

ELECTROENCEPHALOGRAPHIC CORRELATES OF
LATERAL ASYMMETRY IN THE PROCESSING
OF VERBAL AND NONVERBAL AUDITORY
STIMULI

by

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ABSTRACT

Averaged evoked potentials (AEPs) to verbal (digits) and nonverbal (clicks) auditory stimuli were recorded from left and right EEG leads in 10 right-handed Ss. Each S heard both types of stimuli presented dichotically and monaurally, and was required to identify the digits, or count the clicks, heard in each ear. With dichotic presentation, there was no significant difference in accuracy of report of the clicks heard in each ear, but significantly more digits were identified correctly from the right ear than from the left. Recall accuracy was 100% for both clicks and digits presented monaurally. In the dichotic condition, verbal stimuli elicited AEPs whose early components were of greater amplitude, and whose later components were of shorter latency, from the left than the right hemisphere. No consistent latency or amplitude differences were observed between AEPs from the left and right hemispheres when clicks were presented dichotically. For monaural presentations to the right ear, a significant stimulus type x hemisphere interaction occurred, reflecting the shorter AEP latencies in the left than right hemisphere for verbal material, and the reverse for nonverbal material. No such differences were observed for monaural presentations to the left ear. For both left and right monaural stimulation, the amplitude of early components in the AEPs to verbal stimuli was greater

for the left than right hemispheres. Both the electro-physiological and behavioural findings are regarded as evidence of the lateral asymmetry of hemispherical functioning with respect to the processing of verbal and nonverbal material.

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INTRODUCTION

Considerable neuropsychological data suggest that man's cerebral hemispheres are not equipotential in governing cognitive behaviour. An early hemispheric near-equivalence in the newborn is superceded in development by functional specialization so that each hemisphere serves distinctive functions in the mediation of behaviour. Thus, in most people, mechanisms for speech and other symbolic functioning are dependent on cortical structures in the left hemisphere, while the right hemisphere mediates the processing of nonverbal, perceptual material. It is generally the case, however, that when electroencephalograph (EEG) measures are taken they are recorded from only one cerebral hemisphere, and it is assumed that the data are equally applicable to the other hemisphere. The electrophysiological concomitants of the functional asymmetries reported in behavioural and neuro-surgical studies have only recently been investigated. In the present study, S was presented with verbal and nonverbal auditory stimuli under monaural and dichotic conditions. Recall accuracy and evoked potentials were examined for evidence of asymmetrical processing of this information related to the nature of the stimuli and the ear stimulated.

The current concepts of lateralization of cerebral functions were preceded by a long history of

observations concerning the differential effects on various sensory and motor activities of injuries to the left and right hemispheres. The Hippocratic school observed and reported clinical correlates between unilateral head wounds and contralateral convulsions and between temporal wounds and contralateral hemiplegia. Paracelus in the sixteenth century, and Volsolva in 1704, both described the concomitant occurrence of aphasia and right hemiplegia (and thus, at least by implication, of aphasia and left hemisphere disease). However, the inference that aphasia was specifically related to disease of the left hemisphere had not been drawn until the middle of the nineteenth century. Probably both anatomical (the two hemispheres are very similar structurally) and theological considerations played a role in retarding exploration of the idea that some of the higher mental processes could have their seat in one hemisphere but not the other.

In the nineteenth century Broca's area for speech was identified. The weight of clinical evidence showing the association between aphasia and left hemisphere lesions compelled Broca to postulate an asymmetry of functions of the third frontal convolution suggesting that the speech functions may be limited to the left side. Once enunciated, the notion of asymmetrical brain function was immediately accepted along with certain qualifications regarding handedness.

Some people were found to "speak with the right hemisphere". For the most part, however, these people proved to be left-handed and so a relationship between handedness and hemisphere dominance for language was postulated.

These developments led to a concept of hemispheric cerebral dominance in which the term suggested an absolute superiority of one hemisphere (usually the left) over the other. It was not long, however, before it became apparent that such an extreme view of functional asymmetry was untenable. In 1871 Hughlings Jackson postulated the existence of a 'major' and a 'minor' hemisphere. But he was careful in qualifying these concepts. Jackson's important shift of emphasis from the concept 'dominant' to 'dominant for what' proposed that there may be other functions besides language for which the left hemisphere may be dominant and, more important perhaps, functions for which the right or non-language hemisphere may be superior. That is, cerebral dominance is defined by the function under consideration. For those who did not eschew Jackson's suggestions, this is where the limited notion of cerebral dominance was surpassed and the concern with problems of hemispheric functional specialization began. Systematic investigation of the latter wasn't undertaken until about fifty years after Jackson was writing. A survey of the recent literature dealing with brain lesion symptomatology and neurosurgical evidence from 'split-brain' research provides evidence that the cerebral hemispheres

function qualitatively differently and supports the general concepts of functional cerebral specialization.

Neuroanatomical and Neurosurgical Evidence of Lateral Asymmetry

The extensive study of clinical symptomatology in unilateral hemispheric lesions has shown over and over again the greater dependency of speech and other symbolic functioning on the integrity of the left hemisphere (Luria, 1967; Milner, 1958; Milner et al, 1964; Russo and Vignolo, 1967; Weinstein, 1962) and has indicated several functions, primarily of a nonverbal-perceptual nature, for which the integrity of the right hemisphere is necessary. The latter includes performance on visual, tactile and auditory spatial tasks and nonverbal visual and auditory memory (deRenzi, 1967; Kimura, 1963; Milner, 1968; Newcombe and Russell, 1969).

A typical clinical lesion study involves, for example, comparing the performance of patients with left hemisphere lesions (LH group) to a right hemisphere lesioned (RH group) control group on a task thought to require predominantly left hemisphere functioning. If the LH group performs at a significantly lower level than the RH control group one might conclude that the integrity of the left hemisphere was essential for the activity; that is, that the left hemisphere is 'dominant' for that particular function.

Newcombe and Russell's (1969) project to investigate the differential long-term effects of focal missile injury to

the left and right hemispheres was based on the hypothesis of hemispheric asymmetry of function. They investigated the hypothesis that the left hemisphere is leading for language functions and the right hemisphere for visual perceptual and spatial functions. The experimental groups were men with unilateral lesions of either the left or the right hemisphere. The RH group, although unimpaired in standard intelligence tests and tests of language functions, showed a significant deficit on both a visual closure task and visually guided maze task. In contrast, the LH group was impaired in language tests but matched a normal control in the nonverbal visual tests. This dissociation of symptoms illustrates hemispheric asymmetry of function lasting in some cases more than twenty years after initial injury.

That language functioning is disturbed by injury to the left hemisphere has been recognized for a long time. The functional specialization of the right hemisphere is becoming equally well established. Milner (1958, 1964) has reported deficits in pattern identification tasks following right temporal lobectomy but not after left temporal lobectomy. Others have found RH group deficits on the trail-making maze tasks (Reitan and Tarshes, 1959) and on spatial tasks whether visually or tactually presented (deRenzi, 1967).

deRenzi's (1968) study advanced the hypothesis that LH patients would be impaired when required to remember meaningful patterns which could be verbally identified but

not when required to remember meaningless patterns which have no name. A reverse impairment was expected for the RH group. Both hypotheses were confirmed, supporting the notion that left and right hemispheric specialization is related to mnemonic as well as perceptual functioning.

Auditory discrimination and recognition is another area where hemisphere disorders appear to be material-specific. Milner (1962), using the Seashore Measures of Musical Talents, found that RH patients performed poorer than LH patients on tests of time, pitch, loudness, timbre and tonal memory. These findings are consistent with those of Teuber and Diamond (1956) which indicate that there is greater impairment of sound localization with right than with left hemisphere lesions. On the other hand, Kimura (1961) noticed that with verbal auditory material left lesioned patients were more impaired in performance.

The extensive clinical and experimental reports of patients with unilateral brain lesions, while providing fertile ground for experimentation into the concepts of hemispheric asymmetry, must be viewed with caution before any conclusions are drawn about cerebral functioning. There must be an accurate estimate of the site and extent of the anatomical deficit, and it should be established that there are no lesions elsewhere in the brain, or if there are, these should be accurately described. Another important consideration is the effects of the injury upon arterial supply and venous

outflow which may be more widespread than is usually supposed. Care must be taken not to single out one function for examination with the implication that all other functions are intact. Also, it should be more clearly determined what functions are in fact measured by the test materials; often mnemonic and perceptual factors are confused as well as verbal and nonverbal aspects.

Nevertheless the anatomico-clinical facts so far gathered at least establish that the symptomology is different according to the particular hemisphere disturbed, thus obliging us to consider a functional organization of the cortex which is different for each hemisphere.

Ontogenetic and phylogenetic considerations should be kept in mind in any discussion of cerebral asymmetries. The data presented here, unless otherwise specified, refer only to adult humans. There is strong evidence to suggest that the human brain is not functionally specialized at birth but becomes so only gradually during childhood in a process of differentiation and regulation of function. Especially as regards left hemisphere functioning, traumatic lesions in childhood comparable to those in adults have quite different consequences. The prognosis for language functioning is directly related to the age at which the lesion is incurred (Lenneberg, 1967; 1969; Semmes, 1968). If the disturbance occurs early enough in life (at least before twelve years)

the right hemisphere remains competent for language throughout life. Evidence on infrahuman species (Lilly, 1962; Teuber, 1962; Warren, 1962) shows that lasting behavioural changes are most often found only after complete or near complete bilateral ablations of brain regions. However, if the task is very complex, and if the animal is close to the human on the phylogenetic scale, a unilateral lesion is disruptive. These data and data from areas of investigation other than those involving brain lesions suggest that as the quantity and complexity of the information which must be processed and stored increases, cerebral organization becomes more specialized.

Neurosurgical research involving disconnection of the cerebral hemispheres ('split-brain' research) provides supportive evidence for the concepts of hemispheric asymmetry and specialization of functions. The surgery, which is usually performed to relieve intractable epilepsy, typically involves complete division of the forebrain commissures (including the corpus callosum and anterior commissure). The disconnection in man shows that, at least following the surgery, cerebral functioning is lateralized and specialized to a surprising extent (Gazzaniga, 1970; Sperry, 1962; 1968). Only one hemisphere (usually the left) is capable of supporting propositional speech and writing. The commissurotomized patient is able to speak only about sensory information which has reached his verbally dominant hemisphere. For example,

because each visual field projects solely to the contralateral hemisphere, he cannot name or describe objects presented in his left visual field, but only objects presented in his right visual field (which projects to the left hemisphere). Nor can the split brain patient verbally label an object manipulated with his left hand (which connects only with the right hemisphere) although he is able to remember and tactually or visually (i.e. nonverbally) select the same object when it is placed with a collection of other items. There is no problem, however, in verbally describing objects inspected by the right hand.

