

common reference (either active or inactive) equidistant from the two electrodes being compared cannot be overemphasized. The use of a nonequidistant common reference, such as a single ear (Gott & Boyarsky, 1972), the use of equidistant but separate references such as O_1-A and O_2-A_2 (Buchsbaum & Fedio, 1969, 1970; Culver *et al.*, 1970; Fedio & Buchsbaum, 1971), and the use of intrahemispheric bipolar linkages without a common reference, such as C_3-P_3 and C_4-P_4 (Butler & Glass, 1974a; Matsymiya *et al.*, 1972) confound the assessment of hemispheric asymmetry. This problem is especially acute as the reported differences are often a microvolt or less.

A single nonequidistant reference should be avoided, as activity associated with the reference electrode will be unequally represented at the sites of comparison. Different unilateral reference electrodes allow for the possible introduction of systematic artifacts generated at a single reference but mistakenly identified as an asymmetric component. Intrahemispheric bipolar linkages, on the other hand, can mask existing interhemispheric differences, because of the common-mode-rejection characteristic of differential amplification. Although not without problems (Donchin, 1973), linked ears or mastoids and chin or active midline placements avoid most of the difficulties mentioned.

The number of conditions and electrode placements necessary for adequate examination of distributional effects of task variables on ERP components produce too much data to be easily handled by visual inspection or hand-measurement methods alone. Moreover, visual inspection is often inadequate for dealing with subtle differences between complex waveforms. As previously mentioned, marginal asymmetries, although consistent with experimental manipulations, can be washed out by larger, symmetric components (Hillyard, 1973). Also, experimental effects may not always be evident as a measurable peak or trough in the ERP waveform, but may rather be manifest as a modulation of another component.

We employ Principal Components Analysis (PCA) to identify the distinct components of the waveform and to assess their sensitivity to experimental effects (Donchin, 1966, 1969; Donchin, Tueting, Ritter, Kutas, & Heffley, 1975). This procedure provides an objective definition of ERP components and measures their contribution to each waveform with reference to the entire data set. A detailed treatment of the application of PCA to ERP research is beyond the scope of this paper (Chapman, 1973; Ruchkin, Villegas, & John, 1964). Briefly, the ERP waveform can be considered an estimate of the mean vector of a multivariate distribution. The PCA is one technique for decomposing this mean vector into its component vectors. The nature of this extraction procedure allows separate analyses of variance to be performed on derived factor scores to assess the sensitivity of the factors to the experimental variables. Thus, identification and quantification of the experimental effects can proceed in an

objective manner. The use of the technique is illustrated later in this chapter.

Data Analysis

It is commonly acknowledged that exacting data-analysis techniques are essential for the proper evaluation of the effect of experimental manipulations on measures of brain activity. There is certainly no lack of analysis procedures in the literature reviewed; unfortunately, however, the heterogeneity of quantification procedures makes comparisons between laboratories difficult. The ambiguous nature of many of the paradigms as well as the small magnitude of the experimental effects obtained in this type of research should discourage the more liberal approaches to data analysis, which often seem colored by the expectations of the investigator. Fundamental to the statistical evaluation of any data is the measurement of the magnitude and distribution of error variances. The use of grand averaging, qualitative analysis, and multiple univariate analyses can be criticized on several grounds, among them a disregard for the range of variability in the data.

Two forms of data reduction often employed in the analysis of ERPs, grand averaging (averaging waveforms across subjects and/or conditions) and qualitative analysis, give no indication of the real variability in the data. Grand averaging, although a useful means for visually summarizing a multitude of waveforms, should not be used as the sole method of analysis as no estimate of error variance is available. Purely qualitative analyses (e.g., Cohn, 1971) or visual scoring of asymmetry (Butler & Glass, 1974b) are too subject to experimenter bias to be the only method for assessing the influence of independent variables and, of course, do not allow for the evaluation of statistical significance.

Many of the statistical analysis procedures used in the determination of hemispheric asymmetries are not merely inadequate; they are often inappropriate. The comparison of ERP waveforms and EEG power ratios through multiple univariate procedures (Brown *et al.*, 1973; Doyle *et al.*, 1974; Wood *et al.*, 1971) without adjustment for the number of tests being performed can result in misleading conclusions, since the probability of finding spuriously "significant" difference is underestimated (see the excellent paper by Friedman *et al.*, 1975, for a discussion of the Bonferroni test). There are, moreover, multivariate techniques for the analysis of ERPs (such as those referred to previously) that take into account the interdependence of time points and are not subject to the aforementioned criticisms.

SLOW ERP COMPONENTS AND HEMISPHERIC INVOLVEMENT

We now describe studies from our laboratory that were designed to test the proposition that slow, preevent, "anticipatory" waves can be used to index hemispheric utilization. The data provide evidence that scalp-recorded EEG can be used in studies of hemispheric specialization.

