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# EVOKED POTENTIALS TO SYLLABLE PERCEPTION AND PRODUCTION

by

Susan Jean Schumacher

A Dissertation Submitted to
the Faculty of the Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

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Approved by

Robert M. Eason
Dissertation Adviser

## APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of the Graduate School at the University of North Carolina at Greensboro.

Dissertation Adviser Robert G. Eason

Committee Members R. L. Shull
M. Russell Harter
D. R. Soderquist
Ronald L. [illegible]

April 1, 1977
Date of Acceptance by Committee

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The purpose of this study was to devise and test a methodology to investigate cortical activity during speech perception and production that eliminates some of the confounding variables that have existed in previous research, such as the variability of stimuli employed across conditions and the role of muscle artifacts; and to clarify the role of auditory feedback in speech. Evoked potentials to the speech stimulus /ba/ were obtained while the subject was hearing and speaking /ba/ with and without immediate air conducted feedback, as well as while hearing /ba/ 0.6 sec. after each of these three conditions.

Twelve adults were determined to have dominant left hemispheres through a series of seven hemispheric dominance tests. None had a history of a hearing deficiency or indicated a hearing loss during the practice session.

Monopolar recordings were made from the left and right frontal areas corresponding to Broca's area on the left and the left and right temporoparietal areas posterior to the termination of the Sylvian fissure, with a linked earlobe reference.

Subjects were instructed to produce the syllable /ba/ 300 to 380 msec. in length and then indicate by depressing a switch if s/he thought the /ba/ was of correct duration. For the speaking conditions, /ba/ was returned to the ears

immediately through insulated headphones, followed by that same /ba/ being presented 0.6 sec. later, or the subject was given no immediate feedback and heard the /ba/ 0.6 sec. after speaking. The hearing condition consisted of the subject hearing a tape of the previously recorded speaking condition with immediate and delayed feedback in which s/he listened to the sound twice (0.6 sec. interstimulus interval) and then determined if the heard /ba/ was of the correct duration.

The potentials resulting from hearing /ba/ in all conditions at the temporoparietal locations were analyzed in a 4x3x2 ANOVA to investigate the four hearing conditions, the hemispheric differences, and the amplitude differences among the three component measures utilized ($P_1$-$N_1$, $N_1$-$P_2$, $P_2$-$N_2$). Hearing the /ba/ unpreceded by hearing or speaking produced greater amplitude potentials than hearing /ba/ following speaking or hearing ($p < .01$). When the delayed /ba/ was preceded by the spoken /ba/ without immediate feedback, a greater potential occurred than when the delayed /ba/ was preceded by hearing /ba/ only ($p < .05$). The effects of the speaking process on the potential to the delayed /ba/ apparently did not mask the effects of hearing on the delayed /ba/. The left hemisphere gave a significantly greater response to the delayed /ba/ for the $N_1$-$P_2$ component. $N_1$-$P_2$ and $P_2$-$N_2$ were more sensitive to changes in conditions than $P_1$-$N_1$.

Although statistical analysis was limited to the EPs occurring in the hearing conditions at the temporoparietal locations, some apparent trends were noted for potentials at the frontal locations and during speaking conditions. Results were discussed in terms of the importance of feedback for speech and related to existing literature on hemispheric differences during speech.

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# CHAPTER I

# INTRODUCTION

The study of one of man's most distinctive characteristics, speech, historically has been primarily confined to approaches that center around the evolution of the speech process, the investigation of various constituents of speech such as phonemes, morphemes and syllables, and how these components combine to form words and sentences. The neurological approach to understanding speech has been greatly limited by the fact that speech is uniquely human, and as such, can not be investigated by many of the traditional physiological approaches used with other animals, such as lesioning and ablation, brain stimulation, and single unit recording from various locations in the brain. Research with other animals having vocal communication systems has not thus far proven very beneficial in the understanding of neural processes underlying man's verbal functioning. Therefore, a great need exists for a technique that will enable one to investigate the neural mechanisms concerned with the receptive and expressive aspects of speech.

The one methodology that successfully avoids the limitations imposed by human subjects and appears to be a promision tool in the examination of cortical electrical activity during speech is the use of scalp-recorded evoked potentials (EPs) to visual and auditory stimuli. It has been found that by consistently examining the electrical activity of the brain, recorded as the electroencephalogram or EEG, as it repeatedly occurs following the presentation of a constant stimulus and by summating or averaging this time-locked activity, a distinct pattern of responding will emerge to that specific stimulus. This finding has led to the examination of EPs to a variety of stimuli, including many components of speech. If some of the problems that have plagued researchers in the past who have used speech stimuli, such as muscle artifacts, variability in the physical parameters of speech stimuli, and meaning, could be controlled, then the evoked potential would be a useful tool to examine the electrical correlates of speech perception and production. The present investigation has attempted to minimize previous problems with this approach while investigating the underlying cortial activity during speech. Evoked potentials during perception and production of a constant speech stimulus will be contrasted, and the role of muscular activity in these potentials will be determined. Also the contribution of feedback to the EP during and following speech will be examined for a stimulus that is both spoken and heard, in hopes of providing useful information about some of the speech disorders that appear to be related to feedback mechanisms, such as stuttering and aphasia. The role of individual differences will also be discussed.

## Historical Background

Since Richard Caton's (1875) demonstration that electrical activity in the brain is altered by sensory input, researchers have used this technique to investigate cortical processes as a function of external stimulation. Hans Berger in 1929 and Jasper and Carmichael in 1935 began recording EEGs from the human scalp, and later Davis (1939) and Adrian (1941) respectively produced evoked responses to auditory and visual stimuli that could be distinguished from the ongoing activity of the EEG. However, the difficulty of detecting the small amplitude time-locked activity on the scalp in the presence of the spontaneous EEG created a need for more efficient recording techniques. In 1943, Galambos and Davis superimposed several traces on a cathode ray oscilloscope. Dawson (1947, 1951) modified and developed this technique from simple superposition of traces to summating time-locked activity to a stimulus so that the activity resulting from the stimulus presentation would be additive and the random activity would average to a horizontal line. Other techniques were developed in the 1950's (Buller & Styles, 1959; Calvet & Scherrer, 1955; Rémond, 1956), and with the advent of the commercially available digital computer in the early 1960's, wide-spread experimentation using evoked potentials began.

Interest in the use of EEGs and EPs to investigate speech dates back to the late 1930's when Knott (1938, 1939) and Travis and Knott (1936, 1937a, 1937b) investigated brain potentials under a wide variety of stimulus conditions. Travis and Knott (1937b) determined the time it took the EEG to return to the prestimulus value following the presentation of words, nonsense words, and blank cards and concluded that meaningful stimuli take more time to process. Knott (1938) found that the frequency of EEG activity increased during silent and overt reading relative to rest, and was highest during overt reading.

Much of the early EEG work in the area of speech dealt with the problem of stuttering (Douglass, 1943; Freestone, 1942a, 1942b; Knott & Tjossem, 1943; Lindsley, 1940; Rheinberger, Karlin, & Berman, 1943; Scarborough, 1943; Travis & Knott, 1936). Travis & Knott (1937a) discovered that stutterers had smaller hemispheric differences with regard to similarity of brain potentials and more in-phase relationships than normals during speech. However, they also found that a smaller out-of-phase relationship was correlated with less severe stuttering. These findings resulted in a number of studies to further examine the relationship between laterality and stuttering. Rheinberger et al. (1943) reported that stutterers have slightly less laterality than nonstutterers. Recording from the right and left occipital regions, Lindsley (1940) found that stutterers resemble left-handed and ambidextrous normals with regard to alpha activity. Knott and Tjossem (1943), using left and right occipital and motor electrodes, supported the theory that stutterers as a group have alpha present in the left occipital lobe area more often than normals. In accordance with Jasper (1937), they construed this to mean that the left hemisphere of stutterers has less excitability than the right or than the left hemisphere of normals, as an increase in alpha is correlated with a decrease in cortical excitability. Also in line with this interpretation is the work of Freestone (1942a, 1942b) that suggested that stutterers have reduced consciousness with regard to normals. In his studies comparing stutterers to normals using a variety of electrode placements, stutterers were found to have larger EEGs than normals, more alpha similarity between hemispheres than normals, and larger EEGs during stuttered speech versus normal speech or silence. This was interpreted as meaning that stutterers are in a relative state of reduced consciousness due to lack of heightened foci of cerebral activity and a loss of mental specificity.

Most of these early studies lacked sufficient controls, but the studies by Knott were probably the most sophisticated in that they used a variety of electrode placements and monitored resting EEG. A later replication of some of Knott's work using more refined techniques and equipment (Pepin, Kibbee, & Wells, 1952) indicated that Knott's results might better be interpreted as a function of muscle artifacts associated with the complex sensori-motor events of overt reading. Interest in this line of research with stutterers decreased, probably due to insensitivity of existing recording techniques and the advancement of other theories of stuttering not involving laterality, and those studies that were conducted often did not report methods or findings in enough detail to determine the true contribution of the work.

## Rationale for Use of EPs

What the EP reflects. In order to justify the use of EEGs and EPs in the study of speech, it is necessary to briefly examine what the evoked response reflects in terms of underlying neural activity, and how this is related to external stimulation and specifically, speech stimuli. Bremer (1961) concluded that EPs reflect the integrated response of large numbers of cortical units recorded in a volume conductor, and that these units respond successively through the various layers of neocortical mantle. The unit responses are relatively slow postsynaptic potentials. Creutzfeldt, Watanabe and Lux (1966) stated that EPs are composed of compound excitatory postsynaptic potentials (EPSPs) and inhibitory postsynaptic potentials (IPSPs) of cortical cells as well as of synchronous afferent and efferent fiber activity.

Activity of individual cells does seem to be related to certain spontaneous and evoked scalp-recorded potentials (Vaughan, 1969). The work of Fox (1970) and Fox and O'Brien (1965) has consistently shown that the probability of firing for any one cell closely corresponds to the averaged waveform of the evoked potential recorded from the same microelectrode. They concluded that the potential sources contributing to the EP were either directly related to or reflected in the firing of single cells, and a knowledge of the waveform of the EP permits prediction of the firing pattern of single cells.

Regan (1972) has summarized a number of hypotheses concerning the various possible relationships between gross cortical slow waves and underlying cellular activity. The first and least popular is that brief axon spikes (1-2 msec.) are the subunits of gross surface slow waves. The second assumes that small groups of cortical cells have the property of generating long spikes of 10 to 100 msec. duration, and these prolonged spikes are summated over many neurons to form gross slow surface waves. The third hypothesis asserts there are certain slow cellular potentials that, when statistically summated, can lead directly to surface slow waves without assuming temporal summation. The final hypothesis is an elaboration of the Creutzfeldt model mentioned earlier involving graded dendritic postsynaptic potentials and assumes that the major contributor to the EEG is the synchronous firing of the pyramidal cells which are oriented at right angles to the surface of the cortex. Regan also stresses that the observed differences in gross cortical slow waves and individual neuron activity may be a function of whether the waves are evoked potentials or "spontaneous" EEGs, whether the animal is anesthetized or not and other similar physiological state or preparation differences, and the contribution of surrounding glial cells.

Scalp recorded activity has also been related to cortical surface activity (Goff, Matsumiya, Allison, & Goff, 1969), with amplitude attenuation and other differences a result of the effects of the tissue and fluid that overlie the cortex, scalp muscle movement, the choice of extracranial reference electrode position, the distribution of the generator cells over the cortex, and the presence of components generated by primary and nonprimary cortex in scalp recordings. However, there is evidence that these influences are minimal, with studies showing similar recordings from scalp and cortex for both visual EPs (Corletto, Gentilomo, Rosadini, Rossi, & Zattoni, 1967) and somatosensory EPs (Domino, Matsuoka, Waltz, & Cooper, 1964).

Electrical activity recorded from the scalp, cortex, and single units has been shown to be responsive to changes in external stimulation. Moushegian and Rupert (1970) produced diverse responding in the ventral cochlear nucleus of the kangaroo rat in response to low frequency tones, and Moushegian, Rupert, and Whitcomb (1964) illustrated the differential responding of units in the left accessory nucleus of the cat to frequency and intensity differences in a binaural tone. Moushegian has also shown that scalp-recorded early responses in man are unique to different stimulus frequencies (Moushegian, Rupert, & Stillman, 1973). In addition, Lamb and Graham (1967) and Butler, Keidel, and Spreng (1969) have examined the scalp-recorded evoked potentials in humans as a function of stimulus parameters and reported increased amplitude to increases in stimulus intensity.

In view of the above findings concerning the relationships between single cells, cortical activity, and scalp-recorded potentials and their response characteristics to external stimuli, it is strongly suggested that the scalp-recorded evoked potential is a true reflection of underlying variations in electrical activity of cortical and subcortical cells resulting from changes in various parameters of simple and complex external stimuli.

## Background Physiological Studies

There are a number of lines of evidence that indicate that not only are evoked potentials a representation of cortical activity related to stimulus changes, but that this activity may differentially change in various brain regions as a function of the sense modality being stimulated. Three sources of evidence will be briefly examined, focusing on those brain areas thought to be related to speech perception and production: anatomical evidence, lesion studies and dichotic listening findings.