Further, it has recently been shown (Milner, 1968) that in commissurotomed subjects the left or speech hemisphere completely or nearly completely suppresses verbal input from the left or ipsilateral ear. Patients, when presented with two different selections of verbal material simultaneously, one to each ear, complained that they could hear nothing in the left ear although the information to the right ear was responded to normally. The converse was true with nonverbal material -- only material presented to the left ear was perceived. In addition the relation between receptors and cortex is quite different from that in vision and somesthesia. Each ear is represented bilaterally at every stage of the afferent pathway and therefore auditory input cannot be restricted to a single cerebral hemisphere. Milner's findings thus emphasize two points: they demonstrate the

suppression of ipsilateral input in the presence of a competing stimulus from the contralateral ear and support the notion of the dominance of the contralateral over the ipsilateral auditory projection system in man. Additionally, the suppression of left ear input for verbal material and right ear input for nonverbal material indicates a differential functional specialization for auditory experience in the disconnected hemispheres.

Other studies of split brain patients (Gazzaniga et al, 1965) find that in some tests of visuo-spatial perceptual functioning (e.g. the reconstruction of Necker cubes and block designs) the right hemisphere is superior to the left. On the other hand, the right hemisphere seems definitely inferior in handling numerical calculation problems (Sperry, 1968). In nonverbal tests for calculation the patients' disconnected right hemisphere was insufficient to support so simple a task as the subtraction of two from numbers under ten. The disconnected left hemisphere, however, continues to support calculation at a level approximating that which prevailed prior to the surgery.

The split brain research with humans presents much more detailed information than can be appropriately dealt with in this discussion. Suffice it to say that the concepts of hemispheric specialization are clearly supported in these investigations.

A brief consideration of infrahuman split brain

studies may help to place the preceding information in perspective as it relates to cerebral organization generally. In short, in both humans and infrahumans it appears that learning which takes place in one hemisphere is usually inaccessible to the other hemisphere if the commissures between the two are missing (Myers, 1953). This means that in the intact animal the commissures function to allow the two hemispheres to share learning and memory. This can be achieved in either of two ways: by transmission of the information at the time the learning takes place, or by providing the means for access to it at a later time. In the first case the information (engram) is represented twice: once in the directly trained hemisphere and again, by way of the commissures, in the other hemisphere. In the second case, a set of engrams is established only in the directly trained hemisphere but the information is normally available to the other hemisphere by way of the commissures. By cutting the neocortical commissures after learning and before testing for transfer of learning it is possible to determine which of these two memory systems is used in different learning situations and different species. Apparently, the closer to man on the phylogenetic scale the animal is, the less he uses the double engram system. The rat almost exclusively and the cat most often maintain information in both hemispheres; i.e. a task learned in one hemisphere is available to the other even after commissurectomy (Black, 1963;

Myers, 1953; 1964). The monkey sometimes uses the double system, but in a difficult discrimination task, for example, only one hemisphere has access to the information (Downer, 1962; Trevarthen, 1965). Finally, as we have seen above, only one hemisphere in man seems to have exclusive access to specific information. These phylogenetic differences probably reflect a certain evolution of cerebral organization. As the accumulation of memories for complex analyses of information becomes more important, the duplication of information is surpassed by a more efficient system: the division of labour by the assignment of specialized functions to each hemisphere. Evidence for such a functionally specialized cerebral organization is also to be found in behavioural and electrophysiological investigations of the human brain.

Behavioural Evidence of Lateral Asymmetry

Information regarding cerebral asymmetries in normal people has become possible with the employment of the technique known as dichotic stimulation (Broadbent, 1954). Dichotic presentation consists of the simultaneous presentation to each ear of different stimulus material. With normal right-handed subjects this type of presentation of verbal material consistently results in a greater amount of material accurately recalled from the right ear than from the left. This phenomenon has been labelled the right ear effect (Bryden, 1965; Kimura, 1961; 1967; Satz et al, 1965). These results are frequently interpreted as support for the notions of

hemispheric asymmetry: the contralateral auditory pathways in man are stronger or more numerous than the ipsilateral pathways, and the left hemisphere plays a greater role than the right in the processing of verbal material. Because the right ear has better connections with the left hemisphere than does the left ear, right ear sounds have the advantage of better access to these speech centres. Electrophysiological evidence from infrahuman and human studies suggests that the contralateral auditory pathways are indeed stronger (Rosenweig, 1951; Sinha, 1959; Tunture, 1946; Vaughan and Ritter, 1970). Vaughan and Ritter found that, in man, monaural auditory input affects the two hemispheres unequally, the amplitude of the ipsilateral evoked cortical response being appreciably less than the contralateral one. Auditory asymmetries in normal subjects can most often only be demonstrated with dichotic presentation although certain monaural techniques have produced some evidence for a hemisphere effect (Bakker, 1969; Palmer, 1964). It appears that the competition between ears set up by dichotic presentation is more sensitive to the asymmetries. This may be because there is a point of overlap between the ipsilateral and contralateral pathways (Rosenweig, 1951) and at this point the contralateral pathways are capable of occluding impulses arriving along the ipsilateral pathway. Thus, because the speech centre is usually in the left hemisphere and has stronger connections with the right ear and because occlusion enhances the contralateral input, the

right ear provides for more accurate perception and recall of verbal information.

Others have argued that the right ear superiority for verbal material observed in dichotic listening experiments could be more parsimoniously viewed as a deficit in short term memory storage rather than in auditory perception. Inglis (1965) suggested that in free recall situations there is an attentional bias which tends to cause the material presented to the right ear to be recalled before that presented to the left ear, thus creating "an order effect which might be misinterpreted as a laterality effect" (Inglis, 1965, p. 236). However, there is now ample evidence which demonstrates a right ear superiority using an ordered recall procedure, in which the subject reports the left ear first on half the trials and the right ear first on half the trials (Bartz et al, 1967; Bryden, 1968; Satz et al, 1965; Schuloff and Goodglass, 1968; Zurif, 1966; 1968). Inglis and Ankus (1965) failed to obtain any consistent lateral asymmetry in an ordered recall experiment. With this one exception, the data fail to support the order effect hypothesis. The above studies report that order effects do occur, i.e. the material presented to the right ear is often reported first, and this can accentuate left-right differences in dichotic listening. However, it seems more parsimonious to attribute this tendency to the same perceptual effect that leads to the overall right ear superiority.

Two other lines of evidence also suggest that the perceptual asymmetry is in fact related to cerebral specialization. First, recent evidence indicates that there is a relation between handedness and cerebral dominance (Milner et al, 1964), and those studies which have employed both left and right-handers find that left-handed Ss typically identify more verbal material presented to the left ear than to the right ear, both with free recall (Bryden, 1966; Satz et al, 1965; Zurif, 1966) and ordered recall (Bryden, 1965; Zurif, 1968). Additional evidence for functional specialization comes from dichotic listening studies of right-handers which report a greater left ear efficiency (i.e. right hemisphere superiority) in handling certain nonverbal auditory stimuli. Kimura (1964) found melodic pattern perception to be significantly more accurate for the left ear while the same subjects on a verbal task had higher scores for the right ear. Curry (1967) and Knox (1969) also obtained a left ear effect with dichotic presentation of environmental sounds (e.g. dog barking, clock ticking). The dichotic presentation of different numbers of clicks to the two ears may be a task which is neutral with respect to lateral dominance. Kimura (reported in Milner, 1962) found only a slight tendency for the left ear to be more efficient, while others (Schuloff and Goodglass, 1968) have found no differences in accuracy for reporting the number of clicks heard at each ear.

Lateral asymmetries in the perception of verbal and

nonverbal stimuli have been found in the visual modality as well. When verbal stimuli are presented successively either to the left or to the right of a central fixation point, recognition is more accurate in the right visual field (Bryden, 1965; Hines et al, 1968; Mishkin and Forgays, 1952; Orbach, 1967; Zurif and Bryden, 1968) while enumeration of nonverbal material is superior in the left visual field (Kimura, 1966). Further, Zurif and Bryden (1968) found a right visual field superiority in a tachistoscopic paradigm analogous to dichotic listening, in which different letters were presented simultaneously, one to each visual field. These authors also report a clear differentiation between right-handers and familial left-handers, the latter tending to identify verbal material presented to the left visual field more accurately. The data from visual studies like these are most often postulated to be a reflection of cerebral functional asymmetry.

The behavioural evidence from studies employing competing stimuli supports the results from neurosurgical investigations regarding functional specialization. The data indicate left hemisphere specialization for language functions and right hemisphere specialization for certain nonverbal functions. Finally, evidence from electroencephalographic investigations of the two hemispheres will be considered.

Electroencephalographic Evidence of
Lateral Asymmetry

The considerable functional asymmetries of the hemispheres suggest that electrophysiological measures might also show evidence of asymmetries relating to function. The question has not typically been investigated as electrographic recordings are most frequently taken from one hemisphere only or from the vertex.

However, some early investigations of EEG activity of the two hemispheres did show definite asymmetries. Greater alpha wave amplitude was recorded in the right than left hemisphere by Cornil and Gastaut in 1947. Subirana et al, (1952) and Subirana and Oller-Daurella (1960) confirmed these findings for right-handed Ss but found that often the greater alpha occurred in the left hemisphere for left-handers. Raney (1939) also found a greater percentage and amplitude of alpha on the nonlanguage side. Lindsley (1940) confirmed this and also demonstrated that alpha blocking activity was asymmetrical. He found more blocking in the left occiput than in the right for right-handed subjects and the reverse, but to a lesser degree, for those left-handed. The inference is often made that the greater amount and amplitude of alpha in the right or nonlanguage hemisphere results from its lesser contribution in cognitive activity. But the right hemisphere is also specialized for certain functions, so it is difficult to say what such differences might mean. The study of phase

relationships between the hemispheres has also been investigated. Lindsley (1940) observed that alpha was out of phase a greater percentage of the time and that there was more unilateral blocking of alpha waves in ambidextrous and left-handed than in right-handed subjects. He suggests that these asynchronies are related to the lack of a definitely expressed laterality in ambidextrals and some left-handers. Giannitrapani et al. (1966) also investigated EEG phase differences and found that for right-handed Ss the left hemisphere led the right while the subject was awake, but that the relation was reversed while S was asleep. These relations were opposite for left-handers.