These studies were conducted within the general framework of our interest in the endogenous components of ERPs (Donchin, 1975; Donchin *et al.*, 1973, 1975; Rohrbaugh, Donchin, & Ericksen, 1974). The CNV is one of the more prominent of these components (McCallum & Knott, 1973, 1976). There is no doubt that it is a manifestation of anticipatory processes, sensitive to a variety of behavioral manipulations; yet, it turns out to be strangely intractable to theoretical analysis. Various conflicting interpretations have been put forward (see, for example, McCallum & Knott, 1976). The crux is the degree to which the CNV represents generalized attentional variables (Karlin, 1970) or more specific preparatory processes (Tueting & Sutton, 1973). It has also been difficult to tease out the relative roles of motor and cognitive preparation. The evidence indicates that CNVs can be recorded in the absence of specific, overt, experimenter-directed motor activity (Donchin *et al.*, 1972; Irwin, Knott, McAdam, & Rebert, 1966), yet it is also clear that the CNV is larger when a motor response is required. If motor preparation is an important determinant of the slow potentials, then a lateralized response requirement should lead to a lateralization of the potentials, with larger amplitudes recorded contralateral to the responding hand.

We began by examining data collected for other purposes (Donchin *et al.*, 1973) in a choice reaction time paradigm. A warning tone preceded one of two possible flashes by 1500 msec; the subject was required to respond to one flash with the right hand and to the other with the left hand. In one series of trials, the two stimuli alternated; the subject, therefore, knew the hand with which to respond. In another series, the stimuli were presented in a random sequence and the subject could not predict the hand to be used. Data were recorded from laterally placed electrodes; thus differences in the lateral symmetry of the CNVs obtained in the random and the alternating sequences could be determined. If motor preparation affects these potentials, it should operate during the alternating sequence. A comparison of the cortical activity preceding the subjects' responses averaged separately for each responding hand failed to reveal any lateral asymmetry in either of the experimental conditions (Donchin, Kutas, & Johnson, 1974).

These data were puzzling. According to Kornhuber and Deecke (1965) and Gilden *et al.* (1966), asymmetric motor potentials precede self-paced motor responses. A replication of these studies was attempted to determine whether a similar asymmetry could be

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observed when the warning stimulus was eliminated from the sequence. This attempt also failed. When subjects pressed a button at a self-paced rate with one hand, the potentials recorded from the two hemispheres were virtually identical.

A possible explanation for this failure to replicate came from Otto (personal communication), who reported finding a lateral asymmetry in potentials preceding a multiple finger response. This was in accord with reports that the CNV was largest when greater muscular effort was required (Low & McSherry, 1968; Rebert, McAdam, Knott, & Irwin, 1967). These findings were originally interpreted in terms of the motivational state of the subject, but it may be that response-force per se determines the CNV (or RP) amplitude.

A systematic investigation of the effect of force on the RP was therefore conducted. The lateral distribution of the RP over the motor cortex in both right- and left-handed subjects squeezing a dynamometer with either hand at three levels of force were compared. The force levels were calibrated in terms of the subject's capabilities rather than in absolute terms. In right-handed subjects, the premovement RPs (N1) were larger over the hemisphere contralateral to the responding hand. Left-handed subjects showed contralateral dominance only when responding with their right hands (see Figure 1). An analysis of the N1 magnitude revealed that although response-force does accentuate the motor asymmetry, the absolute right-left asymmetry does not change with increasing force levels (for a more detailed account, see Kutas & Donchin, 1974b).

It turns out, then, that past failures to demonstrate conclusively the hemispheric asymmetry of the RP may have been due to the range of the independent variable (response-force, in this case) and to an inattention to subject variables. Many reports concerning the RP have failed to mention subjects' handedness, and the few that did mention it failed to consider it in evaluating the data.

A COMPARISON OF READINESS POTENTIAL AND CNVs

The results described previously led to an investigation of the relationship between the lateral asymmetry of the RP and the CNV (Donchin *et al.*, 1974). Again, subjects were required to squeeze a dynamometer with one hand or the other. In addition, various tests of each subject's lateral preference were administered. After a detailed examination of various tests for handedness (Kutas *et al.*, 1975), we selected the Edinburgh questionnaire (Oldfield, 1971) as an instrument of choice.

