

SPECTRAL ANALYSIS OF HUMAN EVOKED POTENTIALS

by

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ABSTRACT

The purposes of this investigation were: (1) to apply spectral or frequency analysis to visual and auditory evoked potentials (EPs) recorded from the scalp; (2) to meaningfully relate the resulting frequency-domain descriptions to physiological factors such as speech dominance, stimulus modality and cortical area; (3) to determine if simple flash and click stimuli could generate left-to-right hemispheric differences, and if so; (4) to study various aspects of these differences, such as their relationship to handedness, speech dominance and stimulus modality. It was hypothesized that spectral analysis might detect EP differences that were not observable by measures of peak amplitudes and latencies, and that asymmetric responses could be generated by simple stimuli. Reviewed evidence suggested that verbal stimuli, such as speech or letters, were processed within the left, speech-dominant hemisphere, while non-verbal stimuli, such as geometric patterns or melodies, were processed within the right, speech non-dominant hemisphere. The results showed that EP amplitudes were largest over the specific projection cortex of the stimulated modality, but hemispheric differences of amplitudes were not related to the known speech dominance of epileptic patients. In contrast, coherence or similarity of form between pairs of EPs was related to speech dominance, and was greater over the speech-dominant hemisphere for click stimuli, and over the speech non-dominant hemisphere for flash stimuli. These results suggested that the amplitude of responses represented a bilateral cortical response to the sensory stimulus, while the lateralized, coherent spread represented perceptual processing or extraction of meaning from that stimulus.

TABLE OF CONTENTS

I. INTRODUCTION	1
A. General introduction of purpose	1
B. The averaged evoked potential (EP)	2
C. EP analysis	5
D. Spectral analysis	7
E. The bases of hemispheric asymmetry	12
1. Introduction	12
2. Lesion studies	12
3. Studies of split-brain patients	16
4. Dichotic listening	18
5. Asymmetries within the visual system	22
6. Handedness	24
7. Electrophysiological asymmetries	26
8. Conclusions on hemispheric asymmetries	31
F. Statement of purpose	38
II. METHODS	41
A. Introduction	41
B. Spectral analysis	41
C. Subjects	44
D. Electrode placements	45
E. Equipment and experimental conditions	47
F. Experiment I - Power spectral analysis	48
G. Experiment II - Coherence analysis	49
1. Introduction	49

2. Estimation of coherence	50
3. Analysis of variance	51
H. Experiment III - Discriminant analysis	53
1. Introduction	53
2. Spectral analysis	55
3. Asymmetry calculations	56
4. Discriminant analysis	56
III. RESULTS	58
A. Experiment I - Power spectral analysis	58
1. The EP power spectra	58
2. Statistical analysis	61
3. The temporal form of the frequency groups	61
B. Experiment II - Coherence analysis	64
1. Comparison of hemispheric asymmetries	64
2. Multivariate analysis of variance	67
C. Experiment III - Discriminant analysis	72
1. Coherence asymmetries	72
2. Discriminant equations of coherence asymmetries	72
3. Speech dominance of normal subjects	76
4. Discriminant analysis of power spectra	78
5. Coherence asymmetries and handedness	79
IV. DISCUSSION	83
A. Experiment I - Power spectral analysis	83
B. Experiment II - Coherence analysis	88
C. Experiment III - Discriminant analysis	97

V. CONCLUSIONS	105
A: Summary of spectral analysis	105
B. Physiological significance of the spectral components	107
C. Verbal and non-verbal stimuli	108
D. Implications for hemispheric functional asymmetries	109
E. Final conclusions	113
VI. BIBLIOGRAPHY	114
VII. CURRICULUM VITA	136

LIST OF TABLES

I.	Group distribution of maximum VEP and AEP coherences	65
II.	VEP and AEP coherences for single subjects	66
III.	Multivariate analysis of variance of coherence asymmetries	68
IV.	Mean coherence asymmetries	70
V.	Discriminant analysis of coherence asymmetries	73
VI.	Distribution of speech dominance in each subject group	77
VII.	Discriminant analysis of power spectral asymmetries	79
VIII.	Analysis of variance of right and left-handed subject's coherence asymmetries	81

LIST OF FIGURES

1. Typical averaged evoked potentials	3
2. Electrode placements for recordings	46
3. Primary projection area EPs and spectra	59
4. Non-primary projection area EPs and spectra	60
5. Median, occipital-minus-temporal spectra	62
6. Digitally filtered 0-5 hz. and 6-12 hz. components of EPs	63



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## INTRODUCTION

Evoked potentials (EPs), which are small EEG transients generated in response to peripheral sensory stimulation, have been useful in the investigation of the cortical mechanisms of sensory information processing. Among these have been the demonstration that EP asymmetries may be related to hemispheric asymmetries such as speech dominance, and possibly handedness. Most investigations, however, have concentrated upon the temporal form of the EPs, and only a few upon their frequency characteristics.

The purpose of the present investigation was to apply frequency analysis of EPs to the study of various cortical asymmetries. To define this purpose more clearly, however, a review is necessary of evoked potential analysis, frequency or spectral analysis, and aspects of hemispheric asymmetry.

## B. The averaged evoked potential

Evoked potentials (EPs) are small amplitude transients in the EEG recorded from the scalp. They are typically of 1 to 20 microvolts in amplitude against a background EEG which ranges from 2 to 100 times larger. EPs can be generated in response to many types of stimuli, but in this thesis only visual evoked potentials (VEPs) and auditory evoked potentials (AEPs) will be investigated.

Fig. 1 shows some typical EPs generated with flash and click stimuli. A fair degree of variation is present both within the EPs of one subject recorded from different areas and between subjects. Many schemes have been suggested to label the peaks in a consistent morphology (for example: Ciganek, 1961; Gastaut and Régis, 1965; Goff, Matsumiya, Allison and Goff, 1969). None of these schemes has gained full acceptance, though, primarily because of the variability of peak latencies, amplitudes and appearance between recording areas and between subjects.

Since the EP amplitudes are of very much smaller amplitude than the background EEG (2 to 100 times), analysis of a single EP is almost impossible. To accentuate this small waveform against the larger ongoing activity, the averaging technique has been developed. Using a small laboratory computer, many EPs are averaged which in effect retains EEG changes which consistently occur with the presentation of the stimulus, and rejects those that do not.

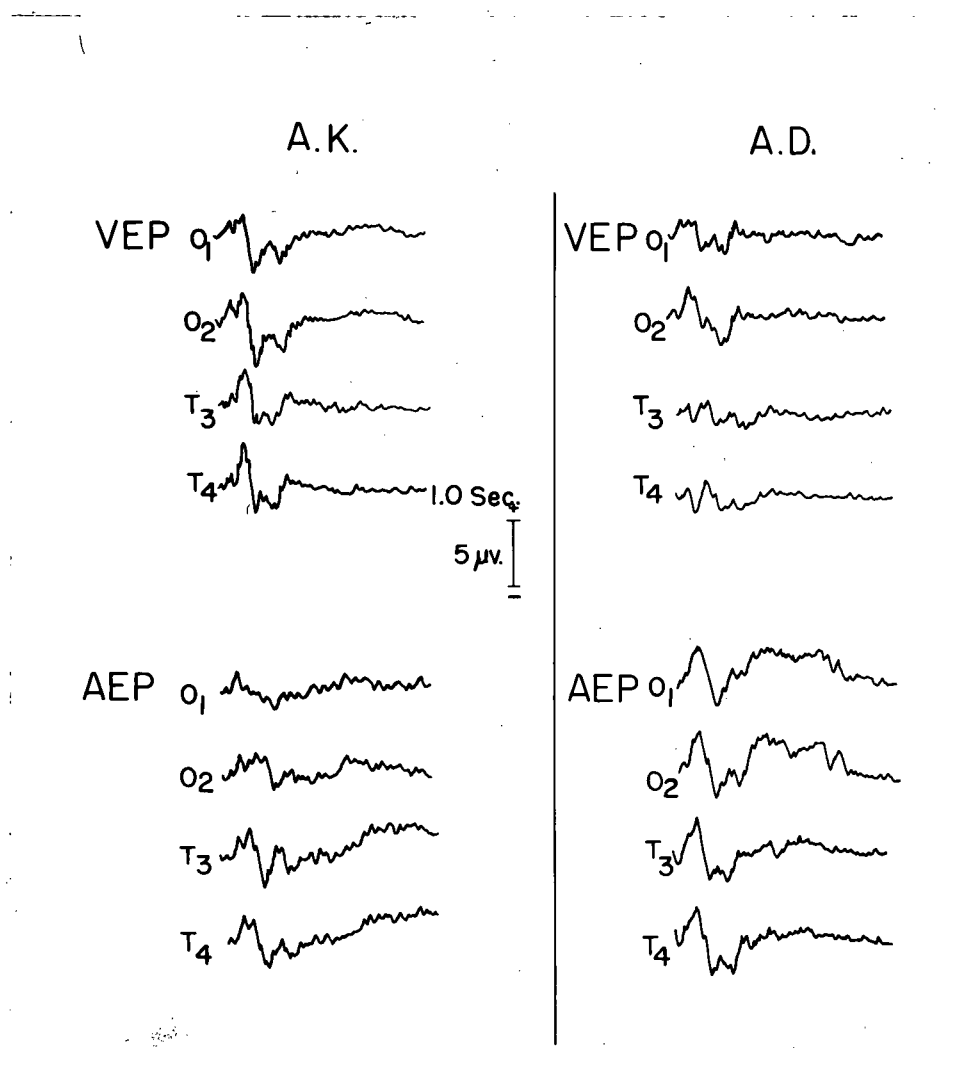


Figure 1

Some typical, averaged ( $N=40$ ) evoked potentials for flash stimuli (VEPs) and click stimuli (AEPs). Left and right occipital (O<sub>1</sub> and O<sub>2</sub>) and left and right temporal (T<sub>3</sub> and T<sub>4</sub>) electrode placements. Two subjects (AK and AD). Each EP is 1 second duration.

The averaging technique is widely used because of its simplicity and because of the many insights it has given into cortical responses to sensory stimuli. It does, however, make certain assumptions about the EP "signal" and the EEG background "noise". The signal is assumed to be time-locked to the stimulus presentation, while the noise is assumed to be independent of the stimulus. It is further assumed that neither the signal nor the noise change with repeated presentations of the stimulus. In particular, this means that the stimulus presentation has no effect on the background EEG that would be recorded if no stimulus were present.

The EEG clearly does not exactly satisfy the assumptions of averaging. For instance, EP amplitudes and latencies change as the subject habituates to the stimulus (Walter, 1964), so the EP form is not constant over time. Complex interactions also occur between the EP and EEG. Background EEG is affected by the stimulus presentation (Gibson and Broughton, 1969; Woods and Broughton, 1969), and EPs recorded during low alpha conditions are of greater amplitude and are less variable than those recorded during high alpha conditions (Spilker, Kamiya, Callaway and Yeager, 1969).

Many more examples could be presented to show that the EEG does not satisfy the theoretical assumptions necessary to derive averaged EPs. The key question, however, is whether these variations from the ideal are small enough to ignore. Since its introduction by Dawson (1951; 1953), signal averaging of physiological data has presented many useful insights.

Generally, it seems that if the variability of individual EPs is considered in the design of experiments, and if situations are avoided where this could become a major factor, the averaged EP technique can be used to derive results which agree with and extend other behavioral and electrophysiological data. This observation has been made many times, and the results of this thesis will demonstrate it again.

### C. EP analysis

The EP consists of an oscillating waveform. Two basic approaches exist for the analysis of this waveform and each makes assumptions about the nature of EP generation. One is called time-domain analysis and the other frequency-domain analysis.

The time-domain approach assumes that the series of peaks in the EP represents some aspect of a sequence of temporal events. That is, the peak at one time interval of the EP is generated by a different process than the peak at another time. The EP is thus considered to be a sequence of events which are triggered one after the other.

The frequency-domain approach assumes that the frequency components of the EP represent some aspect of the cortical response to the stimulus. In other words, the EP components at different frequencies are related to different processes. From this viewpoint, the various peaks of the EP would be considered to be primarily generated by one oscillatory process if they were all in the same frequency range.

The time and frequency-domain analyses thus make fundamentally different assumptions about the way in which EPs are generated. Time-domain analysis assumes that different peaks at different times are produced by different processes, while frequency-domain analysis assumes that different frequencies are produced by different processes.

The assumptions of EP generation implicit in these two approaches have been neither proved nor disproved, and the investigation of the mechanisms remains an active area of research. Both peak and frequency components have been shown to be related to physiological events, and either can be useful in obtaining information on cortical responses to sensory stimuli (Regan, 1972).

#### D. Spectral analysis of EPs

One way of examining the frequency components of evoked potentials is through the use of spectral analysis. This application of the technique is almost completely unexplored, so most of the introduction below has few references to EP studies.

In essence, spectral analysis decomposes a signal or waveform into a sum of sinusoidal components of different frequencies. The amplitude and phase shift of each component with respect to the temporal origin of the signal are such that when summed together, they will produce the original waveform. Measures of amplitude and phase are thus available from this decomposition for each frequency component. In addition, the similarity of form and phase relationships between each pair of waveforms can be derived.

The mathematical techniques of spectral analysis are well developed (Blackman and Tukey, 1956; Jenkins and Watts, 1968; Hannan, 1970), and are based on calculating the fourier transform or spectrum of the signal. This spectrum is a set of numbers which describes the amplitude and phase of each frequency component of the waveform. In this thesis, the spectra are calculated using conventional procedures incorporated in a standard spectral analysis program from the UCLA Biomedical Computing Facility (Dixon, 1973). A brief outline of the program is included in the Methods section.



Power spectral analysis is a method of examining the power or amplitude of each component in the spectrum independently of its phase relationships. This phase removal allows simple comparisons between signals of the distribution of amplitudes at different frequencies.

Analysis of the power spectra of EEG has been useful in attempts to quantify the visual reading of records for abnormalities (for example: Walter, 1963; Hord, Johnson, Lubin, Naitoli, Nute and Austin, 1969; Wennberg and Zetterburg, 1971; Giannitrapani and Kayton, 1974). However, there are many problems concerning the selection of samples, sample length, and the time-varying characteristics of the EEG. In addition, the many divergent theories of EEG generation have limited the usefulness of power spectral analysis in the interpretation of the normal cortical processing of sensory information.

In contrast to the many applications of power spectral analysis to EEG, very few attempts have been made to similarly analyze EP waveforms (Shipley, Jones and Fry, 1968; Emrich and Michael, 1970; Regan, 1972). But, these waveforms are in some ways ideal for this method since they have a precisely known starting point and are fairly stable and repeatable. Their short duration, however, creates several disadvantages. The spectral estimates are quite variable and the original data may not be closely gaussian or normal as assumed by the technique. These two problems can be overcome by pooling the results of many subjects so that the populations approach normality (central limit theorem of statistics; Snedecor and Cochran, 1967) and by statistically analyzing the results of all subjects as a group.

When two or more waveforms are available, comparisons can be made between them by using the cross-spectrum. This is derived from the spectrum of each waveform and expresses the totality of relationships between all the waveforms. It can be shown (Jenkins and Watts, 1968) that the power spectrum of each waveform and the similarity of form between each pair of waveforms, derived from the cross-spectrum, constitute this total description.

Similarity of form is measured by the coherence, which is somewhat similar to correlation, except that coherence measures correlation between two waveforms after constant phase shifts between them have been removed. For example, if an occipital EP has exactly the same waveform but occurs earlier than a temporal EP, they will be shifted in phase with respect to each other. Their correlation will thus be less than unity since they do not behave the same at each time. The coherence between them, however, will be nearly unity since they will be highly correlated after the phase shift between them has been removed. In this sense, coherence measures similarity of form between two waveforms, independently of whether they occur together or at different times.

Once spectral quantities such as the power spectra and coherences have been calculated, a technique is necessary for identifying the differences that occur with different stimulus conditions or subjects. Discriminant analysis (Snedecor and Cochran, 1967; Afifi and Azen, 1970) is such a technique, and is based on selecting properties of the data which

best discriminate between the groups of interest. Generally, the criterion of "best" is a probabilistic one in which the significance of each property's relationship to the group is evaluated. As an example of its use, discriminant analysis could be used to identify which frequency or peak components of the EP were most affected by experimental conditions, such as stimulus modality or attention, or by subject characteristics, such as handedness or speech dominance.

Previous applications of discriminant analysis of evoked potentials have been made in the identification of changes in their time-domain characteristics during shifts of selective attention (Donchin, 1967); in schizophrenic versus normal states (Donchin, Callaway and Jones, 1970); and during various types of cognitive tasks (Donchin, Kubovy, Kutas, Johnson and Herning, 1973). Using a computer simulation of EP generation, Donchin and Herning (1975) have shown that the technique is a powerful and reliable means of detecting significant differences between EPs. However, no use has yet been made of it in detecting differences in the frequency characteristics of EPs.

