EEG COHERENCE AND
HEMISPHERE ASYMMETRY

Thesis submitted for the degree of Ph.D.
by Christopher C. French, 1982
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Following a brief introduction into the areas of hemisphere asymmetries of function and EEG techniques in general, a detailed review of EEG studies of lateralisation, including evoked potential studies, is presented. The evidence concerning anatomical asymmetries between the hemispheres, and the implications of this for EEG studies, are considered. The nature and uses of the coherence function are also reviewed prior to a description of the first experiment. This experiment involved having subjects perform one nonverbal tone-detection task and three verbal tasks which differed in level of difficulty. EEG was recorded from pairs of electrodes in the region of Broca's and Wernicke's areas and right hemisphere homologues. Analysis of power and coherence effects in the alpha band showed greater power and coherence over the left hemisphere than the right for the anterior electrode pairs. It seemed possible that the higher coherence over the left hemisphere was due to the use of auditory stimuli and this was investigated in the second experiment, when simple clicks and flashes were presented to subjects while EEG was recorded from occipital and temporal sites over each hemisphere. More power was found at the temporal sites than the occipital for the theta band, but the only coherence effect was that in all bands coherence was higher for the occipital electrode pair compared to the more widely separated temporal pair. Experiment III repeated the general procedure of Experiment II (with slight modifications) but examined coherence for EPs; once again, no hemisphere effects were found. Studies of phase angle effects are reviewed, and then an attempt is made in the final three experiments to 'map' coherence, phase angle and power effects topographically during a simple task. Several reliable effects were found and are discussed, but problems of interpretation are noted.
For Lesley and for my Parents
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Chapter 1: Introduction

1.1 Hemisphere Asymmetries of Function

The differences in function between the left and right cerebral hemispheres have been characterised in many ways and the popular appeal of the idea of two distinct 'brains' inside the same head has been exploited fully by many authors. Recently, Springer and Deutsch (1981) presented the following characterisations as being among the most widely cited, with each designation subsuming and going beyond the one above it:

<table>
<thead>
<tr>
<th>Left hemisphere</th>
<th>Right hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal</td>
<td>Nonverbal, visuospatial</td>
</tr>
<tr>
<td>Sequential, temporal, digital</td>
<td>Simultaneous, spatial, analogic</td>
</tr>
<tr>
<td>Logical, analytic</td>
<td>Gestalt, synthetic</td>
</tr>
<tr>
<td>Rational</td>
<td>Intuitive</td>
</tr>
<tr>
<td>Western thought</td>
<td>Eastern thought</td>
</tr>
</tbody>
</table>

Such conceptions of hemisphere function have become very influential. For example, it has been claimed that the typical Western system of education concentrates too much on the left hemisphere's skills and neglects to expand the right hemisphere's potential. It has also been suggested that differences between individuals can be explained in terms of their predominant 'mode of consciousness', i.e.
that people can be divided into 'left hemisphere' and 'right hemisphere' types. Unfortunately, these claims and many others in this area go a good deal beyond the actual evidence and it is probably true to say that most neuropsychologists would be unwilling to attribute characteristics other than those at the first level of Springer and Deutsch's hierarchy to the hemispheres. There are many who would not even accept this dichotomy, claiming that the apparent verbal/nonverbal split was in fact due to more basic differences in function. There are notable exceptions, such as Ornstein (1972), where certain neuropsychologists in presenting their own scientifically respectable studies to a lay readership go far beyond justifiable conclusions and thus further fuel popular misconceptions. At least within the field, however, the pendulum seems to be swinging away from the somewhat excessive claims of the early reports to a more balanced and considered appraisal.

Subsequent sections of this introduction will present a detailed account of one particular approach to the study of hemisphere asymmetry of function, i.e. the use of electroencephalographic techniques. The remainder of this section will be confined to a brief outline of the other major approaches used in the study of laterality, although the reader is referred elsewhere for detailed discussions (e.g. Dimond and Beaumont, 1974; Milner, 1975; Kinsbourne, 1978; Springer and Deutsch, 1981).

The notion that the hemispheres may differ functionally has a long history, but it first arose from observations of unilateral cerebral damage (see, e.g., Hecaen and Albert, 1978; Walsh, 1978; Dimond, 1980; Kolb and Whishaw, 1980). Observations in the last century by Broca and
Dax suggested that the left hemisphere was usually responsible for speech production and, as more evidence accumulated, the view developed that the left hemisphere was usually the 'major' or 'dominant' hemisphere, with respect at least to intellectual functioning, while the right was considered as 'minor' or 'subdominant'. Cerebral dominance was found to vary with handedness, insofar as evidence suggested that for dextrals the left hemisphere was, almost without exception, the language-dominant hemisphere, whereas for sinistrals a sizeable minority seemed to demonstrate right hemisphere or bilateral language control. However, it is only within the last few decades that it has come to be appreciated that the right hemisphere also has certain specialisations of function, although they seem to be less clearly defined and less strictly lateralised. For example, the right hemisphere would appear to be the mediator of facial recognition, with the inability to recognise familiar faces (prosopagnosia) usually being associated with right hemisphere damage. Other forms of visuospatial ability also seem to be impaired by right hemisphere lesions. Amusia, or the inability to recognise familiar melodies, is similarly produced, suggesting that the right hemisphere has a special role in this task also.

Studies of the effects of localised damage, or even hemispherectomies, have provided much information, but by far the most influential studies in the clinical field have been those of the so-called split-brain patients (see, e.g., Gazzaniga, 1970; Dimond, 1972; Gazzaniga and LeDoux, 1978). These patients have undergone an operation involving the surgical disconnection of the two hemispheres by cutting the corpus callosum. Thus, it is claimed, the functioning
of each hemisphere can be independently assessed by presenting tasks solely to one or other hemisphere. Generally, results from studies of such patients have supported those from other clinical sources, but it has recently been pointed out (e.g. Beaumont, 1981, 1982b) that much more caution is needed in extrapolating from this highly specific subject group to brain function in normals than has hitherto been shown.

In an effort to confirm and extend the findings from clinical groups using normal subjects, a number of techniques have been developed. Once again, each of these techniques has inherent methodological problems and the reader is referred to the references provided for a detailed discussion. One of the most popular techniques involves presentation of stimuli to one or other visual field. The anatomical structure of the visual system ensures that any information projected solely to one visual field will be directed primarily to the contralateral hemisphere. Hence it would be predicted that verbal stimuli would be processed more efficiently by presentation to the right visual field (RVF), and indeed an RVF advantage is commonly found for such stimuli. Certain nonverbal stimuli, e.g. faces, tend to produce an LVF advantage. Whether reaction time and accuracy differences are produced by (i) the stimulus being processed by the less efficient hemisphere, or (ii) the need to transfer the stimulus information across the corpus callosum to the appropriate hemisphere, is open to debate, but once again there is a broad general agreement between divided visual field studies and clinical data. However there are certain problems with this technique with respect to both methodology and interpretation, and the reader is referred to the

The auditory system does not show such a clear lateralisation, but it appears that the majority of nerve fibres from one ear travel directly to the contralateral hemisphere. This has been exploited experimentally using the dichotic listening technique, whereby information is presented simultaneously to each ear for the subject to process. Usually, verbal stimuli produce a right-ear advantage (REA), while certain nonverbal sounds, such as music, have been reported to produce left-ear advantages (LEAs). Once again, findings seem to agree at least broadly with clinical data, although, of course, the technique is not without problems (see, e.g., Darwin, 1975; Springer, 1977; Berlin, 1977; Springer and Deutsch, 1981).

Whilst the two techniques outlined above are certainly the most common employed in studies of normals, others are available. For example, Witelson (1976) used lateralised tactile processing, by having subjects palpate stimuli with either the left or right hand, to assess laterality of function. Another technique rests on the assumption that the direction of reflective lateral eye movements (LEMs) indicates which hemisphere is more activated, insofar as LEMs are said to be rightward when the left hemisphere is activated by verbal/mathematical questions, or leftward when the right hemisphere is activated by visual/spatial questions (see critical review by Ehrlichman and Weinberger, 1978). Other investigators have attempted to study the issue by observing the effects of concurrent unilateral motor performance on cognitive tasks presumed to be mediated primarily
by one hemisphere (e.g. Kinsbourne and Cook, 1971). It is sometimes argued that if the hemisphere that is appropriate for a particular cognitive task also has to control the motor output for a concurrent motor task, then performance will be worse than if the motor task was mediated by the task-inappropriate hemisphere. This would seem quite reasonable, but it has also been argued that if a hemisphere is activated by one task, this arousal can actually enhance performance of a task mediated by the same hemisphere (e.g. Hellige, 1978). Thus virtually any conceivable set of results can be accounted for.

On the physiological level, the most common techniques are those involving EEG/EP measures, but other techniques have been employed, and a series of studies by Lassen and Ingvar has produced interesting results with respect to differences in regional cerebral blood flow brought about by tasks thought to involve processing predominantly in particular areas of the brain (e.g. Lassen, Ingvar and Skinjoh, 1978). The effects of interfering with brain function chemically, by injecting sodium amytal unilaterally into the carotid artery (Wada and Rasmussen, 1960), or electrically, by applying unilateral electroconvulsive therapy (ECT; see Robertson and Inglis, 1977), also tend to support the general dichotomy of function suggested by other techniques.

Problems have arisen in this field when investigators have attempted to go beyond this general picture to fill in details concerning hemisphere functioning. For example, although it is recognised that differences exist with respect to handedness groups, much controversy surrounds the precise nature of these differences (see Herron, 1980a). Similarly, differences between the sexes in terms
of lateralisation are said to exist, but the evidence for them appears to be suggestive rather than conclusive (McGlone, 1980). Also, more than one view exists with respect to the complex issue of the developmental sequence underlying lateralisation of function (Springer and Deutsch, 1981).

It is to such issues of fine detail that the many studies reviewed in subsequent sections have been addressed. It is probably true to say, unfortunately, that these electroencephalographic studies have not served to clarify many issues, but simply to confuse further already complex controversies. Part of the reason for this may lie in the attitudes adopted by investigators in this area. Some feel that the techniques are still in the process of validation, and hence are not yet ready to provide new information until this process is complete and all major methodological problems have been overcome. Others would maintain that the validation period is over and that any remaining methodological issues are not of great significance and could not account for the findings reported. Thus it is not uncommon for claims to be made on the basis of EEG studies which involve a radical reorganisation of the original neuropsychological models, even though the EEG studies were presumably intended to complement and extend findings from other sources. Before reviewing these studies, I feel it is appropriate to declare my sympathy with the former group of investigators, those who feel that the electroencephalographic approach to the study of hemisphere asymmetry is not yet fully validated. Furthermore, the number of uncontrolled potentially confounding variables in most studies, coupled with the obvious reluctance of investigators to attempt publication of nonsignificant
results, leads me to believe that no-one has yet demonstrated lateralised EEG measures related to cognition whilst also meeting the strict criteria such a demonstration demands.

1.2 EEG Techniques

There are two main approaches to the investigation of hemisphere asymmetries of function using electrophysiological techniques. The first approach involves the collection and analysis of on-going EEG; the second, the collection and analysis of event-related potentials (ERPs). When using either of these approaches, investigators have tended to give subjects tasks demanding primarily left or right hemisphere involvement, as determined from clinical studies, behavioural studies or intuition. Various parameters of the data are then compared between left and right hemisphere sites and any significant differences are interpreted as reflecting neural processing of information by the differentially specialised cortical areas. While this approach is intuitively very appealing, there are various conceptual problems with it; also, much of the work in this field has been characterised by inadequate attention to methodological problems and analysis (Donchin, Kutas and McCarthy, 1977). These problems will be considered later, but first it is necessary to look in more detail at the types of parameter investigators extract from their raw data.

The raw data in most EEG studies consists of oscillating potential differences of the order of 20 microvolts between electrodes attached
to the scalp. Sometimes the EEG is analysed directly as analog data but increasingly it is digitised before further processing occurs. Investigators interested in the on-going EEG will usually decompose the raw data into different frequency bands, either using filters or FFT analysis, which correspond to, say, the traditional ranges of interest (< 4 Hz = delta, 4-8 Hz = theta, 8-13 Hz = alpha, and > 13 Hz = beta) or wider or narrower bands. The actual measures which are compared by statistical analysis are many and varied: mean power, integrated amplitude, percentage time each frequency is present, to name but a few of the more common measures. For a good introduction to frequency analysis see Cooper, Osselton and Shaw (1980).

Particular interest has focussed on the alpha rhythm since its original demonstration (Berger, 1930; Adrian and Matthews, 1934). The alpha rhythm is very distinctive, the large amplitude waves often occurring in bursts which stand out from the low-voltage high-frequency background. It seems to correlate well with states of relaxation and the amount of alpha present in the signal increases dramatically if the subject closes his eyes. The amount of alpha also increases as the recording electrodes move from frontal to occipital sites. Many investigators work on the premise that alpha presence is inversely correlated with cortical activation and thus attempt to demonstrate task-related alpha suppression over the more active hemisphere.

The second main approach is to examine differences in the time-domain, as opposed to the frequency-domain studies of on-going activity. In this case a waveform is obtained from the EEG by averaging (or summing). For sensory evoked potentials (EPs) the data
collection epoch is time-locked to stimulus presentation. The averaging process ensures that as the individual records from each stimulus presentation are added together, those parts of the signal that do not have a constant temporal relationship to stimulus presentation average out to zero. Those parts of the signal that are due to the time-locked neural response to the stimulus are enhanced with respect to the background noise and are thus available for visual inspection and statistical analysis, whereas they would be indistinguishable from background EEG in individual records. The signal-to-noise ratio improves as the square root of the number of averaged EEG samples, but in practice it is common to present between 30 and 150 stimuli in order to avoid fatigue and boredom which themselves may alter the waveform. The EP is usually analysed in terms of the amplitudes and latencies of its various positive and negative peaks, although recently increasing use is being made of more sophisticated techniques, such as Principal Components Analysis (Donchin, 1966; Chapman, McCrary, Bragdon and Chapman, 1979). Donchin, Kutas and McCarthy (1977) divide the EP components into two types - exogenous and endogenous. The exogenous components occur in the early part of the waveform and are thought to correspond to stages in the afferent stream. The shape of these components varies with the physical parameters of the stimulus and their distribution is related to the modality of the stimulus. The endogenous components occur later (after 150 msec) and seem to correspond to information-processing activities. For example, one endogenous component, the P300, can be produced even by the absence of an expected stimulus (Sutton et al., 1967). The term 'event-related potential' (ERP) refers not only to
sensory EPs but also to signals recorded before the eliciting event, such as the Readiness Potential (RP) and the Contingent Negative Variation (CNV). The RP is produced before an intended action (Kutas and Donchin, 1977), and the CNV, in anticipation of a stimulus (Walter, Cooper, Aldridge, McCallum and Winter, 1964). With respect to hemispheric asymmetry of function, the usual approach is, again, to look at various parameters of the signal with subject task as the independent variable. In the case of ERPs the parameters include latency, amplitude and distribution on the scalp.

1.3 EEG Asymmetries - A Review

Other reviews of this field are presented by Donchin, Kutas and McCarthy (1977), Donchin, McCarthy and Kutas (1977), Marsh (1978), Butler and Glass (1976) and Shepherd (1980). Beaumont (in press) and Galin (1979) both present interesting discussions of methodology and Donchin, Kutas and McCarthy (1977) present an excellent "Methodological critique of lateralization studies" which must be considered as required reading by any investigator in this area. Many of the ideas presented in this section will be taken from that paper.

The literature on hemispheric function as indexed by EEG and ERP studies is in a confused state, with more conflicting claims and failed replications than are to be found in the more traditional approaches to hemispheric differences, which are themselves not without controversy. There are many reasons for this. One of the main problems is that this body of work is proceeding in the absence of any
real prior understanding of the various components of the event-related potential or of the EEG. It seems to the uninitiated that comparisons are being made (albeit extremely painstakingly and often ingeniously) of measures on the two sides whose significance even on one side remains to be satisfactorily worked out. At present, workers in the field have adopted a purely empirical approach because there is nothing better available. Because of this, it is often the case that there is no way of ascertaining in advance the expected direction of asymmetry of a particular measure. However, whereas this problem can only be solved by advances in our understanding of the neurophysiological significance of the EEG, much confusion could be avoided if more attention was paid to methodology by investigators. It is usually impossible to directly compare findings from different laboratories because of widely varying techniques of analysis, experimental design, electrode placements, and so on, and this presents a considerable problem in itself. But more seriously, the conclusions arrived at from individual studies may be open to criticism for any or all of the following reasons (Donchin, Kutas and McCarthy, 1977):

(1) The experimental design is not sufficiently sensitive to allow detection of the differences or is inadequate to support the conclusions.

Repeated measures designs are most definitely preferred, as it is well-known that inter-subject variability is very large especially in on-going EEG studies (measuring alpha abundance,
for example). Also, it is essential to include proper control procedures, such that any asymmetries that are found are shown to disappear for a control task. As Donchin et al. (1977) state, "At the least the investigator should demonstrate that the lateral asymmetry can be reversed or modulated with appropriate changes in the task; thus investigators should include tasks designed to engage each hemisphere differentially". As will be discussed later, it is often claimed that the hemispheres are not symmetrical with respect to EEG parameters even in a "resting state", making it imperative that any asymmetries found are shown to be task-dependent.

(2) The tasks assigned to the subjects may not in fact differentially engage the hemispheres.

All too often no check is made on the subjects' performance and so it is not certain that instructions were carried out in the required manner. Many investigators simply ask the subject to mentally perform the task. Data should be presented on task performance as task difficulty could well be a critical factor. Many studies can be criticised on the grounds that very different physical stimuli are presented for each task, even though it is known that stimulus parameters can have great effects on ERPs. The ideal solution to this problem is to use the same stimuli for each task and simply vary the cognitive task of the subject.

(3) The effects may be range-restricted and the values of the
independent variables (usually task demands) are out of the relevant range.

(4) Individual differences are not considered.

For all EEG work it is essential to record age, sex, prior drug ingestion and any other relevant variables. Obviously one of the most relevant variables in this area is subjects' handedness.

(5) The parameters of the EEG used as dependent variables may be unwisely selected.

For example it is common to be presented with a table showing ratios of alpha abundance \( R/L, R/(R+L) \) or \( (R-L)/(R+L) \). Whilst giving a good summary of the data, such tables do not allow the reader to see if the changes in ratios for particular tasks are due to increases in alpha in one hemisphere, decreases in the other or both. Thus it is not possible to infer how the effects are brought about in terms of hemisphere activation.

(6) The measurement techniques used to obtain the parameters may be inappropriate.

As the EEG represents the difference between the potential at two electrodes it would be ideal if there existed an inactive "silent" area on the scalp against which to compare the activity of the active sites of interest. Unfortunately no such area
exists on the head, but noncephalic references (Stephenson and Gibbs, 1951) can be used. Certain electrode montages are to be avoided at all costs in hemisphere asymmetry work.

A single non-equidistant reference electrode will pick up a signal that will have more in common with the nearer electrodes. Thus, by the common-mode-rejection characteristic of differential amplification (Cooper et al., 1980), more of the signals for the closer electrodes will be rejected, possibly resulting in a smaller signal which could be misinterpreted as a genuine asymmetry. If different unilateral electrodes are used, artifacts generated at a single reference could be misinterpreted in the same way. Bipolar intrahemispheric linkages could mask genuine asymmetries, again due to common-mode-rejection. According to Donchin et al. (1977) linked ears or mastoids or chin or active midline placements avoid most of the difficulties mentioned. In fact, though, with any cephalic reference results are open to serious misinterpretation. As Mowery and Bennett (1957) point out, if linked ears or mastoids are used and the resistance of the electrode contact is unequal at each point, the instrument will record mainly from the point with the lower resistance, resulting in a decrease in amplitude over that side due to common-mode rejection. Elsewhere, French (1980) and Beaumont (in press) have described in detail how the phase relationship between reference and active electrodes can confound observed amplitude of potentials recorded from the scalp. There is a great deal of evidence to suggest that a noncephalic reference is to be preferred (e.g. Lehtonen and Koivikko, 1971; Wolpaw and Wood,
The data are improperly quantified and were inappropriately or insufficiently analysed.

As Friedman, Simson, Ritter and Rapin (1975a) point out, multiple use of univariate procedures without adjustment for the number of tests being performed can result in misleading conclusions, since the probability of finding spuriously "significant" differences is underestimated. Another fault is to omit statistical analysis totally and simply describe findings in a qualitative manner. Considering the variance found in EEG data, this is totally unacceptable and, fortunately, is on the decline.

Apart from the criticisms listed above it is of course essential to be sure that all of the usual procedures are observed carefully and artifacts in the data are kept to an absolute minimum. Every effort should be made to keep equipment properly calibrated and electrodes well-attached.

There are certain advantages and disadvantages to both the EEG and ERP methods. The main disadvantage of the ERP technique is its artificiality; it is necessary to repeatedly present stimuli, preferably of a transient nature, with sharp onset and offset times. If one is trying to investigate electrical indices of meaning, say, it is unlikely that a stimulus presented over and over again, often in isolation, will be perceived and processed in the same way as that stimulus presented in its natural context. Looking at on-going EEG
allows one to use more naturalistic tasks, but there is then a danger of picking up artifacts in the data which may quite conceivably be asymmetrically distributed themselves, thus leading to a misinterpretation of the situation. This is especially the case, unfortunately, in the naturalistic tasks involving movement of the limbs and eyes, such as reading, writing and any kind of manual manipulation. It has been argued (Galín, 1979) that use of ERP techniques is very effective in eliminating artifacts which are not time-locked to the triggering event. While this is true to a certain extent, it is very unwise to assume that all artifacts will be "averaged out", because eye-blinks, say, can produce artifacts of up to 50 microvolts at central electrodes. This is too large to "average out" in comparison to background EEG, especially when the ERP waveform is produced sometimes from less than twenty averages and differences in components from one to two microvolts are compared (Desmedt, 1977).

Generally it is more convincing to produce hemispheric asymmetry of EEG and ERP in very well-controlled experiments, involving a minimum of movement (preferably none), using the same stimuli for each task and altering only the cognitive demands of the task. This is not to say that experiments which do not control to this high degree are worthless, but they should perhaps be considered as only suggestive or, better still, as pilot studies to be followed by well-controlled versions of the same experiments in an attempt to show that any task-related hemisphere asymmetries noted are genuine reflections of underlying psychophysiological processes. In fact, it is probably a sensible course of action to first actually find tasks which seem capable of producing the desired asymmetries before putting the extra
time and effort into a stringently controlled study. The direction of eye-movements may well be related to the type of task presented (Ehrlichman and Weinberger, 1978; Kinsbourne, 1970, 1972) in which case the effects could be accumulated by averaging and produce artifactual asymmetries (Anderson, 1977).

No attempt will be made in this chapter to review the large number of studies which have concentrated on hemisphere asymmetries and psychopathology, although such studies will be discussed if they are of relevance to particular topics under discussion. The reader is referred to Gruzelier and Flor-Henry (1979) and volume 4 of Advances in Biological Psychiatry (1980) for collections of papers in this area, but especially to the excellent critical review by Marin and Tucker (1981). Details of asymmetries in coherence studies will be presented in Section 1.4.2.

1.3.1 On-going EEG

1.3.1.1 The "Resting" State

Before examining evidence on the question of task-related EEG asymmetry it is important to ascertain if the hemispheres produce similar patterns of activity during the no-task, "resting" condition. One problem in trying to evaluate such a baseline condition is that one is never sure what the subject is really doing when told simply to "relax". It is certain that subjects do not entirely "switch off" and that their cognitive activity continues, possibly in a predominantly
verbal mode. There is a possibility that slight changes in experimental procedures could affect results, particularly if in some studies baseline measures are taken before subjects have acclimatised to the somewhat unusual surroundings of the EEG laboratory. Whatever the reasons, it is certainly true to say that we still do not have a clear consensus of opinion upon this issue.

The amount of alpha, both in terms of amplitude and percentage of time present over each hemisphere, has been examined in many studies. The first to examine this question directly was by Raney (1939) who used central and occipital electrodes (both unipolar and bipolar) and reported finding a tendency for a greater amount and amplitude of alpha over the non-dominant hemisphere. Strauss et al. (1943) also found essentially the same thing, but stressed that striking asymmetry may be a sign of disease. Corinil and Gastaut (1947) also found lower amplitude alpha and greater alpha suppression over the left hemisphere. Subirana and Oller-Daurella (1960) stated that in “about 90%” of their “100% right-handed” group the right hemisphere showed greater alpha amplitude than the left. They also commented that the degree of laterality was very important with respect to the EEG pattern, in that there were many signs of “immaturity” in the EEGs of less lateralised subjects (e.g. slowing of the basic pattern and the appearance of slow posterior waves). Smyk and Darwaj (1972), recording from the parieto-occipital areas, also noted a R>L asymmetry.

Lehmann (1971), in a study of the topography of the human alpha EEG fields using large numbers of scalp electrodes, found three “preferential areas” for maxima and minima to occur in alpha waves, the main one being the right occipital area. Morgan et al. (1971,
1974) have also found asymmetries in alpha activity during a "resting state" by integrating the difference between the potentials in left and right occipital electrodes (vertex as reference). They estimated the mean integrated amplitude of alpha (in microvolts/second) to be 26.3 over the left hemisphere and 29.0 over the right during an eyes-open baseline measurement (Morgan et al., 1974). It is worth mentioning here that a scalp-recorded alpha amplitude asymmetry may not be due solely to cortical activity, but also to the thickness of the skull. Leissner et al. (1970) found the thickness of the skull, as measured by an ultrasonic technique, to be greater on the left in 52 of 81 cases with a corresponding attenuation of alpha amplitude. Fox (1979) recording from O1 and O2 (referenced to A2 and A1, respectively) found more alpha activity recorded over the right hemisphere than the left in terms of alpha amplitude during a "resting state". Moore and Lang (1977) reported a weak interaction suggesting that percent-time alpha is less over the right hemisphere in a group of stutterers, but over the left for a normal control group for temporal EEG.

Several studies have addressed the developmental aspects of EEG asymmetry in the resting state. Varner et al. (1977) and Peters et al. (1981) report that EEGs from homologous placements over frontal, central, temporal and occipital placements in newborn infants are symmetrical during active and quiet sleep. In 81 school-children, Samson-Dollfus et al. (1975) reported a R>L asymmetry for occipital alpha, while the delta rhythm predominated over the left hemisphere. Matoušek and Petersén (1973), in a large scale study of 401 children and 160 adolescents, reported that, "As a rule, the amplitudes are
larger on the sub-dominant hemisphere". They also calculated an asymmetry ratio which disregarded the direction of asymmetry by dividing the smaller by the larger amplitude, and found that in the temporal regions it increased significantly with age. Matthis et al. (1980), reporting data from occipital and central EEGs in 295 children, stated that "Differences between corresponding regions of the two hemispheres are small". R/L ratios were not correlated with age, and when Matoušek and Petersén's (1973) ratio was employed, occipital asymmetry actually appeared to decrease with age. Matoušek et al. (1981) report that the R>L asymmetry is seen at temporal and parieto-occipital placements, but may be reversed at more anterior derivations (cf. Giannitrapani, 1979a). They also reported finding no differences between handedness groups. In this report they state that L/R ratios are almost independent of age. A large scale study of age-related changes in 110 normal adult males (Wieneke et al., 1980) shows differences in alpha power asymmetries related to electrode placements, with a generally R>L asymmetry which is stronger occipitally. However, as the investigators point out, very few subjects showed a R>L asymmetry at all four scalp areas considered.

However, a great number of other investigators have failed to find any alpha asymmetry. In 1955, Glanville and Antonitis failed to find any consistent relationships between left and right occipital alpha and laterality in a group of fifty normal adult males, either for amplitude or percentage. Marsh (1978) wrongly criticises this study for "the choice of only the right ear as reference...as it would suppress any alpha activity common to the right leads (O2 and the ear reference)". The original paper states, "Silver ear clips were used as
 reference" which is more suggestive of ipsilateral ears being used although admittedly unclear. A more valid criticism is made by Butler and Glass (1976), who point out that the manual measurement used would have been reliable to, at most, 5 microvolts (10-25% of alpha amplitude). Wilson et al. (1959) also found no difference in "percent time alpha" between right and left hemispheres, and Bennett and Trinder (1977) recording from T3 and T4 (Cz reference), using the same index, found no asymmetries either for meditators during meditation or non-meditators during relaxation. Klemm et al. (1980) found no relationship between left and right occipital alpha power asymmetry and handedness.

Provins and Cunliffe (1972) using left and right parietal electrodes (midline parietal reference) could find no consistent differences between the right and left hemispheres using total activity of the EEG, percentage alpha (of total) and percentage beta (of total) as indices. The test-retest reliability of the EEG activity on each side was high, but that of the difference between the sides was not. Marsh (1978) makes the misleading statement, with respect to the comparison made between a right- and a left-handed group, that "the right-handed subjects had the greater abundance of alpha activity. Further, if only right hemisphere activity between the groups was compared, the right-handed group had greater alpha activity". While true, it should be pointed out that the right-handed group also showed higher alpha activity in the left hemisphere and higher EEG activity over both hemispheres than the left-handed group.

Aird and Gastaut (1959), using longitudinal and transverse bipolar chains of electrodes, found that 82.6% of their sample of 500 normal
adult males showed no asymmetry in occipital alpha amplitude, but they only counted differences greater than 20%. More recently, Butler and Glass (1974a, 1976; Glass and Butler, 1973) have examined the distributions of both total EEG activity and filtered alpha over the hemispheres. Glass and Butler (1973) report that during a resting condition (eyes closed and eyes open), and recording with two bipolar electrode pairs over each hemisphere (O1-P3, P3-C3, O2-P4, P4-C4), "Both total EEG and alpha rhythm were symmetrically distributed...". However, in what seems to be a more detailed report of the same study (Butler and Glass, 1974a) they report that total EEG activity is lower over the left hemisphere, although alpha is symmetrical as previously claimed. Also it is claimed (Butler and Glass, 1976) that these asymmetries in total EEG activity are related to handedness but it is not clear if this effect reaches statistical significance for the resting conditions taken alone. An attempt is made to reconcile the different findings on this matter from different studies. Firstly, it is suggested that as most pre-1970 studies used manual measurement of the raw EEG the results may not be very reliable. Specifically, contamination from outside the alpha band may have been included in estimates. Secondly, they suggest that the presence of a potential conversant or an on-going conversation near the subject (e.g. Raney, 1939; Morgan et al., 1971, 1974) may maintain alertness of the verbal left hemisphere and thus lead to artifactual results. Butler and Glass (1974a; Glass and Butler, 1973) used a soundproof chamber to isolate the subject from the experimenters and thus avoided this verbal bias.

The finding of Rémont et al. (1969; Lairy et al., 1969) using their "alpha average" technique are worth mentioning. Using transverse,
longitudinal and cruciform bipolar montages their method showed that there was usually a general symmetry between the hemispheres in terms of "alpha average" amplitude and frequency/phase relationships, but perfect symmetry was very rare. Lairy et al. (1969) found no clear relationship between "alpha average" and direction of laterality, but tended to support the view that degree of laterality is the important factor (more asymmetry was found for stronger laterality). It was also found that learning-disabled children showed disturbed interhemispheric relationships, but less asymmetry of "alpha average" than normal children.

Another aspect of interhemispheric asymmetry which has received much study is that of phase and frequency relationships. Lindsley (1940) using bipolar occipital electrodes claimed that alpha waves were more out of phase between the hemispheres for left-handed and ambidextrous subjects than for right-handers. He also noted a non-significant trend for greater unilateral blocking of alpha in the side contralateral to the preferred hand. In common with Travis and Knott (1937) he found that stutterers show greater asynchrony between the hemispheres. Cohn (1948) also used bipolar occipital electrodes and found that the left hemisphere shows better frequency regulation in terms of the range of duration of individual alpha waves: 100-110 msec in the left hemisphere and 75-175 msec in the right. He did not report "that the nondominant hemisphere usually leads in the initiation of a burst of alpha activity" as Marsh (1978) claims.

Giannitrapani and colleagues have used phase analysis to study the relationship between which hemisphere leads in different areas of cortex during sleeping and waking, and laterality. Giannitrapani and
Darrow (1963) found that the central areas contralateral to the preferred hand and eye lead especially during sleep. Giannitrapani et al. (1964) found that during sleep, "leading was homolateral to laterality preference in anterior areas; during waking, it was contralateral to laterality preference in posterior areas". Giannitrapani et al. (1966) using eighteen scalp electrodes (nine homologous L-R pairs) and linked ears reference found significant differences between the hemispheres in prefrontal and frontal sites (left leads) during sleep, and in parietal and occipital areas (right leads) during wakefulness - but only for left-handed adult subjects. No explanation is offered as to why previous results were not replicated. Giannitrapani (1966) counted visually detectable pen deflections for left and right electrode placements over temporal, occipital, parietal and frontal areas (linked ears reference). He found a just significant difference between left and right frontal and temporal areas, with the left hemisphere producing more deflections.

Liske et al. (1967) found that the right hemisphere tended to lead the left in 24 of 42 subjects. The mean value for the right leading was 0.83 msec (ranged from left leads by 4 msec to right leads by 7 msec). They used bipolar montages and checked their estimates using cross-correlograms. Hoovey et al. (1972) used 01 and 02 placements (end of nose reference) and found the mean value of the interhemispheric peak differences to be between plus or minus 2.5 msec, but for individual alpha wave comparisons this difference ranged between plus or minus 20 msec. The standard deviation of the mean interhemispheric alpha intervals was taken as a measure of synchrony between the two hemispheres and found to vary widely between
individuals. The lower the standard deviation (i.e. the better the synchrony), the better the correlation between alpha amplitudes across hemispheres. It was noted that the right and left hemispheres lead alternately for periods of about 3-5 sec each. It is worth noting that mean peak-to-peak amplitude was found to be equal (72 microvolts) for right and left, although this point is not discussed. A review of other phase angle studies is presented in Chapter 5.

Wiet (1981a, b; Wiet and Goldstein, 1979) has compared academically successful and unsuccessful students in terms of integrated EEG amplitude between 0.5 and 30 Hz. Using electrodes at T3, T4, O1 and O2 (Cz reference), it was found that during an eyes-closed relaxed state the unsuccessful students showed higher R/L amplitude variance ratios and a greater number of polymodal distributions in histogram plots of cumulative amplitudes, especially over the right hemisphere.

Thus it can be seen that there exists a wide range of confusing, often contradictory findings in this area. Many of the apparently contradictory claims probably reflect nothing more than differences in methodology especially with respect to the technique of measurement and the electrode placements used. It is notable that the studies which report striking R>L asymmetries tend to have used occipital placements, whereas frontal sites may even show a reversal of this pattern (Giannitrapapani, 1979a; Matoušek et al., 1981). Differences between age groups and handedness groups have been reported, but as no clear pattern has emerged more research is obviously needed in this area. With reference to the methodological critique outlined earlier it will be seen that many of the studies discussed had one or more of the faults listed. In particular, the vast majority used bipolar
montages. The fact that an asymmetry may exist in the "resting state" makes it all the more necessary to show that any asymmetries found are task-dependent, even though it must once again be emphasised that "resting states" do not fulfil the requirements of an adequate control condition.

1.3.1.2 Photic Driving

Photic driving is the phenomenon whereby the EEG, especially in the posterior regions, shows the same frequency (possibly with harmonics) as a flashing repetitive light. It is of interest to see if any hemispheric asymmetries can be found using this technique, either with unilateral or full-field stimulation.

Adrian (1943) seems to be the only investigator to report that if stimulation is confined to one visual field, the contralateral hemisphere alone is driven. Others (Toman, 1941; Freedman, 1963; Lansing and Thomas, 1964) have found that unilateral stimulation leads to both hemispheres being driven. Kooi et al. (1957) and Hughes and Curtin (1960) report that about 5% of the normal population show amplitude asymmetries of 50% or more during photic driving, but do not report the direction of the asymmetry. More asymmetries are found in patients with unilateral brain damage, the lesser response being on the damaged side. Cornil and Gastaut (1951) found that the driving response for most normal subjects was asymmetrical, being of lower amplitude over the dominant hemisphere.

Celesia et al. (1978) supported this finding using modern
techniques of spectral analysis. In a study involving 19 normal subjects, binocular stimulation was found to produce higher power peaks over the right hemisphere in 79% of cases. This right side predominance increased to 84% when only the left eye was stimulated and decreased to 53% when only the right eye was stimulated.

Lansing and Thomas (1964) found the opposite result, using a group of predominantly right-handed subjects and parietal-occipital bipolar recordings. They found that five of their 29 subjects showed amplitude asymmetries of 50% or more during driving and the majority of subjects showed some amplitude asymmetry in favour of the left hemisphere. Driving laterality was found to be constant across mode of presentation (binocular or monocular), frequency, and field of stimulation. However, it is to be noted that this study found higher amplitude alpha over the left hemisphere (resting, eyes closed), a finding at odds with most other reports using occipital placements. Freedman (1963), using the same electrode placements and right-handed subjects, found more waves in the 7.5-8.5 Hz range over the right hemisphere than the left when 8 Hz photic stimulation was presented either in full-field or unilaterally. The asymmetries were still significant following an adjustment for a "resting" asymmetry in this index, and the greatest asymmetry was found during left-field stimulation. It is important to realise that these results do not necessarily contradict those of Lansing and Thomas (1964) as different indices of photic driving were used. Finally, Crowell et al. (1973) used spectral analysis to investigate photic driving in 97 neonates. Thirty-six babies showed a significant increase in power at 3 Hz and harmonics thereof, in response to 3 Hz full-field photic stimulation.
Of these, 18 showed driving in one hemisphere only, usually the right. A developmental sequence was postulated beginning with no driving, followed by right unilateral driving, and ending with bilateral driving. The results are interpreted in terms of dominance of the right hemisphere for rhythmic visual stimuli and an initial lack of interhemispheric integration.

Whilst not describing a study of photic driving, the report by Heilman and Van den Abell (1980) is perhaps of relevance here, as it too claims to demonstrate a right hemisphere predominance for visual stimulation. Using bipolar montages at F3-C3, C3-P3, P3-O1 and right-sided homologues, the investigators found, by comparing alpha power one second before and one second after a lateralised visual stimulus, that the left parietal lobe desynchronised most after right-sided stimuli, whereas the right parietal lobe desynchronised equally after right or left stimuli. This result is interpreted in terms of a right hemisphere dominance for attention.

In summary then, a right-sided predominance in photic driving would appear to be a well-established result, with only one of several studies finding the opposite asymmetry. However, it is impossible to say whether this effect reflects a possible right hemisphere dominance for visual perception or simply is a result of the generally higher occipital EEG power over this hemisphere.
1.3.1.3 Task-related Asymmetries

The last two or three years have witnessed a great increase in the number of EEG investigations of task-related hemispheric asymmetries, but original observations pertaining to this issue were made by Cornil and Gastaut in 1947. They noted an increase in the resting asymmetry when subjects performed mental arithmetic. However, they also claimed that opening the eyes increased the asymmetry, so this effect was not necessarily task-related and could simply reflect a tendency for EEG to block asymmetrically. Wilson et al. (1959) recorded the occipital EEG in 20 subjects while they wrote with either their left or right hands. Regardless of the hand used, the "percent time alpha" was less over the left hemisphere than the right, although a loud auditory stimulus produced a bilateral decrease. Thus an explanation in terms of a tendency towards a nonspecific asymmetrical blocking of alpha is not tenable and Wilson et al. interpret their findings in terms of "the greater contribution of the left hemisphere in the organisation or control of verbal-motor behavior".

The vast majority of experiments in this area have been performed since 1970, beginning with the work of Morgan et al. (1971, 1974). These investigators recorded occipital EEG (Cz reference) from right-handed subjects during the performance of verbal, numerical, imagery and musical tasks and calculated an asymmetry ratio \( R/(R+L), \) 1971; \( (R-L)/(R+L), \) 1974). The right hemisphere always produced more alpha in absolute terms, but, relatively, the left hemisphere was significantly more activated for the analytical and musical tasks than
for the spatial tasks. The results for the musical task are somewhat unexpected as much clinical and experimental evidence would suggest that perception of music is primarily mediated by the right hemisphere, at least in nonmusicians (Damásio and Damásio, 1977; Wyke, 1977). Morgan et al. attempt to explain this in terms of task difficulty, a topic to be considered in more detail later. It is also of interest that the attempt to engage the right hemisphere preferentially was rather unsuccessful, as much of the later research has shown a similar trend.

Galin, Ornstein and colleagues have carried out a large number of studies in this area. Galin and Ornstein (1971; Galin et al., 1972) recorded from T3, T4, P3 and P4 (Cz reference) and integrated the whole band EEG (1-35 Hz). Subjects performed verbal tasks (writing a letter and mentally composing a letter) and spatial tasks (Modified Kohs Blocks Design and Minnesota Paper Form Board tests) and the R/L ratios were calculated for each one. The ratios showed significant differences between the spatial and verbal tasks at both sites, with the left hemisphere being relatively more activated for the verbal tasks. It is claimed that the results are not affected by whether the eyes were opened or closed, or by eye movement, or by whether or not motor output was involved. Doyle, Ornstein and Galin (1974) used the same electrode montage on ten right-handers performing a variety of tasks. Fourier transforms were used to divide EEG activity into various frequency bands for a more detailed analysis of the ratio scores. It was found that the significant ratio differences between verbal/arithmetic tasks and spatial tasks occurred primarily in the alpha band, with the beta and theta bands showing the effects less
consistently. The magnitude of the effect is two to five times greater when the alpha band is considered as opposed to the whole band activity. Interestingly, tasks requiring motor output produced larger alpha asymmetries. Galin and Ellis (1975, 1977) found higher R/L alpha ratios for writing than for Kohs Blocks at parietal and temporal sites (Cz reference), giving further support to these findings. Johnstone, Galin and Herron (1979) looked at the R/L ratio of power in the 9-11.9 Hz band (log transformed) of central and parietal EEG (Cz reference) while male and female subjects engaged in a speech task and Kohs Blocks task. They found that handedness measures significantly correlated with task-induced EEG asymmetry differences only in females.

Herron et al. (1979) attempted to test Levy and Reid's hypothesis (1976, 1978) that inverted hand posture (IHP), often shown by sinistrals when writing, is due to the fact that in such people the writing hand is controlled by the ipsilateral hemisphere. In most people, they claimed, the noninverted hand posture (NHP) is indicative of contralateral motor control. EEG alpha was recorded from C3, C4, P3, P4, 01 and 02 (Cz reference) while the subjects performed a typical array of cognitive tests: BLOCKS, READ, LISTEN, SPEAK and WRITE. The 90 subjects used in this study were equally divided between males and females, and also handedness groups (dextral, sinistral and ambidextrous). For the purposes of this report, the variable of interest was writing posture and, following rejection of some data due to artifact contamination, three groups of subjects were analysed: 30 right-handers (RH), 33 IHP subjects and 13 NHP (non-dextral) subjects. Alpha asymmetry ratios did differ between handedness groups at central
and parietal placements, especially for the WRITE condition. However, no differences were found between the NHP and IHP groups at these placements. Differences were found between these groups for the occipital data, but they offered no support for Levy and Reid's hypothesis. These same data were also analysed for sex and handedness effects (Galín et al., 1982) and a complex picture emerged. Among dextrals differences were found between the language tasks and the spatial and musical tasks (a SING condition was included), suggesting selective left hemisphere activation for the former. Among the language tasks, differences were found in R/L ratios, producing the following ordering of tasks: WRITE > SPEAK > READ > LISTEN. Task differences were greater at the central than the parietal leads and no differences were found at the occiput. Non-dextrals showed fewer task-related asymmetries, and the ambidextrous group appeared at times not simply to be the mid-range between two extremes, but to demonstrate a totally different pattern of neuropsychological organisation. For certain tasks differences between handedness groups were noted, and the reader is referred to the original report for greater detail. No sex differences were found for alpha asymmetry for any task at any lead for dextral subjects, but it was noted that among non-dextrals the BLOCKS R/L ratio was less than the SPEAK R/L ratio in far more female than male subjects. Herron (1980b) presents further discussion of the above studies. Other evidence of sex-differences in EEG asymmetries will be discussed in Section 1.3.1.3.3.

Butler and Glass (1974, 1976; Glass and Butler, 1973) have looked at the effects of performing mental arithmetic on the amplitude histograms of raw EEG and filtered alpha recorded from bipolar
electrode pairs (01-P3, P3-C3, 02-P4, P4-C4) under eyes closed and eyes open conditions. They found suppression of raw EEG and alpha over the left hemisphere when subjects performed calculations, the asymmetry being greater for the alpha rhythm. This effect was found only for dextral subjects, with sinistrals showing a nonsignificant reversed asymmetry. Griffiths, Butler and Glass (1980) recorded alpha from P3, P4, 01 and 02 (linked mastoids reference) while 12 dextral and 32 sinistral males undertook mental arithmetic, facial recognition and block design tasks. The expected asymmetries were found for dextral subjects, but no asymmetry was found for sinistrals who also showed greater variability. Nava and Butler (1977) studied asymmetric task-related alpha suppression in a series of 90 normal children aged between six months and 9 years. Listening to speech, word and number recognition, simple arithmetic and counting were used to engage the left hemisphere, and listening to music, watching faces and maze puzzles were used to engage the right, while occipital alpha (linked ears reference) was analysed. It is claimed that task-specific alpha asymmetries, similar to those found in adults, were demonstrated.

Robbins and McAdam (1974) investigated integrated alpha from left and right temporoparietal sites (Cz reference) while right-handed subjects covertly imaged familiar pictorial material in visual mode, verbal mode or both modes simultaneously. The L/R ratio was found to be smallest for the verbal mode and largest for the visual mode with both of these being significantly different from the intermediate visual/verbal mode.

Osborne and Gale (1976) looked at the effects of verbal, arithmetical, pictorial and musical tasks on integrated alpha recorded
for nine seconds post-stimulus from bipolar electrodes (O1-P3, O2-P4). They looked at both within- and between-hemisphere effects. Within hemispheres they found that the verbal and arithmetical tasks activated the left hemisphere more than observing abstract pictures. Listening passively to music and, somewhat unexpectedly, checking multiplications seemed to activate the right hemisphere more than the other two tasks, the effect being significantly larger for the musical task compared to the arithmetical task. The expected between-hemisphere differences were found for the verbal and arithmetical tasks, i.e. left hemisphere activation.

Shepherd and Gale (1982) had 20 male subjects take part in a rapid calculation task which required them to respond to sets of four orally presented digits (2 per sec), if both their sum exceeded 19 and all digits were odd. EEG from bipolar (O1-P3, O2-P4) placements was analysed into theta, alpha (low, middle, high) and beta bands, and a number of hypotheses based on previous work were tested. The key findings were that on both hemispheres EEG abundance decreased as the digit set became more similar to the target set, as expected. Also, this effect was more pronounced for the left hemisphere, especially in the mid-alpha band (9.5-11.5 Hz), where the left hemisphere was significantly more activated by the task than the right. Contrary to prediction, however, faster subjects showed a higher amplitude of EEG, although as expected they showed greater differentiation of stimuli, as measured by the EEG gradient, in the left hemisphere only.

Warren, Peltz and Haueter (1976) used a between-subject design to examine the effect of type of rehearsal upon percentage alpha in a recall task. The instructions to one group were to remember the word
by visualising it, while the other group were told to make up a sentence containing the word. Instruction-related asymmetries were seen 3-6 sec after stimulus presentation. A study by Rogers, TenHouten, Kaplan and Gardiner (1977) is perhaps worth mentioning as an example of overzealous interpretation. A single significant result (out of sixteen) at the 5% level, after much data manipulation, is held to support that "linguistic relativity may exist on a neurolinguistic level".

Angelieri et al. (1982) used a CNV-paradigm to compare alpha asymmetries between a group of five normal young men and five older men with slight diffuse cerebral atrophy (all dextral). Two tasks were employed. Firstly, following training, subjects were acoustically presented with four consonants, which were followed five seconds later by four visually presented consonants. Subjects had to indicate if a match or a mismatch had occurred. The second task was the same as the first except that the subjects also had to count backwards in threes. EEGs were recorded from W1 and W2 (Matsumiya et al., 1972) referenced to linked mastoids. CNV results are presented in Section 1.3.2.4. Whereas the older group showed the expected R>L asymmetry in alpha power, the younger group only showed it for the first task. As no control task was employed in this study, further interpretation of this result is not possible.

Recording from central, temporal and parietal sites on the left and right hemispheres (nose reference), Rebert and Low (1978) looked at alpha power while subjects engaged in various verbal and visuospatial tasks. Reading to the subject increased the resting asymmetry while covert visuospatial manipulation reversed it. Compared with rest
periods between games, either playing or watching TV-tennis suppressed right hemisphere alpha, with motor involvement enhancing the alpha asymmetry at central and temporal sites. Performance improved with asymmetry up to a point and then declined. Nava, Butler and Glass (1975) tried to induce alpha suppression over the right occipital lobe relative to the left (linked mastoids reference) in right-handed subjects performing a variety of pattern-recognition and visuomotor tasks. Only a tachistoscopic face-recognition task had the desired effect, while a mental arithmetic and an auditory pitch discrimination task reliably produced suppression over the left hemisphere. Young (1980), recording from O1, O2, T3 and T4 (Cz reference) showed that decoding nonverbal communication cues primarily suppressed alpha over the right hemisphere, particularly at occipital sites and with visual material. Young and Jung (1982) had right-handed hearing-impaired subjects engage in tasks involving imagining that they were writing, communicating in American Sign Language (ASL) or visualising in shapes and colours, while alpha was recorded from P3 and P4 (Cz reference). While the visual-spatial task was said to activate the right hemisphere, both of the language tasks seemed to activate the left, suggesting that the visual-spatial component of ASL is not a predominant factor in processing this type of communication. In contrast, Suter (1982) found no task-related asymmetries in a group of prelingually deaf subjects although normal-hearing controls and ASL interpreters showed left hemisphere activation during Letter Writing as compared to Block Design. The interpreters also showed greater left hemisphere activation during a Signed Story task in comparison to Baseline. Hemisphere activation was assessed by considering alpha
power asymmetry ratios, (L-R)/(L+R), as recorded from T3 and T4 (Cz reference).

Giannitrapani (1966a) examined the frequency of visually detectable pen deflections in EEG recorded from left and right occipital, temporal, parietal and frontal areas (linked ears reference) while the subjects rested or performed calculations with eyes closed. A higher frequency of pen deflections was found for left frontal and temporal sites compared to the right for the subjects at rest and this asymmetry increased when the subjects performed calculations. Giannitrapani (1966b) found greater attenuation of EEG over the left hemisphere for both sinistrals and dextrals for resting and drawing. Giannitrapani (1968, 1969, 1970a, b, 1971, 1975a, b, 1979a, b, 1980, 1981, 1982, in press; Giannitrapani and Kayton, 1974; Giannitrapani and Roccaforte, 1975) has reported details of a series of studies employing a 16-electrode array (presumably always linked ears reference, although often not declared), and a selection of tasks: (1) awake resting, (2) white noise, (3) music, (4) story, (5) mental arithmetic, (6) looking at a picture, (7) looking through diffusing goggles, and (8) awake resting again. All frequencies up to 33 Hz were analysed for power, coherence and phase, and a variety of effects related to task, handedness, psychiatric state, intelligence and so on, have been reported. However, no clear picture emerged with respect to laterisation of function even though many effects were laterised. No attempt will be made to provide a complete review here, although coherence and phase angle findings are reported later.

Only a small minority of studies have considered frequency bands outside the alpha range. Birbaumer et al. (1981) used a CNV paradigm...
to present easy or difficult arithmetic or pattern-matching problems. A tone (S1) indicated the difficulty level of the trial, and lasted for six seconds, until the problem (S2) was presented. EEG was recorded from C3, C4, T3 and T4, and a noncephalic reference was employed. Results for the CNV data are presented in Section 1.3.2.4. During the S1 interval it was noted that beta activity was enhanced over the presumably activated hemisphere, although no effects were found in the alpha range.

Spydell, Ford and Sheer (1979) recorded EEG from the centre of the triangle formed by O1, P3 and T5 and an homologous position on the right hemisphere (Cz reference) while twenty-four right-handed subjects performed a verbal analogies test, maths problems, a facial discrimination test and a shape rotation test. They examined activity in the 36-44 Hz band (carefully controlling for EMG contamination) and calculated a ratio, (R-L)/(R+L), from the amount of time this activity was present. They found significantly more relative left hemisphere 40 Hz activity for the analogies test than for the figure rotation or facial discrimination test and thus concluded that greater 40 Hz activity is to be found over the activated hemisphere. These findings were essentially replicated by Spydell and Sheer (1982).

Gardiner and Walter (1977) looked for signs of cerebral lateralisation of function in four six-month-old infants by recording EEG from C3, C4, P3, P4, O1, O2 and Morrell and Salamy's (1971) W1 and W2, referenced to linked mastoids. Power ratio changes, (L-R)/(L+R), at W1, W2 and P3, P4 in the 3.0-5.0 Hz band when the infants listened to music or speech corresponded to the pattern found for alpha asymmetry in adults. This effect was even greater if only the 3.5-4.5
Hz band was considered.

The question of the stability of EEG laterality effects has been investigated by Amochaev and Salamy (1980). They had six right-handed subjects perform various tasks (reading aloud, reading silently, writing from memory, written arithmetic, block design, Bender Gestalt and pencil maze) while EEG was recorded from P3 referenced to Cz, A1 and C3, and P4 referenced to Cz, A2 and C4. All tasks were performed each session and three sessions were given one to three weeks apart. Spectral analysis of the 8-13 Hz band was used to give a ratio score, \((L-R)/(L+R)\), and Kendall’s \(W\) was used to assess stability across sessions. It is difficult to give an overall summary of the findings in this respect because, although five out of the six subjects showed stable relative ratio scores, these results “were scattered among the reference electrode placements, with no more than three subjects showing consistent session-to-session alpha asymmetries for a given reference”. Certain unexpected findings from this experiment will be discussed later, but it is worth noting that this is only one of many experiments which demonstrate how crucial the choice of reference site can be.

Ehrlichman and Wiener (1979) also looked at test-retest group reliabilities in alpha asymmetries. They recorded temporoparietal EEG (Cz reference) in eleven right-handers performing a variety of tasks (verbal association, word arrangement, syllogisms, vocabulary, cube comparisons, surface development test, shape construction, figure drawing) on two separate occasions. ANOVAs showed the expected hemisphere \(X\) task interaction for the verbal vs. spatial tasks but, unexpectedly, there was a significant main effect showing more
integrated alpha power over the left hemisphere. Subjects' verbal-minus-spatial differences in the ratio of left to right integrated amplitude were reliable both between- and within-subjects. However, four subjects did show the reverse of the expected asymmetry on one or both occasions. The same investigators (Ehrlichman and Wiener, 1980) recorded from the same sites while subjects performed seventeen different tasks which they subsequently rated in terms of the degree to which each had (a) produced verbal thinking, (b) produced imagery, (c) produced affect and (d) required concentration. All tasks were covert (i.e. no stimulus or response) in order to control for external differences between tasks. The ratings were correlated with asymmetry ratios, \((L-R)/(L+R)\), both between- and within-subjects. It was found that both verbalisation and concentration led to left hemisphere activation, whilst imagery produced no asymmetry effects.

Similarly, Barrett and Ehrlichman (1982) found the expected asymmetries in integrated alpha from temporoparietal sites for verbal and visuospatial tasks, but no asymmetry for imagery tasks. The investigators were satisfied that EEG and EOG differences between a high-imagery and a low-imagery task proved that the subjects had produced different degrees of imagery.

Previously, Davidson et al. (1979a) had demonstrated a complex relationship between positive and negative affective states produced by a television show and alpha asymmetry, \((R-L)/(R+L)\), as recorded from F3, F4, P3 and P4 referenced to Cz. During positive affect, the frontal area showed greater relative left hemisphere activation, compared with negative affect. The parietal area showed right

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hemisphere activation during both. The results were replicated in a second experiment involving positive and negative self-generated affective imagery.

The idea that the right hemisphere is activated by affect-laden stimuli is given further support, if rather weakly, by Cacioppo and Petty (1980). They attempted to study the effects of "depth of processing" (as described by Craik and Lockhart, 1972) on asymmetries in alpha recorded from P3 and P4 (linked ears reference). The subjects were presented with a cue-question followed by a word, which was either a positive, negative or neutral personality trait adjective. The required level of processing was indicated by the cue-question which demanded judgements pertaining to (i) rhyme, (ii) volume, (iii) evaluation, and (iv) self-reference. The idea was that only the latter two tasks require consideration of the word's meaning. No effect of depth of processing on EEG asymmetry were found, but a very weak tendency towards relative right hemisphere activation for the affective words was noted.

A wide range of measures was used by Low et al. (1979) in a comparison of normal children and children suffering from minimal cerebral dysfunction (MCD). These included: power spectral analysis of eyes open resting, eyes closed resting, visuospatial tests and verbal tests; coherence functions; speech CNVs; word EPs; pattern VEPs. Correlational and multivariate analysis techniques, including stepwise regression and PCA, showed no consistent intrahemispheric correlations among the different measures. It was noted that the MCD group showed greater intra- and interhemispheric ratios than the normals.

Goldstein (1975, 1979, 1981a, b; Goldstein and Harnad, 1977;
Goldstein and Stoltzfus, 1973; Goldstein et al., 1976, 1980) has made much use of the 'amplitude integration method' and statistics associated with it in studies of different clinical populations, drug effects, perceptual deprivation, cognitive tasks, sleep, and even sexual orgasm. Although some of the reported effects reach statistical significance, much of the data is rather anecdotal, and will not be reviewed in detail.

Using this technique, Goldstein et al. (1972) suggested that during REM sleep the right hemisphere is relatively activated, whereas during NREM activation shifts to the left hemisphere. Hirshkowitz et al. (1979) and Murri et al. (1982) present data supporting the idea that the right hemisphere is more active during REM than NREM, but Antrobus et al. (1978) were unable to demonstrate this asymmetry. LaBerge and Dement (1982) have reported data suggesting that the actual cognitive content of REM dreaming influences alpha asymmetry. They present data from T3 and T4 (Cz reference) recorded while lucid dreamers dreamed that they were singing or counting. Although the reported asymmetries are in line with hemisphere asymmetries found during waking, as only two dextral and two sinistral subjects were used, it is difficult to say how far this is a generalisable finding.