In order to make the dynamometer squeeze less tiresome to the subjects, scenic slide presentations were made contingent on dynamometer squeezes that attained a specified force level. Figure 2 presents the sequence of events in an experimental trial. A self-paced squeeze, if "correct," was followed after 1800 msec

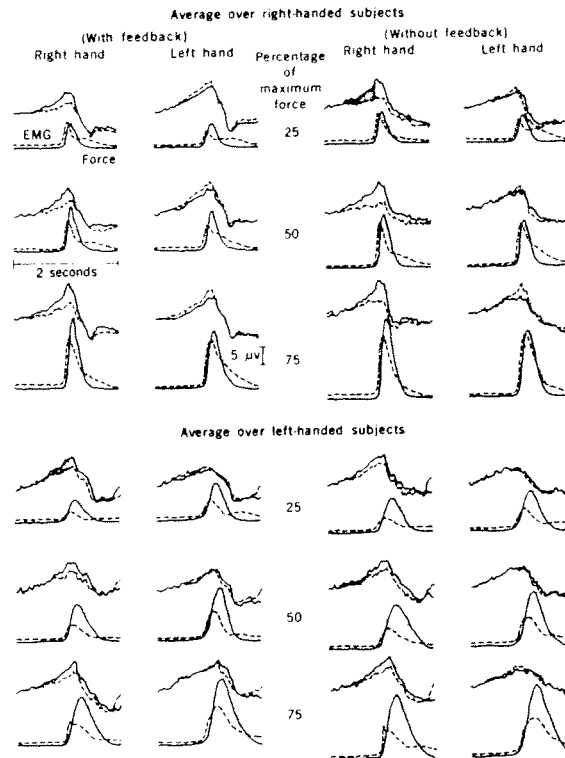


Fig. 1. A comparison of event-related potentials (ERPs) recorded at electrodes placed at left-central (C_3 , solid line) and right-central (C_4 , dashed line) loci during voluntary squeezes. Under each pair of superimposed ERPs we have plotted the integrated electromyogram (EMG) (dashed line) and the output of the force transducer (solid line) averaged over the same trials over which the ERP was averaged. Comparisons are presented as a function of subject's handedness (right versus left), nominal force output (25, 50, and 75% of subject's maximal force), responding hand (right versus left) and feedback (presence or absence of visual signal indicating force level). Averages were obtained over all subjects, after the elimination of trials in which the EEG was contaminated by electrooculogram (EGO) activity. Number of trials per ERP ranges between 600 and 1050. The polarity convention is negative up. Hatching in two areas of the comparisons illustrates the areas measured for the purpose of the quantitative data analysis. From Kutas and Donchin, 1974a.

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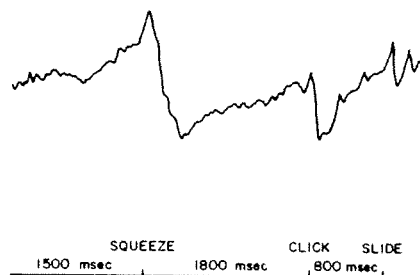


Fig. 2. The sequence of events in an experimental trial. Trial duration was 4500 msec. The waveform drawn above the time line is of the ERP obtained by averaging the entire data set collected from left-handed subjects at a central position. It serves merely to indicate the time of occurrence of the various ERP components.

by an audible click (generated by the mechanism of the slide projector) which was followed after 800 msec by the presentation of the slide. Thus, each trial consisted of three distinct phases: a prerespone interval over which an RP could be recorded, a post response interval, and finally the click-slide interval during which a measurable CNV could be recorded. This paradigm enabled a comparison of the hemispheric asymmetry of the pre-movement RP, which we expected to vary as a function of the responding hand, with the hemispheric symmetry of the CNV. This design thus permitted an examination of the degree to which the asymmetries observed by Kutas and Donchin (1974a) were specific to the premotor interval, or were extended over a long interval. This also allowed for an examination of the possibility that, although the RP is asymmetric, the CNV is symmetric.

In Figure 3 are grand averages for the right- and left-handed subjects, recorded at the frontal, central, and parietal locations. The ERPs recorded at homologous hemispheric sites are superimposed. These averages were obtained by triggering the computer on the dynamometer squeeze. Several aspects of the data are immediately apparent. Clearly, the squeeze is preceded by an RP, which is asymmetric. Moreover, the asymmetry reverses with the responding hand. Following the squeeze, a long-lasting asymmetric slow wave appears, which displays a polarity opposite that of the presqueeze potential. The CNV that follows the click is symmetric, though superimposed on the slow wave. There are substantial differences between the scalp distribution of the CNV and the RP. The CNV is equally large at the frontal and central sites, but the RP is largest centrally. Note also the sharper resolution of the CNV in the parietal sites.