Differences between different responses can also be detected with analysis of variance (Snedecor and Cochran, 1967; Winer, 1971). This technique assumes that the observed responses can be broken down into a number of components, called effects, and interactions between these components. For example, the amplitude of a certain peak of the EP could be observed with different stimulus intensities and colors. Intensity and color would be the two effects, and their interaction would measure

how the pattern of response to different intensities depended on the color.

Although the analysis of variance is a well-known technique in the behavioral sciences, its use in the evaluation of EEG or other spectra seems to have been limited. This may be due to the fact that many investigators with sufficient mathematical background to use spectral analysis, such as electrical engineers or geophysicists, often have a poor understanding of general statistics. Recently, however, this trend seems to be reversing. For example, Giannitrapani and Kayton (1974) have used an analysis of variance of the EEG power spectra of schizophrenic patients and normal subjects to show differences in their dominant frequencies.

#### A note on coherence:

Coherence, as used in this thesis, is actually the magnitude of a more general quantity called the complex coherence, which consists of both a magnitude and a phase. The magnitude measures the degree of similarity of form between two waveforms, while the phase term measures the phase shift between them at which the magnitude is measured. Intuitively, a complete set of any number of waveforms can then be described by their amplitudes or power spectra, their similarities of form or magnitude of coherences, and the phase of coherences between them.

## E. The bases of hemispheric asymmetries

### 1. Introduction

Functional differences between the right and left cerebral hemispheres have been known since the early 1800s. From that time until the 1960s, this knowledge was based almost completely on neurological studies of patients with lesions localized in various cortical areas. In the last decade, however, a variety of behavioral and electrophysiological techniques have become available for the elucidation of hemispheric differences with a wide variety of stimulus conditions and tasks using normal subjects. The purpose of this section is to review these findings, both old and new, and to place them in a suitable perspective for the investigations of hemispheric asymmetry using spectral analysis.

### 2. Lesion studies

Brain asymmetries were first observed in neurological patients with lesions in various cortical areas. Although the inference of function on the basis of the interruption of some aspect of that function must always be made cautiously, a large body of reliable knowledge has accumulated.

The first contributions to this knowledge of the relationship of brain lesions to behavioral deficits of speech and language were noted by Broca (1861) and Wernicke (1874). Their critical observation was that many varieties of speech disorders were almost invariably

linked with lesions in the left hemisphere. Over the years, many aspects of these disorders became apparent, such as the necessity of communicating links to and from the visual centres for reading and writing, and the auditory areas for understanding spoken words. Today, the interrelationships of these areas are well understood from a neurological viewpoint. That is, most deficits can be understood in terms of the pathways and centres which are interrupted or destroyed by the lesion.

The modern contributions to differential left and right hemispheric involvement in the behavior of neurological patients have been mostly based on interruptive processes, either pathological as in tumours, strokes, etc., or intentional as in surgery. Missile or penetrating wounds (Luria, 1969) have been useful but the uncertainties of sites and entering paths have limited the localization of lesions. Stimulation of the cortex during surgery (Penfield and Roberts, 1959) has also been limited because of the short time that is available with each patient, and because only certain structures are accessible. Temporal lobectomy (Milner, 1961) for the treatment of epilepsy has produced a large amount of information. However, the extent of long-time abnormalities and the possibility of compensating mechanisms make these observations uncertain in their extension to normal subjects (Geschwind, 1970). The Wada test (Wada, 1949; Wada and Rasmussen, 1960), in which sodium amytal is injected into one carotid artery, has been a major source of information concerning the cerebral lateralization of language function.

All of the above lines of evidence, in which cortical processes are interrupted, have suggested relatively clearcut differences between the functions of the left and right hemispheres. Lesions of the left, parieto-temporal areas generally interfere with some aspect of language production or comprehension (Hecaen, 1962), and often at the highest levels of the language process. For example, the patient may produce seemingly normal, grammatically correct sentences, but which are almost empty of meaning (Geschwind, 1970). In contrast, the right, parieto-temporal areas are more involved in processes that require non-verbal analysis. Lesions of these areas result in decreased scores on spatial reasoning or discrimination tests (Weinstein, 1962); decreased ability to localize sounds (Neff, 1962); and an inability to understand the meaning of pictures (Critchley, 1962). Patients who have had right temporal lobectomies are impaired on auditory tasks using non-verbal materials, but cannot be differentiated from normal subjects in their performance on verbal tests (Shankweiler, 1966). These same patients perform less well than normal subjects on tests of visual discrimination (Meir and French, 1965; De Renzi and Spindler, 1966). These deficits are especially pronounced with patterns less liable to verbal identification (Milner, 1967).

Asymmetries between the left and right hemispheres also extend to the mechanisms of memory and learning. Focal lesions of the left temporal lobe usually interfere with the efficiency of verbal memory while sparing non-verbal skills, while the converse is true with right temporal lesions (Fedio and Mirsky, 1969; Milner, 1970).

For visually presented material, Milner (1968) has shown perceptual and recognition disorders among right-temporal patients on tasks which use non-verbal stimuli which are not easily decoded into verbal symbols. Conversely, left-temporal patients are consistently impaired in the memorization of visually presented verbal material (Milner, 1969; Samuels, 1971).

Gerner, Ommaya and Fedio (1972) further elucidated the mechanisms involved in these asymmetries of memory. They showed that both left and right-temporal patients had an intact immediate memory span for a long string of verbal or non-verbal material. However, when the test sequence exceeded this memory span, the left-temporal patients did poorly on verbal material, and the right, on non-verbal material.

The complex interactions that occur between seeing, classifying and associating shapes have been investigated by Bisiach and Faglioni (1974). They found that patients with left brain damage were slower than those with right brain damage in recognizing associations between random shapes. This seems at variance with earlier studies which have suggested that spatial processing of patterns is a right hemispheric function. However, they suggested that their results support the hypothesis that the transformation of meaningless shapes into meaningful shapes may be a left hemispheric function which is independent of verbal labelling. This same hypothesis had been suggested earlier by Boller and De Renzi (1967). In support of this, they showed that left-brain damaged patients had the poorest performance for paired stimuli with low measures of association. That is, left hemispheric lesions interfered with the ability to make associations between visual



or spatial patterns.

### 3. Studies of split-brain patients

Another source of evidence for the lateralization of perceptual functions is behavioral data collected from epileptic patients who have had their corpus callosum bisected along the midline. Originally, this radical technique was performed as a final attempt to control the spread of intractable seizures from one hemisphere to the other (Sperry, 1964; Sperry, Gazzaniga and Bogen, 1969). It soon became apparent, however, that these split-brain patients, as they became known, displayed some remarkable perceptual and motor asymmetries which could only be explained on the basis of the lateralization of verbal and non-verbal processing capabilities (Gazzaniga, 1970; Sperry, 1973).

In split-brain patients, stimuli can be selectively transmitted to the right or left hemisphere by presentation in the left or right visual field for visual stimuli, or to the left or right ear for auditory stimuli. Because of the sectioned corpus callosum, no interhemispheric communication exists and so one hemisphere cannot receive information from the other. Using this technique, a patient can name an object shown to him in the right visual field but not when it is shown in the left. Presumably, this occurs because an object in the right visual field is perceived within the left, language-dominant hemisphere, so the patient can name it. Presentation in the left visual field, however, only informs the right hemisphere. Since this hemisphere

has little or no linguistic capability, the patient cannot communicate in words what he has seen. He can point to a picture of what he has seen, thus indicating that the right hemisphere does have perceptual capacities, but these are not verbally oriented (Sperry, 1964, 1969; Gazzaniga, 1970).

The superiority of the right hemisphere for spatial reasoning can be shown by a variety of tests. For instance, the patient's right hand, under the control of the left hemisphere, can write almost normally, but is practically unable to copy geometric figures. Conversely, with his left hand, controlled by the right hemisphere, the patient can copy geometric figures but cannot write words (Bogen and Gazzaniga, 1965; 1970; Sperry, 1968).

As with lesion studies, the split-brain patients have also provided evidence for the lateralization of different aspects of verbal and non-verbal memory. Milner and Taylor (1972) have shown that the right hemisphere is superior in the tactile pattern recognition of previously presented patterns. Teng and Sperry (1974) demonstrated that the right hemisphere is faster and more accurate than the left hemisphere in apprehending the number of dots in a briefly presented pattern. They suggested that this may be due to the right hemisphere's greater ability to remember patterns, so counting could continue after the pattern had disappeared. Better dot counting ability has also been observed in the right hemisphere of normal subjects (Kimura, 1968).

Evidence from split-brain patients has also shown that the left and right hemispheres normally shift in their predominance. This shift depends on the type of cognitive task being performed. For instance, verbal tasks such as reading, speaking or writing seem to be primarily left hemispheric, while non-verbal tasks such as listening to melodies or doing geometric puzzles are primarily right hemispheric functions. In split-brain humans, both verbal and non-verbal processing can take place simultaneously to a greater degree than in normal subjects. For example, different stimuli can be simultaneously presented to each hemisphere, and different simultaneous responses obtained from the left and right hands (Teng and Sperry, 1973; Levy, Trevarthen and Sperry, 1972; Gazzaniga and Hillyard, 1973; Teng and Sperry, 1974). These results suggest that in the normal person, the functions of the left and right hemispheres cannot operate independently and simultaneously.

#### 4. Dichotic listening

The study of neurological and split-brain patients has provided a great deal of information about left and right hemispheric differences. However, all of this has been based on patients whose abnormalities involve the very functions on which the conclusions are based. Since about 1960, several new techniques have become available to circumvent this problem by studying hemispheric asymmetries in normal subjects.

Dichotic listening is one of these new techniques. It has been especially useful in more clearly defining what type of sounds are "verbal" and what type are "non-verbal".

Kimura (1961, 1963) first used the simultaneous presentation of two auditory stimuli, a different one to each ear, to show that generally one or the other ear was consistently more accurate in hearing. Ear superiority can shift to either the left or the right, depending on the stimulus characteristics and the task in which the subject is engaged. Tests of this superiority have mostly been based on accuracy of recall, ability to make fine distinctions between sounds, and reaction times.

The recall superiority of the right ear has been shown for dichotically presented digits (Kimura, 1961; Bryden, 1963); nonsense syllables (Kimura, 1967); word sequences (Bartz, Satz, Fennell and Lally, 1967); and backwards and forwards speech sounds (Kimura and Folb, 1968). Presumably, the right ear superiority for all of these speech sounds reflects the prepotency of the contralateral auditory pathway and the left hemisphere's specialization for the perception of speech (Kimura, 1961; Studdert-Kennedy and Shankweiler, 1970). Ingram (1975) reported that these right ear superiorities occurred in children as young as 3 years of age, which may reflect the very early development of speech specialization within the left hemisphere.

In contrast to these superiorities of the right ear for speech sounds, the left ear is generally superior for melody recognition (Kimura, 1967; Bartholomeus, 1974). This was interpreted as meaning that the left hemisphere predominated for verbal processing and the right hemisphere for non-verbal processing. These were operational definitions, however, since the concepts of "verbal" and "non-verbal" were still defined in terms of how the brain reacted to them, rather than some precise characteristic of the stimulus (Kimura, 1967).

Left ear, and consequently inferred right hemispheric superiorities were also found for other non-verbal stimuli. The recognition of voices (Doehring and Bartholomeus, 1971); frequencies (Yund and Efron, 1974; Efron and Yund, 1974); and tonal contours of non-speech sounds (Blumstein and Cooper, 1974) were among these.

The above results suggested that different types of sounds were processed differently. Language-related sounds such as speech, nonsense syllables, and digits were processed more efficiently by the left hemisphere, while non-verbal sounds such as voices, melodies and tones were processed within the right hemisphere.

Several workers have attempted to determine the primary characteristics of stimuli which direct their processing to either the right or left hemisphere. Kimura and Folb (1968) showed that stimulus familiarity, meaningfulness and conceptual content had no effect on ear superiorities. Shankweiler and Studdert-Kennedy (1967) demonstrated a strong right-ear

superiority for consonant-vowel syllables, but only a weak right-ear superiority for vowels.

From this and other work, Studdert-Kennedy and Shankweiler (1970) proposed that the essential feature that initiated right-ear superiority was the presence of phonetic information encoded in the sounds. They further suggested that both the left and right hemispheres were equipped for processing the auditory parameters of speech, such as pitch, loudness, timbre and duration, hence the almost equal ability of each to respond to vowels. The left hemisphere, however, was supposed to be more able to extract linguistic parameters or meanings from the sounds as represented by the vowel-consonant combinations (Studdert-Kennedy, Shankweiler and Pisoni, 1972).

The theories of Studdert-Kennedy and Shankweiler ignore a critical point, however. The technique of dichotic listening presents stimuli which must be decoded and acted upon by the subject; for instance in the recognition, recall or repetition of digits, phonemes, etc. Bartholomeus (1974) has suggested that not only the stimulus properties, but receptor properties (ie. - the subject!) are important in determining ear dominance. She showed that when the same sequence of letters was sung by two different singers, and to two different melodies, the subjects showed a left ear superiority when they were attempting to identify the melody, and a right ear superiority when they were trying to identify the letters. Thus for the same stimulus, ear superiority can shift to either the left or right, depending on the type of cognitive task in which the subject is engaged.

## 5. Asymmetries within the visual system

Dichotic presentation of auditory information can be used to elicit hemispheric differences in the response to verbal and non-verbal stimuli. Analogously, visual stimuli can be presented to either the right or left visual fields, thus channeling visual sensory input to either the left or right hemispheres.

Overall, this technique has shown that perception of material which can be encoded in words is superior in the right visual field, and hence left hemisphere. Conversely, perception of sensory material with complex spatial attributes is superior in the left visual field (Milner, 1971; Kimura, 1973; Berlucchi, 1974). These asymmetries have been attributed to: (1) the anatomical arrangement of retino-cortical connections, providing for the representation of each half of the visual field in the contralateral hemisphere; and (2) the specialization of the left hemisphere for verbal analysis, and of the right hemisphere for spatial analysis.

Reaction times, which presumably reflect the speed of perceptual processing, are similarly lateralized. Presentation of stimuli in the right visual field, and hence left hemisphere, allows faster naming of alphabetic letters (Moscovitch and Catlin, 1970; McKeever and Gill, 1972). Geffen, Bradshaw and Wallace (1971) found that the speed and accuracy of response to verbal material was greater in the right visual field, and to spatial material in the left visual field. Davis and Schmit (1971), however, found no differences to verbal material.

The recognition of words, rather than letters or geometric shapes, is more accurate in the right visual field (McKeever and Huling, 1971), and independent of their orientation (MacKavey, Curcio and Roseo, 1975). Mere detection of a verbal stimulus, however, is not sufficient to produce asymmetries. Geffen, Bradshaw and Wallace (1971) showed that when a single, meaningless verbal response was made to a digit presented in either visual field, there were no differences in reaction times. But, when the digits had to be named, numbers in the right visual field were responded to more quickly.

The possible mechanisms of the right and left visual field asymmetries have only been recently investigated. Rizzolatti, Umiltà and Berlucchi (1971) proposed that verbal and non-verbal information might be transferred at different rates within each hemisphere. However, this seems unlikely since it would require the optic tract, for instance, to "know" that it is carrying a pattern of verbal information, such as a word, or of spatial information, such as a geometric shape. Kinsbourne (1970, 1972) hypothesized that the faster reaction times for some stimuli might be due to lateral asymmetries of attention, which were directed to the left hemisphere for verbal stimuli and to the right for non-verbal stimuli. However, Berlucchi, Brizzolari, Rizzolatti and Umiltà (1974) showed that the asymmetries persisted with randomized presentation of verbal and non-verbal material, thus precluding the subject's attention to one type of information. The final hypothesis, which is still unproven by the visual presentation techniques, is that the asymmetries are a result of the specialization of the left hemisphere for the processing of verbal material, and of the right hemisphere for the processing of non-verbal material.



## 6. Handedness

Handedness is a more obvious expression of asymmetric function than some of the more subtle differences described above. However, its relationship, if any, to these other asymmetries is still very unclear.

Initially, the possible relationship of right-handedness to the representation of speech function within the left hemisphere was suggested by the neurological finding that most patients with left speech dominance, as it came to be called, were also right-handed. In addition, the speech of left-handed patients was also reported to be less affected by left temporal lesions, indicating a possibly bilateral or even right hemispheric representation of speech. These results were noted for pathological lesions (Benton, 1962; Hecaen and Ajuriaguerra, 1964); temporal lobectomies (Milner, 1962); pharmacological paralysis (Branch, Milner and Rasmussen, 1964); and for electrostimulation of the exposed cortex (Penfield and Roberts, 1959).

In the years since these observations were made, many exceptions have been reported. It is now generally accepted that cerebral laterality for language and handedness are not directly linked, and one does not determine the other (Heilman, Coyle, Gonyea and Geschwind, 1973; Heilman, Gonyea and Geschwind, 1974).

In normal subjects, however, significant differences seem to exist between the cognitive abilities of right and left-handed subjects. Early studies showed that left-handed children scored lower on IQ tests than

their right-handed classmates (Clark, 1957), but more recent work suggests that these decrements are confined to mixed or ambidextrous individuals (Zangwill, 1962; Berman, 1971).

