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INTER-EAR ASYMMETRY AND BINAURAL INTERACTION IN THE
BRAINSTEM AUDITORY EVOKED POTENTIALS

City University of New York

PH.D. 1985

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INTER-EAR ASYMMETRY AND BINAURAL INTERACTION
IN THE BRAINSTEM AUDITORY EVOKED POTENTIALS

by

Lynn Spivak

A dissertation submitted to the Graduate Faculty in Speech and Hearing Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

1985

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This manuscript has been read and accepted for the Graduate Faculty in Speech and Hearing Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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Abstract

INTER-EAR ASYMMETRY AND BINAURAL INTERACTION
IN THE BRAINSTEM AUDITORY EVOKED POTENTIALS

by

Lynn Spivak

Advisor: Professor Michael Seitz

Evidence of binaural interaction has been found in the brainstem auditory evoked potentials (BSAEP). This evidence, which takes the form of a difference trace when the monaural responses are summed and subtracted from the binaural response, however, is subject to artifactual contamination which is introduced when the BSAEP waveforms are subjected to algebraic operations. Right/left response asymmetry has been identified as a confounding variable in studies of binaural interaction.

This study examined right/left response asymmetry and its relationship to measurements of binaural interaction. It was hypothesized that response asymmetry would be present in the monaural responses of a significant number of normal hearing subjects and that the presence of significant asymmetry would cause the sum of right and left monaural responses to be a poor predictor of the binaural response, thereby resulting in a large difference trace (residual component) when the

binaural response was subtracted from the combined monaural response.

Right, left, and binaural BSAEPs were recorded from 24 normal hearing subjects at 70 and 50 dB SL. Monaural responses were classified as asymmetrical when the amplitude of right - left difference trace exceeded the amplitude of the background noise. When significant asymmetry was present, the interaural intensity of the stimuli was adjusted in an attempt to reduce the asymmetry.

A significant proportion of normal hearing subjects had asymmetrical monaural BSAEPs. Classification of responses as asymmetrical was dependent on the operational definition of asymmetry, the criterion used, and the sensation level of the stimulus. Five different patterns of asymmetry were identified depending on the inter-ear wave V latency and amplitude relationships. The degree of asymmetry present was positively correlated with the amplitude of the residual component. It was found that interaural intensity adjustments significantly reduced asymmetry. When asymmetry was reduced, the amplitude of the residual component was significantly reduced.

It was concluded that inter-ear asymmetry in the BSAEP is the rule rather than the exception. The significant correlation between the degree of inter-ear

asymmetry and the amplitude of the residual component indicated that asymmetry is an important factor which must be accounted for in studies of binaural interaction in the BSAEP.

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When one begins a doctoral dissertation it is probably common to be preoccupied with the enormity of the task which awaits the writer. It is only after the project is underway that the writer begins to realize that the task is being shared by many people without whom the dissertation could never be completed. Each individual whom I acknowledge in this section has made a valuable contribution to this dissertation, and I am indebted to each one of them.

Much of the burden of bringing a dissertation to fruition is borne by the student's chairman. I consider myself very fortunate to have had Professor Michael Seitz to guide me through this difficult undertaking. He was insightful when a problem needed solving, critical when he knew I could do better, supportive when I felt overwhelmed, and, most of all a friend on whom I could always rely for direction and encouragement.

I was also fortunate to have a committee which contributed a unique and illuminating perspective to the study. I am grateful to Professor Arthur Boothroyd whose insight and attention to detail contributed enormously to both the manuscript and the data analysis. To Professor Harry Levitt I am indebted for forcing me to realize the true significance of the study and insisting that the

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important but are also the most difficult to adequately express. All of my frustrations as well as my joys were shared by three very special people. I, therefore, dedicate this work to my sons, Joshua and Mitchell, who gallantly managed to get along without me while I was preoccupied with writing the dissertation, and to my husband, Steven without whom I probably would have never started and most certainly could have never finished.