A more detailed look at the data is provided in Figure 4, where waveforms are shown for five individual subjects. The

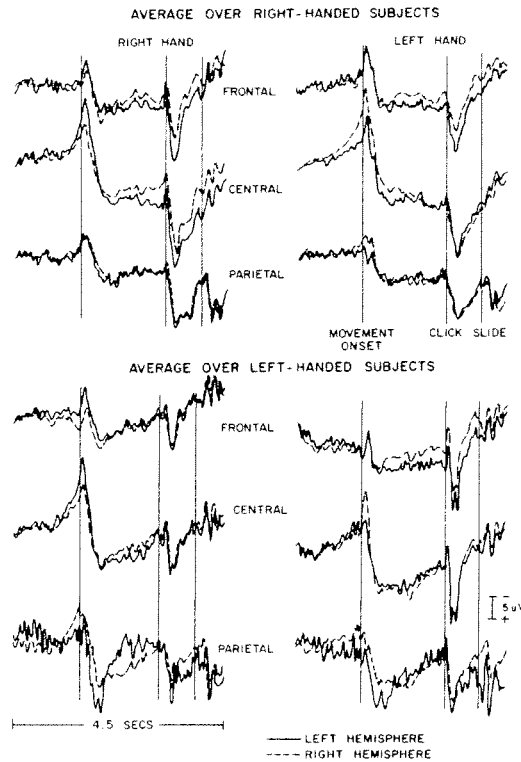


Fig. 3. ERP waveforms recorded from frontal, central, and parietal positions. Data obtained simultaneously from homologous sites are superimposed. There were approximately 75 trials per subject per condition.

curves displayed were obtained by element-to-element subtraction of the ERPs at the right and left central electrodes (these then are equivalent to a "bipolar" recording between the two central electrodes). For each subject, data obtained with right- and left-hand squeezes were superimposed. When the premotor interval is examined, a strong measure of asymmetry is observed. For each subject the potential difference reverses polarity with the responding hand. It is important to note that the degree of polarity reversal is far more evident when intrasubject rather than intersubject comparisons are made. The specific difference waveforms vary considerably from subject to subject, yet within subjects the potentials are of opposite polarity, suggesting a change in the direction of laterality.

No such asymmetries are observable for the CNV. Whereas the postresponse slow potential is quite prominent and seems to

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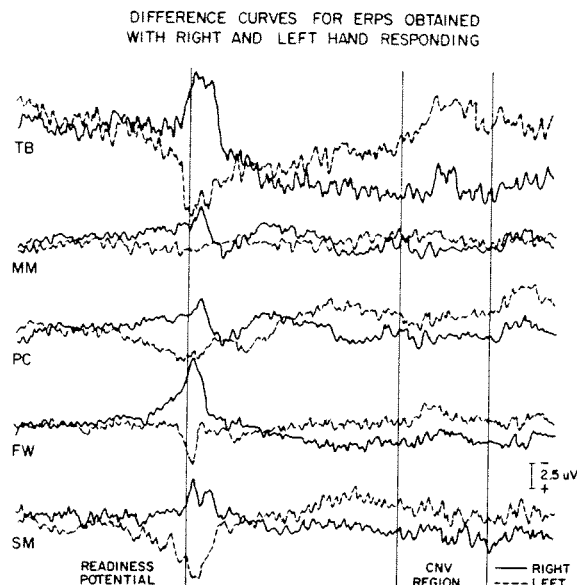


Fig. 4. All waveforms shown in this figure were obtained by point-to-point subtraction of ERPs recorded at the left-central electrode from ERPs recorded at the right-central electrode. This difference will be negative if the left-hemisphere potential is larger, and positive if the right-hemisphere potentials are larger. For five subjects (three dextral and two sinistral) we superimposed data obtained when subjects were squeezing a dynamometer with the right hand (solid line) and the left hand (dashed line). Each waveform represents an average of 75-80 trials. The first vertical line separates pre- from postsqueeze activity; the second and third lines delineate the click-slide interval (CNV).

extend over the entire recorded epoch and probably beyond it, the click-flash CNV is apparently equal in amplitude at both sites. A quantitative statement of this trend is shown in Figure 5. We have fitted a quadratic function to the RP and to the CNV segments of the curve. In Figure 5 is a plot of the coefficients of the quadratic terms that were computed for ERPs associated with right-hand squeezes against coefficients associated with the left-hand squeezes. If the two curves show opposite polarity, the coefficients should be of opposite sign. For the RP, the coefficients are large, and for most subjects the magnitudes of the two coefficients are reasonably similar, but the signs are different. For the CNV, the coefficients are clustered around the origin and show no tendency toward opposite polarity.