Other perceptual capacities may also be depressed in left-handed persons. Levy (1969) showed that, while right-handers scored about equally well on verbal and spatial or non-verbal reasoning tests, left-handers with equally high verbal scores did substantially worse on non-verbal tests. Another study by Miller (1971), however, found this pattern to be only present in mixed handed individuals. Nebes (1971) also demonstrated that left-handers performed more poorly in the perception of part-whole relationships than did right-handers. This is normally considered to be a right hemispheric, non-verbal function.

Nebes and Briggs (1974) extended the deficits of left-handers to the retention and recall of visual material. They showed that right-handers did better than either mixed or left-handers at reproduction from memory of sets of geometric shapes. This supported a hypothesis by Levy (1969), who suggested that the possible lack of hemispheric specialization in these non-right-handed individuals was detrimental, and due to a basic incompatibility between verbal and visuo-spatial modes of processing. Thus, if non-right-handers had their spatial functions primarily within the right hemisphere as well as speech and motor control of their left side, the functions would tend to interfere. This possibility is supported by the observation that split-brain patients can carry on a verbal and non-verbal task simultaneously to a greater degree than can normal subjects.

## 7. Electrophysiological asymmetries

The lesion and psychophysical evidence presented for perceptual asymmetries both have defects. Lesion data is limited because inferences about normal processes are made from abnormal conditions, while measurements of subject responses such as reaction time, recall accuracy and so forth involve complex cortical processes whose principles are only very vaguely understood.

Primarily within the last decade, electrophysiological approaches have been developed which eliminate these problems, although posing a few new ones as well. With these techniques, the perceptual asymmetries of normal subjects can be investigated, either with or without the subject's overt participation. In these experiments, it is assumed that the electrical events occurring concurrently with physiological responses are in some way directly related to the underlying cortical processes.

Transitory EEG changes or evoked potentials generated in response to monaural click stimuli were reported as early as 1946 by Tunturi, and again in 1954 by Rosenzweig. Both authors reported that these responses were of largest amplitude over the auditory cortex contralateral to the stimulated ear. Vaughn and Ritter (1970) repeated these findings, and also reported that the largest asymmetries between cortical areas occurred over the left hemisphere of right-handed subjects. However, Ruhm (1971) reported that the temporal responses were greater in the right hemisphere than in the left for stimulation of the right ear, and that no consistent asymmetries were found for stimulation of the left ear. Peters and

Mendel (1974) also were unable to discriminate between the peak amplitudes of early components (less than 50 msec.) generated by either monaural or binaural stimuli. Finally, to confuse the picture even more, Peronnet, Michel, Echallier and Girod (1974) claimed that right hemispheric responses were greater than those of the left for tone stimuli.

The latencies of evoked potentials in relationship to hemispheric asymmetries have also been the subject of controversy. Majkowski, Bochenek, Bochenek, Knapik-Fijalkowski and Kopec (1971) reported that shorter latencies occurred contralateral to the stimulated ear in 22 of 29 subjects. Peters and Mendel (1974) however, were unable to discriminate between the peak latencies of early components generated in response to monaural or binaural stimuli.

To determine the nature of stimuli which would elicit asymmetrical responses, several types of stimuli have been used which were more structured than simple clicks. Morrell and Salamy (1971) used natural speech stimuli to produce evoked potentials which were largest over the left hemisphere, particularly the temporo-parietal areas. Molfese (1972) recorded evoked potentials which were of greater amplitude in the left hemisphere for speech stimuli, and in the right hemisphere for musical stimuli. Importantly, these asymmetries were detected in babies of less than one year's age, which suggests that lateralization may occur at an early age.

The distinction between the responses to verbal and non-verbal stimuli was further investigated by Wood and Goff (1971), using binaural stimuli during two auditory discrimination tasks. One of these tasks

involved the analysis of acoustic parameters for making a consonant or linguistic distinction, while the other required the analysis of frequency parameters with no linguistic information. They found that the magnitude of evoked potentials generated in response to these 2 stimulus types differed within the left hemisphere but not within the right.

In contrast to verbal and non-verbal stimuli, Matsumiya, Tagliasco, Lombroso and Goodglass (1972) showed that hemispheric asymmetries of amplitudes were also dependent on the meaningfulness of the stimulus. The subjects were required to attend to either single isolated words embedded in non-speech sounds, or to full sentences of instructions. The largest, left-to-right, hemispheric asymmetries of amplitude were obtained when the subject had to use each word maximally in the full sentences. Smaller asymmetries were obtained when the subjects had to count the number of words. It was concluded that stimuli which were a consistent part of a larger whole, such as words of a sentence, produced larger amplitude asymmetries than those same words embedded in a meaningless background.

Similar relations to stimulus meaning were demonstrated by Sharrard (1973), who found that evoked potential amplitudes were greater for a 64 word message played forwards, then for the same message with each word reversed. Words with symmetrical rise and fall times also produced this result, but no consistent laterality effects were observed with either type of stimulus sequence.

Evoked potentials generated in response to visual stimuli have also demonstrated asymmetries. In right-handed subjects, Eason and White (1967) showed that latencies were shorter in the right hemisphere for flash stimuli, but Culver, Tanley and Eason (1970) were unable to replicate these findings. Buchsbaum and Fedio (1969, 1970) attempted to elicit asymmetries with visual stimuli containing verbal or non-verbal information. They recorded the evoked potentials generated with presentation of random dots, words composed of dots, and geometric patterns composed of dots. The amplitudes of responses were found to differ more, and were more variable within the left hemisphere. This suggested that verbal stimuli were processed within a more localized area of the left hemisphere. However, Regan (1972) has pointed out that scalp potentials associated with possible movements or preparation for vocalization of the presented words could have caused these asymmetries.

The above observations of hemispheric asymmetries of EPs have been questioned by Friedman, Simson, Ritter and Rapin (1975). Using statistical tests which they considered to be more appropriate than those used earlier, they were only able to detect amplitude asymmetries generated with speech sounds in 2 out of 8 subjects. A review of earlier results pointed up flaws of design, statistical technique and inconsistencies in reported findings. They suggested that while evoked potentials may sometimes reflect differences in hemispheric functioning, this effect is marginal at best. Their opinions were based on the analysis of amplitude and latency asymmetries of individual peaks of the waveforms.

EEG studies have also suggested laterality of function. Galin and Ornstein (1971) showed that the proportion of total EEG alpha power decreased in the hemisphere engaged in the cognitive task. For example, when the subject was performing a verbal task, the proportion of left hemispheric power decreased; when he was performing a spatial task such as fitting geometric puzzles, the proportion of right hemispheric alpha power decreased.

Continuing these investigations of alpha asymmetry, McKee, Humphrey and McAdam (1973) showed that the proportionate power within the left hemisphere dropped during a linguistic task, and within the right hemisphere during a musical task.

Alpha asymmetries also exist for tasks involving different types of mental imagery. Robbins and McAdam (1974) measured the hemispheric proportion of alpha power when the subjects were engaged in covert imagery modes: shapes and colors, words, or both shapes and words. Alpha power dropped in the left hemisphere for the verbal imagery mode, and in the right hemisphere for the visual imagery mode.

Galin and Ellis (1975) also observed asymmetries of evoked potential amplitudes which were related to cognitive task. As with the EEG, the proportion of evoked potential power and amplitudes decreased in the hemisphere engaged in the cognitive task. These findings were also extended to memory and recall. For the visual task, the subjects were required to memorize a geometric pattern, and then reconstruct it. For

the verbal task, they were required to memorize a word passage, and then rewrite it from memory. Similar asymmetries were observed as described above.

In an interesting extension of these findings, Dumas and Morgan (1975) found that engineers and artists did not show significant differences in the shifting of alpha power as a function of cognitive mode. That is, both groups decreased their alpha power in the hemisphere engaged in the task and these decreases were the same for both groups. The authors had originally hypothesized that artists might tend to be more non-verbally or spatially oriented, and engineers more verbally or analytically oriented. The EEG findings, however, did not support this hypothesis.

## 8. Conclusions on hemispheric asymmetry

Evidence for hemispheric asymmetries have come from many diverse sources: behavioral deficits in neurological patients, observations of split-brain patients, and dichotic listening, visual presentation and electrophysiological investigations in normal subjects.

The correlation between lesion site and behavioral deficits has supplied the oldest and largest body of knowledge about hemispheric asymmetries of speech and visual functions. Most of it indicates a lateralization of verbal processing to the left hemisphere and of non-verbal



spatial processing to the right. More recent observations, however, suggest that most cortical processing of sensory stimuli engages both hemispheres in a coordinated manner which depends upon the stimulus complexity, meaning and level of abstraction required to generate an appropriate response.

The evidence from humans who have had their corpus callosum bisected confirms rather dramatically the conclusions based on cortical lesions. That is, the left hemisphere engages in cognitive tasks requiring verbal, linguistic and counting abilities, while the right hemisphere is oriented towards more non-verbal, spatial processing. In the split-brain patients, these functions can operate simultaneously and independently to a much greater degree than in normal subjects. This suggests that the normal interaction of the hemispheres involves a shifting of function from one hemisphere to the other, or at most a simultaneous processing of different aspects of the same sensory material.

The primary problem with both lesion and split-brain studies is that inference about normal function are made on the basis of abnormalities of that same function. This reasoning may be valid for simple systems in which an input signal directly affects an output. The situation is much more complex, however, for feedback systems such as would be expected to be an integral part of the control mechanisms of the brain. In this case, the inputs affect the outputs, which then in turn affect the system's response to the next inputs. The effects of the interruption of pathways within systems with several feedback loops are almost impossible to predict. In many cases, the system becomes completely

unstable and responds in an erratic and abnormal fashion to random noise within the system (Lathi, 1970).

Dichotic listening has provided a behavioral or psychophysiological way of studying asymmetries in normal subjects. With this technique, highly sophisticated functions such as the analysis and recognition of speech and melody, have been studied. Again, the evidence suggests a lateralization of verbal processing to the left hemisphere and of non-verbal, spatial processing to the right. Dichotic listening has further helped in defining what characteristics constitute the fundamental distinction between a verbal and non-verbal signal. Although several attempts have been made to do this, it is still not apparent what the essential difference is that causes the words of a song to be processed more efficiently within the left hemisphere, and the melody of that same song within the right.

The selective presentation of visual material to either the right or left visual field has also provided psychophysiological evidence of laterality in normal subjects. In a manner similar to dichotic listening, these techniques have shown that the perception and recall of visually presented material than can be encoded in words is superior in the right visual field, and consequently by inference, the left hemisphere. Conversely, perception and recall of non-verbal material with complex spatial attributes is more efficient within the right hemisphere.

Conclusions from the presentation of sounds to either hemisphere, as in dichotic listening, and from the presentation of visual stimuli to either hemisphere are not necessarily congruent. Both geometric shapes and melodies appear to be preferentially processed within the right hemisphere, but their communality is not evident. Similarly, words that are heard, and words that are seen, both seem to be processed more within the left hemisphere, but the common characteristic between them is not clear. One could say that both are "verbal" or "non-verbal" but this does not define their differences; it merely attaches different labels to how the brain responds to them.

One possible difference is that verbal material is anything that can be labelled or associated with a known speech sound. Non-verbal or spatial materials, such as melodies or patterns would not necessarily have this characteristic. Kimura (1968), who advanced this theory, supported it by showing that left visual field superiority for the recognition of geometric patterns decreased as the pattern became more easy to verbally label.

Handedness is a more obvious expression of laterality of function than the others discussed above. In patients, it has become clear that handedness and speech laterality are not causally related, and one cannot be accurately predicted from the other. Left-handed subjects, however, seem to demonstrate less hemispheric specialization, or more bilateral representation of speech than do right-handed subjects. A fair amount of evidence suggests that this may result in interference between verbal and non-verbal processing capabilities. This is supported

by the observation that in split-brain patients, these processes can proceed independently to a greater degree than in normal subjects.

As with the studies of the effects of various lesions, the psychophysiological methods of studying laterality such as dichotic listening and visual field presentation have their particular disadvantages. The primary problem is the requirement that the subject respond to the stimulus in order for the investigator to measure some attribute. This response brings in many complicating factors such as interhemispheric communications for the transfer of sensory information to the motor systems, and decision-making or discrimination functions.

Electrophysiological techniques, such as EEG and evoked potential analysis, do not have this particular problem of subject participation, at least in some experimental paradigms. They are thus well-suited for the study of the processing of sensory information in the normal subject without the further complication of subject participation to measure that response.

The amplitude and latencies of evoked potentials generated in response to auditory stimuli are of interest in more clearly defining the difference between verbal and non-verbal stimuli. Although these have only been elusively related to click stimuli, more complex stimuli with verbal and meaningful associations have indicated a pre-eminence of the left hemisphere for their processing. The evidence suggests that as the stimulus becomes more embedded in a meaningful whole or sequence, left hemispheric involvement becomes greater.

This same finding carries over to the visual system, where a visual pattern consisting of a geometric pattern of dots causes smaller, left hemispheric asymmetries than a pattern arranged in a word.

The reports of asymmetry of EEG alpha when the subject is engaged in different cognitive tasks support the contention that the left hemisphere processes verbal information, while the right hemisphere processes non-verbal information. Again, however, the definitions of verbal and non-verbal are operational. In addition, these EEG studies assume that the alpha state represents a resting cortical condition, since it is observed that the alpha power decreases proportionately in the hemisphere engaged in the cognitive task.. It is further assumed that this is the left hemisphere for verbal tasks and the right hemisphere for non-verbal tasks. Nothing in their data shows that the opposite contention could not be true, that is, that since power increases proportionately within the right hemisphere for verbal tasks, this must be the hemisphere more involved in the processing, since its power is greater.

In all of these studies, the critical question is: what is the difference between a "verbal" and a "non-verbal" stimulus? One possibility may be its sequential characteristics. This is suggested by the following observations: First, dichotic listening showed that consonant-vowel combinations caused larger asymmetries than vowels alone. Second, sounds embedded in a sentence caused larger EP asymmetries than the same sounds embedded in a meaningless background. Third, dots arranged into a word caused larger asymmetries of recognition than dots arranged in a geometric pattern. In all of these, the primary characteristic of the

verbal stimuli is that they are arranged into a sequence of sounds or forms, while the non-verbal stimuli are isolated or a single entity with no relation to earlier stimuli.

Based on these observations, verbal stimuli would be classified as sequential, while non-verbal stimuli would be classified as simultaneous. With these definitions, the two different processing modes would be termed sequential or serial for the left hemispheric function, and parallel, simultaneous, holistic or gestalt-like for the right hemisphere (Levi-Agresti and Sperry, 1968; Diamond and Beaumont, 1972; Cohen, 1973).

In conclusion, the experimental data on human hemispheric asymmetry supports very strongly the separation of verbally analytic functions to the left hemisphere and non-verbal or spatially analytic functions to the right. The distinction between the verbal and non-verbal attributes is useful, although clearly too simplistic. A large body of evidence suggests that most cortical processing of sensory data engages both hemispheres with varying degrees of interaction, depending on the stimulus complexity, meaning and level of abstraction required for the task in which the individual is engaged.

## F. Statement of purpose

Two ways exist for the study of evoked potentials, and each makes assumptions about the way in which the EP is generated. Time-domain analysis studies temporal characteristics such as peak amplitudes or latencies, and assumes that various components are sequentially generated as discrete events. Frequency-domain analysis, on the other hand, assumes that different frequencies are generated by different processes, and studies the amplitude, phase and coherence relationships of these processes. Most EP studies have concentrated upon their temporal characteristics, and only very few upon their frequency characteristics. However, frequency analysis is often a more appropriate means for studying oscillatory processes, and the rhythmic waveform of the EP suggests that such an application might be useful.

Time-domain analysis of peak amplitude and latencies of EPs and other electrophysiological events have been used to study hemispheric asymmetries. Most of these have suggested that the left, speech-dominant hemisphere processes verbal information, and that the right, non-speech-dominant hemisphere processes non-verbal or spatial information. A large body of evidence from the effects of cortical lesions, observation of split-brain patients, dichotic listening and visual field presentation experiments support this viewpoint.

The essential problem with all of these studies has been to define the difference between "verbal" and "non-verbal" stimuli or processing modes. Almost all reports, no matter what the technique, have had to rely

upon complex stimuli, such as words or melodies, to elicit consistent hemispheric asymmetries. This complication has further confused the attempt to define the central difference. Despite many demonstrations of a variety of aspects of the problem, it is still not clear what characteristic of some stimuli triggers left hemispheric processing, and what characteristic of other stimuli triggers right hemispheric processing.

A possible solution to this problem may lie in demonstrating that hemispheric asymmetries exist for simple flash and click stimuli. This would remove the ambiguity of the "verbal versus non-verbal" distinction, and show that asymmetries of hemispheric function were related to processes much more fundamental than those of language.

However, hemispheric asymmetries have not been clearly demonstrated for simple stimuli, especially with EPs (Friedman et al, 1975). This may be due to the possibility that different asymmetries do not exist for flash and click stimuli, or because the analytic techniques have been either too weak or based upon the wrong assumptions.