While the averaged evoked potential (AEP) has been shown to be influenced by such cognitive aspects of stimuli as selective attention, discrimination and decision, problem solving and task relevance, stimulus uncertainty and information delivery (Chapman, 1965; 1966; Davis, 1964; Donchin and Cohen, 1967; Ritter and Vaughan, 1969; Spong et al, 1965; Sutton et al., 1965; 1967), research investigating the symmetry of evoked responses has only recently been reported. Using clicks presented monaurally as stimuli, Price et al. (1966) compared evoked potentials recorded from sites over the contralateral and ipsilateral hemispheres. No consistent differences were observed in latency, but there was a tendency for the peak to peak amplitudes of the major components to be greater on the contralateral side. This seems

to support the evidence above which indicates the greater strength of the crossed auditory pathways.

Eason et al. (1967) demonstrated that the amplitude and latency of evoked responses to light flashes depend on the visual field in which the stimulus occurs. Greater amplitude and shorter latency evoked responses were obtained from left-handed subjects when the stimulus appeared in the left visual field. The overall magnitude of the response of the right hemisphere relative to that of the left was greater for left-handed individuals but no consistent differences were demonstrated for right-handed subjects.

Only one study has been found which examines the relation between the specific content of the stimulus and lateralization with regard to left or right cerebral activity. Buchsbaum and Fedio (1969) recorded AEPs in right-handers from both left and right hemispheres to verbal and nonverbal visual stimulation and found that their waveforms could be reliably distinguished: AEP waveforms for words and nonverbal stimuli were more variable from the left hemisphere than from the right. This finding is consistent with the general notion that verbal information is processed in the left hemisphere. Higher discrimination indexes were computed from AEP on the left than the right hemisphere which suggests that perception and decoding of verbal information may be regulated there. Further, the evidence that AEP replications from the right hemisphere were more similar than replications from the left

indicates that the right hemisphere responds more uniformly and makes less differentiation between stimuli than the left cerebrum. Also consistent is the finding of shorter AEP latencies for verbal stimuli computed from the left site.

In summary, the electrophysiological evidence to date seems to warrant further investigations into EEG characteristics related to lateralized cerebral activity. Hemispheric differences observed so far in the AEP are consistent with the hypothesis that the cerebral hemispheres in man assume an asymmetrical role in governing cognitive behaviour.

The Present Investigation

The aim of the present investigation was to further explore hemispheric specialization in man using both electroencephalographic and behavioural techniques. Specifically, auditory evoked responses were examined to see whether verbal and nonverbal auditory stimulation resulted in dissimilar patterns of electrographic response from the left and right hemispheres. Both monaural and dichotic methods of stimulus presentation were used. Immediate recall of the stimuli was required of S in order to provide behavioural evidence of any functional asymmetry.

The choice of stimuli was determined by the materials used in previous studies of dichotic listening. It was decided to use digits as verbal stimuli since many

investigators have employed them successfully in obtaining the right ear effect. It will be remembered that, although verbal stimuli appear to be processed in the left, and tones and environmental sounds by the right hemisphere, clicks appear to be relatively undifferentiated as regards hemisphere functioning. Thus, the choice of clicks as nonverbal stimuli was made on the assumption that they would not elicit hemispheric asymmetry thereby providing a control for the verbal condition.

Briefly, the independent variables were stimulus type -- verbal (digits) or nonverbal (clicks); manner of presentation -- monaural or dichotic; and hemisphere (left or right) from which the AEP was recorded. The two dependent variables were accuracy of report, and form (latency, amplitude) of the AEP. Three main hypotheses were investigated: (a) recall of dichotically presented digits is more accurate for those presented to the right than to the left ear, while no such asymmetry occurs with dichotically presented clicks; (b) AEPs to digits show consistent differences in amplitude and latency as a function of which hemisphere they were recorded from, while no such asymmetry occurs with clicks; (c) the AEP differences stated in (b) occur in both types of presentation, but are of lesser magnitude with monaurally than dichotically presented stimuli.

THE EXPERIMENT

The purpose of this experiment was to examine averaged evoked potentials (AEP) from the left and right hemispheres, and Ss verbal report, for evidence of lateral asymmetry related to the nature of the auditory stimuli and to the manner of their presentation.

METHOD

Subjects. The subjects were three female and seven male students between 20 and 25 years of age. They were paid \$1.50 per hour for their time. All Ss were self-classified right-handers and stated that their immediate family members were also right-handed. None had any history of auditory impairment.

Apparatus. Evoked potentials were recorded from both right and left temporal sites, approximately five centimetres to the right and left of the vertex. The reference electrodes were linked and located on the right and left mastoids. An active electrode was placed between the eyebrows to provide a check on eye movement artifacts. The ground electrode was placed on the forehead. Modified Beckman silver, silver chlorided electrodes were applied with Beckman electrolytic paste and the electrode impedance was kept below two thousand ohms. Electrical signals were amplified with a Grass polygraph (D.C. Driver Amplifier Model 7DAC; Preamplifier Model 7P5A) set for a bandpass of 0.3 - 75 c/sec. The

sensitivity was set at 30 microvolts/centimetre. The evoked potentials were averaged on-line by a Fabritek computer (Model 1052LS). The sweep interval was 512 milliseconds from stimulus onset, and was stored in 256 addresses in the signal averager. The dwell time was 2 milliseconds per address. Each AEP was transferred to paper tape in digital form for subsequent analysis.

The auditory stimuli were prerecorded on the two channels of a Uher (440) tape recorder and were played into a pair of Hosiden stereo headphones.

Stimuli. Two types of auditory stimuli were used, verbal (digits) and nonverbal (clicks). Only the monosyllabic digits from one to ten were employed, the duration of each digit being approximately 100 milliseconds, and its intensity approximately 85 decibel. The duration and intensity of each click were approximately 10 milliseconds and 85 decibel, respectively.

A verbal dichotic tape was constructed such that S heard one series of three digits at the right ear, and at the same time, another series of three different digits at the left ear. Thus, a digit arrived at one ear simultaneously with a different digit arriving at the other ear. No asynchrony in the onset of the members of a digit pair exceeded 20 milliseconds. Seventy-two pairs of digits were presented in groups of three pairs. The interval between each pair in the group was approximately 500 milliseconds and an interval of ten

seconds elapsed between each group to allow for Ss verbal report. In the verbal monaural condition, only one channel of the dichotic tape was used. That is, S heard 24 single groups of three digits all in one ear.

The nonverbal dichotic tape consisted of 24 groups of from one to five clicks each, the spacing of the clicks being arranged so that each group spanned a period of about two seconds. The sequence of groups on each channel of the tape was such that in all cases the two groups presented to the two ears contained different numbers of clicks. The spacing of the clicks within each group was such that the combined clicks from a pair of groups were equally spaced over the two second period. There was an interval of ten seconds between each pair of groups for S to report the number of clicks heard in each ear. The nonverbal monaural tape consisted of one channel of the nonverbal dichotic tape. Thus, S heard 24 single groups of clicks in the left or right ear.

Procedure. S was seated in a comfortable chair in a dimly lit room and the electrodes were applied. In order to minimize contamination of the evoked potentials with eye movement artifact, S was encouraged to focus his eyes on a fixation point during data collection. Instructions were given (See Appendix 1) describing the nature of Ss task in each part of the experiment.

All Ss performed in each of six conditions: verbal dichotic, verbal monaural (right ear), verbal monaural (left ear); nonverbal dichotic, nonverbal monaural (right ear), nonverbal monaural (left ear).

In the verbal conditions, S was required to report all digits heard after each group of three pairs of digits (dichotic) or three single digits (monaural). In the nonverbal condition, S was required to report the number of clicks heard in each ear after each group of clicks. In all conditions, evoked potentials were recorded from both right and left hemispheres, and a concurrent recording of eye movements was made. All AEPs are averages of evoked potentials to the first 16 stimuli presented (digit pairs, digits or clicks). For the verbal conditions, the AEPs are averages of 16 single responses to different stimuli (digit pairs, digits); the nonverbal AEP comprise 16 single responses to similar stimuli (clicks).

The verbal conditions always preceded the nonverbal conditions, and the dichotic presentations preceded the monaural presentations. Order of left and right ear conditions was balanced over Ss. The tape channels associated with the left and right ears were also balanced across Ss.

A 5 minute rest pause was introduced after each condition during which time E photographed and digitized the AEP. The entire experimental session lasted 1 - 1-1/2 hours.

Data Analysis. In the verbal dichotic condition S was credited with a correct response whenever he identified a digit that had actually been presented. Thus, the total possible score for each ear was 72. In the nonverbal dichotic condition S reported the number of clicks heard in each ear after each of the 24 groups of clicks. S was judged correct whenever he identified the number of clicks actually presented to an ear. The total possible score for each ear was thus 24. Verbal report in the monaural conditions, invariably 100% accurate, was not subjected to further analysis.

Digital printouts of the AEP were obtained from a Hewlett Packard 2116B Computer. Nine measures were taken from each AEP, 5 latency scores and 4 amplitude scores. The latency scores were the time elapsed between the start of the AEP and the peaks of the positive waves conventionally designated P1, P2 and P3, and the peaks of the negative waves N1 and N2. A peak was taken to be the point where the voltage was maximally positive (negative). In cases where a peak could not be unambiguously thus defined (e.g., more than one address at equal, maximal amplitude), curve-smoothing and interpolation were used. The amplitude scores consisted of voltage differences between successive peaks. Thus, four amplitude scores were calculated -- the difference between P1 and N1, N1-P2, P2-N2, and N2-P3.

Separate analysis of variance procedures were used for the results from the dichotic and monaural conditions.