The neurosurgical and electrical stimulation techniques of Wilder Penfield provided a relatively complete map of the cortical areas involved in speech (Penfield & Rasmussen, 1950; Penfield & Roberts, 1959). He identified the area around the Rolandic fissure in both hemispheres as being important in lip, tongue, and jaw movement as well as other sensori-motor functions. The superior intermediate frontal area within the longitudinal fissure (anterior to the precentral motor leg area) in both hemispheres is related to rhythmic vocalization and word production. Penfield identified three areas found only in the speech dominant hemisphere that were important for speech perception or production. In the frontal lobe, anterior to the precentral gyrus and above the fissure of Sylvius, roughly corresponding to Brodmann's area 44 (Brodmann, 1914), is Broca's area, important in counting, naming, word substitution, and expressive functions. In the parietal lobe just above the fissure of Sylvius and posterior to the sensory representation of the lips and mouth (lower half of area 40 of Brodmann) is a region involved in word substitution as well as understanding speech. In the posterior part of the temporal lobe including the angular gyrus and the first, second, and third temporal convolutions is a third speech area, contributing to reception, meaning, and repetition, and producing aphasia and word confusion when damaged.

Following Penfield's early mapping, a second approach developed for the anatomical investigation of structures that might be related to speech. In 1962, von Bonin discovered that in the left hemisphere the Sylvian fissure was longer, the insula were longer and higher, the cingulate sulcus doubled more frequently, and the left hemisphere had a greater specific gravity. Witelson and Pallie (1973) found that both adult and infant brains were larger in the left planum temporale (part of the temporal speech cortex), as did Geschwind and Levitsky (1968) and Geschwind (1970). Geschwind also found that the area behind Heschl's gyrus (Wernicke's area) is significantly larger in the left hemisphere in 65% of the 100 brains examined postmortem but is larger in the right only 11% of the time. LeMay and Culebras (1972) used carotid arteriography to identify larger left parietal operculua in right-handed subjects and discussed the implications of this for speech. McRae, Branch, and Milner (1968) found that, on the basis of pneumoencephalography and ventriculograms, the left occipital horn of the lateral ventricle was longer in 57% of unselected neurological patients, the right longer in 13%, and no difference in the remaining 30%. In right-handed patients with unequal horns, the left horn is five times more likely to be longer than the right. Since the occipital horn is part of the lateral ventricle which underlies the Sylvian fissure and the temporoparietal area, and since the Sylvian fissure, Wernicke's area, and the planum temporale are all larger in the left hemisphere for the majority of people, it would not be surprising if many other left hemisphere areas were found to be larger, even if they are not related specifically to speech. Further anatomical studies are necessary that would include Broca's area as well as some nonspeech structures in the left hemisphere to discover if the anatomical hemispheric differences are confined to speech-related areas. However, it must be acknowledged that speech-related anatomical differences do exist and these differences are correlated, although not perfectly, with handedness.

Brenda Milner soon followed Penfield's brilliant contribution concerning the delimitation of speech in the brain with her own invaluable contribution to the localization of speech by examining patients with lesions, primarily in the temporal and parietal areas. She found that lesions in the dominant temporal lobe will produce disturbances in verbal recall, verbal memory, and verbal learning, while lesions in the corresponding nondominant hemispheric area result in no verbal deficits, but difficulties with tonal memory and pictoral identification. Removal of the dominant frontal area anterior to Broca's area causes a decrease in spontaneous speech, which suggests that generalized verbal control may be fairly widespread in the dominant hemisphere (Milner, 1962, 1965, 1967, 1969). Newcombe (1974) supported Milner's findings of expressive language disturbances in patients with left temporal lobe lesions.

Sperry and Gazzaniga (Gazzaniga & Sperry, 1967; Sperry & Gazzaniga, 1967), after performing a complete midline section of the cerebral commissures and conducting extensive language tests on six patients, concluded that there is some comprehension of the spoken and written word in the minor hemisphere.

Semmes (1968) and Critchley (1962) cite additional evidence to support this conclusion. Butler and Norrsell (1968) even suggest that the minor hemisphere in normal subjects may be inhibited by the major one, which prevents it from initiating speech. Hécaen (1962) examined patients primarily with parietal or temporoparietal lesions and discussed the role of these left hemisphere lesions in repetition, perseveration, alexia, and verbal amnesia.

A number of investigators have stressed the importance of the ear stimulated, regardless of the location of the lesion. Hirsh (1967) reported that unilateral lesions superior to the cochlear nucleus interfere with understanding speech presented through the contralateral ear. Milner (1962) also supported this by finding that, after temporal lobectomy, there is selective impairment in the discrimination of stimuli to the contralateral ear, although the right ear was more efficient when speech was located in the left hemisphere, and the left ear was more efficient when speech was located in the right hemisphere. She, along with Calearo and Antonelli (1963) and Chase (1967), showed a deficit for words presented to the ear contralateral to the temporal lobe lesion.

Milner (Milner, Taylor, & Sperry, 1968) also concluded that there is a difference in the way the auditory system reacts to stimuli presented monaurally or diotically as compared to dichotic presentation in which a different stimulus is presented simultaneously to each ear. There is a large body of uniform evidence showing a strong right ear superiority in perception of all types of dichotically presented verbal material, with the exception of isolated vowels (Broadbent & Gregory, 1964; Bryden, 1970; Dirks, 1964; Haaland, 1974; Kimura, 1967, 1973; Satz, 1968; Studdert-Kennedy & Shankweiler, 1970), and a left ear superiority for dichotically presented melodies and clicks (Broadbent & Gregory, 1964; Kimura, 1964, 1967, 1973). This right ear superiority for verbal stimuli develops at an early age, suggesting that a left-hemisphere predominance for speech functions may exist in children as young as age four (Kimura, 1967). Because dichotic auditory stimulation involves the contralateral and ipsilateral auditory pathways to the temporal lobes of the cerebral cortex, it can be inferred from dichotic studies that the left temporal lobe and its underlying pathways play an important role in the perception of speech.

On the basis of the above three categories of studies investigating speech-related areas of the brain, it can be readily concluded that the left hemisphere seems to play a larger part in verbal processing in most subjects, and that different language functions are located in different areas of the brain, with the major regions being Broca's area in the frontal lobe, the temporal lobe, and the temporoparietal area.

## Auditory Evoked Potentials and Speech Perception

Evoked potentials have been used to examine cortical activity during the perception of linguistic materials. One technique has been to compare evoked potentials to a linguistic stimulus with those to a nonlinguistic stimulus. However, one of the obvious drawbacks to this approach is that the stimuli have other differing characteristics than just their linguistic quality that could account for differences in the resulting potentials. Molfese, Freeman, and Palermo (1975) used syllables, words, and two mechanically produced sounds, a piano note and a noise burst, without attempting to control for stimulus differences and reported larger amplitude responses in the left hemisphere of infants to the speech stimuli and greater right hemisphere responses to the nonspeech stimuli. Greenberg and Graham (1970) also used speech stimuli and piano notes in a learning paradigm and supported Molfese by finding that EP amplitude was greater over the left hemisphere for speech stimuli. Using a technique of Horri's (Horri, House, & Hughes, 1971) which involved shaping noise stimuli so that the rise-decay times and instantaneous amplitude variations exactly matched each linguistic stimulus, Ratliff and Greenberg (1972) attempted to eliminate some of the possible confounding in other studies due to uncontrolled stimulus parameters. Although they found the usual differences in potentials to linguistic versus nonlinguistic stimuli, there were no hemispheric asymmetries evident.

Other investigators have compared cortical electrical activity using verbal stimuli and nonsense syllables or other verbal stimuli. Burian, Gestring, and Haider (1969a, 1969b) matched meaningful words to nonsense equivalents in loudness, duration, and frequency distribution in a contingent negative variation (CNV) paradigm to establish an objective criterion of word discrimination based upon understood meaning. Wood (Wood, Goff, & Day, 1971) employed the synthetically generated syllables /ba/ and /da/, which differ by only one parameter, the direction and extent of the second and third formant transition. They provided 10 right-handed adults with two auditory identification tasks, only one of which required analysis of linguistic parameters. They found that evoked potentials for the two tasks were different over the left hemisphere, but identical over the right. They concluded that different neural events occurred in the left hemisphere during these tasks that were not related to differences in the acoustic signal. Morrell and Salamy (1971), using different nonsense word stimuli, found no systematic differences in waveform for the different speech stimuli and obtained greater amplitude potentials over the left hemisphere, especially for the temporoparietal placement.

A different approach was taken by Teyler, Roemer, Harrison, and Thompson (1973) who found different waveforms to different meanings of the same word and larger amplitude responses to the verbal stimuli in the left hemisphere. These results were similar to those of Brown, Marsh, and Smith (1973) who reported more pronounced differences in the left hemisphere to different contextual meanings of the same word.

Except for the Ratliff and Greenberg article, all of the evidence seems to indicate a major role for the left hemisphere in verbal perceptual processing. This probably develops at an even earlier age than was suspected on the basis of the dichotic studies, as indicated by Molfese (in press), who found speech lateralization for preverbal infants. The lack of asymmetry in the Ratliff & Greenberg study might be explained by differing techniques of data analysis. Possibly the features controlled in the matched noise stimuli they presented were some of the relevant speech features usually detected by the left hemisphere, or these controlled features may have interacted with those features more usually thought to be relevant features for identification of speech, such as formant transitions and rate of frequency or intensity change (Abbs & Sussman, 1971). A third possibility is that in some way the features matched were those that the right hemisphere could also identify, and the role of the right hemisphere was simply more evident in this design.

Another conclusion from the above results is that whatever are considered to be "linguistic" features by the brain are present not just in words, but also in the more elemental aspects of speech such as syllables and phonemes. Although these particular features remain unidentified at this time, studies have shown that the first formant is important for distinguishing voiced from unvoiced stop consonants, and the second formant transition seems to be one of the major cues for identifying consonants (Liberman et al., 1967). Voice-onset time, frequency, intensity, and rate of frequency and intensity change have also been suggested as likely candidates for feature detection (Abbs & Sussman, 1971; Eimas, Siqueland, Jusczyk, & Vigorito, 1970). It is evident that there is a need for more research along the lines of that produced by the Haskins Laboratory researchers, such as Studdert-Kennedy, Shankweiler, and Liberman. This would manipulate what seem to be the basic parameters of speech, but also examine the evoked potential resulting from these various stimuli.

### Auditory Evoked Potentials and Speech Production

The evoked potential literature concerning the investigation of cortical activity during speech production is less complete than that for speech perception, partially because of the complicating factor of muscle artifacts which will be discussed later. The literature also includes studies which examine electrical activity preceding speech, most of which show hemispheric asymmetry regardless of the particular potential examined (Berietschafts potential, CNV, or general preliminary electrical activity), the method used, and the specific set of problems generated by that method (Low & Fox, in press; Grözinger, Kornhuber, & Kriebel, 1975; Ertl & Schafer, 1967; McAdam & Whitaker, 1971).

Earlier studies of cortical potential during speech production indicated that there were potentials that seemed to be of cerebral origin which occurred during speech vocalization; also that there was evidence of hemispheric asymmetry over some electrode locations, primarily Rolandic and temporoparietal (McAdam & Whitaker, 1971; Morrell & Huntington, 1972). However, Grabow and Elliott (1973, 1974) presented and supported several strong arguments to indicate that the asymmetry may be due to contamination by the glossokinetic potential which has been described by Klass and Bickford (1960). Little work to clarify this matter has been done since their findings, probably because of insufficient methodologies to control the confounding sources. Therefore, a methodology or design that would enable one to examine cortical activity while either eliminating or holding constant the possible interfering muscular potentials would greatly advance knowledge of cerebral activity during the speaking process.

## Methodological Issues

### Requirements for EP studies.

Much of the evoked potential research in the area of speech has been seriously criticized for lack of adequate controls, incomplete information, doubtful cortical origin of potentials, and insufficient electrode locations. There are a number of important criteria that should be considered when either designing or evaluating research in this area. The exact nature of the stimuli used must be detailed, including the mode of presentation, the intensity, duration, and other physical parameters, the rate and the order of presentation, and the nature of the control stimuli that have been utilized. The exact locations of all EEG and electromyogram (EMG) electrodes should be defined, relevant areas for the particular stimulus modality employed should be sampled, and the type of recording, monopolar or bipolar, should be specified.

It is extremely important to ascertain that the response obtained is a function of the experimental manipulation. This can be achieved by recording an averaged EP to each stimulus a number of times, preferably counterbalanced across conditions. Upon superposition of these EPs, the number, direction, and location of the various components should be approximately the same. It is advisable to determine that the response obtained is a direct result of the specific stimulus conditions, and not simply a generalized arousal response to a change in any type of stimulation. The waveform of the replications should be distinctly different from the waveform of replications of a different stimulus condition or of an average of ongoing EEG activity not time-locked to stimulus presentation. The different stimulus conditions may consist of a "control" stimulus in a different modality, a simple stimulus such as a click, or a stimulus similar to the original stimulus in which systematic changes are made to investigate the importance of the various parameters of the test stimulus. Counterbalancing conditions also aids in eliminating habituation and fatigue effects.

McGuigan (1970) has noted that it is crucial to avoid contamination of an evoked response by other covert processes. Protection against such contamination requires the simultaneous sampling of responses from various bodily regions; i.e., obtaining EMGs from the lips, tongue, neck, or wrist that are time-locked to the stimulus presentation. Scrutinizing such records would aid in revealing the possible contribution of muscular artifacts.

### Electrode Location

Because of the anatomical hemispheric differences previously discussed and the suggestion of Shagass (1972) that brain-to-scalp relationships may not be constant, the question of electrode placement must be considered in detail, in order to hypothesize generator sites of various potentials. Scalp-recorded potentials from corresponding external hemispheric locations may reflect different distances from generator regions due to cortical size differences.