It is hypothesized that this failure is due to applying the time-domain assumptions to the analysis of the EP waveform. Almost all workers have concentrated upon the behavior of one or a few peaks of the EP, and if the time-domain assumption of sequential events is correct, no other approach is valid. However, Friedman et al (1975) have carefully reviewed all EP studies involving many different types of stimuli, and have



concluded that none have clearly demonstrated differences in amplitudes or latencies which could be related to only the right or left hemisphere. If the EP is truly generated by an oscillatory process, this failure becomes understandable, for then, peaks or troughs are not special events with more significance than other points. Their variability is as great as that of any other instant on the waveform.

To properly analyze an oscillating process, the entire waveform must be considered. Each segment of that waveform may be highly variable, but the overall shape and its relation to other waveforms may be extremely consistent and unvarying. If only a few frequency components are necessary to describe the waveform, then the description will be a much more condensed and accurate representation than that based on any particular part.

The intent, then, is to apply spectral analysis, which is a form of frequency analysis, to the EP waveforms generated by simple flash and click stimuli. If the EPs are generated by an oscillatory process, spectral analysis will probably demonstrate EP characteristics which are not observable with the analysis of peaks. An attempt will be made to meaningfully relate the frequency components of the EPs to physiological factors, in particular to speech dominance and handedness. The implications of the results are great for the different ways in which each hemisphere processes sensory information.

METHODS

## A. Introduction

Three experiments are described. The first is on the amplitude or power spectral characteristics of EP frequency components and their relationship to stimulus modality and the cortical area from which they are recorded. The second experiment shows the relationship of coherence to speech dominance, and the final experiment demonstrates the relationships of both coherence and power spectral asymmetries to speech dominance and handedness.

In each experiment, the primary objective was to meaningfully relate the spectral or frequency characteristics of the EPs to physiological factors such as cortical area, stimulated sensory modality, speech dominance and handedness.

## B. Spectral analysis

Spectral analysis of EPs was the basic method of data reduction in all three experiments. By means of this technique, the oscillatory EP waveforms were transformed to a set of sinusoidal components. Each of these had an amplitude and phase shift such that summing all of them together would reproduce the original waveform.

The fourier transform was the basis of the spectral analytic transformation of the temporal waveform to its frequency components, or

frequency-domain description. From the magnitude of the components of the transform, the amplitude or power spectrum of each waveform was calculated. The coherence, or similarity of form between each two waveforms was calculated from both the amplitude and phase of the components of their corresponding fourier transforms.

The spectral analysis was done with the UCLA Biomedical computer program BMD 03T (Dixon, 1973). The details of the methods in the program were completely conventional (Jenkins and Watts, 1968) and so will be only briefly described.

Prior to the fourier transformation, several steps were taken in preparation of the data. These were included as part of the program and were designed to handle data which contained much more noise and larger discontinuities or artifacts than found in EPs. The data preparation had the characteristic that waveforms that did not require the processing were unaffected by the procedures.

The first step in data preparation was to remove frequencies above and below those of interest by digital filtering. The low frequency cutoff of the EEG was set at 0.3 hz., so frequencies below this, for instance linear trends, were considered artifactual and removed. Likewise, observation of the EP waveforms showed that the major oscillations were in the 1-20 hz. range, while higher frequencies which sometimes occurred were usually due to 60 cycle, line interference or myogenic potentials in nervous subjects. Therefore, frequencies above about 30 hz. were also digitally filtered out. Finally, the first and last 50 msec. of each EP

was tapered so that the waveforms began and ended smoothly. This was necessary for the case of an abrupt jump in the beginning or ending of the data, which would be interpreted as a very large amplitude, high frequency component. However, since the major cyclic components of the EP did not begin until after 50 msec. and were mostly complete by 400 msec., this step had no effect.

After the filtering, removal of trend, and tapering, the EPs were fourier transformed to give the amplitude and phase of each frequency component. The power spectra were then calculated directly from the amplitudes. To calculate the coherences between each pair of EPs, the following steps were taken. The cross-spectrum or product of the fourier transforms at each frequency were first calculated for each pair of EPs. The cross-spectrum represented the amount of activity in one waveform that could be predicted as a simple proportion of the activity in the other waveform. Coherence between the two waveforms was calculated as the square-root of the ratio of the magnitude of their cross-spectrum to the product of their power spectra in each frequency range. Coherence thus represented a ratio of similar activity between 2 waveforms, divided by the magnitude of their individual activities.

Using the above definition, two processes will be highly coherent if the similar activity between them is nearly as great as their individual activity. As mentioned earlier, another way of stating this is that coherence measures similarity of form between two waveforms. High coherence thus means that the form of one waveform can be accurately predicted from the form of the other.

### C. Subjects

The averaged EPs of four groups of subjects were investigated: right-handed normal subjects, left-handed normal subjects, right speech-dominant epileptics, and left speech-dominant epileptics.

The epileptic patients, 6 left speech-dominant (LSD) and 5 right speech-dominant (RSD), 8 male and 3 female, ages 13-47, were all being evaluated for possible surgical treatment of epileptic seizures. Speech dominance was ascertained by the carotid amytal test, using femoral catheterization, and repeated on both sides at least 2 days apart.

Handedness in the normal subjects was determined according to criteria proposed by Annett (1967). All were "pure" in that they used only their left side, or only their right side, for all of the following tasks: writing, ball throwing, match striking, scissor holding, needle threading, dealing cards, hammering a nail, holding a toothbrush, unscrewing a jar lid, holding a tennis racket, looking through a microscope, and kicking a ball.

The normal subjects were university students. The final groups included 12 "pure" right-handed persons, 7 male and 5 female, and 12 "pure" left-handed persons, 6 male and 6 female.

#### D. Electrode placements for EP recording

EEG recordings were made from electrode placements determined from the International 10-20 system (Jasper, 1958). This system attempts to place particular electrodes over particular brain areas independently of skull size. Positions are determined as percentages of the distance from the nasion (bridge of the nose) to the inion (occiput), and on the skull circumference.

In this thesis, evoked potentials to visual and auditory stimuli were of most interest. Electrode placements were therefore chosen to be over the specific projection cortex of the visual and auditory modalities, that is, the occipital and superior temporal areas.

Referring to Fig. 2, recordings were made from the left and right occipital (labelled O1 and O2), and from the left and right temporal areas, midway between T3 and C3 on the left side, and midway between T4 and C4 on the right. The temporal placements were located approximately over the superior temporal gyrus, just posterior and superior to the intersection of the Rolandic and Sylvian fissures. To make them easily comparable to the occipital electrodes O1 and O2, the temporal placements were called T3 and T4.

The potentials at the four electrodes were referred to a linked right and left earlobe reference. These were chosen as points of relative indifference to the evoked activity.

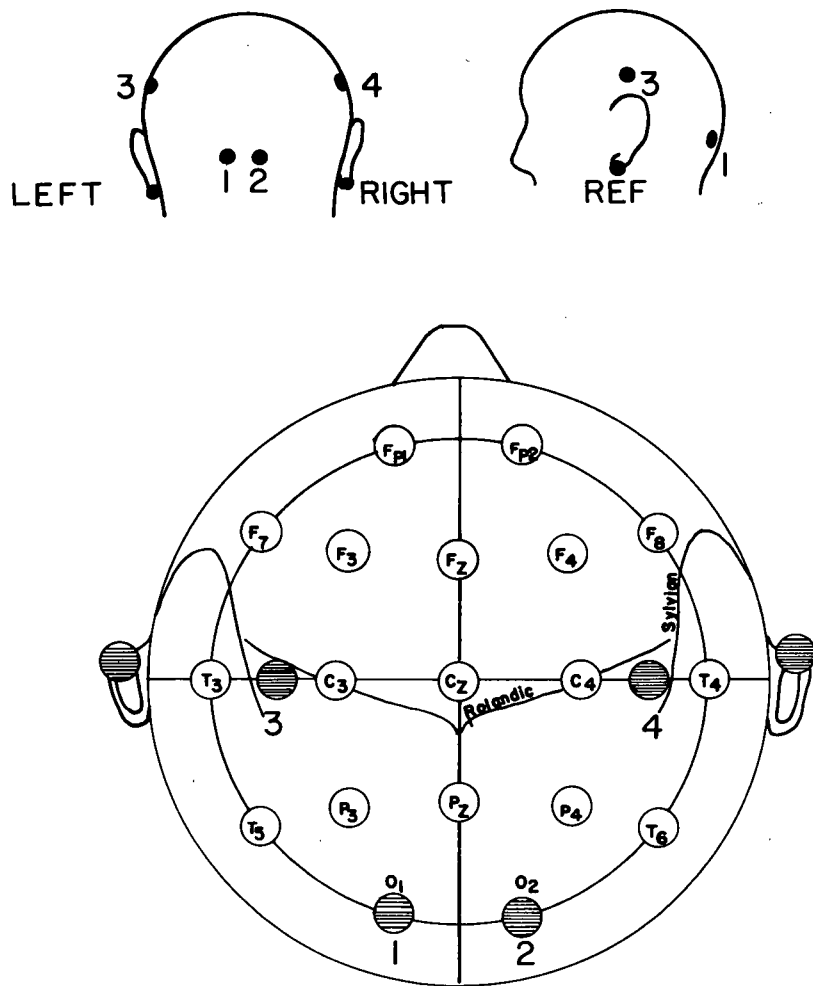


Figure 2

The International 10-20 system of EEG electrode placements and the recording points 1 to 4 used for recording EPs. Baseline measurements are made along the nasion to inion distance (vertical line), the left-to-right, preauricular distance (horizontal line), and the skull circumference (outer circle). The inner circle or temporal line of electrodes is 10% of the left-right, preauricular distance. All other electrodes are placed at 20% intervals along their respective baselines.

### E. Equipment and experimental conditions

The subjects sat upright in an 8' by 8' by 8' soundproofed room, illuminated from above by a diffuse 40 watt ceiling lamp. The flash stimulus was generated by a Grass PS1 photostimulator, 10 microsecond duration, intensity 8, and presented through a 6" circular aperture placed 24" from the subject's nasion. The click stimulus was generated with a Grass S4C click stimulator, 0.1 msec. duration, 4 volt amplitude, and presented through stereo headphones (Sansui-SS1, 8 ohms) with a comfortable listening level of approximately 60 dB. Flash and click trigger pulses were randomly mixed with an average inter-stimulus-interval of 3 seconds, minimum of 2 seconds, on a previously prepared control tape which was used for all subjects.

Four groups of 40 randomly mixed flash and click stimuli were presented with a 1 minute rest between groups. The subjects were instructed to keep their eyes open and fixated on a small 'x' in the middle of the flash aperture, to remain quiet, to avoid eye, tongue or jaw movements, and to remain passively aware of the stimuli.

Monopolar or referential recordings were made from left and right occipital areas (O1 and O2), and left and right temporal areas (T3 and T4), using linked right and left earlobes as a reference with a forehead ground. Grass E5GH electrodes were applied to the scalp with paste.



The scalp potentials were amplified with Grass P511 amplifiers (frequency response 0.3-100 hz.) and recorded on a Technical Measurement Corporation Model 1400 FM tape recorder. These were later played back and averaged into groups of 40 or 160 stimuli, and analysis times of 500 msec. or 1 sec., depending on the experiment. A Technical Measurement Corporation CAT 400B transient averager with a sampling rate of 100/sec. was used. The digitized, averaged EPs were then recorded on a Precision Instrument PI-1167 digital tape recorder for subsequent analysis on an IBM 370 computer.

#### F. Experiment I - Power spectral analysis

In the first experiment, the amplitude characteristics of the EP frequency components were investigated using the power spectra of the right-handed subjects. The fast fourier transform of the EPs was used to calculate the amplitude or magnitude of the spectra at 1 hz. intervals at 0,1,2, 3 hz. etc. The duration of each EP was 1 second.

The relatively fine resolution of 1 hz. for the spectra was necessary to show the detail of the distribution of amplitudes in the occipital and temporal areas, and how these changed with frequency and stimulus modality. The Wilcoxon, non-parametric test for paired comparisons (Siegel, 1956) was used to evaluate the significance of the observed differences between the occipital and temporal amplitudes of the VEPs and AEPs.

## G. Experiment II - Coherence analysis

### 1. Introduction

In the second experiment, the coherence or similarity of form between the EPs from various areas were investigated. The VEPs and AEPs of the right-handed subjects, and the right and left speech-dominant epileptic patients were used to show the relationships of coherence asymmetries to the speech dominance of the subject.

In contrast to the simple fourier transformation of the EPs which was used in the first experiment, the EP analysis of Experiment II was done with the more sophisticated spectral analysis program, BMD 03T - Time series spectrum estimation (Dixon, 1973). This program allowed for noise, linear trend and other artifacts within the data, which could possibly produce distorted results if unaccounted for.

The results of Experiment I suggested that a 1 hz. resolution of the spectra was finer than necessary, so a 3 hz. resolution was chosen to give estimates at 0,3,6,9,12 hz. etc. In addition, observation of the EPs showed that only the first 500 msec. contained cyclic components (see for example, Figs. 3 or 4), so the analysis was confined to this range. This in effect assumed that any variations after 500 msec. were not sufficiently time-locked to the stimulus to be included in either the average or the spectral analysis. Both of these assume that the signal properties, such as frequency and phase, do not change with time.

## 2. Estimation of coherence

The results of Experiment I suggested that the 6-12 hz. component of the EP was most related to the stimulus modality, so further analysis was confined to that frequency band.

Estimation of coherence was done in two ways. First, a single measure of occipital to temporal coherence was made for each hemisphere, by averaging the 6, 9 and 12 hz. coherence estimates over the 4 replications of each subject. This average, composed of the 12 individual coherences, was then used to compare the coherence of the right hemisphere to that of the left on a simple, greater-or-less than basis for each subject.

Averaging of coherences over frequencies and over replications assumes that they do not change with each component of that average. To more rigorously investigate this assumption, analysis of variance was utilized with each frequency and replication as a factor in the analysis. Each coherence estimate thus represented a single observation, which when averaged together for each subject over the 3 frequencies and 4 replications, would give the same value of coherence as with the simpler procedure described above.

Averaging and analysis of variance both assume that the data is normally distributed, which is not the case for any of the spectral quantities (Jenkins and Watts, 1968). In the first experiment, this problem was eliminated by using non-parametric statistics. However, for

the type of analysis done on the coherences, no non-parametric procedures exist, so another approach was used. This involved the transformation of the data to a normal, bell-shaped distribution by a scaling technique. The coherences produced a distribution which was skewed or pushed to the left, with many low values of coherence and only a few high ones. A transformation was used to make the proportion of low coherences approximately equal to the proportion of high coherences.

The coherences were transformed with the Fisher Z-transform (Jenkins and Watts, 1968) which is the  $\text{arctanh}$  of the coherence. This transformation is also used to convert ordinary correlation coefficients to a more normally distributed form (Snedecor and Cochran, 1967). Therefore, each average of coherences was composed of the  $\text{arctanh}$  of the coherence estimates at 6, 9 and 12 Hz. and 4 replications. These same  $\text{arctanh}$ -transformed coherences were used in the analysis of variance.

### 3. Analysis of variance

The simple comparison of right and left hemispheric coherences was done for all three subject groups. A simple decision of coherence greater on the right or left side was made for each subject and each modality. However, other asymmetries were possible between the four recording areas. Multivariate analysis of variance was used to investigate these as well as to clarify the dependence of the coherences on frequency of the spectral estimate.

For the 4 recording areas, left and right occipital (O1 and O2) and left and right temporal (T3 and T4), there were six possible pairs of coherences: (O1:O2), (O1:T3), (O1:T4), (O2:T3), (O2:T4) and (T3:T4). Three possible independent asymmetries of coherence could thus be calculated. These were: between hemispheres (O1:T3 compared to O2:T4), between projection areas of each modality (O1:O2 compared to T3:T4), and between hemispheres and projection areas (O1:T4 compared to O2:T3). These coherence pairs were generated in response to the same stimulus, and were recorded from the same subject, and so were in general correlated. Each of these correlated asymmetries could have been analyzed in a separate analysis of variance, but a better method utilizing a multivariate analysis of variance, allowed a simultaneous comparison of the three asymmetries.

Analysis of variance allows an investigation of the effects and interrelationships of various independent factors on a dependent variable. Multivariate analysis of variance extends this concept to multiple dependent variables, in this case the coherence asymmetries, which are correlated. The exact use and interpretation of the technique will become clearer in the Results and Discussion.

In most respects, multivariate analysis of variance has direct analogs with the univariate concepts of the F-test, main effects and interactions. The U-statistic is the multivariate analog of the univariate F-statistic, and is used to test the significance of the difference between two sets of means. In this experiment, it was used to test the hypothesis that the three coherence asymmetries were significantly different for flash and click stimuli. Main effects

describe the effects of each of the independent factors on the dependent variables. Interactions describe how two or more factors interact to affect the dependent variables in a way that cannot be predicted from any factor by itself.