In each case analyses were carried out independently for each of the 9 latency and amplitude measures. For the dichotic conditions a 2 (hemispheres) x 2 (stimulus types) x 10 (subjects) design was employed. For the monaural conditions, the design was a 2 (hemispheres) x 2 (stimulus types) x 2 (ears) x 10 (subjects). A combined analysis, with manner of presentation (dichotic, monaural-left, monaural-right) as a factor, was also carried out. Overall comparison of AEP waveforms was achieved by address-by-address correlation.

RESULTS

Recall Accuracy. The accuracy of report of the digits and clicks heard in each ear in the dichotic conditions is indicated in Table 1, which shows the mean number of correct responses (and percent accuracy) and the significance of the difference of the scores for each ear. The significantly superior right ear recall for verbal material confirms the hypothesis of behavioural asymmetry in the performance associated with the two ears under dichotic verbal stimulation. The click counting task resulted in approximately equal scores for the two ears, supporting the hypothesis of behavioural symmetry in responding to this type of material.

Evoked Potentials. The waveform of the AEPs was quite consistent and can best be described in terms of five major components occurring in the first 350 milliseconds

after stimulus onset. An initial positive peak (P1) invariably occurred between 20 and 50 milliseconds after the onset of the stimulus. Two other positive peaks typically occurred, the second (P2) between 185 and 230 milliseconds and the third (P3) between 290 and 350 milliseconds following stimulus onset. Two prominent negative peaks usually occurred, the first (N1) between 85 and 130 milliseconds, and the second (N2) between 240 and 280 milliseconds following stimulus onset. Labelled examples of AEP are shown in Appendices 2 to 5. In all figures of AEP, increasing negativity is represented by an upward deflection.

(a) Dichotic AEP

Sample AEPs from one S in the dichotic verbal and nonverbal conditions, from left and right hemispheres, are shown in Appendices 2 to 5. The mean latencies in milliseconds of each of the five major AEP peaks in the dichotic conditions are presented in Table 2. Three factor analyses of variance (2 stimulus types x 2 hemispheres x 10 subjects) showed no significant main stimulus type or hemisphere effects for any of the peaks. In general, the mean latencies in the verbal and nonverbal conditions are about the same except for P1 where the verbal presentation yielded considerably, although not significantly, longer latencies than did the nonverbal presentation.

TABLE 1

Total correct responses and percentage correct responses, averaged over \bar{S} s, for verbal and non-verbal stimuli heard in the right and left ears in the dichotic conditions. Also shown are the t-values associated with the differences between the scores for the right and left ears.

	Right ear	Left ear	t
Verbal	63 (88%)	54 (75%)	3.35*
Nonverbal	17.8 (74%)	18.1 (75%)	0.41

* $P < 0.005$ (one-tailed test)

TABLE 2

Mean latency in milliseconds of AEP peaks from left and right hemispheres, averaged over Ss, in the verbal and nonverbal dichotic conditions.

		P1*	N1	P2	N2	P3
Verbal	Left Hemis.	42.4	99.8	189.2	246.6	307.8
	Right Hemis.	42.6	101.0	205.0	266.2	317.8
Nonverbal	Left Hemis.	27.4	105.0	216.4	254.6	316.2
	Right Hemis.	28.0	97.4	208.6	253.0	316.6

* P1, P2, P3 refer respectively to the first, second and third positive AEP peaks; N1, N2 refer to the first and second negative AEP peaks.

The stimulus type x hemisphere interaction, however, was significant for the N1 ($F=6.75$, $p<.05$), P2 ($F=5.03$, $p=.05$) and N2 ($F=6.12$, $p<.05$) peaks and occurred in the hypothesized direction: the verbal dichotic presentation resulted in earlier latencies from the left hemisphere than from the right; the nonverbal presentation yielded either no latency differences between hemispheres (N2) or shorter latencies from the right than from the left hemisphere (N1, P2). The P3 latencies showed the same interaction tendency but this did not reach significance. No hemisphere x stimulus type interaction was observed for P1. It is also clear (see Table 2) from inspection of the significant interaction effects that greater latency differences between verbal and nonverbal stimuli occurred in the left hemisphere than in the right hemisphere. To the extent that the different latency measures are independent, similar tendencies observed in each peak latency strengthen the confidence in the results. In fact, the peaks' similar tendencies did not appear to result only from their temporal interdependence, since, on the average, an AEP from one subject showed any particular inter-hemispheric latency difference on only 50% (2.6) of the (5) measures.

Since, for each S, AEPs were recorded simultaneously from the right and left hemispheres, the correlations between the two AEPs provide a measure of interhemispheric similarity

for verbal and for nonverbal material. The mean address by address correlation between left and right hemisphere AEPs to verbal stimuli was lower ($r=.825$) than the correlation of AEPs to nonverbal stimuli ($r=.892$), and comparison of the z transformations of the interhemispheric correlations show that this difference is significant ($t=2.08$, $p<.02$). This result is consistent with the latency findings described above and supports the hypothesis of greater hemispheric asymmetry for verbal than nonverbal material.

The mean amplitudes for each component are presented in Appendix 6. There were no consistent differences in the amplitudes of the AEPs according to either stimulus type or hemisphere. However, the P1-N1 difference was significantly greater from the left than the right side in the verbal dichotic condition ($F=15.78$, $p<.005$).

(b) Monaural AEP

The latencies of the major peaks in the left and right hemisphere AEPs, averaged over Ss, are shown in Appendix 7 for left and right monaural presentations of verbal and nonverbal stimuli. Four factor analyses of variance (2 stimulus types x 2 hemispheres x 2 ears x 10 subjects) resulted in significant stimulus type main effects for P1 ($F=13.7$, $p<.005$), N1 ($F=9.2$, $p<.05$), N2 ($F=6.6$, $p<.05$) and P3 ($F=6.3$, $p<.05$). The P2 peak stimulus type main effect just missed significance at the five percent level ($F=4.8$, $p<.10$). These

differences were in the same direction for all peaks; the AEPs to verbal stimuli had shorter latencies than did the AEP to nonverbal stimuli.

No other main or interaction effects reached significance at the five percent level in the 4 factor analyses; however, the monaural right (MR) AEPs tended to have shorter latencies than the monaural left (ML) AEPs. Also, the stimulus type x hemisphere interactions tended to be in the same direction as those in the dichotic condition (i.e. shorter latencies from left hemisphere for verbal stimuli, and either no hemisphere differences or shorter latencies from right hemisphere in nonverbal conditions). However, only the interactions for the P1 and P3 peaks approached significance in the monaural conditions ($F=4.6$, $p<.10$; $F=4.3$, $p<.10$ respectively).

It was also observed that while neither the main effects for ear stimulated nor the interaction terms including this variable reached the 5 percent level of significance, there was a consistent tendency for the MR condition to produce more of the observed differences than the ML condition (see Table 3, where the mean latencies for left and right hemisphere AEPs are presented separately for the MR and ML presentations of verbal and nonverbal stimuli). To further investigate these differences, 2 separate sets of 3 factor analyses (2 stimulus types x 2 hemispheres x 10 subjects)

were performed, one for the right ear and one for the left ear monaural conditions. The results show that most of the significant differences noted in the 4 factor monaural analyses also tended to be significant in the MR presentation analyses but not in the ML presentation analyses. Thus, the stimulus type main effect showing shorter verbal than non-verbal latencies was significant in the MR AEPs for the N1 ($F=7.0$, $p<.05$), N2 ($F=7.5$, $p<.05$) and P3 ($F=15.9$, $p<.01$) peaks but did not reach significance for any peaks of the ML AEPs. Also, for the MR AEPs, the stimulus type x hemisphere interaction effect was significant beyond the five percent level for P1 ($F=8.35$) in the direction of shorter latencies in the left hemisphere for the verbal condition, but shorter right hemisphere latencies for the nonverbal condition. The ML presentation analyses did not show any significant interaction effects.

The mean correlations and corresponding z-scores between simultaneously recorded left and right hemisphere AEPs to verbal and nonverbal material are presented separately for the MR and ML presentations in Table 4. In the MR condition the interhemispheric correlations to verbal material were significantly lower than the AEP correlation to nonverbal material ($t=1.87$, $p<.05$). Similar but non-significant differences occurred in the same direction in the ML condition ($t=1.14$, $p>.05$). These results confirm the hypothesis of

TABLE 3

Mean latency in milliseconds of AEP peaks from left and right hemispheres, averaged over Ss, for verbal and nonverbal stimuli in right and left monaural conditions.

		P1	N1	P2	N2	P3		
Right Monaural	Verbal	Left Hemis.	23.0	94.4	201.0	245.0	303.6	
		Right Hemis.	40.0	103.4	201.0	251.0	315.0	
	Nonverbal	Left Hemis.	51.0	127.0	235.0	301.6	351.6	
		Right Hemis.	49.0	127.0	229.6	300.0	355.4	
	Left Monaural	Verbal	Left Hemis.	26.0	117.0	214.0	274.4	327.0
			Right Hemis.	26.0	113.4	213.6	275.0	333.0
Nonverbal		Left Hemis.	44.0	128.0	235.0	283.0	344.4	
		Right Hemis.	49.0	126.0	231.0	280.0	339.0	

greater hemispheric asymmetry in the verbal than nonverbal conditions, and are also consistent with results showing greater differences in the MR than ML presentation.

The mean peak to peak amplitudes in the monaural AEPs are presented in Appendix 8. Four factor analyses of variance showed that the nonverbal AEPs had significantly higher amplitudes in the right than the left hemisphere for the P2-N2 component ($F=8.90$, $p<.05$). The analyses of MR AEPs showed a significant hemisphere effect for N1-P2 which resulted from the greater left than right hemisphere amplitudes for verbal material ($F=7.08$, $p<.05$). A significant difference of a similar nature for the P1-N1 amplitude was found in the analysis of the ML AEPs ($F=21.1$, $p<.01$).

(c) Comparison of Dichotic and Monaural AEPs

Inspection of the AEPs from dichotic and monaural presentation showed that, generally, the dichotic conditions produced shorter latencies than either of the monaural conditions. However, analyses of variance indicate that the presentation differences between dichotic and monaural right conditions were not significant. The presentation main effects for dichotic and monaural left also fell short of significance at the five percent level but did reach the ten percent level for N1 ($F=3.27$), P2 ($F=3.92$), N2 ($F=4.20$) and P3 ($F=4.34$) in the direction of shorter latencies from the dichotic presentation. There were no other significant main

TABLE 4

Mean interhemispheric correlation coefficients and z-scores for verbal and nonverbal monaural conditions.