Related to anatomical structure is the question of postulated dipole orientation with regard to cortical surface. Vaughan (1969) and Vaughan and Ritter (1970) found that the 200 msec. component of auditory evoked responses recorded above a line formed by the plane of the Sylvian fissure was opposite in polarity to that component recorded below the line. Vaughan offered an explanatory model involving dipole orientation parallel to the scalp and located in the primary auditory cortex. Jeffreys (1972), Jeffreys and Axford (1972), and Halliday and Michael (1970) have reported similar findings with regard to vision. Halliday (1972) later proposed that the visual cortex contains dipoles oriented in a variety of directions, due to its complex structure. Regan (1972) extended this hypothesis by further postulating that dipoles arranged along a concave surface result in greater electrical field strength at some specific distance than similar dipoles arranged along a flat sheet. Dipoles arranged along a convex surface will effect divergence of equipotentials and produce a weaker electrical field at that same distance.

That evoked potentials may reflect electrical activity of different generator sites is supported by research that compares potentials from a number of scalp locations. Gastaut, Régis, Lyagoubi, Mano, and Simon (1967) and Vaughan (1969) used visual, auditory, and somatosensory stimulation while recording over a variety of locations. Both studies found maximum potentials at the vertex for auditory stimulation, at the Rolandic site for somatosensory stimulation, and over the occipital location for visual stimulation.

Studies using stimulation in only one sensory modality also imply multiple generator sites. Morrell and Salamy (1971), recording from frontal, Rolandic, and temporoparietal leads in both hemispheres to natural speech stimuli, obtained differential responding and suggested that these electrophysiological measures may be sensitive indicators of hemispheric specialization of function. Visual evoked potentials were recorded from occipital, parietal, temporal, and frontal locations following stimulation of the fovea by a 10 msec. flash by Groves and Eason (1967). A significantly larger response occurred in the occipital region. These findings strongly suggest that specialized regions of the brain may greatly contribute to the evoked activity recorded at different electrode sites.

There are methodological variations related to electrode placement other than location that may explain differential findings of similar studies. For example, monopolar and bipolar recordings provide different kinds of information. Bipolar recording will detect the smaller of two potential sources if the larger contributor is constant at both recording sites and, therefore, might be considered more sensitive. However, the bipolar technique does not provide information about the absolute value of the potential (Regan, 1972). Goff et al. (1969) state that, although bipolar recording may aid in localizing the source of a component by phase reversal, it produces more variable waveforms and, in general, adds to the confusion and hinders averaged evoked potential research. In the discussion section following this article, Donchin points out that bipolar recording adds nothing, as one can retrieve the bipolar potential by finding the difference between two monopolar recordings. Bergamini and Bergamasco (1967) compromise, suggesting the use of both techniques and implying that the two give similar results. The major problem with monopolar recording is the difficulty in finding an electrically indifferent reference point which is at absolute zero potential and shows no consistent time-locked activity with respect to other sites (Regan, 1972). Some investigators have concluded that the best general reference location is the earlobe contralateral to the stimulus (Goff et al., 1969; Regan, 1972). It should be remembered that monopolar recording really consists of bipolar recording using a common reference electrode for comparison.

In general then, electrode location should be very carefully considered, with pilot mapping studies conducted to determine the best locations for recording potentials to the particular stimuli employed. Because of anatomical factors, dipole orientation, and multiple generator sites, examination of a variety of placements is desirable. An additional reason for the utilization of multiple locations with monopolar techniques, if feasible, is that it gives the option of examining bipolar potentials obtained by derivation.

### Handedness and Hemispheric Dominance

Most of the physiological studies of speech perception and production have dealt with the issue of hemispheric asymmetry, which leads to the question of hemispheric dominance for speech. The most typical approach is to infer that the left hemisphere is dominant for right-handed subjects and contains the primary speech functions. The opposite inference is made for left handers. However, this is not a valid assumption (Davis & Wada, 1974; Penfield & Roberts, 1959). Although the exact percentages vary, there is general agreement that 90% or more of right-handed subjects have speech located in the left hemisphere, while 30%-60% of left-handers also have speech in the left hemisphere (Branch, Milner, & Rasmussen, 1964; Gott & Boyarsky, 1972; Penfield & Roberts, 1959; Rossi & Rosadini, 1967). The most reliable method of determining the dominant hemisphere and the location of speech is the sodium amytal test (Wada & Rasmussen, 1960) in which sodium amytal is injected into the carotid artery. The impairment of various functions controlled by the hemisphere contralateral to the injection is then observed. This technique is available mainly for clinical populations, and its use can not be justified for general research because of the unpleasant side effects and the risk involved for the patient. Although there are a number of other candidates for cerebral dominance tests, such as the Dichotic Listening Test of Broadbent (1954) and the analysis of the alpha rhythm as conducted by Oller-Daurella and Masó-Subirana (1965) and Aird and Gastaut (1959), probably the most practical way to obtain an independent determination of cerebral dominance is some sort of motor dominance test involving the hands, eyes, feet, ears, legs, etc. A variety of tests of this nature have been constructed, such as the Harris Tests of Lateral Dominance (1974), a battery by Subirana (1968), and those mentioned by Studdert-

Kennedy and Shankweiler (1972). As it is thought that these tests correlate more highly with hemispheric dominance than the simple handedness criterion, which can be easily influenced by environmental factors (Hécaen & De Ajuriaguerra, 1964), greater confidence could be placed in correlations of evoked potential asymmetries and cerebral dominance as measured by these batteries.

Muscle Artifacts

A previously mentioned problem that must be controlled in evoked potential research, especially work concerned with speech production, is that of contamination by muscular artifacts. Teece (1970), after reviewing literature concerning scalp and neck muscle effects, pupillary changes, and eye movements, concluded that all of these can affect the EP under certain conditions, although the effect of the scalp musculature seems to be minimal and confined to the first 50 msec. Eye movements and reaction time responses have also been the concern of others (Buchsbaum & Fedio, 1969; Ellis, 1972; Grabow & Elliott, 1974; McAdam & Whitaker, 1971; Morrell & Salamy, 1971; Teyler et al., 1973).

Even more critical for speech studies is contamination by lip and tongue movement. Morrell and Huntington (1971) criticized McAdam and Whitaker's 1971 study for the contaminating effects of lip muscle activity and reported data showing no consistent hemispheric differences when this artifact is controlled. Schafer (1967) and Ertl and Schafer

(1967), investigating cortical activity preceding speech, attempted to control for muscle artifacts, but later questioned their own findings (Ertl & Schafer, 1969) by showing that simultaneous recording from upper lip musculature produced a similar low frequency waveform. Morrell and Huntington (1972) presented evidence to suggest that, in spite of the difficulties in separating muscle artifacts from cerebral potentials, there seem to be cortical potentials time-locked to speech production that are of cerebral origin.

More recently, a study by Grabow and Elliott (1974) stressed the distorting effect of the glossokinetic potential on the EEG during word production or tongue movements while the mouth is closed. They produced hemispheric asymmetries in the EEG during word production by directing the tongue toward either the left or right side of the mouth. On this basis they criticized McAdam and Whitaker's (1971) study, which had attempted to demonstrate the existence of bilaterally symmetrical potentials, which were at a maximum over Broca's area, to spontaneously produced polysyllabic words. They could report no consistent hemispheric asymmetries, and stated that it is premature to conclude that electroencephalographic hemispheric asymmetries are dependent on lateralized language functions.

Two other kinds of artifacts of concern to speech researchers are those arising from differential feedback from vocal musculature and bone conduction following each phoneme and covert movements produced when anticipating or hearing speech, as can be predicted by the motor theory of speech perception. Unless speech stimuli are composed of identical phonemes, each produced syllable will be accompanied by its own distinct feedback which is probably utilized in saying the next syllable. However, this feedback may be neurologically encoded in such a manner that it will be reflected in the ongoing evoked potential to uttered speech. Also, it has been suggested that bone conducted sound will influence the averaged evoked auditory potential (Liebman & Graham, 1967). Although the current motor theories do not require the assumption that speech is perceived only by the minature duplication of those muscular movements used in the actual voicing of those speech patterns, activation is still implied somewhere along the "neuromotor system". This neuromotor system is conceived of as being linked to incoming neural patterns from the ear as well as those muscles actually involved in the speech process (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman, Harris, Eimas, Lisker, & Bastain, 1961; Liberman, 1972). It is entirely possible that the electrical activity involved, regardless of the level of involvement, is reflected in the evoked potential to the heard speech sound.

In view of the multitudinous possible artifacts influencing the evoked potential (speech-related potentials in particular), any methods of monitoring, eliminating, or holding constant the muscular movements that may be simultaneously occurring will increase confidence in the results of studies of cortical activity during speech.

## Control of Stimulus Parameters

Because of the possible contamination by muscle artifacts, it seems imperative that the stimulus parameters in speech studies be manipulated in a known fashion. One way of achieving this is by holding constant the stimulus presented, as was done by Brown et al. (1973), who found different waveforms for different contextual meanings of the same word at two electrode sites in each hemisphere. Wood et al. (1971), used a slightly different approach, manipulating only one parameter of the stimulus and holding the remainder constant.

There are a number of basic characteristics of the acoustic stimulus which affect the resulting evoked response. Lenhardt (1973) and Lowell (1967) obtained larger auditory evoked responses for low frequency stimuli, although there is some evidence to the contrary (Liebman & Graham, 1967; McCandless & Lentz, 1968). The effects of intensity upon the auditory evoked response have been much more reliable. As intensity increases, the amplitude of the response, especially the $N_1$-$P_2$ component, increases in a linear fashion until at approximately 70 dB sound pressure level (SPL) it asymptotes, and further intensity increases produce little change in amplitude (Antinoro, Skinner, & Jones, 1969; Beagley & Kellogg, 1970; Beagley & Knight, 1967; Butler et al., 1969;

Lamb & Graham, 1967; Lindsey, 1971; Madell & Goldstein, 1972; McCandless & Lentz, 1968; Moore & Rose, 1969; Picton, Goodman, & Bryce, 1970; Spoor, Timmer, & Odenthal, 1969; Vaughan & Hull, 1965). In addition, as intensity of stimulation increases, the latency, especially of earlier components, decreases (Beagley & Knight, 1967; Butler et al., 1969; Lamb & Graham, 1967; Lindsey, 1971; McCandless & Lentz, 1968; Moore & Rose, 1969; Nelson & Lassman, 1973; Spoor et al., 1969). Longer rise-times of auditory signals have resulted in smaller amplitude responses for $N_1$-$P_2$ with longer latencies (Lamb & Graham, 1967; Lindsey, 1971; Skinner & Antinoro, 1971). The relationship between stimulus duration and evoked responses is not as well-defined (Muller, 1973; Picton et al., 1970; Skinner & Antinoro, 1971; Taurozzi, 1973), but increases in the interstimulus interval result in increased amplitude in the EP (McCandless & Lentz, 1968; Nelson & Lassman, 1968). With this many variables of a simple auditory stimulus affecting the evoked response, it is certain that a complex stimulus like a word will result in a complicated interaction of these effects and, therefore, should be manipulated in a known and controlled fashion.

Another dimension of the verbal stimulus to be considered is meaning. Studies examining responses to the physical parameters of a stimulus may report differences in responding that are actually due to differences in information content, intelligibility, affect, or attention, and not to the intentionally manipulated characteristics of the stimulus. Only a limited amount of the research on meaning and its related components has attempted to control additional types of variation in the stimulus. One of the best techniques for investigation is to endow the same physical stimulus with different meanings and provide different physical stimuli with the same meaning as did Sandler and Schwartz (1971). In this type of study, it is important that the experimenter predetermine the meaning of his stimuli for each subject to control for differential experience with the stimuli.

Most of the studies of meaning have manipulated a stimulus in the visual modality, such as the Sandler and Schwartz study that used ambiguous figures and mirror images. However, Lenhardt (1973) conditioned pleasant, neutral, and unpleasant verbal stimuli to pure tones and found an effect for the emotionality variable as well as for the frequency of the tone employed. A number of variables can influence the results of this type of study, such as attention (Näätänen, 1967, 1970), arousal, (Eason, Harter, & White, 1969), and relevance and difficulty of the task (Donchin & Cohen, 1967; Gross, Begleiter, Tobin, & Kissin, 1965; McKee, Humphrey, & McAdam, 1973).

## Delayed Auditory Feedback

In order to determine the role of feedback in speech production, investigators have attempted to alter both bone conducted and air conducted feedback resulting from the speaking process. Techniques used include masking air conducted feedback with white noise, accelerating or delaying air conducted feedback, and masking bone conduction by the use of a bone vibrator. The effects of delaying auditory feedback on continuous speech production have been widely documented (Atkinson, 1953; Black, 1951; Fairbanks, 1955; Fairbanks & Guttman, 1958; Lee, 1951; Neelley, 1961; Roehrig, 1965; Tiffany & Hanley, 1956; Webster, Schumacher, & Lubker, 1970; Yates, 1963). The typical investigation involves the overt reading of a passage while experiencing delayed auditory feedback (DAF) through insulated headphones so that the subject hears his/her speaking voice a fraction of a second later than s/he normally would. Then some parameter of DAF is manipulated, such as intensity, duration, or delay interval. These studies all indicate that air conducted feedback plays an extremely important role in continuous speech production.