It is necessary at this point to repeat the warning presented earlier concerning the effects of lateral eye movements (LEMs). Newlin et al. (1982) recently claimed that, contrary to Ehrlichman and Weinberger's (1978) claim, direction of LEMs is a valid indicator of hemisphere activation. They based this claim on the fact that P4/P3 alpha power ratios during resting correlate significantly with (R-L)/(R+L) LEM ratios for reflective questions. Also, a significant
difference was found between left-movers and right-movers. Accepting that alpha power ratios measure hemisphere activation, the authors conclude that LEMs must do so too. However, it is not clear if EOG was monitored during the 'resting' baseline, and thus it is possible that eye-movements during this condition may have actually themselves produced the apparent EEG asymmetry. The work of Warren and Haueter (1981) would add further support to this notion. They recorded EEG from bipolar placements at O1-P3 and O2-P4 and monitored EOG concurrently in 32 dextral subjects as they heard lists of verbal/mathematical and visual/spatial questions. They calculated percentage time alpha was present for the two seconds prior to the first LEM, and the two second epoch beginning one second post-LEM. The expected result was found for LEMs, in that they tended to be in the direction away from the presumably activated hemisphere, and also the expected effects were found for the alpha ratio, \( R/(R+L) \), when these data were analysed independently. However, when the relationship between LEMs and alpha asymmetry was considered, by dividing trials up according to both direction of LEM and type of question, it was found that by far the more important contributor to the alpha asymmetry was LEM direction. The effects of cognitive task on alpha asymmetry was no longer significant. The authors also note that the effect is asymmetrical, such that, "a movement to the left results in a decrease in the ratio of right to left hemisphere alpha, and a movement to the right results in a somewhat larger increase in this ratio".

It is difficult to summarise the results reported so far, but on the basis of these studies it would appear that, despite a fair amount of inconsistency, results generally support traditional
neuropsychological models of hemisphere function. It is perhaps worth emphasising at this point, however, certain trends which are apparent in the studies:

(i) it appears to be easier to preferentially engage the left hemisphere using verbal tasks than to engage the right using supposed 'right-hemisphere' tasks. This is perhaps not too surprising, as studies of lateralisation using other techniques often report a similar trend.

(ii) perhaps as a consequence of this, music, imagery and visuospatial tasks often do not demonstrate the expected asymmetries (for many more examples, see Section 1.3.1.6), but a wide range of possible reasons for such failures ensures that the basic model can always be retained.

(iii) differences between handedness groups have been inconsistently reported, but generally it would appear that, as expected, dextrals seem to be more strongly lateralised than sinistrals.

(iv) despite the fact that it is known on both a theoretical and an empirical level that the choice of reference is crucial in interpreting studies of hemisphere asymmetry of function, virtually all studies have used inappropriate sites. Although Cz, one of the most commonly used references, is certainly not the worst choice, it is known to be a fairly active site, and as such will lead to an inevitable confounding of phase and amplitude relationships between itself and active sites.

(v) although space limitations preclude a detailed critical analysis of every study, it is obvious that many of the warnings
issued by Donchin, Kutas and McCarthy (1977) continue to be ignored. Particular attention is drawn to the fact that many studies involve asymmetric movement of the limbs for certain tasks, e.g. writing. Others involve asymmetric eye-movements, e.g. reading, and the possible role of asymmetric reflective LEMs has also been discussed. All of the above points apply with equal force to the subsequent sections of this chapter.

1.3.1.3.1 Task Difficulty

Many of the experiments just reviewed have presented verbal and visuospatial tasks which differed on many factors besides the required mode of processing. One of the most important of these factors is that of task difficulty and some investigators have examined this directly in order to ascertain whether or not more difficult tasks would produce greater asymmetries. McKee, Humphrey and McAdam (1973) presented subjects with one musical task and three graded language tasks, while temporoparietal EEG was recorded (Cz reference). The 8-13 Hz activity was integrated and L/R ratios showed that the left hemisphere became increasingly activated, in relative terms, as the tasks became more linguistically demanding. Dumas and Morgan (1975) recorded occipital EEG (Cz reference), comparing left and right integrated alpha while subjects performed the following tasks each at three levels of difficulty: face recognition, modified Nebes' Ring Test (Nebes, 1971), verbal recognition and arithmetic. The expected asymmetries, in comparison to a baseline measure, were found but no
effect of task difficulty could be shown.

Some interesting results were produced by Galin, Johnstone and Herron (1978) who recorded EEG from C3, C4, P3 and P4 (Cz reference) while subjects constructed fourteen block designs of graded complexity, as well as reading and writing from memory. Average alpha power and R/L ratios both increased with increasing difficulty. This is unexpected for two reasons: firstly, the classic view of alpha is that as more concentration is required, less alpha is produced; secondly, one may reasonably expect that if the more difficult block design tasks engage the right hemisphere preferentially to a greater extent than the easier ones, then the R/L ratio would decrease. The expected asymmetry differences between writing and block design were found, however. Galin et al. point out that individual subjects varied considerably in the patterns of asymmetry displayed, and they attempt to account for the paradoxical findings in part by appealing to possible different strategies being used by the subjects as the task becomes more difficult. It is of interest that this result fits well with that of Ehrlichman and Wiener (1980) with respect to the amount of concentration required for task performance.

Wogan et al. (1981) had observers rate videotaped performances of Kohs Blocks problems, whilst the EEGs of the performers were recorded from T3 and T4 (Cz reference). They claim that significant correlations were obtained between strategy employed and various factors obtained from multivariate analysis of the EEG data, indicating, amongst other things, that the right hemisphere's involvement in the task is very dependent upon the chosen strategy.

Osaka (1981) performed power spectral analysis upon alpha band EEG
recorded from occipital and frontal sites while subjects engaged in simple and complex addition, visual imagery, spatial rotation and resting. The peak frequency was found to shift to a higher value in that hemisphere which was more activated for the more difficult of each type of task.

Finally, a recent report by Earle and Pikus (1982) investigated the effects of task difficulty on males and females carrying out addition and multiplication tasks. They recorded EEG from P3 and P4 (Cz reference) and found some complex interactions when considering a \((R-L)/(R+L)\) ratio score for alpha activity. All addition and the easy multiplication task were apparently left-lateralised with respect to baseline and spatial tasks. However, males exhibited relative left hemisphere activation for the more difficult addition task and the multiplication task of medium difficulty while females showed left hemisphere activation for the easy tasks and one of the more difficult addition tasks. It is suggested by the authors that differences in ability and strategy interact with the difficulty of the task to produce these complex effects. This may be true, but such *ad hoc* explanations are all too common in this area, where clear straightforward predictions are often not borne out.

In summary, it must be concluded that the level of difficulty of tasks may well have effects on asymmetry in the EEG, but such effects are far from well-understood.
1.3.1.3.2 Level of Performance

Level of performance can vary between subjects (i.e. ability differences) or within subjects (i.e. fluctuations in individual performance), and attempts have been made to examine possible changes in patterns of asymmetry for both of these differences. Many investigators do not analyse the EEG separately for good and bad performance of the tasks given, but Rebert (1977a, b; 1978; Rebert and Mahoney, 1978) has found some interesting results by doing so (see below). The 'inverted U' relationship between asymmetry and performance of TV-tennis has already been mentioned. Earle and Pikus (1982), on the other hand, in the study described above, found no significant relationship between the degree of alpha asymmetry and performance measures.

Gale, Davies and Smallbone (1978) and Gale and Edwards (1980) have looked at both between- and within-subject differences. Gale et al. (1978) visually presented 9-digit strings to right-handed subjects (1 digit/3 sec) in an ordered recall task while recording from bipolar electrode pairs (O1-P3, O2-P4). The 10.5-11.5 Hz band was integrated, and ratio (R/L) and hemispheric abundance scores were analysed. It was found that processing led to activation of the left hemisphere, while there was no effect on the right hemisphere in terms of EEG abundance. It was also noted that as the subjects became more practised at the task, the left hemisphere activation seen for the first six digits of a string disappeared. This was explained in terms of a shift from active processing (rehearsal) to dependence upon an echoic buffer. With respect to performance measures, subjects who recalled well were
more activated in the left hemisphere. Also, performance over the full task could be predicted from the degree of left hemisphere activation over early trials.

McLeod and Peacock (1977) found no relationship between R/L ratios of integrated alpha activity recorded from P3 and P4 (ipsilateral ear reference) during a verbal and a spatial task, and scores on a spatial ability test, but the degree of asymmetry was found to increase with age. Also, although the expected ratio differences were found during task performance for the alpha band, they were not found for the whole band EEG (1-60 Hz). Similarly, Moore and Haynes (1980), while finding the expected asymmetries in alpha ratio, R/(R+L), of integrated amplitude of temporoparietal EEG (referenced to Cz) as subjects listened carefully to a prose passage or a series of tones, found no correlation between asymmetry and verbal and visuospatial ability. Tucker (1976) on the other hand, while failing to find task-related asymmetries, did find that desynchrony in the right parietal and occipital regions was correlated with performance on the Mooney faces closure test for males but not for females. He also administered the Gottschaldt embedded figures test and items from the WAIS vocabulary subtest, but found no correlations for these. Unfortunately, he gives no information concerning his reference site and inadequate information concerning the location of the active electrodes.

Subjects with relatively less right occipitoparietal alpha (Cz reference) were found by Furst (1976) to be better at visuospatial tasks, a relationship which held even if only the baseline resting asymmetry was considered. This effect was also found by Ray et al. (1981) for high spatial ability males, but the opposite was found for
low ability males, i.e. they showed greater activation of the left hemisphere when performing well, possibly suggesting that they tended to use an analytic strategy. Females showed no clear relationship between performance and alpha asymmetry. Glass and Butler (1977) reanalysed their earlier data (Butler and Glass, 1974) and found a parallel relationship for the right-handed subjects in their sample, i.e. that the L/R ratio was significantly correlated with the rate at which calculations were performed.

Kraft et al. (1980) recorded alpha from P3 and P4 (Cz reference) while 18 right-handed 6-8 year old children performed a variety of reading tasks and Piagetian conservation tasks, which involved both actual transformations and the child's explanation of a transformation. Many different ANOVAs were performed on the data, but the investigators conclude that the pattern of activation for the conservation tasks and the reading task shifted from right hemisphere activation during the encoding stage to left hemisphere activation for the question-answering stage. Interestingly though, better performance tended to be correlated with bilateral, as opposed to left hemisphere, activation for the latter stage.

Davidson et al. (1979b, 1980a, b) have also done work relevant to this issue. Davidson et al. (1979b) showed that parietal baseline alpha asymmetry (P3, P4 referenced to linked ears) was significantly correlated with performance of various tasks. Subjects showing greater relative right hemisphere asymmetry were more accurate in Group Embedded Figures Test (GEFT) performance, recognized more tachistoscopically presented female faces and were poorer in recognizing words. Subjects with greater relative left hemisphere
baseline asymmetry were more accurate in dichaptic letter recognition (but only with their right hands) and were more accurate in recognizing words. Frontal asymmetry showed few significant correlations. Davidson et al. (1980a, b) recorded EEG from P3 and P4 referenced to three different sites: Cz, the nose and linked ears. Filtered 9-11 Hz activity was integrated and digitised over 30-second epochs during two verbal (analogies and reading comprehension) and two spatial (GEFT and Kohs Block Design) tasks. The Cz and nose references produced more reliable discrimination on the ratio scores (R-L)/(R+L) between the verbal and spatial tasks than the linked ears reference, and this pattern was supported by ANOVAs which included hemispheres as a factor. However, correlational analysis showed that the baseline asymmetry for the linked ears reference, but not the other references, reliably predicted task performance for both spatial tasks. Also, baseline asymmetry was more predictive than performance asymmetry. Further, when this group of subjects was divided into two groups, those with familial sinistrality (FS) and those without (NO FS), the picture becomes even more complex. One-way ANOVAs by task revealed significant effects on ratio scores for all reference sites for the FS group, but only the ears reference produced significant effects for the NO FS group. Correlations between baseline EEG asymmetry and task performance revealed uniformly higher correlations for the NO FS group compared to the FS, suggesting that asymmetries for the latter group are more affected by task demands and for the former, by dispositional variables. This study once again shows that different effects can be produced by choosing different reference sites.

Obviously, no clear conclusions have emerged from this mixture of
results. It has not been demonstrated conclusively that between- and within-subject performance correlate with EEG asymmetry measures.

1.3.1.3.3 Sex Differences

There is much argument and confusion concerning sex differences in lateralisation (Marshall, 1973; McGlone, 1980) but as evidence has been produced in both clinical and experimental studies of such differences it is natural that this factor has been considered by EEG workers. Unfortunately, their contribution has by no means helped to clarify the issue.

Some investigators have shown that females show greater hemispheric asymmetry in terms of EEG. For example, Davidson et al. (1976; Davidson and Schwartz, 1976; Schwartz et al., 1974) carried out a series of studies on what they call 'self-generated cognitive and affective tasks'. Recording from 01 and 02 (Cz reference) while right-handed subjects whistled, sang and spoke the words to a song, they compared the percent time alpha in terms of a ratio, (R-L)/(R+L). They found significant differences in the ratio related to task, relative left hemisphere activation increasing from whistling to singing to talking. This effect was significantly greater for those subjects without familial sinistrality. Of the 'pure' right-handed subjects, it was found that only the females showed the asymmetry. An attempt to replicate this effect found the expected asymmetry differences between talking and the other two tasks, but no difference between singing and whistling and no sex difference. The lack of a sex
difference was explained in terms of differential musical training between the two groups (see below for a fuller discussion). In the second experiment (Davidson et al., 1976; Expt. II), affective and nonaffective states in either verbal or visual mode were self-induced in subjects while EEG was recorded from P3 and P4 (Cz reference). There was a main effect for emotion, which led to increased right hemisphere activation, although no difference was found between anger and relaxation. The verbal vs. visual dimension had no effect. Looking at right hemisphere activation separately, there was less alpha during the visual imagery and, unexpectedly, during the nonaffective imagery. However, there was an even greater decrease at P3 during the non-affective imagery. When the sexes were analysed separately, it was found that these effects only held for females. Sex differences were also found in pattern biofeedback experiments, and these will be discussed in Section 1.3.1.4. Also, Moore and Haynes (1980) found that females showed greater lateralisation in terms of asymmetry ratios during verbal and nonverbal acoustic tasks.

Haynes and Moore (1981a) presented sentences constructed from either high or low imagery words to male and female subjects. No differences were found between imagery levels for temporoparietal alpha asymmetry, but whereas females seemed to demonstrate greater left hemisphere activation, males seemed to demonstrate the opposite.

Gale et al. (1978) found sex differences in posterior alpha asymmetry in an experiment involving a variety of tasks. For females, the right hemisphere was significantly more activated than the left while watching a moving light and describing it, while imagining a moving light and describing it, and while watching a moving light and
listening to a description. For males, the only difference between hemispheres was for the listening to spelling condition, with the left hemisphere being marginally more active than the right.

The complex interactions between sex of subject and level of task difficulty found by Earle and Pikus (1982) have already been mentioned. They also found that females showed greater asymmetry differences between spatial and arithmetical tasks than males, although no absolute differences in asymmetry were found between the sexes.

On the other hand, several investigators have produced evidence that males are more lateralised in terms of EEG asymmetry. Trotman and Hammond (1979) administered three verbal-numeric and three visuospatial tasks to subjects while recording from T3 and T4 (Cz reference). Males showed the expected asymmetry differences in terms of 'mean alpha amplitude ratio', $R/(R+L)$, while females showed no task-dependent changes. Similarly, Ray et al. (1976) found that the L/R power ratio for the 0.5-30 Hz range gave the expected changes for males, but not females, when verbal and numerical task ratios were compared with musical and visualisation task ratios. Regretably, the reference electrode used is not given.

Willis, Wheatley and Mitchell (1979) administered four tasks to subjects, three of which involved similar three-dimensional configurations in order to hold the perceptual requirement constant. The tasks were (a) mental rotation, (b) perceptual matching and (c) indicating, by marking the configuration, a minimal set of measurements needed to find the area of each face of the configuration. The fourth task was the Similarities subtest of the
WAIS. EEG was recorded from P3, P4, T3 and T4 (Cz reference) and the average log ratio of alpha power was calculated for both between-hemispheres (e.g. T4/T3) and within-hemispheres (e.g. T4/P4). At the temporal sites, perceptual matching led to significantly more right hemisphere activity and at the parietal sites, for males only, perceptual matching and mental rotation also led to significantly more right hemisphere activity. Tucker (1976), as already mentioned, while finding no significant sex X task X hemisphere interaction, did find a significant correlation between speed of response of the Mooney closure faces test and asymmetry at parietal and occipital sites for males only.

Moore and Lorendo (1980) used nonstuttering males and females and stuttering males as subjects in an experiment involving the auditory presentation and recall of high and low imagery words. Electrode placements were as for the other studies by Moore. Nonstuttering males showed less left than right alpha, while females showed no asymmetry. Stuttering males showed the opposite asymmetry pattern to nonstuttering males, and, as in Haynes and Moore (1981a), no effect of word imagery was found.

Wogan et al. (1979) examined T3/T4 asymmetry ratios, (L-R)/(L+R), over seven tasks including Block Designs, Mental Letter, Embedded Figures Test, and the Rod and Frame Test. Each test was repeated four times. Males seemed to be more consistent in their patterns of asymmetry, showing relative right and left hemisphere activation for Block Designs and Mental Letter, respectively. No consistent pattern emerged for the females. Butler, Carter and Glass (1977) and Giannitrapani (1981) also present data suggesting weaker
lateralisation in terms of EEG asymmetries for females.

A complex picture of power asymmetry effects emerged from a study by Beaumont et al. (1978). They had male and female subjects engage in two verbal tasks (verbal fluency and mental arithmetic) and two spatial tasks (flags test and space relations) whilst recording alpha from T3, T4, P3 and P4 (reference Cz). Coherence data are presented in Section 1.4.2, but in addition to these, power and power ratio scores, (R-L)/(R+L), were analysed. Raw power scores revealed no significant task \times\text{hemisphere} interaction, although asymmetry ratios revealed that male subjects showed greater asymmetry than females, but a site by sex interaction revealed that the \text{R}>\text{L} asymmetry tended to be reversed for females at parietal sites. This effect also interacted with site, and the reader is referred to the original report for further details. However, task-related asymmetries in this study are far from straightforward, occurring only for certain subjects at certain sites for certain tasks.

Finally, there are those studies which found no evidence of a sex difference in lateralisation. Ornstein et al. (1980) and Hirshkowitz et al. (1978) in studies to be described more fully later, failed to find any sex differences. Moore (1979) also failed to find any sex differences in EEG patterns, both sexes showing the expected asymmetry in temporal alpha (T3-T5, T4-T6) for a verbal task. Significantly less alpha was found over the right hemisphere during a nonverbal task compared to the verbal task. Haynes (1980) had subjects (a) immediately repeat sentences and (b) listen to sentences, while alpha was integrated from left and right temporoparietal areas (Cz reference) expecting the added motor programming requirement of the
former task to lead to greater left hemisphere involvement. This did, in fact, occur but no sex differences were found. Haynes and Moore (1981b) found no sex differences in asymmetry using the same placements, for data collected during a 'concentration on breathing' (vigilance) condition, and while listening to a banal reading under instruction to perform a recall test and to perform a recognition test, and also while actually performing these tests. Significantly more left hemisphere activation occurred for the retrieval/recognition tasks than for the perceptual listening tasks and the vigilance condition, but no sex differences were found.

Shepherd (1982) used the same methodology and design as Shepherd and Gale (1982) to compare EEG patterns of male and female subjects. However, the task used in this experiment was somewhat easier, in that subjects had to respond to sets of four digits when all were odd, regardless of the sum total. It is perhaps for this reason that only a few small hemisphere differences, restricted to certain frequency bands, were found in this study. No sex differences in lateralisation were found.

Finally, Galin et al. (1982; Herron, 1980b), as reported above, found no sex differences for dextrals, but a possible trend for greater reversed lateralisation among nondextral females than nondextral males.

It is therefore a simple matter to summarise this section, as all possible patterns of sex differences in lateralisation of function have been reported, with several studies suggesting stronger lateralisation in females, several suggesting stronger lateralisation in males and several suggesting no sex differences. Other techniques
for investigating hemisphere asymmetries rarely suggest that females show stronger lateralisation although the opposite pattern is reported fairly frequently.

1.3.1.3.4 Other Group Differences

Differences in hemispheric organisation have been hypothesised to exist between many groups of people for various reasons and differences related to sex and handedness have already been discussed. It is thought, furthermore, that different "cognitive styles" may exist such that two individuals may employ different strategies in solving the same problem and that these strategies may reflect what has been taken to be characteristic left hemisphere and right hemisphere types of processing (Ornstein, 1972). The left hemisphere is supposedly characterised by verbal, analytical, logical, sequential processing, while the right is said to be a visuospatial, holistic, intuitive, parallel processor. It is thought by some that these cognitive styles may be reflected by the way in which a person is employed, with certain jobs placing emphasis on certain types of approach. The study by Dumas and Morgan (1975) already discussed compared the asymmetries between a group of artists and a group of engineers and found no difference.

Doktor and Bloom (1977) on the other hand, found that whereas a group of operations researchers consistently showed the expected shifts in asymmetry in temporal alpha power (T3 and T4 referred to Cz) between a False Premises test and a Gestalt completion test, a group
of executives did not.

Bennett and Trinder (1977) tested the hypothesis that meditation was primarily a right hemisphere activity. They noted the percentage alpha from T3 and T4 (referenced to Cz) while their subjects, a group of meditators and a group of nonmeditators, performed Kohs blocks test, wrote letters, did mental arithmetic, performed a tonal awareness task and practised meditation or relaxation as appropriate. The ANOVA on the ratio scores, \((R-L)/(R+L)\), provided no support for meditation being a right hemisphere activity, but the expected results were found for all the tasks, with meditators being more lateralised than nonmeditators in terms of EEG asymmetry. Stigsby et al. (1981) compared EEGs during Transcendental Meditation (TM) with EEGs recorded during eyes-closed wakefulness, drowsiness, sleep onset and sleep in 13 experienced meditators. They also compared the meditators with a nonmeditating control group. The frequency spectrum during TM was found to correspond to a spectrum between that of wakefulness and drowsiness, and the EEG of meditators was about 1 Hz slower than that for the control group. No differences were found between the hemispheres during TM.

Contrary to the study by Moore and Lorendo (1980) reported above, Pinsky and McAdam (1980) claim that stutterers and nonstutterers exhibit the same asymmetry pattern in terms of task-related alpha recorded from inferior frontal and temporo-parietal placements (Cz reference). They considered each subject's data in terms of the average asymmetry score over a variety of 'right-hemisphere' and 'left-hemisphere' tasks, but no detailed presentation of data is provided. CNV and RP data from this study are discussed later.

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Oltman, Semple and Goldstein (1979) used the integrated EEG method to compare field-dependent (FD) and field-independent (FI) subjects performing a variety of tasks, including facial recognition, word recognition, mental arithmetic and 'resting'. Placements were at O1, O2, T3 and T4 (Cz reference). Although no task-related asymmetries are reported, the report states that, "Fluctuations over time in integrated EEG amplitudes recorded from the left and right hemispheres were more similar to each other (i.e. less differentiated) in individuals with a field-dependent cognitive style than in those who were field-independent". Rapaczynski and Ehrlichman (1979), on the other hand, found task-related temporoparietal alpha asymmetries during two facial and two verbal recognition tasks, but no effect of field-dependence. When analysed using the same technique as Oltman et al., their data did not show the same effects. Furthermore, the EEG asymmetry scores did not correspond to laterality as indexed by a tachistoscopic task. (See also discussion of O'Connor and Shaw (1978) in Section 1.4.2.)

As previously mentioned, there is some evidence that musicians and nonmusicians process musical stimuli in different ways (Damásio and Damásio, 1977; Wyke, 1977). It has been claimed that nonmusicians process music primarily in the right hemisphere, and musicians, primarily in the left. This has been supported by EEG studies. Davidson and Schwartz (1977) reanalysed data from their earlier experiments, combining data from O1 and O2 (Cz reference) from 14 subjects and P3 and P4 (left ear reference) from 20 additional subjects. All subjects had taken part in the 'sing', 'whistle' and 'talk' tasks described earlier. The reanalysis showed that whistling
relatively activated the right hemisphere more than talking, the
effect being significantly greater for the musically unsophisticated
subjects. Hirshkowitz, Earle and Paley (1978) found similar results
when they compared percent time alpha asymmetry ratios between
musicians and nonmusicians listening and attending to (a) a newscast,
(b) silence, (c) guitar feedback, and (d) a pop song. The only
difference between the groups was when they listened to the pop song,
the nonmusicians showing greater right hemisphere activation.
Once again, few clear differences in terms of EEG asymmetry
measures have been demonstrated between individuals differing in a
variety of ways, such as field-dependence, musical sophistication,
occupation, and so on, although several suggestive results have been
reported.

1.3.1.4 Feedback Studies

Several interesting studies have been carried out on training
subjects to produce asymmetrical alpha by using feedback techniques.
The first of these was performed by Peper (1971) using bipolar
electrode pairs on six subjects (02-P4, 01-P3). Of the six subjects,
two appeared to be able to control the asymmetry but Peper shows that
in fact they did not control the asymmetry per se but simply produced
more alpha, thus increasing the chances that asymmetric bursts would
occur. In a follow-up study (Peper, 1972), he distinguished between
the two types of asymmetry (i.e. alpha could be suppressed either over
the left or the right hemisphere) by sounding two different tones to
indicate the presence of alpha over the two homologous central-temporal areas. Eight subjects tried to keep one tone on and the other off, but only one was successful. To suppress the right hemisphere alpha she sang to herself, feeling the rhythm and relaxing; to suppress on the left, she spelled US states and multiplied high numbers.

Davidson, Schwartz, Pugash and Bromfield (1976) and Schwartz, Davidson and Pugash (1976) investigated 'pattern biofeedback' in male and female right-handers with no familial sinistrality while recording from P3 and P4 (left ear reference). There are four possible patterns of alpha distribution: L-on:R-on (i.e. both hemispheres producing alpha), L-off:R-off, L-on:R-off and L-off:R-on. The last three patterns were designated target patterns for different experimental runs and a tone which corresponded to the presence or absence of the pattern had to be regulated. In terms of the amount of time that asymmetrical states were achieved females were more successful than males. It was found that the three target patterns were fairly well regulated, but by different cognitive strategies. As expected, verbal or visual thoughts were used to successfully suppress left and right hemisphere alpha respectively, but the L-off:R-off state was not simply a combination of the other two. Davidson and Schwartz (1976) have also looked at patterns of alpha asymmetry during cardiac biofeedback in both sexes while recording from P3 and P4 (Cz reference). It was found that although males and females show the same prefeedback EEG pattern, with feedback females show the same pattern as they do when generating affective imagery. Males do not differentiate between the two states and it is suggested that males
and females use different strategies to self-regulate heart rate.

Fox (1979), recording from O1 and O2 (contralateral ear reference), had subjects attempt to keep a tone on which signalled the presence of left or right hemisphere activity in the 9.5-10.5 Hz band. When the feedback tone was contingent on the right hemisphere, it produced more activity in this band. Fox concludes that "it may be easier for subjects to learn control of alpha in the nondominant hemisphere". An interesting approach was employed by Cazard (1973) using a bipolar arrangement (O1-P3, O2-P4). The correlation between the two signals (Pearson's r) was calculated on-line during the experiment and its value expressed by the loudness of a tone. A state of 'deep absorption' produced the highest correlations, with relaxation producing a medium variable tone. The tone disappeared altogether if subjects performed mental arithmetic or clenched their fists.

1.3.1.5 Other Examples of EEG Asymmetries

Besides reviewing those studies using more conventional tasks and analytic procedures, mention must be made of several relevant studies which do not quite fit into any of the previous sections.

A novel technique was used by Goodman, Beatty and Mulholland (1980) in a nicely designed study of lateralised functional and anatomical asymmetry. The alpha control ratio (i.e. (mean alpha duration)/(s.d. of alpha durations)) is taken as an index of the replicative reliability of alpha blocking and, by implication, the control of each stimulus type over different cortical areas. Electrodes were placed at
left and right occipitoparietal sites and over Wernicke's area and an homologous area on the right hemisphere (linked earlobes reference). Presentation of spatial or verbal stimuli was either random or contingent on alpha bursts from one of the four leads (per session), with the type of stimulus (spatial or verbal) and the visual field of presentation random. A four-way ANOVA of the control ratio, with visual field, hemisphere of projection, type of stimulus and cortical lobe as factors, showed that the control ratio was significantly greater for contingent presentation (vs. random presentation), contralateral (vs. ipsilateral) visual field, and cognitively appropriate (vs. inappropriate) stimulus-hemisphere combinations. Thus the alpha contingent visual stimulation technique supports previous conceptions of anatomical and functional cerebral organisation.

Surwillo (1975, 1976) has used a central-moments analysis of the interval histograms of the half-wavelength distributions in the EEG. For example, Surwillo (1976) recorded EEG bipolarly (O1-P3, O2-P4) from ten right-handed children during tone-detection and digit recall tasks. He found no differences between left and right interval histograms for dispersion, skewness or kurtosis, but the means from each hemisphere were more similar for the verbal than the nonverbal task, where the right hemisphere means were greater. Higher mean frequency is often interpreted as increased activation. It is to be noted though that EEG samples were taken before presentation of each stimulus, on the assumption that a psychological set would be maintained throughout each task block.

Another useful approach is to look at the 'coupling' between cortical areas as described by Callaway and Harris (1974). At any

-65-
instant in time, the EEG for a particular channel can be categorised as positive (+) or negative (-), and also as increasing (i) or decreasing (d). For a pair of channels a contingency table may be set up, showing the occurrence of each of the four possible contingencies (+i, +d, -i, -d) and from this 4 X 4 contingency table the coupling can be calculated. The familiar chi-square statistic would be one measure of coupling, but Callaway and Harris chose Shannon and Weaver's information transmission statistic, Txy, for its computational ease. They predicted that coupling between two areas that were in active, functional communication should be higher than that between two functionally separate areas. This hypothesis was confirmed by recording from C3, C4 and Pz (Cz reference) while subjects read silently, looked at pictures, listened to Mozart and mentally composed a letter. EEG was sampled once every 4 msec. The reading task increased coupling between the Pz and C3 channels and the picture task increased coupling between Pz and C4, as expected. These findings were essentially confirmed by Yagi, Bali and Callaway (1976) using different electrode placements (F3, F4, P3, P4, Oz; Cz reference) and different tasks (block design and word construction). However, it should be noted that the latter study did produce some significant differences in the opposite direction to that expected. Yingling (1977) offers a good discussion of coupling and a reanalysis of data collected by Ornstein and Galin (1976). He points out that the expected coupling effects can sometimes fail to occur because alpha production itself tends to lead to higher coupling. Thus, if alpha is suppressed over the left hemisphere during a verbal task while still being produced over the right, the coupling effect will be opposite to
that predicted. Various solutions to this problem are discussed.

Without doubt, the most unusual task that subjects have been assigned in the search for EEG asymmetries is that investigated by Cohen, Rosen and Goldstein (1976). They recorded left and right parietal EEG (common earlobe reference) while male and female subjects stimulated themselves to orgasm. They found that in eight of twelve trials the R/L ratio of whole band integrated activity showed significant increases at climax in comparison to preclimax values. In the right hemisphere, the alpha rhythm disappeared and was replaced for a time by large 4 Hz waves. The left hemisphere was unaffected.

1.3.1.6 Discrepant Findings

The evidence presented so far has all been fairly consistent with the accepted notions of hemisphere function. However, as with other techniques of demonstrating laterality differences, many of these effects only become evident with grouped data, individual subjects frequently failing to show the expected asymmetries. Galin (1979) points out that 25% of his subjects show a lower R/L alpha ratio for reading than for block design. A study by Ornstein et al. (1979) rejected six subjects (out of eighteen) before the experiment proper began for showing "negligible or reversed specialization" on preliminary speaking or block design tasks. The investigators then integrated 9-12 Hz activity recorded from C3, C4, P3 and P4 (Cz reference) while subjects read technical matter or stories. Significant effects were found only at central leads and indicated
that reading stories activated the right hemisphere more than reading technical passages. Wogan and Kaplan (1981) recorded alpha from T3 and T4 (Cz reference) while subjects listened to a radio broadcast, a comedy act, a fight story and a legal argument. They claimed that the "reality-oriented" passages (the latter two) were processed primarily by the left hemisphere, whereas the "pleasurable" passages were processed by the right. This is a good example of a situation where EEG findings appear to contradict previous models based on clinical findings, insofar as there are no reports in the clinical literature, to the best of the author's knowledge, of double dissociation between "reality-oriented" and "pleasurable" reading.

Ornstein et al. (1980) recorded from the same sites as Ornstein et al. (1979) while subjects performed a variety of tasks (Nebes arc-circle and circle-circle matching; modified Minnesota Paper Form Board Test; picture completion; mental rotation; facial recognition; definitions). As expected the 'definitions' task produced more alpha over the right hemisphere than the left and higher R/L ratios than the spatial tasks but only at the parietal placements. At the central placements, the 'rotations' task unexpectedly produced the most right hemisphere alpha. Generally, it appeared that the right hemisphere changes were responsible for the task-dependent effects. Another unexpected finding was that of a higher right hemisphere engagement in circle-circle matching compared to arc-circle matching. An explanation is offered in terms of subject strategy.

Amochaev and Salamy (1979) in the study already mentioned found the opposite asymmetry to that expected for reading and, when using a Cz reference, no significant task X hemisphere interactions. Ehrlichman
and Wiener (1979) found that four of eleven subjects showed reversed asymmetry on one or two occasions and that a "per cent time alpha" measure did not show significant task effects and had poor reliability. Haaland and Wertz (1976) failed to show any task-related asymmetry in the 5-15 Hz band when recording from P3 and P4 (Cz reference) when subjects engaged in word/word, word/picture and picture/picture matching. Provins and Cunliffe (1972) found no significant task-related asymmetries in the study already mentioned, when subjects read silently. Leber and Johnson (1980) found no evidence for the lateralisation of emotion when studying parietal alpha as subjects generated affect-laden imagery. Smith et al. (1979) also failed to find any task-dependent asymmetries in alpha power when subjects engaged in memorising designs and prose passages and in viewing emotionally disturbing material. McCarthy and Donchin (1978; see also Donchin, Kutas and McCarthy, 1977; Donchin, McCarthy and Kutas, 1977) recorded EEG from F3, F4, Fz, C3, C4, Cz, P3, P4 and Pz (linked mastoids reference) while subjects took part in tasks involving functional and structural matching which were meant to engage the right and left hemispheres respectively. No task-dependent asymmetries were found although functional matching produced less alpha than structural matching. Walker (1980) found no differences in terms of occipital alpha between the hemispheres during a music recognition task which was presented monaurally. As no control task was employed, this result is not very informative.

Chartock et al. (1975) found no task-dependent asymmetry in parietal activity (P3, P4; linked mastoids reference) in terms of per cent time alpha as subjects learned and overlearned verbal
associations and dot-pattern associations. Significantly less alpha was produced during the learning stage and the right hemisphere always produced more than the left. Interestingly, a correlation was found between change in learning rate and change in alpha asymmetry during the verbal task. Rugg and Venables (1980) found suppression of left temporal alpha (Fz reference) only when subjects were learning a list of high imagery words and not when they were learning low imagery words, the direct opposite of what had been expected. Rugg and Dickens (1982) found no hemisphere effects in the alpha band for EEG recorded from P3 and P4 (linked mastoids reference) while subjects performed a verbal and a visuospatial task, although theta activity was higher in the right hemisphere for the visuospatial than the verbal task. Furthermore, the level of performance on the visuospatial task was correlated with the difference in theta level between tasks.

Grabow et al. (1979) gave subjects a series of alternating left- and right-hemisphere tasks: (1) resting, (2) picture visualisation, (3) story generation, (4) figure visualisation, (5) generate words beginning with 'S', silently, (6) visualisation of clock showing different times, silently, (7) repeat (5) aloud, and (8) repeat (6) but speak the times. EEG was recorded from T5, T6, C3, C4, P3, P4, O1 and O2 (mid-jaw reference) and the alpha band was subdivided into low, medium and high bands. The investigators analysed the data in three ways: (a) comparing left and right alpha activity, (b) comparing left and right alpha activity adjusted for 'resting' asymmetry and (c) comparing left and right alpha activity adjusted for the activity of the immediately preceding task (i.e. looking at shifts between tasks). Only the latter approach produced a considerable number of significant
changes in the expected directions although many asymmetries had been found which were in the opposite direction to that expected. The study also failed to partially replicate Robbins and McAdam (1974).

Rebert (1977a, b; 1978; Rebert and Mahoney, 1978) has performed a series of experiments, the results of which have not easily been accounted for. Rebert (1977a) recorded from left and right temporoparietal and occipital areas (reference not given) while subjects performed verbal and nonverbal detection tasks. The alpha range was decided for each subject individually using spectral analysis and the average power, peak power, and activation index (i.e. frequency/power) was calculated for each lead for each task. There were no significant effects at the occiput, but an almost significant tendency at the temporoparietal sites for the right hemisphere to produce more alpha for the nonverbal task in comparison to the verbal task. Reaction times were found to vary as a function of differential hemisphere arousal in the expected way, i.e. shorter RTs when the appropriate hemisphere was aroused. This study was followed up (Rebert, 1977b) by an experiment in which trials of the task used previously were triggered by hemispheric alpha asymmetry (P3 and P4; linked mastoids reference). The expected relationship between RT and asymmetry was not found. There was a tendency, however, for the pattern of hemispheric asymmetry associated with the fastest RTs to be opposite for the verbal and nonverbal tasks, but the expected pattern was found in only four of eleven subjects. The same basic task was used by Rebert and Mahoney (1978) as they recorded left and right temporal and parietal EEG (linked mastoids reference) in male and female subjects. The average power, peak power and frequency centroid
in the 6-14 Hz band were calculated for each task. Surprisingly, RTs were longer when the hand contralateral to the presumably activated hemisphere was used to respond. It was also found that females showed less alpha than males parietally and that power and frequency decreased over sets with RTs. Most unexpectedly, RTs were longest for verbal targets when R/L alpha power ratios were highest, and longest to nonverbal targets when R/L power ratios were lowest. These experiments are summarised and discussed by Rebert (1978).

Beaumont and Rugg (1979) present results which are of great interest in that they show conclusively that power asymmetry effects are dependent on the reference electrode employed. Twenty-four right-handed male subjects took part in this study, which involved deciding which of a pair of stimuli had been presented previously in the experimental series. Stimuli were either words or abstract pictures. Two different montages were employed: (i) the posterior temporal (PT) montage, for which sites were T3, T4, T5 and T6; and (ii) the anterior temporal (AT) montage for which electrodes were placed 1 cm anterior and 1 cm posterior to T3 and T4. Linked mastoids were used as a reference in this study, but EEG was also recorded from Fz so that data could be analysed with respect to an Fz 'algebraic' reference. Coherence data are presented in Section 1.4.2, and only effects related to power will be discussed here. The authors point out that some effects were observed with both AT and PT montages; "there was more power with the Fz than the linked mastoid reference, ... more power was recorded from anterior than posterior electrodes within pairs, and ... these effects interacted, the difference between anterior and posterior members of intrahemispheric electrode pairs being
greater with the mastoid than the Fz reference". They then go on to explain how differences in activity at the reference sites could produce such results. A second group of effects was noted only for the AT recording sites which showed, surprisingly, a relative increase in alpha band power in the left hemisphere compared to the right for the verbal task. (It should be noted in passing that the sampling frequency used in this study would lead to contamination of the alpha range with higher frequencies due to aliasing.)

Another study which is particularly important from a methodological point of view is that of Ruoff et al. (1981). They recorded alpha from C3, C4, P3 and P4 (Cz reference) while 12 dextral boys engaged in various verbal and spatial tasks, but the lateralisation of motor output of response was also considered in analysing these results. They found that, "the motor component of the task is extremely important in the relative activation of the cerebral hemisphere. In fact, a correction for motor effects may lead to a large reduction of cognitive effects, to the point where they no longer reach statistical significance". In their report, asymmetries at the central placements were found to be due entirely to motor output effects, whereas the parietal placements still appeared to show slight effects due to the cognitive nature of the task following the correction for output effects.

The most serious challenge to workers in this field has come from Gevins and colleagues (Gevins et al., 1979a, b, c; Gevins, 1981). They recorded from F3, F4, C3, C4, P3, P4, O1 and O2 (ipsilateral ear reference) while twenty-three right-handed subjects performed the following tasks: (1) visual fixation (EO), (2) scribbling with the
right hand (SR), (3) reading (RE), (4) writing from memory (WR), (5) Kohs blocks (KB), (6) block manipulation, right hand (MB), and (7) mental paper folding (FO). Spectral intensity in the theta (4-7 Hz), alpha (8-13 Hz), beta1 (14-20 Hz) and beta2 (21-28 Hz) bands for each electrode, as well as four intra- and four interhemispheric ratios of these bands were calculated, as was the characteristic frequency in the 4-14 Hz band. Thus 72 features were generated overall. All data for each subject and pair of tasks to be discriminated were standardised and put through a 2-stage nonlinear multivariate pattern recognition program to see which features were best for discriminating between any two tasks. When data were analysed as Doyle et al. (1974) had done, the expected differences between KB and WR were found for 18 out of 23 subjects, the difference being due to less alpha at P3 for WR. However, asymmetry ratios were not important discriminating features between these two tasks. Instead KB tended to show higher theta and lower beta than WR at most sites. Also, KB was successfully discriminated from MB but WR was not discriminated from SR. The extent to which these changes were due to uncontrolled stimulus characteristics, limb and eye movements, performance-related factors, etc., was checked in a second experiment (Gevins et al., 1979 a). Recordings were made from the same sites, though referenced to linked earlobes. Thirty-two right-handed subjects were given the following tasks equated for task difficulty: serial addition (AR), letter substitution (LE), mental block rotation (BR) and visual fixation (EO). The experimental controls used are as follows, and ought to be included in any such investigation where possible:
(1) utilising tasks requiring different cognitive operations over short (5-15 sec) epochs; (2) eliminating limb movements during performance; (3) reducing the magnitude of eye movements by utilising stimuli subtending small visual angles; (4) discarding the initial and final second of each trial because of likely contamination by sensory-evoked and premotor potentials respectively; (5) adjusting performance-related factors for each subject by presenting items matched to an individual subject's ability; and (6) analysing only trials in which the subject was correctly performing the task.

The data were analysed in the same manner as previously but this time the tasks were not distinguishable at a significant level, although all tasks showed a 10% reduction in alpha and beta in comparison to EO. After criticising other work in this area for not employing stringent controls or attempting to reduce Type I error when using multiple comparisons the authors conclude that they "consider it unproven that there is an EEG sign of lateralization of cognitive processes".

This study and its conclusions were criticised by Davidson and Ehrlichman (1980), essentially on three points, to which Gevins et al. (1980) replied:

(i) Davidson and Ehrlichman claimed that left/right differences have been demonstrated repeatedly in well-controlled studies which Gevins et al. did not cite. In reply, Gevins et al. presented a table showing the methodological shortcomings of the proposed studies.

(ii) Davidson and Ehrlichman claim that the short epochs used by
Gevins et al. would not allow the formation of an appropriate cognitive set. Gevins et al. point out that in their uncontrolled tasks, the first 15 seconds had produced consistently discriminable EEG patterns, suggesting that the length of epochs in the controlled tasks was adequate.

(iii) Davidson and Ehrlichman claim that the BR task used by Gevins et al. was not a task requiring right hemisphere activation. Gevins et al. reply that a great deal of evidence would suggest that BR is a task primarily mediated by the right hemisphere, even though EEG studies have produced equivocal results.

Yingling (1980) proposes that the distinction made by Gevins et al. (1979a, b, c) between "motor" and "cognitive" components of a task is an artificial and misleading one. Although it would seem obvious that for any strong claims to be made concerning EEG and cognitive processing, the cognitive factors must have some effect over and above that due to purely motor effects, Yingling somewhat perversely suggests that, "it is inappropriate to view the movement-related cortical activity in a task such as writing from memory as an artifact, obscuring the 'cognitive' activity which one wishes to study". He reviews a great deal of evidence to show that tasks involving motor output tend to produce greater asymmetries than those which do not involve motor output. He claims, "It seems unlikely that these results can all be explained away as resulting from noncognitive motor activities, since all the larger differences reported were appropriately lateralized despite varying motor demands and hand usages". To support this claim, he cites the Herron et al. (1979) study, maintaining that appropriate asymmetries were found at central
placements for both block design and writing tasks "even though both tasks were performed exclusively by the right hand". In fact, response hand is not specified in the original report, but Galin et al. (1982) when describing the same study state that both hands were used for the block design task, and the preferred hand for the writing task. A survey of most studies claiming to demonstrate task-related asymmetries reveals a very strong tendency for tasks demanding unilateral responses to produce asymmetries, with the hemisphere contralateral to the output side producing lower alpha power. The Ruoff et al. (1981) study, described above, adds very strong support to this notion. It is, of course, possible that these effects reflect not simply movement-related cerebral potential changes but noncerebral movement artifacts. Add to this other potential sources of asymmetric artifacts, such as LEMs, and one is inclined to agree that no asymmetries related to purely cognitive components of a task have been unequivocally demonstrated.

Ironically, Gevins et al. (1981, 1982) have recently demonstrated hemispheric as well as anterior-posterior differences in the brain's response during spatial and numeric judgement tasks which meet the strict criteria they themselves set (e.g. Gevins, 1981). In this method, single-trial time-series correlations between brain macropotentials recorded from different scalp sites are analysed by distribution-independent mathematical pattern recognition. Their findings do not fit a simple lateralisation model, suggesting instead that complex interactions within and between both hemispheres are involved in even simple judgements.

It seems then that although many suggestive findings have been
reported, there are enough negative results, contradictory findings, methodological problems and uncontrolled sources of artifact to justify a somewhat sceptical attitude towards the validity of ongoing EEG measures as indices of lateralisation of function. The alternative approach, that of employing averaging techniques, will now be considered.

1.3.2 Event-Related Potentials

1.3.2.1 Evoked Potentials to Simple Stimuli

Before looking at the evidence for task-related asymmetries in ERPs it is important to look at baseline data concerning the brain's response to simple unstructured stimuli. Unfortunately, as with on-going EEG studies, the picture is not totally clear with different laboratories producing different results possibly due to the use of different recording sites, reference sites and techniques of measurement. The work of Davis and Wada (1974, 1977a, b, c, d, 1978) will be reviewed in detail in Chapter 3.

Dealing first with somatosensory evoked potentials (SEPs), we find that studies fairly uniformly report a clear contralateral predominance for the early components of the SEP when the hand is stimulated electrically. The differences are reported in terms of amplitude (Schenkenberg and Dustman, 1970; Desmedt et al., 1977), latency (Bigum et al., 1970) and distribution (Goff et al., 1962, 1977; Calmes and Cracco, 1971). Cruse et al. (1982) reported that
stimulation of the posterior tibial nerve at the ankle produced higher amplitude early SEP components over the ipsilateral hemisphere, and, at times, polarity reversal over the contralateral. This paradoxical latera1isation may be due, it is suggested, to the position of the cortical generators involved, such that the electrodes on the ipsilateral hemisphere are, in fact, recording the response from the contralateral cortex (cf. Barrett et al., 1976; see discussion of VEPs). Middle and long latency components of the SEP do not present such an obvious pattern. Desmedt and Robertson (1977) used a task which involved having subjects attend to various somatosensory target signals and found that at high rates of presentation the N150 component became larger over the hemisphere contralateral to the target, although a later positive component (corresponding to the P300) was symmetrically distributed. Barrett et al. (1978, 1980) have used a fairly similar design, but found that the peak-to-peak N150-P300 amplitude was larger ipsilaterally.

The picture is even less clear when we look at auditory evoked potentials (AEPs). It is usually found that contralateral AEPs to monaural stimulation are larger than those to ipsilateral stimulation (Vaughan and Ritter, 1970; Andreassi et al., 1975a; Perronnet and Michel, 1977; Wolpaw and Penry, 1977) and of shorter latency (Majkowski et al., 1971; Mononen and Seitz, 1977; Butler et al., 1979). Andreassi et al. (1975a) failed to find any latency differences, however, but did find an unexpected asymmetry in favour of the right hemisphere for a negative-going component when both ears were stimulated. The use of a left earlobe reference could have produced this result. Richlin et al. (1973), recording from 01, 02, C1
and C2 (linked ears reference), on the other hand, found a L>R asymmetry in maximum amplitude of AERs to binaural stimulation for normal children, but not for retarded children. Schenkenberg and Dustman (1970), using binaural stimulation and unipolar recording failed to find any hemispheric asymmetries. Peters and Mendel (1974), looking at early components recorded bipolarily (Cz-A1, Cz-A2, C3-A1, C4-A2) found no differences in peak-to-peak amplitude or latencies between the hemispheres for monaural or binaural stimulation. Ruhm (1971) found that stimulation of the left ear produced AEPs 53% larger at T4 compared to T3 (linked mastoids reference), with right ear stimulation producing no consistent asymmetries. This result was essentially replicated by Peronnet et al. (1974), the right hemisphere response being 19% larger than the left hemisphere response for left ear stimulation. Butler, Glass and Wheatley (1973) report finding larger AEPs over the left hemisphere to tones in relaxed subjects (see Butler and Glass, 1976, for a fuller description). Other, more complex, patterns have been reported (e.g. Shipley, 1977; Benecke et al., 1980; Prasher and Gibson, 1980).

With respect to visual evoked responses (VERs) the scene is once again confusing. Harmony et al. (1973) reported "remarkable cross-hemispheric symmetry" in a large study (139 subjects) recording unipolarly from C3, C4, O1, O2, T3 and T4 (linked ears reference) and bipolarily (C3-O1, O1-T3, C4-O2, O2-T4), and involving four different measures (peak latency differences, amplitude differences, signal energy ratios and Pearson's product-moment correlation coefficient). Yella et al. (1972) using bipolar recordings (T5-O1, O1-Oz, Oz-O2, O2-T6) and Preston et al. (1977) recording unipolarly (P3, P4, O1, O2;
linked mastoids reference) found no asymmetry for unstructured flashes. Similarly, Groth et al. (1970) found no significant left-right hemisphere differences in amplitude of occipital VERs to monocular and binocular light flashes for neonates or adults, apart from a tendency for larger responses in the hemisphere contralateral to stimulation, which was only significant for the neonates. Vaughan et al. (1963) and Kooi et al. (1965) compared occipital VERs between the hemispheres for normal subjects and patients with visual field defects. Large asymmetries were found for the patient group only, although Kooi et al. noted that the vertex sharp wave was regularly of lesser amplitude over the left hemisphere in normals. Schenkenberg and Dustman (1970) recording from F3, F4, C3, C4, O1 and O2 (earlobes reference) looked at the VER in terms of cumulative voltage change, component amplitudes and peak latencies in 160 subjects and found that between 100 and 200 msec the response was larger from the right hemisphere (see also Beck and Dustman, 1972; Beck, Dustman and Lewis, 1975). Richlin et al. (1971, 1976) compared VERs recorded from O1, O2 and Cz (linked ears reference) between normals and retardates, and found the N1-P2 component was greater on the right for dextral normals and on the left for dextral retardates, although sinistral retardates showed no asymmetry. Also, the maximum positive deflection had a longer latency on the left for normals only.

Rhodes et al. (1969) recorded from C3, C4, O1 and O2 (earlobe reference) and found that bright children showed a larger central response over the right hemisphere for late components, whilst dull children showed no asymmetry. Bigum et al. (1970) using the same electrode configuration found no asymmetry in a group of mongoloid
children, although the asymmetry in normals was replicated. Lewis et al. (1969, 1970) found that alcohol attenuated the amplitude of late waves of the VER recorded from the same sites. Only three subjects out of nine showed the asymmetry found previously but this was abolished after drinking alcohol, although marijuana did not affect the asymmetry (Lewis et al., 1973, 1977). The results with respect to alcohol were essentially replicated by Porjesz and Begleiter (1975, 1979). Rhodes et al. (1975) also showed that alcohol significantly reduced amplitude asymmetry of the central P90-N120 component (ipsilateral ear reference) by depressing the right VER more than the left.

Eason et al. (1967a) found larger occipital responses (ipsilateral ear reference) over the right hemisphere than over the left for left-handed but not right-handed males. Eason et al. (1967b) compared occipital VERs from dextral males and females, and reported that regardless of the visual field in which the stimulus appeared, the directly stimulated hemisphere showed a larger, faster response, although no quantitative latency data are presented. Culver et al. (1970) used the same electrode sites on female subjects and found that all subjects, right- or left-handed, showed a R>L asymmetry for left visual field stimulation, but no asymmetry for right visual field stimulation. However it should be noted that this experiment differed from the former by using monocular stimulation and a more arbitrary amplitude measure. Rugg (1982) criticises this series of studies for (i) unclear analysis and presentation of data, (ii) use of asymmetric reference sites, (iii) the possibility of effects related to cognitive set, and (iv) not monitoring subject fixation. Similar criticisms are
levelled at the study of Gott and Boyarsky (1972) who also stimulated the hemispheres directly and indirectly while recording occipital VERs (ear reference). They found that the hemisphere contralateral to the preferred hand in two handedness groups showed longer latencies when directly stimulated than the ipsilateral hemisphere. Also, no amplitude asymmetries were found for the right-handed group when the right and left hemispheres were directly stimulated, while the left-handers show a larger response over the right hemisphere for direct stimulation. Biersdorf and Nakamura (1971) report that asymmetrical stimulation of a visual field with a flash-stimulus elicits an early positive component which is considerably larger over the contralateral hemisphere at parietal and temporal placements. Details of subject handedness were not provided.

Andreassi et al. (1975b) found no amplitude asymmetries in occipital VERs to binocular stimulation (left ear reference), although the hemisphere which was directly stimulated did show shorter VER latencies. Rugg (1982), in his review of VER studies involving divided visual field presentation, questions the assumption that latency differences reflect transcallosal transfer times. Ledlow, Swanson and Kinsbourne (1978a) also questioned this interpretation of contra- and ipsilateral latency effects in their study of occipital VERs (linked mastoids reference).

Pfefferbaum and Buchsbaum (1971) performed an interesting study looking at the response to 10 Hz sine-wave modulated light as recorded from right and left ears and occiput (Cz reference). Left-handed subjects, especially males, tended to show marked increases in the VER first harmonic amplitude with increasing depths of modulation at the
left occiput and minimal increases at the right occiput. Right-handed subjects however showed moderate and symmetric increases. Thus, again, left-handed males show greater asymmetry.

To summarise, it can be seen that even EPs to apparently simple stimuli have been reported to show a variety of hemisphere effects. These discrepancies are probably due to differences in technique, reference site, active sites, stimuli, method of measurement, and so on. In general, when investigators have looked for effects which reflect the underlying anatomy of the nervous system, say by stimulating visual half-fields or using monaural presentation of clicks, such effects have been demonstrated in terms of larger amplitudes and shorter latencies at the directly stimulated cortical site, although there have even been exceptions to this finding. Whilst such results are of great importance clinically and theoretically, of greater concern to the investigator of hemisphere function is the possibility of hemisphere differences over and above such anatomical effects, which have occasionally if inconsistently been reported. Such differences may reflect a special predisposition for one hemisphere to process stimuli of a particular modality, even when the stimuli are apparently very simple. At the very least, the possibility of such effects emphasises the need for studies to include control conditions so that if claims are made that particular asymmetries are due to lateralised cognitive functions, one at least has a comparison condition. Having said this, one must still conclude that no such asymmetries have been proven. Many of the studies claiming to demonstrate such effects used inappropriate reference electrodes, sometimes using unilateral reference sites, sometimes linked bilateral
sites (Mowery and Bennett, 1957). It has been demonstrated that Stephenson and Gibbs' (1951) balanced noncephalic reference is not an active site, at least for VERs (Lehtonen and Koivikko, 1971) and AERs (Wolpaw and Wood, 1982), and is therefore to be preferred. Unfortunately, very few studies employing complex stimuli have used such a reference either, as amply demonstrated in the following section.

1.3.2.2 Complex Stimuli

1.3.2.2.1 Somatosensory Evoked Potentials

For obvious reasons, hemispheric processing is not easily investigated using somatosensory stimuli. Whereas it is a relatively simple matter to present visual and auditory stimuli of a verbal or visuospatial nature, it is difficult to present tactile stimuli carrying this type of information for short durations with sharp onset and offset times. It is not surprising therefore that, to the author's knowledge, only two studies are reported in the literature using SERs in this way. Moldofsky, England and Scarisbrick (1973) instructed their right-handed subjects to compare the quality of soft finger-taps of two intensities in a nonverbal mode. Responses of the right parietal area to left hand stimuli in the interval 0-115 msec after stimulus onset differed in configuration from responses of the left parietal area to right hand stimuli with an additional positive peak at about 85 msec. This is interpreted as reflecting the greater
involvement of the right hemisphere, but as no control task was included such an interpretation is not warranted.

Desmedt and Robertson (1977) did include a control task in their study. They had subjects palpate a plexiglass ridge in order to locate the position of a small gap in the ridge, timing being determined by a mechanical device which dropped the finger into position. The control task involved palpating a smooth plexiglass surface without a ridge. As expected, the N150 component was lateralised over the hemisphere contralateral to the hand used, but a prolonged positive electrogensis was recorded only over the right hemisphere and only for the experimental task.

1.3.2.2.2 Auditory Evoked Responses

Cohn (1971a, b) was amongst the first investigators to look for asymmetries in the AER related to the type of stimulus presented. One derivation electrode of each homologous pair was placed 2 cm anterior to the external acoustic meatus, and the other was placed in a vertical coronal plane 2 cm from the midsagittal line. The response to 10 msec clicks showed a positive peak at 14 msec in the right hemisphere, but a low amplitude variable response in the left hemisphere at least for these early components. In response to 150 msec single-syllable words however, 17 of the 37 subjects showed larger responses over the left hemisphere, while the remaining 20 subjects showed no asymmetry. Cohn concludes that this reflects the fact that noise is processed by the right hemisphere and words by the
left (Kimura and Folb, 1968). However this experiment is open to serious methodological criticism. Firstly, no statistical comparison is carried out, hence experimenter bias is possible. Secondly, it is possible that the early potential asymmetry could be due to asymmetric myogenic reflex, although Cohn (1971a) rejects this idea. Thirdly, as Wood et al. (1971) point out, "Cohn's 'verbal' and 'noise' stimuli differed in many acoustic parameters such as duration, frequency composition, rise-time, total amplitude, and amplitude contour. Differences in neural activity evoked by such stimuli could be related to any or all of such acoustic differences, none of which need have any direct bearing upon the issue of speech versus non-speech perception", (note 7).