The techniques of multivariate analysis of variance are described by Anderson (1958) and are incorporated in the UCLA Biomedical computer program BMD X69 - Multivariate analysis of variance and covariance (Dixon, 1973). The program was used to analyze the arctanh-transformed coherence asymmetries, with each 3 Hz. resolution estimate at 6, 9 and 12 Hz. used as a single observation.

The factors and their levels were subjects S(12), stimulus modality M(2), frequency band of the coherence estimate F(3), and the replications for each subject R(4). The correlated, dependent variables were the three coherence asymmetries calculated as paired differences (O1:O2-T3:T4), (O1:T3-O2:T4) and (O1:T4-O2:T3). Differences between each arctanh-transformed coherence were calculated for each subject, modality, frequency and replication. The experimental design was a 3-way factorial with 4 replications and 3 dependent variables, and was intended to investigate the effects of subject, stimulus modality, and frequency component on the three coherence asymmetries.

## H. Experiment III - Discriminant analysis

### 1. Introduction

In the third experiment, discriminant analysis of the EP spectra was used to further investigate the relationships of both coherence and

autospectral asymmetries to speech dominance. In addition, a computer test for the EP determination of speech dominance was constructed. This was then applied to the normal subjects to obtain distributions of speech dominance in the normal, right or left-handed population.

A primary aim of this experiment was to clarify some of the methodological uncertainties of the previous experiment. The first of these centred around the estimation of the 6-12 hz. coherence as an average of the 6,9 and 12 hz. coherences over 4 replications. A more conventional, though not necessarily more accurate procedure, would have been to calculate a single coherence over the entire 6-12 hz. range for one EP. This was done by using spectra of 6 hz. resolution calculated from a single, averaged EP of 160 stimuli. A cross-validation was then possible for the conclusions based on the novel and conventional procedures.

The second problem involved the evaluation of which spectral asymmetries were most related to speech dominance. This was only approached qualitatively in the second experiment, but in this experiment, discriminant analysis was used to evaluate the significance of each asymmetry's relationship to speech dominance.

## 2. Spectral analysis

The UCLA spectral analysis program was again used, this time to calculate spectra with 6 hz. resolution from the 500 msec. EPs. The spectral estimate centred at 6 hz., and extending over the frequency range of 3-9 hz., was used for all analyses.

The 3-9 hz. bandwidth produced by the program did not numerically overlap the 6-12 hz. range examined previously, but it was the closest one available. Also, from a practical viewpoint, the two were almost equal. The 3-9 hz. band and the 6-12 hz. band contained the largest amplitude component of any in the 500 msec. spectra, and encompassed from 60-80% of the total power in all subjects. In addition, the power spectra of all subjects showed that most of the low frequency, 0-5 hz. power was below 3 hz., and most of the high frequency, 6-12 hz. power was below 10 hz. (for example, see Fig. 3 of the Results). The 3-9 hz. conventional spectrum was thus a good overlap with that of the 6-12 hz. band, but with the advantage that averaging over frequencies for either coherences or power spectra was not necessary. This was useful in confirming the conclusions based on the novel estimation of coherence, but it was necessary for the discriminant analysis, since some of its theoretical requirements limited its application to a single coherence or power spectral estimate.

As with the analysis of variance, discriminant analysis required a normal distribution of data. Coherences were arctanh-transformed as before, and power spectra were  $\log_{10}$  - transformed since this scale is normalizing for them (Jenkins and Watts, 1968; Hannan, 1970).



### 3. Asymmetry calculations

Coherence asymmetries were calculated in the same way as in the last experiment. That is, from the 4 recording areas O1, O2, T3 and T4, six coherence pairs were calculated. From these, three independent asymmetries of coherence were derived: (O1:O2-T3:T4), (O1:T3-O2:T4), and (O1:T4-O2:T3).

Power spectral asymmetries were calculated between homologous areas of each hemisphere. These were left-minus-right occipital (O1-O2) and left-minus-right temporal (T3-T4).

Asymmetries were calculated for both AEPs and VEPs, so the final data included 6 asymmetries of coherence and 4 of autospectra for each subject.

### 4. Discriminant analysis

The coherence and power spectral asymmetries were each separately subjected to discriminant analysis (Afifi and Azen, 1970), using the UCLA Biomedical computer program BMD 07M - Stepwise discriminant analysis (Dixon, 1973). Two problems were set up: one with 6 coherence asymmetries, and one with the 4 power spectral asymmetries of each subject as input.

In each of the above problems, the program evaluated the significance of each asymmetry's relationship to speech dominance. This was based on a comparison of the known speech dominance of each patient and his corresponding spectral asymmetries. Equations were derived by the program which quantified these relationships for asymmetries significantly related to dominance at a probability of  $p$  less than 0.05. These equations were then applied to the spectral asymmetries of the normal subjects to predict their speech dominance.

## RESULTS

### A. Experiment I - Power spectral analysis

#### 1. The evoked potential power spectra

Fig. 3 shows the VEPs, AEPs and power spectra of two subjects. The responses in the primary projection area of the stimulated modality (ie. - occipital for flash or temporal for click) consisted of two major frequency components, a 0-5 hz. component, labelled as Group I, and a 6-12 hz. component, labelled as Group II. These two groups were present in the power spectra of all 4 areas in all 12 subjects, and constituted at least 95% of the total power in each response.

Fig. 4 shows the corresponding power spectra of EPs in areas which were not specific to the stimulus modality, for example, the occipital response to click stimuli, or the temporal response to flash stimuli. Both the Group I and II frequencies were still present, but the Group II, 6-12 hz. component varied more than in the primary projection areas and usually represented a smaller proportion of the total EP power. In some subjects, the Group II response disappeared almost entirely.

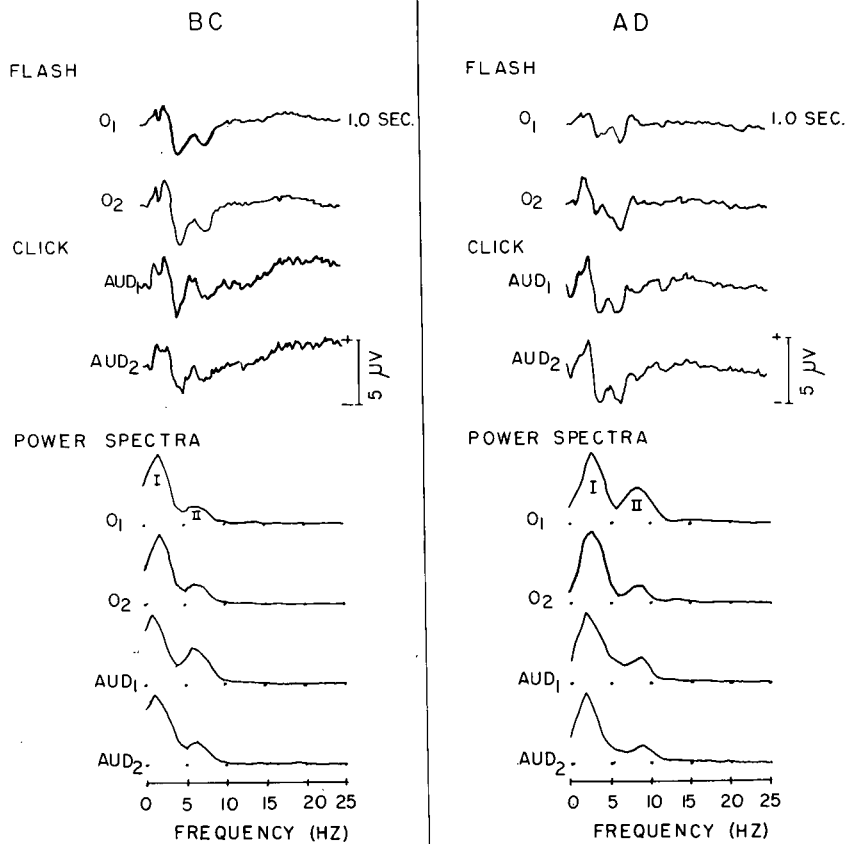


Figure 3

Primary projection area EPs and power spectra of 2 subjects. Note the two major frequency groups (I and II) in the spectra. O<sub>1</sub>, O<sub>2</sub> = left, right occipital; AUD<sub>1</sub>, AUD<sub>2</sub> = left, right temporal.

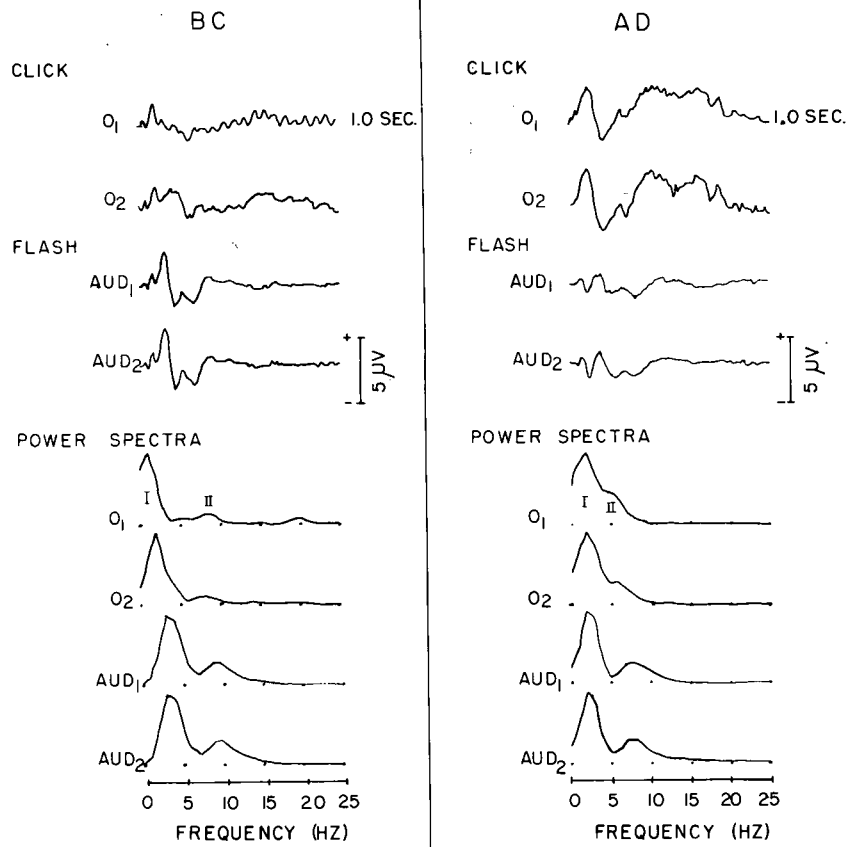


Figure 4

Non-primary projection area EPs and spectra of same subjects as Fig. 3. Note the more variable Group II as compared to the primary area responses of Fig. 3.

## 2. Statistical analysis

Comparisons of the magnitudes of response spectra in the primary and non-primary projection areas were made with the Wilcoxon, non-parametric, paired samples test (Siegel, 1956). The test was done at each frequency to determine the frequency distribution of amplitude changes between pairs of recording areas. Each test involved 48 pairs, composed of 4 VEPs and 4 AEPs from each recording area of each of the 12 subjects. A two-tailed,  $p$  less than 0.05 level of significance was used.

Fig. 5 shows the median, paired differences and associated probabilities between the occipital and temporal area spectra of each hemisphere. Two major frequency groups of differences appeared in the same ranges as the individual subject spectra. The low frequency, 0-5 hz., Group I differences (occipital minus temporal response) were always significantly negative for both flash and click stimuli. In other words, the temporal responses were always greater than the occipital. In contrast, the Group II, 6-12 hz. responses were significantly greater in the occipital areas for flash and in the temporal areas for click. The right hemisphere VEP also showed this pattern, but the differences were not significant.

## 3. The temporal form of the frequency groups

The 0-5 hz. and 6-12 hz. frequency components were extracted by digitally filtering the EPs shown in Fig. 3. The filtered components

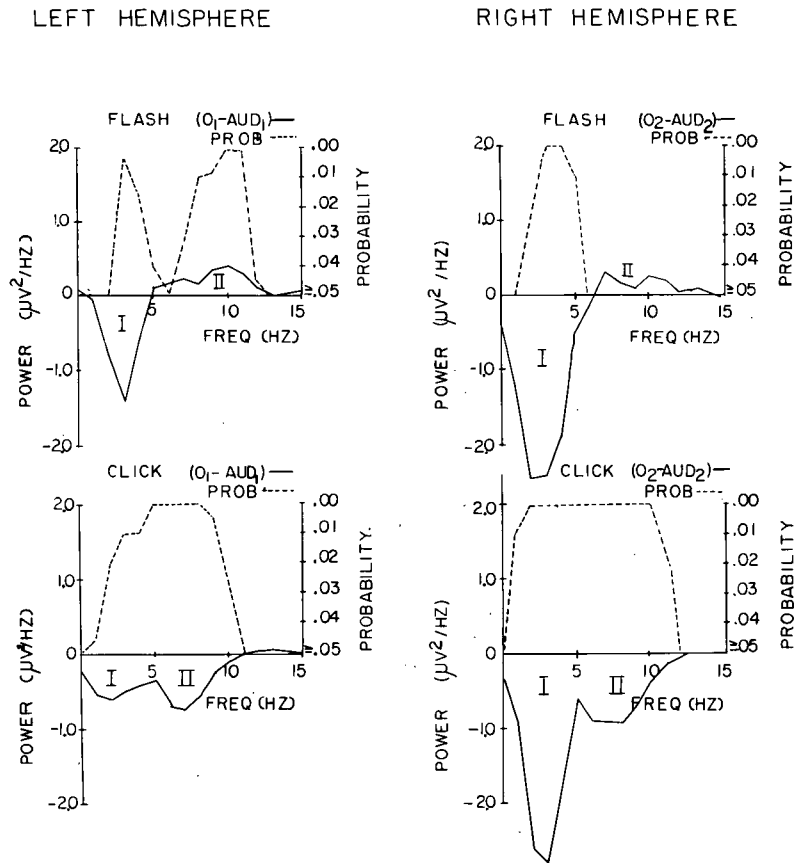


Figure 5

Median, occipital (O1 or O2) minus temporal (AUD1 or AUD2) spectra and associated probabilities of all subjects. Group I, 0-5 Hz. responses are greater in the temporal areas for both flash and click, while Group II, 6-12 Hz. responses are greater in the primary projection area of the stimulus modality.

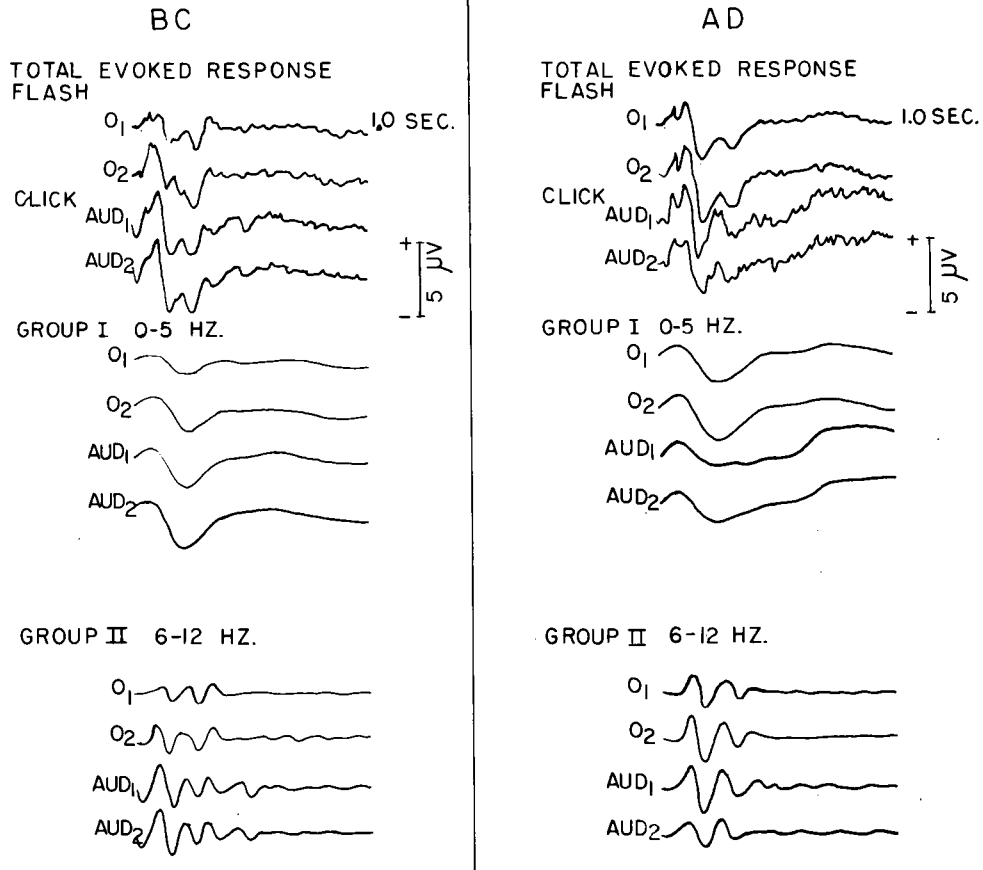


Figure 6

Digitally filtered Group I (0-5 Hz.) and Group II, (6-12 Hz.) components of the same EPs as Fig. 3.



are shown in Fig. 6. Group I, 0-5 hz. frequencies consisted of a slow, biphasic wave, very similar for both flash and click in the first 300 msec., and corresponding to positive peaks at about 100 and 300 msec. Group II, 6-12 hz. frequencies first appeared at about 50 msec., recurred at about 50 msec. intervals, and were dissimilar for the flash and click stimuli.