However, there is another way that DAF can be used to investigate speech that does not require continuous vocalization on the part of the subject. This permits the examination of cortical activity during and following the production of simple speech sounds such as phonemes or syllables. If the subject produces isolated syllables at a slow rate while experiencing DAF, the typical effects of increased voice intensity, decreased duration, and increased articulation errors usually associated with DAF presentation do not occur. This procedure allows a subject to speak a syllable and hear, through air conducted feedback, that same sound just produced but delayed by a fraction of a second until the bone conducted and kinesthetic feedback have occurred. In addition, the subject may or may not receive immediate air conducted feedback through the headphones while s/he is speaking. In this manner the stimulus spoken and later heard remains constant with regard to air conduction for each trial. Also, the entire DAF tape, which contains both spoken and heard sounds, may be replayed to the subject so that s/he may hear the same speech stimulus twice, eliminating production of the sound which results in contamination of the cortical potentials by the speaking process. In this manner the effects of the speaking process, including muscle movement and muscular and bone conducted feedback, may be separated from the effects of hearing that sound through air conduction.

As this technique involves presenting a pair of stimuli in rapid succession, a decrease in the amplitude of the EP to the second stimulus can be predicted on the basis of the habituation literature. There is general agreement that the auditory evoked response decreases as a result of repeated stimulation (Cook, Ellinwood, & Wilson, 1968; Fruhstorfer, Soveri, & Jarvilehto, 1970; Ritter, Vaughan, & Costa, 1968), but what causes this decrease is still a matter open to question. This decrease is most commonly labelled habituation (Dorman & Hoffman, 1973; Fruhstorfer, 1971; Fruhstorfer et al., 1970), although it has also been attributed to attention (Gross et al., 1965) and refractoriness in the auditory system (Ritter et al., 1968; Webster, 1971).

The evidence that the evoked potential reflects the underlying cortical activity of individual cells as well as cortical surface activity, that it is responsive to changes in external stimulation, and that it can be used with human subjects makes it an excellent measure to reflect the changes occurring in the brain as a function of speech. Because of the existing physiological evidence on the localization of speech activity in the dominant hemisphere in the vicinity of Broca's area and the temporoparietal region, it would seem that these areas should, within the limitations previously discussed, provide electrophysiological correlates of speech perception and production. The use of a constant simple auditory stimulus across conditions such as a syllable, aids in controlling the physical parameters of the stimulus and eliminates the variable of meaning which often confounds studies using linguistic stimuli. The use of DAF with individual speech stimuli can shed light on the difference in cortical activity during speaking and hearing the same stimulus and, coupled with simultaneous recording of EMGs, the role of muscular artifacts can be at least partially assessed.

## Purpose

The general purpose of this study was to devise and test a methodology to investigate cortical activity during speech reception and expression that controls as many of the variables discussed in this chapter as possible within the limitations of the available equipment. EPs were contrasted during the perception and production of a constant speech stimulus. In view of the undetermined effects on the EP of differential feedback from producing different speech sounds and the possible role of neuromotor pathways in speech perception, as proposed by Liberman (Liberman et al., 1967), a single syllable was chosen as stimulus for all conditions. The simplicity of a syllable reduces muscular movement while speaking and controls contamination by meaning, which has been shown to affect EPs. Not only were the potentials during speaking and hearing this syllable contrasted, but also the auditory evoked responses to the same syllable presented 0.6 sec. later were examined as a function of speaking and hearing conditions to attempt to assess the role of feedback in speech. The role of air conducted feedback in speech was further evaluated by comparing potentials during and after speech with and without immediate auditory feedback. Because a decrease in the EP can be expected as a result of presenting two stimuli in rapid succession, the differential effects of speaking and hearing on the potentials to the delayed syllable were investigated.

As has been suggested earlier, there is considerable evidence to indicate that speech is located primarily in the left hemisphere for right-handed subjects and that Broca's area is important in speech production, while Wernicke's area and the temporoparietal region seem to be concerned more with speech reception. Although dipole orientation, volume conduction, and cortical interaction may tend to distort the amplitude of the potentials recorded over these two speech areas, McAdam and Whitaker (1971), Brown et al. (1973), and others have reported differing potentials for these two locations in the left hemisphere. Therefore, frontal and temporoparietal electrode placements in both hemispheres were used to determine if differences existed as a function of conditions.

# CHAPTER II

# METHOD

## Subjects

Twelve adults who were determined to have a dominant left hemisphere by scoring "right-sided" on five out of seven hemispheric dominance tests were selected from a larger population of self-proclaimed right-handed adults with normal hearing. Two males and four females were experimentally naive with regard to electrophysiological research, and three males and three females had participated in previous evoked potential studies. None of the subjects had a previous history of hearing difficulties or indicated a hearing loss during the practice session.

## Apparatus

Hemispheric dominance tests. One eye, one ear, two foot or leg, and three hand dominance tests which could be rapidly administered were chosen and modified from a variety of tests previously shown to reflect hemispheric dominance (Dimond & Beaumont, 1974; Harris, 1974; Hécaen & De Ajuriaguerra, 1964). Eye dominance was tested by asking subjects to hold a broom like a rifle and "sight" an object in the distance. The dominant eye remained open. A watch was then held directly in front of the subject's face, and the subject was asked if s/he could hear if the watch was still ticking. The ear used to listen was considered dominant. If the subject tried to hold the watch in his/her hand and then move it to his/her ipsilateral ear, the ear reported as used when first answering the telephone was scored dominant. Observing the subjects kick a ball of paper that had been placed on the floor equidistant from both feet, and requesting they hop across the room on one foot served as foot dominance tests, with the foot used in each case being declared dominant.

Hand dominance was measured three ways. The subject was handed the broom and asked to sweep. The hand placed higher on the broom was declared dominant. The subject was then asked to pick up a deck of cards and deal five cards. The hand used for dealing was marked dominant. The subject was then seated at a table with a blank piece of paper in front of him/her, given a pencil for each hand, and asked to write the numbers 1-10 in a column simultaneously with both hands. Dominance was determined by mirror images and/or legibility. The hand that wrote any numbers reversed was the nondominant hand, and, if there were no reversals, the experimenter determined which hand wrote the more legible column of numbers and declared it dominant. In no case were there reversals by both hands nor did the reversal criterion contradict the legibility criterion.

Hearing tests. After eliminating subjects with knowledge of previous or current hearing loss or problems, each subject was exposed to approximately 3 min. of DAF during which s/he read aloud a passage from a statistics book and heard his/her voice through headphones with 0.2 sec. delay, the delay interval shown to produce maximum disruption in normal speakers (Fairbanks, 1955; Lee, 1950; Melrose, 1953). The purpose of this was to determine if air conducted feedback was adequately reduced by the earphones and to discover what intensity would result in the subject experiencing the usual speech disfluencies of increased voice intensity, increased articulation errors, and decreased speed that accompany speaking with DAF. Volume levels ranged from 80 to 90 dB SPL, which is in agreement with other reports for subjects with normal hearing and normal voice intensities (Tiffany & Hanley, 1956).

Physiological equipment. The subjects were seated in an electrically-shielded sound-deadened chamber. EEGs were recorded through gold disc electrodes attached to the scalp with Redux electrode jelly and held in place by elastic headbands. Monopolar recordings were made from the left and right frontal areas corresponding to Broca's area (FB1 and FB2) and the left and right temporoparietal areas (TP1 and TP2). These electrode locations are shown in Figure 1. FB1 and FB2 were located 40% of the distance between F7 (or F8) and T3 (or T4) and 37% of the distance between F7 (or F8) and F3 (or F4), measured from F7, according to the Ten Twenty System of the International Federation (Jasper, 1958). TP1 and TP2 were located roughly 2 cm posterior to

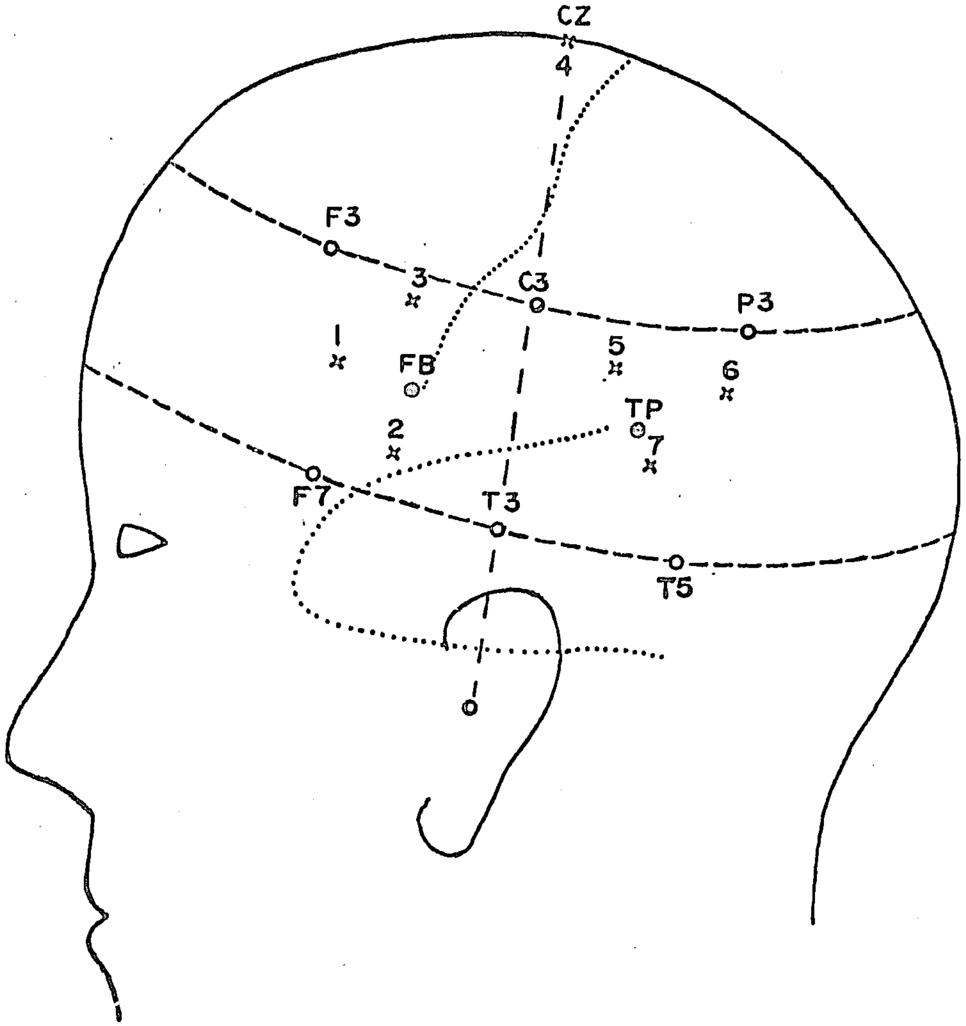

Figure 1. Electrode Locations for Pilot Study (1-7) and Major Investigation (FB and TP)

the termination of the Sylvian fissure and identified on the scalp as the point formed by the intersection of lines from T3 (or T4) to P3 (or P4) and from T5 (or T6) to C3 (or C4). Initially, recordings were made from the vertex (CZ) to determine if they differed in form from those made from the TP placements, and in no case were there waveform differences, although the vertex response was often of greater amplitude. A linked-ear earlobe reference was used. Skin resistance was maintained under 10,000 ohms throughout all sessions. Cortical activity for 1024 msec. following each of 64 presentations of the first stimulus in the pair was amplified with a Grass Model 7 polygraph with 7P5A preamplifiers whose half amplitude high and low frequency filters were set at 35 and 0.3Hz. The signal was then averaged with a Fabri-Tek Model 1062 signal averaging computer and plotted on a Hewlett Packard 7035B X-Y recorder at an amplitude factor which resulted in a 1 cm pen deflection representing 5.8 μV. The computer was triggered by a negative pulse from a laboratory built phonation timer[1] which detected the first voiced cycle of speech above the chosen threshold with a constant error of less than 5 msec. for each threshold level, regardless of sound intensity.

Spoken sounds were first recorded on a Lafayette-modified Bell and Howell variable interval delayed feedback recorder, from which both normal and delayed signal outputs were mixed and equated for volume by a laboratory built auditory mixer (see Footnote 1). Mixer output was recorded by a Sony stereo TC-650 tape recorder and further amplified by a Kenwood KA-2002 amplifier before being conducted to the ears through insulated Sony stereo DR-7A earphones. During the conditions when the subject did not speak but received the previously recorded stimuli through the earphones, a simultaneous output from the Kenwood amplifier was passed through a second adjustable amplifier to a speaker in the experimental cubicle to activate the phonation timer. The amplitude of the speaker output was equated with the subjects' spoken output at the level of the microphone of the phonation timer by a General Radio 1565-A sound pressure level meter, using the A scale, which discriminates against low frequency sounds, resulting in a level closely correlated with subjective estimates of loudness, annoyance, and speech interference. Sound pressure level was also equated at the earphones for all auditory feedback conditions and maintained at 80-85 dB SPL for most subjects, with individual adjustment increases up to 90 dB SPL made for subjects shown to require greater volume levels on the preliminary hearing test.