		Verbal	Nonverbal
Monaural Right	r	.823	.895
	z	1.212	1.521
Monaural Left	r	.867	.893
	z	1.413	1.520

or interaction effects in the comparison of latencies in the three presentation conditions.

DISCUSSION

The results of this experiment are interpreted as providing strong support for the hypothesis of asymmetry of hemispherical functioning. The behavioural evidence confirms previous findings of differential accuracy of verbal report as a function of the nature of the auditory stimulus and the ear stimulated. Furthermore, new evidence is presented indicating corresponding asymmetry in the waveforms of the evoked potentials elicited by the different stimuli in the various experimental conditions. Before discussing these findings, however, some consideration should be given to the extent to which factors other than those directly manipulated might have influenced the results.

The importance of similar electrode position and interelectrode impedance for the recording of physiologically comparable evoked potentials has been demonstrated by Vaughan et al (1963). The amplitude of the peaks in an AEP and, to a lesser extent, their latency, are sensitive to changes in these variables. Care was taken in the present experiment to locate the electrodes at corresponding points over the two hemispheres and to maintain equality of electrode impedance. The effect of within-S variation of these factors would have been to differentially bias amplitude and/or latency of AEP

components in a consistent manner across conditions. Since it is the between-condition differences that are of prime concern, and in view of the precautions taken, it is considered unlikely that electrode characteristics had an important influence on the observed pattern of results.

Another generally recognized potential source of artifact in the recording of evoked potentials is the electrical activity generated by muscular movement. An electrode located on S's forehead enabled eye movements to be monitored during the period over which evoked potentials were being recorded. Inspection of photographs of averaged eye movement signals revealed negligible stimulus-related activity. While this appears to rule out eye movements as a source of contamination of AEPs, it is possible that muscular activity occurred in the form of subvocalization. Although it seems unlikely that this could account for the pattern of results observed, it may be argued that the cortical activity underlying the vocal (and subvocal) response to a stimulus is asymmetrical with respect to the two hemispheres, and that this difference is reflected in the potential changes evoked by the stimulus. It is not immediately obvious how this potential source of influence on the evoked potential might be assessed or controlled.

Auditory thresholds at the two ears were not checked for differential hearing loss in the present study. However, all Ss stated that they had negative histories for

any auditory impairment and each S performed with 100% accuracy on the left and right monaural tasks, suggesting the absence of influence of severe auditory deficit on the results.

A recent report (Karlin, 1970) suggests that certain slow voltage changes, such as the contingent negative variation and other 'readiness' potentials are associated with the development of differential 'non-cognitive' preparatory states before the presentation of critical stimuli and produce the positive enhancement in evoked potentials which investigators usually attribute to cognitive influence (Donchin and Cohen, 1967; Haider, Spong and Lindsley, 1964; Sheatz and Chapman, 1969; Sutton et al, 1965, 1967). Although none of the late components in the present study showed amplitude differences, the amplitude of the early P1-N1 component was consistently greater from the left than the right hemisphere for verbal material. Karlin suggests that the rapid return to baseline of the slow negative shifts associated with intention to respond could be picked up in AEP recordings and thus introduce enhanced early positive components into the AEP obtained to the stimuli. In the present study all of the stimuli were 'critical' (required a response from S) and thus it is unlikely that differential 'readiness' states resulted in the amplitude differences between AEP to verbal and nonverbal stimuli. It may be argued that the two tasks (i.e. identifying digits and

counting clicks) were sufficiently different to have resulted in the AEP differences, but such specific differentiation is clearly not compatible with Karlin's argument which states that AEP changes are a consequence of change in some generalized state, such as arousal, and are not linked to delivery of information per se. Furthermore, the results of the present study showing enhancement in the left but not the right hemisphere in verbal AEP, strongly suggest that, if in fact slow potential changes do influence differences in AEP, these changes do not simply result from nonspecific, generalized activation, but at least in part reflect specific cognitive states and influence the AEP accordingly.

It is possible that the overall latency differences between the dichotic and monaural methods of presentation resulted in part from variations in stimulus intensity. McCandless and Lentz (1968) found that tones of low intensity produced longer AEP latencies than high intensity tones. In the dichotic condition, in the present study, the intensity of the stimuli arriving at each ear was the same as the stimulus intensity in the monaural condition. However, because the two stimuli were presented simultaneously in the verbal dichotic condition the intensities from the two ears would have partially summated along the afferent pathways (Rosenweig, 1951) resulting, perhaps, in shorter AEP latencies than for the monaural condition. Although the nonverbal stimuli were separated by at least 500 milliseconds (in both dichotic and

monaural conditions), intensity summation may still account for some of the observed reduction in latency in the dichotic compared with monaural conditions.

Although nonverbal AEP were averages of 16 clicks, the verbal AEP were averages of 16 responses to different stimuli. It is difficult to know how such different AEP compositions might affect a comparison of the verbal and nonverbal AEP; however, it is not immediately apparent that this factor would have resulted in the increased hemispheric differentiation and generally shorter latencies observed for verbal than nonverbal AEP.

Finally, the quantification of the AEP data by a visual estimation scoring procedure is recognized to be prone to error. However, confidence in the latency data thus obtained may be drawn from the complementary nature of the results of address-by-address computer correlations derived from the same initial data.

The results for recall accuracy of the two ears in the dichotic presentations clearly demonstrate a behavioural asymmetry which is specific to stimulus type. The superior recall of verbal material presented to the right ear confirms the results from other studies employing the dichotic technique (Bryden, 1962; Kimura, 1961, 1967; Satz, 1968). Kimura (1961) tested Ss in whom the locus of speech functioning was established by sodium amytal tests and found a significant right ear superiority for verbal material in Ss

with a left hemisphere dominance for speech, and the reverse -- a significant left ear superiority -- for Ss in whom the right hemisphere was verbally dominant. Assuming that the Ss in the present study had speech functions represented in the left hemisphere (about 90% of all right handers do), it is reasonable to assume that this factor caused the behavioural and electrographic asymmetries which were observed.

The observation of shorter AEP latencies from the left hemisphere for dichotically presented verbal material is consistent with the general notion that verbal information is processed in this hemisphere. Presumably, the longer latencies from the right hemisphere result from the necessity of a cross-commissural analysis of verbal input to that hemisphere. While the latency of synaptic transmission is in the order of 0.5 millisecond, latency differences between the hemispheres reported here range from 1.2 to 19.6 milliseconds. Apparently, the information crossing to the left hemisphere does not take the form of one discrete signal or several simultaneous signals alone. Transmission of this type of information seems to require several successive signals over one or more neurons. It remains for future research to explore the nature of these signals and to determine how the transmission varies with different tasks. In fact, one study (Gazzaniga, 1970) investigated reaction times in normal humans

when an interhemispheric transmission was necessary for making a discrimination and responding appropriately. The results showed that reaction times to visual information requiring transmission were approximately 40 milliseconds longer than reaction times of responses not requiring such transmission. Jeeves (1969) reports similar results for normals, and reported also that acallosal Ss had much longer response times than normals on the tasks requiring interhemispheric transfer. Many other studies also suggest that the neocortical commissures are of primary importance in the interhemispheric transmission of information (see Introduction). Although the auditory system includes a number of possible subcortical sites for bilateral interaction, the critical role of the cortex in processing of verbal material points to the probability that the transfer of verbal auditory information normally takes place at the cortical level via the corpus callosum. Thus, latency differences noted in this experiment may well be indicative of the necessity for verbal input to the right hemisphere to be relayed (perhaps via the corpus callosum) to the verbally dominant left hemisphere.

The analysis of the individual peaks of dichotic verbal AEPs showed no hemisphere latency differences at P1, few at N1, but more at later stages of the waveform, all in the direction of shorter latencies for the left hemisphere. Other evoked potential studies (Chapman and Bragdon, 1964; John, 1968; Smith et al, 1969; Sutton, 1967; Uttal and Cook,

1964) suggest that early AEP components reflect primarily the registration of afferent input via the lemniscal pathways upon the neural structures, while late components, which are more labile with respect to variables of past experience, are released from memory storage by the activation of extralemniscal pathways and represent the analysis and readout of the information. Perhaps the increased hemispheric differentiation at later stages in the AEP suggest a less specialized speech representation in the right hemisphere where verbal input is registered immediately but the information readout from this hemisphere is delayed by callosal transmission to the left hemisphere for the information analysis.

Specifically, the early response reflects the transmission of information into the nervous system by direct pathways from the receptor through the specific thalamic relays to the relevant sensory projection area of the cortex (Kooi and Bagchi, 1964). Psychologically, the early neural event appears to be related to the simple reception and identification of sensory information, but is not probably in itself sufficient for either the conscious perception or storage of the sensory event (Brazier, 1964). The P1 and N1 peaks observed in the present study probably do not constitute the primary evoked response, which typically occurs within 10 to 20 milliseconds of stimulus onset. However, to the extent that early components of AEPs reflect the

simple transmission and reception of the physical stimulus, the absence in the present study of differences in the latency of the early components is accounted for. The greater left than right hemisphere amplitude of the P1-N1 measure for verbal material does, however, indicate some early differentiation of input. A plausible interpretation of this result might be simply in terms of the greater left hemisphere neural involvement for the processing of verbal material.

The later events of the cortical response are more diffuse and likely to consist of synchronous firing over wider areas of the cortex (Kooi and Bagchi, 1964). The time course suggests that the secondary response may reflect activation via the indirect pathways through the brainstem reticular formation to cortical areas other than specific sensory projection areas. Psychologically, the later components are responsive to a number of experimental influences such as relevance of the stimulus (Chapman, 1965), the uncertainty of the stimulus (Sutton, 1965; 1967), errors (Haider et al, 1964), stimulus masking (Lindsley and Emmons, 1958), habituation (Brazier, 1964), differences in cognitive meaning (John et al, 1967) and differences in affective meaning (Begleiter and Platz, 1969), and these late components are regarded as necessary for the conscious perception and storage of sensory input (Brazier, 1964). The results of the present investigation showing increased hemispheric

differentiation according to stimulus type in the latencies of later AEP peaks are clearly consistent with the apparent importance of later AEP components in the analysis and readout of stimulus material.