Greenberg and Graham (1970) recorded from T3 and T4 while subjects learned ensembles of speech and nonspeech stimuli. EPs for EEG collected at different levels of performance were subject to Fourier analysis and the authors conclude that their results are due to hemispheric specialisation, a conclusion which is little more than wishful thinking. Again, no statistical support is presented, and even if it was, the choice of right ear as reference would render the results uninterpretable. Morrell and Salamy (1971) also made a gross methodological error when studying EPs from frontal, central and occipital sites (linked earlobes reference) in response to presentation of five nonsense words. They found that the N1 component (40-50 msec) was larger on the left by 40% on average, with the asymmetry largest at the temporoparietal leads. Unfortunately, they failed to include a non-language control task and so their findings tell us nothing about lateralised functions. An attempted replication
by Grabow et al. (1980b) which did include appropriate control tasks failed to find any consistent hemisphere asymmetries.

Wood, Goff and Day (1971) held stimulus-related factors constant by recording EPs to the same stimulus in each task and simply altering task demands. They had subjects perform a phonetic discrimination task (between /ba/ and /da/) and a tonal discrimination task (between two different fundamental frequencies of /ba/) while they recorded EPs from T3, T4, C3 and C4 (linked ears reference). They found that EPs were significantly different over the left hemisphere between the two tasks when a decision was being made, but not over the right hemisphere. However, Friedman et al. (1975a) have criticised the analysis used in this study which involved the use of multiple univariate procedures without any adjustment of the required level of significance. Wood (1975, 1977) again used this inappropriate analysis in a further series of four experiments. In the first he essentially replicated his previous finding, using different phonemes (i.e. /bae/ and /gae/). In the following three experiments he varied other parameters of the stimuli and found no similar effects, thus supporting his claim that the differences were due to the fact that the original discrimination was based on phonetic distinctions. Unfortunately, attempts at replication by Smith et al. (1975) and Grabow et al. (1980a) were both unsuccessful, although the latter did report that EPs were attenuated at T3 in comparison to T4 regardless of task.

Matsumiya et al. (1972; Matsumiya, 1976) recorded bipolarly with one electrode presumably close to Wernicke's area (W1, defined as the centre of a triangle formed by P3, T3 and T5) linked to P3 and an
homologous link over the right hemisphere. Four experimental conditions were employed, the subjects' task in each was (i) to tally the number of words in a randomly mixed series of sounds and monosyllabic words, (ii) to tally the number of sounds and words in such a series, separately, (iii) to determine how many different types of sound were in a series without words, and (iv) to passively listen to ten sentences totalling 150 words. A "W-wave" occurred about 100 msec poststimulus which showed the largest asymmetries, being larger on the left in two-thirds of the subjects. Comparing conditions using a ratio, L/(L+R), of peak-to-peak amplitudes of the W-wave, the following relationships were found. Condition (iv), meaningful speech, produced the largest asymmetry, while condition (iii), discriminated sounds, produced a larger asymmetry than conditions (i) and (ii), undiscriminated words and undiscriminated sounds, respectively. There was no difference between conditions (i) and (ii). From such findings Matsumiya and colleagues conclude that it is the meaning attached to the stimulus which produces laterality effects, not the fact that the stimuli are verbal per se. Matsumiya (1976), using the same paradigm, looked at three additional conditions: (v) click presentation, (vi) tone presentation, and (vii) dichotically presented words (with a discrimination task). Seven right-handed subjects were examined and it was predicted that the latter condition would produce large asymmetries, with the other two producing none. This is essentially what was found, but the asymmetry for the dichotic condition was unexpectedly less than that for condition (iv). The use of a bipolar montage, however, makes further interpretation of these findings difficult.
Neville (1974) recorded EPs from C5 and C6 (linked mastoid reference) while subjects listened to dichotically and monaurally presented numbers, which they had to repeat, or clicks, which they had to count. The latencies for P1, N1, P2, N2 and P3 and the peak-to-peak amplitudes of these components were analysed using ANOVAs. With dichotic presentation, the verbal task produced earlier latencies for N1, P2 and N2 over the left compared to the right hemisphere and also P1-N1 amplitude was larger over the left hemisphere. In response to clicks, AERs were more similar over the two hemispheres. No significant hemisphere effects were found using monaural presentation, although P1, N1, N2 and P3 latencies were all shorter for verbal compared to click stimuli. Interestingly, a behavioural comparison showed a right-ear advantage (REA) for digits, but no difference in accuracy of report of the clicks heard in each ear. Neville (1980) followed up this study by recording EPs from P3, P4, C3 and C4, unfortunately referred to the right mastoid, while subjects performed two auditory and two visual tasks. The data for the visual tasks is discussed in the next section. The auditory tasks consisted of listening to dichotically presented words or melodies for subsequent recall. Subjects also took part in a control task involving passively listening to tones. The dichotic presentation of words resulted in a significant advantage in recall for the right ear, and the ERPs tended to be larger at the left than the right parietal leads. The dichotic presentation of melodies produced neither significant behavioural nor ERP lateral asymmetries. ERPs to tones were also symmetrical.

Haaland (1974) presented CVC monosyllables dichotically, diotically and monaurally while recording from T3, T4, F7, F8 and Cz referenced
to linked mastoids. The subjects showed REA for dichotic presentation when they had to record the initial consonant. A large positive (P) and negative (N) component were each examined, but only P showed any significant differences, being larger over the right hemisphere in all conditions. No "pathway effects" were found when contralateral and ipsilateral ears and electrode sites were compared. Taub et al. (1976) attempted to engage the right hemisphere by presenting subjects with computer-generated musical chords monaurally. They recorded from C3 and C4 and points midway between T5 and C3, and T6 and C4, which they labelled W1 and W2 respectively. Unfortunately they used ipsilateral earlobes as references and failed to include a control task. However, they found no latency differences for P1, N1 and P2 between hemispheres, while P1-N1-P2 integrated amplitude at W2 to left ear stimulation was greater than that at W1 to right or left ear stimulation. Also, the differences summed across both ears were greater at W2.

Two groups of investigators have looked at the effect of meaning on EPs by employing ambiguous stimuli in a disambiguating context. For example, Teyler et al. (1973; Roemer and Teyler, 1977) recorded EPs from C3 and C4 (reference not given) to a click presented one to five seconds after a stimulus word. The experiment was in three phases. In the first, the ambiguous stimulus word was disambiguated when presented, e.g. 'a rock' vs. 'to rock', and the subject reported the stimulus in response to the click. In the second, the subjects provided their own meaning to the word, which they reported in response to the click. The third phase was exactly the same, but the subjects response was delayed until fifteen seconds after the click.
N1-P1 amplitudes were shown to be larger over the left hemisphere in all phases of the experiment, with the asymmetry being twice as large for nouns as for verbs. Also, intrahemispheric waveforms were different for verbs and for nouns, but interhemispheric waveforms were similar for a given word type. (It is interesting to compare the findings of this study with those of later experiments employing a 'probe' technique to be discussed later.)

The second group to investigate the effect of meaning on AERs is Brown, Marsh and Smith (1973, 1976, 1979; Marsh and Brown, 1977). In their initial study, Brown et al. (1973) presented subjects with sentences containing ambiguous words (e.g. "Ready, aim, fire" vs. "Sit by the fire"). They compared AERs from "Broca's area" (F7) and "Wernicke's area" (2 cm posterior and dorsal from T3) and homologous areas over the right hemisphere. Data collection began 100 msec prior to stimulus word onset and correlational analysis was used to compare the similarity of the AERs. It was found that they were more dissimilar over the left hemisphere when the stimulus word fell at the end of the sentence (and were therefore not ambiguous) than when it was at the start (and, hence, ambiguous). The greatest effect was seen at "Broca's area". Unexpectedly, larger AERs were found at the right posterior locus than at the others. Marsh and Brown (1977) mention a study in which the same issue was investigated using only sentences with the ambiguous words at the beginning, e.g. "Fire is hot" vs. "Fire the gun". The sentences were disambiguated by being presented in blocks, so that the meaning would be known in advance on each trial. This gives similar results to the original study, whereas presenting the sentences in a random series showed no differences between the
noun and the verb form of the critical word. As stimulus factors had not been held constant in the original study, Brown et al. (1976) repeated the experiment using the ambiguous sentence "It was /led/" and instructed the subjects before trials as to which meaning was to be attached to the sentence (corresponding to either "the horse was led" or "the metal was lead"). AERs were found to be similar for verb and noun forms of /led/ at all sites except Broca's area. The data from this study were later reanalysed using Principal Components Analysis (PCA). Brown et al. (1979) used PCA to define three meaning-related components comprising 40.3% of the entire data variance. When all components were considered together it was again the left anterior lead which showed the greatest meaning-related difference.

The effect of age of acquisition of a second language was studied by Genesee et al. (1978) by presenting English words and their French equivalents to bilinguals and measuring their RTs to indicate manually the language used. No differences in RTs were found, but the AER recorded from C3 and C4 (referenced to separate mastoids) showed shorter latencies for N1 at C3 compared to C4 for those subjects who had learned their second language in infancy or childhood, but a reversed asymmetry in those who had learned their second language in adolescence. The latter also showed shorter latencies for N1 and P2 overall. The authors suggest that this finding may be due to adolescents using a more "right-hemisphere biased" strategy in learning a second language.

Before discussing the long series of experiments carried out by Molfese and colleagues using PCA, their early studies using the "R
ratio" will be described. The "R ratio" was derived by calculating the magnitude of change in the EP between a maximum negative and a maximum positive peak occurring within a certain temporal range in the EP, which depends on the age of the subject. This measure was taken from T3 and T4 and the R ratio calculated by: \( R = T3/(T3+T4) \). Thus Molfese et al. (1975; Molfese, 1977 a, Experiment 1; 1977 b, Experiment 1) found that the N1-P2 amplitude asymmetry in response to syllables, words and nonspeech sounds in infants, children and adults was in favour of the left hemisphere for the speech stimuli and the right hemisphere for the nonspeech stimuli. Surprisingly, these asymmetries decreased with age. Molfese (1977 a, Experiment 2; 1977 b, Experiment 2) also showed that the R ratio for the P250-N540 component was larger than 0.5 for speech and less than 0.5 for nonspeech in 14 neonates, when the nonspeech stimuli were the same as the speech stimuli (normal formant CV syllables /gae/ and /ae/, CVNF) except in bandwidth (pure tones were used corresponding to the central frequency of the formants; sinewave formant, CVSF). Molfese (1977 b, Experiment 3) also used the technique of dishabitation to examine differences between the adult and infant brain in categorical speech perception. Dishabitation occurs when a novel stimulus occurs following a series of repeated stimuli to which the organism has habituated. The EP usually shows an increase in amplitude in response to the dishabituating stimulus. The stimuli used were a bilabial stop consonant and vowel (/ba/) with different voice-onset times (VOTs): Ba0, Ba20 (both perceived as /ba/); Ba40, Ba60 (both perceived as /pa/). A second stop consonant and vowel (/da/), characterised by a different place of articulation was also presented (VOT: 0 msec). Thus, fifteen preshift stimuli of
one type would be followed by fifteen postshift stimuli of another type. The shift could be either within or across the phoneme boundary, or be a change of place. The effects of this shift were examined by averaging together the responses for the last seven preshift stimuli, and comparing these with those for the first seven postshift stimuli. Although no statistical analysis is presented, it appears that for adults dishabituation only occurs for changes in place of articulation or phoneme boundary crossings, and then only in the left hemisphere. The neonates, on the other hand, showed a very different pattern of response. Dishabituation occurred in both hemispheres when the phoneme boundary was crossed, but in neither when a change in the place of articulation occurred.

Molfese and colleagues have also carried out a long series of experiments using Principal Components Analysis (PCA). The details of PCA can be found elsewhere (Donchin, 1966; Suter, 1970; Chapman et al., 1979). It does seem to have advantages over conventional EP analysis in that it leads to a very parsimonious representation of a vast amount of data, by accounting for a large proportion of the variance with a few factors. Also it allows for the fact that EP components will probably overlap in time, but still allows the relationship of each individual component to experimental manipulations to be examined independently. Molfese et al. (1976; Molfese, 1977a) report a partial replication of an earlier study (Molfese, 1977a, Experiment 2; 1977b, Experiment 2), details of which are presented above. Again, fourteen neonates were used, and PCA isolated four factors which together accounted for 96% of the variance in the EP data and related to sex differences, formant structure,
bandwidth and hemispheric differences, respectively. Molfese (1978a) used the same CVNF and CVSF stimuli as used in the last experiment as well as artificially produced stimuli which were similar in formant structure but impossible to produce vocally, in an attempt to show that it was the phonemic nature of the stimuli which was critical and not the acoustic nature. Thus eight stimuli were used: CVNF, CVSF, CVNF* and CVSF* versions of /bae/ and /gae/ (where "*" denotes that stimuli are impossible to produce vocally). Subjects were divided into a low dextral group and a high dextral group. Six factors were found which together accounted for 97% of the variance. Factors 2 and 3 both reflected differences in formant structure and hemispheric effects. Factor 1 showed that only the left hemisphere differentiated between phonetic transitions and factor 6 reflected degree of manual preference. Molfese concluded that both hemispheres are involved in speech analysis, but in different ways. In a related study of ten adults, Molfese (1979; Molfese et al., 1979) used CVC syllables differing factorially in meaning, voicing and place of articulation. Ten factors accounted for 93.2% of the variance, some varying as a function of voicing or place of articulation and many showing hemisphere effects independently of other variables. Both hemispheres seemed to differentiate the meaningful from the nonmeaningful syllables in different ways. Also, an early component was isolated possibly reflecting subcortical involvement in semantic processing. Molfese (1980a) used six varied CVNF syllables and recorded from T5, T6, P3 and P4 besides T3 and T4 in twenty right-handed females. Seven factors accounted for 70% of the data variance. One factor showed a hemisphere X consonant interaction (/b/ vs. /g/), with only the left
hemisphere differentiating between consonants on the basis of phoneme class. Another factor showed a main effect for consonants and on such grounds Molfese concludes that "at some level within the cortex of man the phoneme may in fact be the basic perceptual unit of language".

Following up the VOT studies, Molfese and Hess (1978) presented the Ba0, Ba20, Ba40 and Ba60 stimuli as used by Molfese (1977b; Experiment 3) to six male and six female right-handed children, and isolated four factors which accounted for 64.6% of the variance. VOT had a main effect on Factor 1, which also showed a sex X hemisphere interaction. Factors 2 and 4 showed hemisphere effects, but Factor 2 also showed a hemisphere X VOT interaction indicating, surprisingly, that only the right hemisphere differentiated between-category phonemes. Molfese (1978b) used the same stimuli while adults (eight male, eight female) performed a discrimination task. Four factors accounted for 91% of the variance. Factors 2 and 3 both showed main effects for hemispheres, with Factor 2 also showing a main effect for VOT. Both Factors 1 and 4 showed main effects for VOT and VOT X hemisphere interactions. Only the right hemisphere distinguished between voiced and unvoiced stimuli (i.e. Ba0, Ba20 vs. Ba40, Ba60).

Molfese and Molfese (1979a) presented the same stimuli to 16 infants, 8 male and 8 female, between two and five months old. Five factors accounted for 96.58% of the variance and it is claimed that the results show a very similar pattern to that found for adults (Molfese, 1978b) and children (Molfese and Hess, 1978). In all three studies there were two AER components that varied systematically with changes in VOT. Factor 2 characterised a phoneme discrimination process in the right hemisphere. A second VOT effect indicated by
Factor 3 was present in both hemispheres, but with longer latencies than those for Factor 2. AERs of infants, children and adults consistently differentiate between VOT stimuli along phoneme boundaries. A further experiment presented the same stimuli to neonates while they were in a state of quiet sleep, in the hope that this would cast light on the question of whether or not VOT distinctions were learned or innate. The latter alternative was not supported. In all experiments using these stimuli, both hemispheres seemed to be involved in processing, but in different ways. As summarised by Molfese and Molfese (1979a), a developmental sequence is apparent:

"In newborns the two hemispheres respond differently to the VOT stimuli, but show no evidence of categorical response. Differential VOT responses were found in the infant and child populations, but only occurred in the right hemisphere. In adults, this response was again found in the right hemisphere, but the left hemisphere differentiated between specific VOT stimuli, that is between endpoints on the VOT continuum (0 and +60) and between endpoints and the middle values (+20 and +40)."

Interestingly, sex differences in AER components were only found in newborns, infants and children, not adults, possibly indicating that maturational factors are involved.

Molfese (1980b) reviews his work on VOT in speech perception, and also attempts to determine a more specific basis for VOT perception. Repetitive series of two-tone stimuli were presented to 16 dextral
adults in which the frequency of the lower tone was 500 Hz while that for the higher tone was 1500 Hz. The onset time of the lower tone in relation to the higher tone was varied, so that it lagged by 0, 20, 40 and 60 msec. The higher tone lasted 230 msec and both tones ended simultaneously. A larger array of electrodes was used by Molfese in this study and hence the reader is referred to the original report for a detailed account of the many effects found. However, Molfese concludes that portions of the AERs were found to vary systematically in a manner similar to that previously reported for VOT stimuli.

Molfese and Molfese (1979b) used normal and sinewave formant CV syllables (as in Molfese, 1977a, Experiment II; see above) in a study which appears to use the same group of neonates as subjects as that used by Molfese and Molfese (1979a), although this is not explicitly stated. As with that study, sex differences in AER components were found. It was also noted that the left hemisphere was sensitive to second formant transition differences, as indicated by an early component, whilst a later independent component behaved similarly but appeared to reflect a process common to both hemispheres.

Molfese and Erwin (1981) examined AER components of adults in response to normal formant and sinewave formant vowel stimuli, as recorded from T3, T4, T5, T6, P3 and P4 (linked earlobes reference). Although changes in component structure varied as a function of different vowel sounds and formant bandwidths, no hemisphere differences were found. This result was expected in the light of previous studies using dichotic presentation (e.g. Shankweiler and Studdert-Kennedy, 1967) suggesting that vowel sounds are processed equally efficiently by both hemispheres.
Papanicolaou and Molfese (1978) looked at the brain's response to the words "two", "three", "four" and "five". Subjects responded with a differential key-press to "end (2, 5) vs. middle (3, 4)" numbers or "odd (3, 5) vs. even (2, 4)" numbers, depending upon their group. Each group contained equal numbers of high and low dextral subjects. Eight factors were found accounting for 94.5% of the variance. It was thought that Factor 1 might reflect the subjects' anticipatory state before stimulus onset; Factors 2 and 3 related to manual preference; Factors 4, 5 and 8 reflected differential processing of different aspects of stimuli, with the semantic grouping of "odd vs. even" not being demonstrated, although the grouping "end vs. middle" was. Factors 6 and 7 were dependent on hemisphere effects alone. Molfese et al. (1979) report an experiment in which the same stimulus word ("ball") was used in all conditions. Subjects, four female and four male, were cued to think of one of four concepts on each trial: a baseball, a football, a fireman's ball or a masquerade ball. Also, subjects were to either visualise the concept or to think of the word. Ten factors were isolated which accounted for 93.9% of the variance. Factor 10 appeared to reflect conceptual differences (object vs. dance) particularly in the left hemisphere. Other factors related to task variables, hemisphere main effects and sex x hemisphere interactions. The study by Pace et al. (1979) will not be discussed here as the nature of the subjects (right- and left-brain-damaged patients) and the size of the groups (three subjects each) prevent generalisation.

It is instructive to consider the general pattern of results and conclusions produced by this long series of interesting studies by
Molfese and colleagues, as they reflect on a small scale the pattern followed by all EEG/EP asymmetry studies taken as a whole. Early studies using PCA tended to indicate a few components which accounted for a large proportion of the variance, and which furthermore corresponded to simple and accepted notions of hemisphere function. Later studies tended to produce more factors (up to ten, as Papanicolaou and Molfese, 1978, and Molfese, 1979) and/or account for less variance (e.g. 64.6%, Molfese and Hess, 1978). Also many results were found which did not fit a simple model of lateralisation. For example, Molfese (1978b), Molfese and Hess (1978) and Molfese and Molfese (1979a) suggest that the right hemisphere produces differential VOT responses and, further, that at certain ages only the right hemisphere produces such responses. Molfese et al. (1979) claim that both hemispheres can distinguish meaningful from nonmeaningful stimuli. A detailed examination of the studies produces many more examples. What is crucial here is whether or not one accepts that this technique is a valid way to investigate these issues. If one accepts that the couple of early studies which produced uncontroversial findings constitute an adequate validation of the technique, then it follows that the more complex findings of subsequent studies must also be accepted, even though they do not correspond to any simple model. It is quite possible that they are valid findings. However, one cannot help wondering how well this technique would be accepted if it had produced such unexpected findings in the first experiments performed using it.

Again, some studies have failed to find the expected effects. Friedman et al. (1975a) recorded from Pz and points midway between Pz
and the left and right mastoids, referenced to the tip of the nose. Subjects had to listen to real speech words and nonspeech human sounds in a "task" and a "no task" condition. The "task" condition involved making a finger-lift movement in response to a target item, and separate EPs to target, non-target and "no task" stimuli were collected from eight right-handed subjects. When corrections were made to the acceptable significance levels in order to take into account the large number of tests performed, only two results remained significant from the hemispheric comparisons of N1, P2 and P300 to words and sounds in the three conditions. N1 was greater over the left hemisphere to target words and P300 was greater over the left hemisphere to non-target sounds. A very critical attack on the other studies in the field is made in this paper, but it ought to be borne in mind that the two differences reported in this study, while difficult to account for, may represent genuine EP asymmetries insofar as they survived a very conservative statistical procedure. Galambos et al. (1975) also failed to find any statistical differences between the hemispheres when comparing N1, P2 and, when present, P3. EPs had been recorded from Cz and points midway between T3 and T5 (presumably, though "P5" is reported) and T4 and T6. Binaural natural speech syllables (/pa/ and /ba/) or pure tones were presented and subjects had to listen and count target items.

Tanguay et al. (1977) presented voiced stop consonants (ba, da, ga) monaurally to 18 right-handed males while recording from central and temporal placements (ipsilateral earlobe reference). They found that the response of the hemisphere contralateral to the stimulated ear was bigger than that produced by ipsilateral stimulation, although no
latency differences were found. No hemisphere differences over and above pathway effects were found. Ratliff and Greenberg (1972), while finding differences in the AER response to linguistic and nonlinguistic signals, also failed to find any hemisphere differences.

To end this section on a note of caution, the findings of Anderson (1977) should be borne in mind. He recorded from left and right inferior frontal sites (as in McAdam and Whitaker, 1971a) and monitored EOG from the left and right outer canthus (reference: linked mastoids). Subjects were presented with /ba/ and /ga/ and responded to target items with a finger press, as well as engaging in speech production tasks. A strong correlation was found between averaged EPs and averaged EOG. It is known that the direction of reflective lateral eye movements may be directly related to hemisphere activation (Ehrlichman and Wienberger, 1978) and thus, as Anderson warns, many EP studies may be suspect.

General conclusions from studies employing complex stimuli are presented at the end of the next section.

1.3.2.2.3 Visual Evoked Responses

Many studies of the VER use checkerboard patterns, as the contrast inherent in such stimuli can be expected to produce more cortical activation than a simple unstructured light flash. It could be argued that such stimuli may be preferentially processed by the right hemisphere (Butler and Glass, 1976) as they are essentially "visuospatial", but most of the studies performed using these stimuli
have not used them to examine hemisphere function. For example, Cobb and Morton (1970) used pattern reversal to show that the contralateral cortex was selectively stimulated by stimulation of either visual half-field, as shown by large VERs in comparison to an almost flat response ipsilaterally. Barrett et al. (1976a, b) pointed out that these findings were in fact due to Cobb and Morton's use of a bipolar electrode montage over the occipital area. They found that by using a unipolar montage, referenced to a common midfrontal site, all nine of their subjects showed a larger response over the hemisphere ipsilateral to the stimulated half-field, and the midline placement, compared to the contralateral response. However if the electrodes were joined in a bipolar chain, the potential gradient differences between the hemispheres did produce an apparent maximum on the contralateral side. This finding seems at first to contradict the expectations generated by our knowledge of the visual pathways, but Barrett et al. suggest that although the VER is larger over the ipsilateral scalp, this is because the electrodes are in a better position to pick up signals from the opposite hemisphere produced by cortical generators on the contralateral medial and posteromedial surface. Beauchamp et al. (1976) did not accept this. They claimed that only the earliest components of the VER were definitely striatal in origin, and so they examined the earliest component produced by pattern-reversal which they found to be positive over the hemisphere contralateral to the field of stimulation, and negative, but of equal amplitude, ipsilaterally. Thus they suggest that Barrett et al.'s (1976a, b) results are due to measuring from this more negative baseline. However, recent work (Blumhardt et al., 1977; Barrett et al., 1980)
with patients who have undergone occipital lobectomy supports the idea that the major positive component optimally recorded from the ipsilateral scalp is generated in the contralateral hemisphere.

The basic finding of larger VEPs over occipital cortex ipsilateral to the stimulated visual half-field, at least for pattern-reversal, has been confirmed many times (e.g. Arruga et al., 1980; Kuroiwa and Celesia, 1981; Haimovic and Pedley, 1982), and thus the question naturally arises of whether all VEPs are recording potentials mainly generated in the contralateral cortex. In considering this question, Rugg (1982) concludes that this is unlikely and cites the series of studies reported by Halliday et al. (1979) to support his argument. They found that the main P1 component is "paradoxically" lateralised as a result of asymmetrical stimulation of the macular region of the visual fields up to approximately 2.5 degrees from the midline. Stimulation extending 15 degrees into the periphery, but with no stimulation of the macular region, gave rise to VERs with a prominent positive-negative-positive component which was larger when recorded from contralaterally placed electrodes. Rugg also suggests that the "paradoxical lateralisation" effect may be limited to certain types of stimuli, as Biersdorf and Nakamura (1971) reported that if a semi-circular flash is used to stimulate the hemiretina, a larger VEP is recorded contralaterally. In fact, though, as this study did not use occipital placements, there would be no reason to expect paradoxical lateralisation to occur anyway. A more valid point made by Rugg is that as many of the components studied in investigations of hemisphere asymmetries are of long latency, the issue of possible striate origin would not arise.

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Vella et al. (1972) used pattern-onset and light-flashes while recording bipolarly from thirty right-handed subjects (Oz-01, Oz-02, O1-T5, O2-T6). As previously stated, they found no significant effects for light-flashes, but pattern-onset produced a larger response over the right hemisphere, especially at the occipitotemporal leads, but only when the hemispheres were not being directly stimulated. The use of bipolar placements makes any clear interpretation of this finding difficult. Shagass et al. (1976) failed to replicate this effect when they recorded both pattern-onset and pattern-reversal VEPs in thirteen subjects, using both bipolar and unipolar montages (linked ears reference) with thirteen active electrodes. The pattern-onset VEPs in this study were mirror images when left- and right-visual-field stimulation were compared. The pattern-reversal VEPs essentially confirmed the findings of Barrett et al. (1976a, b).

More recently the stability of the pattern-onset VEP has been used to discriminate between psychotics and normals. Roemer et al. (1978) examined the spatial distribution of waveform stability over twelve electrodes (linked ears reference). They found that stability was generally lower in schizophrenics, especially in the left hemisphere, compared to normals. Also the stability differed more between the hemispheres in schizophrenics and psychotic depressives than normals. Psychotic depressives were also shown to have lower left hemisphere stability at various sites in response to intermingled pattern-onset stimuli, clicks and electrical stimulation of the left and right median nerves (Shagass et al., 1980). Purves et al. (1980) showed that the latency of the major positive peak of the pattern VEP did not differ between 37 normals and a group of 17 children with minimal
cerebral dysfunction (MCD). However the peak-to-peak amplitude of the P110-N160 was significantly lower over the left occipital lobe than over the right, but only in the MCD children.

As with ongoing EEG (Warren and Haueter, 1981; Newlin et al., 1982) and auditory evoked potentials (Anderson, 1977), a relationship between direction of LEMs and VER asymmetry may exist. Shevrin et al. (1980) classified subjects as right-lookers and left-lookers on the basis of reflective LEMs in response to standard verbal or visuospatial questions. Recording ERPs in response to a pattern-reversal stimulus from O1 and O2 (reference undeclared), the results suggest that left-lookers had a greater positive component (P90) at O2 than O1, while the reverse was true for the right-lookers. The investigators were unable to say whether or not the subjects were fixating different points on the visual display.

Whilst it is not clear whether or not studies looking at pattern VERs could be expected to tap right hemisphere function, attempts have been made to preferentially engage this hemisphere and observe the VER asymmetries produced, if any. For example, Krynicki (1976) used a polygon recognition task which had been shown in behavioural experiments using the divided visual-field technique to be performed better by the left hemisphere when the comparison polygon was in the same orientation as the original, but was performed more effectively by the right hemisphere if the orientation was different. The VERs in the preferred hemisphere for each task were large and elaborate with distinct components, but simply characterised by a large slow component in the other hemisphere.

Differences between the VERs of deaf and hearing children in
response to a picture recognition task were investigated by Neville (1977), recording from T5 and T6 (linked earlobes reference). She found that while in hearing children the right hemisphere produced a VER 3.2 microvolts larger than the left, the deaf children simply showed a visual field X hemisphere interaction reflecting the structure of the visual system. Within the deaf group an interesting tendency for those children who knew sign language to show an asymmetry opposite to that of the hearing children was observed.

Galbraith et al. (1979) compared responses from Cz, Broca's and Wernicke's areas and homotopic sites on the right hemisphere (reference linked ears) between normals and mental retardates using a P300 paradigm. The experimental tasks were an easy and a difficult form discrimination and a colour discrimination task. Typically, the posterior>anterior differences in P300 which were found were the same over each hemisphere for normals, but showed asymmetries in the retardates although not in a consistent direction.

Pictures of ambiguous male and female infant faces were presented to the right- and left-visual-fields randomly while VERs were recorded from O1, O2, F3 and F4 (linked ears reference) by Leslie et al. (1980). Subjects had to indicate the gender of the infant verbally. An early negative component (about 100 msec) was found to discriminate the gender of the slide irrespective of the subjects' responses for LVF presentations only. A late negative component (about 323 msec) discriminated between the subjects' responses irrespective of the gender for VERs recorded from F3.

Lehmann and Julesz (1978) presented random-dot stereograms to subjects and recorded VERs from left and right occipital sites
(referenced to mid-occiput). Such stimuli produce depth effects when viewed binocularly and the investigators were testing the hypothesis that the right hemisphere predominates in such perception, by time-locking data collection to the appearance of depth. No support was found for this hypothesis although the directly stimulated hemisphere produced larger mid-latency components than the indirectly stimulated hemisphere when stimulation was limited to either visual half-field.

Klemm et al. (1980) studied "steady-state" VERs evoked by alternating a vertical-bar pattern monocular stimulus which reversed at rates of 6, 11 and 16 Hz. The signals were recorded from occipital areas and submitted to Fourier analysis following averaging. There was no evidence of any effects related to ocular dominance, but subjects did develop larger responses, at either reversal frequency or a harmonic, over the presumed language-dominant hemisphere. This result does not, of course, fit easily with the view that such pattern-reversal stimuli are processed in the right hemisphere.

Many studies have presented verbal stimuli visually, such as words or letters. The first study of this kind was that of Buchsbaum and Fedio (1969) who looked at VERs to words, random dots and designs whilst recording from O1 and O2, with ipsilateral earlobe as reference. They used a discrimination index to show that words were discriminated from designs more, in terms of waveform similarity, over the left hemisphere than the right, although this was not found for the word-dot discrimination. Also the word stimuli produced more replicable EPs with shorter latencies. The right hemisphere produced more replicable EPs than the left. This was followed up by a similar
study using divided visual-field presentation of words and their random-dot equivalents (Buchsbaum and Fedio, 1970). This study again found greater stability of the VERs in the right hemisphere and also that the direct visual pathway (e.g. left hemiretina to left hemisphere) produced more stable VERs than the indirect route. However, in contrast to the previous study, dot arrays produced more stable responses than words. Although the direct route to the left hemisphere produced larger differences between VERs to dots and words than the equivalent right-hemisphere route, significant differences were found for the right hemisphere suggesting possible discriminant processing in this hemisphere too. These results were compared with those of eleven epileptics who had undergone anterior temporal lobectomy (Fedio and Buchsbaum, 1971). It was found that the left-lobectomy patients showed less stable EPs for words and the right-lobectomy patients, for dots.

Gott et al. (1975, 1977) used the same type of analysis when comparing VERs recorded from O1, O2, P3 and P4, unfortunately referenced to the left ear, from normals and commissurotomy patients. They presented words or patterns to RVF, LVF or centrally and the subjects' task was a rhyme-detection task or a spatial-matching task, respectively. Behavioural data showed that only the verbal task produced lateralised effects typical of split-brain patients. Higher correlations between VERs were taken to indicate dependent functioning between areas, and the results thus interpreted suggested that commissurotomy patients had highly dependent within-hemisphere functioning, but, for the verbal task, independent between-hemisphere functioning, in comparison to normals. Also, while RVF inputs to the
left hemisphere resulted in identical correlations in both groups, LVF inputs to the right hemisphere produced an increase in right hemisphere correlation for patients but a decrease for normals. This is interpreted as reflecting the fact that in normals the right hemisphere does not attempt to process verbal information, but in the split-brain patients, it may attempt such processing. In both normals and patients VERs from each hemisphere were more similar when elicited by central as opposed to lateralised stimuli.

A study by Berman (1976) involved the presentation of the single word 'RUN' to seven different spatial locations while recording VERs from "right and left hemispheres". It failed to produce any hemisphere asymmetries beyond a nonsignificant tendency for greater amplitudes over the right hemisphere, not even reflecting the typical anatomical pathway effects. It is difficult to account for such a result as inadequate detail of methodology is provided.

Ciesielski (1982) attempted to ensure that subjects performed a nonverbal shape-matching task without resorting to verbal strategies by pre-training them up to a level at which the task was performed 'automatically'. Then, pairs of stimuli were presented to either LVF or RVF for same/different judgements while VERs were recorded from P3, P4, C3 and C4 (referenced to common earlobes). The N2 (180-290 msec) and P3 (290-380 msec) components were found to be larger and of shorter latency over the right hemisphere during performance of the nonverbal task. A verbal control task, given three weeks later, produced slightly larger P3 over the left hemisphere and no lateral differences in N2. However, as the verbal control task consisted simply of the same task as previously given with the additional
requirement of a verbal "same" or "different" response, it is very questionable if it would be expected to produce such differences in components normally associated with stimulus processing, not motor output.

Connors (1971) presented results which he claimed demonstrated that the VER response to simple flashes was attenuated over the P3 site (compared to O1, O2 and P4) in a family of poor readers. However, Kooi (1972) rightly criticised the use of a Cz reference in this study, pointing out that as Cz is a very active site, nothing can be said concerning absolute differences in the size of the VER. Connors (1972) replied to this criticism by claiming that hemisphere asymmetry was shown even if the differences were relative. Strictly, this is true, but one cannot know the nature of the differences. For example, a large simultaneous response at both Cz and P3 would be cancelled out using bipolar recording, when perhaps (a) a smaller response at the other three sites would survive though inverted, or (b) a time-shifted response may survive, though in a distorted form. Also, Connors (1971) can be criticised for not using a control group. However, his study did provide the interest to stimulate a series of similar experiments, some of which used complex visual stimuli.

For example, Lombroso et al. (1974) recorded VERs from vertex, occipital and parietal areas in a group of dextral normal readers and a group of dextral disabled readers, during each of four conditions: (1) words requiring discrimination, (2) same words without discrimination, (3) nonsense syllables and nonmeaningful figures requiring discrimination, and (4) the same syllables and figures without discrimination. Waveforms exhibited by the dyslexic and normal
groups were different, but interhemispheric asymmetry within each group was small, with the largest asymmetry occurring for a few early components within the dyslexic group. The same investigators (Symann-Louett et al., 1977), using the same placements, present data for VERs derived from a word-presentation task which did not require discrimination. This study claimed to demonstrate that normal readers exhibit more waves than disabled readers over the left superior and inferior parietal areas, although no analysis of amplitude or latency effects is presented.

Sobotka and May (1977) recorded VERs from O1, O2, P3 and P4 (Cz reference) during a task in which subjects were required to respond to dim flashes in a series of brighter flashes. An overall R>L amplitude asymmetry is reported for both dyslexics and normals, although dyslexics exhibited slower reaction times to attended stimuli and larger amplitudes to unattended stimuli.

Preston et al. (1974) compared the VERs to 50 and 300 msec flashes and presentations of the word "cat" whilst recording from five electrodes (referenced to left mastoid) on a group of nine reading-disabled children and two carefully chosen control groups. Perhaps significantly, only the data for the P3 electrode in response to the 50 msec stimuli are presented. The absolute deviation from zero at 180 msec showed the disabled group to have a lower amplitude negative wave than the other two groups although no differences were seen at 600 msec. A second study (Preston et al., 1977) recorded from adult normal and disabled readers during presentation of passively viewed light-flashes and a series of three-letter words containing a target item. VERs were recorded from O1, O2, P3 and P4 (linked
mastoids reference) and the peak-to-peak amplitude for P100-N140 and N140-P200, as well as the amplitude for P200 and the Late Positive Component (LPC), were obtained. The main findings were (i) increased amplitude for P200 and LPC on the left for words only, (ii) increased amplitude for the LPC on the parietal leads for flashes and words, the effect being stronger for words, and (iii) a larger difference was found between word and flash stimuli at P3 for normal compared to disabled readers for P200 and LPC. Preston (1979) reviews previous studies of reading disability and presents baseline data from a study on the members of six families of normal readers giving 36 subjects in all (two left-handed). He recorded from the same sites, this time with an ipsilateral mastoid reference, during presentation of a series of light-flashes which subjects had to count or a series of three-letter words containing target items. Two sessions of each task were included in the analysis, but no main effect for testing session was found. However larger LPCs were shown to be related to (i) words (vs. flashes), (ii) parietal (vs. occipital) sites, and (iii) left (vs. right) hemisphere. Several interactions were found, the main finding being that the response at P3 was greater than at P4 for words, but the same for flashes.

Once again, it is difficult to derive any general conclusions from this series of studies on poor readers, but there are two strong reasons for continued research efforts in this area. Firstly, there is certainly more consistency in studies comparing dyslexics and normals for hemisphere asymmetry to a variety of stimuli than is typically found in comparing other types of groups, insofar as many of these studies have reported differences in asymmetry at parietal sites.
(Note, however, that Matsumiya, 1976, found no asymmetries recording from a variety of sites and using a variety of visual stimuli for either normals or dyslexics; see below.) It is difficult to interpret this effect further, as all studies have used active reference sites, but future work could avoid this. Secondly, one need not be too worried about the actual interpretation of effects if one is simply searching for a reliable way to discriminate good from poor readers, a perfectly valid and useful aim.

Neville (1980) presents ERP data recorded while subjects performed verbal and nonverbal auditory and visual tasks. Results of the auditory tasks are presented in the previous section. The visual tasks consisted of presenting two different words simultaneously to the two visual fields for subsequent recall or presenting line drawings to LVF or RVF for subsequent recognition. ERPs to word pairs were asymmetric, insofar as the base-N1 and N1-P2 amplitudes were significantly larger from the left than from the right hemisphere parietal sites, but were symmetric at the central sites. This task produced a strong RVF advantage behaviourally. No significant ERP asymmetries were found if the words were presented out of focus. Although no significant behavioural asymmetries were found for the pictures task, ERPs were asymmetrical at central but not parietal electrodes, with base-N1, N1-P2 and base-P3 amplitudes being significantly larger over the right hemisphere.

Neville (1980) also presents preliminary data from a task in which the same stimulus, a matrix containing letters, is used for both a verbal and a nonverbal task. The 'letter' task involved presenting the matrix and then a single 'probe' letter to which the subject had to
respond if it directly followed alphabetically one of the letters already presented. For the 'spatial' task, the subjects had to process the information in the matrix with respect to the positions of occupied cells. Recording from O1, O2, P3, P4, F7, F8 and left and right temporal placements (referred to linked mastoids), preliminary results suggested both ERP asymmetries and the expected behavioural asymmetries when the stimulus was restricted to a single visual field. The ERP asymmetries consisted of a small but reliable L>R positivity at around 200 msec for the letter task, and a slow positivity at around 300 msec and lasting at least one second for the spatial task, recorded from right hemisphere temporal and frontal sites.

Neville et al. (1979, 1980) present the results of a small study of three patients suffering from alexia without agraphia and matched controls (one left-hander in each group). VERs were recorded from O1, O2, P3, P4, C3 and C4 (linked mastoids reference) and the amplitude of N1 and P3 relative to prestimulus baselines was measured. In response to full-field white flashes N1 was found at both hemispheres for normals, but only at the left hemisphere sites for patients. When four-letter words were presented in RVF and LVF, N1 was larger at the contralateral sites for normals, who also showed a symmetric P3 response at the central and parietal leads. The patients, on the other hand, showed no VER to RVF stimulation and no N1 at occipital sites for LVF stimulation. Also, P3 was broader and larger over the left hemisphere, especially at the parietal leads. In response to divided visual-field presentation of line-drawings, normals showed the same response pattern as to words. In patients, however, such stimuli led to the N1 component being recorded from P4 and O2.
More recently, Neville, Kutas and Schmidt (1982a) investigated ERP asymmetries to tachistoscopic presentations of words, either unilaterally or bilaterally. EEG was recorded from left and right occipital, parietal, temporal, anterior temporal and frontal sites, and also the vertex (all referred to linked mastoids). The typical RVF advantage was noted in terms of accuracy. The occipital ERPs reflected anatomical pathway effects, but the more anterior regions displayed large asymmetries which were in the same direction regardless of the visual field of presentation. The most prominent such asymmetry was a negativity (N410) in the latency range 300-500 msec which was larger in the left than the right hemisphere in every subject. A second study (Neville, Kutas and Schmidt, 1982b) compared these findings with those from a group of congenitally deaf adults. It was found that the deaf subjects did not display visual field asymmetries in accuracy, even though their overall level of accuracy was the same as that for the normal subjects. It might be expected that due to differences in linguistic development between normals and deaf subjects they would demonstrate different patterns of cerebral organisation. This seemed to be confirmed, with the ERPs from frontal and temporal regions in the deaf subjects differing in both wave shape and lateral distribution from those found with hearing subjects. No N140 was observed. More unexpectedly, the occipital ERPs, while similar in waveshape, did not conform to those of hearing subjects in lateral distribution.

Both words and letters were used as stimuli by Thatcher (1977; Thatcher and April, 1976) using the Background Information Probe (BIP) technique which involves presenting random-dot stimuli before, between
and after two stimuli to be compared. Letters to be matched for identity and words to be matched semantically were used to produce VERs which were recorded from several electrodes. Waveform analysis, including PCA, was used to compare EPs. Some subjects showed asymmetry to dots presented before the first comparison stimulus, but the asymmetries were more consistent to information presentation, especially at temporal sites. For the semantic task, LPC was greater on the left for some sites, but only for informative stimuli, not the first set of dot stimuli. The dot stimulus after the test stimulus sometimes did show asymmetries and it was thought that this might reflect rehearsal mechanisms.

Bentin (1980) used a P300 paradigm to explore task-related asymmetries. He recorded from Wernicke's area and a homotopic area on the right, as well as Cz, referenced to linked ears. He presented Hebrew words of the same letters but of different meanings in one condition and random dot patterns of different orientations in another. His Israeli subjects had to count target items. The P300 was around 511 msec for the verbal task and showed a L>R asymmetry in 22 out of 24 subjects, and around 464 msec in the visuospatial task showing interhemispheric symmetry. This may be explained by the fact that counting could well be a "left hemisphere" task and also the tasks obviously differ in difficulty. Further analysis revealed that while the males showed task-related asymmetries, the females showed a constant L>R asymmetry.

Ledlow, Swanson and Kinsbourne (1978b) carried out an interesting study in which behavioural and electrophysiological measures were obtained simultaneously. The subjects' task was to respond with a
key-press to letter pairs in which both letters had the same name (i.e., matched). Six variables were altered factorially: (a) location of letter pairs (central, RVF, LVF), (b) knowledge of location (trials were either random or blocked presentation to a particular location), (c) type of letter combination (same or different case), (d) blocking of pair type (all same, all different or mixed), (e) match vs. mismatch, and (f) response hand. Occipitoparietal derivations referenced to linked mastoids were used on eight right-handed subjects in a completely repeated measures design. In contrast to previous studies, a LVF advantage for physical matches was not found. Name-matching with no knowledge of location or type produced a RVF advantage, which was not present if the location was known. The P300 data failed to mirror these RT effects, with direct (as opposed to transcallosal) transmission producing larger amplitudes for name-matching, but no difference for physical-matching, in the left hemisphere. A reverse trend for the right hemisphere failed to reach significance. No effects for latency were found. N70, N170 and P300 were all larger over the right hemisphere and P130 and N170 were smaller for different- than for same-case matches over the left hemisphere. N70, P130 and N170 were smaller and P300 larger for contralateral vs. ipsilateral stimulation. Hence it can be seen that no simple relationship between the behavioural and the VER measures was obtained.

Recently, Kutas and Hillyard (1980a, b, c; 1982) have employed a slightly modified version of a task originally used by Friedman et al. (1975b; see below). ERPs were recorded from subjects as they read 7-word sentences presented one word at a time. Kutas and Hillyard
(1980a) recorded from Fz, Pz and Cz referred to linked mastoids and
noted that words that were physically aberrant (i.e. larger than
normal) elicited a late positive series of potentials, whereas
semantically inappropriate words elicited a late negative wave (N400).
The N400, possibly a sign of "semantic reprocessing", was investigated
further in the subsequent studies employing lateral placements in
addition to the midline sites. The N400 had been found to be virtually
absent at F7 and F8 (Kutas and Hillyard, 1980a, b) but Kutas and
Hillyard (1980c), using a short time-constant, found that the N400
elicited by semantically incongruous words and the "difference N400"
(incongruous minus congruous ERP) were slightly larger and more
prolonged over the right than the left temporo-parietal area. Also, a
L>R amplitude asymmetry in a slow positivity associated with the
processing of the first six words of the sentence was reported (Kutas
and Hillyard, 1980b, c, 1982). ERPs to congruent endings showed
different directions of asymmetry in different experiments. Of course,
as no nonlinguistic control task was possible in these studies, it is
impossible to determine whether or not these asymmetries reflect
purely linguistic factors.

Chapman and McCrary (1979) looked for hemispheric asymmetry effects
between a letter comparison task and a number comparison task. On each
trial, two numbers and two letters were presented to the subject in a
random order, each one preceded and followed by a blank flash. The
subjects task was to compare either the numbers or the letters on any
one trial and to indicate the numerical or alphabetical order. EPs
from O1, O2, P3 and P4 (referenced to linked earlobes) were obtained
for sixteen conditions: relevant vs. irrelevant; number vs. letter;
each at four intertrial positions. Results from the left and right sites were very similar for the mean amplitude over 480 msec although some differences were seen, and this similarity was also noted for the amplitudes at 0 msec (indexing CNV activity) and 105, 225 and 315 msec as well. Discriminant analysis showed that the left hemisphere was better at discriminating between conditions, although the right hemisphere did quite well. It is claimed that the right hemisphere showed up subject individual differences more.

Many studies have failed to find any hemispheric asymmetries in the VER, or asymmetries which did not appear to be task-related. For example Shelburne (1972, 1973) presented CVC syllables one letter at a time whilst recording VERs to each letter from Cz, P3 and P4 referenced to linked ears. The last letter was crucial for the word/nonword discrimination task which the subjects had to perform, and produced a larger EP presumably due to decision-making processes. However, no differences were found between the hemispheres. Shelburne (1973) showed that the EP to the third letter was only bigger than the EP to the first letter if the subject was performing well.

Seales (1973) found no asymmetries recording from O1 and O2 and left and right "Wernicke's" areas (linked earlobes reference) in letter discrimination tasks based on the size or the names of letters used. No asymmetry was found in the simple RT condition either, but P270 was found to decrease in amplitude and increase in duration with increased task complexity. Similarly, Bell (1973) failed to find asymmetry recording from the left and right temporal areas during two verbal and two facial recognition tasks. The more difficult task of each type produced a reduction in amplitude of certain components.
Friedman et al. (1975b) recorded VERs to each sequentially flashed word comprising sentences. They recorded from left and right temporoparietal placements and vertex (tip of nose reference) in eight dextrals, but noted no hemisphere asymmetries. However, as the same three sentences were used throughout the experiment it seems likely that this task would not be linguistically taxing.

Matsumiya (1976) recorded from Cz, O1, O2, P3, P4, W1 and W2 referenced to linked earlobes while children were presented with words, anagrams or nonmeaningful patterns, both passively and for a discrimination task. No differences related to the stimulus-type were found either for normals or dyslexics. Marsh and Brown (1977) repeated Experiment II of their series using visual instead of auditory presentation. Thus the sentences "Fire the gun" and "Fire is hot" were presented in blocks or mixed randomly. This experiment produced larger, more stable EPs than the auditory presentation but the differences between left and right correlations was less than in the previous study and failed to reach significance. However 11 out of 14 subjects showed lower correlations on the left for the anterior pair of electrodes, and 10 out of 14 for the posterior pair, for blocked presentation. The mixed condition showed comparable differences for the anterior pairs, but no differences for the posterior pairs. Hence, the trend here may support the auditory findings, with meaning-related effects being swamped by sensory evoked potentials.

Rugg and Beaumont (1978) examined EP and behavioural measures of hemispheric activation by presenting letters in RVF and LVF and recording from a point 25% of the distance from O1 to T5 and an homologous site on the right hemisphere (Cz reference), whilst also
obtaining RTs. In Experiment I, subjects pressed a key if the letter contained an "ee" sound; in Experiment II, if it contained a right-angle. Latency and amplitude analysis revealed that in both experiments P1 and N1 showed shorter latencies for direct pathway presentations. Additionally, in Experiment I direct transmission produced larger N1-P2 amplitude (peak-to-peak). In Experiment II, left hemisphere amplitude was the same regardless of the field of stimulus presentation, whereas the right hemisphere showed a larger response for LVF presentation. P2-N2 amplitude was larger in the left hemisphere in this experiment, too. It is suggested that these differences may reflect types of processing as stimuli were held constant. The same electrode montage and verbal task were used in the subsequent study (Rugg and Beaumont, 1978 b) but this time the nonverbal task was to select targets which were symmetrical about the vertical axis from letter-like nonsense patterns. P75 latencies were shorter over the right hemisphere for both tasks and it is suggested that the right hemisphere may be predominantly involved in the early processing of information in both tasks. P230-N265 amplitude was larger for letter stimuli and, as in the previous study, no RT differences were found. P3 and P4 (referenced to linked mastoids) were used by Rugg and Beaumont (1979) in a study in which subjects responded to letters if they contained an "ee" sound and spatial patterns if they were symmetrical, the probability of a target being 0.33. N180 was larger and P150 had shorter latency over the right hemisphere, and P400 had a shorter latency for letters. P400 was larger and RTs shorter for spatial stimuli. These results were taken once again to reflect the preeminence of the right hemisphere in early
visual processing. Surprisingly, there was no difference between the P400 for target and nontarget items.

Begleiter et al. (1979) present data relating to the VER recorded from P3 and P4 (linked ears reference) in response to neutral, and positive and negative affective five-letter words. Subjects were presented with the words twice; once to indicate the position of the last vowel in the word (LI run) and once to make an affective rating of the word on a five-point scale (AR run). VERs were averaged in three ways: (i) EPs on the LI run were averaged according to the LI response, (ii) EPs on the AR run were averaged according to the AR response, and (iii) EPs on the LI run were averaged according to the AR response. Latency and amplitude measures did not differ between the hemispheres for condition (i). Comparing conditions (ii) and (iii), however, produced significant differences for four out of five comparisons. Essentially what this comparison did was to compare the VERs for the same words when they were rated affectively or analysed orthographically. Although these differences were more striking in the left hemisphere, the hemisphere differences were not significant.

An investigation of the Stroop effect in terms of behavioural and electrophysiological indices was performed by Warren and Marsh (1979). They presented either congruent or incongruent Stroop stimuli in either LVF or RVF and had subjects respond to a particular name or ink colour while they recorded from O1, O2, P3 and P4 (linked mastoids reference). Occipital and parietal data were pooled and it was shown that N1 latency was shorter and N2 amplitude larger in the hemisphere of first arrival. The RT data showed a clear Stroop effect. A second experiment looking at prerresponse potentials showed several
recently, Boddy (1981; Boddy and Weinberg, 1981) has used a word
discrimination task and VERs evoked thereby to investigate certain
cognitive models of language. No lateralisation of any component was
found in either study.

It is not easy to attempt to draw conclusions from such a wide
range of studies, but it may be useful to focus on certain points.
Firstly, there are a considerable number of methodological issues,
such as potential sources of artifacts, inappropriate reference sites
and lack of suitable control tasks, which characterise most of these
studies. A detailed methodological critique of individual studies is
not possible without making this introduction much longer, but it is
usually obvious from the description provided that very few studies
even approach the criteria suggested by Donchin, Kutas and McCarthy
(1977) or Gevins (1981). Secondly, although studies sometimes appear
to replicate previous findings, this is often not the case when the
results are considered in detail. Many investigators seem to accept
any difference in amplitude or latency of any component between the
hemispheres as indicative of lateralisation of function. Replication
of effects across studies down to the level of a particular component
at a particular site at a particular latency is very rare indeed. In
fact, very few investigators ever attempt exact replications, and thus
the post hoc explanation of "differences in procedure" is always at
hand to explain away apparent discrepancies. One exception to this
statement is the work of Grabow et al. (1980a, b), who have so far
failed to replicate at least two very commonly cited studies. Thirdly,
considering the known reluctance of investigators to attempt to
publish negative findings, there are enough failures to find anticipated asymmetries in the literature to justify a sceptical approach, at least for the time being.

1.3.2.3 **Probe Studies**

Each type of approach reviewed so far, i.e. on-going EEG and ERP studies, has its own disadvantages. As Galin (1979) points out, the use of ERPs involves the repeated presentation of simple stimuli and hence tasks are far from natural. On the other hand, on-going EEG studies may well be more affected by artifacts in the data which will tend to average out in the averaging process required for ERP studies. Thus, recently a new technique has come into being which attempts to avoid these disadvantages by presenting task-irrelevant stimuli to the subjects while they are engaged in on-going, fairly natural tasks. The idea behind this approach is simple. If one hemisphere is activated more than the other by a particular task, we might expect this to be reflected in the EP to the irrelevant "probe" stimulus. Thus Galin and Ellis (1975, 1977) in the study already reported, used an irrelevant light-flash probe while subjects engaged in verbal and spatial tasks and found that the R/L power ratio (100-350 msec) was greater during the verbal than the spatial task for parietal and temporal placements. Peak amplitudes showed similar effects, but there were no effects on latency. Mayes and Beaumont (1977) in an attempted replication used motor and nonmotor versions of the tasks used by Galin and Ellis (i.e. Modified Koh's Blocks and writing from memory), but failed to find the
expected effects. However, Galin (1979) rightly criticises this study for the use of bipolar electrodes (O1-P3, O2-P4; original report is in error) when trying to replicate an effect found with a unipolar montage. Beaumont and Mayes (1977) did use unipolar electrodes referenced to Cz while subjects mentally went through a nursery rhyme deciding if each letter contained (a) an "ee" sound (on verbal task) or (b) a curve (on visuospatial task). Half the subjects had VERs to flashes recorded from C3 and C4 and half from P3 and P4, there being equal numbers of males and females in each group. Again, there was little evidence of a task X hemisphere interaction for any of the twelve components examined although several independent task and hemisphere effects were found. Also, in the study by Buchsbaum and Drago (1977) no asymmetry was found in the VER to flashes presented in either visual field while subjects engaged in mental arithmetic.

However, other studies have supported Galin and Ellis's observations. Rasmussen et al. (1977) used a double-flash probe while subjects engaged in mental arithmetic or control conditions. The peak-to-trough amplitude of a biphasic wave (75-150 msec) recorded from C3 and C4 (ipsilateral ear reference) was noted and a R/L ratio calculated. The results showed that left hemisphere amplitude decreased more than the right hemisphere amplitude during the mathematical compared to the control conditions. Mental arithmetic, musical pattern recognition and attention-to-breathing were the tasks used by Caperall and Schucard (1976) when recording flash-evoked potentials from temporal and parietal leads of right-handed musically naive subjects. Again, the hemisphere presumably most involved in the task showed a more attenuated VEP. More recently, Papanicolaou (1980)
used a photic probe paradigm while recording from F7, F8, T3, T4 and points midway between T3 and P3, and T4 and P4 (linked ears reference). He had subjects listen to meaningless strings of English words under four conditions: (i) attend to flashes, ignore words (control condition), (ii) detect acoustically distinct targets, (iii) detect words containing certain stop consonants, and (iv) detect semantic targets. No overt response was required. P1 (40-100 msec) and N1 (100-140 msec) were identified and amplitude ratios of each experimental condition compared to the control condition were calculated for each site. It was found that the experimental conditions produced enhancement of the right hemisphere VERs and attenuation of the left hemisphere VERs, this "bilateral divergence" being significant for the phonetic and semantic tasks only.

An interesting variation on this theme is reported by Wilson (1980) using "steady state" VERs recorded from O1, O2, P3 and P4 in response to a 14 Hz photic stimulator. A verbal task produced reduced O1 amplitude in comparison to O2, whereas spatial tasks had the opposite effect.

Other investigators have used auditory probes and the finding of attenuation in the EP over the engaged hemisphere has been totally reversed, an effect which has received little, if any, discussion. For example, Shucard et al. (1976, 1977) used a double-tone probe (2 second interstimulus interval) while subjects detected (i) clicks embedded in white noise, (ii) key words in prose and (iii) recurring themes in musical passages. AERs from T3 and T4 (reference Cz) showed higher AER amplitudes, especially for the second tone, as well as less of a decrement in AER from the first to the second tone, over the more
activated hemisphere. It is suggested that this could be the result of there being fewer unengaged neurons to respond to the probe in the activated hemisphere, thus producing a lower amplitude response. The use of an active reference (Cz) means that this will appear as a higher amplitude response because the difference between the response at T3 and Cz will be greater for the verbal task and smaller for the musical task than the T4-Cz response. While this is true, it does not explain Galin's (1979) claim that, "Shucard et al. (1977) have replicated our basic finding using auditory tasks...and task-irrelevant tone-pairs as the ERP probe stimuli. They found lower response in the left temporal lobe than the right during the verbal task and lower in the right than the left during the musical task". For the discrepancy in findings is obvious as the same reference electrode site was used by Galin and Ellis (1975, 1977).