## Procedure

Pilot studies. A mapping study was conducted to determine which electrode locations produced the largest and most consistent potentials during both speaking and hearing. Waveforms from seven electrode locations were examined in four subjects who spoke the syllable /ba/ and then tapped the table with a pencil held in their right hand to indicate if the /ba/ was not of the specified duration of 250-500 msec. Two to eight replications were obtained for each electrode location for speaking /ba/ and for hearing the tape of the /ba/s previously spoken. Sound intensity at the headphone level was 80 dB SPL for both speaking and hearing conditions. The three anterior, three posterior, and the vertex locations investigated are shown in Figure 1. As each right hemisphere location was shown to give a waveform similar to that of the corresponding left hemisphere location, only left hemisphere placements were consistently studied in all four subjects. All anterior locations gave analogous waveforms, as did all posterior ones, but exhibited generally greater amplitude changes. Figure 2 presents potentials from a representative subject for the locations numbered in Figure 1 for two replications when speaking the syllable /ba/. Potentials for the anterior placements obtained while hearing the syllable /ba/ were similar in form, as were all posterior placements, as illustrated by the potentials in Figure 3, which are from the same subject as those in Figure 2. The electrode sites chosen as a result of these findings were thought to best represent electrical activity for this type of stimulus situation for both anterior and posterior regions. The syllables /ba/ and /da/ were originally selected for pilot work because they have been used by a number of investigators (which would

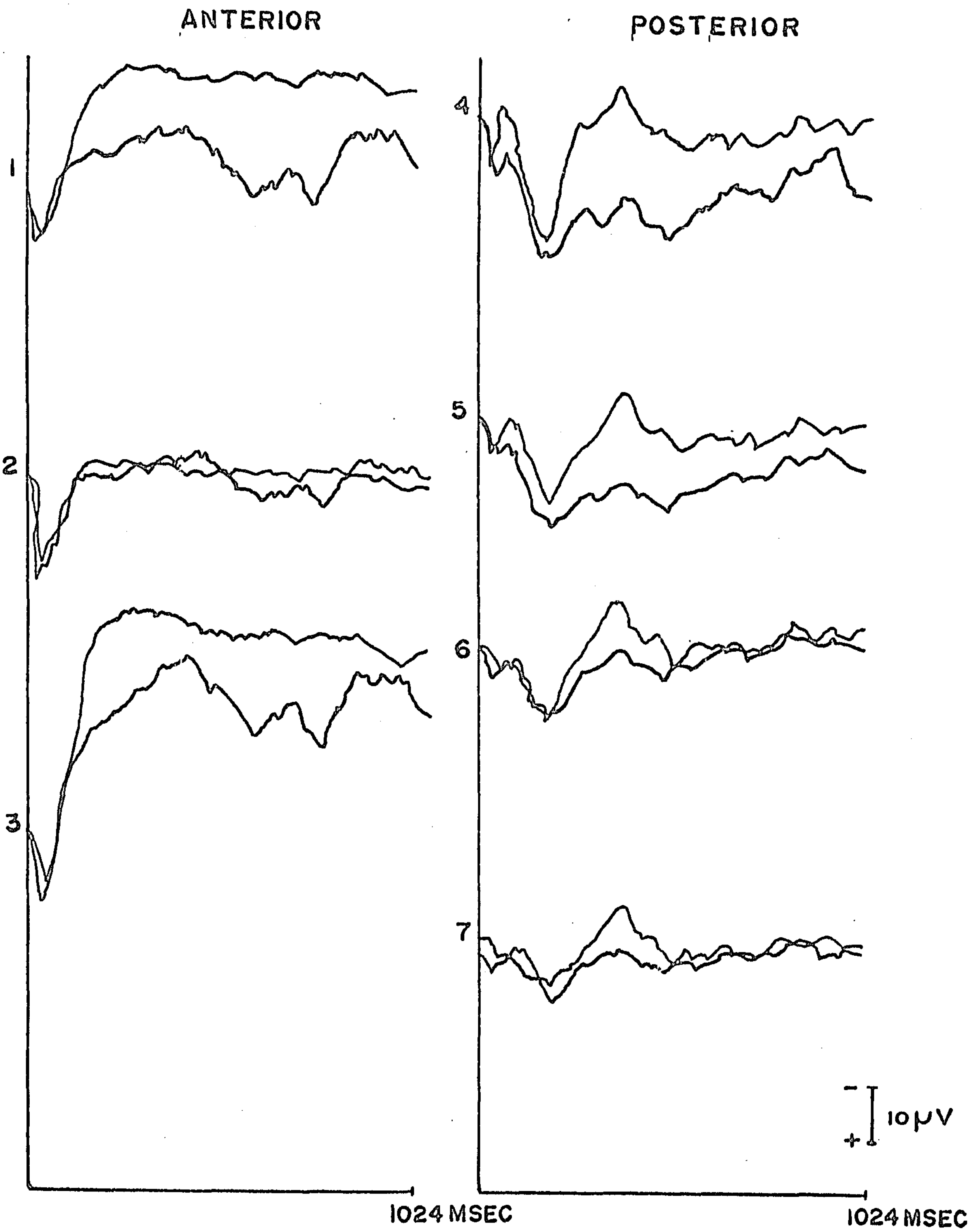

Figure 2. Potentials to Speaking /ba/ from Different Electrode Placements Used in Pilot Study in a Representative Subject

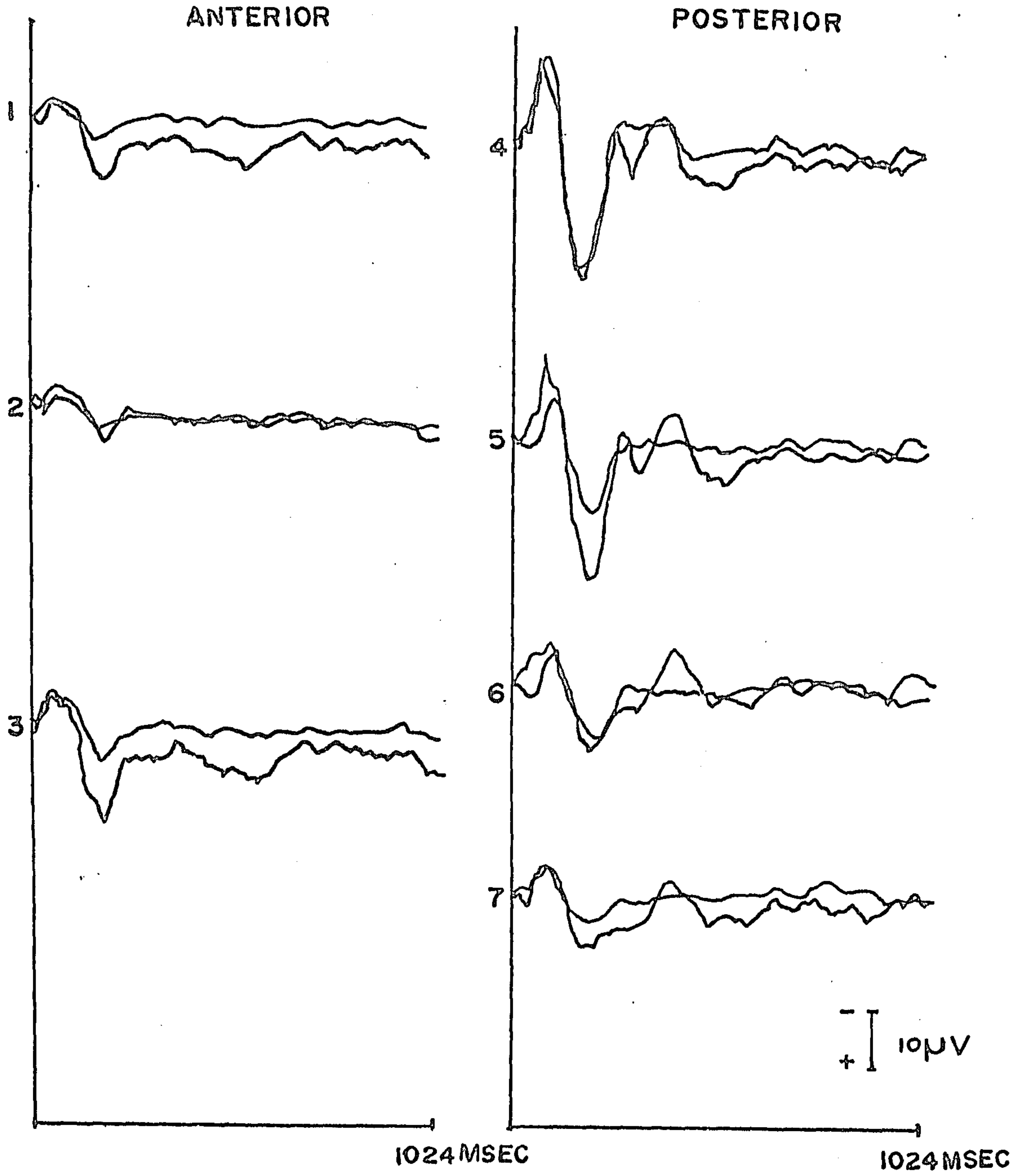

Figure 3. Potentials to Hearing /ba/ from Different Electrode Placements Used in Pilot Study in a Representative Subject

permit comparison of results to those of other studies), because they can be equated on all characteristics except direction and extent of second and third formant transitions when synthetically produced (Wood et al., 1971), they begin with plosives which provide a sufficiently fast rise time for the production of a clear auditory evoked response (Tobin, 1968), and they differ in only one of the two articulation features, that of place (Studdert-Kennedy & Shankweiler, 1970). As pilot work showed that the potentials to the syllable /ba/ were quite comparable in form to those to /da/ for speaking and hearing, only /ba/ was chosen for the main experiment. The use of syllables instead of words reduced confounding by meaning, muscle artifacts, and difficulties in producing a consistent stimulus across trials.

Preliminary and practice session. Immediately prior to the first experimental session on Day 1, each subject was given the hemispheric dominance tests. Then exact electrode placement was determined and marked on the scalp with India ink. The locations were cleaned with alcohol and scrubbed with Redux electrode jelly, and the electrode cups, also filled with Redux jelly, were placed on the scalp and secured by an elastic headband. After it had been determined that skin resistance was less than 10,000 ohms for each placement, the subject was comfortably seated in the shielded chamber and the headphones carefully fitted. S/He was instructed to place his/her forehead in a headrest positioned so the phonation timer and tape recorder microphones were 5 in. from his/her lips. The hearing test was then conducted and the volume through the headphones adjusted appropriately.

The subject was told to relax and visually fixate upon a point directly in front of and 2 ft. from him/her and to keep his/her eyes open during all sessions. During the speaking conditions s/he was instructed to utter the syllable /ba/, 300-380 msec. in duration, whenever s/he observed the onset of a white signal light, which was at the approximate rate of once every 5-7 sec. and to hold his/her mouth in the open position that results from speaking the syllable until signalled by the light offset to close it. This long a delay between stimulus presentations is necessary to permit recovery of electrical activity from the preceding potential (Davis, Mast, Yoshie, & Zerlin, 1966; Ohman & Lader, 1972). The light offset not only served as a signal to close his/her mouth, but also to give his/her response in a task designed to maintain a constant attentional state and to insure uniformity of the test stimuli and thus decrease variability within and across sessions. The task consisted of determining whether the syllable just spoken was of the correct or incorrect duration as defined by the preliminary instructions. The subject was to depress the appropriate side of a rocker switch with one of the first two fingers on his/her right hand to report his/her judgement response. A correct judgement produced a green flash and an incorrect judgement produced a red flash, followed by the onset of the white light 1.5 sec. after the switch was depressed. During the hearing condition the subject was told to listen to the previously recorded /ba/s and indicate following the offset of the light whether the duration of the heard stimulus was between the 300 and 380 msec. specified. All subjects were given sufficient time to practice this task until they could produce a /ba/ of the correct duration at least 60% of the time and were confident that they understood the task and the meaning of the feedback lights. The practice session was concluded by an illustration of each condition to be experienced during the actual experimental sessions and a complete run through one condition while recording from all electrode locations using the vertex (CZ) location instead of the TP1 placement. The subject was then permitted to leave the experimental cubicle for a 5 to 10 min. break, during which the CZ electrode was replaced by the TP1 placement.

Testing sessions. After the short break, subjects were again escorted into the experimental chamber and seated. Electrode resistance was again checked to insure good contact after repositioning the headphones. The subject was told what condition to expect next and asked if s/he had any questions about the procedure. S/He was given the opportunity to practice again if s/he desired. This procedure was followed for the other two conditions in this session as well. The data were plotted and the tapes rewound after every condition, permitting the subject to rest in place about 3 min. before the next series of 64 stimulus presentations. Upon completion of the session, the subject was requested to return another day for the concluding two sessions. Except for counterbalancing the order of conditions, the procedure for the next two sessions was identical to that for the first testing session, using the method of electrode placement utilized in the practice session and giving the subject a 5-10 min. break between sessions.

Conditions. The stimulus situation for each condition was composed of two parts separated by an interval of 0.6 sec. The first part ($S_1$) consisted of the syllable /ba/ being spoken and heard (SH) immediately through the headphones, being spoken and not immediately heard (S) through the headphones, or being heard (H) through the headphones without being spoken by playing a tape of a prior condition in which /ba/ was spoken. The second part ($S_2$) was always the same: the syllable /ba/ being heard (H) through the headphones 0.6 sec. after the onset of $S_1$. This resulted in each subject experiencing each of the following conditions during each session:

1. Speak /ba/ with no immediate auditory feedback but with the sound returned to the ears 0.6 sec. after the onset of phonation, designated S-H.

2. Speak /ba/ with the sound heard both instantaneously and 0.6 sec. after phonation onset and labelled SH-H.

3. Hear the recorded sounds from the SH-H condition from a previous session in which /ba/ occurred both immediately and 0.6 sec. after phonation onset (H-H).

All subjects experienced three orders of the three conditions, with half of the subjects being given the first three possible condition orders and the other half being given the remaining orders. Table 1 shows the order of presentation of conditions for each session for all subjects. The tape used inthe H-H condition was always the one recorded during the SH-H condition of the previous session or of the preliminary practice session. The practice session and the first experimental session occurred on Day 1 and the next two sessions occurred on Day 2 to prevent fatigue in subjects. Amplifier differences were controlled by counterbalancing for left and right hemisphere locations within each condition (switching amplifiers for corresponding left and right locations after 32 of the 64 stimulus presentations).