The interpretation of the absence of hemisphere differences in amplitude in later components seems less clear. Perhaps amplitude differences are affected more by factors pertaining to differential registration of input, while latency differences represent differential hemispheric specialization for the analysis and readout of the input. In this view left hemisphere specialization for speech would be reflected in the early stages of AEP as more marked registration (higher amplitude) in the left hemisphere than in the right, but is not reflected in the simultaneous (equal latency) registration in the two hemispheres. The asymmetrical analysis of the input would be reflected in later components as latency differences (only) showing shorter latencies for verbal information arriving directly at the left hemisphere.

In contrast to the results for the verbal stimuli, there was little difference in the latency of the AEP peaks for the dichotically presented clicks. The slight tendency toward shorter latencies from the right hemisphere is consistent with previous evidence of a right hemisphere superiority in the processing of this type of material (Milner, 1962), but the differences observed in the present study fell short of

significance. The substantially greater latency differences between AEP peaks for verbal and nonverbal material in the left than right hemisphere confirms the results of Buchsbaum and Fedio (1969) obtained in a similar manner for visual AEP, and indicate that verbal and nonverbal material are differentiated more in the left than in the right hemisphere.

Finally, the lower correlation between left and right AEPs obtained to dichotic verbal stimulation than to dichotically presented clicks is consistent with this hypothesis of more lateralized cerebral activity for the verbal than the nonverbal material. Buchsbaum found the reverse relation in his study, verbal stimuli producing more similar AEPs from the two hemispheres. This may be explained by the fact that his nonverbal stimuli were unfamiliar random dot arrays and nongeometrical designs and were therefore perhaps more complex than his verbal stimuli.

Clearly, the dichotic stimulation resulted in lateralized AEP characteristics which support previous findings concerning differences in function between the left and right hemispheres. These data alone, however, indicate only that differences in function occur between the left and right hemispheres. They do not permit an assessment to be made of the possible anatomical and physiological mechanisms underlying the observed behavioural asymmetries, such as the dominance of the crossed auditory pathways over the uncrossed. Evidence regarding these notions is found in the AEP data from

the monaural presentations.

It was assumed that the neural organization responsible for the expected behavioural and electrographic asymmetries in the dichotic conditions would also result in similar, although perhaps fewer, differences with monaural stimulation. Such asymmetry in verbal report (the right ear effect) had previously been observed with monaural verbal presentation when the material is complex (e.g. recall of long word lists) and when ordered rather than free recall is required (Bakker, 1967, 1968, 1969, 1970; Simon, 1967). In the present study, the task used in monaural presentation was relatively simple. Consequently, recall in these conditions was virtually 100%, precluding the appearance of asymmetrical behavioural results. The electrographic measures may be considered as more sensitive indices, however, and, indeed, a considerable number of differences were found in the latency and amplitude of AEPs from the left and right hemispheres that were related to the nature of the monaurally presented stimulus.

The generally shorter latencies for verbal than nonverbal material in the monaural presentations is consistent with the results from other studies that report shorter latencies to semantic stimuli. Buchsbaum and Fedio (1969) found that their AEP to word stimuli had considerably shorter latencies than AEP to design stimuli. Also, Begleiter and Platz (1969) report that both neutral and taboo words produced

significantly shorter visual AEP latencies of the P3 peak than did flashes of light. An earlier study (Begleiter et al., 1967) found that conditioned emotional significance affected AEP latencies -- a negative stimulus produced significantly shorter latencies than a neutral one.

The significantly shorter latencies in AEP for verbal than nonverbal stimuli in the monaural right (MR) presentation seem to indicate greater differentiation according to stimulus type for this presentation than for the monaural left (ML) presentation where no significant latency differences occurred. Confirming this result, and suggesting greater hemispheric differentiation in MR than ML are the significantly lower interhemisphere correlations for verbal than for nonverbal material in the MR (but not ML) presentation. These differences observed between MR and ML presentations seem most parsimoniously interpreted as evidence that the crossed auditory pathways are stronger than the uncrossed. In the MR presentation the dominant (crossed) pathways lead directly to the verbally dominant (left) hemisphere. Presumably, processing of verbal input to that hemisphere would be faster (shorter latencies) than the processing of verbal input via the weaker uncrossed pathways which arrives initially at the verbally nondominant (right) hemisphere. In the ML verbal presentation the situation is reversed. The dominant pathway leads to the verbally nondominant hemisphere, and weaker pathways go to the verbally dominant

hemisphere. Thus, the greater hemispheric asymmetry in the verbal MR presentation may accrue from the fact that the dominant hemisphere received the dominant input, while the nondominant hemisphere receives the weaker input. Fewer hemispheric asymmetries result in the ML presentation because the situation is more balanced: the dominant input arrives at the verbally nondominant hemisphere, the nondominant input at the dominant hemisphere. This same analysis would account for the observation that the verbal ML AEPs all tend to have longer latencies than the verbal MR AEPs.

In the case of certain nonverbal monaural stimulation the dominant hemisphere would be the right hemisphere and the ML presentation would be expected to show the greater hemispheric asymmetry and the MR presentation the slower overall latencies. In this study, however, the monaural presentation of clicks to the left and right ears resulted in highly similar AEPs, supporting the inference made from the dichotic data that the right hemisphere is not as highly specialized with regard to processing these stimuli as it is for other nonverbal material.

The major electrographic differences between methods of monaural presentation can be explained according to the hypothesis of stronger crossed than uncrossed auditory pathways. Another postulate regarding the arrangement of the auditory pathways may explain differences observed between dichotic and monaural presentations.

Rosenweig (1951) proposed that there is a point of overlap between the crossed and uncrossed pathways, and that at this point the crossed pathways from one ear are capable of occluding impulses from the other ear arriving along the uncrossed pathways. According to this postulate, when different stimuli are presented to the two ears, as is the case in the dichotic condition, the impulses arriving along the uncrossed pathway would be partially occluded, and thus the advantage of the contralateral over the ipsilateral pathways would be enhanced. Indeed, some mechanism in addition to the greater strength of the crossed pathway seems necessary to explain Milner's (1968) results with split brain patients and dichotic listening. In that study, it will be recalled, Ss obtained near zero scores for the left ear input under verbal dichotic stimulation while the right ear input was handled normally. In contrast, under monaural conditions the callosal patients correctly reported digits to the left ear without difficulty, showing that the ipsilateral pathway could be utilized when there was no competing input from the right ear. The greater suppression of ipsilateral input in the presence of a competing stimulus from the contralateral ear clearly suggests that under these conditions mechanisms enhance the contralateral dominance (ipsilateral weakness) found under monaural presentation.

Thus, in this study mechanisms of afferent and central occlusion may have suppressed the weaker and presumably

slower ipsilateral input in the dichotic conditions, resulting in the tendency for all dichotic AEP to show shorter latencies than monaural AEP.

Postulation of some type of central occlusion, especially within the dominant hemisphere may explain the tendency for reversed hemispheric asymmetry in the verbal and nonverbal dichotic conditions which was absent in the monaural conditions. Perhaps the enhancement in the dichotic condition of the contralateral nonverbal input to the right hemisphere somehow intensified that hemisphere's specialization for the nonverbal material resulting in the asymmetrical tendencies, these not being observed in the monaural nonverbal conditions. The central occlusion mechanism would also account for the tendency for greater hemispheric asymmetry in the dichotic than monaural verbal conditions.

Generally, the two methods of presentation produced compatible results suggesting that the hemispheric asymmetries are quite consistently reflected in electrographic information.

This study has been based on the assumption that there exist definite relations between nervous activity and behaviour and that the study of cerebral cortical phenomena will eventuate in a fuller understanding of 'higher' human functioning. It has also been assumed that the evoked potential waveform in some way reflects the temporal pattern

of activity in a large number of single cellular units and is thus a useful tool for investigating the neural basis of behaviour. The recent accumulation of data on intracellular activity shows high correlations between the graded synaptic activity in particular cells and corresponding wave shapes of potentials evoked by the stimulation (Cruetzfeld, 1966; Fox and O'Brien, 1965; John, 1968; Landau, 1968) suggesting that the evoked potential is indeed based on neural activity which may reflect the fundamental chemical processes by which information becomes acquired, stored, and retrieved. Of course, the nature of the neural events which underlie behaviour and which are the genesis of the evoked potential remain to a large degree unknown. New information regarding these events will certainly contribute a great deal to electrophysiological investigations of behaviour, but it is unreasonable to think that the absence of all the answers should preclude meaningful neuropsychological investigations in the interim.

If functional differences between the hemispheres are reflected in AEP characteristics, as this study suggests, the electrographic approach could be very fruitfully applied to many problems of cerebral organization.

A study similar to the present one is suggested by the results. The nonverbal material would be melodies or environmental sounds or some other stimuli shown to result

in a left ear effect. To the extent that AEP latencies and amplitude differences reflect hemisphere dominance, the hypothesis for right hemisphere specialization for these materials could be investigated.

Similar studies in the visual modality may be very compelling since the arrangement of the visual system allows input to be restricted to only one hemisphere. Verbal material projected exclusively to the left and right hemispheres could be compared for electrographic asymmetries. As was mentioned in the introduction, behavioural asymmetries are also found when visual tasks analogous to dichotic listening are employed. Thus, evidence for corresponding behavioural and electrographic asymmetries in the visual modality could be investigated.

Electrographic asymmetry also provides a new technique for the study of development of hemisphere asymmetries. The age at which the left hemisphere becomes specialized for speech functions has been a focus of concern for some time. Clearly, the use of electrographic indices could be used as an indication of the age at which neural organization gives up its functional equivalence and the two hemispheres assume specialized roles for the processing of different information. Kimura (1967) and Knox (1969) reported that behavioural asymmetries are observed at 5 years but it is possible that some evidence of electrographic asymmetry occurs before then in view of the fact that language

acquisition begins around 2 years.

The electrographic investigation of lateralization in people for whom language development proceeds abnormally also seems an interesting line of research. The incidence of dyslexia in young children may in some cases occur because the hemispheres are not fully lateralized according to functional specialization (Bakker, 1969). If a dyslexic child is simply neurologically immature, therapeutic attempts may only be frustrating. On the other hand, some procedures may be developed which could aid the lateralization process in such cases.

The investigation of congenitally deaf people may show that their unusual course of language development produces some cerebral differences regarding lateralization of cerebral functioning. Since deaf people have been observed to have essentially the same cognitive abilities as hearing people, one could investigate whether lateralization proceeds more as a function of speech acquisition or of the conceptual formation which accompanies language.