## B. Experiment II - Coherence analysis

### 1. Comparison of hemispheric coherences

Table I shows the hemisphere in which the maximum VEP and AEP coherence occurred for the right and left-speech dominant epileptics, and the normal, right-handed subjects, who were presumably left-speech dominant. Coherences were calculated as the average of the 6, 9 and 12 hz. estimates over 4 replications for each subject.

For the great majority of subjects, the click responses or AEPs were more coherent on the speech dominant side. Conversely, the flash responses or VEPs were more coherent on the speech non-dominant side in most subjects.

Table II shows the coherences of subjects who best illustrated the trends of Table I.

TABLE I

Number of subjects with maximum occipital-temporal coherence in the dominant hemisphere for auditory evoked potentials (AEPs) and in the non-dominant hemisphere for visual evoked potentials (VEPs). L,R = left, right.

Subject group	Total number of subjects	Subjects with maximum AEP coherence on dominant side	Subjects with maximum VEP coherence on non-dominant side
Normal, R. handed (assume L. dominant)	12	10	9
L. dominant amytal	6	5	5
R. dominant amytal	5	4	3

TABLE II

Occipital-temporal, 6-12 hz. coherences in the left and right hemispheres.

For 4 subjects best illustrating the trends of each subject group.

A coherence of 0.50 means that  $0.5 \times 0.5 = 0.25$  of the variance of one response can be explained as a linear version of the other.

Subject dominance	VEP hemispheric coherence		AEP hemispheric coherence	
	Left	Right	Left	Right
Left	0.89	0.92	0.88	0.84
Right	0.72	0.59	0.76	0.81
Right-bilateral	0.70	0.70	0.65	0.66
Normal, right-handed	0.75	0.80	0.76	0.68

## 2. Multivariate analysis of variance

Table III shows the results of the multivariate analysis of variance of all three possible coherence asymmetries as the dependent variables. This analysis was designed to investigate the effects and interactions of the subject, stimulus modality and frequency of coherence estimate on the coherence asymmetries.

The interpretation of the multivariate analysis of variance table is similar to the that of univariate analysis. The sources represent the effects or interactions of interest, which are the subjects (S), modality (M), frequency (F) and their interactions. The generalized variance, U-statistic and degrees of freedom are the multivariate analogs of the variance, F-statistic, and degrees of freedom, and measure the variability and reliability of the effects. Finally, the probability that the observed U-statistic could be due to chance is used to evaluate significance levels. For instance, if an effect had a U-probability of 0.015, this would mean that there were 1.5 chances out of 100 that the observed effect was due to chance. However, the analysis itself only determines whether the means of the effects are significantly different. To interpret just what the significant effect is and what form it takes, requires an examination of the means.

Table I shows that with a probability of  $p$  less than 0.01, the significant main effects on coherence asymmetries were subject (S) and stimulus modality (M). The significant interactions were subject x modality (SM) and subject x modality x frequency (SMF).

TABLE III

Multivariate analysis of variance of arctanh-transformed coherence asymmetries. Dependent variables were the asymmetries of coherence. 01,02 = left, right occipital; T3,T4 = left, right temporal. Factors and levels were subject S(12), Modality M(2), Frequency F(3) of coherence estimate, and replications R(4). \* = significant at p less than 0.01.

Dependent variables = (01:02-T3:T4), (01:T3-02:T4), and (01:T4-02:T3).

Source	Log (generalized variance	U-statistic	Degrees of freedom	Probability of greater than U
S	13.67176	0.453242	3 11 216	0.0000 *
M	12.93489	0.946997	3 1 216	0.0087 *
F	12.90911	0.971728	3 2 216	0.4052
SM	13.23715	0.699971	3 11 216	0.0000 *
SF	13.24435	0.694952	3 22 216	0.0907
MF	12.93388	0.947956	3 2 216	0.9737
SMF	13.36088	0.618509	3 2 216	0.0009 *
R(SMF)	13.88043			

From this analysis, the following inferences were made. The significant subject (S) main effect showed that different subjects had different magnitudes of coherence asymmetries. The significant modality (M) effect showed that the coherence asymmetries differed significantly for VEPs and AEPs. The significant modality x subject (SM) interaction showed that not all subjects responded in the same way to the same stimulus modality. That is, some subjects had a pattern of coherence asymmetries which were different than the majority. This agrees with the results shown in Table I, which show that not all the normal, right-handed subjects followed a left-speech dominant pattern. The significant subject x modality x frequency (SMF) interaction indicated that the VEP and AEP coherence asymmetries depended in some complex fashion on the frequency.

To interpret more clearly the significant relationships of the factors, observation of the mean coherences was necessary. Table IV shows the significant modality (M) effect for the flash and click, mean coherences and asymmetries in both their original and arctanh-transformed, normally distributed forms. The (O1:O2-T3:T4) asymmetries changed in degree with the stimulus modality. The (O1:T4-O2:T3) asymmetries remained about the same for both modalities. Only the right-to-left hemisphere asymmetries (O1:T3-O2:T4) changed in direction or sign with the stimulus modality. That is, for VEPs, the occipital-to-temporal coherence was greater in the right hemisphere, while for AEPs, this coherence was greater in the left hemisphere. Table IV also shows that in general, the AEP coherences were smaller than the VEP

TABLE IV

Coherence and coherence asymmetry means for 12 subjects. 01,02 = left, right occipital; T3,T4 = left, right temporal.

Coherence asymmetries (arctanh-transformed)

	(01:02-T3:T4)	(01:T3-02:T4)	(01:T4-02:T3)
VEP	-0.0807	-0.0912	+0.0809
AEP	-0.2688	+0.0775	+0.0752

Coherences

	(01:02)	(T3:T4)	(01:T3)	(02:T4)	(01:T4)	(02:T3)
VEP	0.92	0.93	0.82	0.84	0.85	0.82
AEP	0.87	0.91	0.74	0.70	0.73	0.70

coherences. Also, the highest coherences occurred between homologous areas of the left and right hemisphere (O1:O2 and T3:T4), but these did not seem to be clearly related to stimulus modality.

The nature of the significant interactions was indicated by observation of all the means (not shown). The subject x modality (SM) interaction was due to some subjects having coherence asymmetries which were opposite of those of the majority. The subject x modality x frequency (SMF) interaction was due to VEP coherences tending to be maximal at 9 or 12 hz., while AEP coherences were generally maximal at 6 or 9 hz. This suggested that VEP activity was generally of slightly higher frequency than AEP activity. These frequency dependencies were observed for both the coherences themselves and their asymmetries.



### C. Experiment III - Discriminant analysis

#### 1. Coherence analysis

Table V shows the discriminant analysis of coherence asymmetries. There were only two asymmetries which were related to speech dominance at a significance level of  $p$  less than 0.05. These were the left-minus-right hemispheric coherence (01:T3-02:T4) for VEPs and AEPs. The LSD and RSD group means of these two asymmetries were significantly different ( $p$  less than 0.005), as shown by the U-statistic produced by the program.

The discriminant equations produced by the program were:

$$S_{LSD} = -1.79 - 5.92 (F) + 14.67 (C) \quad (1)$$

$$S_{RSD} = -1.14 + 1.93 (F) - 11.59 (C)$$

where:  $S_{LSD}$  and  $S_{RSD}$  are the LSD and RSD scores respectively, and (F) = flash coherence asymmetry (01:T3-02:T4), and (C) = click coherence asymmetry (01:T3-02:T4). Using these equations, an unknown subject's coherence asymmetries are inserted into the (F) and (C) terms, and he is assigned to the speech dominance group for which he attains the most positive score.

TABLE V

Discriminant analysis of arctanh-transformed coherence asymmetries.

O1,O2 = left, right occipital; T3,T4 = left, right temporal.

F,C = flash, click. LSD,RSD = left, right-speech dominant.

Discrimination probability evaluates the asymmetry's contribution to speech dominance determination.

Coherence asymmetry	LSD mean (6 patients)	RSD mean (5 patients)	Discrimination probability
(O1:O2-T3:T4) <sub>F</sub>	+.02	+.08	.286
(O1:O2-T3:T4) <sub>C</sub>	-.18	-.06	.243
(O1:T3-O2:T4) <sub>F</sub>	-.34	-.19	.037 ( p less than .05)
(O1:T3-O2:T4) <sub>C</sub>	+.11	-.24	.001 ( p less than .005)
(O1:T4-O2:T3) <sub>F</sub>	-.36	+.09	.240
(O1:T4-O2:T3) <sub>C</sub>	-.05	-.17	.941

The probabilities,  $P_{LSD}$  and  $P_{RSD}$ , that a subject has been misclassified are:

$$P_{LSD} = \frac{1}{1 + \exp (S_{LSD} - S_{RSD})} \quad (2)$$

$$P_{RSD} = \frac{1}{1 + \exp (S_{RSD} - S_{LSD})} = 1 - P_{LSD}$$

Subjects were classified as bilateral if their probabilities of misclassification were greater than 0.05.

These equations were derived on the basis of the coherence asymmetries of the patients and were then used to evaluate the speech dominance of the normal subjects. In addition, by inserting the coherence asymmetry values of the patients into the equations, "posterior" probabilities were evaluated. These gave a measure of how well the equations classified the patients whose speech dominance was already known. Using the coherence asymmetries of the patients, 5/6 LSD and 5/5 RSD patients were correctly classified, with posterior probabilities of  $p$  less than 0.05 in 5/6 LSD and 3/5 RSD patients. The two RSDs with insignificant differences were clinically classified with the carotid amygdal test as bilateral, but with major representation of speech in the right hemisphere.

As an example of the use of these equations, the coherence asymmetries of the left speech-dominant patient RG were:

$$(F) = \text{left hemispheric VEP coherence minus right hemispheric VEP coherence}$$

$$= 0.88 - 0.98 = -0.10$$

$$(C) = \text{left hemispheric AEP coherence minus right hemispheric AEP coherence}$$

$$= 0.89 - 0.79 = +0.10$$

The discriminant scores were:

$$\begin{aligned} S_{LSD} &= -1.79 - 5.92 (F) + 14.67 (C) \\ &= -1.79 - 5.92 (-.10) + 14.67 (+.10) \\ &= +.27 \end{aligned}$$

$$\begin{aligned} S_{RSD} &= -1.14 + 1.93 (F) - 11.59 (C) \\ &= -2.49 \end{aligned}$$

Since the LSD score was more positive than the RSD score, this patient was classified as left speech-dominant.

To evaluate the probability that this patient was actually RSD, rather than LSD, the equations (2) were used to calculate the probability of misclassification, as follows:

$$P_{LSD} = \frac{1}{1 + \exp (S_{LSD} - S_{RSD})} = \frac{1}{1 + \exp (.27 + 2.49)} = 0.059$$

$$P_{RSD} = 1 - P_{LSD} = 0.941$$

Therefore, there were 5.9 chances out 100 that the person had been

misclassified as LSD, when he was actually RSD.

The equations and example show how changes in occipital-to-temporal coherence affected the probability that the person was either left or right-speech dominant. If the left-minus-right hemispheric VEP asymmetry (F) became more negative, the RSD score would have become smaller, and the LSD score larger. Similarly, if the left-minus-right hemispheric AEP asymmetry (C) became more positive, the person's RSD score would have decreased and his LSD score increased.

Since a more positive LSD score increased the probability that the person was LSD, and vice-versa for the RSD scores, the equations showed the following relationship: High AEP coherences within one hemisphere increased the probability that speech dominance was localized within that hemisphere. Conversely, high VEP coherences within one hemisphere increased the probability that speech dominance was localized within the opposite hemisphere..

### 3. Speech dominance of normal subjects

Table VI applies the above discriminant equations of speech dominance, as determined from the coherence asymmetries and corresponding speech dominance of the patients, to the coherence asymmetries of the normal, right or left-handed subjects. For the 12 right-handed subjects, 8 were LSD, 3 RSD and 1 bilateral. For the 12 left-handed subjects, 5 were LSD, 1 RSD and 6 bilateral.

TABLE VI

Speech dominance determination using discrimination equations of the coherence asymmetries. LSD,RSD = left, right speech dominant, BIL = bilateral. Subjects were assigned to either LSD or RSD classifications if their discrimination probabilities were less than .05, and to BIL if greater than .05.

Subject group	Number of subjects	Coherence asymmetry class		
		LSD	RSD	BIL
LSD amyta1	6	5	1	0
RSD amyta1	5	0	3	2 (2 RSD)
Right-handed	12	8	3	1 (1 RSD)
Left-handed	12	5	1	6 (2 RSD, 4 LSD)

#### 4. Discriminant analysis of power spectral asymmetries

Table VII shows the discriminant analysis of the power spectral asymmetries between the left and right hemispheres. For all patients, this frequency component contained from 60-80% of the total power of the response and was the largest amplitude, or dominant component. There were no significant predictors of speech dominance, even at a reduced significance level of  $p$  less than 0.25. The U-statistic showed no significant differences between the LSD and RSD groups. Discriminant analysis of the power spectra themselves, rather than the differences between the left and right hemispheres also gave insignificant results.

#### 5. Coherence asymmetries and handedness

The coherence asymmetry measuring the difference between the occipital to temporal coherences of the left and right hemispheres (O1:T3-O2:T4), was the only asymmetry which was significantly related to speech dominance. Consequently, a study of this asymmetry by itself in normal subjects could be used to derive inferences about the relationship of speech dominance to handedness.

A univariate analysis of variance of the (O1:T3-O2:T4) coherence asymmetry was done. The experimental design was a repeated measures format, with subjects (S) nested in handedness (H) and crossed with stimulus modality.(M). Intuitively, this meant that the

TABLE VII

Discriminant analysis of  $\log_{10}$ -transformed power spectral asymmetries.  
 01,02 = left, right occipital; T3,T4 = left, right temporal. LSD, RSD  
 = left, right speech dominant.

Asymmetry	LSD mean	RSD mean	Discrimination probability
VEP			
01-02	-.048	-.074	.763
T3-T4	-.106	-.081	.849
AEP			
01-02	-.043	-.049	.880
T3-T4	-.115	-.017	.466



the flash and click stimuli were both presented to the same subjects, so their intercorrelations had to be accounted for in a special type of analysis of variance called repeated measures. Subjects nested in handedness meant that the 12 subjects in the right-handed group were different than the 12 subjects in the left-handed group, but both groups were nested or were part of the factor called handedness. Stimulus modality crossed with the other factors meant that each stimulus was applied across all subjects. All of these interrelationships of factors produced a certain pattern of correlations which were accounted for by specifying the experimental design when the computer program was run.

Table VIII shows the results of the analysis of variance for the 24 normal subjects, using the UCLA Biomedical computer program BMD 08V - Analysis of variance (Dixon, 1973). The VEP and AEP means were significantly different as indicated by the significant modality (M) effect, but the left and right-handed means were not, since the handedness effect (H) was not significant and no interaction occurred between handedness and modality (HM).

These results indicated that there were significant differences between the VEP and AEP coherence asymmetries, but not between those of the left and right-handed subjects. The lack of interaction between modality and handedness indicated that the coherence asymmetries of both left and right-handed subjects changed in the same way for flash and click stimuli.

TABLE VIII

Analysis of variance of 12 right-handed and 12 left-handed normal subjects. Dependent variable is left-minus-right hemispheric, occipital-to-temporal coherence (O1:T3-O2:T4) asymmetry.

Source	F-value	F-probability
Mean	2.734	.109
Handedness (H)	0.489	.498
Modality (M)	5.926	.022 (p less than 0.05)
Interaction (HM)	1.514	.230

Mean, left-minus-right hemispheric coherences

	Flash	Click
Right-handed	-.08	+.13
Left-handed	-.05	+.10

The mean coherence asymmetries of Table VIII show the significant changes which occurred between the VEPs and AEPs of both subject groups. In both the left and right-handed subjects, the left-minus-right hemispheric differences were positive for AEPs, indicating greater left hemispheric coherences, and negative for VEPs, indicating greater right hemispheric coherences. The asymmetries of the left-handed subjects appear to be slightly smaller in magnitude than the right-handed subjects, but the analysis of variance showed that these differences were not significant.

DISCUSSION

## A. Experiment I - Power spectral analysis

In the first experiment, the amplitude characteristics of EPs, and their relationship to stimulus modality and cortical recording area were investigated in the normal, right-handed subjects.