## Table 1

### The Order of the Three Conditions, S-H, SH-H, and H-H, for Each Subject During Each Session

| | Sessions | | | | Sessions | | |
|---|---|---|---|---|---|---|---|
| Subjects | 1 | 2 | 3 | Subjects | 4 | 5 | 6 |
| $S_1$ | S-H | SH-H | H-H | $S_2$ | S-H | H-H | SH-H |
| | SH-H | H-H | S-H | | H-H | SH-H | S-H |
| | H-H | S-H | SH-H | | SH-H | S-H | H-H |
| | 1 | 3 | 2 | | 4 | 6 | 5 |
| $S_3$ | S-H | H-H | SH-H | $S_4$ | S-H | SH-H | H-H |
| | SH-H | S-H | H-H | | H-H | S-H | SH-H |
| | H-H | SH-H | S-H | | SH-H | H-H | S-H |
| | 2 | 3 | 1 | | 5 | 6 | 4 |
| $S_5$ | SH-H | H-H | S-H | $S_6$ | H-H | SH-H | S-H |
| | H-H | S-H | SH-H | | SH-H | S-H | H-H |
| | S-H | SH-H | H-H | | S-H | H-H | SH-H |
| | 2 | 1 | 3 | | 5 | 4 | 6 |
| $S_7$ | SH-H | S-H | H-H | $S_8$ | H-H | S-H | SH-H |
| | H-H | SH-H | S-H | | SH-H | H-H | S-H |
| | S-H | H-H | SH-H | | S-H | SH-H | H-H |
| | 3 | 2 | 1 | | 6 | 5 | 4 |
| $S_9$ | H-H | SH-H | S-H | $S_{10}$ | SH-H | H-H | S-H |
| | S-H | H-H | SH-H | | S-H | SH-H | H-H |
| | SH-H | S-H | H-H | | H-H | S-H | SH-H |
| | 3 | 1 | 2 | | 6 | 4 | 5 |
| $S_{11}$ | H-H | S-H | SH-H | $S_{12}$ | SH-H | S-H | H-H |
| | S-H | SH-H | H-H | | S-H | H-H | SH-H |
| | SH-H | H-H | S-H | | H-H | SH-H | S-H |

# CHAPTER III

# RESULTS

Examination of the raw data for all subjects indicated that the evoked potentials occurring during the process of speaking /ba/ (designated by the underlined stimulus in S-H and SH-H) differed in form from those occurring while hearing /ba/ (also indicated by the underlined stimulus in S-H, SH-H, H-H, and H-H). As shown in Figure 4, the potentials during the speaking process exhibited much more variability in waveform for different subjects, with some subjects producing a slow positive DC shift beginning within the first 100 msec. and continuing for approximately 300 msec. This shift was totally absent for some subjects and present in varying degrees for others, which made the application of uniform standards for quantification of corresponding peaks and troughs extremely difficult. Figure 4 contasts the potentials for a subject producing the DC shift with those of a subject not displaying this shift for the two speaking conditions in comparison to the hearing condition.

For the purposes of this dissertation, only the potentials obtained during the various listening conditions (S-H, SH-H, H-H, and H-H) for the TP electrode placements were subjected to quantitative analysis. This limitation was imposed because of the highly variable DC shift present

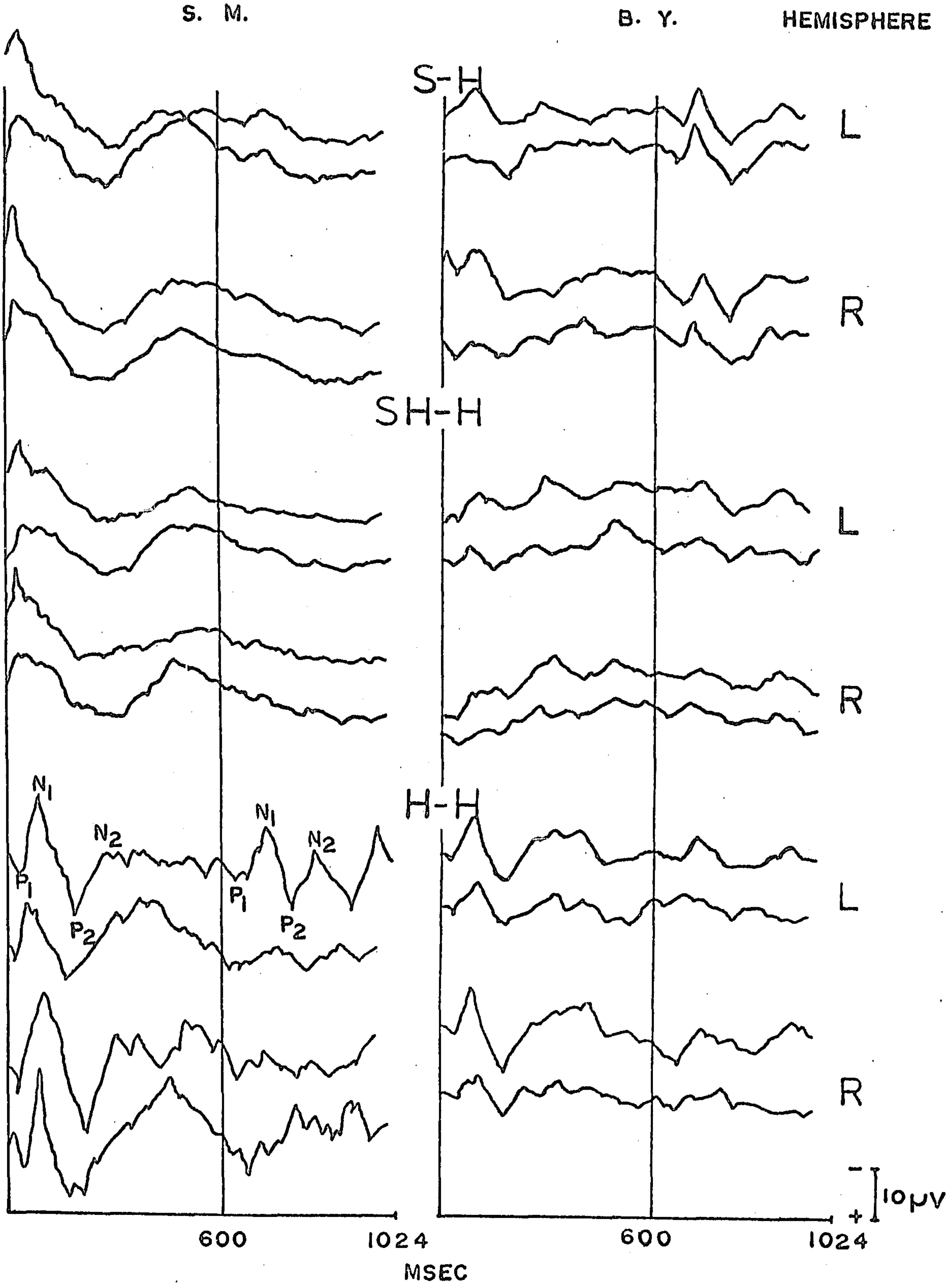

Figure 4. Potentials for Subjects with and without DC Shifts for Speaking and Hearing Conditions

in the potentials while speaking and the extremely voluminous amount of data generated by the experiment, which was exploratory in nature. In addition, one subject was excluded from the quantitative analysis due to failure to obtain complete data resulting from equipment difficulties. A brief descriptive section was included to summarize the data not analyzed quantitatively.

### Quantification of Evoked Potentials

Evoked potential components selected for analysis were the most positive deflections occurring at 50 to 100 msec. ($P_1$) and 150 to 220 msec. ($P_2$) and the most negative deflections at 100 to 150 msec. ($N_1$) and 250 to 350 msec. ($N_2$) following stimulation. These components have been labelled for subject S.M. in Figure 4. Davis and Zerlin (1966) and Picton, Hillyard, Krausz, and Galambos (1974) have shown these components to be the most common longer latency components to occur following auditory stimulation. Amplitude measurements were made between the peaks and troughs for $P_1$-$N_1$, $N_1$-$P_2$, and $P_2$-$N_2$. Data were analyzed in two ways. First, an overall analysis of variance (ANOVA) was conducted (Winer, 1971) in which there were four conditions (S-_H_, SH-_H_, H-_H_, and _H_-H), two electrode locations (TP in each hemisphere), and three amplitude measures ($P_1$-$N_1$, $N_1$-$P_2$, and $P_2$-$N_2$). Pairwise comparisons were then made on significant factors using the Newman-Keuls test (Soderquist, in preparation; Winer, 1971). Because there were significant component by condition and component by hemisphere interactions, [*F* (6, 60) = 6.26, $p < .001$; *F* (2, 20) = 4.85, $p < .025$] as seen in Figures 5 and 6, and because of the questionable relationship between components within an EP, individual ANOVAs were performed on each separate component amplitude measurement and on a composite amplitude measurement that was a sum of the individual amplitude components. Pairwise comparisons were then made using the Newman-Keuls (N-K). In every case there was agreement in the significance levels for the Newman-Keuls following the 4x3x2 ANOVA and the individual ANOVAs and their pairwise comparisons. Table 2 compares the significant results for all ANOVAs and Newman-Keuls tests. Complete ANOVAs are reported in Appendix I. As the composite ANOVA provided the same information as the overall ANOVA with the exception of the component interactions, it will not be discussed further. Utility Indices (UI) were conducted for all significant factors to determine the proportion of variance accounted for by that particular manipulation (Gaebelein & Soderquist, in preparation).

Conditions. The four hearing conditions differed significantly for the overall analysis [*F* (3, 30) = 14.08, $p < .001$, UI = .24]. Figure 5 illustrates the overall amplitude differences resulting from the various conditions as well as the effects of conditions on each component. As previously stated, the condition by component interaction

## Table 2

## A Comparison of the Significant Results for All ANOVAs and Newman-Keuls Pairwise Comparisons

| Significant Effects | Overall ANOVA Test | Overall ANOVA Probability Level | Individual ANOVAS ANOVA | Individual ANOVAS Test | Individual ANOVAS Probability Level |
|---|---|---|---|---|---|
| Conditions | *F* | .001 | Composite | *F* | .001 |
| S-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| SH-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| H-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| S-*H* > *H*-*H* | *N-K* | .05 | | *N-K* | .05 |
| Components | *F* | .001 | - | - | - |
| $P_1$-$N_1$ < $N_1$-$P_2$ | *N-K* | .01 | - | - | - |
| $P_1$-$N_1$ < $P_2$-$N_2$ | *N-K* | .01 | - | - | - |
| Conditions x Components | *F* | .001 | - | - | - |
| Conditions at $N_1$-$P_2$ | - | - | Component $N_1$-$P_2$ | *F* | .001 |
| S-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| SH-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| H-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| Conditions at $P_2$-$N_2$ | - | - | Component $P_2$-$N_2$ | *F* | .001 |
| S-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| SH-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| H-*H* < *H*-H | *N-K* | .01 | | *N-K* | .01 |
| S-*H* > H-*H* | *N-K* | .05 | | *N-K* | .05 |
| Components at *H*-H | - | - | - | - | - |
| $P_1$-$N_1$ < $N_1$-$P_2$ | *N-K* | .01 | - | - | - |
| $P_1$-$N_1$ < $P_2$-$N_2$ | *N-K* | .01 | - | - | - |
| Hemisphere x Components | *F* | .025 | - | - | - |

Table 2 (continued)

| Significant Effects | Overall ANOVA | | Individual ANOVAS | | |
|---|---|---|---|---|---|
| | Test | Probability Level | ANOVA | Test | Probability Level |
| Hemispheres at $N_1$-$P_2$ | *N-K* | .05 | Component $N_1$-$P_2$ | *F* | .05 |
| Components at L Hemisphere | - | - | - | - | - |
| $P_1$-$N_1$ < $N_1$-$P_2$ | *N-K* | .01 | - | - | - |
| $P_1$-$N_1$ < $P_2$-$N_2$ | *N-K* | .01 | - | - | - |
| Components at R Hemisphere | - | - | - | - | - |
| $P_1$-$N_1$ < $N_1$-$P_2$ | *N-K* | .05 | - | - | - |
| $P_1$-$N_1$ < $N_1$-$P_2$ | *N-K* | .05 | - | - | - |