It is surprising to note that virtually no electrographic studies of split brain patients have been reported in the literature. Surely the most compelling behavioural evidence for hemispheric functional specialization is found in the work on these people. Probably equally as compelling electrographic evidence would result from studies of split

brains. For example, a comparison of verbally evoked visual responses from the left hemisphere when S reports the stimulus, and from the right hemisphere when he maintains he saw nothing would be very interesting.

Electrographic investigations could also aid in a more precise delineation of the different hemisphere roles by examining the critical characteristics which distinguish, for example, 'verbal' from 'nonverbal' material. Varying stimulus characteristics such as meaning, familiarity, pronouncability, relative structure or syntax may enable some further conclusions to be drawn regarding the nature of the differential neural processing of different stimuli in the two hemispheres.

The results of the present investigation support the notions of hemispheric specialization found in other investigations and, equally as important, they demonstrate the value of the electrographic approach to problems of cerebral organization.

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APPENDICES

APPENDIX 1

Instructions to the Subject

Dichotic Verbal

The purpose of this experiment is to see how accurately you can report certain verbal stimuli. The stimuli, which you will hear through the earphones, are numbers from one to ten. In one second you will hear three pairs of numbers. The members of each pair will be heard at the same time. There will be 20, one second trials of three pairs of numbers and each trial will be separated by a ten second interval. Immediately following each 1 second trial I would like you to verbally report all of the numbers which you heard, in any order. Try and pay attention to both earphones at the same time. You are encouraged to guess. There will be one practice trial before we begin. Any questions?

Monaural Verbal

Now, you will hear numbers in your right (left) ear only. In one second you will hear 3 single numbers. There will be about 20 of these 1 second trials. Following each trial I would like you to tell me all of the numbers that you heard. Any questions?

Dichotic Nonverbal

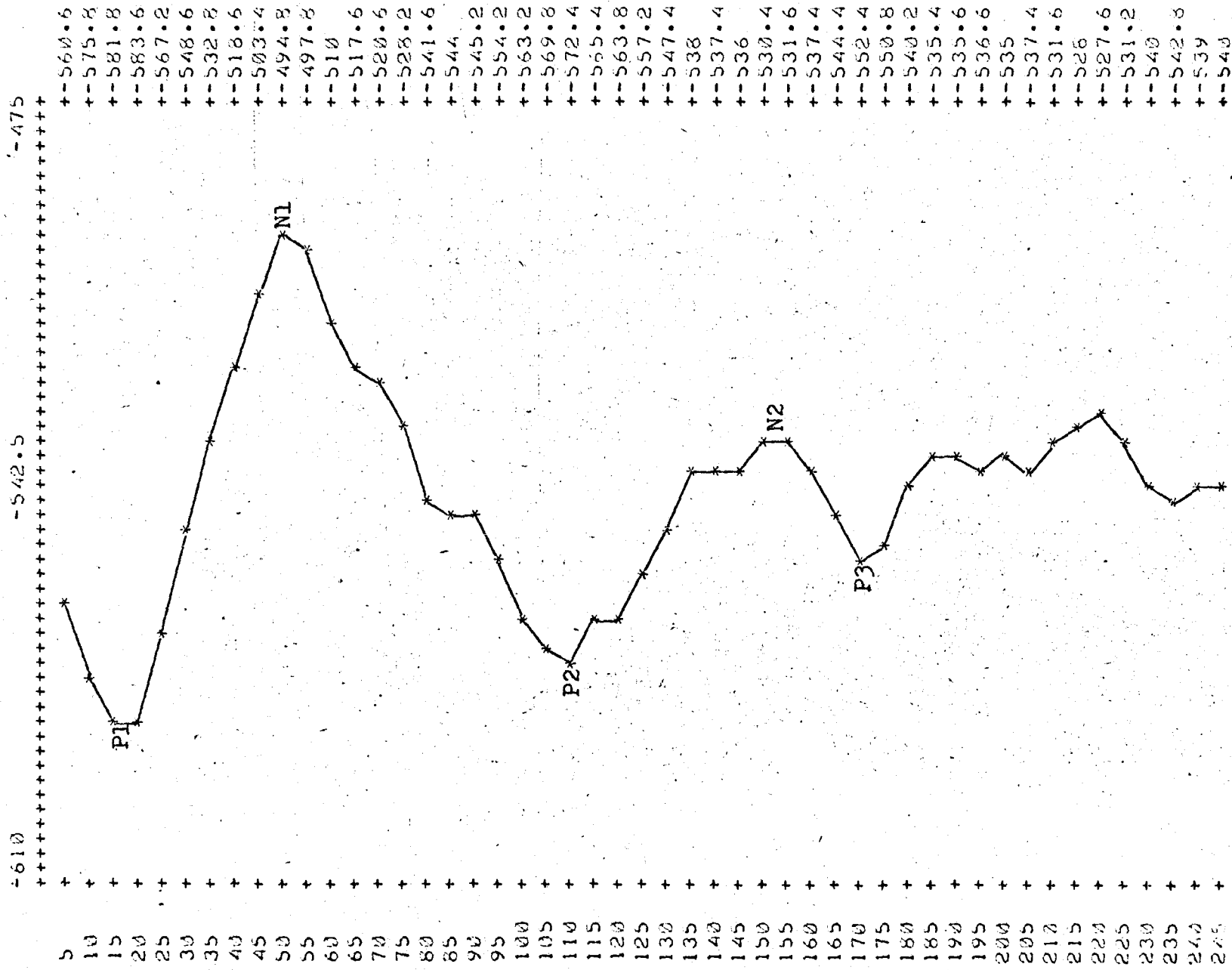
This part of the experiment is also concerned with your accuracy in reporting back sounds that you hear. But this time the sounds will simply be clicks. I want you to tell me how many clicks you hear in each ear. In 2 seconds you will hear from 1 to 5 clicks in each ear. The number of clicks in each ear will be different. For instance you may hear 5 clicks in your right ear and at the same time say only 3 clicks in your left ear. There will again be about 20 of these 2 second trials followed by a 10 second interval. After each trial I would like you to tell me how many clicks you heard in each ear. It doesn't matter which ear you report first as long as I know which one you are reporting. For instance say "left 3", "right 2" and so on. There will be one practice trial before we begin. Any questions?

Monaural Clicks

Now you will hear some more clicks but this time the task is much easier. You will hear from 1 to 4 clicks in 2 seconds, but in your right (left) ear only. After each trial, simply tell me how many clicks you heard. Any questions?

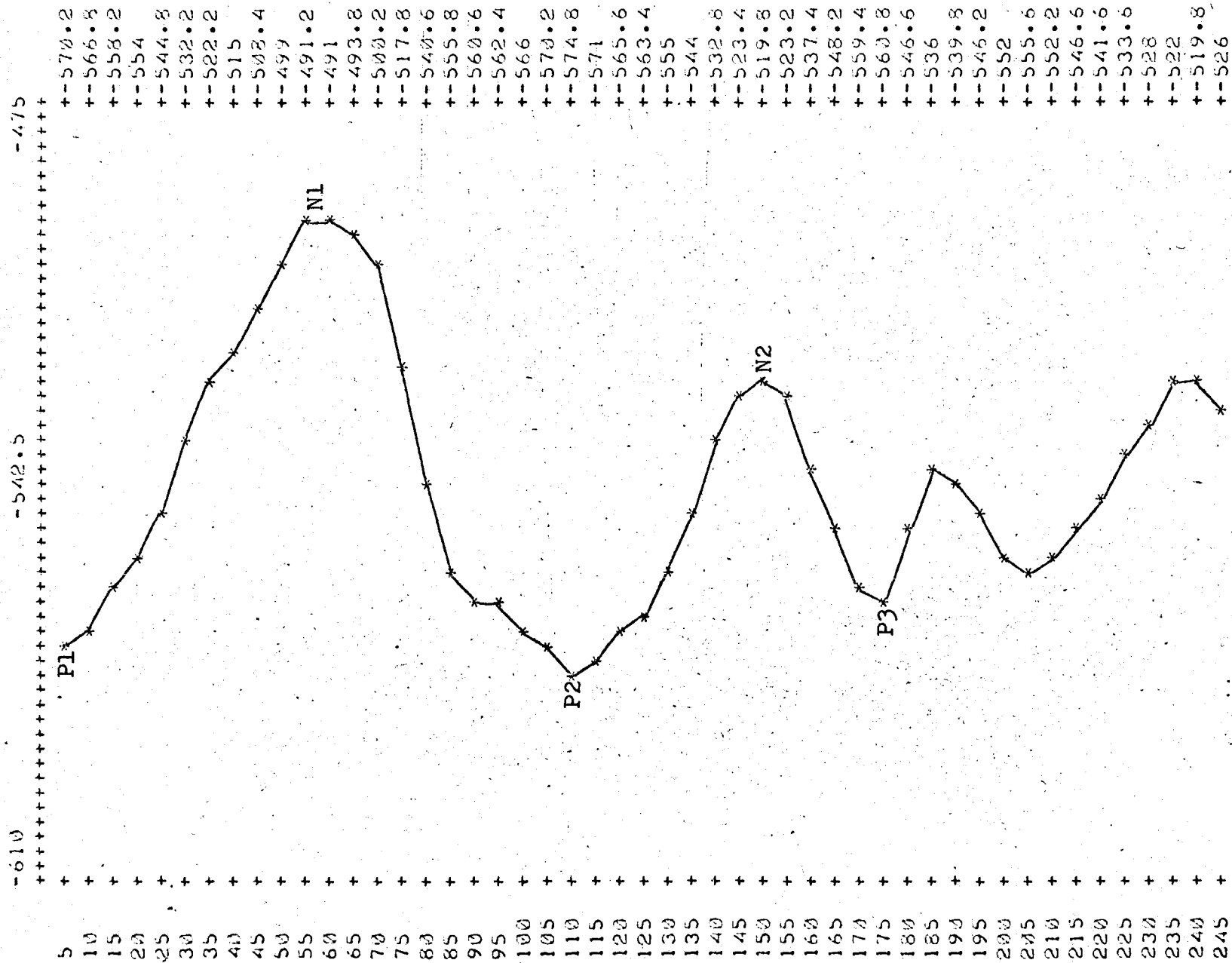
APPENDICES 2, 3, 4 and 5

The following AEP figures are smoothed averages of 16 evoked potentials. Each point on the AEP waveform represents the average of the data stored in the five preceding addresses. Thus, only 50 points from the initial 256 addresses are represented. Also, although it is not apparent from the arbitrary numerical values at the top of each figure, increasing negativity is represented by an upwards deflection.