These data provide support for the idea that lateral asymmetry can be used as an index of hemispheric utilization. Shifts in

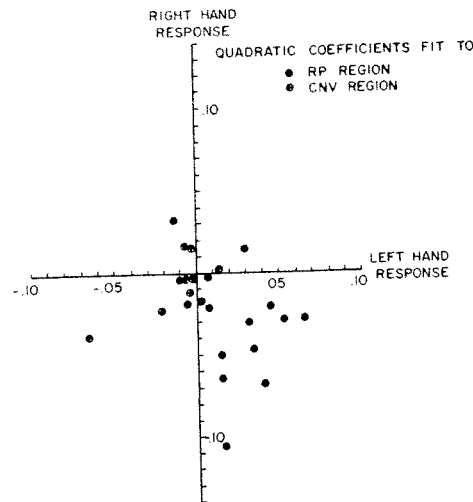


Fig. 5. Regression coefficients of the quadratic term obtained from a polynomial fit to the premovement (full circles) and CNV (crossed circles) region of the difference waveforms illustrated in Figure 4. Coefficients computed on the basis of right-hand response data are plotted against coefficients obtained when subjects were squeezing with their left hands.

asymmetry appear to be quite rapid and are finely tuned to shifts in the subject's tasks. The nature and significance of the long, slow, postresponse wave is not clear, yet it is obvious that the more rapid shifts in asymmetry can be detected when they are superimposed on such long-term trends. Thus, these data lend plausibility to the "two-factor hypothesis," which views anticipatory negative shifts as a mixture of motor and cognitive preparatory processes (Hillyard, 1973).

LATERAL ASYMMETRIES IN A CNV PARADIGM

Although the data presented in the preceding section demonstrate the differential anterior-posterior and interhemispheric distribution of the RP and CNV, it remains to be determined if the CNV is always symmetric or perhaps, with proper choice of tasks, can be lateralized. Conceivably, just as a forceful squeeze was required to demonstrate the asymmetry of the RP, a stronger cognitive "squeeze" might be required to demonstrate the lateralization of the CNV. An experiment was designed, therefore to manipulate task variables that might contribute to the formation of an asymmetric CNV.

The task chosen was patterned after the Structure-Function matching task developed by Levy (1974) in her work with commissurotomy patients. One of two warning tones (1000 Hz or 2000

Hz) preceded, by 1000 msec, a brief (50 msec) presentation of a slide. Each slide contained three figures, two of which formed a structural or "look-alike" match (right-hemisphere dominant task) and two of which formed a functional or conceptual match (left-hemisphere dominant task). Both types of matches could be made from each slide with one figure common to the two matches (see Figure 6). Subjects responded by pressing one of three

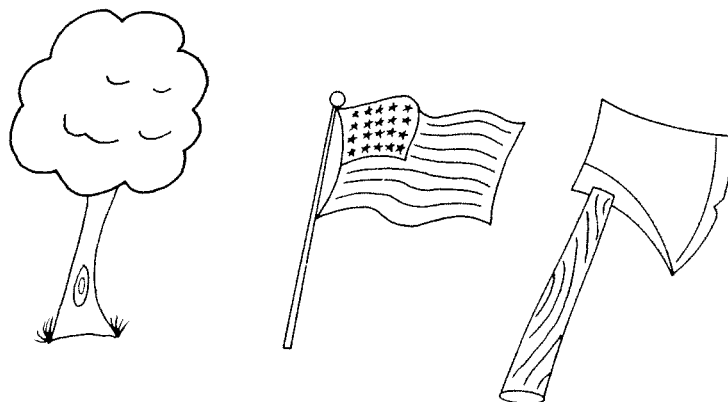


Fig. 6. One of the 42 slides used in the study. The ax and the tree are functionally matched; the ax and the flag are structurally matched. If cued to make a functional match, the subject would respond by pressing a button with the second finger of his right hand. For a structural match, the subject would press a button with the third finger.

buttons (with one of three fingers of the right hand) coded for the three possible figure combinations. Subjects were instructed to respond as quickly as possible following the slide presentation. Reaction time (RT) and the subject's choice were recorded for each trial along with 2000 msec of EEG from a nine-electrode montage (F_3 , F_4 , C_3 , C_4 , P_3 , P_4 , F_2 , C_2 , P_2 --according to the 10-20 system for electrode placement). The vertical electrooculogram (EOG) was recorded on a separate channel. Trials associated with eye movements were excluded from analysis. Recording of the EEG data began 200 msec prior to the warning stimulus. (For data-acquisition procedures see Donchin & Heffley, 1975.)

Two general experimental conditions were used. In *fixed-match* series the warning tone was the same on all trials in a run, the subject making the same match on each trial. In *mixed-match* series, the tones varied randomly from trial to trial, and the required match varied accordingly. For each subject each tone pitch was always associated with one match type. An additional series was used in which the subject was instructed to respond by

using a single response button to all slides. Results were obtained in a pilot study of five female subjects, all dextral (as verified by the Edinburgh Inventory, Oldfield, 1971) and all without sinistral relatives.

The reaction times and matching errors are presented in Figure 7. It is apparent that both measures differ significantly as a function of task. These data establish that the two tasks placed different demands on the subjects. This does not, of course, prove that the two tasks engaged the hemispheres differentially.