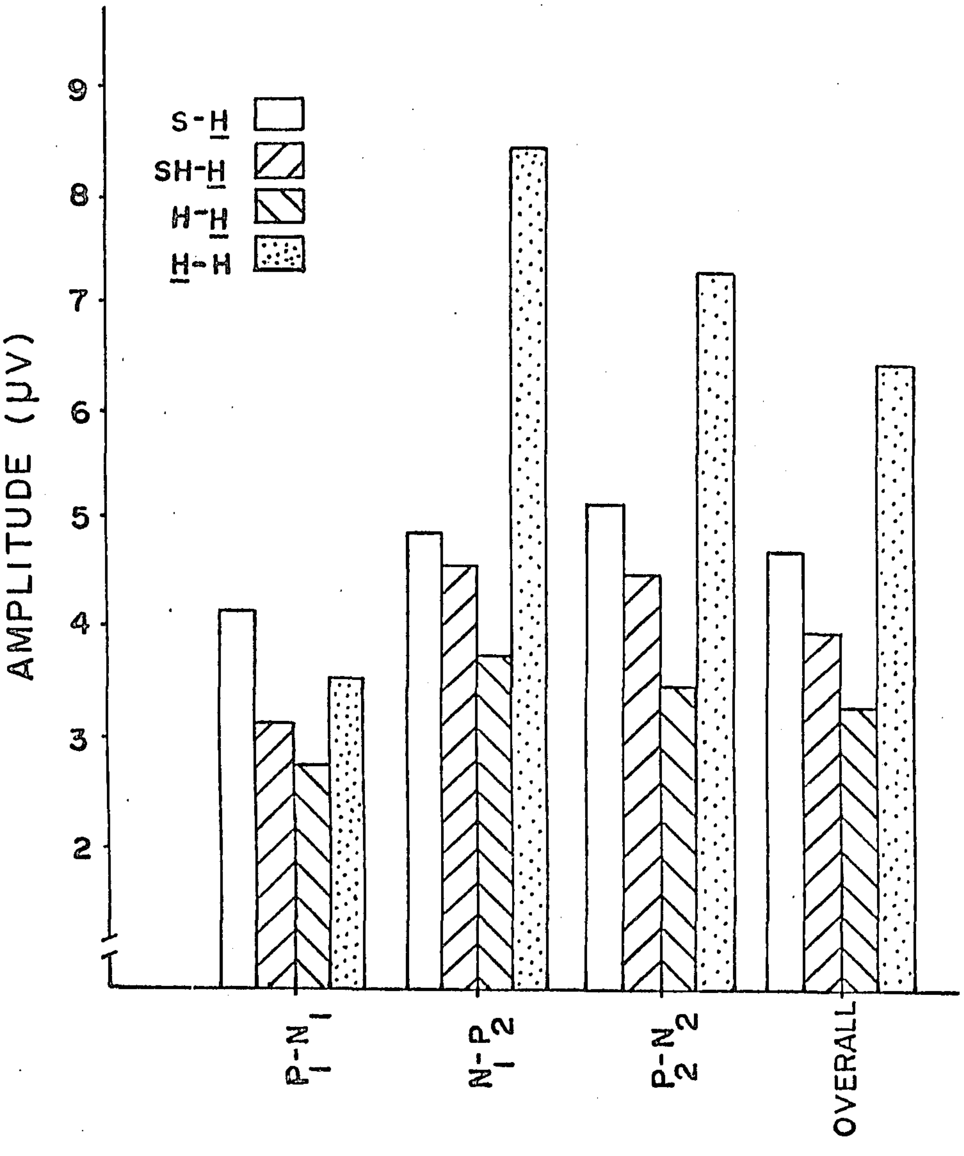

Figure 5. The Effects of the Speaking and Hearing Conditions on the Amplitude of the Potentials to $S_2$ for Each Component Measured and Overall

was also significant [_F_ (6, 60) = 6.26, $p < .001$, UI = .09], and the ANOVAs for individual components indicated that the various hearing conditions differed significantly for both components $N_1$-$P_2$ [_F_ (3, 30) = 14.38, $p < .001$, UI = .67] and $P_2$-$N_2$ [_F_ (3, 30) = 11.78, $p < .001$, UI = .35]. In view of the relatively high values of the UIs for these tests, it can be concluded that the manipulation of conditions was quite effective.

The N-K for the overall analysis revealed that the potential to the first /ba/ when heard only (_H_-H) was significantly greater at the .01 level than that to the /ba/ that had been preceded by a spoken and/or heard /ba/ (S-_H_, SH-_H_, and H-_H_). As the potential for hearing /ba/ after speaking (S-_H_) was also greater than that for just hearing /ba/ the second time (H-_H_) ($p < .05$), it would appear that hearing the /ba/ previously decreases the amplitude of the potential to $S_2$. This is also supported by the fact that the SH-_H_ and H-_H_ potentials do not differ significantly ($p > .05$). The Newman-Keuls revealed that this is primarily a result of the S-_H_ potential being greater than the H-_H_ one for component $P_2$ - $N_2$ ($p < .05$). The effects of the speaking process did not apparently mask the effects of then hearing /ba/, since, as stated earlier, the potentials SH-_H_ and H-_H_ did not differ significantly and H-_H_ was actually less than S-_H_. Whether or not the subject received immediate auditory feedback had little influence on $S_2$, as can be seen by comparing SH-*H* to S-*H* in Figure 5. Newman-Keuls tests indicated that the *H*-H potential was of greater amplitude than the S-*H*, SH-*H*, or H-*H* potentials for the $N_1$-$P_2$ and $P_2$-$N_2$ components ($p < .01$), which accounts for the condition effect in the overall ANOVA.

Hemispheres. Figure 6 shows that there was a significant component by hemisphere interaction [$F$ (2, 20) = 4.85, $p < .025$, UI = .01], primarily due to the greater response from the left as compared to the right hemisphere for only the $N_1$-$P_2$ component [$F$ (1, 10) = 5.71, $p < .05$, UI = .03]. The magnitude of this effect was similar for all conditions and was not great, as indicated by the low UIs. Figure 6 also shows that $P_1$-$N_1$ was smaller in amplitude than both $N_1$-$P_2$ and $P_2$-$N_2$ in the left and right hemispheres ($p < .01$ and .05 respectively). $N_1$-$P_2$ and $P_2$-$N_2$ seemed to be the most sensitive components to changes in conditions and hemispheric differences. $P_1$-$N_1$ failed to differentiate among conditions or hemispheres.

### Behavioral Data

A record was kept of the duration of the spoken and heard /ba/s and the subject's ability to judge whether the duration of the /ba/ was correct, and after any condition in which either the durations or the judgments fell below 60% accuracy, additional practice was given to the subject before the next run began. A one way ANOVA was conducted on the mean percent of correct judgments for each condition and indicated that

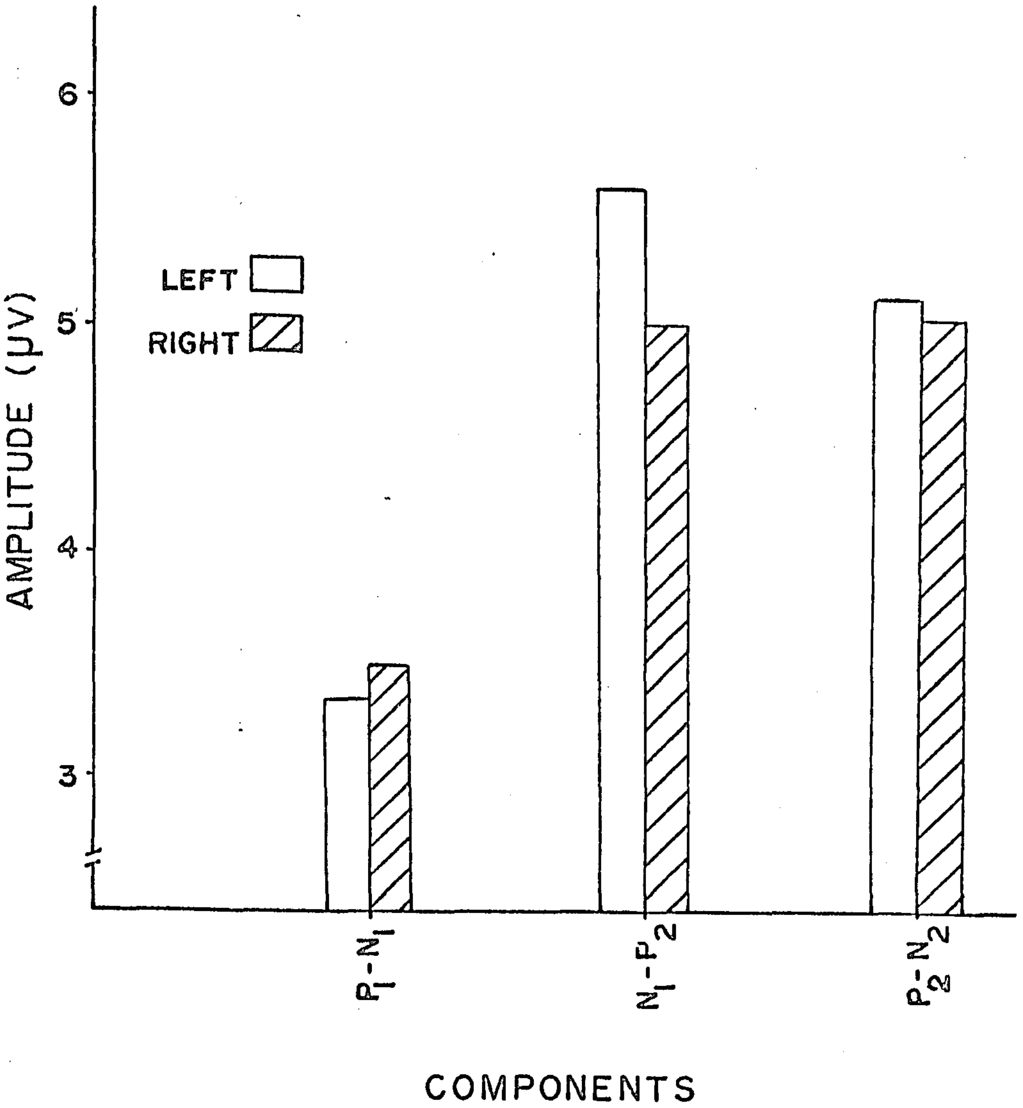

Figure 6. The Amplitude of the Three Components Measured in Each Hemisphere

the conditions did not differ significantly in difficulty [$\underline{F}$ (2, 20) = 1.27, $\underline{p} > .05$]. No subject fell below 60% accuracy more than once in any session. This, coupled with the extra practice periods, insured relative uniformity of the /ba/ produced.

## Some Apparent EP Changes Based Upon Visual Inspection

Visual inspection of all of the data collected indicated that there were apparent trends that should be explored more extensively in the future. Although, as pointed out earlier, no attempt was made to quantify these trends because of the problems involved, it seemed desirable to briefly mention them as directions for possible future research. A comparison of SH-H with H-H for subject S.M. in Figure 4 shows that the waveform occurring to the heard /ba/ was masked in some subjects during speaking by the positive DC shift. It was interesting to note that this difference in waveform between SH and H existed to some extent in all females. The amplitude of the positive DC shift was not consistently different in the S-H condition as compared with SH-H, which is in line with the finding of no significant differences in $S_2$ for these two conditions, and this shift seemed of equal magnitude in both hemispheres. As the shift appeared to be greater at the FB locations, in one subject (S.B.) whose data contained this shift, EMGs were recorded simultaneously with EPs at the FB1 placement while speaking /ba/. EMG electrodes were placed 1 cm to the left and right of the corners of the mouth and .5 cm above and below the center of the lips. Although in two cases the DC shift seemed to have the same waveform as one of the EMGs, for the remaining six trials there were either latency or relative amplitude differences that produced a lack of correspondence between the EP and the EMGs. Then an attempt was made to produce this positive DC shift in a subject (R.H.) whose EPs showed no evidence of it, using these same electrode placements. The subject was shown records with and without this DC component and told that the difference in the two data records may be due to lip or mouth movement. The subject was first instructed to "try not to produce this DC shift while saying /ba/". Then he was given four trials of saying /ba/ while trying to induce this shift into his EP record. In no trial did the subject's EP contain the DC shift, although the resulting EMG data resembled that of subject S.B. Therefore, it cannot be concluded that the positive DC shifts appearing in some of the EP records during the speaking process are a result of lip or mouth movement. It is realized that many additional EMG placements are needed, however, before this can be ruled out as the primary source of this shift.

With regard to electrode location, there were no clear indications of amplitude differences for the FB and TP placements for the first 300 msec., but these two locations seemed to be differentially sensitive to hemispheric asymmetry for $S_2$ after speaking and hearing. The FB position appeared more sensitive to hemispheric differences to $S_2$ after the speaking conditions, while the same was true for TP after the hearing condition. Additional suggested hemispheric asymmetries in the majority of subjects not involving FB and TP differences included greater amplitude $N_1$-$P_2$ potentials on the right for 70.6% of the subjects exhibiting asymmetry when /ba/ is first heard (*H*-H) compared to greater potentials on the left in 78% of the subjects showing asymmetry when /ba/ becomes $S_2$ (H-*H*). There was also evidence of greater amplitude $N_1$-$P_2$ EPs on the right for $S_1$ across all conditions for 74% of subjects producing asymmetrical potentials.

Although it would be extremely preliminary to draw conclusions concerning latency differences until additional data were collected to assure that the signal averager was being triggered at exactly the same latency and amplitude points on the speech stimulus for the spoken and heard conditions, the data suggest that analysis of latency measures may provide valuable information. Future research is needed to verify the suggested trends that the latency of $N_1$ may be shorter for *H*-H than for H-*H* for both electrode positions and hemispheres and that there may be overall latency differences for the FB and TP placements for the hearing conditions.

# CHAPTER IV

# DISCUSSION

The evoked responses to the syllable /ba/ for all heard conditions resembled those to the /ba/ in studies by Molfese (in press) and Wood et al. (1971) with regard to overall waveform and latencies of the major components. The finding that the $N_1$-$P_2$ component is one of the most sensitive to various manipulations corresponds with the report of Dorman and Hoffmann (1973), who also presented successive /ba/s in a habituation paradigm using infants. Dorman and Hoffmann's study demonstrated that the greatest amplitude decrease was present following the second in a series of four stimuli, which corresponds to the reports of Fruhstorfer (1971) and Ritter et al. (1968). In the present study this amplitude decrease following the second stimulus was also demonstrated by the reduction in the H-H potential compared to H-H. The two /ba/s in the H-H condition were returned to the ears through different amplification systems in order to delay the /ba/ and operate the phonatimer during heard conditions. Even though these two /ba/s were equated for intensity, the possibility remains that the difference in amplitude of the EPs during the H-H and H-H conditions could have resulted from amplifier differences. There were no such amplifier differences for the three delayed /ba/s (S-H, SH-H, and H-H).