The importance of the choice of reference has been underlined in a recent study (Shucard et al., 1981a; Shucard and Shucard, 1979) which showed a negative relationship between results found using Cz as reference compared to linked mastoids. When using Cz the previous results were replicated, but using linked mastoids led to the AER being smaller over the hemisphere presumably more engaged in the task. It is also reported (Shucard et al., 1981b) that a sex difference has been shown in infants using this technique. Seven out of eight males showed a R>L asymmetry for the N300 component of the AER to tones when presented with complex stimuli such as music or language. The same number of females showed the opposite asymmetry, and similar relationships were found for P200 and P400 although no asymmetries were noted in a second group of infants when tones were presented.
against white noise. Note that no task-dependent asymmetries were noted for these 3-month-old infants. (See also criticisms of this study by Molfese and Radtke, 1982, and reply from Shucard et al., 1982.) A later study on 6-month-old infants using the same paradigm suggested that by this age female infants were showing the same pattern of response as adults, whereas males still showed a R>L asymmetry regardless of condition.

The possibility that these effects are simply related to stimulus characteristics was not supported by a study by Thomas et al. (1980), who used identical stimuli, tones superimposed on music, for both a musical recognition and a counting task. The expected result, of larger AERs over the engaged hemisphere, was found.

The notion that using linked mastoids as reference will produce a pattern of results where smaller AERs are found over the presumably activated hemisphere has not been supported by a couple of other studies using this reference. For example, Butler et al. (1973; Butler and Glass, 1976) recorded the AERs from C3 and C4 to tone bursts while subjects were "at rest" or engaged in mental arithmetic. In a group of commissurotomy patients, it was found that doing arithmetic attenuated the AER over the left hemisphere but in a group of normals the only effect to reach significance was a larger negative component over the left hemisphere during this task. It should be noted however that a tendency for a positive component to be smaller at the same site for the arithmetic only just failed to reach significance. The study by Teyler et al. (1973; Roemer and Teyler, 1977) which has been discussed previously is also pertinent, insofar as the click-evoked N1-P1 amplitude during verbal tasks was found to be larger over the left hemisphere.
hemisphere.

In summary then, it appears that the probe technique may be of potential value provided that attempts are made to cope with the problems outlined earlier for EEG/EP methodology. It seems obvious that Cz is not the best reference for such studies and it would be of great interest to know if the apparently opposite effects of light probes and tone probes are still demonstrated if a noncephalic reference is used.

1.3.2.4 Contingent Negative Variations

Any consistently demonstrable asymmetries in the CNV would have great impact on psychological theories of hemisphere functioning. Two extreme positions could be adopted concerning hemisphere differences in function. On the one hand it could be maintained that the brain deals with each input purely on the basis of stimulus properties and that stimuli are inherently 'verbal' or 'nonverbal'. This 'data-driven' approach would be a very difficult position to defend, and much experimental evidence would argue against it. At the other extreme is the notion of 'hemisphericity', i.e. the idea that individuals can be characterised in terms of their predominant mode of processing into right- and left-hemisphere types. The right-hemisphere type would be characterised as artistic, creative, wholistic, intuitive and so on, whereas the left-hemisphere type would be characterised as rational, verbal, logical, scientific or a generally sequential processor of information. Thus stimuli are processed mainly
verbally or nonverbally regardless of stimulus properties. There is very little evidence to directly support such simplistic characterisations of left- and right-hemisphere function, let alone the 'hemisphericity' concept itself, and the main line of support for these ideas may well stem from the many popularisations of this area (e.g. Ornstein, 1972). Most neuropsychologists would probably adopt an intermediate position, whereby the brain can to a certain extent be 'primed' to process information in particular ways, but actual stimulus characteristics are still of great importance.

The CNV would seem to be an ideal tool to use in the investigation of priming effects. This slowly increasing scalp negativity would appear to be the perfect measure of the brain 'preparing itself' for input, and if task-related asymmetries could be demonstrated while the subject is waiting for a particular type of stimulus to be presented, this would be fairly conclusive proof of the priming hypothesis. Unfortunately, however, once again no clear overall picture has emerged with respect to these issues.

Before considering studies which have used the CNV paradigm to investigate cognitive variables, we shall first briefly consider those which have used this paradigm to study asymmetries in motor preparation, although other motor-related potential asymmetries will be discussed later (see Section 1.3.2.6). Brunia and colleagues in particular have made great use of CNVs in this area (Brunia, 1980a, b, c; Brunia et al., 1980, 1982; Brunia and Schiers, 1980; Brunia and Vingerhoets, 1980, 1981). To summarise this series of experiments, they generally involved a simple CNV design with a 50 msec tone as S1, a light as S2 and response to be performed within 400 msec. Electrode
placements were generally over central, parietal and sometimes frontal areas with linked mastoids reference. The studies found that for right-handers making right-foot plantar flexion responses to S2, the late wave of the CNV is, surprisingly, larger on the ipsilateral side, whereas for right finger movements the response is larger contralaterally, as one might expect given the contralateral cortical control of limb movements. A tentative explanation in terms of differing dipole orientations is proposed by the authors, but this hypothesis is not strengthened by the following three findings: (i) flexions of the left foot in right-handers leads to a greater CNV response contralaterally (e.g. Brunia, 1980a), (ii) left finger responses in right-handers are said to produce no asymmetry (Brunia, 1980a), and (iii) left-handed subjects show a contralateral preponderance in CNV amplitude regardless of which hand is used to respond (Brunia and Schiers, 1980), leading to the suggestion that perhaps both dipole orientation and cerebral dominance are important interactive factors in this issue. According to these investigators, the readiness potential (RP) shows a similar pattern of distribution to the CNV, but not as strongly, with the asymmetry for foot flexions failing to reach significance (Brunia and Vingerhoets, 1981). Contralateral predominance of RPs prior to finger flexions was very clearly demonstrated and, indeed, McCallum (1976) reports that the RP (or Bereitschaftspotential, BP) prior to finger movements is more lateralised than the CNV. McCallum and Curry (1979, 1980) also reported larger CNVs over the hemisphere contralateral to the responding hand in experiments involving large arrays of scalp electrodes referenced to either the mastoids or a non-cephalic
reference. S1 was either a high or low monaural tone which indicated that either an ipsi- or a contralateral response was required following S2, an intermediate tone. Besides the CNV asymmetry, as expected several AEP components were larger over the hemisphere contralateral to the ear of stimulation. It can be seen from these studies that response mode is a crucial factor in studies of EP hemisphere asymmetries.

A number of studies have claimed to demonstrate an asymmetry in the CNV with larger amplitudes being recorded over the presumably activated hemisphere. Butler and Glass (1971, 1974b, 1976) reported the results of a study of 13 subjects (one left-handed) in which CNVs were recorded from F3, F4, C3 and C4 referenced to ipsilateral mastoid. Stimuli were presented tachistoscopically with an interstimulus interval of 1.25 sec. S1 was a fixation spot and S2 was a numeral. The subjects' task was either (a) to add the numbers or (b) to report which numbers were missing from a previously presented series. A control task in which a digit 'zero' was continuously presented as S2 and subjects were asked simply to check that no other number was presented was also included. CNVs were reported to be larger and to start earlier over the left hemisphere for all conditions, except for the left-handed subject who showed opposite trends to the other subjects. This is not a particularly convincing demonstration as the so-called 'control' task showed the same asymmetry as the experimental tasks, although the authors attempt to account for this finding in terms of subject strategies.

More recently, Butler, Glass and Heffner (1981; Glass, Butler and Heffner, 1975) recorded CNVs from the same placements referenced to
linked mastoids in nine subjects. S1 was followed 2 sec later by S2 for the matching tasks employed, and the hands used to indicate match versus mismatch were varied across subjects. The first task involved presenting two faces and having subjects match for identity, whereas the second involved the presentation of words with subjects matching for meaning. Strangely, the 'CNVs' produced on the 'faces' task were actually positive, a fact which Butler et al. (1981) attempt to account for by pointing out that when S1 was a face, large P300s were produced, and hence the starting point of the CNV was more positive. The 'words' task produced greater negativity over both hemispheres, but especially over the left, and the left hemisphere was significantly more negative than the right for this task. There was a weak task x hemisphere interaction in the expected direction, but this was only significant for the frontal sites. The 'after-positive-wave' (APW) was also measured, defined as the mean amplitude between 250-1565 msec after S2, and hence including the P300. The APWs were larger for the 'faces' task and although no L-R asymmetries were significant, a weak task x hemisphere interaction was found suggesting larger APWs over the opposite hemisphere to that activated by a particular task. The authors tentatively suggest that this may indicate that the 'inappropriate' hemisphere treats the stimulus as having lower subjective probability. The authors do not feel that EOG and motor potentials could have artifactually produced these results.

The third study to have found larger CNVs over the presumably activated hemisphere is that of Rebert and Lowe (1981; Rebert, Lowe and Hatchel, 1979). They used five-letter words or four-dot patterns as stimuli (2 sec interstimulus interval) in match/mismatch tasks
requiring unimanual responses. Electrodes were placed over Broca's area and its right homologue and over the left and right angular gyri (linked mastoids reference). EOG was monitored. The parietal CNVs did not differ between the hemispheres for the verbal trials, but a R>L asymmetry was found for the nonverbal task. The expected pattern was found at the frontal placements. A negative transient evoked by S2 and a late post-imperative slow wave showed a similar pattern of lateralisation.

On the other hand, there are studies which have reported smaller CNVs over the presumably activated hemisphere. Marsh and Thompson (1973) recorded CNVs from T3, T4 and the left and right angular gyri (linked mastoids reference) while subjects performed a verbal and a nonverbal task. S1 was always a brightening of the fixation point which was followed 1380 msec later by S2. For the verbal task, S2 was a five to eight letter word in LVF or RVF. This was followed 2.5 sec later by a signal to the subject to report the word. In the nonverbal task, S2 was a line and the subject's task was to choose a line of the same orientation from an array. A strong RVF advantage was found on the verbal task but no differences in CNV amplitude between the hemispheres were found. However, preliminary results of a second experiment are reported in which trials were mixed, not presented in blocks as in the first experiment. These data suggested that fourteen subjects had shown smaller CNVs over the hemisphere primarily involved in a particular task, but only on those trials where a correct response was given. Marsh, Poon and Thompson (1976, Experiment II) present the results of an experiment using two groups of subjects. Group I had CNVs recorded from T3, T4 and left and right angular gyri,
whereas Group II had frontal instead of temporal placements. S1 was a red or green light which indicated whether a word or a slanted line would be presented for S2, 1.4 sec later. Subjects had to speak the word or point to a matching line on an answer slide, when signalled to do so by the fixation point being switched off 1.4 sec after S2. For both groups, larger potentials were recorded in the parietal region and the differences between conditions were largely confined to the right hemisphere. Although the authors report that L-R hemisphere differences were found only for correct answer trials, they fail to give the actual direction of the asymmetry. However, working on the assumption that if these results had directly contradicted their earlier report they would have reported this, it seems safe to assume that once more, smaller CNVs were recorded over the activated hemisphere. In the study by McCarthy and Donchin (1978; Donchin, Kutas and McCarthy, 1977) which has already been described (see Section 1.3.1.3), the Principal Components Analysis performed on their data revealed a component corresponding to the CNV. This component was larger over the left hemisphere for structural matching and over the right hemisphere for functional matching, supporting the notion of smaller CNVs over the activated hemisphere.

A large number of studies have failed to find any evidence of task-related CNV asymmetries. Poon et al. (1976) in their study described in Section 1.3.2.2 found no significant differences between hemispheres for either a simple reaction time task or a vowel-consonant matching task, although a trend towards a L>R asymmetry was noted for both tasks. Also previously described (in Section 1.3.1.3) is the study by Angeleri et al. (1982) which found
task-related asymmetries in alpha power, but not for CNV and P300 amplitude. The results of the study by Birbaumer et al. (1981) with respect to spectral power have also been described previously (Section 1.3.1.3) and we may note that slow cortical potentials showed no clear pattern although a late negative component did show task-dependent asymmetries, but only prior to easy tasks, not difficult ones. Brix and Burian (1973) present data from a study of nine dextrals and ten sinistrals with CNVs recorded from C3 and C4 (referenced to linked mastoids). S1 was an auditory word followed 1680 msec later by S2, a flash. It was reported that independent of whether presentation was monaural or binaural CNVs were symmetrical. This is not really surprising as CNVs are usually assumed to index preparatory processes with respect to S2, not processing following S1. It was also reported that if the subject focussed attention on one ear, CNVs were still symmetrical. Friedman et al. (1977) discuss a number of well-controlled but unsuccessful attempts to demonstrate lateral asymmetries in CNVs in their laboratory. Of particular interest in this area is the failure of Gazzaniga and Hillyard (1976; Hillyard, 1971) to demonstrate asymmetrical CNVs in four split-brain patients when S1 (a light flash) was confined to one visual half-field.

To conclude this review of CNV studies we shall discuss those studies which have demanded a spoken response immediately following S2. There is a great deal of overlap here with the following section on speech-related potentials, and many of the methodological issues discussed later apply with equal force to the CNV studies. The motivation behind many studies of speech-related potential asymmetries is to provide a safe noninvasive alternative to the Wada
carotid-amytal test, but it has to be admitted that so far this objective has not been achieved. Low et al. (1973, 1976) recorded CNVs from F7, F8, T3, T4, Cz and T1 and T2 (defined as half the distance from the tragus to F7 and F8) using a contralateral ear reference. S1 was a flash, S2 a tone and interstimulus interval was 1.4 sec. The subjects' task was to emit a verbal response (either 'hi', or the subject's Christian name) following S2. Of 11 epileptic patients of known cerebral dominance, it was found that for 10 of them, a larger CNV was recorded over the dominant hemisphere. Of 22 normals tested, there was a significant correlation between CNV asymmetry and presumed language dominance. An updated report (Low and Fox, 1977) stated that these findings also applied to a group of normal children, but attention was drawn to methodological problems with the technique, such as EOG contamination. Within subjects, there was considerable variability both in direction and degree of asymmetry, and the investigators took 'the most consistent left-right relationship' over the two conditions (each used twice) to determine language dominance.

Pinsky and McAdam (1980) used the same electrode placements in a fairly similar study which produced very different results. S1 was the onset of a 1000 Hz tone, and S2 was its offset 1.45 sec later. The task conditions required either no response, a bimanual button press response or a vocal response. For the vocal response, subjects were required to produce the same multisyllabic response (beginning with /p/) although a choice of words was offered at the start of each experiment, to ensure that none of the five stutterers would have great difficulty in articulation. No trials involving poor articulation were included in the averages. The statistical analyses
presented with this report contain several very basic errors, including incorrect usage of t-tests and incorrect associated degrees of freedom. However, even examining the data in a purely qualitative manner, it is apparent that all five stutterers showed a larger CNV over the left hemisphere for the vocal task, whereas no consistent direction of asymmetry was found for the five normal controls. Pinsky and McAdam do point out that their study did differ in several possibly important respects from Zimmerman and Knott's. Unfortunately, such ad hoc explanations are all too easy and efforts are rarely made to test such 'explanations' experimentally. Pinsky and McAdam's results with respect to alpha asymmetries have already been presented, and their results with respect to speech-related RPs are presented in the following section.

Zimmerman and Knott (1974, 1976) compared the CNVs of stutterers and normals recorded from left and right inferior frontal lobes and vertex referenced to linked mastoids. Three conditions were employed: (i) a control condition in which S1 was a high or a low tone and S2 was a flash. The subjects' task was to press a key after S2 if S1 was high; (ii) an 'expectancy' condition in which S1 was a visually presented word and the subjects' task was to indicate, by pressing one of two keys following S2 (light flash) whether or not he thought he would stutter if he read the word; (iii) a 'verbal response' condition in which the subject did not press a key but actually read the word. Vertex CNVs were similar for both groups. However, preceding speech four out of five normals showed a L>R asymmetry, whereas only one out of nine stutterers showed this pattern. Similar results were also found in the 'expectancy' condition.
On the other hand, at least three studies, in addition to Pinsky and McAdam's (1980) results for normals, have failed to find any correlation between CNV asymmetry and language dominance. Curry et al. (1977) used placements at left and right inferior frontal areas, T1 and T2, and vertex (referenced to either linked or contralateral mastoids) and employed three recording conditions: (i) TONE - LIGHT - KEYPRESS; (ii) WORD - ??? - KEYPRESS; (iii) WORD - ??? - SPEAK WORD. The 'WORD' and '???' stimuli were presented on a TV monitor and interstimulus interval was 1.5 sec. After six subjects had each been tested on four weekly occasions the investigators concluded that, "The data do not offer any uncompromising evidence for hemispherical differences in CNV amplitude attributable to preparation for speech".

In a similar study by Michalewski et al. (1977) nine males and nine females, all dextral, were studied under four conditions: (i) TONE - CLICK - KEYPRESS; (ii) WORD - TONE - SPEAK WORD; (iii) TONE - WORD - SPEAK WORD; (iv) WORD - TONE - SPEAK ASSOCIATED WORD. Words were presented via a TV monitor and CNVs were recorded from Cz, F3, F4, Broca's area and its right hemisphere homologue (linked mastoid reference). Although several subjects showed some asymmetrical activity in some of the word conditions no consistent lateralisation effects were found over the left hemisphere prior to vocalisation.

Finally, House and Naitoh (1979) compared the CNVs of ten normal subjects and ten subjects who were deaf since birth, recorded from Broca's area, its right hemisphere homologue and Cz, referenced to linked mastoids. A variety of different S1 and S2 stimuli and required responses were involved providing different combinations of manual and oral, verbal and nonverbal conditions. (L-R) voltage differences for
verbal conditions were subtracted from (L-R) corresponding nonverbal conditions to eliminate asymmetries not specific to verbalisation, such as glossokinetic potentials, extracranial EMG effects and response-related effects. Lateral-frontal slow potential shift asymmetry did not correlate with hemisphere language dominance. The authors suggest that this may be due to the explicit control of horizontal eye movements and the suppression of electrodermal activity via atropine iontophoresis which was employed in this study.

To summarise this section, it is obvious that CNVs have so far not proved to be as useful in hemisphere function studies as might have been hoped. Studies are almost equally divided between those that find no task-related CNV asymmetries (Brix and Burian, 1973; Poon et al., 1976; Friedman et al., 1977; Angeleri et al., 1982; Gazzaniga and Hillyard, 1976) and those that do report such asymmetries. Of the latter group, half report larger CNVs over the activated hemisphere (Butler and Glass, 1974b; Butler, Glass and Heffner, 1981; Rebert and Lowe, 1981) and half report smaller CNVs over the activated hemisphere (Marsh and Thompson, 1973; Marsh et al., 1976; McCarthy and Donchin, 1978). It is possible that all these patterns of asymmetry and symmetry are genuine reflections of the underlying psychophysiological processes involved but if this is the case, greater effort is required in making explicit the conditions which will produce each pattern. Several studies have reported asymmetries of CNVs when a unilateral response is required following S2, and some interesting differences in patterns of CNVs have been noted (e.g. Brunia, 1980a). With respect to CNV asymmetries preceding speech, once again there is controversy, with some studies finding asymmetries which correlate with language.
dominance (Low et al., 1973, 1976; Low and Fox, 1977; Zimmerman and Knolt, 1974, 1976) and others finding no such correlation (Curry et al., 1977; Michalewski et al., 1977; House and Naitoh, 1979). It is at present impossible to say if the asymmetries which have been reported in CNV studies are simply due to artifacts such as EOG or if they represent genuine neuropsychological phenomena. However, several of the sources of artifact discussed in the next section on speech-related potentials are of great relevance to speech-CNV studies.

1.3.2.5 Speech-Related Potentials

Besides those studies reviewed in the previous section which used the CNV paradigm in investigating motor preparation for speech production, many attempts have been made to study speech potentials by time-locking data collection to the actual speech act. The methodological complexity of this work is considerable, the major issues being the appropriate triggering event and the innumerable potential sources of artifact. With the benefit of hindsight it is perhaps not surprising that the search for speech-related analogues of the readiness potential (RP; also known as the Bereitschaftspotential, BP), pre-motion positivity (PMP) and motor potentials (MP), should be a difficult task. The act of speaking necessarily involves the use of head muscles in close proximity to the very electrodes used to record the EEG signals of interest. Speaking also tends to be in phase with respiration, which, as Grözing and colleagues (1973, 1975, 1976,
1977, 1980) have demonstrated, means that speech-related cerebral potentials would often be confounded with R-waves (see below). Glossokinetic potentials produced by movements of the tongue are another potential source of artifact to be considered. To date, as will be shown, no unequivocal demonstration of lateralised speech-related potentials has been presented despite claims to the contrary, but at least our understanding of the criteria such a demonstration would have to fulfil has been deepened.

The search for cortical 'command potentials' associated with speech production began fifteen years ago. Ertl and Schafer (1967) compared averaged brain potentials recorded from C4 (reference undeclared) preceding 100 voluntary contractions of the fist and also 100 repetitions of the word 'tea'. EMG was used to trigger averaging in the former case and a microphone in the latter. They claimed that "command potentials" preceded each act as demonstrated by a positive peak extending from 170-70 msec prior to the act followed by a negative peak at 50-10 msec. Schafer (1967) presented data recorded from himself (C4-A2, T5-A1) while repeating 'T', 'O' and 'P' fifty times each, claiming that different waveforms were elicited for different spoken letters. Ironically, gross differences in morphology of waveshape were to be taken by Szirtes and Vaughan (1977) as evidence against the neural origin of such waves. A foretaste of future developments was provided by Ertl and Schafer's (1969) "Erratum", in which they pointed out that since their original publication they had noted low frequency myogenic or movement artifacts originating from upper lip musculature contaminating EEG preceding speech, making their previous results equivocal.
McAdam and Whitaker (1971a) claimed to have provided the "first
direct physiological evidence for localisation of language production
functions in the intact human brain". They had recorded from
placements over left and right precentral gyri and left and right
inferior frontal areas (LIF, RIF), presumably overlying Broca's area
and its right hemisphere homologue (reference: linked mastoids).
Attempts were made to control for eye movements, swallowing and body
movements by having subjects adopt a "neutral position" prior to each
self-paced speech act. The airburst recorded from a voice trigger was
used to initiate a two second sweep for each of four verbalisation
conditions: (i) a "spitting" gesture, (ii) generating different
three-syllable words beginning with 'k', (iii) a "coughing" gesture
and (iv) generating different three-syllable words beginning with 'p'.
These conditions were chosen with the intention of having verbal and
nonverbal analogues of the same "p" and "k" sounds. However, it is
unfortunate that while the verbal conditions involve the generation of
new responses for each trial, the nonverbal conditions involve the
repetition of a standard response as it is well known that habituation
effects occur for ERP phenomena. Although the data for three of the
eight right-handed female subjects had to be rejected because of
artifacts, the remaining subjects showed a localised negativity over
the left frontal placements prior to and peculiar to speech
production. Morrell and Huntington (1971) severely criticised this
study on methodological grounds and pointed out that they had been
unable to replicate McAdam and Whitaker's findings in a study of six
subjects. McAdam and Whitaker (1971b) replied to these criticisms, and
claimed that the reason that the attempted replication by Morrell and
Huntington (1971) had failed was because of important methodological differences between the two studies.

One of the criticisms which Morrell and Huntington (1971) had levelled at McAdam and Whitaker (1971a) had been the latter's use of a microphone to trigger data collection, but they presumably changed their views on this as they used the same trigger themselves in a later study (Morrell and Huntington, 1972). In this investigation they had twelve subjects engage in a variety of speech acts, including self-paced repetition and speaking in response to a tone cue, while EEG was recorded from Broca's and Wernicke's areas (and right hemisphere homologues), right and left Rolandic placements, T3, T4, Cz, Pz and Oz (referenced to either single or linked ears). EMG was recorded from the lower lip, larynx, jaw and sometimes tongue, and EOG was usually monitored. The authors maintain that a negative-going wave starting 200-500 msec prior to speech onset and peaking 10-200 msec prior to phonation, is probably of cerebral origin. They state that, "Hemispheric differences were not marked in the majority of cases; however, when such differences were noted, it was commonly observed that left hemisphere potentials were larger than those from homologous sites on the right". Morrell and Huntington's claim that the observed potentials have cerebral origins is based primarily upon the observation that the scalp-recorded potentials follow a different time-course than the integrated EMG records. However, given that different bandpasses were used for each type of data and that the act of integration itself would introduce a considerable delay, this argument is not very convincing.

Grabow and Elliot (1974) attempted to replicate McAdam and
Whitaker's (1971a) study using 14 subjects (11 dextral) and paying particular attention to sources of experimental error such as calibration errors and sensitivities of amplifiers and write-out systems. They reported "wide variability both between and within subjects, without visually apparent hemispheric electropotential lateralisation before, during or after verbalisation". This study did show that the glossokinetic potentials could produce clear asymmetries in scalp-recorded potentials if the subjects were instructed to move their tongues laterally during the repetitions. They suggest that perhaps they failed to replicate McAdam and Whitaker's (1971a) results because the latter study was more contaminated by artifacts, or even that perhaps the inputs to McAdam and Whitaker's computer might have been "inadvertently interchanged" or that "mislabelling occurred in the report of their work". Another possible reason for the discrepancy between the two studies is that Grabow and Elliot (1974) had subjects repeat the same word, whereas McAdam and Whitaker (1971a) had subjects generate different words for each trial.

A series of methodologically sophisticated studies have been reported by Grözinger et al. (1973, 1975, 1976, 1977, 1980), in which a great variety of experimental conditions have been employed, including word repetition, sentence production, humming (i.e. phonation without articulation) and articulatory movements without phonation. Potentials have been recorded from bilateral placements (over speech areas on dominant side) and vertex, referred to linked mastoids, linked ears or a noncephalic site. Nose respiration has been recorded using a thermocouple, along with EOG and GSR. Both EMG from orbicularis oris and onset of phonation as indicated by a throat
microphone have been used to trigger data collection, although it was noted that large latency differences existed between the two, and Grözinger et al. (1975) state that the phonogram should not generally be used as it will not allow a reliable interpretation of brain potentials preceding speech. Particular attention is paid to two types of potential. The first is a low frequency wave-like potential with a high correlation to respiration, which they call the R-wave. It is not too surprising to find that in word-repetition experiments the R-wave tends to be in phase with word production. Grözinger et al. conclude that the R-wave is probably of cortical origin by excluding all of the following artifactual sources as causes: GSR, electrical field artifacts, head movements, EMG, eye blinks, glossokinetic potentials, position of the reference electrode and varying time constants. The R-wave is often larger over one hemisphere than the other, with the side showing the less pronounced wave also showing alpha- and theta-blocking. Occasionally, it is phase-reversed between hemispheres. Grözinger et al. (1976) expressed the view that "these hemispherical differences might be a bioelectric correlate of hemisphere dominance", but Grözinger et al. (1977) regretted that, "As yet, however, we cannot predict hemisphere dominance for speech from our results". The GSR does correlate slightly with the R-wave, but not enough to completely account for it, and Grözinger et al. (1977, 1980) are very critical of investigations which fail to monitor either. In particular it is pointed out that as large asymmetries in R-waves can exist between the hemispheres as much as seven seconds prior to speech production, the use of small sweep times can produce very misleading conclusions. "BP-like" potentials are superimposed upon the R-waves,
but these are more complex than the motor-related potentials seen for limb movements, beginning up to two seconds prior to the speech act. These too seem to demonstrate hemispheric asymmetry, but not consistently, and can sometimes even be positive instead of negative. Whether these "BP-like" waves are of cerebral origin is, according to Grözinger et al. (1980) still a controversial issue, with the glossokinetic potentials, posing particular problems of interpretation.

Szirtes and Vaughan (1977) present further evidence which they claim suggests that speech-related potentials represent activity of solely extra-cranial origin or are heavily contaminated by such activity. They employed a variety of conditions involving speech, non-speech and non-articulatory movements, using 18 subjects (15 dextral). Twelve subjects wore the 'standard array' of electrodes, i.e. Broca's area and Wernicke's area, plus right hemisphere homologues, referenced to linked ears. The remainder underwent 'detailed mapping' involving additional placements on nose, cheek and cranial sites and a variety of references including a noncephalic site. EMG was recorded from lips, tongue and larynx and sampling was triggered by sound onset detected by a microphone close to the mouth, which they claimed was the most reliable method. They noted great variability in the scalp-recorded potentials, with activity often starting up to one second prior to the phonogram. Asymmetries were often seen in the antecedant slow waves and phasic components, but not in any consistent direction. They interpret their results in terms of extra-cranial contamination mainly because of three lines of evidence: (a) the occurrence of substantial changes in speech-related potential
morphology with different utterances, (b) the distribution of speech-related potentials with maxima overlying the lower face and polarity inversions across the oral region for some speech sounds, and (c) similarities in form and distribution between speech-related potentials and non-vocal movements of the speech musculature.

Levy (1977) used eight subjects, each of whom was highly trained in order to avoid artifacts, in another attempt to replicate McAdam and Whitaker's (1971a) study in a methodologically sound manner. He did not actually include a word-repetition condition however, because he hypothesised that a crucial aspect of left hemisphere function was phonological complexity, not necessarily related to meaningful stimuli. He employed six conditions: (i) repeating a single 'huff' ("h") sound, (ii) repeating a single 'puff' ("p") sound, (iii) repeating a single syllable ("pa"), (iv) repeating a multiple 'huff' sound ("h-h-h-h"), (v) repeating a multiple 'puff' sound ("p-p-p-p") and (vi) repeating a multisyllabic nonsense word ("patapute"). Backwards averaging from an airburst trigger was employed for four sites (Broca's area, its right hemisphere homologue and right and left Rolandic sites), and EOG and mouth EMG were recorded thus allowing analysis of both "uncorrected" signals and signals "corrected" for EOG/EMG contamination. Reliable hemisphere differences were found for slow potential activity with, as hypothesised, a L>R negativity for complex phonological acts. Levy presents a detailed discussion of his painstaking attempts to deal with potential sources of artifact but even then prefers to explicitly refer to 'scalp-recorded potentials' in preference to 'brain potentials' being aware of "the possible subtlety of confounds or the number of muscles of the head that might
remain unmonitored", (Levy, 1980).

Pinsky and McAdam (1980), in their series of experiments comparing a group of five stutterers with five normal controls, examined RPs elicited by vocal and bimanual voluntary responses. The details of procedure are similar to those presented in the previous section describing the CNV comparisons performed by these investigators. Data collection was triggered by the air-burst from the initial plosive for the vocal response. Once again the statistical analyses reported are not valid, although the authors do note that for all ten subjects there was a relatively greater negativity at LIF than at RIF in the speech condition.

Brooker and Donald (1980a, b) also attempted to replicate the original McAdam and Whitaker (1971a) study with appropriate control of sources of artifacts such as eye movements, blinks, body movements, anticipatory lip, jaw and facial movements and facial tension. An electrode was placed on the cheek (G1) to record glossokinetic potentials and care was taken to avoid R-wave contamination. No significant hemisphere asymmetries were found but a significant correlation was found between activity at left and right frontal and central placements and G1 activity, suggesting that these sites were contaminated by glossokinetic effects. At the vertex, apparently, uncontaminated speech RPs could be recorded. A second experiment was carried out to find out what contribution the major articulatory muscles make to waveforms recorded at EEG sites by recording from additional muscle sites and testing for correlations with EEG signals. Responses of the temporalis and masseter muscles as well as the tongue were found to correlate with EEG at specific latencies prior to speech.
suggesting that no part of the EEG record was free from myogenic
confounds". Any significant differences in terms of EEG between speech
and nonspeech conditions were subsequently eliminated by covariance
analysis, using selected muscle channels as covariates.

Finally, Empson (1982) had 24 subjects, equally divided between
males and females, sinistrals and dextrals, perform one of two tasks
while EEG was recorded from C3, C4, F3 and F4 referenced to linked
mastoids. One group had to repeat the same word ("yes") 25 times,
while the other group had to generate words beginning with each letter
of the alphabet in turn. Sampling was triggered "by speech sound", and
no attempt was made to record EOG, EMG or any other potential source
of artifact. The investigator attempted to eliminate 'occasional'
artifacts by rejecting averages if their 95% confidence interval
exceeded 10 microvolts. Analysis was based upon the average potential
for each of four 200 msec blocks prior to vocalisation. The report
claims that ANOVAs performed for each block reveal that a negativity
developed earlier preceding the generation of novel responses in
comparison to repetition and that this negativity was greater
frontally. For the 400 msec prior to a response the negativity was
larger on the left for right-handers and on the right for
left-handers, and, as one might further expect, the lateral asymmetry
was greater for dextrals. Higher order interactions revealed that the
asymmetry was found centrally for males and frontally for females.

This report is open to many criticisms, including the following.
Firstly, the important issue of regularly recurring artifacts is
glossed over by Empson, who writes, "As Brooker and Donald (1980) have
pointed out, slow potentials preceding speech may...occur at the same
time as activity in the pharynx, but not be caused by it". This is perfectly true of course, but the obvious main thrust of Brooker and Donald's (1980a, b) argument is that one cannot simply assume that asymmetries recorded at the scalp are genuine reflections of cortical activity. Indeed, they themselves found asymmetries which only became nonsignificant using covariance analysis and data from selected muscle channels as covariates. Secondly, no reasons are given for the strange choice of tasks in this study. No non-speech control task was employed for comparison purposes. Furthermore the two tasks differed in obvious ways to which Empson does not refer. Simple repetition could lead to habituation effects, whereas generating new words would not. On a methodological point, sampling was triggered "by speech sound" which is a good way to ensure that sampling will begin from a variety of latencies with respect to articulation for the word generation task, given the range of voice-onset times for words starting with different letters. Thirdly, Empson claims that it is "unlikely that myogenic artifacts should be differentially affected by...handedness". Five years earlier Szirtes and Vaughan (1977) had, on the other hand, pointed out that "consistent lateralization of extracranial shifts preceding speech could conceivably be correlated with handedness, but not directly reflect cortical activity". It is certainly far from inconceivable that a subject variable such as handedness which is based on a motor asymmetry, could also lead to asymmetric artifacts in EMG. Finally, Empson presents only grand average waveforms and makes no attempt to account for the fact that these bear little resemblance to those found in previous studies.

Fifteen years on from the first study in this area we must still
conclude that no unequivocal demonstration of speech-related potential asymmetries has been forthcoming. It is fitting to conclude this section with a quotation from Brooker and Donald (1980a):

"The muscular activity of the vocal apparatus is an inevitable part of the act of speaking, therefore the presence of large myogenic potentials is unavoidable in the study of speech potentials. They are not merely an artifact to be controlled in the normal sense, by simple elimination or by subtraction; they are an integral part of the problem of recording lateral scalp potentials during speech. This is not to say that the problem of recording 'speech potentials' from the brain is unsolvable, only that the form of an adequate solution is not obvious".

1.3.2.6 Movement-Related Potentials

No attempt will be made here to review the large number of studies which have addressed the issue of movement-related potentials, but investigators searching for asymmetries of cortical potentials related to cognitive factors should at least be aware that they exist as a possible confound. Following the terminology of Deecke and Kornhuber (1977), cerebral potentials related to the initiation of voluntary movement are often categorised as follows:

(a) Bereitschaftspotential (BP) or Readiness Potential (RP) is bilaterally distributed prior to unilateral and bilateral movements and consists of a surface negativity starting about 800 msec prior to
the EMG.

(b) Pre-Motion Positivity (PMP) is also bilateral and widespread and occurs in about two out of three subjects, at between 90 and 80 msec prior to the EMG. Deecke and Kornhuber (1977) believe that this component may correspond to the actual command for movement following the general preparatory stage which was indexed by the BP.

(c) Motor Potential (MP) is usually unilateral and for finger movements occurs 60-50 msec prior to the EMG. It may correspond to the actual discharge of neurons.

With respect to hemispheric asymmetries in these potentials a rather confusing picture emerges. Concerning BPs and MPs recorded from precentral sites Deecke and Kornhuber (1977) state that BPs show a "larger potential at the contralateral motor cortex" and that "the negative MP is restricted to the contralateral precentral area". They then totally contradict these statements by stating that "both the BP and MP are significantly larger over the dominant hemisphere in right-handed individuals (irrespective of whether the movements of the contralateral or ipsilateral hand are under consideration)" and no significant hemisphere differences are found for left-handers. Not surprisingly many different patterns of hemispheric asymmetry (or lack of it) have been reported (e.g. Vaughan et al., 1968; Deecke et al., 1969; Shibasaki et al., 1980, 1981) especially when handedness has been considered (e.g. Kutas and Donchin, 1974, 1977, 1980; Kristeva and Deecke, 1980; Papakostopoulos, 1980; Bashore et al., 1982; studies by Brunia et al., reviewed in Section 1.3.2.4). These differences are probably a reflection of complex interactions between such factors as techniques used, electrode placements and required
movements.

Although it is difficult to present a clear summary of this area it behoves the investigator to control for the possible asymmetric potentials which could be produced by unilateral movements unless movement-related potentials are themselves of primary interest. Such control can be achieved by (i) ensuring that any unilateral responses are counterbalanced across subjects and/or conditions, (ii) ensuring a suitable interval between data collection and response, or (iii) avoiding overt responses altogether while EEG is being sampled.

1.3.3 Anatomical Asymmetry

Up to about twenty years ago it was generally believed that even if anatomical asymmetries did exist between the hemispheres, they were too small to be of any functional significance (von Bonin, 1962), although the existence of certain asymmetries had been documented since the last century (e.g. Cunningham, 1892; Eberstaller, 1890). In recent years, however, there has been a dramatic change of opinion on this issue, probably dating from Geschwind and Levitsky's (1968) clear demonstration of left-right asymmetries in the planum temporale. This section will consider the anatomical asymmetries between the hemispheres that have been reported to date and consider their implications for EEG studies. The reader is referred elsewhere for more detailed reviews (Geschwind, 1974; LeMay, 1976; Galaburda et al., 1978).

In Geschwind and Levitsky's (1968) classic study, they chose to
examine an area of the cortex, the planum temporale, which from clinical experience would be expected to be implicated in cerebral functional asymmetry. They found the planum temporale to be larger on the left in 65 of their sample of 100 brains, and larger on the right in only 11. Furthermore, the left planum was found to be one third larger than the right planum. These findings have been directly confirmed by many other studies (Wada, 1969; Teszner, 1972; Witelson and Pallie, 1973; Kopp et al., 1977; Falzi et al., 1982). Other investigators have found asymmetries in the posterior region of the Sylvian fissure that give indirect support to Geschwind and Levitsky (Rubens et al., 1976; Yeni-Komshian and Benson, 1976). Studies using arteriographic techniques (LeMay and Culebras, 1972; Hochberg and LeMay, 1975; Ratcliff et al., 1980) add yet further support. These differences have been found in infants (Wada et al., 1975; Witelson and Pallie, 1973) and even primates (LeMay and Geschwind, 1975).

Rubens (1977; Rubens et al., 1976) demonstrated the asymmetries between the left and right Sylvian fissures in a very graphic manner. Left lateral and right reversed lateral photographic slide projections of 36 adult human brains were superimposed. The sulci and fissures of each hemisphere were separately traced and the results showed that in 25 of the brains the right and left Sylvian fissures follow similar courses until the right fissure angulates sharply upward into the inferior parietal area, while the left one continues posteriorly. This means that on the right there is a shorter planum temporale, a smaller parietal operculum, a higher Sylvian point and a compensatory expansion of the inferior parietal region posterior to the lateral fissure.
What then are the implications of these anatomical asymmetries for EEG studies? Current opinion tends to support the idea that these gross morphological differences around the temporal auditory cortical regions underlie the lateralisation of function between the hemispheres. This may or may not be so. It has been frequently pointed out that the proportion of persons with right hemisphere control of language is smaller than the proportion with a larger planum on the right. However, a natural consequence of the assumption that anatomical and functional asymmetry are related has been that EEG investigators have tended to place their active electrodes at homologous sites with respect to 10-20 system, over the temporoparietal areas, when searching for task-related asymmetries in EEG. Unfortunately, as Rubens (1977) points out, "Electrodes placed midway between temporal and parietal locations (10-20 system) so that they overlie Wernicke's area (Matsumiya, Tagliasco, Lombroso, and Goodglass, 1972; Morrell and Salamy, 1971) may be suprasylvian in some left hemispheres but infra- and/or retrosylvian in most right hemispheres. The greater upward inclination of the right posterior sylvian fissure may also affect recordings because a considerable plate of intrasylvian auditory association cortex assumes an almost vertical orientation in many right hemispheres". Most of the studies reporting asymmetries have found them in this region (T3/T4, P3/P4, T5/T6). Such homologous electrode pairs are overlying areas of cortex which are not anatomically equivalent even in gross terms, without considering the possible complicating effects of asymmetries in cytoarchitecture (Galaburda and Geschwind, 1980; Gur et al., 1980) and neurochemistry (Gainotti et al., 1982).
Differences in gross anatomy have been reported between different handedness groups (see Witelson, 1980, for an excellent review) and the sexes (see McGlone, 1980, for a general discussion), supporting the notion that sinistrals and females are not as strongly lateralised as dextrals and males. This does not, of course, help us to decide whether or not EEG asymmetries reflect functional asymmetry, or simply structural asymmetry.

Other areas have been reported to be asymmetric. Wada et al. (1975) found that the left frontal operculum (part of the anterior speech region) was somewhat smaller than that on the right. This would seem to contradict those who infer functional superiority from size, but Falzi et al. (1982) claim that when they measured both extrsulcal and intrasulcal cortical areas, a L>R asymmetry emerged. When they considered only that part of the cortex visible on the surface, they found no difference interhemispherically. It is difficult to assess what effects these complex gyral patterns could produce in EEGs.

LeMay (1977) demonstrated that asymmetries also exist between the occipital and frontal poles of the cerebral hemispheres, asymmetries which are reflected in local impressions upon the skull known as "petalias". LeMay noted the presence of left occipital petalia in 69% of her 158 right-handed subjects, but only 9% showed right occipital petalia. Frontal petalia on the right was observed for 30% of the sample, and on the left for 7%. Furthermore, in the occipital region 64% showed wider left hemispheres and 16% showed wider right hemispheres. For her 62 left-handed subjects, a similar pattern of petalia distribution was found, but the pattern with respect to occipital width was reversed. Chang Chui and Damasio (1980) replicated
these findings with respect to petal distribution. Almost all studies reporting more alpha activity over the right than the left hemisphere during "resting" have used occipital placements. It seems at least possible that this is related to the anatomical asymmetry in some way, perhaps because of different orientations of the occipital cortices.

The issues are further complicated by the fact that strict localisation of function within the hemispheres is probably not a tenable position anyway. Bogen and Bogen (1976) point out that Wernicke's area does not in fact occupy a well-defined area but varies from textbook to textbook. Whitaker and Selnes (1976) and Whitaker and Ojemann (1977) have also discussed this issue, and Ojemann (1979; Ojemann and Whitaker, 1978; Ojemann and Mateer, 1979) has shown by stimulation mapping during craniotomies that the variation between actual brains in terms of language function possibly even exceeds that between textbooks. Given that this is the situation, it is best to adopt a "probability distribution" approach and simply hope that in most subjects the active electrodes actually do overlie the target area. However, it is as well to be aware of this additional complication.

It is sometimes argued that the investigator need not worry too much about the underlying cortical anatomy as the EEG is too gross to show any significant differences between signals recorded from points which are close together. If this is the case, the use of EEG as a research tool is severely limited in terms of furthering our knowledge of neuropsychology, and furthermore, many claims put forward on the basis of EEG studies would have to be retracted. However, a
consideration of the literature would suggest that this argument is not valid. Multichannel studies (e.g. Lehmann, 1971; Giannitrapani, 1979a) support the idea that even fairly closely spaced electrodes can show very different patterns of EEG.

The implications of anatomical asymmetries for EEG studies should have been recognised at least since Geschwind and Levitsky's demonstration. In fact, it appears to have been Rubens (1977), almost a decade later, who first spelt out the fact that anatomical asymmetries pose a very difficult problem for the investigator wishing to study asymmetry of function using EEG techniques. Since then, others (Calin, 1979; French, 1980; Beaumont, in press) have repeated the warning, but so far there has been no real attempt to deal with the problem. The investigator faces a dilemma. Either he can limit his placements to areas that, so far, we have no reason to suspect of being asymmetric, and thus he will be unable to record EEG from the areas of greatest interest; or he can place his electrodes over areas of known asymmetry and be unsure whether any effects he may find reflect inter- or intrahemispheric differences. The only other alternative is to face the problem by attempting to take the asymmetries into account. It would be ideal if one had independent knowledge of the underlying cortical structure of each subject, but so far there is no cheap and efficient method to obtain such knowledge. Another approach would be to attempt to detect the location of asymmetric features by using the EEG measures themselves, prior to studies of task-related effects which would take the position of the asymmetric features into account. This issue is addressed further in Chapter 5.

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1.4.1 Coherence Analysis

Within the last ten years a form of analysis originally used by engineers has been growing in popularity among EEG investigators. This is coherence analysis. A review of work involving the use of coherence analysis to study hemisphere asymmetries is presented in the next section but first a brief discussion of the nature of coherence will be presented. For more detailed discussions see Walter (1963), Shaw and Ongley (1972), Orr and Naitoh (1976), Glaser and Ruchkin (1976), Beauchamp and Yuen (1979) and Shaw (1981). An excellent general introduction to Fourier analysis is provided by Stuart (1961).

Nowadays most EEG research involves the digitisation of the on-going EEG, a procedure which, thanks to the advent of inexpensive mini- and microcomputers, even small laboratories can achieve with ease. The stored signals may be averaged if the experimental procedure involves the examination of averaged evoked potentials, but if coherence analysis is to be performed, techniques of spectral analysis are applied to the data after only limited preprocessing (although Davis and Wada have employed coherence analysis in investigating VEPs and AEPs; see Chapter 3). The other major breakthrough with respect to the increased availability of spectral analysis techniques was the rediscovery in 1965 of a fast computational procedure which permitted the calculation of Fourier coefficients of discrete periodic functions in an economic way (Cooley and Tukey, 1965). This is the famous Fast Fourier Transform (FFT; see Bergland, 1969; Dumermuth and Keller, 1973).

One of the simplest ways to study the relationship between two
time-series of any sort is to calculate the cross-correlation function. This involves measuring the correlation between the whole pattern of amplitude fluctuations in the two signal epochs being compared, as a function of the temporal displacement (delay) between the signals. In this way, if the two signals in fact have a very similar form except for one being delayed by a certain interval with respect to the other, their similarity can be deduced by examining the cross-correlation function. If there is a maximum correlation approaching unity at a particular delay, then that delay corresponds to the interval between the two time-series. This can obviously be very useful if one is considering travelling-wave phenomena (see Chapter 5). Also, any shared periodicity between the two signals will be reflected by a series of peaks in the cross-correlation function having the same frequency as that shared periodicity.

The coherence function differs from the cross-correlation function in that it measures the similarity between two signals as a function of frequency, not as a function of delay. Time differences may however be obtained as a function of frequency by computing the phase spectrum. Both correlation coefficients and coherence have maximum values of one, indicating exact correspondence of the two data sets being considered, but unlike a correlation coefficient, coherence cannot have a negative value. For both measures zero implies no relationship between the two data sets.

Shaw (1981) illustrates the concept of correlation as a function of frequency by a consideration of analogue selective filters centred on different frequencies. If the two signals under consideration are each filtered, using the same filter, prior to calculating the
cross-correlation function, it can be seen that the maximum correlation and appropriate delay will vary depending upon the central frequency of the filter. By passing the signals through a bank of filters varying in central frequency a cross-correlation spectrum could be built up. Shaw points out that if the bandwidth of the filters were vanishingly small, then the outputs from the filters would always be sine waves at the filter frequency (or nothing at all) and this would lead to a cross-correlation of one regardless of whether in fact any relationship did exist between the two signals. However, as selective filters do have an appreciable bandwidth, more meaningful results would be obtained.

It has already been pointed out that nowadays digital methods are much more common than analogue methods. Digital spectral analysis involves the Discrete Fourier Transform (DFT), which, while very similar to the continuous Fourier transform (Stuart, 1961), does exhibit several differences resulting from the constraint that the DFT must operate on sampled waveforms defined over finite intervals. Any complex signal may be synthesised by the addition of component sine waves of different amplitudes and phases, with the consequence that any waveform may be represented by amplitude and phase spectra. A signal can also be represented by sine and cosine spectra due to the fact that any sine wave can be represented as the sum of two sine waves of the same frequency and amplitude as each other, but 90 degrees out of phase (hence, sine and cosine). Digitisation requires the signal to be represented by amplitude samples obtained at appropriate time intervals. If the epoch length is $T$ seconds, then the maximum signal resolution will be into bands $1/T$ Hz wide, with the
lowest frequency being centred on a value of 1/T Hz. The highest discernible frequency, commonly known as the Nyquist frequency, is given by f/2, where f = sampling frequency.

The autospectrum reflects the amount of activity at a specific frequency band. This can be computed by multiplying the raw data by the cosine, and independently again by the sine, for the frequency of interest. The averaged product of the raw data and cosine is known as the cosine coefficient of the finite DFT, and that of the raw data and sine, the sine coefficient. The actual autospectral value is arrived at by squaring and adding the respective sine and cosine coefficients. Spectrum intensities estimated from these coefficients are very unstable and therefore the raw spectrograms are very rarely considered. However the degrees of freedom associated with an estimate can be increased by averaging over adjacent frequency bands or over epochs or both.

To calculate the coherence spectrum, the first step is to calculate the autospectra of each of the two signals under consideration. Secondly, the cross-spectrum must be derived. This measures the extent to which energy at a single frequency band is common to both signals. This involves a consideration of both the cospectrum and the quaspectrum. The cospectrum refers to those components of each signal that are "in-phase", i.e. the sine coefficients of both signals and the cosine coefficients of both signals are considered together. The quaspectrum refers to the "out-of-phase" components, i.e. the sine coefficient of the first signal is related to the cosine coefficient of the second, and vice versa. To use the notation of Orr and Naitoh (1976), given:
\[ a(n) = \text{cosine coefficient for the } f \text{ frequency for signal A} \]
\[ b(n) = \text{sine coefficient for the } f \text{ frequency for signal A} \]
\[ u(n) = \text{cosine coefficient for the } f \text{ frequency for signal B} \]
\[ v(n) = \text{sine coefficient for the } f \text{ frequency for signal B} \]

the cospectrum and quaspectrum are then defined as:

\[
\text{Cospectrum } (f) = a(n)u(n) + b(n)v(n) \\
\text{Quaspectrum } (f) = a(n)v(n) - b(n)u(n)
\]

The cross-spectrum is complex-valued, and defined as:

\[
\text{Cross-spectrum } (f) = \text{cospectrum } (f) + j\sqrt{-1} \text{ quaspectrum } (f)
\]

The cross-spectrum amplitude is, however, real-valued, and is equal to the absolute value of the complex-valued cross-spectrum. This is a quantity used in calculating coherence.

\[
\text{Cross-spectrum amplitude } (f) = \sqrt{(\text{cospectrum } (f))^2 + (\text{quaspectrum } (f))^2}
\]

Coherence is defined as:

\[
\text{Coherence } (f) = \frac{\left| \text{cross-spectrum } (f) \right|^2}{(\text{autospectrum } (f) \text{ of A})(\text{autospectrum } (f) \text{ of B})} = \frac{\text{cross-spectrum amplitude } (f)^2}{(\text{autospectrum } (f) \text{ of A})(\text{autospectrum } (f) \text{ of B})}
\]

Expressed in terms of sine and cosine coefficients:

\[
\text{Coherence } (f) = \frac{\left( \sum (a(n)u(n) + b(n)v(n))^2 + (\sum (a(n)v(n) - b(n)u(n))^2 \right)}{\sum (a(n)^2 + b(n)^2) \sum (u(n)^2 + v(n)^2)}
\]

where the summation sign represents not simply summing but averaging over frequencies or epochs. Such "smoothed" values must be used in the calculation otherwise coherence would always be unity (Orr and Naitoh, 1976). Coherence is sometimes defined and computed as the positive square-root of the above expression (the resulting value sometimes being referred to as "coherency", although this practice is often not
adhered to, and, in fact, will not be followed here). The square-root value is analogous to the more familiar correlation coefficient. Like a correlation coefficient, the square-root coherence should be transformed before any kind of statistical analysis to ensure that it is normally distributed. Fisher's z-transformation is usually appropriate. With respect to the interpretation of the coherence function, once again the parallel with a correlation coefficient is apt. In the words of Orr and Naitoh (1976), "If the coherence spectrum relating the electrical activity of two brain structures shows uniformly high values, it may be hypothesised that one is actively or passively controlling the other, or that they are both under the influence of a common third structure".

The smoothed coherence value has nominally two degrees of freedom associated with each frequency or epoch over which smoothing took place. This estimate is 'nominal' because adjacent components in the spectrum are unlikely to be truly independent. If a sufficient number of degrees of freedom are associated with a sufficiently high value of coherence (Benignus, 1969), the phase angle between the two time series becomes meaningful. This is given by:

\[ \text{Phase angle (f)} = \arctan \left( \frac{\text{smoothed quaspectrum (f)}}{\text{smoothed cospectrum (f)}} \right) \]

Calculation of the phase spectrum allows one to examine which signal leads or lags the other at various frequencies of interest, but unless the coherence values are fairly high it is probably best not to attempt to interpret them (Vos, Scholten and van Woerden, 1975).

There are several other problems associated with spectral analysis in general and coherence analysis in particular that the investigator
should be aware of. Firstly, it is debatable to what extent the process under analysis remains stationary over the period of interest, i.e. its statistical properties should not change with time. It is certain that the assumption of stationarity is violated over a long period, but by using strictly controlled experimental conditions and limiting analysis to periods over which mental state is not likely to change, it is possible that a tolerable approximation to stationarity can be achieved.

Also, for an epoch of finite length, it is impossible to measure the power at any specific discrete frequency because, as already stated, each estimate is for a band 1/T Hz wide, where T sec is the epoch length. The analysis of short epochs of abrupt beginning and end also produces artifacts, having the effect of multiplying the original time-series by a rectangular gate function. A non-zero value at the start of the epoch introduces a square wave containing a wide range of frequencies which will appear as spurious components in the spectrum. This "leakage" can be minimised by tapering the signal, for example by a cosine bell (see Dumermuth and Keller, 1973; Bergland, 1969).

Walter (1963) gives a very clear account of another common problem in spectral analysis. This is the problem of aliasing. Without going into detail, it is best to ensure that the sampling frequency is at least 2.5 times higher than the highest frequency present in the data. This is because high frequency components can impersonate low frequencies. If the sampling frequency is f samples per second, then the Nyquist frequency is f/2 Hz. This frequency is also referred to as the "folding frequency", because any higher frequencies present in the data (at f+x Hz, say) will "fold" around the Nyquist frequency and be
indistinguishable from lower frequencies (at f-x Hz). It is not advisable to simply double the highest frequency present in the data in order to obtain a suitable sampling frequency, because a certain amount of leakage is inevitable. These and other issues are discussed fully in Bergland (1969), Glaser and Ruchkin (1976), and standard texts on spectral analysis.

1.4.2 Coherence and Hemisphere Asymmetry

Having briefly considered the nature of coherence, a short review of its use in studies of hemisphere asymmetry will be given. It must, however, be noted that coherence has been used in many types of study besides those investigating hemisphere asymmetry. For example, Schoppenhorst and colleagues have used coherence to differentiate between alpha waves and mu waves at central placements (Schoppenhorst et al., 1975, 1977, 1980a, b; Brauer et al., 1975). Storm van Leeuwen et al. (1978) have also used coherence to study the mu rhythm, claiming to show that, unlike the alpha rhythm, mu lacks bilateral coherence. Lopes da Silva et al. (1978, 1980a, b), in a series of ingenious studies using partial coherence analysis and phase spectra, have examined the thalamo-cortical and intracortical processes in the generation of the alpha rhythm in dogs. The work of Davis and Wada involving coherence analysis of evoked potentials (1974, 1977a, b, c, d; 1978) will be reviewed in Chapter 3, and a consideration of phase effects will be deferred until Chapter 5. The current review will be solely concerned with studies involving possible asymmetries in
coherence effects between the hemispheres as related to various subject- and task-related variables.

One of the most common uses of coherence is that of differentiating between clinical populations and normals on the basis of EEG alone. One of the earliest studies of this type was that of Sklar et al. (1972, 1973; Hanley and Sklar, 1976) which used auto- and cross-spectral estimates of EEG activity between 1 and 32 Hz as input to a stepwise discriminant analysis program in order to differentiate between 12 dyslexics and 13 controls. The children were at rest or engaged in various mental activities such as mental arithmetic, reading word lists and reading text. EEG was recorded bipolarly from F3-T3, F3-P3, P3-O1 and O1-T3, and homologous placements on the right, and it was found that the groups could be discriminated during all tasks although results were best during rest and reading text. During rest, the parieto-occipital placements showed more energy in the 3-7 Hz and 16-32 Hz bands for the dyslexics and in the 9-14 Hz band for the normals. During the text-reading task, coherences between 02-T4/T4-F4 and P3-01/P4-02 were more important discriminators than power effects, with the former being higher for dyslexics and the latter higher for normals. This general pattern of higher intrahemispheric coherence for dyslexics and higher interhemispheric coherence for normals was also reported by Leisman and Ashkenazi (1980) in a comparison of 20 dyslexics with 20 controls who were "undergoing continuous performance tests". Autospectral density for P3-O1 turned out to be the most discriminating index between groups, with the dyslexics demonstrating greater energy in the 3-7 Hz and 16-28 Hz bands and the normals in the 9-12 Hz band. Although this
appears to be a remarkably strong confirmation of Sklar et al.'s findings, a full assessment of this study is not possible due to the inadequacy of the published report.

A similar pattern was reported by Montagu (1975) in a comparison of ten hyperkinetic children with ten matched controls. On the basis of four 10 second epochs recorded from left and right centroparietal placements (Cz reference), Montagu found that the hyperkinetic children showed higher coherence within the right hemisphere than the normals in the 2-8 Hz band, and that coherence between the hemispheres tended to be lower for the patient group, though not significantly so. The patients showed less power at 10 Hz than the normals for the right hemisphere placements, and no difference between the groups in terms of phase angle effects were found.