PERFORMANCE DATA FOR EACH EXPERIMENTAL CONDITION

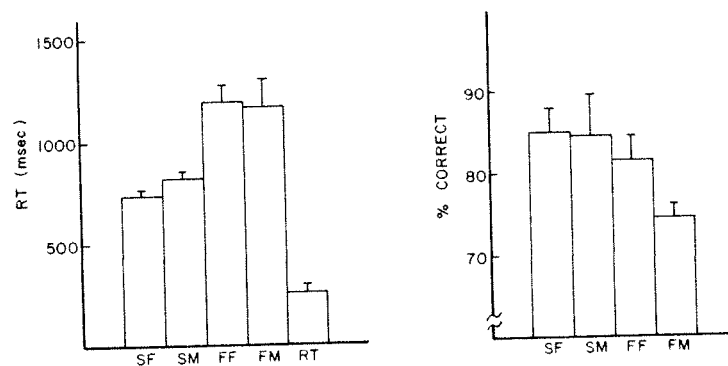


Fig. 7. Performance data (mean and standard error). Differences in reaction time ($p < .0005$, $F = 21.66$, $df = 1,16$) and in percentage correct ($p < .048$, $F = 4.57$, $df = 1,16$) between structural and functional matching are significant. Abbreviations: SD, structural/fixed-match condition; SM, structural/mixed-match; FF, functional/fixed-match; FM, functional/mixed-match; RT, baseline reaction time to signal with no match required.

Hemispheric engagement was assayed by spectral analysis of the single-trial EEG data. It was necessary to determine if changes in the distribution of power within the delta (1-3.5 Hz), theta (4-7.5 Hz), and alpha (8-12 Hz) bandwidths accompanied performance of the tasks. The data analyzed were the 2000-msec epoch, which included 1200 msec of preslide EEG as well as 800 msec of data taken while the subject was actively performing the task. Figure 8 (top frame) presents the distribution of power within each frequency band. An analysis of variance of power measures at each band was performed to determine if the nature of the matching task affected the scalp distribution of the power. Our data indicated that, within the alpha bandwidth only, the tasks differentially affected the distribution of power, primarily at the parietal electrode sites ($p < .03$; $F = 2.97$, $df = 5,20$). There is relatively less alpha activity (see Figure 8, bottom

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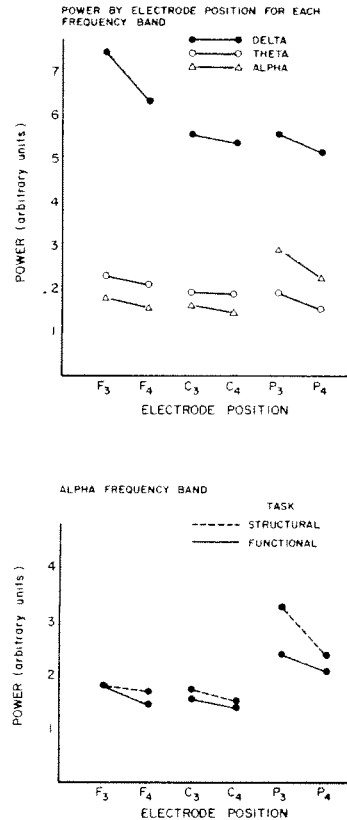


Fig. 8. Top: distribution of the mean power for the delta (1-3.5 Hz), theta (4-7.5 Hz), and alpha (8-12 Hz) bands is shown for left and right frontal (F₃, F₄), central (C₃, C₄), and parietal (P₃, P₄) electrode sites. The data for analysis were obtained from the fixed-structural or functional-match conditions. Data from 15 trials in which the subject responded correctly were used for each analysis. Bottom: the task by electrode interaction for power and the alpha band. The power associated with functional matching is lower at all electrode positions than the power associated with structural matches. The difference, however, is accentuated at the left parietal position.

frame) at the left parietal (P₃) during functional matching than during the structural matching. Our data are too preliminary to permit a strong statement concerning the relationship of these differences to hemispheric specialization; it is conceivable that the changes at P₃ are related to task difficulty--recall that functional matching was performed more slowly and less accurately than structural matching. Figure 8 (bottom) shows that the func-

tional match power is smaller than structural match power at all electrode sites. Nonetheless, the differences are interesting and provide suggestive evidence of the efficacy of our tasks in differentially engaging the hemispheres.

Of central concern in the design of this experiment was the extent to which preparation to perform different analyses, presumed to engage the hemispheres differentially, would result in the formation of asymmetric CNVs prior to slide presentation.

Grand averaged waveforms (Figure 9) for all experimental conditions reveal large asymmetries in the CNVs for all match conditions relative to the RT conditions. The most consistent asymmetries appear in the mixed conditions. Note that, when asymmetric, the left-hemisphere potential amplitudes always exceed the right-hemisphere potentials. In the mixed series, a prominent positive component appears 450 msec after the warning stimulus.