Although the typical waveform to the *H* stimulus was sometimes masked in the *SH*-H condition by the large positive DC shift, this masking did not continue into the $S_2$ period, as evidenced by the similarity of the SH-*H* and H-*H* potentials. When H was presented as $S_2$, the corresponding potential was less than when H was unpreceded as in *H*-H, which would indicate a type of masking, habituation, or fatigue as a result of the prior stimulus. Apparently, the *SH*-H does not result in as great a decrease in the $S_2$ potential as *H*-H, as shown in Figure 5, which may be due to the damping effect of the middle ear reflexes. These have been shown to be activated just prior to speech onset (Metz, 1946; Salamon & Starr, 1963), which could reduce the masking effect of the first heard /ba/ in the *SH*-H condition.

That there was a significant difference between S-*H* and H-*H*, but not between SH-*H* and H-*H*, would indicate the additional suppressing effect of air conducted feedback, implying habituation occurred to *H* when combined with speaking. Being preceded by speech alone had a decremental effect on the potential to the heard /ba/ (S-*H* vs *H*-H), which is probably due to incomplete neuronal recovery. However, the exact effects of the addition of immediate auditory feedback during speech on the $S_2$ potential cannot be determined, due to the lack of significant difference between S-*H* and SH-*H* and also between SH-*H* and H-*H*. Figure 5 suggests a definite trend related to the addition of air conducted feedback that will require future verification.

In view of the vast number of anatomical, dichotic listening, and evoked potential studies demonstrating that the left hemisphere is dominant for speech in most right handers, greater evoked potentials for the left hemisphere electrode placements would be expected in this study. This effect was demonstrated in the $N_1$-$P_2$ measurement. The magnitude of the obtained differences was slightly smaller for this component (0.74 $\mu$V) than is usually reported (1-2 $\mu$V) (Grabow & Elliott, 1974; Molfese, in press) in similar studies. Since there are anatomical differences in size, the right hemisphere may have a different orientation of dipoles, fewer cells, and more distance between the area of the cortex activated and the scalp electrodes, all of which would tend to diminish the EP to speech stimuli by a small amount.

Why this laterality is demonstrated in only one of the three amplitude measures is not clear, nor is the reason why the laterality is present in the middle component rather than the latest one measured. $P_2$-$N_2$, the measure with the longest latency, supposedly reflects psychological parameters such as meaningfulness and stimulus evaluation (Regan, 1972), instead of just the physical parameters of the stimulus, and therefore, should be correlated with speech activity. The lack of asymmetry for the earliest component measurement is easier to explain. The $P_1$-$N_1$ component may reflect some activity of a subcortical nature and/or contamination by scalp musculature, neither of which would be expected to be asymmetrical and could have masked any hemispheric differences originating from the cortex (Picton et al., 1974).

In general, a lack of hemispheric asymmetry for speech, such as obtained by Ratliff and Greenberg (1972), can be explained in a number of ways. Penfield (Penfield & Rasmussen, 1950) and Sperry (Gazzaniga & Sperry, 1967) have demonstrated that the minor hemisphere is involved in speech, and Butler and Norrsell (1968) suggest that the nondominant hemisphere is normally inhibited during speech processing by the dominant one. If the nondominant hemisphere receives speech information, the mere reception of this information should activate cortical cells in the right hemisphere, resulting in an EP and small hemispheric differences. If this information is not processed, due to some simultaneous inhibitory effect of the dominant hemisphere, removal of the speech areas in the dominant hemisphere should result in only temporary impairment of speech skills, and the minor hemisphere should rapidly assume the verbal functions of the major one. However, Milner (1967) has provided evidence that this does not usually occur in adults. An alternative hypothesis is that speech is processed in both hemispheres, but information in the nondominant hemisphere must be sent to the dominant side for expression. Support for this position comes from the ingenious testing of split brain patients conducted by Sperry (Sperry & Gazzaniga, 1967). If this second hypothesis were true, then hemispheric differences in evoked potential amplitude would also be expected to be small.

The stimuli in this study were all brief and thought to be without specific meaning. Perhaps this lack of meaning can explain the absence of asymmetry in the $P_2$-$N_2$ component. It is also possible that, after several repeated utterances, the minor hemisphere did not encode them as speech, but rather as rhythmic stimuli, and therefore, was more active in processing this information than it would be for words or sentences.

Because identification of the dominant hemisphere for language is only about 90% accurate (Branch et al., 1964), it is possible that one or more subjects were right dominant for speech, or at least not strongly left dominant (Studdert-Kennedy & Shankweiler, 1972), which could have made statistical detection of hemispheric differences across subjects more difficult. Therefore, an analysis of data for individual subjects might be more appropriate for detection of these differences. All of these explanations support a lack of hemispheric asymmetry in general, but none can satisfactorily account for the differential reflection of asymmetry in the $N_1$-$P_2$ and $P_2$-$N_2$ measures.

## Questions and Speculations Based upon Visual Inspection of the Data

The evidence reported by Penfield (Penfield & Rasmussen, 1950; Penfield & Roberts, 1959) and Milner (1962, 1965, 1969) of localization of speech processing within the speech dominant hemisphere indicates that speech production is controlled primarily by Broca's area and perception is located in the temporoparietal area, especially Wernicke's area. For this reason, differences in EPs at the FB and TP locations were expected. The only difference in potential amplitude for these two locations was the indication based upon visual inspection that the FB position might be more sensitive to hemispheric asymmetry for $S_2$ after the speaking conditions. TP was possibly more sensitive to $S_2$ following the hearing condition. If this difference would prove to be statistically significant, it would be supported by the localization of speech functioning within the dominant hemisphere as described by Penfield.

A more puzzling trend which needs statistical verification was the apparent greater amplitude $N_1$-$P_2$ potentials in the right hemisphere for $S_1$ across all conditions, which could not be explained on the basis of amplifier differences which were counterbalanced in this study. A similar finding has been reported for subjects engaged in mental arithmetic (Butler & Glass, 1974). Additional research is needed to determine whether and under what conditions this difference exists, and why it is in conflict with other studies.

Grabow and Elliott (1974), Morrell and Huntington (1971), Ertl and Schafer (1969), and Grözinger, Kornhuber, and Kriebal (1975) proposed that asymmetry in EPs for the hemispheres is probably due to contamination by face, mouth, and tongue movement. Grabow and Elliott produced hemispheric asymmetries during word production by purposely directing the tongue to one side of the mouth. Conversely, Low and Fox (in press) found little asymmetry in the glossokinetic potentials. Although this study produced no EMG evidence that the resulting EPs contained extracerebral artifacts, Ertl and Schafer's (1969) report of contamination of EEGs preceding speech by upper lip movement would suggest that additional and systematic research on this issue is needed. Certainly more EMG placements are necessary, including EOG electrodes to record horizontal eye movements, as this has been found to influence EEG activity recorded at frontal and temporal locations (Low & Fox, in press).

The large positive DC shift occurring in the EPs of some subjects remains unexplained. Its duration was approximately 300 msec. in most subjects, which is roughly the duration of the spoken /ba/. Although subjects were instructed not to move their mouth after saying /ba/, possibly changes in other structures associated with speech termination, such as the vocal cords, larynx, pharynx, soft palate, and epiglottis (Denes & Pinson, 1973), could be responsible for this shift and should be carefully monitored in future investigations. The contamination by horizontal eye movements that might have been associated with the judgement task can not be eliminated, nor can other contributions by facial musculature, although this position was not supported by the limited amount of EMG data collected in this study. The direction of the shift is opposite to that for expectancy waves such as the CNV and Bereitschaft's potential. A number of investigations have observed slow DC shifts in both directions prior to articulation and have reported that these shifts are a function of type of task and electrode location (Ellis, 1972) or respiration (Grözinger et al., 1975). Examination of EPs prior to voice onset might possibly provide additional information about the onset and origin of the DC shift reported here, as the shift resembles those reported by Grözinger et al. (1975) and Morrell and Huntington (1972).

## Conclusions and Implications

The purpose of this study was to develop a methodology suitable for examining cortical activity during and following speech perception and production that controlled many of the variables that have hindered this type of research in the past. The cortical effects after speaking and hearing as well as the effects of immediate versus delayed auditory feedback were investigated using the single stimulus /ba/.

Examination of the data revealed a large positive DC shift in the evoked potentials during speech which prevented analysis of the data obtained during speech. The analysis of the potentials during all hearing conditions for the TP placements has shown that the $N_1$-$P_2$ and $P_2$-$N_2$ components were sensitive to changes in speaking and hearing conditions.

The $N_1$-$P_2$ was also of greater amplitude in the left hemisphere than the right following the speaking ahd hearing conditions. The differential effects of the stimuli preceding the delayed /ba/ indicated that there were differential cortical effects resulting from changes in the auditory feedback associated with speech.

The determination of the precise role of feedback in speech is important for theoretical models as well as clinical applications. Issues such as open- versus closed-loop feedback theories of speech, a motor theory of speech perception versus a more central one without articulatory reference, and the identification of the basic units of speech must be approached through refined techniques employing adequate controls for a sufficient understanding of the neurological processes underlying speech. This basic knowledge is required to broaden understanding of the role of feedback in speech disorders. Stuttering, for example, is dramatically affected by changes in feedback such as delaying auditory feedback, reducing air conducted feedback by masking or having the stutterer whisper, and altering the timing or rhythm of speech by increasing external cues by presenting a rhythmic stimulus like a metronome or having the stutterer sing or speak in unison. A better understanding of the cortical processes during such altered states of feedback may provide valuable clues to the successful treatment of similar speech problems.

Both the statistical findings of this study and the trends that have been suggested by visual inspection of the data produced many questions and directions for future investigations. The origin of the DC shift present in some subjects, the differential effects of speaking with and without immediate feedback on the potentials to a delayed presentation of that same sound, and hemispheric differences reported in this study demand additional exploration. A more complete evaluation of the contribution of the vocal and facial musculature to speech-related EPs is needed. Finally, a variety of systematic manipulations of the speech stimulus employed in this design would result in a greater understanding of cortical activity during speech.

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# Footnote

[1] The phonation timer operates with instantaneous attack time (0.5 msec.) and a fixed decay time, while the standard voice key has an attack time delay and both attack and decay times are a function of amplitude. The author is grateful to George Girod for construction of the phonation timer and the auditory mixer.

# Appendix A: Analyses of Variance

## Table A

The Overall ANOVA for Conditions, Components and Hemispheres

| Source of Variation | Error Term | Sum of Squares | Degrees of Freedom | Mean Square | F |
|---|---|---|---|---|---|
| Conditions (C) | CS | 1033.83 | 3 | 344.61 | 14.08** |
| Subjects (S) | | 1153.37 | 10 | 115.34 | |
| Hemispheres (H) | SH | 10.37 | 1 | 10.37 | 1.14 |
| Components (P) | SP | 559.33 | 2 | 279.67 | 7.13** |
| CS | | 734.19 | 30 | 24.47 | |
| CH | CSH | 22.41 | 3 | 7.47 | 2.17 |
| SH | | 90.60 | 10 | 9.06 | |
| CP | CSP | 408.45 | 6 | 68.07 | 6.26** |
| SP | | 784.58 | 20 | 39.23 | |
| HP | SHP | 27.60 | 2 | 13.80 | 4.85* |
| CSH | | 103.12 | 30 | 3.44 | |
| CSP | | 652.89 | 60 | 10.88 | |
| CHP | CSHP | 11.39 | 6 | 1.90 | 1.02 |
| SHP | | 56.94 | 20 | 2.85 | |
| CSHP | | 112.24 | 60 | 1.87 | |

*$p < .025$

**$p < .001$

## Table B

## ANOVA for Component $P_1 - N_1$

| Source of Variation | Error Term | Sum of Squares | Degree of Freedom | Mean Square | *F* |
|---|---|---|---|---|---|
| C | CS | 72.76 | 3 | 24.25 | 2.05 |
| S | | 291.17 | 10 | 29.12 | |
| H | SH | 1.37 | 1 | 1.37 | .46 |
| CS | | 354.12 | 30 | 11.80 | |
| CH | CSH | 7.28 | 3 | 2.43 | 1.17 |
| SH | | 29.70 | 10 | 2.97 | |
| CSH | | 61.76 | 30 | 2.06 | |

Table C

ANOVA for Component $N_1 - P_1$

| Source of Variation | Error Term | Sum of Squares | Degrees of Freedom | Mean Square | *F* |
|---|---|---|---|---|---|
| C | CS | 844.45 | 3 | 281.48 | 14.38** |
| S | | 455.71 | 10 | 45.57 | |
| H | SH | 36.06 | 1 | 36.06 | 5.71* |
| CS | | 587.43 | 30 | 19.58 | |
| CH | CSH | 19.07 | 3 | 6.36 | 1.64 |
| SH | | 63.12 | 10 | 6.31 | |
| CSH | | 116.50 | 30 | 3.88 | |

*$p < .05$

**$p < .001$

## Table D

## ANOVA for Component $P_2 - N_2$

| Source of Variation | Error Term | Sum of Squares | Degrees of Freedom | Mean Square | *F* |
|---|---|---|---|---|---|
| C | CS | 525.07 | 3 | 175.02 | 11.78* |
| S | | 1191.08 | 10 | 119.10 | |
| H | SH | .55 | 1 | .55 | .10 |
| CS | | 445.59 | 30 | 14.85 | |
| CH | CSH | 7.45 | 3 | 2.48 | 2.01 |
| SH | | 54.72 | 10 | 5.47 | |
| CSH | | 37.10 | 30 | 1.24 | |

*$p < .001$