The power spectra of both the visual and auditory evoked potentials showed two major frequency groups; Group I, 0-5 hz., and Group II, 6-12 hz. These two frequency groups were remarkably constant between trials and between subjects and seemed to change mainly in their amplitudes and latencies, rather than in their form. This suggests that much of the observed intra- and inter-subject variability of EPs could be due to changing amplitude and phase relationships between two frequency components which are themselves quite constant.

The spatial distribution of the two components was different and a function of stimulus modality. Group II, 6-12 hz. responses were of largest amplitude in the primary projection area of the stimulus modality. The Group I, 0-5 hz. responses were always greater in the temporal areas for both VEPs and AEPs. This indicates that the Group I, low frequency responses retain a constant spatial distribution which is not specifically related to the stimulus modality. In contrast, the higher frequency, Group II responses shift and become greatest in the primary projection area of the stimulated modality.

The Group II, 6-12 hz. components were greater in the specific projection area of the stimulated modality for all areas and modalities, except the right hemisphere VEP. This anomaly may be related to speech dominance, since most reported differences in event-related potentials such as EPs or contingent negative variation (CNV) have occurred on the left, presumably speech-dominant side. Morrell and Salamy (1971) found maximum EP amplitudes to natural speech stimuli in the left hemisphere. McAdam and Whittaker (1971) found slow, negative potentials generated when the subjects spoke and which were larger on the left side. Buchsbaum and Fedio (1969, 1970) showed that occipital responses to tachistoscopic or flash presentation of words and similarly patterned visual stimuli were more different on the left, dominant side. These studies and other indicate that visual or auditory stimuli with verbal content generate responses which are more different in the left hemisphere than in the right. The power spectral analysis suggests that hemispheric differences may also be demonstrated with simple flash and click stimuli. This possibility will be dealt with more fully in the next experiment.

The waveform and peak latencies of each of the EP frequency groups is shown by the digital filtering. The Group I, 0-5 hz. frequencies consist of a slow, biphasic wave with peak latencies at about 100 and 300 msec. Both flash and click stimuli produce very similar Group I waveforms, thus supporting the hypothesis that they are non-specific to the stimulus modality. The Group II, 6-12 hz. responses appear first at about 50 msec., and recur at intervals of about 50 msec. The VEPs and AEPs from different areas have visually

different forms, suggesting their modality and area specificity.

The physiological meaning of the low frequency components is suggested by their latencies. Peaks occur at about 100 and 300 msec., which is too late to be carrying primary sensory information. The 300 msec. peak has been implicated in a wide variety of mechanisms involving aspects of cortical information processing which can be manipulated by various types of cognitive activity (Donchin, Kubovy, Kutas, Johnson and Herning, 1973). Picton and Hillyard (1974) and Schwent and Hillyard (1975) showed that the amplitude of both the 100 and 300 msec. peaks of AEPs could be reliably altered by changes in the subject's attentive set. Friedman, Simson, Ritter and Rapin (1975) reported that the latency of the 300 msec. VEP component became greater for words with informational content, than for those which were redundant repetitions of earlier information. These studies suggested that both the 100 and 300 msec. components of the EP were related to processes which were non-specific to the stimulus modality.

The functional role of the peaks and Group I, low frequencies is also suggested by their spatial distribution. These frequencies were widespread and of largest amplitude in the temporal areas for both flash and click stimuli, which again indicates a process which is not specifically related to the stimulus modality. The late components of the EP have a similar spatial distribution. Gastaut, Régis, Lyagoubi, Mano and Simon (1967) showed that these components

of the visual, auditory and somatosensory EPs were of largest amplitude near the vertex, and decreased towards the occiput. These findings were replicated for AEPs, and their dependence on the subject's attentive set was shown by Ritter, Simson and Vaughn (1972); Picton and Hillyard (1974); Hillyard, Courchesne, Krausz and Picton (1975); and Squires, Squires and Hillyard (1975).

All of the above studies thus suggest that the long latency components of both VEPs and AEPs are involved in processes which are not specifically related to the stimulated modality or recording area.. The 100 and 300 msec. peaks, especially, seem to be associated with generalized functions such as attention and extraction of meaning, as indicated by changes in their amplitude and latency when these subjective variables are manipulated.

Since the 100 and 300 msec. peaks are also the only positive peak components of the Group I, 0-5 hz. response, it is reasonable to suggest that these two separate peaks may be due to a single oscillatory process. The spatial distribution of this process is widespread over the cortex, and possibly related to aspects of sensory information processing which are not specific to the modality conveying that information.

The physiological meaning of the higher frequency, Group II, 6-12 hz. component is also suggested by its spatial distribution and peak latencies. The peaks first appear at about 50 msec., and then continue at about 50 msec. intervals. Early components of the EP, from about 30 to 100 msec., have been classed as specifically related

to the stimulus modality and to the recording area (Perry and Childers, 1967). However, from a frequency viewpoint, the 6-12 hz. group also is stimulus and area specific. Again, as with the low frequency components, inclusion of all the peaks with specific modality or area characteristics into a single frequency group would simplify their description. This unification would also be more meaningful than individual peak description if the EP was due to a single oscillatory process, rather than a sequence of separate events.

The Group II, 6-12 hz. component is largest over the specific projection cortex of the stimulated modality. It is therefore probably related in some way to the sensory information being transmitted to the cortex from lower centers. Its long latency of 50 to 100 msec. makes it unlikely that sensory information is being carried in the time-varying characteristics of its waveform, since a complete cycle takes about 100 msec. A more likely possibility is that the amplitude of this waveform might be modulated by afferent sensory patterns. Information would thus be carried in the spatially varying or spatial frequency characteristics of the waveform, rather than in its temporal form.



## B. Experiment II - Coherence analysis

In this experiment, the coherence or form similarity between pairs of EPs was investigated in relation to speech dominance and stimulus modality. Consequently, only the 6-12 Hz., modality-specific component was analyzed.

Speech dominance is the behavioral manifestation of the supposed lateralization of the cerebral mechanisms of speech comprehension and production to one or the other hemispheres. In most cases, this lateralization is to the left hemisphere, but a few percent of the patients who have been observed are either right speech-dominant or bilaterally represented. Right-handedness and left speech dominance are highly correlated, but the dominance of left-handed subjects is much less certain. This uncertain relationship makes it impossible to study either right or left-handed subjects and apply the results to both left and right hemispheric asymmetries of speech dominance. In normal subjects, however, it is not possible to use definitive tests of speech dominance, such as the carotid amytal test (Wada, 1949; Wada and Rasmussen, 1960), in which a barbiturate is used to paralyze the speech-dominant hemisphere, or electrical stimulation of the exposed cortex (Penfield and Roberts, 1959). These procedures are only justified for diagnostic or therapeutic purposes.

In this study, 3 groups of subjects were investigated to circumvent the problem of unknown speech dominance. Basic coherence asymmetries were investigated using right and left speech-dominant (RSD and LSD) epileptic patients, whose dominance had been ascertained

by the carotid amytal test. The results of the LSD patients were then compared with a group of normal, right-handed, and hence presumably left speech-dominant subjects. Agreement of these two groups would indicate that asymmetries of LSD and RSD patients were probably also applicable to normal subjects.

The comparison of left and right hemispheric coherences showed that, in most subjects, click responses or AEPs were more coherent on the speech-dominant side while flash responses or VEPs were more coherent on the speech non-dominant side. Not all subjects showed these general group tendencies; however it was not clear if the exceptions were due to experimental or analytic technique deficiencies, individual variation, or pathological responses in the patients.

Individual variation could account for some of the normal subject variation, since their left speech dominance was only assumed. For the amytal patients, the single exception to maximum click coherence on the speech-dominant side was one of the three RSD patients who had shown some bilaterality with the amytal test. One of the flash exceptions was also from a bilateral patient, but no further trends of bilateral representation were evident. Table II shows one RSD bilateral patient in whom the flash and click coherences were very nearly equal between hemispheres.

A possibly important factor in coherence variations may be analytic. The estimation of coherence from short records such as EPs is still very much unexplored, since most applications of spectral analysis to data have been on long data records such as EEG, meteorological and

geophysical data. Coherences are highly variable unless either long records or many estimates of coherences from short records are available. Analyses of group tendencies with many subjects, and consequently many coherence estimates, are thus useful indicators of overall group behavior. For single subjects, however, the methods of this chapter have produced only a few, highly variable estimates. It is thus not surprising that some subjects do not seem to fit the overall pattern of the speech-dominant group.

The estimation of coherence for single subjects might possibly have been improved by averaging fewer stimuli in each averaged EP. For example, the 160 stimuli of each subject might have been averaged into 16 groups of 10 stimuli, rather than 4 groups of 40. This method might not necessarily give better estimates of coherence, however, since the averaged EP on which they were based would be more variable. The situation is clearly of a "tradeoff" type in which the increased number of coherences available must be balanced against their increased variability.

The multivariate analysis of variance was used to investigate in more detail the source of the coherence asymmetries. The results indicate that the two significant main effects on the asymmetries are the subject and the stimulus modality. In other words, different subjects have different degrees of coherence asymmetry, and this asymmetry changes, depending on the stimulus modality.

The analysis also showed several significant interactions. The subject x modality (SM) interaction indicates that not all subjects

respond in the same way to the same stimulus. The mean coherences of this interaction showed that not all of the right-handed subjects showed left speech-dominant asymmetries. The mean coherences of the significant subject x modality x frequency (SMF) interaction suggested that VEP coherences and asymmetries tended to be greater at 9 and 12 Hz., while AEP coherences tended to be larger at 6 and 9 Hz. This suggests that the processes are independent which generate the widespread AEP activity in the left hemisphere, and the widespread VEP activity in the right hemisphere.

The results of Table III show that the mean asymmetries were significantly different for flash and click. It is possible to apply specific tests of hypotheses to these 3 asymmetries to determine which is most significantly related to the factors (Anderson, 1958). However, these are difficult to use and no computer programs are generally available which include them. The present analysis has established that significantly different asymmetries do exist for VEPs and AEPs. Only a qualitative evaluation of the 3 asymmetries will be dealt with further at this time. In the next experiment, another technique will be used to evaluate the significance of each asymmetry and its relationship to hemispheric asymmetry.

Table IV shows that the two main asymmetries contributing to the difference between VEPs and AEPs are the occipital to temporal (O1:O2-T3:T4) and left to right hemisphere (O1:T3-O2:T4) pairs. The differing ways in which they behave allow some inferences to be made about their meaning or relation to cortical processes.

The occipital-to-temporal asymmetry (O1:O2-T3:T4) appears to be related to stimulus strength, rather than stimulus modality. Its value increases for click stimuli, and in addition, the click coherences between each area are less than the corresponding flash asymmetries. Lower coherences could indicate a lower intensity of response, hence less interaction between the specific projection area of the stimulated modality and other areas. This would manifest itself as the observed low overall coherences but higher, occipital-to-temporal coherence differences.

The right-to-left hemispheric asymmetry (O1:T3-O2:T4) represents the conventional concept of hemispheric asymmetry, ie. differences between homologous areas of the right and left hemispheres. Table IV shows that it is also the only coherence asymmetry which changes in direction with stimulus modality. For AEPs, the left hemispheric coherence is greater, while for VEPs, the right hemispheric coherence is greater. This shifting of coherence asymmetries agrees with the simple analysis of the average 6-12 hz. coherences for each subject.

In summary, the multivariate results indicate that significant modality-dependent asymmetries exist but only the conventional, left-to-right asymmetry reverses with stimulus modality. The asymmetries differ in degree with different subjects, and are of slightly higher frequency for VEPs than for AEPs. The magnitude of coherence is smaller for click than for flash, but no pattern related to modality is present in the specific projection area of the stimulated modality. Only in the interaction between the occipital

and temporal areas of each hemisphere does the stimulus modality appear to be a controlling factor in the direction of asymmetry.

The direction of coherence asymmetry, either to the left or right hemisphere, was controlled by simple flash or click stimuli with no verbal content. This indicates that hemispheric asymmetries exist at a more fundamental level than verbal processing and that visual and auditory processes at this level are lateralized to opposite hemispheres.

These coherent processes within each hemisphere suggest similar activities occurring at widely different cortical locations. It is possible that this observed activity represents some widespread, high-level cortical process acting on, or generated concurrently with all stimulus patterns reaching the cortex, regardless of their ultimate meaning to the subject. The parieto-temporal association areas, located between the occipital and temporal recording sites, may be the common point of this activity for both visual and auditory stimuli. Associative activity between these areas, as measured by the coherence, would be lateralized to the speech-dominant hemisphere for auditory stimuli, and to the speech non-dominant hemisphere for visual stimuli.

Perception and recognition of verbal stimuli are lateralized to the speech-dominant hemisphere. Left temporal lobe lesions are known to produce many disorders of language production and comprehension (Mountcastle, 1962; Geschwind, 1970). Pharmacological paralysis (Wada and Rasmussen, 1960) or electrical stimulation of the exposed

cortex (Penfield and Roberts, 1959) in these areas results in transient impairment of speech. Patients in whom the corpus callosum has been sectioned can describe in words what they have seen when the left speech-dominant hemisphere is shown a picture via the right visual field. However, they cannot when the picture is shown via the left visual field, presumably because the left speech-dominant hemisphere has received no information about the picture (Sperry, 1964, 1969; Gazzaniga, 1970).

In contrast, visual perception appears to be more lateralized to the speech non-dominant hemisphere. Non-dominant temporal lesions result in decreased visual perception as measured by discrimination and spatial relationship tests, while dominant temporal lesions have little effect on these functions (Penfield and Roberts, 1959; Milner, 1962). In corpus callosum-sectioned humans, visual spatial perception seems stronger on the non-dominant side as measured by a variety of discrimination tests (Bogen and Gazzaniga, 1965, 1970; Sperry, 1968).

This evidence, as well as a large amount of data collected in normal subjects using dichotic listening (Kimura, 1961, 1963), therefore suggests that the speech-dominant hemisphere possesses superior auditory perceptual capacities, at least so far as speech verbalization and recognition are concerned. Visual perception, however, is a more non-dominant hemisphere function. These are the same hemispheres in which the most coherent auditory and visual evoked potentials occurred. It is thus possible that the coherent processes are in some way related to the perception of visual and auditory information.

It should be pointed out that most of the evidence for the lateralization of auditory and visual functions has been confined to right-handed, presumably left speech-dominant subjects. The extension to the much smaller population of right speech-dominant persons has been hypothetical. The results of the coherence analysis, however, suggest that right speech-dominant persons may also have their visual functions reversed from those of left speech-dominant persons. Speech dominance would then be one aspect of a larger configuration of visual and auditory asymmetries which were lateralized to opposite hemispheres. In most persons, this lateralization would be to the left hemisphere for auditory functions and to the right for visual functions. A much smaller group would have both these asymmetries reversed, with auditory functions in the right hemisphere, and visual functions in the left.

The possibility that coherent or correlated processes are related to perception is also suggested by the work of several Russian investigators. They reported that the correlations of EEG activity between many scalp areas increased during problem solving (Aslanov, 1970); during conditioned reflex formation (Dumenko, 1970); and were abnormally high in persons with associative disorders related to schizophrenia and epilepsy (Gavrilova, 1970).

In conclusion, these results indicate that significant hemispheric asymmetries exist for simple, unstructured flash and click stimuli, and that right and left speech-dominant patients show opposite asymmetries between hemispheres. These asymmetries are related to speech dominance, but appear to be of a more fundamental nature than speech processing since



they can be elicited by stimuli without verbal content. Greater intra-hemispheric coherence occurs in the speech-dominant hemisphere for auditory evoked potentials and in the speech non-dominant hemisphere for visual evoked potentials. This concept of intra-hemispheric asymmetry of evoked potentials, as indicated by the lateralized coherent activities, may represent associative processes occurring between sensory and associative cortical areas.

### C. Experiment III - Discriminant analysis

In the third experiment, the relationships of coherence and power spectral asymmetries to speech dominance and handedness were investigated with discriminant analysis.

The results of the discriminant analysis showed that asymmetries of coherence were significantly related to speech dominance, but power spectral asymmetries were not. This was demonstrated with the U-statistic for the significance of the difference between the LSD and RSD means. For the coherence asymmetries, the U-statistic was significant at  $p$  less than 0.005, but for the power spectral asymmetries, it was not significant at the very conservative level of  $p$  less than 0.25.

In terms of the characteristics of the EPs, these results indicate that the differences in amplitudes between hemispheres are not related to speech dominance. In contrast, the differences in form for the EPs recorded from different areas are related to speech dominance.

Amplitude asymmetries of various types of event-related potentials have been reported for natural speech stimuli (Morrell and Salamy, 1971); during linguistic versus non-linguistic tasks (Wood and Goff, 1971); with meaningful versus non-meaningful stimuli (Matsumiya, Tagliasco, Lombroso and Goodglass, 1972); for tachistoscopic presentation

of words and similarly patterned stimuli (Buchsbaum and Fedio, 1969, 1970); and for motor potentials preceding articulation (McAdam and Whittaker, 1971). In a lower frequency range, Morrell and Huntington (1971) and Low, Wada and Fox (1973) have reported amplitude asymmetries of cerebral slow potentials preceding speech.