At least four studies have used coherence analysis to compare schizophrenic patients with other groups. Shaw et al. (1979) compared groups of 12 normals, 12 neurotics and 12 first-rank schizophrenics with respect to the coherence patterns produced while the subjects were either at rest, or involved in mental arithmetic or a spatial imagery task. The spatial imagery task involved having the subject mentally reconstruct a figure composed of vertical and horizontal lines from information presented verbally. These tasks had been used in earlier studies with normals (Shaw et al., 1977, 1978) but it ought to be noted that the verbal component of the spatial imagery task would complicate any interpretation of effects with respect to hemisphere function. For all conditions subjects had their eyes closed and EEG from O2, P4, T4, T6 and homologous sites on the left hemisphere was analysed (Fz reference). Many differences were found.
between the three groups for both power and coherence and the reader is referred to the original report for a full account. It is certainly worthy of note however that schizophrenics tended to have higher intrahemispheric and lower interhemispheric coherence than both other groups in all frequency bands, once again reflecting the pattern seen with other patient groups. Also coherence tended to be greater in the left hemisphere for schizophrenics, but in the right hemisphere for the other groups. Normals and neurotics tended to show lower coherence for mental arithmetic than for the spatial task, while schizophrenics showed the opposite pattern. Hemisphere asymmetries were also assessed by examining the log (R/L) ratios for homologous power and coherence measures. Power ratios tended to be positive (i.e. more power on the right side) but two interesting effects were noted in the theta band. Firstly, for both tasks, the occipital power ratio was negative for both normals and schizophrenics, but positive and significantly different for neurotics. Secondly, for the rest condition, the log (T6/T5) ratios were all positive, but greater for the normals than the schizophrenics. The log (P4-T4/P3-T3) coherence ratio was positive for normals and neurotics and negative for schizophrenics across all frequency bands.

Shaw et al. (1979) drew attention to a number of methodological problems in their study and these merit repetition, as they apply with equal force to many other studies in the area. Firstly, there is the problem of the use of a common reference electrode, whereby activity at the reference will contribute to both signals involved in the coherence analysis and influence the value of coherence obtained. The choice of reference is thus critically important and, as Beaumont and
Rugg (1979; see below) have shown, coherence levels vary depending upon the reference used. As Shaw et al. (1979) go on to point out,

"The same change in coherence may result from a change in EEG activity at the common reference site, at one or both of the non-reference electrodes, or at all three electrodes. Our use of a common reference electrode is particularly troublesome in this respect. For example, desynchronisation of the EEG at one non-reference site due to activation in that region would result in increased coherence because the reference site would contribute a larger proportion of the common signal variance. The same result would occur if both non-reference sites became desynchronised. But an increase in synchronisation at both non-reference sites could also increase coherence, so that both activation and deactivation might have the same effect."

The best solution to this particular problem is a non-cephalic reference (Stephenson and Gibbs, 1951) which will not be active with respect to EEG signals.

A further problem is that activity in different frequency bands and at different electrodes are not necessarily independent. Thirdly, like many other studies in this area, groups were not matched for age, sex and medication. Finally, Shaw et al. (1979) consider the possibility that, as many of the effects found were in the higher frequency ranges, they may be due to EMG contamination, but they reject the idea that EMG effects offer an adequate explanation of all the effects found. This possibility must be taken very seriously however,
particularly in the light of two studies (Flor-Henry et al., 1979; Volovka et al., 1981) suggesting that different patient groups demonstrate different asymmetric patterns of EMG distribution.

Weller and Montagu (1979, 1980) reported the results of a preliminary study comparing power and coherence between six schizophrenic subjects and six matched controls. Bipolar linkages placed at F3-C3, T3-T5, O1-P3 and homologous locations on the right hemisphere were used to record EEG while subjects rested either with eyes open or eyes closed. For the eyes closed condition, schizophrenics showed less power at both the parieto-occipital and temporal placements, although this only reached significance in the 20-30 Hz band and only at the parieto-occipital sites. Log (R/L) power ratios were significantly higher for the schizophrenics than the normals in the 6 Hz band for this condition, but no differences were found for the eyes open condition. With respect to interhemispheric coherence, schizophrenics showed higher coherence than normals between temporal pairs (2, 4, 6 Hz) and parietal pairs (2 Hz). For the right hemisphere, schizophrenics showed higher coherences between F4-C4 and T4-T6 than normals (2, 4 Hz), but no effects were found for the left hemisphere. Although this study found totally different effects to those reported by Shaw et al. (1979) it is quite possible that these differences are due to variations in montage, task, recording conditions and so on.

Giannitrapani (1979b, 1980) reports yet different effects in a reanalysis of the data from 16 unipolar electrodes (linked ears reference) recording EEG from 10 schizophrenics and 10 matched controls. Autospectral results of this study had first been reported
by Giannitrapani and Kayton (1974; see Section 1.3 for experimental details). Some interesting phase angle effects were found (see Chapter 5), but only the coherence effects will be mentioned here. The data presented refer to averages over all eight conditions used in the experiment. Essentially, Giannitrapani found higher coherence for schizophrenics at all frequencies except the 11 Hz band, which corresponded to the peak power in the normal EEG, and a peak in coherence for the patient group at 29 Hz, where they, but not the normals, also showed a peak in the power spectrum. Whereas normals show a drop in coherence with increasing interelectrode distance, the schizophrenics surprisingly maintain high coherence. Giannitrapani also reports that the 29 Hz coherence scores for normals and schizophrenics are more differentiated over the right hemisphere than the left, especially at frontal sites. It should be noted that no other investigator of schizophrenic EEG has found these interesting effects at 29 Hz, although an excess of fast activity is quite commonly reported.

Flor-Henry et al. (1979; see also Flor-Henry and Koles, 1980; Flor-Henry, 1976, 1979) present data concerning EEG differences between 20 depressives, 21 manic patients, 20 schizophrenics, and 23 normals, all right-handed. EEG was recorded from P3, P4, T3 and T4 referenced to Cz while the subjects relaxed with eyes open (EO), or eyes closed (EC), performed a verbal task (vocabulary subtest of the WAIS, VM) and a spatial task (block design subtest of the WAIS, SM). The data for the normal subjects are reported fully by Koles and Flor-Henry (1981), and a fairly detailed account of them will be given here, so that the effects found for the patient groups can be properly
compared. During EO, alpha was found to be biased towards the left temporally, which, although unusual has been reported occasionally in other studies (e.g. Giannitrapani, 1979a). Task performance led to a general suppression of alpha (not significant) and a significant increase in power in the so-called extended gamma range (20-50 Hz) which was, however, smaller over the presumably activated hemisphere. In each of the bands considered, 43 features of the EEG expressed in terms of average power densities, coefficients of power density variation, coherences and phases were calculated. An attempt was made to differentiate between those features related to the nature of the mental task and those which were related only to the workload represented by the task. This was achieved by considering the effects of each of the two tasks in comparison to the EO condition. If the difference between EO and VM and the difference between EO and SM are both in the same direction, then the feature may merely reflect the fact that a mental workload has been imposed. However, if the differences are in opposite directions, then the actual nature of the tasks must differ. Of the features considered, many were found to be workload-related, but only five showed task-dependent effects. Of this five, only two seemed to point to the traditional lateralisation of function between the hemispheres for verbal and spatial abilities. These two were (i) log (R/L) power ratio in the alpha band (an effect which is stronger parietally than temporally), and (ii) on average, coherence is higher over that hemisphere which is cognitively activated. It was also found that coherence was reduced by mental activity, except for the interparietal coherence. The P3-P4 coherence was always higher than the T3-T4 coherence, but this is not

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surprising, as the parietal electrodes were nearer to each other than the temporal electrodes. The log \((P3-P4/T3-T4)\) coherence ratio increased with mental activity. Several interesting phase angle effects were found (see Chapter 5).

Several reports have compared these findings for normals with those of manic, depressed and schizophrenic patients (Flor-Henry, 1976, 1979; Flor-Henry and Koles, 1980; Flor-Henry et al., 1979). In this study a great number of significant differences were found and no attempt will be made here to give a comprehensive list of all effects found. The possibility that many of these results are spurious cannot be ignored when one considers the exceedingly large number of statistical tests carried out on these data. The reader is referred to Flor-Henry et al. (1979) for a detailed account of these effects. A further reason for not going into great detail in considering these effects is that the authors admit that their data are contaminated by EMG which subsequent analysis showed to be asymmetrically distributed in different ways for different psychotic groups. Thus it is impossible to determine which, if any, of the effects found are genuine reflections of differing neuropsychological organisation. However the general conclusions of the study were as follows:

"1. The power density distribution in psychosis suggest that for the frequencies lying between 20-50 Hz schizophrenia, mania and depression have a significant increase in energy in the temporal regions, bilaterally. In the 13-20 Hz band, however, the energy distribution is lateralised to the left in schizophrenia and to the right in depression. Mania furthermore shows increased
left parietal energy (20-50 Hz) although both mania and depression have a significant reduction of right parietal power in the alpha frequencies, compared to normals.

"2. Schizophrenia and depression share a reduction of the left temporal coefficient of variation, although the right parietal coefficient of variation is increased in depression, mania and schizophrenia. The right and left temporal variance is increased in all three psychoses, compared to normals.

"3. Intra-hemispheric coherence is reduced in the right and left hemisphere in schizophrenia, but only in the left hemisphere in mania and does not differ from normals in depression. On the other hand, inter-hemispheric coherence is reduced both parietally and temporally in schizophrenia, but only temporally in mania.

"4. Further shifts of laterality are suggested: cognitive activation of the non-dominant hemisphere during verbal processing in schizophrenia, activation of the dominant hemisphere during spatial processing in depression and mania. In mania there is also evidence of some engagement of the non-dominant hemisphere during verbal tasks."

Phase angle effects will be discussed in Chapter 5.

Thus it can be seen that this study has produced yet another pattern of coherence effects with respect to schizophrenic EEGs. To summarise these studies of schizophrenic patients, we may note that:

a) Shaw et al. (1979) suggest that schizophrenics have higher intrahemispheric and lower interhemispheric coherence than normals
over all frequencies, although problems of interpretation are noted.

b) Weller and Montagu (1979) suggest that schizophrenics have higher intrahemispheric coherence for the right hemisphere (but not for the left) for low frequencies, and also higher interhemispheric coherence than normals.

c) Giannitrapani (1979b, 1980) found higher coherences for all frequencies, both inter- and intrahemispherically for schizophrenics.

d) Finally, Flor-Henry et al. (1979) found lower coherences both inter- and intrahemispherically for schizophrenics in comparison to normals.

It would be very difficult for a future coherence study of schizophrenia to fail to replicate one of these studies, as virtually all possible patterns appear to have been reported. This may simply be a reflection of differences in methodology (for example, all studies used different reference sites), but it at least means that any attempt to account for the observed results in terms of, say, "shifts in laterality" (Flor-Henry and Koles, 1980) must be premature. Indeed, any attempt at interpretation of coherence effects is bound to fail unless the fact that these effects are dependent upon the reference used is taken into account (Beaumont and Rugg, 1979). The problems of attempting such interpretations without a good theoretical foundation are nicely highlighted by this quotation from Flor-Henry et al. (1979):

"Taken together, the changes in average power, in coherence, in phase relationships and in variability reported here show a complex pattern of bilateral abnormalities in depression, mania
and schizophrenia which in several aspects appear to implicate more the dominant hemisphere in schizophrenia and the non-dominant in depression. At the same time some of the data presented, for example left temporal hypovariability in schizophrenia and depression or increased left temporal power (20-50 Hz) in depression, mania and schizophrenia link these three psychotic modes to the left hemisphere. On the other hand the increased right parietal variability common to the three psychoses establishes a communality in the opposite hemisphere!" (exclamation mark in the original!).

O'Connor, Shaw and Ongley (1979) compared groups of depressives, arteriosclerotic patients and patients suffering from senile dementia in terms of EEG power and coherence. Only results for bipolar placements at C3-P3, C4-P4, P3-O1, P4-O2, T3-T5 and T4-T6 are reported, for three recording conditions: eyes open, eyes closed and 8 Hz photic stimulation. The hypotheses of the study were that because some patients with senile dementia have diffuse pathology, this group would show higher coherence between recording sites than the depressed group, and, secondly, that the presence of more focal pathology in the arteriosclerotics would result in a lower coherence between some areas than for the depressives. These hypotheses were supported. The arteriosclerotics, while showing more power than the senile group, showed the lowest intrahemispheric centroparietal to temporal coherence. This within-hemisphere coherence was greatest for the senile group. A discriminant function analysis based on the eyes-closed condition showed that the centroparietal to temporal

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coherence at 8 Hz and the occipitoparietal to temporal coherence at 12 Hz (both for the right hemisphere) were quite effective at differentiating the groups.

Summarising the studies of hemisphere differences in coherence related to psychological abnormality:

(i) With respect to so-called "learning disorders" (dyslexia, hyperactivity), a pattern of decreased interhemispheric and increased intrahemispheric coherence in comparison to normals has been reported.

(ii) Shaw et al. (1979) found a similar pattern for schizophrenic subjects, but three other studies have failed to find it, each producing different results.

(iii) Depression and organic impairment have also been investigated, but as the number of studies is so limited, it would be premature to draw general conclusions.

(iv) Several methodological points have been noted. These often apply with equal force to the studies of normals that are now to be considered.

Turning now to a consideration of studies of normal subjects, Wienekel et al.'s (1980) normative study examined coherence as well as power (see Section 1.3) in 110 normal male subjects. Results for coherence between left and right placements (reference: ipsilateral frontal) during eyes-closed relaxation showed that coherences fell into the following order: (O1-P3), (O2-P4) > (O1-O2) > (P3-P4) > (T5-T6) > (T3-T4). The most obvious explanation for this is in terms of a decrease in coherence as interelectrode distance increases.

Koles and Flor-Henry's (1981) study of coherence, phase and power
effects has already been considered in some detail. The same data are presented by Flor-Henry and Koles (1980), but this report also includes a comparison of the data for males and females. This analysis revealed that neither the (R/L) intrahemispheric coherence effects or the increase in interparietal coherence with task performance found for the overall group were found when the females' data were analysed separately. In fact, women showed a decrease in the interparietal coherence with task performance. Also, women showed more power in all bands at all sites and less lateralization with respect to power.

Sex differences were further examined by Flor-Henry and Koles (1982) using the same methodology to investigate a group of 37 males and a group of 46 females, each of which contained dextrals and sinistrals. Once again females seemed to show more power than males, although the distributions were not the same as those previously reported. Interhemispheric coherence was found to be higher for women. There were no systematic differences between dextrals and sinistrals for power but the sinistrals had higher right hemisphere coherence in the 20-35 Hz range. In this report the authors work on the assumption that activation of a particular cortical area leads to an increase in beta-2 (20-35 Hz) activity, as well as an increase in coherence. They claim that women activate the right hemisphere relatively more and that men activate the right hemisphere relatively more, independent of handedness. They further claim that similarly sinistrals activate the right hemisphere relatively more and dextrals the left, independent of sex, but that for spatial tasks sinistrals males activate the right hemisphere whereas sinistrals females activate the left. Once again, no attempt will be made here to consider the multitude of effects
reported and the reader is referred to the original paper for this information. One point worth noting however, is that an examination of the data for the dextral group in this study reveals many discrepancies when compared to the data collected from the dextral subjects in previous studies (e.g. Koles and Flor-Henry, 1981). No attempt is made to account for these.

Handedness was a relevant factor in Shaw, O'Connor and Ongley's (1977) study employing the same methodology as that used by Shaw et al. (1979). Results presented refer only to EEGs recorded from Fz-P3 and Fz-P4 in the alpha band, where it was found that for the 'spatial' task, interhemispheric coherence increased in 8 of 11 right-handers and decreased in 8 of 11 left-handers. The arithmetic task produced similar results. Power changes between rest and task did not differentiate the two groups. Shaw, O'Connor and Ongley (1978) replicated and extended these findings on a further group of subjects, 12 right- and 12 left-handed. In both experiments a significant correlation between the coherence change score (from rest to task) and a laterality score (as shown by handedness) was obtained, although as may be expected this was stronger for the right-handed subjects.

The relationship between field-dependence/independence and laterality was considered by O'Connor and Shaw (1978) using these same data. Based on previous findings it was expected that field-independent (FI) subjects would show a more lateralised cerebral organisation than field-dependent (FD) subjects, in the same way that dextrals are considered to be more lateralised than sinistrals. This predicted association between FI and dextrality, and FD and sinistrality was confirmed. Further, a consideration of Beaumont's
(1974) proposal that less lateralised subjects operate with small functional units in the cortex, each of relatively low specificity, whereas strongly lateralised subjects have larger, more specific functional units, led to the following predictions: (i) for right-handers, FDs would tend to be less lateralised, and would show a relatively higher coherence between and within hemispheres than the more strongly lateralised FIs; (ii) for the left-handers FDs would tend to be strongly sinistral, and show a similar difference in coherence between FIs and FDs as the dextrals. These predicted differences in coherence are based upon the assumption that higher coherence between cortical areas is associated with less specificity and independence of function between those areas. O'Connor and Shaw used the Rod and Frame Test to assess FI/FD scores, and considered alpha band resting EEG coherence (eyes closed) between P3, P4, O1 and O2 (Fz reference). They found all of the predicted differences with the exception of the coherence in the left-preferents' right hemisphere (where lower coherence concords with strong sinistrality and field dependence). It is worth noting however, that this line of reasoning would predict higher coherences for sinistrals than dextrals generally. As sinistrals are generally recognised to be less lateralised than dextrals, then, according to this interpretation of Beaumont's model, they should have higher inter- and intrahemispheric coherences than dextrals, independent of FD/FI. No attempt seems to have been made by O'Connor and Shaw to test this possibility, but as the z-transformed coherences were presented for individual subjects in Table 1 of their report (pp 100-101) it was possible to carry out t-test comparisons between the right- and left-preferent groups for
inter- and intrahemispheric coherences. The result is that no significant differences were found between groups. This lack of systematic differences between handedness groups was also reported by Flor-Henry and Koles (1982), and it would appear to be difficult to reconcile this with the general line of reasoning used by O'Connor and Shaw. Giannitrapani (1975a) in reanalysing data collected previously (Giannitrapani, 1968) from 16 left-, 16 mixed- and 16 right-preferent subjects found higher coherence in the alpha band for right-preferents, and lower coherence in the same group in the 29 and 33 Hz bands.

Giannitrapani and colleagues have made extensive use of coherence analysis in their studies of task- and subject-related EEG variables. Unless otherwise stated, all of these studies followed exactly the same experimental procedure as that outlined previously (see Section 1.3), and, as usual, phase angle results will not be considered until Chapter 5. Giannitrapani and Roccaforte (1975; see also Giannitrapani, 1975a) used 12 right-handed male subjects (aged 11-13 years) to assess the reliability of coherence and associated measures across sessions. They varied epoch length (8, 16 or 32 sec) and interval between epochs (10 sec, 40 sec or 40 min). Large increases in reliability were found for autospectral estimates as epoch length increased, with small decreases in reliability with increasing intervals between epochs. Reliabilities were generally quite reasonable for autospectra and cross-spectra, but quite low for coherence and nonexistent for phase. However, there was wide variation across frequency bands and brain areas studied. For example, reliability of coherence estimates was highest in the 29 Hz band, although no clear picture of task-related
effects emerged. The reader is referred to the original reports for more detail. Clusin and Giannitrapani (1970) claimed that for a sample of 32 11-13 year old right-handed males, short-term digit-learning ability was inversely related to coherence in the occipital, lateral-parietal and prefrontal areas. This relationship was strongest for the 25-33 Hz band.

The experimental procedure used by Beaumont, Mayes and Rugg (1978) has already been described, and the reader is referred to Section 1.3 for these details and results related to power. Only the alpha band was considered in this study. The spatial tasks produced more coherence over the right hemisphere than over the left, with an increase in coherence in this hemisphere compared to that found for the verbal tasks. The verbal tasks did not produce increased coherence over the left hemisphere. Interestingly, females showed higher interhemispheric coherence than males, a result in line with Flor-Henry and Koles (1982). It is suggested that this may be an electrophysiological reflection of the postulated greater lateralisation of cerebral organisation in males, a suggestion which would receive further support from the finding that in females the splenium is larger than that found in males (de Lacoste-Utamsing and Holloway, 1982). Both of these findings can be viewed in terms of greater anatomical connectivity between the hemispheres for females. Further, interparietal coherence was found to be much higher than intertemporal coherence, again in line with Flor-Henry and Koles (1982), a finding which was interpreted as a possible reflection of different degrees of transcallosal connectivity between homologous sites. In fact both results may be more parsimoniously accounted for
in terms of a decrease in coherence with increasing interelectrode distance (Giannitrapani, 1975; current series, especially Experiment IV), if it is granted that males generally have larger skulls than females.

An important experiment from a methodological point of view is that of Beaumont and Rugg (1979), using 24 right-handed males as subjects (see Section 1.3.1.6 for other details). Although linked mastoids were used as a reference in this study, EEG was also recorded from Fz so that this could be used as an 'algebraic' reference. Also, half of the subjects in the experiment had a posterior temporal montage (PT) and half, an anterior temporal montage (AT). This study showed conclusively that coherence levels differ depending upon the choice of reference electrode. For the AT montage alpha coherence was higher with the Fz reference than with linked mastoids. Also the right hemisphere was significantly more coherent than the left, and the nonverbal task produced higher coherence than the verbal, although no significant interactions were found. For the PT montage, the only significant effect was greater alpha coherence for the Fz as opposed to linked mastoids reference. Despite the fact that in this study coherence was only altered in terms of absolute level by changing the reference used, there are strong arguments to suggest that the actual pattern of coherence effects can be altered. These arguments are presented in Section 7.5.

Rugg and Venables (1980; see Section 1.3.1.6) reported finding no differences in intertemporal coherence between the learning of high imagery (HI) and low imagery (LI) words. However it was noted that, "subjects in whom the difference in the recall of HI and LI words was
small tended to have large differences in interhemispheric coherence in the alpha band and small differences in the theta band." This observation is not readily interpretable.

Busk and Galbraith (1975) examined coherence in the 4-20 Hz range of EEG recorded from Oz, C3, C4 and Fz referenced to the right earlobe. These investigators were interested in possible EEG coherence correlates of visual-motor practice in man. They had three groups of subjects, each containing five males, involved in a pre-test session, a main practice session and a post-test session. Three types of task were involved: hand-tracking (H), which involved performing the same movements as would be involved in a standard pursuit-rotor task, but without actually looking at the rotor; eye-tracking (E), which required the subject to follow a pursuit-rotor with his eyes; and, finally, eye-hand-tracking (EH), which corresponded to the standard pursuit-rotor task whereby the subject attempts to keep a stylus in contact with a point on a rotating disc. During the pre-test stage, all subjects performed two trials of each type of task. Coherences between all six pairings were examined at each stage of the experiment and during the pre-test, Fz-C3, Fz-C4 and Fz-Oz showed significantly higher coherences than other sites. Busk and Galbraith suggest that this may be due to known anatomical visual-motor connections. Coherence between C3 and C4 was the lowest of all pairs, and again it is suggested that this may reflect the fact that these areas are not connected by callosal fibres (although other areas of the motor cortex are). However, once again there are problems in interpreting effects when an active reference has been used. It seems quite possible that an explanation in terms of the issues raised by Shaw et al. (1979)
could account for this finding. After all, if the signals at the central sites and at the right ear were fairly similar, common-mode rejection would ensure that this similarity was removed. For the other placements, if they were recording signals quite different from the right ear, then the active reference would in fact enhance the coherence between sites. Superimposed upon this general picture of coherences during the pre-test phase, was a task-related coherence effect, with the most difficult task (EH) producing highest coherence and the least difficult (E), the lowest. For the main practice stage of the experiment, each group performed just one of the three tasks. For the post-test session, all groups performed the EH task. It was found that whereas the group which had practiced the EH task showed a small decrease in coherence, the other two groups showed a small increase.

A promising new application of coherence analysis has recently been described by Tucker, Roth and Sawler (1981). They used multivariate analysis to describe the spatial patterning of covariance in the spectral information of a multichannel EEG. They factor analysed coherences for all frequencies and all possible pairings of eight electrodes while a single subject rested or engaged in a word fluency task. Five weekly observations were made and the factors isolated seemed to be stable for the word fluency task, but not so stable for the 'resting' condition. There was a suggestion of lateralisation, but as only one subject's data are reported general conclusions would be premature.

Another novel approach is that employed by Berkhout and Walter (1980) who used a real time display of interhemispheric coherence at
6, 10 and 14 Hz between parietal and occipital areas to investigate the effectiveness of particular behavioural strategies in modifying coherence. Five subjects were used. Behaviour tending to increase levels of arousal increased interhemispheric coherence between occipital sites at 6 and 14 Hz, but decreased it at 10 Hz. Interparietal coherence was far less amenable to volitional control.

A number of studies have been published involving the use of coherence analysis in the study of Transcendental Meditation (TM). For example, Levine et al. (1977) recorded EEGs from 28 subjects with between 0 and 15 years experience of TM. Electrodes were placed at O1, P3, T3, C3, F3 and homologous areas on the right, with either single or linked ears as reference. A typical session would involve the following stages: eyes open (EO, 5 min), eyes closed (EC, 10 min), TM (20-30 min), EC (10 min), EO (10 min). Whether or not one accepts the more metaphysical aspects of the study, one cannot fail to be impressed by the way the data are presented. An adaptation of the compressed spectral array technique is used whereby those coherence peaks which exceed a threshold value of 0.95 are emphasised. This presentation is referred to as a COSPAR, and 108 COSPARs have been computed from many experiments on TM with a wide variety of effects being found. Essentially though, TM is said to increase coherence, especially in the theta and alpha bands relative to the EC condition. The authors also claim that drowsiness and loss of consciousness lead to a decrease in coherence thus supporting the claim that the Transcendental State is qualitatively different from normal states of consciousness. They report that the most striking increases in coherence can occur equally often in the right or left hemisphere,
although it usually occurs at interhemispheric frontal sites.

Haynes et al. (1977; see also Orme-Johnson and Haynes, 1981; Orme-Johnson et al., 1977) studied coherence between frontal placements (F3, F4) of 23 males taking part in a six-month "Age of Enlightenment advanced training program". The experimental procedure was as described above. The COSPARs were used to estimate a value referred to as COH which was the product of the percentage of the time that alpha coherence was above the 0.95 threshold and the mean spectral width of this suprathreshold band. Highly significant intercorrelations were found between COH and creativity (as assessed by the Torrance Test of Creative Thinking), H-reflex recovery and "the experience of transcendental consciousness". These findings and others are reviewed by Orme-Johnson (1977a, b) and reports by Dillbeck and Bronson (1981) and Dillbeck et al. (1981) also involve the use of interhemispheric coherence in investigating TM, producing results in line with those described.

To summarise this section then, several points can be made:

(i) Coherence has been much used in studying various psychiatric populations, and it is possible that a common pattern of inter- and intrahemispheric coherence characterises certain learning disorders. Simple differentiation of clinical groups is a valid, if limited, use for coherence, but any attempt to go beyond this and interpret the meaning of any differences is fraught with problems.

(ii) Although a couple of experiments have produced relative increases in coherence over the presumably more active hemisphere (Beaumont, Mayes and Rugg, 1978; Koles and Flor-Henry, 1981), others have failed to show these task-related hemisphere differences (Shaw et
al., 1979; Beaumont and Rugg, 1979). The question of whether task performance leads to a general increase in coherence in comparison to a "resting" state has also not been answered conclusively.

(iii) Differences between handedness groups have been reported in various studies, but no clear overall pattern has emerged.

(iv) The only studies to consider sex of subject as a variable with respect to coherence (Beaumont, Mayes and Rugg, 1978; Koles and Flor-Henry, 1981) have both reported higher interhemispheric coherence for females than males, although this is possibly only a reflection of differing skull sizes.

(v) Several reports have shown a relationship between increased coherence and practice of the Transcendental Meditation technique.

(vi) Several methodological problems have been noted. However, by far the most serious is the use of a cephalic reference which makes any clear interpretation of coherence effects virtually impossible.

1.5 Conclusions

It was originally intended that this review would consist of a detailed critical assessment of all previous attempts to investigate hemisphere asymmetries in EEG/EP data. It soon became clear that such an undertaking would involve a prohibitive amount of time, effort and paper. It was therefore decided to present this introduction in the present format, in which the general methodological issues were presented prior to a brief description of the relevant studies. Attention was occasionally drawn to particular methodological issues,
but in general it is apparent simply from the description given that many of the guidelines proposed by Donchin, Kutas and McCarthy (1977) and Gevins (1981) had not been adhered to.

Having said that, it would appear that despite the many negative results the predominant trend is towards patterns of lateralisation of function which correlate with those suggested using other techniques and the generally accepted notions of hemisphere function. However, as already pointed out, this trend may be more apparent than real. Firstly, very few investigators would attempt to publish negative findings. Secondly, although general patterns of 'hemisphere activation' often appear to be replicated across a variety of studies, close examination often reveals that different measures were used and, indeed, there exists a wide range of EEG/EP indices which could nowadays be taken as indicative of hemisphere activation.

Another very noticeable tendency is for investigators to fall back on a number of stock excuses when attempts to reproduce particular task-related effects fail. For example, it may be asserted that the task which was chosen as a 'nonverbal' task could, in fact, have been performed using a verbal strategy (e.g. block rotation). Given the range of attributes which have been freely applied to characterise right (and left) hemisphere function (see Section 1.1), there can few tasks to which the left hemisphere could not turn its metaphorical hand, thus ensuring a ready explanation for all failures to activate the right hemisphere. Another standard excuse is to state that the apparent discrepancy with other findings results from differences in experimental procedure. Given the very large number of variables which should be taken into account in this type of work, it is not
surprising that in anything less than a direct attempt at replication, there will be a number of factors which differed which could reasonably be responsible for apparent discrepancies. Unfortunately, it is very rare for investigators to test whether these factors really did make a crucial difference, hence another stock of excuses is at hand. Of course, these 'excuses' could be valid reasons, but much greater effort is required if we are seriously trying to determine which factors are of importance, and in what ways they effect findings. Yet another approach, popular when results imply the opposite of what one would have expected on the basis of accepted knowledge, is to simply reject that accepted knowledge, as if EEG/EP data had a surer theoretical basis. So, for example, it may be implied that the right hemisphere can read pleasurable or non-technical text, a finding which may be news to clinicians. Many more startling assertions could be culled from the literature, but the point has been made.

However, it must be realised that a few well-controlled studies producing reliable positive results would be worth many apparently positive results from badly controlled studies. Unfortunately, it is questionable if any study so far attains the required degree of control, although, in fairness, some studies are far sounder methodologically than others. There appears, however, to be a strong tendency for the more well-controlled studies to be less likely to produce apparent hemisphere asymmetry and thus I find myself in strong agreement with Beaumont (in press):

"At best we should conclude that, although there is a trend
towards the finding of task-related asymmetries, the mechanisms which underlie these asymmetries are complex and poorly understood. Clear and reliable task related effects have not as yet been demonstrated. At worst, we should be very suspicious of any claim to have demonstrated such asymmetries, and conclude that artifacts may be responsible for the lateral differences which have been reported. Certainly, claims in this area should be cautious, and future investigations based upon much more rigorous and carefully controlled research designs."

Throughout this review particular attention has been directed towards several very common methodological problems. Firstly, the use of an active cerebral reference has been severely criticised. Secondly, attention has been drawn to potential sources of artifact, especially LEms and movement-related potentials. Thirdly, the use of badly matched control tasks is the rule, rather than the exception. Unfortunately, when the current series of experiments commenced, I was unaware of many methodological issues, and therefore must admit to certain methodological flaws, which are pointed out later. However, I sincerely feel that if the general trend in this area was towards attempting to eliminate such problems as they came to light, as was done here, rather than sticking to a technique which appears to be superficially 'productive', the issue of whether or not EEG/EP signs of lateralisation of cognitive function can be demonstrated would be closer to resolution, one way or the other.
Chapter 2: Experiment I

2.1 Introduction

The first experiment in this series examined the effects on electroencephalographic indices of having the subject perform verbal tasks which differed in difficulty level. Previous experiments which have studied effects of task difficulty (McKee et al., 1973; Dumas and Morgan, 1975; Galin et al., 1978) have produced inconsistent results and thus any clear prediction of outcome is not possible. The current study involved using the same stimulus words for each verbal task and varying only the subjects' task. This ensures that any differences which are found cannot be attributed to differences between the stimuli used for each task and presumably must be due to the type of processing that the subject is engaged in.

In most experimental studies using coherence analysis, the pairs of electrodes involved are fairly well-separated on the scalp, e.g. T3-T4. It was decided to try to use the coherence index in a slightly different way in this study by having the electrodes close together (2 cm apart) to see if coherence could be used to give any meaningful information about what was happening within a single small area, rather than about the relationship between two distant points (cf. Beaumont and Rugg, 1979). It was further decided to try to locate these areas over Broca's area (see Brown et al., 1973, 1976) and Wernicke's area (see Matsumiya et al., 1972) and homologous areas over the right hemisphere as one might expect these areas to show maximum asymmetry with respect to verbal processing. Of course, one must bear
in mind at this point the problems raised by anatomical asymmetry and variability discussed previously.

The restriction of subjects to right-handed males was an attempt to maximise the chances of finding significant indices of lateralisation. It is generally accepted that sinistrals' cerebral hemispheres are not as lateralised with respect to function as dextrals, and may even show opposite lateralisation (see, e.g., Herron, 1980a). The hypothesis that females are not as lateralised as males is less well-supported (McGlone, 1980) but the weight of the evidence can be taken as supporting this assertion. Obviously, such groups could be investigated in later work if any interesting effects were found.

2.2 Method

2.2.1 Subjects

Subjects were 24 males, all right-handed (by self-report), aged between 16 years 1 month and 30 years 6 months with an average of 22 years 11 months.

2.2.2 Apparatus and Recording

EEG was recorded from Ag/AgCl electrodes positioned at F7 and F8 (10-20 System; Jasper, 1958) and two centimetres posterior to these two points in order to have a pair of electrodes approximately over
Broca's area and the homologous area of the right hemisphere (Brown, Marsh and Smith, 1973, 1976). EEG was also recorded from one centimetre anterior and one centimetre posterior to W1 and W2 (Matsumiya, Tagliasco, Lombroso and Goodglass, 1972). W1 is presumably close to Wernicke's area and is defined as the centre of a triangle made by P3, T3 and T5 (10-20 System). W2 is similarly determined on the right hemisphere. All electrodes were referenced to linked mastoids with interelectrode resistance maintained at less than 5 k-Ohms. Henceforward the notation used for the electrode pair will indicate hemisphere and brain area - thus RB refers to the pair over the right hemisphere "Broca's area".

Due to lack of equipment, the channels from Broca's area and Wernicke's area were amplified with different amplifiers, and thus the two sites could not be directly compared during analysis. The EEG channels from LB and RB pairs were amplified using Neurolog amplifiers and preamplifiers with a total gain of 20 K and LF cutoff of 0.1 Hz. Kemo dual variable filters (type VBF3) set the HF cutoff at 25 Hz. The LW and RW pairs were amplified using Devices AC high gain amplifiers set to 20 K amplification, time constant of 0.3 seconds and HF cutoff at 25 Hz. After half the subjects had been run, channels for left and right hemisphere sites were exchanged, to control for any imbalances in the system.

For each task (described below) 20 two-second epochs of EEG from each of the eight channels were recorded. The recording was triggered by means of a tone recorded on channel II of a Ferrograph Super Seven tape recorder just after stimulus offset on channel I. This caused a Schmidt trigger on the PDP8/e to signal the start of EEG recording.
The 20 epochs consisted of 64 data points per channel recorded at 32 Hz. During the experiment the EEG was visually inspected and afterwards the data points were displayed so that, upon inspection, any epochs containing gross artifacts could be rejected and replaced by artifact-free epochs. For each subject, the number of epochs rejected for each task was noted.

2.2.3 Procedure

The subjects were required to perform four tasks, three verbal and one nonverbal. The verbal tasks differed in difficulty, the subject having to make increasingly difficult choices before deciding whether or not a word belonged to a target group. In the first verbal task the subject simply listened to the words and pressed the response key after a tone had been presented, which followed stimulus-onset by about 4 sec. By asking subjects to respond after the tone it was hoped to reduce any movement artifacts in the EEG, which was recorded between stimulus offset and the tone. Words were presented once every 7 seconds. In the second verbal task subjects had to press the response key if the word referred to a living creature, again after a tone following the stimulus. The most difficult verbal task involved responding (after the tone) to ambiguous words - both homonyms and homophones, as it was emphasised that spelling was not to be considered. Also, in this condition, the subject was asked to think of as many meanings for a word as possible between word presentation and the tone. The tasks had to be presented in the same order each time to
control for effects of psychological set; i.e. if 'animals' was the
target set after 'ambiguous words', subjects would probably be unable
to prevent themselves thinking about the alternative meanings
previously considered. Possible differences between the stimulus tapes
were controlled for by producing a master-tape of all the words, and
then re-recording the words in three different orders on separate
tapes. Thus any differences in volume, inflection, and so on, were
controlled for. All words were monosyllabic and spoken in a monotone.
The different orders of the words on each tape ensured that memory
played no part. Of the 80 stimulus words used, 20 were
'ambiguous/animal' words, 20 were 'ambiguous/non-animal', 20 were
'unambiguous/animal' and 20 were 'unambiguous/non-animal', (see
Appendix A). Thus, in all verbal conditions, subjects responded for
'ambiguous-animal' words. All subjects were given written instructions
(see Appendix A), asking them to respond with the index finger of
their right hands and to keep their eyes closed throughout the
experiment. They were asked to relax, to avoid gross movements and to
take their time in responding, reaction times being unimportant.

As a partial control, order of tasks was alternated, half the
subjects receiving the non-verbal tone-detection task before the
verbal tasks, and half receiving it following the verbal tasks. The
rationale for including this task involves the frequent observation
that in the 'resting' condition normally used as a comparison base
line in this type of study, there may be an alpha-power asymmetry
showing more alpha over the right hemisphere. This may reflect a real
physiological asymmetry, or, it has been suggested, simply the fact
that in a 'resting' condition, most people would day-dream, probably
verbally. It was hoped that by giving a non-verbal task, the tendency to think verbally would be reduced. The task involved detecting and responding to 40 randomly presented tones embedded in a white noise background. The task lasted as long as the verbal tasks, the tones being presented once every 14 seconds on average. During the tasks subjects were seated in a comfortable armchair and stimuli were presented at a comfortable volume, with the tape recorder positioned behind the subject's head, three feet away.

Subjects' responses to the 20 'ambiguous-animal' words and 20 of the 40 tones in the tone detection task were evaluated by the PDP8/e (response within three seconds following the tone scored as correct), and a score out of 20 printed at the end of each task.

2.2.4 Analysis

The data were analysed using FFT routines on the PDP8/e (see Appendix B for listings of programs used). Spectrum resolution was 0.5 Hz and the total power was calculated for the band 8-12 Hz for each channel pair. Also coherence was calculated for each pair of electrodes over a particular site (LB, RB, LW, RW). Average coherence was found for the 8-12 Hz band by averaging the $z$-transforms of the square root of the coherence values within this range.

Two types of analysis of variance were employed. In the first, hemispheres were included as a factor and thus if any task effects were found it would be possible to say whether they were due to changes in the left hemisphere, the right hemisphere or both. The
second type simply used an asymmetry score, \(((L-R)/(L+R)) \times 100\), to assess "relative" hemisphere activation and thus one would be unable to say in which hemisphere changes had taken place. A positive asymmetry score for power would imply greater power over the left than the right hemisphere, and thus, according to conventional EEG wisdom, greater right hemisphere activation, and vice versa. Both types of analysis are common in EEG studies of hemisphere function and involve different underlying assumptions. They do not necessarily lead to the same conclusions for a particular set of data, but there are no clear grounds for thinking of one as more valid than the other. Hence, both types were employed to allow a comparison to be made.

2.3 Results

ANOVA tables for all analyses of variance can be found in Appendix C.

The pattern of errors of the four tasks supported the hypothesis that the tasks differed in difficulty (Friedman two-way analysis of variance, \(X^2 = 33.725, p < 0.001\)). Further analysis using Wilcoxon tests showed that more errors were produced on the 'ambiguous-words' task (AMB) than on the 'animal-words' task (ANI; \(T = 10.5, N = 20, p < 0.005\)), more errors were made on ANI than the 'listening-to-words' task (LIS; \(T = 11, N = 17, p < 0.005\)) and the 'tone-detection' task (TON; \(T = 17, N = 18, p < 0.005\)). There was no significant difference between the number of errors on LIS and TONE. The errors which did occur during LIS and TONE were presumably due to lapses in attention.
There was no significant difference between the number of epochs rejected for each type of task (see Table 1).

Table 1. Errors and epochs rejected for each task in Experiment I.

<table>
<thead>
<tr>
<th>TASK</th>
<th>TONE</th>
<th>LIS</th>
<th>ANI</th>
<th>AMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN NO. OF ERRORS</td>
<td>0.500</td>
<td>0.375</td>
<td>1.917</td>
<td>3.917</td>
</tr>
<tr>
<td>MEAN NO. EPOCHS REJECTED</td>
<td>1.375</td>
<td>1.500</td>
<td>2.125</td>
<td>1.750</td>
</tr>
</tbody>
</table>

In this experiment each pair of electrodes was used to record the type of activity of a particular brain site in terms of average power and coherence in the alpha band of that site. Table 2 shows the mean coherence in the alpha band for sites in the left and right hemispheres for the twelve subjects doing the tone-detection task before the verbal tasks and for the twelve subjects doing this task after the verbal tasks. The mean asymmetry scores, \(((L-R)/(L+R))\times100\), are also shown.

The data for 'Broca's' and 'Wernicke's' areas were analysed separately because different amplifiers had been used which prevented direct comparison. Thus, for each site, a task x order x hemisphere analysis of variance was performed which showed that LB showed significantly higher coherence than RB (\(F_{1,22}=6.92, p<0.05\)). No other
Table 2. Mean alpha band intrahemispheric z-coherence for left and right "Broca's" and "Wernicke's" areas for each task and ordering of tasks, and associated mean ratios: \(((L-R)/(L+R))\times100\).

<table>
<thead>
<tr>
<th>TASKS</th>
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<tbody>
<tr>
<td>(ORDER 1)</td>
<td>LB</td>
<td>RB</td>
<td>RATIO</td>
<td>LW</td>
<td>RW</td>
<td>RATIO</td>
</tr>
<tr>
<td>LIS</td>
<td>1.92</td>
<td>1.78</td>
<td>3.33</td>
<td>1.51</td>
<td>1.52</td>
<td>-0.06</td>
</tr>
<tr>
<td>ANI</td>
<td>1.80</td>
<td>1.57</td>
<td>6.44</td>
<td>1.50</td>
<td>1.46</td>
<td>1.78</td>
</tr>
<tr>
<td>AMB</td>
<td>1.81</td>
<td>1.63</td>
<td>5.17</td>
<td>1.49</td>
<td>1.39</td>
<td>4.31</td>
</tr>
<tr>
<td>TONE</td>
<td>1.76</td>
<td>1.68</td>
<td>0.90</td>
<td>1.47</td>
<td>1.47</td>
<td>-0.34</td>
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</table>

<table>
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<tr>
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<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ORDER 2)</td>
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<td>RB</td>
<td>RATIO</td>
<td>LW</td>
<td>RW</td>
<td>RATIO</td>
</tr>
<tr>
<td>TONE</td>
<td>1.99</td>
<td>1.87</td>
<td>2.85</td>
<td>1.48</td>
<td>1.54</td>
<td>-5.43</td>
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<tr>
<td>LIS</td>
<td>2.04</td>
<td>1.80</td>
<td>5.89</td>
<td>1.42</td>
<td>1.55</td>
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<tr>
<td>ANI</td>
<td>2.12</td>
<td>1.84</td>
<td>6.92</td>
<td>1.43</td>
<td>1.58</td>
<td>-0.47</td>
</tr>
<tr>
<td>AMB</td>
<td>1.98</td>
<td>1.76</td>
<td>6.92</td>
<td>1.46</td>
<td>1.47</td>
<td>-3.84</td>
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</table>
significant results were found for intrahemispheric coherence. The coherence asymmetry scores also failed to produce any significant effects.

The analysis of raw power (see Table 3) revealed some interesting but puzzling results. Again, a task x order x hemisphere analysis of variance revealed a significant difference in power between LB and RB, the left side showing more alpha power (F1,22=7.91, p<0.05). The analysis showed no significant difference between LW and RW sites in terms of raw alpha power. The asymmetry ratios, \((\frac{L-R}{L+R})\times100\), were submitted to a task x order analysis of variance, which produced an unexpected main effect for order for both 'Broca's' (F1,22=8.37, p<0.01) and 'Wernicke's' (F1,22=5.07, p<0.05) areas. In each case the mean ratio was higher, showing relatively more power over the left hemisphere than the right, if the tone followed the verbal tasks than if it preceded them. Also, a significant order x task interaction was found for the 'Broca's' area sites (F3,66=2.76, p<0.05). Further analysis showed this to be due to the differences between the ratios for the AMB task and the TONE task, the other two verbal tasks not differing significantly from each other. There seems to be no obvious explanation for these differences.

2.4 Discussion

Before discussing the results of this experiment, attention must be drawn to the fact that the sampling frequency employed in this study would produce aliasing around a folding frequency of 16 Hz. Thus
Table 3. Mean alpha band power for left and right "Broca's" and "Wernicke's" areas for each task and ordering of tasks, and associated mean ratios: \(((L-R)/(L+R))\times100\).

<table>
<thead>
<tr>
<th>TASKS</th>
<th>MEAN</th>
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<th>MEAN</th>
<th>MEAN</th>
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</thead>
<tbody>
<tr>
<td>(ORDER 1)</td>
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<td>RB</td>
<td>RATIO</td>
<td>LW</td>
<td>RW</td>
<td>RATIO</td>
</tr>
<tr>
<td>LIS</td>
<td>3279</td>
<td>2595</td>
<td>9.59</td>
<td>2124</td>
<td>1587</td>
<td>15.39</td>
</tr>
<tr>
<td>ANI</td>
<td>3409</td>
<td>2679</td>
<td>10.63</td>
<td>2052</td>
<td>1566</td>
<td>13.63</td>
</tr>
<tr>
<td>AMB</td>
<td>3889</td>
<td>2925</td>
<td>16.30</td>
<td>2444</td>
<td>1768</td>
<td>16.25</td>
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<tr>
<td>TONE</td>
<td>4171</td>
<td>2890</td>
<td>17.26</td>
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<td>17.42</td>
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<td></td>
<td></td>
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<tr>
<td>TONE</td>
<td>3840</td>
<td>3608</td>
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</table>

-206-
activity in the alpha band would be irretrievably confounded with that in the 20-24 Hz range. As a consequence, it must be borne in mind that when the following discussion refers to activity in the alpha band, the contribution from the higher frequency range will be present. Unfortunately, this experiment was performed prior to the author becoming aware of this problem.

Leaving aside the findings relating power asymmetry to the order in which the tasks were carried out, there are a few aspects of this data worthy of further comment. Firstly, the experiment failed to show any clear-cut task effects on EEG at all. This may be due to the methodology employed in that the tasks may simply have not been difficult enough to engage sufficient cognitive processing, although the error data show that the subjects did produce a significant number of errors on the two most difficult tasks. However, this does not rule out the possibility that subjects were not actually engaged in the tasks for the full two second epochs during which EEG was recorded. But even if we accept this, most previous studies have found more alpha activity over the right hemisphere during 'resting' states, whereas the present findings indicate more alpha activity at F7 than F8. This finding is not entirely without precedent. Giannitrapani (1979a) found an asymmetry of this kind at these placements over a wide range of tasks for his right-handed subjects. The apparent contradiction with other reports of an opposite asymmetry or no asymmetry can probably be resolved by a consideration of the electrode placements involved. Almost all studies reporting greater alpha activity over the right hemisphere during rest have used occipital placements (Raney, 1939; Morgan et al., 1971, 1974; Fox, 1979) whereas
studies reporting no asymmetry have used other placements. Very few studies have used frontal placements. This account is further supported by the fact that although Giannitrapani (1979a) found a general trend towards L>R asymmetry for alpha activity for right-handers, this asymmetry was reversed at the occiput.

Another point worthy of note is the different pictures which emerge from the two different types of ANOVAs, for both coherence and power data. As previously stated neither type can be said to be less valid than the other. On the one hand, an ANOVA involving hemispheres as a factor allows one to judge if effects are due to changes in one or both hemispheres. On the other hand, the use of an asymmetry ratio of some kind takes some account of the huge variability between subjects with respect to EEG data. However it would be quite possible for the same data to lead to opposite conclusions concerning which hemisphere had been activated by a particular task if both types of analysis are performed. Indeed, if one were to compare the mean LW and RW power scores with the mean asymmetry ratios in the current experiment (see Table 3), they would seem to contradict each other. The question of which approach is more valid remains an open one, but it points out the need for a firmer theoretical foundation in interpreting EEG effects. However, for the remaining experiments in this series the more conservative and interpretable type of analysis, i.e. taking hemispheres into account as factors in any ANOVAs, has been adopted.

Finally, the sole coherence effect found was the relatively higher coherence at the left frontal site in comparison to its right homologue. Even if one could say with certainty that the experimental tasks had engaged a particular hemisphere, one could still not state
whether or not this should lead to an increase or decrease in coherence, either on theoretical grounds or on the basis of previous studies of hemisphere function using coherence analysis. However one apparently very reliable hemisphere coherence effect is that reported by Davis and Wada (1974, 1977a, b, c, d, 1978). These studies will be considered in more detail in the following chapter but in essence they found that VERs to simple flashes recorded from occipital and temporal sites were more coherent over the non-dominant hemisphere, whereas AERs to simple clicks were more coherent over the dominant hemisphere. These findings they tried to relate to the functional asymmetry of the brain. The facts that all tasks in the present study had involved auditory stimuli and all had shown relatively higher coherence at the left anterior site in comparison to the right could thus be related, although the Davis and Wada studies used EPs whereas this study used on-going EEG. This possibility was tested in the next experiment.
Chapter 3: Experiment II

3.1 Introduction

In the mid-1970s a series of reports appeared in the literature involving a unique use of the coherence function. Whereas all other investigators had used coherence to investigate on-going EEG, Davis and Wada (1974, 1977a, b, c, d, 1978) used it to analyse EP data. Although criticised, for example by Callaway (1975) for using an approach which "assures one of the disadvantages of both averaging and time-series analysis", it is difficult not to be impressed by the apparent reliability of the coherence effects found. As stated, the essential findings were that AEPs to simple click stimuli were more coherent between occipital and temporal points on the dominant hemisphere than the nondominant, and vice versa for flash-evoked VEPs.

The first report in this series (Davis, 1973) did not involve coherence analysis, but did entail power spectral analysis of AEPs and VEPs. As many of the methodological details did not vary between experiments, a fairly detailed account will be given here and the reader's attention will only be drawn to those aspects of other studies which differ from this. Monopolar recordings were made from O1 and O2, and C5 and C6, the latter pair being midway between T3 and C3, and T4 and C4, respectively. In the different reports C5 and C6 are also referred to variously as T1 and T2, or T3 and T4, but with the exception of Davis and Wada (1977d) and Wada and Davis (1977) the anterior active electrodes are always at the same C5 and C6 position (Jasper, 1958). All studies used linked ears as reference and forehead
ground. Four groups of 40 flash and 40 click stimuli, randomly mixed, were presented, with a one minute rest between groups, and a sampling rate of 100 Hz was used. Davis (1973) based each EP on 40 stimulus presentations and subjected the resulting waveforms from 10 right-handed subjects to power spectral analysis. He found two major frequency groups. Group I (0-5 Hz) occurred for both flash and click and was always more prominent at the temporal sites. It appeared to reflect long latency components. Group II (6-12 Hz) reflected shorter latency components of the original EP and was generally more variable, but interestingly it was more prominent at the primary projection area (i.e. occipital sites for flashes, temporal sites for clicks) in all cases except the right hemisphere response to flashes.

Davis and Wada (1974) reported upon a study of 10 epileptic patients, of whom five were known to be right-speech dominant (RSD) and five left-speech dominant (LSD) as determined by the carotid amytal test (Wada and Rasmussen, 1960). In this study, four sets of 20 clicks and flashes, randomly mixed, were used and each EP was based on 20 presentations, giving 4 AERs and 4 VERs per subject per electrode. Coherence analysis was limited to the first 0.5 second of the EP, and the 6-12 Hz band. Mean coherence for each subject was calculated by z-transforming and averaging at 6, 9 and 12 Hz over the four replications. The same type of analysis was performed on data from 12 normal right-handed subjects, who were assumed to be LSD. On this assumption, it was found that 19/22 subjects showed maximum occipital-to-temporal coherence over the dominant hemisphere for AERs, and 16/22 showed maximum coherence over the nondominant hemisphere for VERs. It was also reported that coherences were largest for homologous
sites, with temporal sites generally being more coherent interhemispherically than occipital sites, and that flashes produced more coherent EPs than clicks.

Davis and Wada (1977a) reported a similar study on 11 patients (6 LSD, 5 RSD as assessed by carotid amytal test), with a few methodological differences. Once again, four sets of 40 randomly mixed clicks and flashes were used, but each 0.5 second EP was based on 160 stimulus presentations, thus giving only one VER and one AER per electrode per subject. Coherence was not transformed and ANOVAs were used to analyse both power and coherence effects. With respect to power, it was found that the occipital response was greater than the temporal for the flash stimuli, and vice versa for the click. For coherence, once again the homologous pairs produced the highest coherences, but this time there was no difference between occipital and temporal pairings. For the interhemispheric coherences, no effects were found of type of stimulus used or speech-dominance of subjects. Again, clicks produced larger coherences in the dominant hemisphere and flashes in the nondominant. Maximum AER coherence occurred in the dominant hemisphere for 5/6 LSD and 4/5 RSD subjects. Maximum VER coherence occurred in the nondominant hemisphere for 6/6 LSD but only 2/5 RSD subjects. It would appear that these findings refer to the 3-9 Hz band, although at times this is not clear.

Generally, the same experimental format was used by Davis and Wada (1977b) in an attempt to extend and validate their earlier findings. Once again, each EP was based upon 160 stimulus presentations and the 3-9 Hz band is the one of interest, but in this analysis coherence is z-transformed again. The aim of this study was to determine
discriminant equations (using step-wise discriminant analysis) based on the results of 6 LSD and 5 RSD patients and to use these equations to ascertain the speech dominance of 12 'pure' right-handers and 12 'pure' left-handers. The final analysis included 3 independent coherence asymmetries: \((01:02-C5:C6)\), \((01:C5-02:C6)\) and \((01:C6-02:C5)\), for both AERs and VERs. The autospectral asymmetries \((01-02, C5-C6)\) were also included for both AERs and VERs. Only two of these measures were significant discriminators of speech dominance. These were the left minus right occipital-to-temporal coherence \((01:C5-02:C6)\) for both AERs and VERs. Using these two measures in the discriminant equations, 10/11 patients were correctly classified. When the normal subjects were classified according to the equations, eight right-handed and five left-handed subjects were classified as LSD and three right-handed and one left-handed as RSD. The remaining subjects were classed as having bilateral speech, insofar as the probability of correct classification was less than 0.95.

Davis and Wada (1977c) employed basically the same technique in a study of 16 LSD and 6 RSD patients, with the difference that rather than dealing only with the 3-9 Hz band analysis was based on the frequency of greatest cross-spectral activity which turned out to be 0-3 Hz for four patients. For AERs the dominant hemisphere had the more coherent response in 13/16 LSD and 5/6 RSD. For VERs maximum coherence occurred in the nondominant hemisphere in 13/16 LSD and 4/6 RSD.

Analysis focussed on the 3-9 Hz band for all subjects in Davis and Wada's (1978) study, which considered both power and coherence effects in relation to speech-dominance, handedness and sex of subject.
Subjects for this study were 16 LSD (nine male, seven female) and 6 RSD (three male, three female) patients and 12 'pure' right-handed normals (seven male, five female) and 12 'pure' left-handed normals (five male, seven female). The first part of the analysis was concerned with obtaining a discriminant function based on left hemisphere coherence minus right hemisphere coherence for both AER and VER asymmetries. This version of the discriminant function did not allow for a 'bilateral' classification and when both AER and VER asymmetries were utilised 14/16 LSD and 5/6 RSD patients were correctly classified. VER asymmetries did not seem to be consistently related to speech dominance according to this report, since 12/16 LSD and 4/6 RSD patients showed larger VER coherences in the right hemisphere. Also, a discriminant function based upon just the AER asymmetry correctly classified one more patient than the function based upon both AER and VER results. AERs seemed to be very consistently related to speech dominance in that 13/16 LSD and 6/6 RSD all showed larger AER coherences in the speech-dominant hemisphere. Using the discriminant function based just on AER coherence scores, 10/12 right-handers and 12/12 left-handers were classified as LSD.

The second part of the analysis involved ANOVAs of coherence and power data of the normal subjects which included handedness and sex of the subjects as factors. As expected flashes produced more coherent EPs in the right hemisphere and clicks in the left hemisphere overall. In order to investigate an interaction, coherences in the left and right hemispheres for VERs and AERs are presented separately for sex and handedness groups. It is claimed that the various groups "showed a basically LSD pattern", but looking at the histogram for right-handed
males it certainly appears that there is little coherence asymmetry with respect to AERs and that VER coherences are higher in the left, presumably speech-dominant hemisphere. The fact that this group clearly fails to show the typical LSD pattern could be of some importance in considering the results of the next two experiments in the current series.

With respect to power it was found that temporal area power increased for AERs and decreased for VERs and, conversely, occipital area power increased for VERs and decreased for AERs. Occipital-temporal differences in power were larger for AERs for right-handed subjects and VERs for left-handed subjects. Also, in right-handers the right hemisphere showed larger VERs and smaller AERs than the left. This pattern was reversed for left-handed subjects. When sex was considered, males showed a power distribution similar to right-handers, but females almost reversed this pattern for VERs and completely reversed it for AERs.

Davis and Wada (1977d) used 16 infants (mean age five weeks) as subjects and used electrode placements O1, O2, T3 and T4, referenced to linked earlobes. One second EPs based on 160 stimulus presentations were analysed with respect to coherence and power in the 3-9 Hz band. 13 of the 16 infants showed greater coherence in the left hemisphere than the right for click-evoked responses and 10 showed the opposite pattern for flash-evoked responses. VER power was greater at the occipital sites than the temporal and AER power was greater at the temporal sites than the occipital. Also, for the VERs, O2 showed greater power than T4, with the left hemisphere placements not differing in power. Again, this pattern was reversed for the AERs with
T3 showing more power than O1, but no difference between the right hemisphere placements. Wada and Davis (1977) mention extending the infant study to include 50 infants with essentially the same pattern of results, but no details of statistical analysis are presented.

Hence the coherence effects reported seem to be replicable in both adult and infant populations. In Experiment I in this series the only coherence effect found was the relatively higher coherence at the left frontal site in comparison to the right frontal site. It seemed possible that if the coherence of EPs showed the pattern reported by Davis and Wada with respect to modality of stimulation that such an effect may be found for on-going EEG also, thus accounting for the left-sided asymmetry of coherence in Experiment I where only auditory stimuli were used. This possibility was investigated in the following experiment. It was also decided, in contrast to Experiment I, to analyse EEG from the theta (4-7.99 Hz) and beta-1 (13-21.99 Hz) bands in addition to the traditional alpha band (8-12.99 Hz), because asymmetrical effects have been occasionally noted in these bands despite the fact that they are generally neglected.