APPENDIX 2

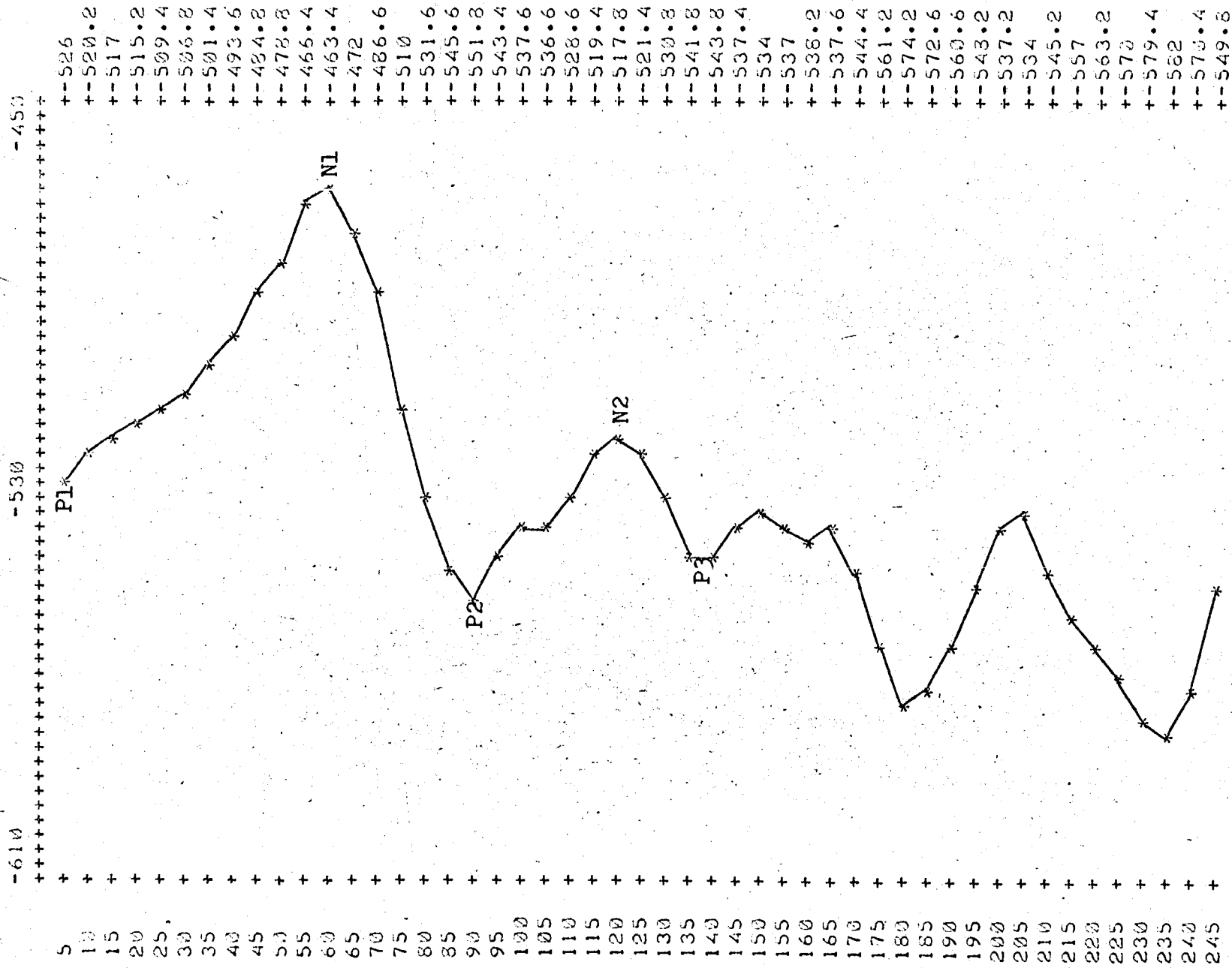
AEP from the left hemisphere to dichotic verbal stimuli.
(Subject D.G.)



APPENDIX 3

AEP from the right hemisphere to dichotic verbal stimuli.

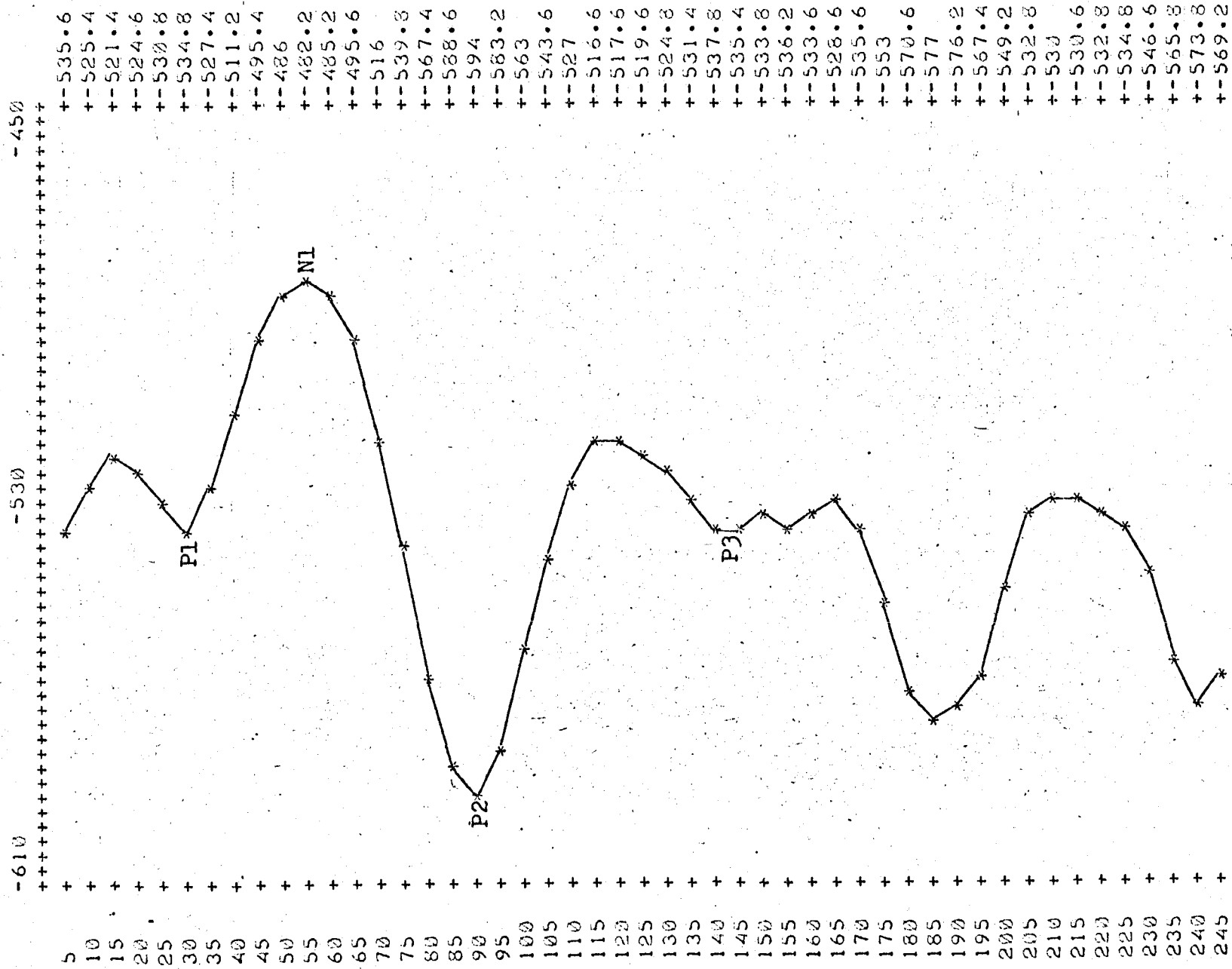
(Subject D.G.)



APPENDIX 4

AEP from the right hemisphere to dichotic nonverbal stimuli.

(Subject D.G.)



APPENDIX 5

AEP from the left hemisphere to dichotic nonverbal stimuli.

(Subject D.G.)

APPENDIX 6

Mean peak to peak amplitude in microvolts of AEPs from left and right hemispheres, averaged over Ss, in the verbal and nonverbal dichotic conditions.

		P1-N1	N1-P2	P2-N2	N2-P3
Verbal	Left Hemis.	6.3	9.7	2.6	3.4
	Right Hemis.	5.3	9.7	3.2	3.2
Nonverbal	Left Hemis.	4.9	12.6	3.2	3.6
	Right Hemis.	4.9	12.3	2.8	3.4

APPENDIX 7

Mean latency in milliseconds of AEP peaks from left and right hemispheres, averaged over Ss, for verbal and nonverbal stimuli, averaged over right and left monaural conditions.

	P1	N1	P2	N2	P3
Left Hemis.	24.6	105.6	207.4	260.6	315.2
Right Hemis.	33.6	108.6	207.2	263.0	324.0
Verbal					
Left Hemis.	47.6	127.4	235.0	292.2	348.0
Nonverbal Right Hemis.	49.0	126.6	230.2	290.0	347.2

APPENDIX 8

Mean peak to peak amplitude in microvolts of AEPs from left and right hemispheres, averaged over Ss, in the verbal and nonverbal monaural right and monaural left conditions.

		P1-N1	N1-P2	P2-N2	N2-P3	
Right Monaural	Verbal	Left Hemis.	5.9	10.4	2.6	3.2
		Right Hemis.	5.6	8.7	3.0	3.6
	Nonverbal	Left Hemis.	5.3	10.8	4.9	3.9
		Right Hemis.	5.0	10.7	5.7	4.2
Left Monaural	Verbal	Left Hemis.	6.6	11.1	3.0	3.2
		Right Hemis.	4.9	10.2	3.4	2.6
	Nonverbal	Left Hemis.	6.1	10.8	3.6	3.0
		Right Hemis.	5.8	11.1	4.2	2.6