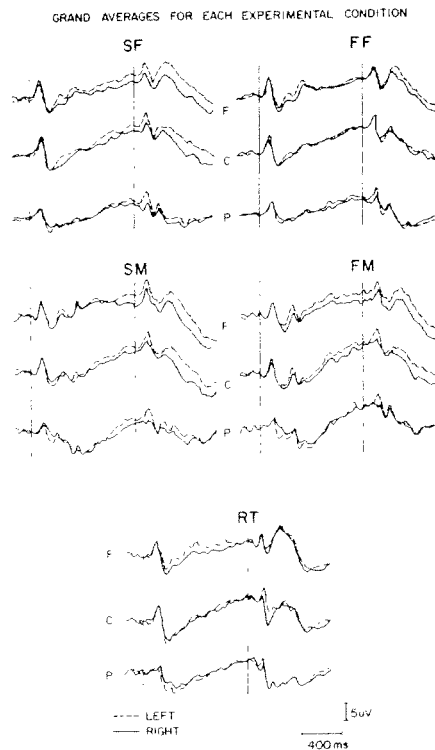


Fig. 9. Grand-averaged waveforms for frontal, central, and parietal electrode positions for all experimental conditions for all trials in which the subject responded correctly. Right (solid line) and left (dashed line) lateral positions are superimposed. The vertical lines indicate the occurrences of the warning tone (S1) and slide (S2).

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To illustrate the variability in the data, averaged waveforms from individual subjects for the mixed series are presented in Figure 10. For a more objective analysis, the waveforms from

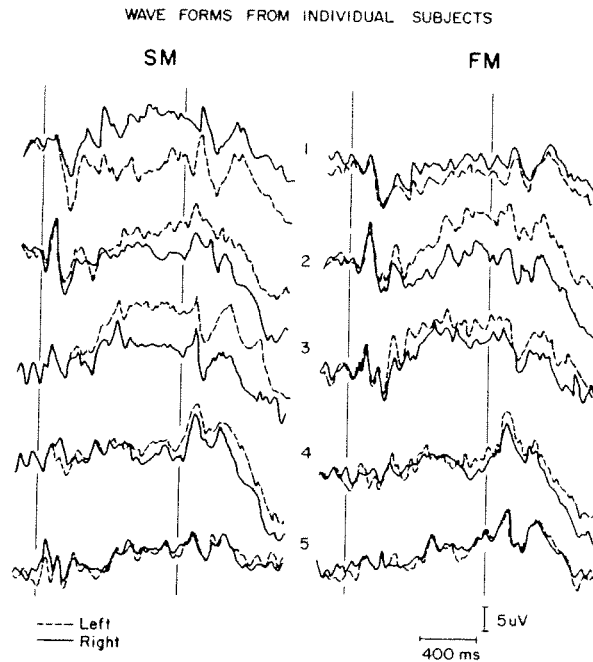


Fig. 10. ERP from five subjects for left (dashed line) and right (solid line) frontal electrode positions (superimposed) are shown for the mixed-match condition.

each subject, electrode, and condition were submitted as a data matrix to a Principal Components Analysis followed by Varimax rotation. Six orthogonal factors were extracted from the data, accounting for 78% of the experimental variance. A plot of the factor loadings, representing the degree of association of each time point with each factor, is presented in Figure 11. Such a plot identifies the temporal locus of activity for each of the factors. Factor scores, derived from these factor loadings, measure the degree to which each factor contributes to the waveforms for each condition and electrode placement. Thus, it is possible to assess the degree to which each factor is affected by the experimental conditions and to evaluate the relationships statistically. Space does not permit a full discussion of the behavior of each factor; attention will therefore be restricted to the two factors (1 and 2) clearly within the CNV region.

The time course of factor 1 is similar to that of a CNV, peak-

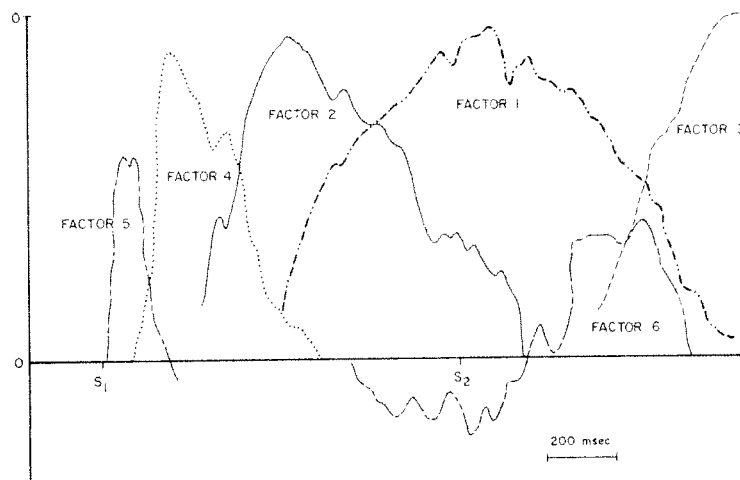


Fig. 11. Factor loadings for six orthogonal factors extracted by Principal Component Analysis and rotated by the Varimax procedure. The loadings represent the temporal locus of activity for each of the six factors.