3.2 Method

3.2.1 Subjects

12 male subjects were used, aged between 17 years 3 months and 34 years 6 months (mean = 22 years 7 months). All subjects reported themselves to be right-handed.
3.2.2 Apparatus

Silver/silver chloride electrodes were used and interelectrode resistance was less than 5 k-Ohms. EEG was amplified to a gain of 20K using an SLEep Model 10/8 EEG machine with low pass filter set at 25 Hz and a time-constant of 0.3 seconds, and incorporating a notch filter at 50 Hz to minimize mains interference. A PDP8/e computer was used to control stimulus presentation and data collection (see Appendix B for program listings). EEG was constantly monitored on oscilloscopes during an experimental session and the actual epochs analysed were also recorded on paper.

Flashes (20 microsecond duration through six inch aperture) were presented using a Flash-tac Stroboscope positioned approximately two feet from the subject. Light intensity was approximately 100 Lux and energy per flash, 0.3 Joule. Clicks (0.1 millisecond duration) were presented binaurally using Lafayette 767 Stereo headphones, an Interstate 20 MHz Log-Linear Sweep Generator-F77 and a Leak Stereo 30 amplifier. It was not possible to measure the transient intensity of the clicks, but when the signal generator was set to 'continuous' the noise level was 95 dB. The clicks were then at a comfortable volume.

Subjects sat upright in a wooden chair in a quiet, dimly lit room fixating a cross at the centre of the stroboscope's circular aperture for the duration of the experiment.
3.2.3 Procedure

Active electrodes were positioned at O1, O2, C5 and C6, with linked mastoids as reference, and a ground electrode on the forehead. Every effort was made to relax the subject in order to ensure as far as possible an artifact-free recording.

Collection of data and presentation of stimuli were controlled by a PDP8/e computer running the U/W-Focal program DW1 (see Appendix B). This program ensured that flashes and clicks would be randomly presented with a randomly varying interstimulus interval of two to three seconds. EEG was digitised at a rate of 64 Hz for one second immediately following stimulus presentation and the data were stored for each of 30 presentations of each type of stimulus. Unfortunately it was not possible to collect data for both types of stimulation during a single block due to limitations of the PDP8/e's file-handling capability. This meant that two blocks of stimuli were presented, each containing 30 flashes and 30 clicks, but that EEG was collected for only one type of stimulation in each block. The order of data collection was counterbalanced across subjects, with half of the subjects having EEG recorded following the clicks in the first block and flashes in the second block and the reverse order for the remaining subjects. Subjects were allowed to rest for a minute or two between blocks. Also, the amplifier channels were counterbalanced with respect to electrode position across subjects to control for any possible slight imbalances, and the position of the headphones was reversed for half of the subjects.

Before analysis all data were examined using an artifact-rejection
program (ARP; see Appendix B) which rejected any epochs containing artifacts. Thus, from the 30 epochs collected, the first 20 which were acceptable were used in the subsequent analysis.

3.3 Results

Mean power scores (arbitrary units) for each activity band, electrode position, modality of stimulation and order of data collection are presented in Table 4.

For each of the three frequency bands under consideration a 2x2x2x2 ANOVA was performed for the power data with Stimulus Type (flash v. click), Order of data collection ("flash EEG" first v. "click EEG" first), Hemisphere (left v. right) and Site (central v. occipital) as factors (see Appendix C for ANOVA tables). No significant effects were found in either the alpha or beta-1 bands with respect to power, but in the theta band significantly more power was found at the central placements (62.44) than at the occipital placements (40.68), (F1,10 = 24.15; p<0.001). Also, a significant Order x Stimulus Type interaction was found for theta power (F1,10 = 11.35; p<0.01). This reflects the fact that for Order 1 subjects (those for whom EEG data were collected in response to flashes in the first experimental block) theta power for flashes (53.85) was greater than theta power for clicks (48.20), whereas for the remaining subjects for whom the EEG data was collected in the opposite order, theta power to clicks (57.73) was greater than that for flashes (46.48). In other words, regardless of the type of stimulus, more theta activity was
Table 4: Mean power (arbitrary units) in theta, alpha and beta-1 bands at each electrode site for click and flash stimuli, for both orders of data collection (S.D.s shown in brackets).

ORDER 1 (n=6)  01  02  C5  C6

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<td>17.61</td>
<td>15.19</td>
<td>19.87</td>
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<td>(14.58)</td>
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produced during the first half of the experimental session than during the second, which could perhaps reflect the subjects becoming accustomed to the experimental situation, although it is not clear why this should affect theta band activity.

Mean z-coherences for each activity band, electrode pair, modality of stimulation and order of data collection are presented in Table 5.

For each pair of independent coherences (i.e. 01-02 vs. C5-C6; 01-C5 vs. 02-C6; 01-C6 vs. 02-C5) in each of the three frequency bands a 2x2x2 ANOVA was carried out with Stimulus Type, Order of data collection and Channel Pair as factors. For both the intrahemispheric coherences (01-C5 vs. 02-C6) and the 'diagonal' coherences (01-C6 vs. 02-C5) no significant effects were found in any frequency bands with the exception of a significant Stimulus Type x Order of data collection interaction for the theta band 01-C6/02-C5 coherences ($F_{1,10} = 5.15, p<0.05$). This reflected the fact that subjects in the Order 1 group showed much higher coherence to flash (0.53) than to clicks (0.40) for these channel pairs, whereas the Order 2 subjects showed little difference between click (0.47) and flash (0.46) coherence. No obvious explanation for this finding presents itself and indeed, it could well be a spurious result given the low level of statistical significance and the large number of tests performed. It is possible however that this effect is related in some way to the similar interaction in the theta band noted previously with respect to power.

For all three bands it was found that the occipital coherence was higher than the central coherence, reflecting the trivial effect of greater coherence with smaller interelectrode distance. For theta,
Table 5: Mean z-coherence in theta, alpha and beta-1 bands for each electrode pair, type of stimulation and order of data collection (S.D.s in brackets).

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<td>(0.319)</td>
<td>(0.209)</td>
<td>(0.320)</td>
<td>(0.215)</td>
<td>(0.196)</td>
<td>(0.261)</td>
</tr>
<tr>
<td>Flash</td>
<td>1.183</td>
<td>0.466</td>
<td>0.471</td>
<td>0.428</td>
<td>0.372</td>
<td>0.398</td>
</tr>
<tr>
<td></td>
<td>(0.251)</td>
<td>(0.134)</td>
<td>(0.196)</td>
<td>(0.145)</td>
<td>(0.112)</td>
<td>(0.146)</td>
</tr>
</tbody>
</table>
occupital coherence = 1.54, central coherence = 0.73 (F1,10 = 171.77, p<0.001); for alpha, occipital coherence = 1.31, central coherence = 0.49 (F1,10 = 205.03; p<0.001); for beta-1, occipital coherence = 1.23, central coherence = 0.53 (F1,10 = 165.90, p<0.001).

3.4 Discussion

Before commenting on the somewhat negative results of this experiment it is once again necessary to focus attention upon the methodological issue of aliasing. This experiment employed a sampling frequency of 64 Hz as it was felt that there would be no danger of aliasing occurring (Walter, 1963) with respect to mains (50 Hz) contamination due to the setting of the low pass filter at 25 Hz and the notch filter at 50 Hz. Aliasing occurs if the sampling rate is too low, so that frequencies equidistant from the folding frequency (half of the sampling frequency) are indissolubly confounded. Generally, the sampling rate should be at least 2.5 times the highest frequency present in the data. It became apparent upon completion of this experiment that in fact some 50 Hz contamination probably had occurred as many subjects showed a slight peak in the spectrum at 14 Hz. This, of course, would be due to the 50 Hz activity aliasing into this band around the 32 Hz folding frequency. Although attempts had been taken to filter out this higher frequency activity they had obviously not been successful and thus all findings in the beta-1 range should be treated with extreme caution.

It was hoped that the current experiment would both help to account
for the sole coherence effect found in Experiment I and also perhaps extend Davis and Wada's findings concerning coherence patterns produced by simple auditory and visual stimuli to the realm of on-going EEG. Despite different methodologies, it can certainly be concluded that the optimistic hypothesis that modality of stimulus presentation bears a simple relationship to coherence within the cerebral hemispheres has not been supported.

This result of course reflects only indirectly on the work of Davis and Wada reviewed earlier. Their studies involved a consideration of the coherence of EPs, not on-going EEG, and, as outlined, seems to show a very reliable effect. Thus it was decided to attempt a closer replication of their work in Experiment III. A detailed discussion will be deferred until the next chapter.
4.1 Introduction

Although Davis and Wada (1974, 1977a, b, c, d, 1978) have consistently reported finding that coherence was relatively higher from the left hemisphere for AERs in response to clicks and from the right hemisphere for VERs in response to flashes, no other investigators have attempted to replicate this effect. The finding is interesting in itself, but could have even greater potential as a reliable base from which to extend investigations. Thus it was decided to attempt a replication in the present experiment. Such an undertaking is not a simple one as Davis and Wada often used different techniques of analysis, for example sometimes transforming power and coherence measures and sometimes not, and often failed to give all of the required information to make an exact replication possible. However, the basic effect seems to be robust enough to show through despite these variations and so, although the following experiment attempts to follow the same methodology as Davis and Wada in all important respects, where it does occasionally employ a slightly different technique this will be pointed out.
4.2 Method

4.2.1 Subjects

Subjects were 14 males, right-handed (by self-report), aged between 19 years 5 months and 37 years 8 months with an average age of 24 years 1 month.

4.2.2 Apparatus

Apparatus was as for Experiment II with the difference that a Commodore Pet computer was used to control stimulus presentation and to trigger data collection on the PDP8/e (see Appendix B for program listing). This was used in conjunction with the LAB8/e Basic Averager Program Systems Software which enabled AER and VER data to be collected in separate files during a single experimental block.

Whereas Davis and Wada used a low pass filter set at 100 Hz and then digitally filtered at 20 Hz upper cut off, the present study (like Experiment II) had low pass filter set at 25 Hz and a 50 Hz notch filter. Time constant was once again set at 0.3 seconds, and data were digitised at 128 Hz (c.f. 100 Hz for Davis and Wada). Every attempt was made to make the flash and click stimuli as similar to those used by Davis and Wada as possible, but this was only feasible to a limited extent as Davis and Wada used different settings across studies. Current settings were as for Experiment II.
4.2.3 Procedure

Details of EEG recording were as for Experiment II.

Flashes and clicks were presented in a random order with randomly varying interstimulus intervals (between two and three seconds) until 40 of each type of stimulus had been presented in an experimental block. Four blocks were presented giving a total of four VERs and four AERs per electrode per subject. Subjects were allowed to have a break between blocks if they wished, and headphones were reversed half-way through the experiment to control for any possible imbalance.

The digitised EEG was averaged and EPs displayed automatically by the software. The stored data were converted into a suitable format for analysis by the coherence analysis program and then transferred to the Leicester University CYBER 73 for analysis. Thus the final analysis for each subject was based on the coherence (z-transformed) for all possible electrode pairings and the power for each electrode in the 3-8.99 Hz band, the activity band most commonly considered by Davis and Wada. Coherence and power values relate to the full one second EP (as used by Davis and Wada, 1977d; Davis, 1973; Wada and Davis, 1977), as it was felt that this would give a better estimate of coherence than the analysis of just the first 0.5 second of the EP as used in the remaining studies.
4.3 Results

Table 6 summarises power (arbitrary units) in the 3-8.99 Hz band for the AERs and VERs at each electrode.

Table 6: Power (3-8.99 Hz) for AERs and VERs at each electrode position (S.D.s shown in brackets).

<table>
<thead>
<tr>
<th></th>
<th>O1</th>
<th>O2</th>
<th>C5</th>
<th>C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>2.922</td>
<td>2.609</td>
<td>10.253</td>
<td>9.724</td>
</tr>
<tr>
<td></td>
<td>(1.585)</td>
<td>(1.227)</td>
<td>(4.568)</td>
<td>(5.672)</td>
</tr>
<tr>
<td>Click</td>
<td>2.779</td>
<td>2.922</td>
<td>11.685</td>
<td>11.538</td>
</tr>
<tr>
<td></td>
<td>(1.464)</td>
<td>(1.759)</td>
<td>(6.239)</td>
<td>(7.765)</td>
</tr>
</tbody>
</table>

Two aspects of the data are striking. Firstly the great variability in response between subjects which was also apparent in the two previous experiments and is a common problem with electrophysiological data. Secondly, the much larger responses recorded from the central electrodes. A 2 (Type of Stimulus) x 2 (Hemispheres) x 2 (Placement) ANOVA confirmed this by showing a significant difference (F1,13 = 30.66, p<0.001) between central power (10.80) and occipital power (2.81). This was the only significant effect (see Appendix C). This is puzzling as one might reasonably expect a significant Type of Stimulus x Placement interaction, if the occipital lobes responded more to the visual stimulation, and the central placements to the auditory stimulation. It is possible that the particular frequency band analysed did not reflect such an interaction where perhaps others
might have done. However it was noted when the experiment was actually in progress that the central responses seemed to be much clearer and stronger than the occipital regardless of the type of stimulus being presented, although the reason for this was not clear.

Table 7 presents the mean z-coherences for the AERs and VERs of all electrode pairs over the 3-8.99 Hz band.

Table 7: Mean z-coherences for all electrode pairs for VERs and AERs (S.D.s in brackets).

<table>
<thead>
<tr>
<th></th>
<th>01-02</th>
<th>C5-C6</th>
<th>01-C5</th>
<th>02-C6</th>
<th>01-C6</th>
<th>02-C5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>1.822</td>
<td>1.848</td>
<td>1.277</td>
<td>1.221</td>
<td>1.149</td>
<td>1.201</td>
</tr>
<tr>
<td></td>
<td>(0.495)</td>
<td>(0.342)</td>
<td>(0.383)</td>
<td>(0.429)</td>
<td>(0.419)</td>
<td>(0.378)</td>
</tr>
<tr>
<td>Click</td>
<td>1.758</td>
<td>1.707</td>
<td>1.040</td>
<td>1.086</td>
<td>1.019</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>(0.283)</td>
<td>(0.335)</td>
<td>(0.354)</td>
<td>(0.369)</td>
<td>(0.337)</td>
<td>(0.323)</td>
</tr>
</tbody>
</table>

No significant main effects or interactions were found for either of the ANOVAs involving interhemispheric z-coherences (i.e. 01-02 vs. C5-C6 and 01-C6 vs. 02-C5). However, the 2 x 2 ANOVA for intrahemispheric z-coherences produced a significant main effect ($F_{1,13} = 4.89; p<0.05$) for Stimulus type showing that intrahemispheric z-coherences were higher for VERs (1.25) than for AERs (1.06); (see Appendix C for ANOVA tables). Davis and Wada (1977a) performed ANOVAs on untransformed coherence scores. Disregarding the question of the validity of such an analysis, the present data were also analysed in their untransformed state, but this failed to produce any significant effects, and full details of this analysis are not presented here.
Thus the main hypothesis of this experiment, that AERs would be relatively more coherent in the dominant (presumably left) hemisphere and that VERs would be relatively more coherent in the nondominant (presumably right) hemisphere, was not supported.

4.4 Discussion

Although the current experiment failed to support the main hypothesis under investigation, i.e. that coherence would be relatively higher in the dominant hemisphere for AERs and in the nondominant hemisphere for VERs, several points are worthy of further discussion. Firstly, the distribution of power in the 3-8.99 Hz band failed to reflect the expected distribution which would have shown a relative increase in power at the primary projection area for a particular stimulus modality. It will be recalled that Davis (1973) reported finding two major frequency groups. Group I (0-5 Hz) power was always greater at the central placements for both flash and click stimuli and reflected the long latency components of the EP. As the present experiment analysed the EPs for the full one second epoch, it might be argued that the current analysis in the 3-8.99 Hz range is showing a similar pattern to Davis's (1973) Group I frequencies. His Group II frequency range (6-12 Hz) was the one which reflected the shorter latency components and was greatest at the primary projection area. If the most influential frequencies within this range were outside the current range, say 9-12 Hz, then a parsimonious account of the present findings could be offered. However, this seems very
unlikely as in most of Davis and Wada's later studies they concentrated on the 3-9 Hz range, and all found that primary projection areas were more responsive to the appropriate type of stimuli. It is also possible that the explanation lies in the equipment used to generate the stimuli. It was noted by many subjects that the stroboscope made a slight clicking sound as it fired, as did that used by Davis and Wada (1977a; p 804). If the flash produced by the stroboscope was not bright enough to produce a sizeable VER, it is possible that all of the EPs were, in fact, AERs although this seems very unlikely. The exact intensities of stimulation might have differed from those used by Davis and Wada, but as they state (1974; p 6), "preliminary experiments seem to indicate that the asymmetries exist for a variety of flash and click intensities".

The only significant coherence effect showed that intrahemispheric coherence was higher for flash than for click stimuli. Davis and Wada (1974) write, ".....in general, the click coherences were smaller than the flash coherences, and that the highest coherences for each modality were between left and right occipital (O1:O2) and left and right temporal areas (T1:T2)". Although the finding of higher flash than click coherences was not supported in later reports involving statistical analysis, it was supported by this study. Also, an examination of Table 7 offers some support, not too surprisingly, for the assertion in the latter half of the above quotation. With respect to the main hypothesis of the current experiment however, no support was forthcoming. Flash coherences were not significantly higher on the nondominant (presumably right) side. Click coherences were not significantly higher on the dominant (presumably left) side.
This failure to replicate was quite unexpected in the light of the number of reports produced by Davis and Wada. Over the total number of studies there were many changes in technique and procedure including:

a) sometimes coherence was z-transformed (Davis and Wada, 1974, 1977b), sometimes it was not (Davis and Wada 1977a, c, d, 1978)

b) sometimes power was log-transformed (Davis and Wada, 1977a, b, 1978), sometimes it was not (Davis and Wada, 1977d),

c) sometimes EPs were one second long (Davis, 1973; Davis and Wada, 1977d; Wada and Davis, 1977), sometimes they were 0.5 seconds long (Davis and Wada, 1974, 1977a, b, c, 1978),

d) EPs were usually based on 160 stimulus presentations, but sometimes on only 20 (as in Davis and Wada, 1974),

e) the number of EPs analysed per electrode was usually only one, but four in the case of Davis and Wada (1974),

f) the frequency band of interest was usually 3-9 Hz, but sometimes 6-12 Hz (Davis and Wada, 1974), or even 0-3 Hz (Davis and Wada, 1977c),

g) various types of statistical analysis were employed across the studies, such as multivariate ANOVAs (Davis and Wada, 1974), univariate ANOVAs (Davis and Wada, 1974, 1978), discriminant analysis (Davis and Wada, 1977b, 1978), Fisher exact probability test (Davis and Wada, 1977a) and Wilcoxon and Friedman tests (Davis and Wada, 1977d).

Thus, it seems possible that the current study differed in some crucial respect from the appropriate technique, design or procedure, even though the reported coherence effect appears to be so robust and reliable. However, a closer inspection of Davis and Wada's series of

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reports reveals some interesting, though not obvious, aspects to their work. Firstly, a conscious decision was made when designing the current study to use right-handed males as subjects because they are generally regarded as being the type of subjects most likely to show the strongest signs of lateralisation. However, if one examines Davis and Wada's (1978) Figure 2 (p 47), one can see that when the subjects in this study are divided into four groups on the basis of sex and handedness, that the right-handed males show no asymmetry of coherence for AERs and higher coherence over the left hemisphere for VERs. This histogram directly contradicts the claim made in the text that all groups "showed a basically LSD pattern". In the light of this, it is perhaps not surprising that the 'typical LSD pattern' was not produced by the right-handed (presumably LSD) males used in this study.

A second point worth noting is that it seems at least highly possible that the same subjects were used repeatedly in the different experiments, or possibly even that the same raw data were reanalysed in different ways, even though no mention is made of this by Davis and Wada. If indeed this is the case then it is not surprising that the effect was so apparently reliable. This claim is made on the basis of an examination of the age and sex distributions of the normal and patient samples used in the studies involving adult subjects, which were as follows:
1974: Patients: 5 LSD, 5 RSD; 7 male, 3 female; age 13-47 years
Normals: 12 right-handed; 7 male, 5 female; age 19-28 years

1977a: Patients: 6 LSD, 5 RSD; 8 male, 3 female; age 13-47 years

1977b: Patients: 6 LSD, 5 RSD; 8 male, 3 female; age 13-47 years
Normals: 12 right-handed; 7 male, 5 female; ages not given
12 left-handed; 6 male, 6 female; ages not given

1977c: Patients: 16 LSD 6 RSD
11 male, 5 female;
3 male, 3 female;
Age of total sample 12-43 years

1977d: Patients: 16 LSD 6 RSD
9 male, 7 female;
3 male, 3 female;
Age of patient sample 13-43 years
Normals: 12 right-handed; 7 male, 5 female;
12 left-handed; 5 male, 7 female;
Age of normal sample not given.

A general criticism of the Davis and Wada studies, which applies to a lesser extent to the study just reported here, is that the number of degrees of freedom associated with each coherence estimate appears to be very small indeed. It is a serious methodological short-coming of the Davis and Wada series, but the full extent of the problem is hard to assess as full details of smoothing procedures (if any) are not presented. At times it would appear that smoothing may be restricted
to, at most, six frequency bands, with no smoothing whatsoever across replications (e.g. Davis and Wada, 1977a, b, c).

In conclusion then, the last two experiments not only failed to extend Davis and Wada's findings but actually failed to replicate them. The possible reasons put forward for this may or may not be valid, but it does appear that at the very least the effect they reported is not as robust and reliable as one might have hoped and therefore does not offer a sound base from which to extend studies of hemisphere asymmetry utilising coherence analysis. It must also be pointed out that the initial three studies in this series were not without methodological flaws. The sampling rates used in the first two studies could have produced aliasing, although this probably only affected the beta-1 band in Experiment II. All three studies have employed a linked-mastoid reference which, whilst by no means the worst choice, is not without problems as outlined previously. The issue of possible anatomical asymmetries between the cerebral hemispheres has, as in most other studies, been conveniently ignored. The remaining three studies in this series do take account of these issues and also attempt to topographically map coherence, phase angle and power relationships on the scalp during a simple task in the hope that more basic groundwork of this type might help to cast light on possible interpretations of task-related effects and findings from non-normal populations.
Chapter 5: Experiment IV

5.1 Introduction

Before considering the aims of this particular experiment, it will be useful to consider previous studies that have examined phase angle relationships, both in terms of methodology and findings. Certain studies involving phase relations have already been mentioned (Section 1.3.1.1) and various aspects of spectral analysis have been outlined (Section 1.4.1). Those discussions will not be repeated here.

Papakostopoulos et al. (1971) explain how Fourier analysis may be used to separate the frequency components of a signal and allow a phase spectrum to be produced based on the sine and cosine coefficients. This in itself is not usually meaningful because obviously phase is determined by the arbitrary point in time that sampling begins, but if two phase spectra are considered, then the phase difference between them can also be calculated and this can be very useful. Its main usefulness comes in studies of EEG which consider the oscillations in potential as reflecting "travelling wave" phenomena (Petsche and Shaw, 1972; Vos et al., 1975). Unfortunately, much of the research performed to date has produced inconsistent results using a variety of different techniques. One possible reason for contradictory findings is the age-old problem of the use of a reference electrode which is active with respect to EEG. As many authors have pointed out (e.g. Cooper, 1959, 1975) amplitude and phase relationships will always be confounded if an active reference is employed, and no cephalic reference is inactive although the forehead
may be preferable to other sites (Pocock, 1976). The best solution is probably, once again, a noncephalic reference electrode (Stephenson and Gibbs, 1951).

Garoutte et al. (1959) did not declare the reference used in their study of twenty subjects in which they recorded normal alpha from sagittal and parasagittal chains of electrodes. They noted a finding which many others have reported since, namely that sometimes the waves appeared to travel from the anterior to the posterior scalp while at other times the opposite occurred, especially for the parasagittal chains. The difference in terms of time was of the order of 30-40 msec, although there was a great deal of variation between and within subjects. For the midsagittal placements, Garoutte et al. claimed that the waves tended to appear simultaneously.

These two different types of wave were also noted in a report of an extensive study of the alpha waves of a young man by Cooper and Mundy-Castle (1960) using the famous toposcope (see Cooper, Osselton and Shaw, 1980). They state that, "two main categories of anteroposterior, spatio-temporal distribution were distinguished, one in which the instant of maximal amplitude of alpha waves became progressively later or earlier according to the proximity of the recording electrodes to the occiput, the other in which maximal amplitude occurred simultaneously in all channels, usually with a change of sign over the occipital areas. Exact interhemispheric synchrony was rare". They also noted that the direction of sweeping can change. In twenty normals the direction was predominantly anterior to posterior, but in a group of 16 mentally disturbed patients the opposite was found.
Hori et al. (1969) also used a toposcope in their analysis of phase relationships in six normal adult males' EEGs. The subjects were chosen because of the quality of their alpha, and three chains of anterior to posterior electrodes were attached over one hemisphere (nose reference). The similarity of the change in phase difference of alpha waves obtained through adjacent electrodes was quantified by using the correlation coefficient (r). According to the values of r, the brain could be divided into three areas: (1) frontal (r = 0.91-0.98), (2) parietal and occipital near the midline (r = 0.65-0.87), (3) temporal (r = 0.52-0.65).

Shaw and McLachlan (1968) used the delay required to produce the maximum covariance between two EEG signals to estimate the alpha rhythm propagation time. The signals were recorded from two points over the posterior left hemisphere, referred to an average common reference of some twelve electrodes. The investigators were investigating a tentative hypothesis proposed by Cooper and Mundy-Castle (1960) that the propagation time of alpha waves was related to the level of arousal of the subject. Arousal was gauged in this study by measuring palmar resistance over a number of situations, and then within-subject correlations were calculated between the level of arousal and alpha time delay. Seven subjects showed a positive correlation out of a total of eight subjects, and these were significant in five cases, thus offering support for the hypothesis. Montagu (1975) interpreted the fact that he found no differences in phase angle between normal and hyperkinetic children as indicating that the latter were not overaroused.

Giannitrapani (1970b) using his standard array of electrodes and
variety of tasks (see Section 1.3.1.3) investigated task effects on phase angle relationships in 32 right-handed boys. Giannitrapani proposes that the dominant hemisphere for a particular task might be expected to lead or to lag depending upon two alternative hypotheses. He states that,

"The dominant area could be characterised by 'leading activity', inasmuch as the waveforms appeared earlier on that side. The dominant area could also be characterised by 'lagging' activity inasmuch as the waveforms on that side were delayed by intervening neural networks responsible for the bilateral execution of a given task."

Phase angles were compared across five conditions, all eyes closed: (1) awake resting, (2) listening to white noise, (3) listening to music, (4) listening to a voice reading a story and (5) awake resting (again). Of 36 anterior-posterior and lateral comparisons only five showed significant asynchronies. The degree of asynchrony varied as a function of frequency, condition and sites, but there was generally anterior leading for prefrontal-occipital and central occipital comparisons, and left-leading in the temporal areas. Consideration was also given to changes in phase relationship between rest and task conditions. The anterior leading present while resting underwent an increase during auditory stimulation, whereas music and voice produced a decrease in the temporal left leading. However, in the alpha band, listening to a voice decreased anterior leading, but only over the left hemisphere. The reader is referred to the original report for a
Pocock (1980a, b) reports on a very interesting study of alpha waves recorded from fifteen right-handed males using twelve scalp electrodes placed in a regular matrix of three transverse sites (left hemisphere, midline and right hemisphere) in four rows (occipital, parietal, central and frontal) according to the 10-20 system. The reference electrode was in the middle of the forehead. Data was analysed for two second epochs in two conditions: either resting or just prior to a manual button press. Fourier analysis with respect to phase concentrated on that frequency component within the alpha range which produced maximum power across all components, channels and trials. The results showed that the waves usually appeared to travel from the anterior to the posterior sites, although sometimes they travelled in the opposite direction. Spreading was found to be slightly faster just prior to a response. By averaging together all the anterior leading (AL) and posterior leading (PL) components, and ignoring the "relatively few components" that could not be seen to conform to either of these patterns, Pocock estimates that the waves appear to travel at a rate of about 10 m/sec. Neither hemisphere consistently led the other.

Pocock points out that many different patterns of propagation have been reported in the literature, some investigators observing only anterior to posterior sweeping (Suzuki, 1974; Shaw and McLachlan, 1968), some only the reverse (Nunez, 1974; Walter et al., 1966), some both (Cooper and Mundy-Castle, 1960; Rémond et al., 1969; Barlow and Estrin, 1971) and others not discerning any consistent pattern (Lopes da Silva and Storm van Leeuwen, 1978; Petsche and Rappelsberger,
Also, the velocity of propagation has been variously estimated as 0.5 m/sec (Nunez, 1974), 3 m/sec (Rémond et al., 1969), 5 m/sec (Cooper and Mundy-Castle, 1960), 6 m/sec (Suzuki, 1974) and 7 m/sec (Walter et al., 1966), although animal work, using more closely spaced electrodes has tended to produce slower estimates (Lopes da Silva and Storm van Leeuwen, 1978; Petsche and Rappelsberger, 1970). Pocock proposes an ingenious 'spatial aliasing' hypothesis to account for these apparently contradictory findings, but a full discussion of this hypothesis will be deferred until Section 7.5 for the sake of clarity of presentation. That is, the results of the final three experiments will be presented and discussed in such a way as to demonstrate the actual reasoning behind them, for at the time of execution the author was not aware of Pocock's hypothesis. However, the results will be considered vis à vis Pocock's hypothesis later.

The 'spatial aliasing' hypothesis is essentially based upon the idea that any estimate of phase based upon Fourier coefficients is usually limited to the range -180 degrees to +180 degrees. Thus there is no way to distinguish, for a particular component and a particular pair of electrodes, between a leading phase angle of x degrees and a lagging phase angle of (360 - x) degrees. To make matters even worse, any integer multiple of 360 degrees could be added to a particular phase angle without altering it from the point of view of spectral phase analysis. Inouye et al. (1981a, b; 1982) claim that their method of 'entropy analysis' is thus preferable to standard phase spectral analysis insofar as it can give the direction of 'information flow' between two cortical areas, as well as a genuine estimate of the delay involved. Inouye et al. (1981a) used their method to study the
direction of alpha spread in ten normal subjects during eyes-closed resting. The electrodes were placed at O1, P3, C3 and F3, and homologous sites on the right hemisphere, each referred to a linked ear reference. The intrahemispheric dominant direction of information flow was found to be from anterior to posterior, whereas the interhemispheric dominant direction varied from subject to subject, although more information tended to flow from right to left. Generally, the intrahemispheric information flow was greater than the interhemispheric.

Inouye, Shinosaki and Yagasaki (1982) used the same type of analysis to determine the dominant direction of information flow in the central area during voluntary movement. Ten right-handed subjects performed opposing thumb movements with the right hand, the left hand or both hands simultaneously, while EEG was recorded from C3, C4, O1 and O2 referred to the ipsilateral ear. In the central area, information flow from right to left hemisphere was larger than from left to right hemisphere for right thumb movements. This relationship was reversed for left thumb movements. With bilateral thumb movements, no dominant direction could be discerned. As expected, these effects were not found at the occipital electrodes.

All of the studies to be mentioned in the remainder of this section involve estimates of phase derived along with coherence. Inouye et al. (1981b) carried out a direct comparison of entropy analysis and coherence analysis. Fourteen right-handed subjects listened to meaningful and non-meaningful verbal stimuli while EEG was recorded from O1, O2, W1 and W2 (Matsumiya et al., 1972) referred to linked ears. A resting baseline condition was also included in this study. In
the alpha band, information flow from W1 to W2 was significantly
greater than flow from W2 to W1 in the meaningful stimuli condition,
although no other significant differences were found. Coherence was
found to be significantly higher between occipital electrodes compared
to temporal, although this may well simply reflect the fact that they
were nearer, and no significant interhemispheric phase differences
were found. Vos et al. (1975) analysing EEG from bipolar placements at
T5-01 and T6-02 in one subject also found no evidence of a wave
travelling between the hemispheres. They noted that if coherences in
the alpha and beta bands were high, phase angles tended to be low,
whereas if coherence was low phase angles were erratic.

In Section 1.4.2 a number of coherence studies were reviewed,
although a consideration of phase angle effects was deferred until
this section. The reader is referred back to Section 1.4.2 for a more
detailed account of the experimental procedures involved.
Giannitrapani (1975a; Giannitrapani and Roccaforte, 1975), as already
mentioned, found reliabilities for phase differences to be very low
indeed, although variability in the reliability coefficient was noted
across tasks and frequency components. Giannitrapani (1979b, 1980) in
a comparison of normals and schizophrenics noted that most significant
differences were obtained for those comparisons involving the most
distant brain areas. Frontal to occipital comparisons did not give
consistent anterior-to-posterior (AP) or posterior-to-anterior (PA)
leading across frequencies, but for the 11 Hz component, the AP
pattern predominated. Interestingly, in the 13 Hz band normals again
showed the AP pattern, while the schizophrenic group showed the
reverse. With respect to interhemispheric pairs, T3 led T4 across most
frequencies for the normals, but no consistent phase differences were noted at the occipital placements.

Koles and Flor-Henry (1981) reported that for alpha frequencies, when normal subjects were performing a verbal task, temporal placements led parietal placements, but this pattern was reversed when a spatial task was performed. This effect occurred more strongly over the left hemisphere than the right. Flor-Henry and Koles (1980) point out that when the female subjects' data were analysed separately the phase relationships described were only found for the spatial task. Further analysis of phase relationships in the alpha band revealed that in normals with eyes open P3 led P4, T3 and T4, and that P4 led T3. In manic subjects none of these phase relationships were significant, and for depressives the only significant effect was that P3 led P4. Many other differences between the psychotic groups and normals were noted and the reader is referred to the original reports for further details (Flor-Henry et al., 1979; Flor-Henry and Koles, 1980). No easily interpretable pattern emerges from the data.

Flor-Henry and Koles (1982) attempted to extend their findings from normals using the same methodology but a larger group containing both males and females, dextrals and sinistrals. Once again, there is little point in cataloguing all of the significant phase differences between groups as it is difficult to see any clear pattern emerging from these results. However, it is certainly worth noting that if one studies the results from the dextral subjects alone, many of the findings differ from those reported for normals in the previous study. No attempt is made to account for these discrepancies. Using the same electrode placements as Flor-Henry and colleagues, Beaumont et al.
(1978) report no interhemispheric phase differences in the alpha band, but a consistent lead of parietal over temporal placements across all conditions, which was usually stronger for males.

One interesting point is that all of the studies of phase angle effects using coherence analysis reported so far have produced much smaller estimates of phase difference between electrodes than studies using other forms of analysis. This point will be discussed more fully later. There are, however, at least two exceptions to this general observation. Firstly, Hord et al. (1974) found differences of around 150 degrees between frontal and occipital placements (corresponding to 40.3 msec delay for a 10 Hz wave) in six normal subjects in the non-feedback stage of an alpha self-regulation study. Electrodes were placed at Fp2, T4 and O2 (linked mastoids reference), and fairly low coherences were reported throughout for all channel pairs. During a feedback session in which subjects were reinforced for producing alpha waves the phase difference increased by about 25 degrees (7 msec).

The second study to find phase angle differences of fairly large magnitude using coherence analysis is that of Suzuki (1974). He placed electrodes at equidistant intervals along the midsagittal line on eleven normal subjects and, to the author's knowledge, is the only study prior to the current series to use a non-cephalic reference electrode when investigating phase angle effects. Power, cross-spectra, phase angle and coherence were calculated for EEG recorded while subjects relaxed with eyes closed. Phase angle results are presented separately for long periods of EEG (one or three minutes) and short periods (ten seconds), but the actual procedures involved in data analysis, such as details of smoothing, are not
presented. Suzuki distinguishes between what he calls a 'generalised' EEG component, which has a high value of coherence over a wide scalp area, and a 'localised' component which is "found in power spectra of EEGs only at a circumscribed region on the scalp without having significant values of correlation and coherence to EEGs of remote areas". According to Suzuki, for the longer periods of EEG, the generalised component shows a gradual phase advance towards the frontal region, but seldom reaches 180 degrees. The phase shift at intermediate points is not linearly related to the distance between them. Suzuki also notes that high coherence values are associated with low phase angle differences. On the one hand, this is to be expected as high coherences will also be associated with shorter interelectrode distances, but perhaps it ought to be borne in mind that the lower the coherence, the less reliable the phase angle estimate (Vos et al., 1975). The localised components did not show such consistent trends with much more variability between subjects. When phase analysis was performed upon the shorter periods of EEG (10 sec), phase angles were found to vary more or less around the value produced by the analysis on the longer periods. This variability was much greater for the localised components. These findings led Suzuki to conclude that alpha rhythms could be classified into two types corresponding to his localised and generalised components.

In summary, several points emerge as worthy of note:

(1) With respect to interhemispheric phase differences, most studies fail to note any consistent leading by either hemisphere (Vos et al., 1975; Beaumont et al., 1978; Pocock 1980a, b) although it is generally recognised that exact interhemispheric synchrony is rare.
There have been occasional reports of one hemisphere leading the other, but such effects often seem to be dependent upon such factors as electrode placement (Giannitrapani, 1979b), task effects (e.g. Flor-Henry et al., 1979) and subject variables (Flor-Henry and Koles, 1982).

(ii) With respect to intrahemispheric phase differences, many reports have noted both AP and PA waves, although anterior leading does seem to be more common. A number of studies have also remarked upon a wave pattern in which maxima appear at all electrodes simultaneously.

(iii) With respect to phase difference estimates produced by coherence analysis, it has been noted that these estimates are generally much smaller than those produced by other means of analysis, although there are exceptions (Hord et al., 1974; Suzuki, 1974). Also, a general tendency for high coherences to be associated with low phase estimates has been observed.

(iv) Possible problems of interpretation have been mentioned, but not discussed in detail. Such a discussion will be presented in Chapter 7.

Having presented this brief review of previous studies of phase angle effects, the aims of this particular experiment will be outlined. A consideration of anatomical asymmetries between the hemispheres and their implications for EEG studies has already been presented (Section 1.3.3), but the first three experiments in this series were carried out, like virtually all others in this area, without taking such findings into account. It would appear that the
investigator has two options. Firstly, investigations could be limited to areas of cortex where, to the best of our knowledge, no asymmetries exist. This is not a very satisfactory proposal as obviously it greatly limits the scope of investigations and, besides, most studies that report asymmetries in EEG have involved placements at areas of cortex that are known to be asymmetric across the midline. The second and preferable option is to place electrodes in approximately the same areas that are currently studied, but to take the anatomical asymmetries into account. This could perhaps be done using a group of electrodes clustered together over a particular cortical area of each hemisphere in such a way that the likely extent of any anatomical asymmetry would be covered. Then results could be considered in terms of whether all, any or none of the interhemispheric pairs showed the expected asymmetries. Hopefully, in this way, a step could be taken towards deciding if effects previously reported were genuine reflections of asymmetry of function, and not simply of anatomy.

Another approach, the one which will be pursued in this study, is to attempt to use EEG techniques to locate the position of various fissures, especially the Sylvian fissure, and to use this information in order to place electrodes at points which are equivalent anatomically with respect to the hemispheres, rather than just symmetrical with respect to the surface of the scalp. Previous studies have claimed to demonstrate methods of using EEG or EP techniques to demonstrate the position of various fissures. For example, Vaughan and Ritter (1970) looked at the distribution of AERs on the scalp and reported that both N100 and P200 inverted in polarity across the approximate location of the Sylvian fissure, but Kooi et al. (1971)
claimed that these polarity inversions were due to the use of a nose reference, and that they were thus not related to the position of the Sylvian fissure. Kooi et al. supported their case by presenting data recorded using both a nose reference and a balanced non-cephalic sternovertebral reference (Stephenson and Gibbs, 1951), the latter reference producing no phase reversal. McCallum and Curry (1979) and Streletz et al. (1977) also reported no polarity inversion using a noncephalic reference electrode (NCRE). Thus it would appear that the polarity inversion is probably not due to activity from dipole layer sources within the primary auditory projection cortex of the supratemporal plane (Vaughan and Ritter, 1970), but to activity at the nose reference. Vaughan (1974) attempted to refute Kooi et al.'s claim by arguing on theoretical grounds that the sternovertebral reference used by the latter group was in fact the active one, but the latest study addressed to this issue (Wolpaw and Wood, 1982) strongly supports Kooi et al. Thus, this would not appear to be a reliable approach to locating the position of the Sylvian fissure.

Giannitrapani (1975) claims that it is possible to identify cortical structures using spectral analysis. He presents data from one subject who had 16 needle electrodes placed in the scalp of the left hemisphere overlying the central sulcus. The subject was directed to either (1) be still for the resting condition, (2) move his right hand, wrist and fingers or (3) lie still while his hand was stroked. Giannitrapani claims that the pattern of EEG data reveals the location of the central sulcus, due to the fact that the different conditions activate different areas of cortex, i.e. the sensory and motor strips. It has to be stated that the presented data are not a very convincing
demonstration of the original claim, considering the known inter- and intrasubject variability of EEG data. In general, most studies would support Vos et al.'s (1975) claim that, "in scalp potential maps there is almost never an indication of discontinuities near the midline or the central sulcus".

However, it seemed possible that if coherence in some way measures functional communication between cortical areas (cf. Callaway and Harris, 1974) that coherence between points of high intracortical connectivity might be higher than that between points less richly interconnected. Thus, two points overlying the same cortical area might show higher coherence than points separated by a principal fissure, such as the central sulcus or the Sylvian fissure, provided these points were not known to have rich interconnections, such as homologous points between the hemispheres. This line of reasoning, that coherence is an index of cortical connectivity, has been invoked in many coherence studies, either implicitly or explicitly (e.g. Busk and Galbraith, 1975; Giannitrapani, 1975). It was decided to test this approach by affixing a chain of electrodes across the scalp in such a way that the longitudinal fissure was spanned. If the hypothesised lower coherence was found, then chains of electrodes spanning the Sylvian fissure might be used to determine asymmetries between the hemispheres electrophysiologically prior to testing for task-related asymmetries.

Secondary aims of this experiment were to investigate coherence, phase and power topographically during a simple task across all frequencies, rather than considering just the alpha band. Essentially this will involve mapping coherence distribution on the scalp in order
to examine possible coherence 'gradients' and comparing these results with those for power distribution. The information provided by the phase spectra will also be analysed, although a consideration of possible problems of interpretation will be deferred until Section 7.5.

As the remaining three experiments in this series all involved essentially the same methodology apart from the use of different montages, a general outline of the method will be given here, and the montages will be described individually for each experiment.

5.2 General Method

5.2.1 Subjects

Ten young adult subjects were used in each experiment. Experiment IV was not designed with the intention of investigating hemisphere differences and thus one left-handed female and one ambidextrous male were included in the subject set, as assessed by self-report. All other subjects reported themselves to be entirely right-handed. Three subjects took part in all three of the remaining experiments and four took part in two of the three.
5.2.2 Recording and Task

Electrode montage was the only important factor which differed between experiments, and the montages will be described individually for each experiment. Silver/silver chloride scalp electrodes (9 mm in diameter) were always used and interelectrode resistance was less than 5 k-Ohms. A balanced non-cephalic reference electrode (Stephenson and Gibbs, 1951) was used to ensure that the reference electrode was not recording EEG. This choice of reference electrode avoids the difficulties of interpreting coherence changes which may be due to desynchronisation at the reference itself (Shaw et al., 1979) and also makes interpretation of phase differences less problematical (Cooper, 1959). On occasions it was impossible to completely balance the cardiac potentials and thus eliminate them from the trace. Hence two subjects had to be replaced in Experiment IV and one in Experiment VI. A ground electrode was attached to the forehead.

Subjects relaxed in a semi-reclining position in a comfortable armchair in a darkened room with eyes closed. Their task was to respond within 0.5 sec to an easily detected tone presented at random time intervals (varying between 1.7 sec and 3.7 sec) with a left-hand index finger press on a response key. Task performance was scored and all subjects performed at an acceptable level of over 90 percent correct detections. Data collection, stimulus presentation and task performance were controlled by means of a PDP8/e computer. The program controlling data collection (Appendix B) ensured that there was always a pause of at least 2.2 sec between stimulus presentation and data collection. This was done by ensuring that EEG was only recorded
during the largest interval (3.7 sec), and was done in order to minimize movement-related potentials and artifacts. The session lasted approximately 17 min for Experiment IV and 24 min for Experiments V and VI, and epochs were sampled once about every 42 sec in the former case and every 60 sec in the latter, giving a total of twenty-four 1 sec epochs. During each session a paper trace of the EEG was monitored using an SLEEP Model 10/8 EEG machine. The signals were amplified to a gain of 20 K, with low pass filter set at 25 Hz and a time-constant of 0.3 sec. A 50 Hz notch filter was also used. Data were acquired at 128 Hz to avoid aliasing.

5.2.3 Analysis

Data were transferred to a CYBER 73 computer for analysis and spectral plotting for each subject and the average over all subjects in an experiment. Data were first run through an artifact-rejection routine which selected 20 artifact-free epochs for further analysis. Data for each epoch were set to a zero-baseline and a split-cosine-bell taper was applied before FFT transformation was performed. Fast Fourier Analysis was used to calculate power for each channel and coherence and phase for selected channel pairs, over 30 bands of 1 Hz resolution from 0 to 30 Hz. The resulting spectra were plotted using the GHOST Graphical System. Results for the theta (4-7.99 Hz), alpha (8-12.99 Hz) and beta-1 (13-21.99 Hz) bands were calculated by arithmetic averaging over the relevant frequency ranges for power and phase angle and by averaging the z-transform of the
square root in the case of coherence. Results for the peak alpha frequency, which was specified for each subject individually as the frequency producing maximum power within the alpha band, were also examined. It was felt that effects may show up at this frequency which would be lost in averaging over the entire alpha range.

5.2.4 Montage

In this first experiment a chain of six scalp electrodes were affixed as shown in Figure 1. The line of electrodes ran diagonally across the scalp at 45 degrees to the nasion-inion line, and passed through Cz. A chain of electrodes at 45 degrees to the nasion-inion line was chosen rather than a chain at 90 degrees to this axis because it was felt that coherence may be higher between two electrodes at homologous sites on the cerebral hemispheres than between electrodes which were not so situated. Such an effect has been previously reported in coherence studies (Giannitrapani, 1975; Vos et al., 1975; Walter et al., 1966) and this effect in itself gives some credence to the idea that coherence may to some extent reflect intracortical connectivity. This hypothesis was tested directly in Experiment V, but if such an effect were to occur in this experiment it may mask the hypothesised reduction in coherence as a fissure is crossed which was of primary interest in this case. All electrodes were 3 cm apart (from centre to centre) to ensure quite high coherence and thus give more reliable phase angle estimates. Thus, the main hypothesis would predict lower coherence between channels 3 and 4 than between other
Figure 1: Montages used in Experiment IV. Electrode positions are marked by filled circles and the distance between neighbouring pairs of electrodes is 3 cm. All positions are marked with respect to Cz. Half of the subjects had montage A, half had montage B.
electrode pairs. In order to balance any possible hemisphere effects, half of the subjects had the chain of electrodes running from left to right (montage A) and half from right to left (montage B) as the chain went from the front to the back of the scalp. However, the task was not intended to preferentially engage either hemisphere but simply to ensure that all subjects did essentially the same thing during the experimental session. This was felt to be an improvement over recording EEG from subjects supposedly 'at rest' who could obviously be engaged in many types of cognitive activity and would most certainly not be 'doing nothing'.

5.3 Results

ANOVA tables for analyses can be found in Appendix C.

5.3.1 Power

Power over the six electrodes for theta, alpha, beta-1 and peak frequency is summarised in Table 8.

The average power over all subjects across all frequencies is plotted in Figure 2. Figure 3 (a-d) shows the relationship between electrode position and power in the theta, alpha, alpha-peak and beta-1 bands.

a) Theta: Analysis of variance showed there to be a significant effect of electrode position on power in the theta band (F5,45=4.49, p<0.005). Further analysis using Newman-Keuls tests showed that theta
Table 8: Power in the theta, alpha, peak-alpha and beta-1 bands at all electrode placements for Experiment IV.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Theta mean</th>
<th>Theta S.D.</th>
<th>Alpha mean</th>
<th>Alpha S.D.</th>
<th>Peak-alpha mean</th>
<th>Peak-alpha S.D.</th>
<th>Beta-1 mean</th>
<th>Beta-1 S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>160.8</td>
<td>65.5</td>
<td>154.9</td>
<td>95.9</td>
<td>285.1</td>
<td>206.6</td>
<td>29.1</td>
<td>9.3</td>
</tr>
<tr>
<td>2</td>
<td>175.3</td>
<td>62.9</td>
<td>182.3</td>
<td>112.4</td>
<td>342.5</td>
<td>243.2</td>
<td>31.4</td>
<td>10.5</td>
</tr>
<tr>
<td>3</td>
<td>200.7</td>
<td>72.0</td>
<td>225.0</td>
<td>142.4</td>
<td>443.1</td>
<td>318.7</td>
<td>34.6</td>
<td>10.8</td>
</tr>
<tr>
<td>4</td>
<td>191.7</td>
<td>84.1</td>
<td>248.3</td>
<td>180.2</td>
<td>518.1</td>
<td>455.1</td>
<td>32.9</td>
<td>9.7</td>
</tr>
<tr>
<td>5</td>
<td>171.6</td>
<td>80.3</td>
<td>244.4</td>
<td>173.4</td>
<td>497.2</td>
<td>429.7</td>
<td>33.1</td>
<td>9.3</td>
</tr>
<tr>
<td>6</td>
<td>147.9</td>
<td>66.7</td>
<td>239.2</td>
<td>170.2</td>
<td>440.3</td>
<td>378.9</td>
<td>33.2</td>
<td>9.5</td>
</tr>
</tbody>
</table>
Figure 2: Average power over all subjects (n=10) across all frequencies in Experiment IV.
Figure 3: The relationship between electrode position and power in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment IV. Vertical bars show standard deviations.

**AVERAGE POWER IN SEPARATE FREQUENCY BANDS, EXPERIMENT IV**
power was significantly greater at channel 3 than channels 6 (p<0.01) and 1 (p<0.05). Also, power was significantly higher at channel 4 in comparison to channel 6 (p<0.05).

b) Alpha: Again, effect of electrode position was highly significant (F5,45=4.77, p<0.005) due mainly to suppression of alpha at frontal electrodes 1 and 2. Newman-Keuls analysis confirmed this, showing that channel 1 had significantly lower power than channels 4, 5, 6 (p<0.01) and 3 (p<0.05) although it was not significantly lower than channel 2.

A similar distribution was reflected in the peak power in the alpha band. The peak-alpha power showed much more variability than the average alpha power though, with some subjects showing very large peaks and some showing none. This led to fewer significant differences between electrodes (F5,45=2.90, p<0.05) with only the difference between channels 4 and 1 reaching significance in further analysis (p<0.05).

c) Beta-1: Distribution of beta-1 power was again related to electrode position (F5,45=6.81, p<0.005). Channel 1 showed significantly less power than channels 3, 4, 5, 6 (p<0.01) and 2 (p<0.05) and also channel 2 showed significantly less power than channel 3 (p<0.05).
5.3.2 Coherence and Phase Angle

Coherence and phase angle data over all possible pairs of electrodes for theta, alpha, beta-1 and peak-alpha frequency are summarised in Table 9. Positive phase angles indicate that the first channel of the pair leads.

The average z-transformed coherence and phase data over all subjects across all frequencies are plotted in Figure 4 (a-e). Figure 5 (a-d) shows the relationship between electrode pair and coherence and phase angle in the various frequency bands for neighbouring pairs of electrodes.

First, the data for neighbouring pairs of electrodes were analysed. The results were as follows:

a) Theta: No significant effects were found for coherence but phase angle was significantly related to electrode pair \((F_{4,36}=2.98, p<0.05)\). Newman-Keuls analysis failed to explicate this relationship. A series of two-tailed t-tests were performed in order to ascertain those phase angles which differed significantly from zero across subjects, but none were found in this band. In interpreting the results of these t-test comparisons caution is recommended, given that sixty such tests were carried out for this experiment.

b) Alpha: Coherence differed significantly between electrode pairs \((F_{4,36}=16.91, p<0.001)\) and further analysis showed that although channel pairs 1-2 and 2-3 did not differ significantly from each other they both showed higher coherence than all other pairs \((p<0.01\) in all cases). Also, channel pair 3-4 showed higher coherence than channel pair 5-6 \((p<0.01)\). Once again, although there was a weak relationship
Table 9: Coherence and phase angles between all electrode pairs in Experiment IV. Positive phase angles indicate that the first channel of the pair leads.

<table>
<thead>
<tr>
<th>Channel Pair</th>
<th>Theta mean</th>
<th>S.D.</th>
<th>Alpha mean</th>
<th>S.D.</th>
<th>Peak-alpha mean</th>
<th>S.D.</th>
<th>Beta-1 mean</th>
<th>S.D.</th>
</tr>
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<td>1-2</td>
<td>2.259</td>
<td>.192</td>
<td>2.499</td>
<td>.353</td>
<td>2.674</td>
<td>.481</td>
<td>2.236</td>
<td>.248</td>
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<td>1.301</td>
<td>2.359</td>
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<td>3.811</td>
<td>3.896</td>
<td>.615</td>
<td>1.211</td>
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<td>2.471</td>
<td>1.529</td>
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<td>.324</td>
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<td>.312</td>
<td>2.177</td>
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<td>.981</td>
<td>.278</td>
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<td>1.148</td>
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<td>.867</td>
<td>.269</td>
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Figure 4: Average z-coherence and phase angle data over all subjects (n=10) across all frequencies for interelectrode distances of (a) 3 cm, (b) 6 cm, (c) 9 cm, (d) 12 cm and (e) 15 cm in Experiment IV.
Figure 5: The relationship between electrode pair and z-coherence and phase angle for neighbouring pairs of electrodes in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment IV. Vertical bars show standard deviations.
between channel pair and phase angle (F4,36=3.11, p<0.05), further analysis failed to show significant differences between pairs. However, channel 4 led channel 3 by a mean phase of 1.7084 degrees, which was significantly different from zero (t9=2.8892, p<0.02). Alpha-peak coherence also differed between electrode pairs (F4,36=4.94, p<0.01), with channel pairs 1-2 and 2-3 both showing significantly higher coherence than pair 5-6 (p<0.01). Also, this time a stronger relationship was found between phase angle and channel pair (F4,36=4.96, p<0.01) than was found for the average over the alpha band. This was due to the fact that the phase angle at pairs 1-2 and 2-3 were significantly higher than all other pairs (p<0.05 in all cases) although they were not significantly different from each other.

c) Beta-1: Once again, coherence differed between electrode pairs (F4,36=11.17, p<0.001). Channel pair 2-3 showed significantly greater coherence than pairs 3-4, 4-5, 5-6 (p<0.01) and 1-2 (p<0.05). Channel pair 5-6 was also significantly less coherent than pairs 1-2 (p<0.01) and 3-4 (p<0.05). There was also a highly significant effect on phase angle (F4,36=7.76, p<0.001), with channel pair 3-4 showing a lower phase angle than pairs 1-2, 2-3 (p<0.01) and 4-5 (p<0.05). Also, channel pair 1-2 showed a greater phase angle than pair 5-6 (p<0.05). The phase angle between channels 3 and 4 was shown to be significantly smaller than zero (t9=2.8353, p<0.02) with a mean value of -1.8043 degrees.

One would naturally expect that as distance between electrodes increased coherence would decrease. Thus the coherence between electrode 1 and all of the other electrodes was subjected to an analysis of variance. Coherence dropped dramatically as interelectrode
distance increased for all frequency ranges (theta: F4,36=380.53; alpha: F4,36=715.62; peak-alpha: F4,36=210.76; beta-1: F4,36=657.76; all p<0.001). A similar set of analyses was carried out using coherences between channel 6 and all other channels as data, and produced similar results (theta: F4,36=418.58; alpha: F4,36=578.62; peak-alpha: F4,36=323.45; beta-1: F4,36=683.98; all p<0.001). Further analysis showed that in all cases an increase in interelectrode distance significantly lowered coherence (p<0.01). Analysis of phase angle data for these channel pairs revealed no significant effects for theta or alpha-peak, but a weak effect was found for the beta-1 band for the first set of analyses (1-2, 1-3, etc.), (F4,36=2.77, p<0.05). For the alpha band, phase angle showed a fairly strong relationship with interelectrode distance (F4,36=10.69, for analysis with respect to channel 1; F4,36=7.07, for analysis with respect to channel 6; p<0.001 in both cases) but as the homogeneity of variance assumption is obviously violated in these cases the data were not analysed further.

Again, t-tests were performed on all phase angle relationships to test if they differed significantly from zero. Apart from those results already reported, channel 6 led channel 2 by 7.8786 degrees (t9=3.2410, p<0.02) and channel 1 by 7.5423 degrees (t9=2.6606, p<0.05).
5.4 Discussion

With respect to the main hypothesis of the experiment, no support was found for the idea that coherence would be lower between a pair of electrodes which spanned a fissure (electrodes 3-4) than for other pairs which did not. There was no effect on coherence in the theta band but alpha, alpha-peak and beta-1 bands all showed a highly significant trend towards higher coherence at frontal electrodes with channel pairs 1-2 and 2-3 usually being more coherent than other pairs, a finding reminiscent of that reported by Hori et al. (1969).

Phase angle showed some interesting effects related to electrode position, although again no clear effect in the theta band. Alpha-peak showed a much stronger effect than alpha average, with higher positive phase angles at the two frontal pairs. Somewhat unexpectedly, an interesting effect on phase angle was found at electrodes 3-4 where, in the beta-1 band, the phase angle was significantly lower than for three out of four other channel pairs. Also, in the alpha and beta-1 bands channels 3-4 had shown a phase angle significantly less than zero, which would normally be taken as implying that channel 4 led channel 3 in a fairly consistent way. This effect cannot be due to the fact that channels 3 and 4 span the longitudinal fissure, that is, record EEG from different hemispheres. If this effect was simply due to one hemisphere consistently leading the other, any relationship between channels 3 and 4 would be cancelled out as half the subjects had montage A and half had montage B. However, all subjects had phase angle measured in the same direction along the longitudinal axis and hence this result could reflect the possibility that the postcentral
cortex (electrode 4) consistently leads the precentral cortex (electrode 3) as the Rolandic fissure is crossed. One puzzling feature of these results is the fact that the alpha and beta-1 bands both show very similar measures of phase difference (1.7 and 1.8 degrees, respectively) between these two positions, implying different lead times for the two bands. If we base an estimate of the delays involved upon the assumption that alpha activity is centred around 10 Hz and beta-1 around 17 Hz, delay times of 0.472 msec and 0.294 msec, respectively, are produced. These in turn correspond to wave propagation speeds of 63.5 m/sec and 102 m/sec respectively, far in excess of other estimates. However, a full discussion of the difficulties associated with interpreting these phase angles will be deferred until Section 7.5.