There are thus indications from a variety of sources that differences exist in the amplitudes of left and right hemispheric processes. The negative results for amplitude asymmetries related to speech dominance do not necessarily contradict these findings. Only the report by Low et al used subjects whose speech dominance was definitely known. In most of the other reports, only right-handed subjects were used and it was suggested or inferred that observed amplitude asymmetries might be more generally related to speech dominance. The results of the discriminant analysis, however, show that this extension is not likely to be correct.

The discriminant equations (1) for the coherence asymmetries give a quantitative comparison of the contributions of VEP and AEP asymmetries to the determination of speech dominance. First, the LSD and RSD factors have opposite signs for both flash and click. This indicates that flash and click asymmetries contribute oppositely to speech dominance determination and that LSD and RSD patients tend to have opposite asymmetries. For example, a larger left hemispheric click coherence and a larger right hemispheric flash coherence will contribute to a higher

LSD score and a lower RSD score. Second, the approximately equal magnitudes of the click discriminant factors (14.67 and 11.59) for the LSD and RSD groups show that click asymmetries are about equally important in determining LSD or RSD membership. The smaller flash discriminant factors (5.92 and 1.93) for the LSD and RSD groups show that flash asymmetries are comparatively less important than click asymmetries in determining speech dominance. They also show that VEP maximum coherences are more clearly related to the right hemisphere in LSD patients than to the left hemisphere in RSD patients.

In terms of probabilities, the discriminant equations show that a high AEP coherence between the occipital and temporal areas of one hemisphere increases the probability that speech dominance is localized within that hemisphere. Conversely, a high VEP coherence between the occipital and temporal areas of one hemisphere increases the probability that speech dominance is localized within the opposite hemisphere.

The application of these findings to normal subjects is of great interest, since there is no way of unequivocally determining speech dominance in normal subjects. Definitive procedures, such as the carotid amygdala test, or electrostimulation of the exposed cortex are clinical techniques with little experimental usefulness. Dichotic listening, which can be applied to normal subjects, is only about 70% accurate in assessing ear-dominance in the same subjects over a one month period (Pizzamiglio, De Pascalis and Vignati, 1974).

Discriminant analysis of EP coherence asymmetries seems to give very similar results to the carotid amytal test. The computer and amytal predictions of speech dominance agree in about 90% of the patients. The amytal test itself has been surgically validated as being greater than 95% accurate by Branch, Milner and Rasmussen (1964). Since only 11 patients have been tested with the computer procedure, it would be premature to state more than a correspondence seems to exist between the amytal and computer tests.

The discriminant analysis of the normal subjects showed slight but not significant differences between the right and left-handed groups. Using a significance level of  $p$  less than 0.05 to definitely assign speech dominance, the analysis classified the 12 right-handed subjects into 8 LSD, 3 RSD and 1 bilateral (more RSD than LSD). The left-handed subjects were classified into 5 LSD, 1 RSD and 6 bilateral (4 subjects more LSD than RSD). Thus, if bilaterality is ignored, about 70% of the right-handed subjects (8/12) and 75% of the left-handed subjects (9/12) were LSD.

The analysis of variance of the normal subjects very clearly confirms the significant shifting of coherent activity from the left hemisphere during auditory stimulation to the right hemisphere during visual stimulation. Handedness had no significant effect on the coherence asymmetries and there was no interaction between handedness and stimulus modality. This indicates that both the right and left-handed subjects respond in the same way to the stimulus modality, that is,

larger VEP coherences in the right hemisphere and larger AEP coherences in the left.

The VEP and AEP asymmetries did not change significantly for left and right-handed subjects, but did for LSD and RSD patients. This indicates that handedness is not related to speech dominance. The majority of the normal population is thus probably left speech-dominant, regardless of their handedness. Left-handed subjects, however, show a much greater trend to bilateral representation, although the LSD component of this bilaterality is still larger than the RSD component.

The relationship of handedness to speech dominance has been investigated by many authors, with often differing conclusions. It has been stated that right-handedness is a good indication of left speech dominance, but that the speech dominance of left-handed subjects is either unpredictable or slightly favoured to the right hemisphere (Benton, 1962; Hecaen and Ajuriaguerra, 1964). It is important to note, however, that this relationship has been assumed on the basis of very little direct evidence. Almost all has involved patients in whom the speech process has been interrupted by pathological, surgical or pharmacological means. It has also been difficult to determine the extent to which early injuries or unknown conditions have affected maturation and lateralization of the speech process (Geschwind, 1970).

Penfield and Roberts (1959), using electrostimulation of the exposed cortex, concluded that most persons were left speech-dominant regardless of their handedness. They estimated 98% LSD and 2% RSD in the right-handed population, and 90% LSD and 10% RSD in the left-handed population. Bilaterality was not considered.

Branch et al (1964), using the carotid amygdal test, estimated 90% LSD and 10% RSD in the right-handed population, and 40% RSD, 50% LSD and 10% bilateral in the left-handed population. They admitted, however, that the question of bilaterality had only become apparent some distance through their series of patients.

Neither of the above studies made clear definitions of handedness, which require much more subtle distinctions than which hand is used for writing, or the person's own evaluation of his handedness.

Low et al (1973) have reported CNV-like asymmetries in a group of 8 LSD and 3 RSD patients whose speech dominance had been determined with the carotid amygdal test. They also applied their technique to 11 "pure" (Annett, 1967) right-handed and 11 "pure" left-handed normal subjects. Using maximum CNV amplitude preparatory to speech as an index of laterality, they were able to correctly predict the speech dominance of 8/8 LSD patients and 2/3 RSD patients. In the normal populations, they found a distribution of CNV asymmetries corresponding to 8 LSD, 1 RSD and 2 bilateral in the right-handed subjects, and 3 LSD, 6 RSD and 2 bilateral in the left-handed subjects.

The above distribution for right-handed subjects is similar to that derived from the discriminant analysis. The left-handed distribution is different, mainly in the number of RSD classifications. However, since only 3 RSD amyotrophic patients were tested with the CNV procedure and one of these was misclassified, their conclusions about RSD grouping must be weighed cautiously. They also reported considerably more bilaterality in the normal population than had been previously suspected, which agrees with the discriminant analysis.

Wada, Clark and Hamm (1975) found that significant morphological asymmetries exist in the cortical speech zones of both infant and adult brains. This suggests the possibility that asymmetries related to speech dominance in adults may also be present in young children, or even babies. Molfese (1973) reported EP asymmetries to speech and musical stimuli in infants. An ongoing longitudinal study of neonatal evoked potential asymmetries using spectral analysis is currently underway to clarify the possibility of early or even predetermined speech lateralization.

Using the above results, a fairly simple computational procedure for the determination of speech dominance can be defined. The BMD programs are widely available, but any spectral analysis program could be used to calculate the coherence asymmetries. Speech dominance classification and probabilities can then be calculated using equations (1) and (2).



The discriminant analysis shows several differences and improvements over those of the previous experiments. First, the relationship of left and right hemisphere coherences to speech dominance has been evaluated statistically with the patients. Second, in the normal subjects, the shifting of higher coherence to the left hemisphere with auditory stimuli and to the right hemisphere with visual stimuli has also been shown to be significant. Third, these results have been established for the largest amplitude component of the 500 msec. EP, rather than the modality-dependent, 6-12 hz. component. Of course, the frequency ranges of these two components are approximately the same, but the results are independent in that the components were chosen on the basis of two different criteria.

CONCLUSIONS

## A. Summary of spectral analysis

The power spectral analysis of EPs showed the existence of two major frequency groups, one from 0-5 Hz. and the other from 6-12 Hz. Their spatial distributions and latencies suggested that the 0-5 Hz. group was involved in processes which were not specifically related to either the stimulus modality or cortical recording area - such as attention or extraction of meaning. The 6-12 Hz. component, on the other hand, was a function of both the stimulus modality and recording area and was of largest amplitude over the cortical projection area of the stimulated modality. It thus seemed to be related to the processing of sensory information in specific cortical areas.

In the second experiment, the coherence or form similarity between pairs of EPs, and their relationship to stimulus modality and speech dominance were investigated. In both left and right speech-dominant epileptic patients, and in normal, right-handed, presumably left speech-dominant subjects, the occipital-to-temporal coherence of EPs was greater in the speech-dominant hemisphere for click stimuli, and greater in the speech non-dominant hemisphere for flash stimuli. Although other asymmetries of coherence were possible between the four recording areas, only the above, left-minus-right hemispheric coherence changed in direction with different stimulus modalities.

In the third experiment, the asymmetries of coherence were investigated using discriminant analysis. This technique showed, as was qualitatively deduced in Experiment II, that only the occipital-to-temporal coherence within each hemisphere was significantly related to speech dominance. A large AEP coherence within one hemisphere increased the probability that speech dominance was lateralized to that hemisphere. Conversely, a large VEP coherence within one hemisphere increased the probability that speech dominance was lateralized to the opposite hemisphere. In contrast to asymmetries of coherence, the discriminant analysis showed that power spectral or amplitude-related asymmetries between the right and left hemispheres were not significantly related to speech dominance.

Finally, the discriminant equations, expressing the relationships between coherence and speech dominance were applied to the EP coherences of normal, right or left-handed subjects. This analysis showed that the majority of both groups showed a significant left speech-dominant pattern. There was no significant difference between the coherence asymmetries of the two groups, although the left-handed subjects tended to show more bilateral or ambiguous representation. Since these coherence asymmetries were significantly related to the speech dominance of the patients, it was concluded that speech dominance and handedness were not related, and that the majority of both left and right-handed subjects were left speech-dominant.

## B. Physiological significance of the spectral components

The spectral descriptions of the EP waveforms showed clear relationships to physiological factors such as stimulus modality, cortical area, speech dominance and handedness. This was shown for both the power spectral and coherence characteristics of the EPs, which together constitute a complete description of the waveforms and their interactions with each other.

The power spectral or amplitude characteristics of the EPs depend on stimulus modality, recording area and frequency component of the EP. The low frequency, 0-5 hz. component is spatially generalized, independent of the stimulus modality, and of similar latency to EP correlates of such non-sensory processes as selective attention. In contrast, the higher frequency, 6-12 hz. component is modality-specific, and of largest amplitude over the cortical projection area of the stimulated modality. Its shorter latency and higher frequency suggests a possible role in the cortical processing of incoming information.

The coherence, or form similarity of different EPs, is dependent on stimulus modality, which hemisphere the recording is made from, and the person's speech dominance. It is not related to handedness. Click stimuli produce EPs which are more coherent within the speech-dominant hemisphere, while flash stimuli produce more coherent responses within the speech non-dominant hemisphere. The majority of both left and right-handed, normal subjects show this asymmetry, although those of left-handed subjects are somewhat less accentuated.

The different characteristics of the power spectral and coherence asymmetries suggest that these measures represent different aspects of cortical processing. Amplitudes were largest over both hemispheres of the cortical projection area of the stimulated modality, and were not related to speech dominance. Coherences were largest over the hemisphere related to the processing of the stimulated modality, and were related to speech dominance. This indicates that large amplitudes are characteristic of incoming sensory data, while large coherences represent the occurrence or spread of these amplitudes over large areas of one hemisphere.

The widespread occurrence of similar forms of EPs may represent associative activities within the temporal and parietal areas. These would be lateralized to the speech-dominant hemisphere for the perception and associative processing of auditory information, and to the speech non-dominant hemisphere for visual information. In other words, incoming data may produce equal responses in both hemispheres, but the perceptual processing of that information is lateralized to only one hemisphere and is associated with high coherences.

### C. Verbal and non-verbal stimuli

It is of great importance that the spectral asymmetries were produced with simple flash and click stimuli. These have very little spatial or temporal structure, and yet generate clear asymmetries. This suggests that cortical asymmetries of processing exist at a more

fundamental level than that of verbal encoding or decoding.

If the asymmetric, coherent responses are assumed to represent some widespread, possibly associative processing of information, then the coherence results suggest that opposite lateralities exist for visual and auditory information. The question of "verbal versus non-verbal" is thus reduced to one of "auditory versus visual" processing.

#### D. Implications for hemispheric functional asymmetries

The observation that simple flash and click stimuli produce opposite hemispheric asymmetries is a great simplification from earlier verbal or non-verbal distinctions. However, it still does not seem to answer the question: what is the basic difference between stimuli processed in the left hemisphere, and those processed in the right?

A possible answer to this question may lie in hidden assumptions of the question itself, which are that, first there is a difference between stimuli, and second, that somehow the brain recognizes that the stimulus is verbal, non-verbal, visual, auditory or whatever.

What are the consequences of assuming that no difference exists between a visual and an auditory stimulus? It is obvious, of course, that they are generated by different means and different sensory systems

respond to them. But phrasing the question in this way suggests another possibility. For there are two parts to the system, - the stimulus, and the perceiver, and it may be possible that the key to hemispheric asymmetries lies with the perceiver, rather than with the nature of the stimulus.

The simplest of visual and auditory stimuli produce hemispheric asymmetries which are related to perceptual asymmetries. It is thus possible that all visual stimuli are initially perceived within the right hemisphere, and that all auditory stimuli are initially perceived within the left hemisphere. Of course, at higher levels of processing, as in determining the linguistic meaning of words seen on a page, this initial lateralization would not hold, but the possibility for the very first steps of processing seems reasonable.

To make more inferences about these asymmetries, the nature of perception must be more carefully defined. The dictionary defines perception as a response to a pattern coupled with an understanding of what that pattern is, or represents. There are thus two components to the process; the first responding to the characteristics of the stimulus, and the second extracting meaning from it.

These two components of the perceptual process may be related to the power spectra and coherences. The power spectra, or amplitude-related characteristics of the EPs were largest in the cortical projection area of the stimulated modality, and were not related to speech dominance. In contrast, the coherence or similarity of form of responses was different between hemispheres, and was related to the person's speech dominance.

The magnitude of the response thus depends on the nature of the stimulus, that is, whether it is visual or auditory, but not on the subject, that is, his speech dominance. In contrast, the coherence of responses depends both on the stimulus modality and on the subject's perceptual asymmetries, of which speech dominance is probably only one aspect.

These observations suggest that the amplitude of responses, which is modality-dependent, may represent the bilateral, response component of the perceptual process. Similarly, the component of understanding, or cognitive mechanism which attaches meaning to what is seen or heard, may be represented by the lateralized, widespread coherent activities of the occipital, temporal and parietal areas.

Returning now to the question of which type of stimuli are processed within each hemisphere, a simple answer appears. Since asymmetries are produced for very elementary stimuli, it seems likely that all auditory information is initially processed within the left hemisphere, and all visual information within the right. If it is assumed that the amplitude of responses represents the sensory response, and the coherences, the process of understanding the meaning of the stimulus response, then auditory cognition is primarily a left hemispheric function, and visual cognition, a right hemispheric function. Consequently, the hemisphere chosen for processing does not depend on the nature of the sensory information, but on which sensory pathway it enters the cortex. The problem of stimulus identification, or the difference between verbal and non-verbal stimuli, is thus eliminated.



Why would such a lateralization of visual and auditory functions occur? The results do not answer this question, but they do suggest a generalization of hemispheric modes of processing which would require such a separation.

This necessity may lie in the different ways in which auditory and visual information are processed. It is probable that, initially at least, auditory information is sequentially analyzed in its temporal relationship to sounds that occurred earlier, as in speech. In contrast, visual information at any instant is simultaneously analyzed as a complete, spatial pattern. These two modes of processing are antagonistic in that simultaneous processing involves the analysis of sets of data at one time, while sequential processing involves the analysis of sets of data at different times. This is supported by the observation that split-brain humans are more adept than normal subjects at simultaneously performing two conflicting, verbal and non-verbal tasks. It is consequently understandable that the two different modes of processing, sequential for auditory information, and simultaneous for visual information, must be separated to opposite hemispheres.

## E. Final conclusions

The purposes of this investigation were to apply spectral analysis to EP waveforms, to meaningfully relate the results to physiological factors, to determine if simple flash and click stimuli could generate hemispheric differences in EPs, and if so, to study various aspects of these differences. It was hypothesized that, first, spectral analysis might detect differences that were not observable by peak amplitude and latency measurements, and second, that asymmetric responses could be generated by simple stimuli. If such were the case, this would indicate that differences between the so-called verbal and non-verbal processing modes were only subclasses of a larger classification.

The spectral analysis of EPs has fulfilled all of the above purposes. Interpretation of the EP waveform as a set of frequency components has shown that the behavior of these components can be related to stimulus modality, cortical area, speech dominance and handedness. The meaning of the components can thus be extended far beyond their original mathematical definitions. The behavior of the amplitude and form characteristics of the EPs has suggested electrophysiological correlates of the sensory and cognitive aspects of perception. Finally, the question of what type of stimulus produces hemispheric asymmetries has been shown to be misleading. Perception involves the interaction of both the object and subject, or perceiver of that object, and neither can be ignored in studying that interaction.

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