ing just after the slide (S2). The factor scores indicate that this factor is maximal at the central electrodes declining in amplitude in the frontal and parietal electrodes ($p < .001$, $F = 20.44$, $df = 7, 28$). The decline is steeper toward the parietal than frontal sites. This scalp distribution has often been reported for the CNV. These scores also indicate that this component, which we identify with the CNV, is laterally asymmetric; it is more negative at the left hemisphere for all homologous pairs. This asymmetry appears to be affected by mode, appearing to be more marked for the mixed than the fixed series ($p < .025$, $F = 2.77$, $df = 7, 28$). The three-way interaction, electrode position \times matching task \times mode ($p < .007$, $F = 3.51$, $df = 7, 28$), indicates that this factor is largest for the two mixed conditions and indicates that the asymmetry is least pronounced in the functional fixed condition.

Factor 2 peaks approximately 475 msec after the warning tone (S1). Its latency suggests that this factor may be the same as the early component of the CNV described by Loveless and Sanford (1974, 1975) and heretofore only seen with very long interstimulus intervals. Mode has a very pronounced effect upon the anterior-posterior distribution of this factor ($p < .001$, $F = 8.05$, $df = 7, 28$). When S1 conveys no information about the task to the subject (as in the fixed series), this factor is negative at all electrode sites, appearing largest frontally. When S1 is task relevant (as in the mixed series), this component becomes positive in the parietal regions and marginally more negative frontally. The effect of matching tasks on this component is not

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statistically significant ($p < .066$, $F = 2.18$, $df = 7,28$) but nonetheless intriguing. At the frontal sites, this component appears to change its lateral distribution as a function of task; appearing larger over the left hemisphere for functional tasks and larger over the right hemisphere for structural matching.

The data just described demonstrate that CNVs of different amplitudes can be simultaneously recorded from homologous electrodes. The CNV is asymmetric when the matching mode varies randomly from trial to trial. The evidence also indicates that when the mode of matching is uniform over a block of trials (as in the fixed condition) the CNV is more symmetric. It seems then that the extent to which the asymmetry is observable may depend on the strategies the experimental situation permits the subject to adopt.

It is noteworthy that the direction of asymmetry is independent of the match required (structural versus functional). Clearly, the CNV does not reverse asymmetry in preparation for tasks that presumably engage one or the other hemispheres. A detailed replication of the experiment is now underway, using a larger sample and a richer set of control conditions. Although the new data seem to corroborate the data presented here, the nature of the observed asymmetry must be more fully elucidated in relation to the response requirements of the task.

Not directly related to the asymmetry question, yet a theoretically important aspect of these data, is the support they lend to the reports (Weerts & Lang, 1973; Loveless & Sanford, 1974, 1975), that two distinct components may operate in the CNV interval. These components vary in scalp distribution and in their sensitivity to task demands.

SUMMARY

We have reviewed the evidence for the proposition that differences between the electrical activity recorded at homologous scalp locations over the left and right hemispheres can be used to index hemispheric utilization. There seems to be adequate support for the assertion that the ratio of EEG power over the hemispheres is sensitive to task variables. The direction of the difference is to some extent consistent with predictions derived from contemporary ideas about hemispheric specializations. Of the various ERP parameters studied, the sturdiest results come from investigations of anticipatory potentials that appear to be asymmetric, again, in the predicted direction.

These trends are far from conclusive. Some methodological problems were reviewed. Attention should be paid to the independent validation of the behavioral effects of experimental instructions, to the greater sensitivity of within-group repeated-measures designs, to the choice of EEG parameters for study, and to the measurement and analysis of data.

We have presented data that demonstrate that (1) slow potentials preceding a voluntary self-paced motor response are largest over the hemisphere contralateral to the responding hand (at least in dextrals); (2) the prereshponse asymmetry can coexist with cognitive anticipations which are symmetric; (3) the prereshponse asymmetric readiness potentials appear to be followed by a prolonged potential shift with a polarity apparently inverse to that of the motor potential; (4) when the information-processing load is increased, some lateralization effects seem to occur in the CNV; and (5) both this CNV negativity and task-related shifts in power in the alpha band appear mostly as modulation of left-hemisphere activity rather than as reciprocal changes in hemispheric activities.

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