It is clear from this study that coherence bears no simple relationship to power. The trivial relationship between electrode separation and coherence has also been confirmed.
Chapter 6: Experiment V

6.1 Introduction

One of the most interesting results of Experiment IV was the consistent phase angle relationship between the precentral and postcentral electrodes. However, it is impossible to say from the results obtained whether or not this effect is stronger in, or possibly even confined to, one of the two cerebral hemispheres. It would also be interesting to know if any consistent phase angle differences are found between the hemispheres, a question which was not open to investigation in the previous study due to the balancing of montages. Hence the experiment was repeated using the montage described below.

6.2 Montage and Aims

The montage is shown in Figure 6. Again, distances between electrode centres were 3 cm so that results would be directly comparable with those of Experiment IV. The electrodes were arranged in a ring of eight with Cz at centre. This arrangement produced a useful montage whereby between- and within-hemisphere effects could be studied. Also, the Rolandic fissures on the left and right hemispheres are spanned, as is the longitudinal fissure frontally and parietally.

Thus, the aims of this study were:

a) to examine the distribution of power,
Figure 6: Montage used in Experiment V.
Electrode positions are marked as filled circles and the distance between neighbouring pairs of electrodes is 3 cm. All positions are marked with respect to Cz at the centre of the ring.
b) to examine coherence and phase angle relationships between neighbouring pairs of electrodes, paying particular attention to electrode pairs spanning principal fissures,
c) to examine coherence and phase angle relationships between more distant electrode pairs homotopically located with respect to the hemispheres, and compare these with the relationships for nonhomotopic pairs. This will enable us to ascertain whether or not homotopic pairs are more coherent, which might be anticipated if coherence measures functional communication in a way similar to cortical coupling (Callaway and Harris, 1974), due to the rich transcallosal interconnections.

6.3 Results

ANOVA tables for all analyses are presented in Appendix C.

6.3.1 Power

Power over the eight electrodes for theta, alpha, beta-1 and alpha-peak frequency is summarised in Table 10.

The average power across all subjects over all frequencies is plotted in Figure 7. Power in the theta, alpha, alpha-peak and beta-1 bands is plotted against channel in Figure 8 (a-d).

Power data were submitted to two-way analyses of variance with hemispheres and electrode position as factors, but a significant effect was found only in the beta-1 band where the hemisphere X
Table 10: Power in the theta, alpha, peak-alpha and beta-1 bands at all electrode placements for Experiment V.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Theta</th>
<th>Alpha</th>
<th>Peak-alpha</th>
<th>Beta-1</th>
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</thead>
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<td>S.D.</td>
<td>mean</td>
<td>S.D.</td>
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<td>152.7</td>
<td>121.0</td>
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<td>56.2</td>
<td>164.0</td>
<td>139.3</td>
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<td>53.8</td>
<td>247.1</td>
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<td>152.3</td>
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-272-
Figure 7: Average power over all subjects (n=10) across all frequencies in Experiment V.
Figure 8: The relationship between electrode position and power in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment V. Vertical bars show standard deviations.

AVERAGE POWER IN SEPARATE FREQUENCY BANDS:
EXPERIMENT V

(A) THETA

(B) ALPHA

(C) PEAK-ALPHA

(D) BETA-1

ELECTRODE POSITION
position interaction was significant (F3,27=7.23, p<0.005). Further analysis revealed that this was due to the difference in power between channels 3 and 7 (p<0.001) with channel 3 showing greater activity. (All further analysis with respect to two-way ANOVAs was carried out using marginal means comparisons as described by Snodgrass, 1977.)

6.3.2 Coherence and Phase Angle

Coherence and phase angle data over appropriate channel pairs are summarised in Table 11. Positive phase angles indicate that the first channel of the pair leads.

6.3.2.1 Analyses for Neighbouring Pairs

The average z-transformed coherence and phase angle data across all subjects over all frequencies are plotted in Figure 9. The relationships of channel pair to coherence and phase within particular bands are shown in Figure 10.

These data were analysed in two ways. Firstly, one-way analyses of variance were carried out which included the coherence data for the interhemispheric pairs 5-1 and 8-4. Then two-way analyses were performed using hemisphere and position as factors which included only the intrahemispheric data. Phase angle was analysed using only two-way analyses because it was not possible to include the interhemispheric phase angles as their direction would be arbitrarily specified.

a) Theta: One-way analysis revealed that in this case theta
Table 11: Coherence and phase angles between appropriate electrode pairs in Experiment V. Positive phase angles indicate that the first channel of the pair leads.

<table>
<thead>
<tr>
<th>Channel Pair</th>
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<th>Peak-alpha</th>
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Figure 9: The average z-coherence and phase angle data over all subjects (n=10) over all frequencies for neighbouring pairs of electrodes in Experiment V.

AVERAGE Z-TRANSFORMED COHERENCE AND PHASE ANGLE FOR NEIGHBOURING PAIRS OF ELECTRODES OVER ALL SUBJECTS; EXPERIMENT V

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Figure 10: The relationship between electrode pair and z-coherence and phase angle for neighbouring pairs of electrodes in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment V. Vertical bars show standard deviations.

AVERAGE Z-TRANSFORMED COHERENCE AND PHASE IN SEPARATE FREQUENCY BANDS FOR NEIGHBOURING PAIRS OF ELECTRODES, EXPERIMENT V

\[ \text{ELECTRODE PAIR} \]

-278-
coherence was related to electrode pair position (F7,63=12.29, p<0.001) and further analysis revealed that this effect was due entirely to the much higher coherences at the interhemispheric channel pairs. Channel pair 8-4 was more coherent than pair 5-1 at the 0.05 level and more coherent than all other pairs at the 0.01 level. Channel pair 5-1 was more coherent than pair 7-8 at the 0.05 level and more coherent than all other pairs at the 0.01 level.

Two-way analysis excluding the interhemispheric coherences revealed an effect of position (F2,18=3.81, p<0.05) but no difference between the hemispheres. Further analysis revealed that coherence at the central electrodes was lower than the average of the other pairs (p<0.05).

Again, t-tests were carried out to ascertain which phase angles differed significantly from zero across subjects. As 64 tests were performed, those showing only slightly significant effects must be viewed with caution. Channel 5 led channel 6 by a mean phase of 1.3200 degrees (t9=3.1253, p<0.02) and channel 8 led channel 7 by a mean of 0.4111 degrees (t9=2.5799, p<0.05). At the posterior interhemispheric pair, the right hemisphere led the left by 0.4517 degrees on average (t9=2.4524, p<0.05). These relationships are reflected in the results of the analysis of variance which demonstrated a significant effect of position (F2,18=12.37, p<0.001) on phase angle and a significant interaction of position with hemisphere (F2,18=3.87, p<0.05). Further analysis revealed that the phase angle at the frontal electrodes was significantly greater than the average of the other pairs (p<0.01) and, further, that this effect was significantly stronger over the left hemisphere (p<0.05).
b) Alpha: Again, one-way analysis revealed a significant relationship between coherence and position (F7,63=5.90, p<0.001). Apart from channel pair 8-4 being more coherent than pair 6-7 (p<0.05), this effect was due entirely to the higher coherence of pair 5-1, which was greater than pair 8-4 at the 0.05 level and greater than all other pairs at the 0.01 level. Two-way analysis did not produce any significant effects. Analysis of peak-alpha coherence reflected the findings for average alpha closely. One-way analysis produced a significant effect (F7,63=3.36, p<0.005), again due to the higher coherence of the anterior interhemispheric pair (greater than pairs 1-2, 2-3 and 6-7 at the 0.01 level and greater than all others at the 0.05 level). The two-way analysis again failed to demonstrate any significant differences.

In the alpha band channel 7 led channel 6 by 2.3347 degrees (t9=2.8163, p<0.05) and this result was also found in the alpha-peak data (mean = 4.6879 degrees, t9=3.2895, p<0.02). For both average alpha and alpha-peak, analyses of variance were nonsignificant.

c) Beta-1: A significant effect of position of electrode pair was also found in the beta-1 band (F7,63=11.12, p<0.001), which was again due to the much higher coherences at the interhemispheric pairs. Channel pair 8-4 showed more coherence than all other pairs except pair 5-1 (p<0.01 in all cases) and pair 5-1 were more coherent than all other pairs except pair 8-4 (p<0.05 for 1-2, 5-6 and 7-8; p<0.01 for others). The two-way analysis excluding the interhemispheric pairs revealed a significant effect of position (F2,18=4.92, p<0.05) which further analysis showed to be due to reduced coherence at the central pair of electrodes in comparison to the average of the other positions.
In testing the phase angle data, some interesting effects were found. On the right hemisphere, channel 3 led channel 2 (mean = 0.9263 degrees, t9=2.4910, p<0.05) and channel 4 led channel 3 (mean = 1.0746 degrees, t9=3.9960, p<0.01). However, on the left hemisphere, channel 7 led channel 6 by a mean phase angle of 2.0978 degrees (t9=4.3910, p<0.002) but also led channel 8 by 0.7985 degrees (t9=2.6042, p<0.05). The analysis of variance reflected these effects with a significant effect of position (F2,18=12.54, p<0.001) and a significant hemisphere X position interaction (F2,18=9.75, p<0.005). Further analysis of the main effect showed it to be due to lower (i.e. more negative) phase angles at the central pair in comparison to the average of the other positions (p<0.001). The interaction was due to the fact that the phase angle was more negative over the left hemisphere than the right for the central electrode pair (p<0.05) and more negative for the right hemisphere than the left for the posterior electrode pair (p<0.005).

6.3.2.2 Analyses for Distant Pairs

In order to find out whether or not coherence would be higher between electrodes at homotopic points on the hemispheres in comparison to equidistant nonhomotopic points, the coherences for pairs 2-6, 3-7, 1-7, 2-8, 3-5, 4-6, 1-4 and 5-8 (see Figure 6) were also submitted to one-way analyses of variance. Such higher coherences were found in the analysis of neighbouring electrodes and might
possibly reflect in some way cortico-cortical connections between the
hemispheres. It would be of interest to know if this relationship
holds when the electrode pairs are more distant. Phase angle data for
these pairs were not analysed using analysis of variance as, in this
case, the sign of the phase angle is determined by an arbitrary choice
of directionality. However, those phase angles which differed
significantly from zero will be reported. The coherence data are
plotted in Figures 11 and 12.

a) Theta: A highly significant effect was found in the theta band
\( F(7,63)=18.11, p<0.001 \) and this was due to two effects: (i) the much
higher coherences of the two homotopic pairs which differed
significantly from all other pairs \( p<0.01 \) in all cases) but not from
each other, and (ii) the much lower coherences of the two
intrahemispheric pairs which were significantly lower than all other
pairs except each other \( p<0.05 \) for 1-7; \( p<0.01 \) in all other cases).

The only phase angle which differed significantly from zero
was that for pair 4-6 \( \text{mean}=1.0844, t=2.2800, p<0.05 \).

b) Alpha: A significant effect on coherence was found in the alpha
band, too \( F(7,63)=4.80, p<0.001 \). In this case the effect was due to
the higher coherence between the anterior pair of homotopic electrodes
which were significantly more coherent than all other pairs \( p<0.05 \)
for 3-7 and 2-8; \( p<0.01 \) in all other cases). This pattern was
reflected in the analysis of alpha-peak data \( F(7,63)=3.38, p<0.005 \).
Again, the anterior pair of homotopic electrodes were more coherent
than all others \( p<0.01 \) for 1-4, 5-8 and 4-6; \( p<0.05 \) for all others).

No phase angles differed significantly from zero for the average
alpha band.
Figure 11: The average z-coherence over all subjects (n=10) over all frequencies for more distant pairs of electrodes in Experiment V.

AVERAGE Z-TRANSFORMED COHERENCE
FOR MORE DISTANT PAIRS OF ELECTRODES
OVER ALL SUBJECTS: EXPERIMENT V

![Graph showing z-coherence over frequency]

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Figure 12: The relationship between electrode pair and z-coherence for more distant pairs of electrodes in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment V. Vertical bars show standard deviations.

AVERAGE Z-TRANSFORMED COHERENCE IN SEPARATE FREQUENCY BANDS FOR MORE DISTANT PAIRS OF ELECTRODES, EXPERIMENT V
c) Beta-1: The effect on coherence was again highly significant (F7,63=7.01, p<0.001) and again due mainly to the higher coherence of the homotopic pairs. These pairs were significantly more coherent than the intrahemispheric pairs (p<0.01 in all cases) and pairs 1-7 and 2-8 (p<0.05 in all cases). The intrahemispheric pairs were significantly less coherent than channel pair 4-6 (p<0.05 in both cases).

Results of t-test analysis showed that channel 4 led channel 1 (mean = 1.6122 degrees, t9=2.4159, p<0.05) and channel 4 led 6 (mean = 1.3335 degrees, t9=2.5546, p<0.05).

6.4 Discussion

The only band to show significant effects of position of electrodes on power was the beta-1 band. The fact that channel 7 showed much less power than channel 3 could be related to the interesting phase angle relationships in this area.

The analysis of coherence for neighbouring electrodes showed fairly similar effects across frequency bands. Contrary to the initial hypothesis of Experiment IV, coherence was significantly higher for electrodes spanning the longitudinal fissure for the theta and beta-1 bands. For alpha and peak-alpha this effect only occurred for the anterior interhemispheric pair of electrodes, probably a reflection of the higher coherence at frontal electrodes noted in Experiment IV. More in line with initial expectations is the finding of lower coherence between electrodes spanning the Rolandic fissure in the theta and beta-1 bands. However, this may not be due simply to the
fact that these electrodes span the Rolandic fissure, as outlined below.

A traditional interpretation of the phase angle effects would suggest that channel 5 leads channel 6 fairly consistently in the theta band, and channel 7 leads channel 6 fairly consistently in the alpha band. However, the most interesting results were found in the beta-1 range. In the right hemisphere channel 4 leads channel 3 strongly and channel 3 leads channel 2 fairly strongly. Hence the more posterior of each pair leads. In the left hemisphere, although channel 7 leads channel 6 very strongly, it also leads channel 8. This might be taken to suggest that the generator of beta-1 activity in the left hemisphere is located fairly near to the position of electrode 7, that is, in postcentral cortex. It is worthy of note also that the effect which led to the more negative phase angle between electrodes 3 and 4 in Experiment IV seems to occur more strongly in the left hemisphere. However, once again, it is pointed out that other interpretations of this data are possible, and will be discussed later.

Coherence of more distant electrode pairs showed a strong tendency in the theta band to be high for homotopic pairs and low for intrahemispheric pairs. This tendency was reflected less strongly in the beta-1 band. In the alpha band, both for average and peak, just the anterior homotopic pair showed significantly higher coherence, probably due to the tendency towards higher coherence at frontal electrodes already noted for this frequency band.

Thus far the attempt to build up a 'map' of coherence seems to be characterised by two factors; firstly, the fact that as we move from precentral to postcentral areas coherence shows a sharp decrease and
continuing decline posteriorly in the alpha range, and to a lesser extent in the beta-1 band. Superimposed upon this 'coherence gradient' effect there is a second factor, which in association with the gradient would account for all the coherence effects found so far; that is, that it appears that differences in coherence between equally spaced electrodes are related to the distance along the nasion-inion (longitudinal) axis. This factor is particularly strong for theta and beta-1 bands but also seen for alpha. Thus the electrode pairs at homotopic locations on the two hemispheres, having minimum separation along the longitudinal axis, showed the highest coherence, while the intrahemispheric pairs, having maximum separation along this axis, showed the lowest coherence. This occurred for both the near and distant electrode pairs. It must be emphasised that these effects only apply to equally spaced pairs of electrodes and that any increase in separation in absolute terms will lead to a dramatic decrease in coherence as shown in Experiment IV. Giannitrapani (1975) reports just this effect, pointing out that the coherences between electrodes at homologous sites over each hemisphere showed higher coherence than electrodes separated along the anterior-posterior axis, even if the former interelectrode distances were 50 per cent greater than the latter. He interprets this finding as indicating better connections through the callosum than through the anterior-posterior tracts. Vos et al. (1975), Walter et al. (1966) and several other investigators have also reported this effect.

The possible interpretations of the coherence gradient and longitudinal axis effects are not obvious but it is possible that the axis effect is related in a very direct way to the underlying
anatomical connections of the cortex. Thus the higher coherence found at homotopic pairs could be a reflection of interhemispheric cortico-cortical connections. The lower coherence of the transrolandic pairs could reflect the fact that the electrodes in these cases were overlying areas of cortex separated by the Rolandic fissures without the rich transcallosal connections of the homotopic pairs. Those pairs of electrodes overlying the same cortical area might be expected to have coherences intermediate between the other two cases, as was in fact found. Unfortunately, the fact that certain nonhomotopic interhemispheric pairs showed higher coherence than intrahemispheric pairs in the theta and beta-1 band is difficult to reconcile with such an explanation. However, it was decided to test the hypothesis directly in Experiment VI.
Chapter 7: Experiment VI

7.1 Introduction

In order to test the hypothesis proposed in the previous section the experiment was repeated using the montage described below.

7.2 Montage and Aims

The montage used is shown in Figure 13. Electrodes 2, 3, 6 and 7 are in the same position as in Experiment V, but electrodes 1, 4, 5 and 8 are positioned in such a way as to create two chains of electrodes approximately 7.24 cm apart, the same as the interelectrode distance for pairs 2-6 and 3-7 in the previous experiment. The centres of the electrodes within a chain are again 3 cm apart. If the hypothesis outlined above is correct, then the lower coherence at the central pairs of electrodes is due to spanning the Rolandic fissure, and not the distance apart along the longitudinal axis per se. Thus we would expect to find the effect again in this study. Also, this montage made it possible to investigate interhemispheric coherences between homotopic points, and to see how they are related to position along the longitudinal axis.

Thus, the aims of this experiment were:

a) to test the specific anatomical hypothesis outlined above,

b) to replicate the phase angle effects found in the previous study,
Figure 13: Montage used in Experiment VI. Electrode positions are marked by filled circles. Intrahemispheric neighbouring pairs are 3 cm apart and the two chains are 7.24 cm apart. All positions are marked with respect to Cz at the centre of the rectangle of electrodes.
Fig 13
c) to study the effect on coherence of position along the longitudinal axis of homotopic interhemispheric electrode pairs. In particular, to see if coherence decreases posteriorly for alpha and beta-1,

d) to examine the phase angle relationships between the cerebral hemispheres in order to ascertain whether or not one hemisphere consistently leads the other.

7.3 Results

7.3.1 Power

Power over the eight electrodes in the theta, alpha, beta-1 and alpha-peak frequencies is summarised in Table 12. Note the considerably reduced standard deviations for alpha and alpha-peak in comparison to the two previous studies. This is due to the fact that all subjects in the present experiment produced relatively little alpha, whereas in the previous experiments one or two subjects had very large spectral peaks in the alpha band.

The average power across subjects over all frequencies is plotted in Figure 14. Data for individual frequency bands are plotted in Figure 15 (a-d).

All power data were submitted to two-way analysis of variance (hemisphere X position).

a) Theta: A significant hemisphere X position interaction was found for theta power ($F_{3,27}=5.54$, $p<0.01$). Simple effects analysis revealed
Table 12: Power in the theta, alpha, peak-alpha and beta-1 bands at all electrode placements for Experiment VI.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Theta mean</th>
<th>Theta S.D.</th>
<th>Alpha mean</th>
<th>Alpha S.D.</th>
<th>Peak-alpha mean</th>
<th>Peak-alpha S.D.</th>
<th>Beta-1 mean</th>
<th>Beta-1 S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>166.8</td>
<td>66.5</td>
<td>106.9</td>
<td>56.8</td>
<td>201.1</td>
<td>144.4</td>
<td>29.5</td>
<td>14.5</td>
</tr>
<tr>
<td>2</td>
<td>161.9</td>
<td>54.5</td>
<td>108.7</td>
<td>53.4</td>
<td>198.6</td>
<td>129.7</td>
<td>30.0</td>
<td>14.8</td>
</tr>
<tr>
<td>3</td>
<td>159.0</td>
<td>50.8</td>
<td>117.0</td>
<td>54.5</td>
<td>202.7</td>
<td>121.7</td>
<td>33.3</td>
<td>16.0</td>
</tr>
<tr>
<td>4</td>
<td>139.8</td>
<td>47.8</td>
<td>117.6</td>
<td>54.6</td>
<td>193.5</td>
<td>109.9</td>
<td>32.9</td>
<td>14.9</td>
</tr>
<tr>
<td>5</td>
<td>163.8</td>
<td>62.9</td>
<td>106.1</td>
<td>53.8</td>
<td>198.8</td>
<td>137.7</td>
<td>28.8</td>
<td>13.9</td>
</tr>
<tr>
<td>6</td>
<td>158.8</td>
<td>52.5</td>
<td>106.0</td>
<td>49.9</td>
<td>192.6</td>
<td>124.4</td>
<td>29.5</td>
<td>13.8</td>
</tr>
<tr>
<td>7</td>
<td>150.9</td>
<td>51.8</td>
<td>106.8</td>
<td>48.2</td>
<td>187.7</td>
<td>119.0</td>
<td>29.9</td>
<td>13.7</td>
</tr>
<tr>
<td>8</td>
<td>145.2</td>
<td>55.3</td>
<td>119.9</td>
<td>55.1</td>
<td>204.0</td>
<td>121.6</td>
<td>33.2</td>
<td>14.7</td>
</tr>
</tbody>
</table>
Figure 14: Average power over all subjects (n=10) across all frequencies in Experiment VI.
Figure 15: The relationship between electrode position and power in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment VI. Vertical bars show standard deviations.

AVERAGE POWER IN SEPARATE FREQUENCY BANDS.

EXPERIMENT VI

![Bar charts showing average power in separate frequency bands for different electrode positions.](image-url)
that this was due to significantly higher power at electrode 3 in comparison to its left hemisphere counterpart (p<0.005) and at electrode 8 compared to electrode 4 (p<0.05).

b) Alpha: Again a significant interaction was found (F3,27=7.60, p<0.005) which further analysis showed to be due to the significantly higher alpha power at electrode 3 compared to electrode 7 (p<0.005).

The alpha-peak power also produced a significant interaction (F3,27=7.77, p<0.001) and again, simple effects analysis showed significantly higher power at electrode 3 compared to 7 (p<0.001). Also, as in the theta band, more power was found at channel 8 than 4 (p<0.05).

c) Beta-1: In the beta-1 band, besides a significant interaction (F3,27=8.36, p<0.001), a significant effect due to position was found (F3,27=12.87, p<0.001). Further analysis of this main effect showed that precentral electrodes produced significantly less beta-1 activity than postcentral electrodes (p<0.001). Of the postcentral placements the posterior placements produced more activity than the anterior (p<0.001). The interaction was again due to greater power at channel 3 than 7 (p<0.001).

7.3.2 Coherence and Phase Angle

Coherence and phase angle data over appropriate channel pairs are summarised in Table 13. Positive phase angles indicate that the first channel of the pair leads.
Table 13: Coherence and phase angles between (a) intrahemispheric channel pairs and (b) interhemispheric channel pairs in Experiment VI. Positive phase angles indicate that the first channel of the pair leads.

(a) Intrahemispheric Pairs.

<table>
<thead>
<tr>
<th>Channel Pair</th>
<th>Theta</th>
<th>Alpha</th>
<th>Peak-alpha</th>
<th>Beta-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>S.D.</td>
<td>mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>1-2</td>
<td>2.209</td>
<td>.195</td>
<td>2.246</td>
<td>.202</td>
</tr>
<tr>
<td>Phase</td>
<td>1.312</td>
<td>1.282</td>
<td>1.720</td>
<td>1.305</td>
</tr>
<tr>
<td>2-3</td>
<td>2.271</td>
<td>.124</td>
<td>2.136</td>
<td>.216</td>
</tr>
<tr>
<td>Phase</td>
<td>1.021</td>
<td>1.239</td>
<td>.905</td>
<td>2.364</td>
</tr>
<tr>
<td>3-4</td>
<td>2.347</td>
<td>.116</td>
<td>2.162</td>
<td>.177</td>
</tr>
<tr>
<td>Phase</td>
<td>.121</td>
<td>.690</td>
<td>-2.92</td>
<td>2.929</td>
</tr>
<tr>
<td>5-6</td>
<td>2.290</td>
<td>.106</td>
<td>2.335</td>
<td>.170</td>
</tr>
<tr>
<td>Phase</td>
<td>2.423</td>
<td>.866</td>
<td>1.498</td>
<td>1.424</td>
</tr>
<tr>
<td>6-7</td>
<td>2.289</td>
<td>.157</td>
<td>2.097</td>
<td>.302</td>
</tr>
<tr>
<td>Phase</td>
<td>.542</td>
<td>1.094</td>
<td>-1.34</td>
<td>2.198</td>
</tr>
</tbody>
</table>

(b) Interhemispheric Pairs.

<table>
<thead>
<tr>
<th>Channel Pair</th>
<th>Theta</th>
<th>Alpha</th>
<th>Peak-alpha</th>
<th>Beta-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>S.D.</td>
<td>mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>1-5</td>
<td>1.753</td>
<td>.198</td>
<td>1.862</td>
<td>.210</td>
</tr>
<tr>
<td>Phase</td>
<td>-1.146</td>
<td>1.489</td>
<td>.642</td>
<td>1.107</td>
</tr>
<tr>
<td>2-6</td>
<td>1.805</td>
<td>.168</td>
<td>1.800</td>
<td>.200</td>
</tr>
<tr>
<td>Phase</td>
<td>.910</td>
<td>1.583</td>
<td>.630</td>
<td>.815</td>
</tr>
<tr>
<td>3-7</td>
<td>1.807</td>
<td>.164</td>
<td>1.655</td>
<td>.241</td>
</tr>
<tr>
<td>Phase</td>
<td>.440</td>
<td>1.738</td>
<td>-.118</td>
<td>1.644</td>
</tr>
<tr>
<td>4-8</td>
<td>1.838</td>
<td>.175</td>
<td>1.626</td>
<td>.252</td>
</tr>
<tr>
<td>Phase</td>
<td>1.314</td>
<td>2.054</td>
<td>1.550</td>
<td>4.587</td>
</tr>
</tbody>
</table>
7.3.2.1 Intrahemispheric Analyses

All coherence and phase angle data for each frequency band were submitted to two-way analyses of variance. The average z-transformed coherence and phase angle data are presented in Figure 16. Relationships for individual frequency bands are plotted in Figure 17 (a-d).

a) Theta: No significant effects were found for coherence, but a highly significant effect of position (F2,18=21.36, p<0.001) and a hemisphere X position interaction (F2,18=21.64, p<0.001) were found for phase angle. Further analysis revealed that the main effect of position was due to the significantly greater phase angle for the anterior pairs in comparison to the average for the other pairs (p<0.001) and also to the significantly greater phase angle of the middle in comparison to the posterior pairs (p<0.01). The interaction was due to the larger phase angles over the left hemisphere than the right at anterior (p<0.001) and posterior (p<0.05) pairs and over the right compared to the left at the middle pair (p<0.01).

These strong phase angle relationships were also found in the t-test comparisons to see if the phase angle differed significantly from zero. (Again, as forty tests were carried out, slightly significant results may be spurious.) Channel 1 led 2 by a mean of 1.3124 degrees (t9=3.0705, p<0.02), channel 2 led 3 by a mean of 1.0209 degrees (t9=2.4719, p<0.05) and channel 5 led 6 by a mean of 2.4232 degrees (t9=8.3985, p<0.001).

b) Alpha: Again, no significant effects on coherence were found, but a significant hemisphere X position interaction was found for
Figure 16: Average z-coherence and phase angle data over all subjects (n=10) across all frequencies for intrahemispheric pairs of electrodes in Experiment VI.
AVERAGE Z-TRANSFORMED COHESION AND PHASE IN SEPARATE FREQUENCY BANDS FOR INTRAHEMISPHERIC PAIRS OF ELECTRODES. EXPERIMENT VI

Figure 17: The relationship between electrode pair and z-coherence and phase angle for intrahemispheric pairs of electrodes in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment VI. Vertical bars show standard deviations.
phase angle ($F_{2,18}=19.86$, $p<0.001$). This was due to the significant
difference in phase between the middle pairs on the left (-1.1223
degrees) and right (0.9049 degrees) hemispheres. No phase angles
differed significantly from zero.

The analysis of peak-alpha frequency showed a significant effect of
the electrode pair on coherence ($F_{2,18}=4.83$, $p<0.05$). Subsequent
analysis showed this to be due to higher coherence at the anterior
pairs in comparison to the average of the other pairs ($p<0.001$). A
significant interaction of hemisphere X position was found for the
phase angles ($F_{2,18}=7.75$, $p<0.01$) due to the significantly greater
phase angle on the right hemisphere for the middle pair of electrodes
($p<0.05$) and on the left for the posterior pair ($p<0.01$). Again, no
phase angles differed significantly from zero.

c) Beta-I: A hemisphere effect was found for beta-1 coherence
($F_{1,9}=11.74$, $p<0.01$) indicating that the left hemisphere was more
coherent than the right. This trend was also apparent in Experiment V
but failed to reach significance. For phase angle, both an effect due
to position ($F_{2,18}=18.04$, $p<0.001$) and a hemisphere X position
interaction ($F_{2,18}=96.03$, $p<0.001$) were found. The main effect was due
to the greater phase angle of the anterior electrode pairs in
comparison to the average of the others ($p<0.001$) and also the more
negative phase angle of the posterior electrodes in comparison to the
middle pairs ($p<0.05$). The significant interaction was due to the
greater phase angle over the left than the right hemisphere at the
anterior and posterior pairs ($p<0.001$ in both cases) and the greater
phase angle over the right hemisphere compared to the left at the
middle pair ($p<0.001$). The phase angle between channels 3 and 4

-300-
differed significantly from zero (mean = -1.9053, t9=3.8293, p<0.01) as did that between channels 6 and 7 (mean = -1.6060, t9=2.5421, p<0.05).

7.3.2.2 Interhemispheric Analyses

All coherence and phase angle data were submitted to one-way analysis of variance. The data are plotted in Figures 18 and 19.

a) Theta: Coherence was not related to position of the homotopic electrode pairs, but phase angle was (F3,27=3.25, p<0.05). Newman-Keuls analysis showed that channel pair 4-8 had a significantly larger phase angle than pair 1-5 (p<0.05).

b) Alpha: As expected coherence was strongly related to the position of the electrodes (F3,27=11.65, p<0.001) with the precentral pairs having higher coherence than the postcentral pairs (p<0.01 in all cases). No significant effect of electrode position on phase angle was found. Channel 2 led channel 6 by a mean phase angle of 0.6300 degrees, which differed significantly from zero (t9=2.3188, p<0.05). This was the only significant t-test comparison for the interhemispheric pairs.

Alpha-peak frequency showed an essentially similar pattern with a significant effect of position on coherence (F3,27=8.81, p<0.001) but not on phase angle. The effect on coherence was again due to the precentral pairs greater coherence compared to the postcentral pairs (2-6 vs 3-7, p<0.05; p<0.01 in all other cases).

c) Beta-1: In the beta-1 band, position had an effect on coherence
Figure 18: Average z-coherence and phase angle data over all subjects (n=10) over all frequencies for interhemispheric pairs of electrodes in Experiment VI.

AVERAGE Z-TRANSFORMED COHERENCE AND PHASE ANGLE FOR INTERHEMISPHERIC PAIRS OF ELECTRODES OVER ALL SUBJECTS: EXPERIMENT VI

---

**Z-TRANSFORMED COHERENCE**

0.0

1.0

2.0

2.5

0

5

10

15

20

25

FREQUENCY (C/SEC)

**PHASE ANGLE (DEGREES)**

0

-2

-4

4

0

5

10

15

20

25

FREQUENCY (C/SEC)

---
Figure 19: The relationship between electrode pair and z-coherence and phase angle for interhemispheric pairs of electrodes in the (a) theta, (b) alpha, (c) peak-alpha and (d) beta-1 bands in Experiment VI. Vertical bars show standard deviations.

AVERAGE Z-TRANSFORMED COHERENCE AND PHASE IN SEPARATE FREQUENCY BANDS FOR INTERHEMISPHERIC PAIRS OF ELECTRODES, EXPERIMENT VI

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(F3,27=4.07, p<0.05) and phase (F3,27=3.81, p<0.05). The effect on coherence was due to the significantly greater coherence between channels 1 and 5 in comparison to the postcentral pairs (p<0.05 in both cases). The effect on phase angle was due to significantly greater phase angle between channels 2 and 6 in comparison to channels 3 and 7.

7.4 Discussion

Unlike Experiment V, relatively lower coherence at the central pairs of electrodes was not found and thus the specific anatomical hypothesis suggested was not supported. It thus appears that one of the most important factors affecting coherence, at least in the scalp area studied, is the separation of electrodes along the longitudinal axis. The finding of higher coherence over the left hemisphere than the right in the beta-1 band was rather unexpected, although the same trend can be seen in the results of Experiment V.

With respect to the phase angle effects, the left precentral area once again showed a strong consistent relationship in the theta band, with channel 5 leading channel 6. Again, the phase angles were larger at the anterior pairs than at other pairs. The phase angle between channels 6 and 7 in the alpha band did not differ significantly from zero, but it was significantly more negative than its right hemisphere equivalent. In the beta-1 band, the phase angle was again more negative over the left hemisphere than the right at the central pairs, and vice versa at the posterior pair, as in Experiment V. In addition,
the phase angle was larger over the left hemisphere than the right at the anterior pair of electrodes. Channel 4 led 3 and channel 7 led 6, as in Experiment V, but the phase angles between channel pairs 2-3 and 7-8 failed to differ significantly from zero. The general pattern of results was, however, remarkably similar.

Turning to an examination of interhemispheric effects, coherence followed the expected pattern of a large 'gradient effect' for the alpha band, a weaker one for beta-1 and no 'gradient' for theta. Hence, this finding seems very reliable, although again no obvious explanation is at hand. In only one instance was a significant interhemispheric phase difference found, in that channel 2 seemed to lead channel 6 in the alpha band. This result was only weakly significant, but it was noted that if the significance level used had been 0.10 instead of 0.05 several other interhemispheric phase differences would have emerged and, interestingly, all showed right hemisphere leading (cf. Liske et al., 1967; Giannitrapani, 1979b; Inouye et al., 1981b).

The analysis of power produced some interesting effects, in that for all bands channel 3 recorded greater activity than channel 7. In Experiment V such an effect was only found for the beta-1 band, and perhaps ought to be treated with caution, even though every effort was made to maintain correct calibration. However, Giannitrapani (1979a) and a few other investigators have found a similar L>R asymmetry for certain homologous points. Just as Giannitrapani (1979a) found this asymmetry to be reversed to the more usual R>L asymmetry at the occiput, so the present study found a R>L asymmetry at the most posterior electrode pairs for theta and peak-alpha activity. Such
findings emphasise the dangers of interpreting asymmetry at one pair of electrodes as being representative of the pattern of activation of the whole hemisphere. Even given the current lack of detail in neuropsychology, it should still be apparent that intrahemispheric topography cannot be ignored.

7.5 General Discussion

Unfortunately, the experiments failed to contribute to the problem of anatomical asymmetries in the desired manner. It does not seem likely that coherence analysis can be used to detect the position of principal fissures, at least using such a basic approach as that employed here. However, taking the last three experiments as a group, many interesting and reliable effects have been found. Before considering them further it must be asked whether they could be artifactual, perhaps due to the unilateral manual response or asymmetric EKG contamination from the NCRE. With respect to the former possibility, it would seem unlikely that the fact that all subjects used their left hand to respond could be responsible for the asymmetries found, as EEG was never recorded during or immediately following or preceding a response. Whether or not subtle EKG contamination could be responsible for the effects found is a debatable issue, but it is unlikely considering the care that was taken to minimise this particular problem. It would be ironic if the problem of anatomical asymmetries itself was to cast doubt on the validity of the reported effects. In fact, this possibility can
probably also be safely rejected as none of the sites employed in the experiments were near or overlying areas of known anatomical asymmetry.

Some apparently reliable coherence effects were noted:

a) a coherence gradient was found, with coherence being higher for precentral pairs of electrodes than for postcentral pairs for the alpha band and, to a lesser extent, for the beta-1 band, but not for the theta band.

b) coherence was dramatically reduced by increases in interelectrode distance.

c) for equally spaced pairs of electrodes, the interelectrode separation in the sagittal plane showed an inverse relationship with coherence.

It must always be borne in mind when considering these results that they apply only to a fairly limited area of the scalp. The electrode placements for all three experiments would probably fit within the square formed by F3, F4, P3 and P4 of the 10-20 System (Jasper, 1958). Whether the effects found can be generalised to other areas of the scalp remains to be seen. Another point which makes comparison with other coherence studies difficult is that very few other studies have ensured that electrodes were equally spaced. If they are not, it is impossible to interpret differences in coherence which could easily reflect nothing more than interelectrode distance.

The coherence gradient for alpha and beta-1 was found very reliably, although it has not been noted before, probably because so few studies have employed equally spaced electrodes. One might expect that higher coherence would be found at occipital placements, and
indeed this may be the case, but the maximum in alpha power at the occiput need not necessarily imply maximum coherence. Mathematically, the two are independent, and an examination of those studies reporting maximum coherence at the occipital poles usually reveals that such studies have followed the 10-20 system, and thus O1 and O2 are the electrode pair with minimum interelectrode distance.

The present series, along with most other coherence studies, found a dramatic reduction in coherence as interelectrode distance increased. Interestingly, Giannitrapani (1979b) claims that such a decrease in coherence does not occur for schizophrenics. The finding that homologous sites on each hemisphere produced maximum coherences has been reported several times before and thus appears to be very reliable (Giannitrapani, 1975; Vos et al., 1975; Walter et al., 1966). It would be of great interest to know whether these higher coherences are due to the fact that the electrodes are homologously located with respect to the hemispheres or simply to the fact that they are positioned so as to have minimal separation along the sagittal plane. For example, would the coherence between Fz and F7 equal that between F3 and F4? An answer to such questions would give some guidance on how coherence effects might be interpreted. Most investigators either implicitly or explicitly assume that coherence reflects functional communication effects superimposed upon 'baseline' coherences due to anatomical connectivity. Although the current series failed to support the specific anatomical hypothesis tested, it is still possible that coherence could reflect such effects.

The dramatic reduction in coherence with increases in interelectrode distance highlights once again the problems associated
with the use of a cephalic active reference in studies attempting to
topographically map EEG phenomena. Any activity recorded at the
reference electrode will presumably show a decrease in coherence with
activity at other sites as the distance to those sites increases (with
respect to a hypothetical ideal inactive reference). However, this
could paradoxically produce results suggesting that coherence between
equidistant adjacent electrodes actually increases with distance from
the reference, because common-mode rejection would cancel out the
coherent components for close electrodes and thus activity at the
reference would be reflected more strongly at distant locations,
producing an increase in coherence at these placements. It must be
emphasised that as coherence is a frequency-based form of analysis,
whereas common-mode mode rejection is time-based, this argument would
only apply if the coherent activity was not greatly time-shifted
between reference and active sites. In fact, it is even possible that
a 180 degree shift would produce the opposite effect to that
described, but such large phase shifts are very unlikely, as already
discussed. This postulated apparent increase in coherence with
distance from the reference provides a further possible reason why the
coherence gradient found in the last three experiments has not been
noted by investigators using cerebral references. A consideration of
previous studies supports this account. For example, Shaw et al.'s
(1979) data (Table I) would seem at first to contradict the coherence
gradient effects reported here, but in fact all of the data can be
accounted for in terms of differences due to interelectrode separation
and distance of electrode pairs from the (frontal) reference, with the
former being the more influential factor. Giannitrapani's (1979b) data
also support this notion. His Figure 7 (page 136) shows a tendency for lower coherence between equidistant pairs of electrodes, the nearer these pairs are to the linked ears reference.

The above account renders any explanation of coherence differences in terms of anatomical connectivity untenable, at least for those studies employing a cephalic reference. It does not, of course, apply to task-related changes, but here the arguments of Shaw et al. (1979) apply, as outlined previously. A further complicating factor in any attempted interpretation involving a cerebral reference is the degree of localisation of coherent activity, which could be an important influence with respect to task-related changes. Using similar arguments to those above, if, for example, a task produced increased coherence in one hemisphere (with respect to an ideal inactive reference) but this area of highly coherent activity included the actual reference, common-mode rejection might lead to an apparent reduction in coherence over that hemisphere. Alternatively, the same effect could be produced if the effect of the task was simply to make activity at the reference more coherent with that at the sites over one hemisphere, whilst activity at those sites remained unchanged (cf. Yingling's (1977) discussion of cortical coupling). Furthermore, differences between subject groups may themselves reflect nothing more than differences at the reference site, adding further weight to the assertion that no attempt should be made to explain such differences in terms of current neuropsychological models. For example, it is possible that Giannitrapani's (1979b) findings concerning differences between normals and schizophrenics in the 29 Hz band might reflect nothing more than increased EMG at the linked ears reference in the
schizophrenic group.

Certainly the most problematic aspect of these results relates to the phase angle effects. It was noted in Experiment IV that the phase angle differences were much smaller than those found by other investigators, thus leading to very high estimates of wave propagation speeds. Similar small phase angles were found in the two subsequent experiments, and a consideration of other coherence studies reveals that they produce estimates more or less in line with those reported here, with the exception of Hord et al. (1974) and Suzuki (1974). In the case of Suzuki (1974), it is possible that the large phase angles found were a result of differences in analysis procedure, although precise details are not provided. It is noteworthy however that when analysis was based on shorter epochs of 10 sec, as opposed to longer epochs of 60 or 200 sec, phase angles "varied more or less around the value determined for the entire length of the record". Examination of Suzuki's Figure 6 (page 576) shows that this variation was sometimes quite considerable, especially for the localised components. It is possible that by using short epochs (1 sec) in the present study, and smoothing across both epochs and frequency bands, any phase effects which occurred only at particular narrow frequency bands may have been diluted. On the other hand, there are advantages to the procedure of considering many small epochs instead of a few long ones, and smoothing across epochs and frequencies. The major advantage is the increase in the number of degrees of freedom associated with the coherence estimate that such a procedure brings about (Shaw, 1980, personal communication; Shaw, 1981). This increases the reliability of the coherence estimate as outlined earlier. This in turn leads to more
reliable phase estimates, if coherence is high. In the present series, it was ensured that coherence would be high by using closely spaced electrodes, and although Suzuki used similar spacing, he then considered coherence and phase between the posterior electrode and all others, rather than between adjacent pairs as in the current series. This adds the complicating factor that his coherences (and thus the reliability of his phase angle estimates) decrease as the interelectrode distance increases, sometimes reaching zero. Although theoretically there seems to be no good reason for phase angle estimates to decrease as coherence increases, many investigators have noted this effect (e.g. Vos et al., 1975). It is worth mentioning here that Hord et al's (1974) coherence values are also rather low. Thus it is difficult to say which estimates of phase differences are more valid.

Many of the studies described in the review of phase analysis reported both anterior- and posterior-leading waves. Therefore another possible explanation of the discrepancy between coherence studies and studies using other techniques to analyse phase effects is that the coherence studies might produce such small phase difference estimates because they smooth AP and PA waves together. The fact that the predominant direction of leading can change could offer an explanation of Giannitrapani's (1975) generally very low reliabilities for phase. However, in the current series, certain phase angle effects did appear to be reasonably reliable, producing similar patterns of phase effects across different experiments.

In order to try to ascertain if the small phase difference estimates found in this and other studies using coherence analysis
were due to smoothing over AP and PA travelling waves, it is necessary to consider epochs individually. In fact Pocock (1980a, b) considers not only each epoch, but also each frequency component, individually. This would appear to be a very dubious procedure when using Fourier analysis as the estimates of sine and cosine coefficients are notoriously unreliable if no smoothing is carried out. These are the same coefficients that are involved in estimating phase differences in coherence analysis, and as Glaser and Ruchkin (1975) point out, "The phase estimator, like the squared coherence estimator, is useful only when it is preceded by smoothing of the cross spectrum". Surprisingly, Papakostopoulos et al. (1971) make no mention of smoothing in their discussion of phase estimation. However, it was felt that despite reservations, it would be worth examining phase angle estimates at different frequencies in individual epochs if only to highlight the source of the discrepancy between this study and Pocock's. Such an analysis was carried out, but the results are not presented because they did not in fact cast any light on the issue. It was apparent however that unlike Pocock's study, the majority of epochs did not fall either into the AP or PA types, although this type of epoch was certainly more common than would be expected by chance.

Other possible reasons for the discrepancies between studies were considered. Firstly, Pocock's use of a cephalic reference (frontal) would have produced unknown effects due to the confounding of amplitude and phase. The present series avoided this problem by the use of a NCRE. The possibility of comparing Pocock's results with the present data transformed to simulate an 'algebraic' anterior reference was considered, but rejected, as the most anterior of the electrodes
in the current series was still several centimetres posterior to the Fpz reference used by Pocock. Secondly, it is possible that as some of the data in Pocock's study were collected by the experimenter triggering data collection, it might consist of well-defined bursts of alpha. The current experiments simply collected samples of EEG under computer control, and analysed the samples into various frequency bands, regardless of the nature of the waves present.

With respect to the phenomenon of travelling waves, Pocock (1980a, b) has proposed an interesting hypothesis to account for the apparent disparity between studies in terms of velocity and direction of propagation of alpha waves. The essentials of Pocock's hypothesis have already been presented (see Section 5.1) and at first sight it does seem to offer a parsimonious way to account for many seemingly discrepant results (including the present ones). Pocock shows, in fact, that virtually all of the previous findings could be interpreted in terms of PA travelling waves. Pocock points out that his hypothesis would predict that closer electrode spacing would lead to larger estimates of phase difference, and thus slower propagation speeds, a prediction that seems to be borne out by the literature. The present series, using fairly small interelectrode distances for studies of human EEG, would seem to be exceptional in that it suggests very small phase angle differences and thus very high wave velocities. However, the spatial aliasing hypothesis can still be applied to the results and if we simply assume that all the phase angle differences in the present study were out by one whole cycle (360 degrees), then a completely different picture emerges. For example, if we consider the alpha band and, to simplify the situation, assume that the central
frequency (10 Hz) can be taken as representative of the whole band, the difference of 1.7 degrees between electrodes 3 and 4 found in Experiment IV, would really correspond to a difference of 361.7 degrees, producing an estimate of velocity of propagation of around 0.3 m/sec, much more in line with estimates from other sources (e.g. Lopes da Silva and Storm van Leeuwen, 1978). However, this does not offer such strong support for Pocock's hypothesis as might first be assumed. Consider that if a component with a frequency of f Hz travels d metres between A and B, and we interpret this in terms of a travelling wave, the velocity of propagation is given by:

\[ V = \frac{360 \cdot f \cdot d}{x + n \cdot 360} \]

(where \(n = 0, 1, 2, 3, \ldots\) to allow for spatial aliasing)

Now, if \(f=10\) and \(d=0.03\) (as in this case),

\[ V = 0.3 \cdot \frac{360}{x + n \cdot 360} \]

Because of the limitations of phase analysis, \(x\) will always have a value between 0 and 360 degrees (or, if preferred, plus or minus 180 degrees). This results in the situation that if \(x\) is small and \(n=0\), extremely high estimates of propagation velocity are obtained, but if it is assumed that the actual values of the phase difference must be out by 360 degrees, the actual value of \(x\) becomes irrelevant as the
expression $360/(x+360)$ will be approximately one producing a value for $V$ of around 0.3 m/sec. In fact, reference to Figure 20 shows that no matter what value of $x$ is found, it can always be interpreted as being "really" due to waves propagating from occipital to frontal areas at "acceptable" velocities of between 0.2 and 1 m/sec. This diagram also illustrates another feature of spatial aliasing. For a given frequency and wavelength, the actual value of $x$ is only of much importance with respect to the value of $V$ if it is taken to be a 'true' value (i.e., $n=0$ in the equation). Otherwise, all values of $V$ can be seen to be fairly close to the product of $f$ and $d$, at least for reasonably low values of $n$ (note that although only two lines are shown in Figure 20, $n$ can take any positive integer value). The value of $(fd)$ can thus be seen to be critically important. If the "acceptable" range of values for the velocity of propagation includes $(fd)$ any values of $x$ can be adequately accounted for in terms of PA travelling waves - or, if the investigator prefers, AP travelling waves! Given the usual range of values of $d$ (0.01 to 0.1 m), and the fact that the alpha range traditionally extends from 8 to 13 Hz, it is apparent that very few values of $x$ could not be accounted for.

Thus, although it is undeniable that spatial aliasing could occur in the manner described by Pocock, it must be realised that the present results, and most others, could hardly fail to be consistent with the spatial aliasing hypothesis and therefore neither support nor refute it. Pocock (1980a) is aware of the hypothetical nature of his suggestions, and after a detailed discussion of his hypothesis he surprisingly concludes that,
FIGURE 20: Graph to illustrate Pocock's (1980a) 'spatial aliasing' hypothesis. See text for full account.
"In general, the results here help corroborate the notion of localised alpha band rhythmic activity being generated, under thalamic influences, potentially over the whole cortex at numerous 'epicentres' and spreading cortically in all directions" (emphasis added).

There are however one or two observations which would appear to be difficult to reconcile with the spatial aliasing hypothesis. For example, if spatial aliasing occurs when spatial sampling is inadequate, it is very surprising that no study (to the author's knowledge) has ever shown a cumulative phase shift along a line of electrodes on the scalp or cortex of over 360 degrees. At the other extreme, there have been suggestive reports of waves peaking at all points simultaneously (Garoutte et al., 1959; Cooper and Mundy-Castle, 1960), i.e. of possibly near-zero phase shifts. Minima have never been recorded simultaneously with the maxima, at intermediate points, although this is open to empirical investigation. Secondly, it would seem, given the large variability in electrophysiological measures, almost incredible that the particular spacing of electrodes used in the present experimental series corresponded more or less exactly to a whole number of complete cycles in terms of phase shifts. It is of course possible, as discussed, that the nature of coherence analysis produces inaccurate phase angle difference estimates, but this argument could still be applied to other studies where spatial aliasing might be invoked.

In the final analysis it is impossible to say whether or not the estimates found represent "real" phase differences or not. If they do,
then several issues need to be dealt with. Firstly, all other studies of phase differences not using coherence analysis must be in error, and if the results are viewed in terms of travelling waves, (a) the velocity is much higher than previously thought, and (b) more problematically, all of the different frequency components must travel at different speeds. The latter problem is really tied to interpretation of phase angle effects. As Shaw (1981, personal communication) points out,

"If we are considering a narrow frequency band of 1 to 2 cycles, and we are interested in the phase difference between two sites, it is only meaningful if the whole waveform within that band is preserved at the two sites. Phase change is then proportional to frequency and we have a true travelling wave phenomenon. Otherwise we have mathematically correct figures tied to individual frequency components and I find it difficult to see what this means physiologically although it is a valid way of describing the signal topography".

Thus it possibly is an error to treat these results as though they reflect a "true travelling wave phenomenon". Perhaps the time differences reflect not a travelling wave at all, but the effects of some subcortical (thalamic?) influence which arrives at the cortex at slightly varying times at different points. What would be of great assistance in interpreting these results would be a clear underlying theoretical framework concerning the genesis of EEGs. Despite many attempts (Andersen and Andersson, 1968; Elul, 1972; Thatcher and John,
1977) it must be admitted that we still have no clear picture of what the intracortical sources of EEG are. However, the work of Lopes da Silva et al. (1973, 1980a, b; Lopes da Silva and Storm van Leeuwen, 1977, 1978) may be particularly relevant here. Their work suggests that both intracortical and thalamocortical influences are very important in the cortical organisation of rhythmic activity, and in particular, "cortical alpha rhythms appear to be generated in relatively small cortical areas which act as epicenters; from these, alpha activity spreads around in different directions up to distances of 4 mm", (Lopes da Silva et al., 1980b). Incidentally, note that such limited spreading is unlikely to be picked up by electrodes 9 mm in diameter.

The possibility remains that phase angle estimates deduced from coherence analysis are not valid, due to smoothing or spatial aliasing. It is even possible that two types of activity are being confused by the different studies. Perhaps in some studies the waves analysed contain large well-defined bursts of alpha activity originating at the occiput, while others concentrate on 'background' activity which happens to fall in the alpha range. Only further, more refined, studies will decide the issue.
Chapter 8: Conclusions

Several themes have recurred constantly throughout this thesis, in both the review section and the experimental reports. An attempt will be made here to summarise these themes and to evaluate their importance with respect to possible future research.

The initial review section highlighted the fact that this area of research is still plagued by methodologically inadequate studies. It was felt that of all the various EEG/EP techniques used for investigating hemisphere asymmetry of cognitive function, including on-going EEG, AERs, VERs, 'probes', CNVs and speech-related potentials, none could be said to have unequivocally demonstrated task-related effects which could not have been due to artifacts. In particular, attention was drawn to potential contamination in the vast majority of studies from unilateral or asymmetric motor components of tasks or unmonitored EOG, which could well produce asymmetric effects due to reflective LEMs. Furthermore, the use of active cerebral reference electrodes has been very severely criticised.

The implications of the anatomical asymmetries of the cerebrum were also discussed. This problem is considerably more perplexing than those considered elsewhere, insofar as it is not easily solved. Various suggestions as to how it might be approached were made, but unfortunately the approach opted for in this series of studies proved not to be fruitful. In retrospect, perhaps it was naive to hope that coherence could provide such a 'window' through the skull, but at least some interesting effects were found, as outlined below. Meanwhile, the issue of anatomical asymmetries remains a problem,
constituting as it does a possible confounding factor in virtually all studies of cognitive hemispheric function.

A fairly detailed discussion and review of coherence was also provided in Chapter 1. This measure would appear to be a promising addition to EEG spectral analysis techniques and it is becoming increasingly popular, but once again it was noted that the use of an active cerebral reference renders coherence effects virtually uninterpretable.

Turning to a consideration of the experiments, the only coherence effect to reach significance in Experiment I was a L>R asymmetry for frontal pairs of electrodes across all tasks. No effects of task difficulty or type of task were found, making this yet another study which failed to produce the expected asymmetries in on-going EEG. I would like to feel that this reflects the fairly stringent control of potential sources of artifacts employed in this study, but it is of course possible that the tasks simply failed to engage the hemispheres differentially because they were too easy.

Experiments II and III consisted of attempts to extend and/or replicate Davis and Wada's apparently very reliable coherence effects in response to simple click and flash stimuli. They had reported in a number of studies that coherences were higher in the dominant hemisphere for AERs and in the nondominant hemisphere for VERs. It was felt that the sole coherence effect reported in Experiment I might reflect the fact that this experiment employed auditory stimuli in all conditions, even though it had involved on-going EEG whereas Davis and Wada had analysed averaged responses. Experiments II and III considered coherence effects for on-going EEG and averaged evoked
responses, respectively, for simple flash and click stimuli. No confirmation of Davis and Wada's findings was forthcoming, and so the hypothesis that a simple relationship exists between coherence and modality of stimulation was not supported.

Experiments IV, V and VI were more fruitful in that a number of reliable coherence and phase angle effects were found. For example, if we consider the three experiments as a group, (a) a coherence gradient effect was found, with coherence being higher for precentral pairs of electrodes than for postcentral pairs for the alpha band and, to a lesser extent, for the beta-1 band, but not for the theta band, (b) coherence was dramatically reduced by increases in interelectrode distance, and (c) for equally spaced pairs of electrodes, the interelectrode separation along the nasion-inion axis showed an inverse relationship with coherence. Furthermore, certain reliable phase angle effects appeared, but serious problems of interpretation of these effects were noted and fully discussed. It would appear to be questionable whether phase angle spectra produced by coherence analysis can be taken at face value.

With respect to future research, the single most pressing need is for studies to be more tightly controlled. However, as previously stated, the time and effort required to produce such stringent control would probably be better spent if applied to tasks which previous loosely controlled studies had suggested may produce the desired asymmetries. Such an approach would serve another useful purpose insofar as if it was found that the apparent asymmetries did not occur in the strictly controlled condition, an attempt could then be made to ascertain precisely which of the numerous potential sources of
artifact were important (cf. Gevins et al., 1979a, b, c). Systematic research on the effects of different reference sites is another area which would reward further study.

In conclusion then, the question must be raised of just how useful the EEG/EP approach has proved to be in the study of hemisphere asymmetries. The immense usefulness of such techniques both clinically and experimentally when applied to other areas cannot be denied, but it would appear that there are still serious problems to be resolved with respect to lateralisation studies. Many of these problems arise because the investigator of hemisphere asymmetries must face the issue of localisation of function, and thus the problems of anatomical asymmetry and the use of active cerebral references become acute. Such considerations do not apply to researchers using ERP techniques to study 'purely cognitive' issues, e.g. using the P300 to index 'surprise', or to those who simply wish to use EEG/EP measures to differentiate between different clinical populations.

However, it must be borne in mind that many of the techniques of analysis employed at the moment are still in their infancy, as inexpensive microcomputers have only become widely available in the last decade. All of the problems discussed, with the exception of anatomical asymmetries, could be avoided with proper attention to methodology, and it is quite possible that the future will provide a definitive answer to the question of whether or not EEG/EP indices of cognitive lateralisation can be demonstrated. Such a demonstration would be of great value but it is certain that it cannot be provided unless the problems discussed herein are faced squarely, and resolved.
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Laterality of change in the EEG during right and left activity.


Appendix A: Instructions and Stimuli

For Experiment I

AI: Instructions

The following written instructions were given to subjects in Experiment I.

a) TONE task: This part of the experiment involves listening out for tone bursts which are embedded in a "white noise" background. You are required simply to press the response button with the index finger of your right hand when you hear the tone. There is no need to hurry - this is not a reaction time experiment, and any press given within two seconds of the tone will be counted as a correct detection. Keep your eyes closed, relax, and try to avoid gross movements if possible.

b) LIS task: The next three sections of the experiment involve responding to words. In this first section you are required simply to press the response button with the index finger of your right hand for all words. However, do not respond until you have heard the tone burst which follows the word. There is no need to hurry - this is not a reaction time experiment, and any press given within two seconds of the tone will be counted as a correct response. Keep your eyes closed, relax, and try to avoid gross movements. Simply listen to the words and press the response button with the index finger of your right hand after you hear the tone.
c) ANI task: In this part of the experiment you are to respond only to words that refer to living creatures, e.g. slug, shrimp, thrush, etc. Again, respond after you hear the tone. Do not rush - reaction times are not being measured. Keep your eyes closed, relax, and try to avoid gross movements. Listen to the words and press the response button with the index finger of your right hand after you hear the tone if the word refers to a living creature.

d) AMB task: In this part of the experiment you are to respond only to words that have more than one meaning. Do not consider the spelling of the word - e.g. "male", if presented, would require a response as it could refer to "male" (vs. "female") or "mail" (letters). Other examples of words requiring responses would be "file", "pip", "witch" (which), "cast", and so on. Keep your eyes closed, relax, and avoid gross movements. Listen to the words and press the response button with the index finger of your right hand if the word has more than one meaning. Consider only the sound (not the spelling) of the word and think of as many meanings as you can between word presentation and the tone.
A2: Stimuli

The following monosyllabic words were used as auditory stimuli in Experiment I. The 'ambiguous/animal' targets are marked with asterisks.

<table>
<thead>
<tr>
<th>ARM</th>
<th>BEAK</th>
<th>BEAR*</th>
<th>BOAR*</th>
<th>BOOK</th>
<th>BOX</th>
<th>BILL</th>
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<tr>
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<td>CROWN</td>
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<td>DOG</td>
<td>DUCK*</td>
<td>ELK</td>
<td>FIRE</td>
<td>FLEA*</td>
<td>FLY*</td>
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<td>GROUSE*</td>
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<td>GULL</td>
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<td>MODE</td>
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<td>POST</td>
<td>QUAIL*</td>
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<td>RING</td>
<td>ROLL</td>
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<td>SPOT</td>
<td>STOAT</td>
<td>STORK*</td>
<td>TASK</td>
<td>TENCH</td>
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<tr>
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<td>TOOTH</td>
<td>TRAIN</td>
<td>VOLE</td>
<td>WASP</td>
<td>WHALE*</td>
<td>WREN</td>
<td>ZONE</td>
</tr>
</tbody>
</table>
Appendix B: Program Listings

The programs below are in no way a complete presentation of all programs written by the author and used in running the experiments and data analysis. For example, programs written to carry out specific statistical tests (e.g. t-tests, Newman-Keuls comparisons) have not been presented, and neither have the many programs used to reformat data, so that it could be analysed by software packages or plotted. Also, only one version of each major program is presented, despite the fact that many modifications may have been made to suit the requirements of particular experiments, and the limitations of the computing facilities available at particular times. With respect to the latter, many advances were made in terms of data analysis over the period during which the studies were carried out. The single most important advance was the linking of the departmental PDP8/e minicomputer to the University's mainframe CYBER 73 computer following Experiment I. This produced many real gains including:

(i) virtually unlimited storage of data, thanks to the ARCHIVE facility (in contrast to having to dispose of data following analysis on the PDP8/e).

(ii) vast increases in speed of analysis (from several hours on the PDP8/e to a fraction of a minute on the CYBER 73).

(iii) access to several powerful statistical and graph-plotting packages.

Even with the vast increases in storage space, problems of limited
workspace remained, but these were gradually overcome, firstly by software modifications, and finally by increases in filespace on the CYBER itself.

Altogether three different computers were involved in this series of experiments. Firstly, the PDP8/e was always used to run the experiments and digitise the EEG. This necessitated the use of U/W-FOCAL, with an overlay to allow A-D sampling. Another overlay was used to enable FFTs to be performed, but a coherence analysis program written in FOCAL was only used to analyse data from Experiment I. A second coherence analysis program written in FORTRAN was also used for a brief period on the PDP8/e, prior to being transferred to the CYBER 73. All coherence analysis programs were written by Dr Graham Beaumont, and only slightly modified by the current author. The second computer to be employed in this series of studies was the CYBER 73 and all programs run on this machine were in FORTRAN. Finally, one program presented below was written in BASIC and run on the Commodore PET computer to control stimulus presentation in Experiment III.

N.B.: In FOCAL the arithmetic operation of exponentiation is indicated by an upward-pointing arrow. Unfortunately this symbol was not available on the daisy-wheel used in printing this thesis, and so the FORTRAN double asterisk ('**') has been substituted where this operation is required. Such substitution means, of course, that those programs would not actually run in the form presented.
1.1 TDIF

This FOCAL program collects data during the subject's performance of three verbal and one nonverbal task. Data collection is initiated by Schmidt triggers linked to channel II of a tape recorder. The program prints a measure of the subject's performance at the end of each task. A second version of this program (TDIF2) was used to collect data when the tasks were presented in the alternative order.

01.10 C PROGRAM FOR EEG EXPERIMENT ON TASK DIFFICULTY.
01.20 C WRITES TEMPA.FD, TEMPB.FD, TEMPC.FD AND TEMPD.FD,
01.30 C WHICH ARE 8 CHANNELS (LB1, LB2, RB1, RB2, LW1, LW2,
01.40 C RW1, RW2/REF) OF 64 SAMPLES AT 32 HZ * 20 TRIALS.
01.50 C RUNS ON CIGS. INPUT=DIG(8).
01.70 T !!"EEG TASK DIFFICULTY EXPERIMENT"!!

02.10 0 0 TEMPA; Z N, CO; T %5; D 4
02.20 0 0 TEMPB; Z N, CO; T %5; D 4
02.30 0 0 TEMPC; Z N, CO; T %5; D 4
02.40 0 0 TEMPD; Z N, CO; T %5; D 4
02.50 Q

04.10 Y N
04.20 X FDO(2,-2,-3125,2887) FDO(2,-1,1,64,8,0)
04.60 X FDO(2,1)
04.70 X FDO(2,-2,-300,2695); S Z=FDO(2,-4,1,-300,4)
04.75 F J=1,512; T FG(J)
04.80 I (Z)4.9,4.9; Y CO
04.90 I (N-20)4.1
04.95 0 C; D 7
04.96 T !!"NO. CORRECT OF 20 CRITICAL WORDS=", %2, CO

07.20 F L=1,3; X FDO(2,-3,-50) FOUT(135)
07.30 X FDO(2,1)

1.2 TDIS

This FOCAL program was used following the experiment to display the EEG collected on a TEKTRONIX 613 storage scope, allowing the rejection of trials showing gross artifacts.
01.10 C PROGRAM TO DISPLAY SAMPLES TAKEN DURING
01.11 C RUNNING OF TDIF AND TDIF2. THOSE SAMPLES WHICH ARE NOT
01.12 C ACCEPTED ARE REPLACED BY ACCEPTABLE ONES.
01.13 C RUNS ON CIGS.
01.40 A "1 OR 2?" P,
01.50 I (1-P)1.7,1.6
01.60 F XX=1,4; S ZX=2+XX/10; D XX
01.65 Q
01.70 F XX=5,8; S ZX=2+XX/10; D XX
01.80 Q

02.10 0 I TEMPA;O 0 TEMPA2;D7
02.20 0 I TEMPB;O 0 TEMPB2;D7
02.30 0 I TEMPC;O 0 TEMPC2;D7
02.40 0 I TEMPD;O 0 TEMPD2;D7
02.50 0 I TEMPE;O 0 TEMPE2;D7
02.60 0 I TEMPF;O 0 TEMPF2;D7
02.70 0 I TEMPG;O 0 TEMPG2;D7
02.80 0 I TEMPH;O 0 TEMPH2;D7

03.10 0 R I;F QQ=1,512; A Z; X FP(QQ,Z); S Z+Z/8; X FP(QQ+512,Z)
03.15 D 19
03.20 F JJ=,7; D 10,11,5
03.25 0 I,E
03.30 S X=FIN(); I (X-217)3.4,3.5,3.4
03.40 Y C;R
03.50 0 R 0; F J+1,512; S Z+FG(J); T %5,Z
03.60 R

05.10 S Z=1; D 8; S Z=-511; D 8; S Z=488-JJ*128; D 8; S Z=2; D 8
05.20 S Z=15; D 8; S Z=4; D 8
05.30 X FD(-7,1537+64*JJ) FDO(7,64)
05.40 D 20

06.10 0 I TEMPA2;L D TEMPA.FD;O 0 TEMPA
06.20 0 I TEMPB2;L D TEMPB.FD;O 0 TEMPB
06.30 0 I TEMPC2;L D TEMPC.FD;O 0 TEMPC
06.40 0 I TEMPD2;L D TEMPD.FD;O 0 TEMPD
06.50 0 I TEMPE2;L D TEMPE.FD;O 0 TEMPE
06.60 0 I TEMPF2;L D TEMPF.FD;O 0 TEMPF
06.70 0 I TEMPG2;L D TEMPG.FD;O 0 TEMPG
06.80 0 I TEMPH2;L D TEMPH.FD;O 0 TEMPH

07.10 Z C;F Q=1,20; D 3
07.20 0 C;S Z=6+XX/10; D Z
07.30 S K+512*(20-C); F KK=1,K; A Z; T Z
07.40 0 R R,S K=C*512; F KK=1,K; A Z; T Z
07.50 0 C;T "NO. REJECTED=" C,

08.10 X FD(FD(),Z); S Z=FD(FD()+1)
10.10 X FDO(6,0)

-B4-
The following Focal program is a modification of a coherence analysis program written by Dr Graham Beaumont.

01.10 C PROGRAM TO ANALYSE DATA FROM EEG EXPERIMENT USING 01.20 C WORDS AS STIMULI. READS DATA FROM TEM1.FD, TEM2.FD, 01.30 TEM3.FD AND TEM4.FD WRITTEN BY TDIF.FC. 01.40 RUNS ON CIGF. 01.60 T """"TASK DIFFICULTY: EEG EXPERIMENT ANALYSIS""""!! 01.80 F XX=1,4;D 2 01.90 Q 02.10 S Z=10+XX/10;D Z 02.20 F II=1,4;S ZZ=12+II/10;D 13,ZZ,3 02.30 D 3.9 03.10 F J=19;D 4 03.20 T """"RAW POWER : CH.1 CH.2""""!;Z C,D 03.30 F K=1,9;D 20,21
The following FOCAL program was used to collect data and present stimuli for Experiment II.

01.10 C THIS PROGRAM COLLECTS ONGOING EEG DATA FOLLOWING PRESENTATIONS OF FLASH AND CLICK STIMULI. DATA ARE COLLECTED AT 64 HZ FOR 1 SEC FOLLOWING THE STIMULUS. TWO RUNS REQUIRED AS EACH DATA FILE PRODUCED SEPARATELY.
01.15 X FDO(2,-2,-50,2695);T %5.01;Z N;G 2.1
01.60 Q
01.70 F B=16*A-15,16*A;T FG(B)
02.10 O I ORDER(N);0 O FILE(N)
02.15 X FDO(2,1)
02.20 S Z=FDO(2,2);I (Z-1)2.2,2.3,2.2
02.30 A Z;I (Z-9)2.4,2.9,2.4
02.40 I (Z-1)2.6
02.50 X FDO(2,3,2);G 2.7
02.60 X FDO(2,3,16)  
02.70 X FDO(2,4,18)  
02.80 I (Z-N)3.1,3.2,3.1  
02.90 X FOUT(192);0 C  
02.95 F Q=1,3;X FDO(2,-3,-50) FOUT(135) FDO(2,1)  
02.97 Y N;I (N-2)2.1,1.6  
03.10 S Z=FDO(2,-4,1,-439,4);G 3.5  
03.20 X FDO(2,3,4) FDO(2,-2,-1563,2887)  
03.30 X FDO(2,-1,-1,64,4,0) FDO(2,4,4) FDO(2,-2,-50,2695)  
03.40 F A=1,16;D 1,7;T !  
03.50 A Y;S Z=FDO(2,-4,1,-Y,4);I (Z-2)2.3,2.2,2.3

2.2 ARP

The following FORTRAN program was run on both the PDP8/e and the CYBER, sometimes linked to the following coherence analysis program and sometimes independently. The previous method of artifact-rejection, i.e. using TDIS to display each epoch individually and reject those which were contaminated, was very time-consuming, taking over one hour to review a single subject's data. It was felt that the decisions involved in accepting or rejecting a particular epoch could be formalised to allow a crude but effective program to examine the epochs. The output from this program consists of the acceptable data in the correct format for further analysis. Several trial runs showed good agreement between the experimenter and the program with respect to which epochs were rejected.

Essentially, the program checks for four types of artifacts:

(a) the signal may have reached the limits of the A-D range of the PDP8/e, i.e. it may have been 'chopped'.

(b) movement artifacts tend to produce large deflections from baseline. If the signal did not cross the baseline for more than 0.75 sec, the epoch was rejected.
(c) if for any reason the signal was flat (i.e. between plus and minus four units on the A-D range) for more than 0.25 sec it was rejected.

(d) any noise introduced into the signal produces a large spread of data points. By measuring this spread for a range of artificially produced noisy signals, a critical value was established, which, if exceeded, led to rejection of an epoch.

```
PROGRAM ARP (TEMP,CCFOUT,EEG,INP,TAPE1=TEMP,
1 TAPE4=CCFOUT,TAPE5=EEG,TAPE6=INP)
C
THIS PROGRAM TAKES IN EEG IN A SUITABLE FORMAT
C
AND DUMPS ANY SAMPLES WITH GROSS ARTIFACTS.
C
VALUES MUST BE PRESET IN DATA STATEMENTS.
DIMENSION A(768), DIF(9), IC(16), JC(16)
DATA NF,NE,NSUB/1,25,20,6,128,128,1/
DATA IC/1,2,3,4,5,1,2,3,4,1,2,3,1,2,1,99/
DATA JC/2,3,4,5,6,3,4,5,6,4,5,6,5,6,6,99/
WRITE (4,125)
125 FORMAT (1HO,"ARTIFACT REJECTION PROGRAM C.C.F.,1979")
NP=N*NC
WRITE (5,100)NFILE
100 FORMAT (17)
IE=0
15 IF(IE.EQ.NFILE)GO TO 255
IE=IE+1
TIME=FLOAT(N)/FLOAT(IHZ)
WRITE (5,128) NR,NC,N,TIME
128 FORMAT (317,F11.4)
WRITE (4,121)IE
121 FORMAT (1HO,"FILE NO.",I2)
REWIND 1
IR=0
ID=0
IT=0
20 SUM=0.0
J=0
IF(IT.NE.NE)GO TO 220
ICC=IR
610 REWIND 1
ICO=0
620 READ (1,605) (A(K),K=1,NP)
605 FORMAT (8F8.1)
WRITE (5,605) (A(K),K=1,NP)
ICC=ICC+1
IF(ICC.EQ.NR)GO TO 500
ICO=ICO+1
```
IF(ICO.EQ.IR)GO TO 610
GO TO 620
220 IEE=5+IE
READ (IEE,118) (A(K),K=1,NP)
118 FORMAT (8F8.1)
IH=0
30 IH=IH+1
C CHECK IF DATA WITHIN AD RANGE OF PDP8
IF((A(IH).EQ.-512.0).OR.(A(IH).EQ.511.0))GO TO 90
IF(IH.LT.NP)GO TO 30
C NEXT SECTION CHECKS FOR MOVEMENT ARTIFACTS
IG=0
Z1=A(1)
IG=0
IB=2
35 Z2=A(IB)
IF(Z1*Z2.GT.0.0)GO TO 40
IG=0
50 IB=IB+1
Z1=Z2
IF(IB.GT.NP)GO TO 45
GO TO 35
40 IG=IG+1
IF(IG.EQ.3*IHZ/4)GO TO 90
GO TO 50
45 I=0
65 I=I+1
IF(I.EQ.NP)GO TO 60
C NEXT SECTION ENSURES SIGNAL IS NOT FLAT
IF((A(I).GT.-4.0).AND.(A(I).LT.4.0))GO TO 55
J=0
GO TO 65
55 J=J+1
IF(J.GT.IHZ/4) GO TO 90
GO TO 65
60 IS=0
C NEXT SECTION CHECKS FOR SPREAD OF DATA POINTS
DO 70 IY=1,9
DIF(IY)=(A(IY)-A(IY+1))**2
70 CONTINUE
85 DO 75 IM=1,IHZ/8
SUM=SUM+DIF(IM)
75 CONTINUE
IF(SUM.GT.1000000.0) GO TO 90
IS=IS+1
IF(IS.EQ.NP-IHZ/8) GO TO 80
DIF(9)=(A(8+IS)-A(9+IS))**2
SUM=0.0
DO 71 INK=1,8
DIF(INK)=DIF(INK+1)
71 CONTINUE
GO TO 85
80 IR=IR+1
-B10-
IT=ID+IR
WRITE (5,119) (A(K),K=1,NP)
WRITE (1,119) (A(K),K=1,NP)
119 FORMAT (BF8.1)
IF(IR.EQ.NR) GO TO 500
GO TO 20
90 ID=ID+1
IT=ID+IR
WRITE (4,120)IT
120 FORMAT (1HO,"EPOCH NO.",I2," REJECTED.")
C PRINT OUT SUMMARY
IF(SUM.GT.1000000.0) GO TO 205
IF(J.GT.IHZ/4) GO TO 210
IF(IG.EQ.3*IHZ/4) GO TO 215
WRITE (4,122)IH,A(IH)
122 FORMAT (1HO,"POINT NO.",I4,"=",F8.1)
GO TO 20
215 WRITE (4,123)IB
123 FORMAT (1HO,"MOVEMENT ARTIFACT(?) AT ",I4)
GO TO 20
210 WRITE (4,124)I
124 FORMAT (1HO,"SEGMENT FLAT AT ",I4)
GO TO 20
205 WRITE (4,126)IS
126 FORMAT (1HO,"SPREAD (DUE TO NOISE?) AT ",I4)
GO TO 20
500 REWIND 1
WRITE (4,127) ID
127 FORMAT (1HO,"TOTAL REJECTED=",I2)
GO TO 15
255 ENDFILE 5
REWIND 5
WRITE (4,130)
130 FORMAT (1HO,"-----------------------------")
REWIND 1
STOP
END

2.2 COAN

This is one of several versions of a coherence analysis program written in FORTRAN by Dr Graham Beaumont, which was used on both the PDP8/e and CYBER 73. This version produces two values of phase - one corrected for multiplex delay (see Appendix D), and also the uncorrected value. The uncorrected values were routinely analysed for comparison purposes.
PROGRAM COAN3 (CCFOUT,EEG,TAPE4=CCFOUT,TAPE5=EEG)
C THIS IS A VERSION OF COAN WITH FIXED VALUES, WHICH IS CALLED AS
C A SUBPROGRAM BY ARP.
C
DIMENSION XR(128),XI(128),IC(17),JC(17)
COMMON BATA(320,128)
DATA NSUB/1/
DATA IC/1,2,3,5,6,7,1,2,3,4,99/
DATA JC/2,3,4,6,7,8,5,6,7,8,99/
WRITE (4,200)
200 FORMAT (1H0,"COHERENCE ANALYSIS PROGRAM G.B. 1979")
WRITE (4,210)
210 FORMAT (1H0"FREQ. BANDS: THETA 4- 7.99  ALPHA 8-12.99")
WRITE (4,211) /
211 FORMAT (1H0"BETA1 13-21.99  BETA2 22-29.99")
DO 950 IS=1,NSUB
WRITE (4,104) IS
104 FORMAT (1H0,30X,"*****SUBJECT",I3," *****")
ISS=4+IS
READ (ISS,106) NCON
106 FORMAT (17)
FORMAT (17)
DO 900 I=1,NCON
WRITE (4,107) I
107 FORMAT (1H0"CONDITION ",I3)
READ (ISS,110) NEP,NCH,NSAM,SLEN
110 FORMAT (3I7,F11.4)
L=1
M=2
NNN=NEP*NCH
DO 20 J=1,NNN
READ (ISS,115) (XR(K),K=1,NSAM)
20 CONTINUE
FORMAT (8F8.1)
CALL TAPER (XR,NSAM,0.5)
DO 10 K=1,NSAM
XI(K)=0
10 CONTINUE
INV=0
CALL FFT (XR,XI,NSAM,INV)
IF (INV.LT.0) GOTO 910
DO 333 K=1,NSAM
BATA(L,K)=XR(K)
BATA(M,K)=XI(K)
333 CONTINUE
L=L+2
M=M+1
20 CONTINUE
DO 25 J=1,NCH
CALL POWER (NEP,NCH,NSAM,SLEN,J)
25 CONTINUE
J=0
30 J=J+1
-B12-
IA=IC(J)
IB=JC(J)
IF (IA .GT. 8) GO TO 35
CALL COHER (NEP,NCH,NSAM,SLEN,IA,IB)
GO TO 30
35 WRITE (4,125)
125 FORMAT (1HO,"---------------------------------------------------------------",//)
900 CONTINUE
950 CONTINUE
WRITE (4,120)
120 FORMAT (1HO,"RUN COMPLETE")
RETURN
910 WRITE (4,920)
920 FORMAT (1HO"ERROR EXIT")
END

SUBROUTINE COHER(NEP,NCH,NSAM,SLEN,IA,IB)
C CALCULATES COHERENCE SPECTRUM TO 30 HZ.,
C AND AVERAGED Z COHERENCE OVER EEG BANDS,
C TOGETHER WITH PHASE (AND PHASE CORRECTED FOR DELAY)
C FROM FFT COEFFICIENTS HELD ON R-A FILE, UNIT 1.
C NEP = NO. OF EPOCHS
C NCH = NO. OF CHANNELS
C NSAM = NO. OF SAMPLES
C SLEN = SAMPLE LENGTH (SEC)
C IA,IB = CHANNEL NO.'S FOR COHERENCE.
C NEEDS FUNCTIONS PHASE AND ZC.
C DIMENSION A(128),B(128),U(128),V(128),X(128),Y(128),C(128),
D(128)
COMMON BATA(320,128)
XNEP=FLOAT(NEP)
DC=FLOAT(IB-IA)
DO 10 I=1,NSAM
X(I)=0.0
Y(I)=0.0
C(I)=0.0
10 D(I)=0.0
THC=0.0
THP=0.0
THCP=0.0
ALC=0.0
ALP=0.0
ALCP=0.0
BIC=0.0
B1P=0.0
B1CP=0.0
B2C=0.0
B2P=0.0
B2CP=0.0
DO 15 I=1,NEP
L=((I-1)*NCH+IA)*2-1
M=((I-1)*NCH+IB)*2-1
DO 66 J=1,NSAM
A(J)=BATA(L,J)
U(J)=BATA(M,J)
66 CONTINUE
M=M+1
L=L+1
DO 77 J=1,NSAM
B(J)=BATA(L,J)
V(J)=BATA(M,J)
77 CONTINUE
DO 15 J=1,NSAM
X(J)=X(J)+(A(J)*U(J)+B(J)*V(J))/XNEP
Y(J)=Y(J)+(A(J)*V(J)-B(J)*U(J))/XNEP
C(J)=C(J)+(A(J)**2+B(J)**2)/XNEP
D(J)=D(J)+(U(J)**2+V(J)**2)/XNEP
15 CONTINUE
WRITE (4,100) IA,IB
100 FORMAT(1HO"CHANNELS ",2I2," RAW COHERENCE AND PHASE")
WRITE (4,101)
101 FORMAT(1HO" (PHASE = CH. 1 LEADS")",/)
DO 40 I=1,NSAM
XF=FLOAT(I-1)/SLEN
IF (30.0-XF.LE.0.0) GOTO 40
CO=(X(I)**2+Y(I)**2)/(C(I)*D(I))
PH=PHASE(X(I),Y(I))
CPH=PH-DC*XF*0.020988
WRITE (4,110) XF,CO,PH,CPH
110 FORMAT(1HO,F6.2,3F15.4)
IF (XF-4.0.LT.0.0) GOTO 40
IF (8.0-XF.LE.0.0) GOTO 25
SN=4.0*SLEN
THC=THC+IC(CO)/SN
THP=THP+PH/SN
THCP=THCP+CPH/SN
GO TO 40
25 IF (13.0-XF.LE.0.0) GOTO 30
SN=5.0*SLEN
ALC=ALC+IC(CO)/SN
ALP=ALP+PH/SN
ALCP=ALCP+CPH/SN
GO TO 40
30 IF (22.0-XF.LE.0.0) GOTO 35
SN=9.0*SLEN
B1C=B1C+IC(CO)/SN
B1P=B1P+PH/SN
B1CP=B1CP+CPH/SN
GO TO 40
35 SN=8.0*SLEN
B2C=B2C+IC(CO)/SN
B2P=B2P+PH/SN
B2CP=B2CP+CPH/SN
40 CONTINUE

-B14-
WRITE (4,120)
120 FORMAT (1HO"MEAN (Z) COH. AND MEAN PHASE IN BANDS")
WRITE (4,121) THC,THP,THCP
121 FORMAT (1HO"THETA = " ,F12.4,2F1S.4)
WRITE (4,125) ALC,ALP,ALCP
125 FORMAT (1HO"ALPHA = " ,F12.4,2F1S.4)
WRITE (4,130) B1C,B1P,B1CP
130 FORMAT (1HO"BETA1 = " ,F12.4,2F1S.4)
135 FORMAT (1HO"BETA2 = " ,F12.4,2F1S.4)
RETURN
END

FUNCTION PHASE (CO,QUA)
C CALCULATES PHASE ANGLE IN DEGREES.
C CO = AVERAGED CO-SPECTRUM
C QUA = AVERAGED QUA-SPECTRUM
C + RESULT INDICATES CHANNEL 1 LEADS.
C
DATA PI /3.141593/
5 IF (CO) 10,5,10
P=90.0
IF (QUA .GT. 0.0) GO TO 25
P=-90.0
GO TO 25
10 P=((ATAN(QUA/CO))/PI)*180.0
IF (CO) 15,25,25
15 IF (P.LT.0.0) GOTO 20
P=P-180.0
GO TO 25
20 P=180.0+P
25 PHASE=P
RETURN
END

SUBROUTINE POWER (NEP,NCH,NSAM,SLEN,J)
C CALCULATES AND PRINTS POWER SPECTRUM TO 30 HZ., FROM
C FOURIER COEFFICIENTS HELD BY RANDOM ACCESS FILE, UNIT 1.
C NEP = NO. OF EPOCHS
C NCH = NO. OF CHANNELS
C NSAM = NO. OF SAMPLES
C SLEN = SAMPLE LENGTH
C J = CHANNEL NO.
C
DIMENSION XR(128),XI(128),SP(128)
COMMON BATA(320,128)
XNEP=FLOAT(NEP)
THETA=0.0
ALPHA=0.0
BETA1=0.0
BETA2=0.0
DO 10 I=1,NSAM
   SP(I)=0.0
DO 15 K=1,NEP
   II=((K-1)*NCH+J)*2-1
DO 666 L=1,NSAM
   XR(L)=BATA(I,I,L)
   CONTINUE
   II=II+1
DO 777 L=1,NSAM
   XI(L)=BATA(I,I,L)
   CONTINUE
00 15 I=1,NSAM
   X=(XR(I)**2+XI(I)**2)/XNEP
   SP(I)=SP(I)+X
   CONTINUE
   I=I+1
DO 40 L=1,NSAM
   XF=FLOAT(L-1)/SLEN
   IF (XF-.4.0.LT.0.0) GOTO 40
   IF (8.0-XF.LE.0.0) GOTO 25
   SN=4.0*SLEN
   THETA=THETA+SP(L)/SN
   GO TO 40
   IF (13.0-XF.LE.0.0) GOTO 30
   SN=5.0*SLEN
   ALPHA=ALPHA+SP(L)/SN
   GO TO 40
   IF (22.0-XF.LE.0.0) GOTO 35
   SN=9.0*SLEN
   BETA1=BETA1+SP(L)/SN
   GO TO 40
   IF (30.0-XF.LE.0.0) GOTO 35
   SN=8.0*SLEN
   BETA2=BETA2+SP(L)/SN
40 CONTINUE
WRITE (4,120) J
120 FORMAT (1HO"MEAN POWER: CHANNEL ",I3,/) DO 50 K=1,NSAM
   XF=(K-1)/SLEN
   IF (XF.GT.30.0) GOTO 55
   WRITE (4,122) XF,SP(K)
122 FORMAT (1H,F6.2,3X,F15.4) 50 CONTINUE
55 WRITE (4,125) THETA
125 FORMAT (1HO"THETA = "F15.4) WRITE (4,130) ALPHA
130 FORMAT (1H."ALPHA = "F15.4) WRITE (4,135) BETA1
135 FORMAT (1H."BETA1 = "F15.4) WRITE (4,140) BETA2
140 FORMAT (1H."BETA2 = "F15.4) RETURN
END

-B16-
SUBROUTINE FFT (XR, XI, N, INV)
C
SANDE-TUKEY RADIX-2 FFT
C
PERFORMS FFT TRANSFORM ON REAL DATA IN ARRAY XR(N).
C
ARRAY XI(N) INITIALLY SET TO 0 FOR REAL DATA.
C
ON OUTPUT XR HOLDS REAL COEFFICIENTS,
C
XI HOLDS IMAGINARY COEFFICIENTS.
C
INV = 0 FOR DIRECT TRANSFORM (ERROR RETURN SET TO -1).
C
DIMENSION XR(N), XI(N), UR(15), UI(15)
LOGICAL FIRST
DATA FIRST /.TRUE./
IF (.NOT. FIRST) GO TO 120
UR(1)=0.0
UI(1)=1.0
DO 110 I=2,15
UR(I)=SQRT((1.0+UR(I-1))/2.0)
UI(I)=UI(I-1)/(2.0*UR(I))
FIRST=.FALSE.
110
IF (N .GT. 0 .AND. N .LE. 2**16) GO TO 130
INV=-1
RETURN
130
NO=1
II=0
140
NO=NO+NO
II=II+1
IF (NO .LT. N) GO TO 140
II=NO/2
I3=1
IO=II
DO 260 I4=1,II
DO 250 K=1,I1
WR=1.0
WI=0.0
KK=K-1
DO 230 I=1,10
IF (KK .EQ. 0) GO TO 240
IF (MOD(KK,2) .EQ. 0) GO TO 230
JO=IO-I
WS=WR*UR(JO)-WI*UI(JO)
WI=WR*UI(JO)+WI*UR(JO)
WR=WS
KK=KK/2
230
IF (INV .EQ. 0) WI=-WI
L=K
DO 250 J=1,13
L1=L+I1
ZR=XR(L)+XR(L1)
ZI=XI(L)+XI(L1)
Z=WR*(XR(L)-XR(L1))-WI*(XI(L)-XI(L1))
XI(L1)=WR*(XI(L)-XI(L1))+WI*(XR(L)-XR(L1))
XR(L1)=Z
XR(L)=ZR
XI(L)=ZI

-B17-
SUBROUTINE TAPER (X, N, P)
C SPLIT-COSINE-BELL TAPER
C SETS ZERO BASELINE BEFORE APPLYING TAPER.
C X = ARRAY CONTAINING DATA TO BE TAPERED.
C RETURNS WITH TAPERED DATA IN X.
C N = NO OF POINTS IN X
C P = PROPORTION OF ARRAY TO BE TAPERED.
C
DIMENSION X(N)
DATA PI/3.141593/
IF ((P .LE. 0.0) .OR. (P .GT. 1.0)) RETURN
SUM = 0.0
DO 5 I = 1, N
SUM = SUM + X(I)
CONTINUE
AVE = SUM/FLOAT(N)
DO 7 I = 1, N
X(I) = X(I) - AVE
CONTINUE
M = INT(P*FLOAT(N)+0.5)/2
DO 10 I = 1, M
WEIGHT = 0.5-0.5*COS(PI*(FLOAT(I)-0.5)/FLOAT(M))
X(I) = X(I)*WEIGHT
X(N+1-I) = X(N+1-I)*WEIGHT
CONTINUE
RETURN
END

L = L1 + 1
I0 = I0 - 1
I3 = I3 + 1
I1 = I1/2
UM = 1.0
IF (INX .EQ. 0) UM = 1.0/FLOAT(NO)
DO 310 J = 1, NO
K = 0
J1 = J - 1
DO 320 I = 1, II
K = 2*K + MOD(J1, 2)
320 J1 = J1/2
K = K + 1
IF (K .LT. J) GO TO 310
ZR = XR(J)
ZI = XI(J)
XR(J) = XR(K)*UM
XI(J) = XI(K)*UM
XR(K) = ZR*UM
XI(K) = ZI*UM
310 CONTINUE
RETURN
END
FUNCTION ZC(CO)
  RETURNS Z-TRANSFORMED VALUE OF COHERENCE (CO).
  IF CO = 1, THEN RETURNS 999.999.
  IF (CO.LT.0.0) GOTO 5
  IF (CO.EQ.0.0) GOTO 10
  IF (CO.GE.1.0) GO TO 15
  CO=SQRT(CO)
  ZC=(ALOG((1.0+CO)/(1.0-CO)))/2.0
  RETURN
5
  WRITE (4,100)
100 FORMAT (1HO"NEGATIVE COHERENCE !!")
10  ZC=0.0
  RETURN
15  ZC=999.999
  RETURN
END

3.1 DW2

The following simple BASIC program ran on the Commodore PET, controlling stimulus presentation and triggering data collection by the PDP8/e for Experiment III. In this experiment, data was collected using Basic Averager System Software.

10 POKE59459,240
20 B=0
30 C=0
40 FOR I=1 TO 80
50 D=RND(1)*2
60 IF B=40 THEN 100
70 IF C=40 THEN 100
80 A=RND(1)*2
90 IF A<1 THEN 160
100 C=C+1
110 POKE59471,144
120 TIS="000000"
130 IF TI<15 THEN 130
140 POKE59471,32
150 GOTO 200
160 B=B+1
170 POKE59471,80
180 TIS="000000"
190 IF TI<15 THEN 190
200 TIS="000000"
210 IF TI<15 THEN 210
220 POKE 59471,0

-B19-
4.1 COHMAP

This simple FOCAL program, or slight modifications of it, was used to control data collection, stimulus presentation and performance monitoring in Experiments IV, V and VI. Following the experiment, data was transferred to the CYBER for further analysis and graph-plotting using the GHOST plotting package.

01.10 C THIS PROGRAM COLLECTS 24*1 SEC. EPOCHS AT 128 HZ.
01.20 C THE INITIAL PART OF THE PROGRAM PRODUCES 20 TONES, TO WHICH
01.21 C S RESPONDS WITH A KEY PRESS WHICH MUST BE WITHIN 0.5 SEC OF
01.22 C TONE-OFFSET TO COUNTED AS A DETECTION. THE SAME TASK IS
01.23 C PERFORMED DURING DATA COLLECTION.
01.24 C DIGIN=1;STOP=64(5);RESTART=128(4);OUTPUT=64(5)
01.45 X FDO(2,-2,-5,2695)
01.50 O O DATA;O RANTIM;Z C,X,K
01.54 A A;S Z=FDO(2,-4,1,-A,4)
01.55 X FDO(2,1) FDO(2,3,64)
01.56 S Z=FDO(2,-4,1,-1,4);X FDO(2,1)
01.60 S Z=FDO(2,-4,1,-50,4)
01.61 I (Z-1)1.7,1.65,1.7
01.65 Y C
01.70 Y X;I (X-10)1.54
01.80 I (K-24)2.1
01.90 T !;X FOUT(192);O C
01.95 T "NO. DETECTED =",C;Q
02.10 S Z=FDO(2,-4,1,-170,4);Y K
02.15 X FDO(2,-2,-781,2887) FDO(2,-1,-128,6,0)
02.16 S Z=FDO(2,-4,1,-100,4);D 1.55,1.56,1.6
02.17 I (Z-1)2.18;Y C
02.18 Z B;D 3
02.20 G 1.8
03.10 X FDO(2,-2,-5,2695)
03.20 D 4;A A;S Z=FDO(2,-4,1,-A,4);I (Z-64)3.3,3.6
03.30 X FDO(2,3,64);S Z=FDO(2,-4,1,-1,4);X FDO(2,1)
03.35 S =FDO(2,-4,1,-50,4)
03.40 I (Z-1)3.5, 3.45, 3.5
03.45 Y C
03.50 Y B; I (B-16)3.1; R
03.60 X FDO(2,1); S Z=FDO(2,-4,1,-100,4); I (Z-128)3.6, 3.3

04.10 F M=7; D 4.2; T!
04.15 R
04.20 F N=1,8; T %5.01, FG(B*64+M*8+N)
Appendix C: Analysis of Variance Tables

All analyses of variance were performed using the PSYDAIN program on the University of Leicester's CYBER 73 computer.

**AMOVA 1.1.1**

Analysis of variance table for alpha z-coherence data for "Broca's" area for Experiment I.

Factors
- A - Order (2)
- B - Type of Task (4)
- C - Hemisphere (2)
- S - Subjects (12)

Grand Mean = 1.83300

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ANOVA 1.1.2

Analysis of variance table for alpha z-coherence data for "Wernicke's" area for Experiment I.

Factors
A - Order (2)
B - Type of Task (4)
C - Hemisphere (2)
S - Subjects (12)

Grand Mean = 1.48349

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### ANOVA 1.2.1

Analysis of variance table for alpha z-coherence asymmetry data for "Broca's" area for Experiment I.

Factors
- A - Order (2)
- B - Type of Task (4)
- S - Subjects (12)

Grand Mean = 4.80184

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### ANOVA 1.2.2

Analysis of variance table for alpha z-coherence asymmetry data for "Wernicke's" area for Experiment I.

Factors
- A - Order (2)
- B - Type of Task (4)
- S - Subjects (12)

Grand Mean = -.95964

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-C3-
ANOVA 1.3.1

Analysis of variance table for alpha power data for "Broca's" area for Experiment I.

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- B - Type of Task (4)
- C - Hemisphere (2)
- S - Subjects (12)

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ANOVA 1.3.2

Analysis of variance table for alpha power data for "Wernicke's" area for Experiment 1.

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C - Hemisphere (2)
S - Subjects (12)

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ANOVA 1.4.1

Analysis of variance table for alpha power asymmetry data for "Broca's" area for Experiment I.

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B - Type of Task (4)
S - Subjects (12)

Grand Mean = 7.40749

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ANOVA 1.4.2

Analysis of variance table for alpha power asymmetry data for "Wernicke's" area for Experiment I.

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- C - Electrode Position (2)
- D - Hemisphere (2)
- S - Subjects (6)

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### ANOVA 2.1.2

Analysis of variance table for alpha power data from Experiment II.

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- **B** - Type of Stimulus (2)
- **C** - Electrode Position (2)
- **D** - Hemisphere (2)
- **S** - Subjects (6)

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ANOVA 2.1.3

Analysis of variance table for beta-1 power data from Experiment II.

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C - Electrode Position (2)
D - Hemisphere (2)
S - Subjects (6)

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-C9-
Analysis of variance table for theta z-coherence data for electrode pairs 01/C5 vs 02/C6 in Experiment II.

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C - Electrode Pair (2)
S - Subjects (6)

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Analysis of variance table for alpha z-coherence data for electrode pairs 01/C5 vs 02/C6 in Experiment II.

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- B - Type of Stimulus (2)
- C - Electrode Pair (2)
- S - Subjects (6)

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Analysis of variance table for beta-1 z-coherence data for electrode pairs 01/C5 vs 02/C6 in Experiment II.

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C - Electrode Pair (2)
S - Subjects (6)

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ANOVA 2.2.2.1

Analysis of variance table for theta z-coherence data for electrode pairs 01/C6 vs 02/C5 in Experiment II.

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ANOVA 2.2.2.2

Analysis of variance table for alpha z-coherence data for electrode pairs 01/C6 vs 02/C5 in Experiment II.

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- S - Subjects (6)

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Analysis of variance table for beta-1 z-coherence data for electrode pairs 01/C6 vs 02/C5 in Experiment II.

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S - Subjects (6)

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ANOVA 2.2.3.1

Analysis of variance table for theta z-coherence data for electrode pairs 01/02 vs C5/C6 in Experiment II.

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### ANOVA 2.2.3.2

Analysis of variance table for alpha z-coherence data for electrode pairs 01/02 vs C5/C6 in Experiment II.

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- C - Electrode Pair (2)
- S - Subjects (6)

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ANOVA 2.2.3.3

Analysis of variance table for beta-1 z-coherence data for electrode pairs 01/02 vs C5/C6 in Experiment II.

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B - Type of Stimulus (2)
C - Electrode Pair (2)
S - Subjects (6)

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ANOVA 3.1

Analysis of variance table for power in the 3-8.99 Hz frequency range in Experiment III.

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B - Hemisphere (2)
C - Position (2)
S - Subjects (14)

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ANOVA 3.2.1

Analysis of variance table for z-coherence in the 3-8.99 Hz range for electrode pairs 01/02 vs C5/C6 in Experiment III.

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B - Electrode Pair (2)  
S - Subjects (14)

Grand Mean = 1.78391

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ANOVA 3.2.2

Analysis of variance table for z-coherence in the 3-8.99 Hz range for electrode pairs 01/C5 vs 02/C6 in Experiment III.

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B - Electrode Pair (2)  
S - Subjects (14)

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ANOVA 3.2.3

Analysis of variance table for z-coherence in the 3-8.99 Hz range for electrode pairs O1/C6 vs O2/C5 in Experiment III.

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B - Electrode Pair (2)
S - Subjects (14)

Grand Mean = 1.09184

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### ANOVA 4.1.1

Analysis of variance table for alpha-peak power data from Experiment IV.

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- S - Subjects (10)

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### ANOVA 4.1.2

Analysis of variance table for theta power data from Experiment IV.

Factors
- A - Position (6)
- S - Subjects (10)

Grand Mean = 174.67544

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### ANOVA 4.1.3

Analysis of variance table for alpha power data from Experiment IV.

**Factors**
- A - Position (6)
- S - Subjects (10)

Grand Mean = 215.68947

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### ANOVA 4.1.4

Analysis of variance table for beta-1 power data from Experiment IV.

**Factors**
- A - Position (6)
- S - Subjects (10)

Grand Mean = 32.38676

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ANOVA 4.2.1.1.1

Analysis of variance table for alpha-peak z-coherence data (multiplied by 100) for neighbouring electrode pairs from Experiment IV.

Factors
- A - Channel Pairs (5)
- S - Subjects (10)

Grand Mean = 255.35360

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ANOVA 4.2.1.1.2

Analysis of variance table for alpha-peak phase angle data for neighbouring electrode pairs from Experiment IV.

Factors
- A - Channel Pairs (5)
- S - Subjects (10)

Grand Mean = -.76444

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ANOVA 4.2.1.2.1

Analysis of variance table for theta z-coherence data (multiplied by 100) for neighbouring electrode pairs from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 226.61640

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ANOVA 4.2.1.2.2

Analysis of variance table for theta phase angle data for neighbouring electrode pairs from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = .71083

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ANOV A 4.2.1.3.1

Analysis of variance table for alpha z-coherence data (multiplied by 100) for neighbouring electrode pairs from Experiment IV.

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ANOV A 4.2.1.3.2

Analysis of variance table for alpha phase angle data for neighbouring electrode pairs from Experiment IV.

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ANOVA 4.2.1.4.1

Analysis of variance table for beta-1 z-coherence data (multiplied by 100) for neighbouring electrode pairs from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 218.37320

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ANOVA 4.2.1.4.2

Analysis of variance table for beta-1 phase angle data for neighbouring electrode pairs from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = -.42450

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**ANOVA 4.2.2.1.1**

Analysis of variance table for alpha-peak z-coherence data (multiplied by 100) for pairs 1-2, 1-3,...,1-6 from Experiment IV.

Factors
- A - Channel Pairs (5)
- S - Subjects (10)

Grand Mean = 179.27640

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**ANOVA 4.2.2.1.2**

Analysis of variance table for alpha-peak phase angle data for pairs 1-2, 1-3,...,1-6 from Experiment IV.

Factors
- A - Channel Pairs (5)
- S - Subjects (10)

Grand Mean = -.51787

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### ANOVA 4.2.2.2.1

Analysis of variance table for theta z-coherence data (multiplied by 100) for pairs 1-2, 1-3, ..., 1-6 from Experiment IV.

Factors
- A - Channel Pairs (5)
- S - Subjects (10)

Grand Mean = 149.48320

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### ANOVA 4.2.2.2.2

Analysis of variance table for theta phase angle data for pairs 1-2, 1-3, ..., 1-6 from Experiment IV.

Factors
- A - Channel Pairs (5)
- S - Subjects (10)

Grand Mean = 2.82514

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-C29-
ANOV A 4.2.2.3.1

Analysis of variance table for alpha z-coherence data (multiplied by 100) for pairs 1-2, 1-3....1-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 161.43660

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ANOV A 4.2.2.3.2

Analysis of variance table for alpha phase angle data for pairs 1-2, 1-3....1-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = -1.89339

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ANOVA 4.2.2.4.1

Analysis of variance table for beta-1 z-coherence data (multiplied by 100) for pairs 1-2, 1-3,...,1-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 145.06380

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ANOVA 4.2.2.4.2

Analysis of variance table for beta-1 phase angle data for pairs 1-2, 1-3,...,1-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = -1.13250

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## ANOVA 4.2.3.1.1

Analysis of variance table for alpha-peak z-coherence data (multiplied by 100) for pairs 1-6, 2-6.....5-6 from Experiment IV.

**Factors**
- A - Channel Pairs (5)
- S - Subjects (10)

**Grand Mean** = 160.51580

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## ANOVA 4.2.3.1.2

Analysis of variance table for alpha-peak phase angle data for pairs 1-6, 2-6.....5-6 from Experiment IV.

**Factors**
- A - Channel Pairs (5)
- S - Subjects (10)

**Grand Mean** = -5.15992

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ANOV 4.2.3.2.1

Analysis of variance table for theta z-coherence data (multiplied by 100) for pairs 1-6, 2-6....5-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 146.80160

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ANOV 4.2.3.2.2

Analysis of variance table for theta phase angle data for pairs 1-6, 2-6....5-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 1.81747

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### ANOVA 4.2.3.3.1

Analysis of variance table for alpha z-coherence data (multiplied by 100) for pairs 1-6, 2-6.....5-6 from Experiment IV.

Factors  
- A - Channel Pairs (5)  
- S - Subjects (10)

Grand Mean = 137.42600

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### ANOVA 4.2.3.3.2

Analysis of variance table for alpha phase angle data for pairs 1-6, 2-6.....5-6 from Experiment IV.

Factors  
- A - Channel Pairs (5)  
- S - Subjects (10)

Grand Mean = -4.89822

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ANOVA 4.2.3.4.1

Analysis of variance table for beta-1 z-coherence data (multiplied by 100) for pairs 1-6, 2-6....5-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = 128.91620

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ANOVA 4.2.3.4.2

Analysis of variance table for beta-1 phase angle data for pairs 1-6, 2-6....5-6 from Experiment IV.

Factors
A - Channel Pairs (5)
S - Subjects (10)

Grand Mean = -2.35134

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-C35-
### ANOVA 5.1.1

Analysis of variance table for alpha-peak power data from Experiment V.

**Factors**
- A - Hemispheres (2)
- B - Position (4)
- S - Subjects (10)

Grand Mean = 390.92850

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### ANOVA 5.1.2

Analysis of variance table for theta power data from Experiment V.

**Factors**
- A - Hemispheres (2)
- B - Position (4)
- S - Subjects (10)

Grand Mean = 138.88797

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-C36-
ANOVAs 5.1.3 and 5.1.4

### Analysis of Variance Table for Alpha Power Data from Experiment V

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### Analysis of Variance Table for Beta-1 Power Data from Experiment V

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-C37-
ANOVA 5.2.1.1

Analysis of variance table (one-way) for alpha-peak z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

Factors
A - Channel Pairs (8)
S - Subjects (10)

Grand Mean = 227.35113

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ANOVA 5.2.1.2

Analysis of variance table (one-way) for theta z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

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S - Subjects (10)

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ANOVA 5.2.1.3

Analysis of variance table (one-way) for alpha z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

Factors
A - Channel Pairs (8)
S - Subjects (10)

Grand Mean = 221.79713

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ANOVA 5.2.1.4

Analysis of variance table (one-way) for beta-1 z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

Factors
A - Channel Pairs (8)
S - Subjects (10)

Grand Mean = 214.39500

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### ANOVA 5.2.2.1.1

Analysis of variance table (two-way) for alpha-peak z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

**Factors**
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- B - Channel Pairs (3)
- S - Subjects (10)

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### ANOVA 5.2.2.1.2

Analysis of variance table (two-way) for alpha-peak phase angle data for neighbouring pairs of electrodes from Experiment V.

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- B - Channel Pairs (3)
- S - Subjects (10)

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Analysis of variance table (two-way) for theta z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

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- B - Channel Pairs (3)
- S - Subjects (10)

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## ANOVA 5.2.2.2.2

Analysis of variance table (two-way) for theta phase angle data for neighbouring pairs of electrodes from Experiment V.

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- B - Channel Pairs (3)
- S - Subjects (10)

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**ANOVA 5.2.2.3.1**

Analysis of variance table (two-way) for alpha z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

Factors

- A - Hemispheres (2)
- B - Channel Pairs (3)
- S - Subjects (10)

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**ANOVA 5.2.2.3.2**

Analysis of variance table (two-way) for alpha phase angle data for neighbouring pairs of electrodes from Experiment V.

Factors

- A - Hemispheres (2)
- B - Channel Pairs (3)
- S - Subjects (10)

Grand Mean = -.84860

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### ANOVA 5.2.2.4.1

Analysis of variance table (two-way) for beta-1 z-coherence data (multiplied by 100) for neighbouring pairs of electrodes from Experiment V.

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- **A** - Hemispheres (2)
- **B** - Channel Pairs (3)
- **S** - Subjects (10)

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### ANOVA 5.2.2.4.2

Analysis of variance table (two-way) for beta-1 phase angle data for neighbouring pairs of electrodes from Experiment V.

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- **B** - Channel Pairs (3)
- **S** - Subjects (10)

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-C43-
**ANOVA 5.2.3.1**

Analysis of variance table for alpha-peak z-coherence data (multiplied by 100) for distant pairs of electrodes from Experiment V.

Factors
- A - Channel Pairs (8)
- S - Subjects (10)

Grand Mean = 143.49375

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**ANOVA 5.2.3.2**

Analysis of variance table for theta z-coherence data (multiplied by 100) for distant pairs of electrodes from Experiment V.

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- S - Subjects (10)

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### ANOVA 5.2.3.3

Analysis of variance table for alpha z-coherence data (multiplied by 100) for distant pairs of electrodes from Experiment V.

Factors
- **A** - Channel Pairs (8)
- **S** - Subjects (10)

Grand Mean = 139.92525

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### ANOVA 5.2.3.4

Analysis of variance table for beta-1 z-coherence data (multiplied by 100) for distant pairs of electrodes from Experiment V.

Factors
- **A** - Channel Pairs (8)
- **S** - Subjects (10)

Grand Mean = 136.80563

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### ANOVA 6.1.1

Analysis of variance table for peak-alpha power data from Experiment VI.

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### ANOVA 6.1.2

Analysis of variance table for theta power data from Experiment VI.

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### ANOVA 6.1.3

Analysis of variance table for alpha power data from Experiment VI.

**Factors**
- A - Hemispheres (2)
- B - Position (4)
- S - Subjects (10)

**Grand Mean = 111.12428**

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### ANOVA 6.1.4

Analysis of variance table for beta-1 power data from Experiment VI.

**Factors**
- A - Hemispheres (2)
- B - Position (4)
- S - Subjects (10)

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### ANOVA 6.2.1.1.1

Analysis of variance table for intrahemispheric alpha-peak z-coherence data (multiplied by 100) from Experiment VI.

**Factors**
- A - Hemispheres (2)
- B - Channel Pairs (3)
- S - Subjects (10)

**Grand Mean = 226.53400**

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### ANOVA 6.2.1.1.2

Analysis of variance table for intrahemispheric alpha-peak phase angle data from Experiment VI.

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- B - Channel Pairs (3)
- S - Subjects (10)

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ANOVA 6.2.1.2.1

Analysis of variance table for intrahemispheric theta z-coherence data (multiplied by 100) from Experiment VI.

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B - Channel Pairs (3)
S - Subjects (10)

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ANOVA 6.2.1.2.2

Analysis of variance table for intrahemispheric theta phase angle data from Experiment VI.

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S - Subjects (10)

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-C49-
ANOVA 6.2.1.3.1

Analysis of variance table for intrahemispheric alpha z-coherence data (multiplied by 100) from Experiment VI.

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B - Channel Pairs (3)
S - Subjects (10)

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ANOVA 6.2.1.3.2

Analysis of variance table for intrahemispheric alpha phase angle data from Experiment VI.

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S - Subjects (10)

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ANOVA 6.2.1.4.1

Analysis of variance table for intrahemispheric beta-1 z-coherence data (multiplied by 100) from Experiment VI.

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B - Channel Pairs (3)
S - Subjects (10)

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ANOVA 6.2.1.4.2

Analysis of variance table for intrahemispheric beta-1 phase angle data from Experiment VI.

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S - Subjects (10)

Grand Mean = -.55841

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-C51-
Analysis of variance table for interhemispheric alpha-peak z-coherence data (multiplied by 100) from Experiment VI.

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S - Subjects (10)

Grand Mean = 195.74150

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Analysis of variance table for interhemispheric alpha-peak phase angle data from Experiment VI.

Factors
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S - Subjects (10)

Grand Mean = 1.75771

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<th>MS</th>
<th>Error Term</th>
<th>Error DF</th>
<th>F</th>
<th>Sig. Level</th>
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<td>27</td>
<td>.44</td>
<td>ns</td>
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<td>347.000</td>
<td>27</td>
<td>12.852</td>
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</table>
ANOVA 6.2.2.2.1

Analysis of variance table for interhemispheric theta z-coherence data (multiplied by 100) from Experiment VI.

Factors
A - Channel Pairs (4)
S - Subjects (10)

Grand Mean = 180.06325

<table>
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<th>F Ratio</th>
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ANOVA 6.2.2.2.2

Analysis of variance table for interhemispheric theta phase angle data from Experiment VI.

Factors
A - Channel Pairs (4)
S - Subjects (10)

Grand Mean = .62936

<table>
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<th>F</th>
<th>Sig. Level</th>
</tr>
</thead>
<tbody>
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</table>


**ANOVA 6.2.2.3.1**

Analysis of variance table for interhemispheric alpha z-coherence data (multiplied by 100) from Experiment VI.

Factors

- A - Channel Pairs (4)
- S - Subjects (10)

Grand Mean = 173.57900

<table>
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<th>Error DF</th>
<th>Error Ratio</th>
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</tbody>
</table>

**ANOVA 6.2.2.3.2**

Analysis of variance table for interhemispheric alpha phase angle data from Experiment VI.

Factors

- A - Channel Pairs (4)
- S - Subjects (10)

Grand Mean = 0.67568

<table>
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<tr>
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</table>
ANOVA 6.2.2.4.1

Analysis of variance table for interhemispheric beta-1 z-coherence data (multiplied by 100) from Experiment VI.

Factors
A - Channel Pairs (4)
S - Subjects (10)

Grand Mean = 160.73875

<table>
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<td>2555.469</td>
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</tr>
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ANOVA 6.2.2.4.2

Analysis of variance table for interhemispheric beta-1 phase angle data from Experiment VI.

Factors
A - Channel Pairs (4)
S - Subjects (10)

Grand Mean = 0.02338

<table>
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<th>Error F</th>
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<td>18.152</td>
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<td>6.051</td>
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<tr>
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<td>1.588</td>
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</table>
Appendix D: Multiplex Delay

During program testing it became apparent that the slight delay between sampling different channels on the PDP8/e's A/D convertor was large enough to introduce systematic errors into phase angle estimates. It was noted that when the same 10 Hz sine wave signal was fed into all eight inputs simultaneously, the results of the coherence analysis program indicated a fairly constant phase angle shift of about 0.21 degrees between adjacent channels. Because the delay between all adjacent channels was fairly constant it was a simple procedure to include a line in the COAN program to correct the value of phase produced:

\[
\text{CPH} = \text{PH} - \text{DC} \times \text{XF} \times 0.020988
\]

where CPH = corrected phase  
PH = uncorrected phase  
DC = difference between channel numbers  
XF = frequency

The modified version of COAN was tested using several different sine wave inputs, and the results for 10 Hz and 20 Hz inputs are presented in Table D for the channel pairs considered in Experiment V. It can be seen that the corrected phase angle estimates are very close to the correct value of zero, although even with the correction they are not exactly equal to zero. However the corrected values are far too small to account for any of the significant differences reported.
For the final three experiments in this series both the uncorrected and the corrected phase angle data were routinely analysed so that the full significance of this potential source of artifact could be assessed. Obviously, for ANOVAs involving only adjacent channel pairs with respect to A/D inputs, the fact that the uncorrected estimates were incorrect by a fixed amount would have no effect in terms of producing different patterns of significant effects. For the t-test comparisons of phase angles with zero, however, a very different pattern of results would have emerged. Furthermore, the results of ANOVAs involving channel pairs which, while having the same interelectrode separation on the scalp, were not 'equidistant' with respect to A/D inputs (e.g. 1-7 vs. 1-4 in Experiment V) would be totally distorted. This was shown clearly by comparing the results of analyses for the corrected and uncorrected phase angles, where it was found that on occasion results which were apparently significant for uncorrected estimates became nonsignificant for the corrected estimates, and vice versa. The results of the analyses for the uncorrected phase angle data have obviously not been presented, but it was felt that attention should be drawn to this potential source of distortion. The question of the actual interpretation of phase angle effects using coherence analysis is discussed fully in Chapter 7.
Table D: Uncorrected and corrected phase angles between channels for 10 Hz and 20 Hz sinewave input for the corresponding frequency component.

<table>
<thead>
<tr>
<th>Channels</th>
<th>10 Hz sinewave</th>
<th>20 Hz sinewave</th>
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<tr>
<td></td>
<td>Uncorrected</td>
<td>Corrected</td>
</tr>
<tr>
<td>1-2</td>
<td>0.2015</td>
<td>-0.0084</td>
</tr>
<tr>
<td>2-3</td>
<td>0.1993</td>
<td>-0.0105</td>
</tr>
<tr>
<td>3-4</td>
<td>0.2123</td>
<td>0.0024</td>
</tr>
<tr>
<td>5-6</td>
<td>0.2133</td>
<td>0.0034</td>
</tr>
<tr>
<td>6-7</td>
<td>0.2183</td>
<td>0.0085</td>
</tr>
<tr>
<td>7-8</td>
<td>0.2145</td>
<td>0.0046</td>
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<td>5-1</td>
<td>-0.8271</td>
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</tr>
<tr>
<td>8-4</td>
<td>-0.8600</td>
<td>-0.0205</td>
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<tr>
<td>2-6</td>
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<tr>
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<tr>
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<tr>
<td>3-7</td>
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<td>5-8</td>
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