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CHAPTER 1

INTRODUCTION AND BACKGROUND LITERATURE REVIEW

There are many auditory phenomena which result from hearing with two ears that cannot be replicated by hearing with one ear alone. Depending on the time, phase and intensity relationships of the signals as they reach the two ears, sounds are localized in space, loudness is increased, threshold is improved, and the masking effects of noise are reduced. The unique perceptual experiences to which binaural hearing gives rise, result from neural processing of binaural signals that is fundamentally different from the neural processing of monaural signals. Signals which are received by the two ears are not independently transmitted through separate neural channels within the central auditory nervous system (CANS). On the contrary, interaction between the two channels is evident at every level of the CANS, from the auditory cortex to the superior olive (Altman, 1978). The term binaural interaction is used to denote the special properties of binaural hearing that cannot be explained on the basis of a simple summation of monaural effects.

Studies of binaural interaction have traditionally approached the subject from either a

psychoacoustic or an electrophysiological point of view. The following will briefly review binaural interaction from each perspective.

Psychoacoustic Studies

Psychoacoustic studies of binaural interaction include those studies which examine the perceptual effects of binaural stimulation. They attempt to describe how the perception of binaurally presented sound differs from the perception of monaurally presented sound. They also attempt to identify the specific combinations of stimulus parameters which give rise to specific binaural perceptions. These studies reveal that the effects of binaural stimulation are not easily predictable based on the expected effects of merely adding or omitting a second input to a central processor. The non-linear nature of binaural phenomena, where $1 + 1$ does not equal 2, is evident in three major categories of binaural phenomena, namely, loudness summation, sound localization and the binaural masking level difference. A brief description of each of these phenomena follows. In each case, there is an underlying assumption that signals from the two ears must converge somewhere within the CNS where they undergo a form of processing which is unique to binaural signals.

Loudness Summation. The monaural threshold

can be improved by approximately 3 dB by presenting sounds simultaneously to the two ears. This phenomenon, Hirsh (1948a) points out, is dependent on the equality of the two ears and appears to be explainable based on a simple central power summation of two auditory inputs. Other explanations, however, have been suggested. Diercks and Jeffress (1962) considered the monaural threshold to be a masked threshold and therefore attributed the improvement in binaural threshold to binaural release from masking. It has also been proposed that, since the probability of detecting a signal presented to two ears is greater than the probability of detecting a signal presented to only one ear, binaural loudness summation is explainable as a purely statistical advantage (Smith and Licklider, 1949). This explanation, of course, does not necessarily require a central processor where binaural interaction takes place.

The role of a central processor becomes more evident when loudness perception of sounds above threshold is examined. As the intensity of sounds is raised above threshold, the relationship between monaural and binaural loudness does not remain constant. There is a proportionately larger increase in the loudness of binaural sounds as compared to equally intense monaural sounds. Reynolds and Stevens (1960) found that loudness grows as a power function of intensity with an exponent

of 0.53 for monaural stimuli and 0.60 for binaural stimuli. The effect is an increase in the loudness of binaural as compared to monaural sounds from 3 dB near threshold to as much as 10 dB for 90 dB SPL sounds. The increase in loudness summation with increases in intensity has been linked to neural recruitment (Treisman and Irwin, 1967) and points to a central summation process. Reynolds and Stevens attribute the value of the binaural exponent, at least partially, to a central summation process, noting that the superiority of binaural over monaural hearing increases as stimulus level increases.

Sound Localization. The ability to localize a sound in space depends on comparison of interaural differences in the sound as it reaches the two ears. Sound which reaches both ears simultaneously and with equal intensity is localized directly in front of the listener. On the other hand, sound which does not reach the ears equally, is localized toward the ear stimulated first, or the ear receiving the more intense signal. (Trimble, 1928 in Mills, 1972). Interaural time differences have been identified as most important for the localization of low frequency signals, while interaural intensity differences provide an important cue for localization of signals above 1500 Hz (Mills, 1960).

A perceptual experience, analagous to sound

localization in free space, occurs when sounds are presented through earphones (Jeffress and Taylor, 1961). When sounds are transduced through earphones, time and intensity cues can be independently manipulated to produce combinations of cues which could not occur in nature. In this way the trading relationship between time and intensity can be examined. It was discovered that a sound image which is displaced from the midline (lateralized) on the basis of an interaural time difference favoring, for example, the right side, could be brought back to midline with an interaural intensity difference favoring the left side (Deatherage and Hirsch, 1959; Harris, 1962). This phenomenon was believed to be mediated by a central mechanism, the operation of which has been the subject of much speculation.

The latency hypothesis formed the basis for the early models of sound localization. According to this theory, the central mechanism analyses time differences only. Interaural differences in intensity are converted to differences in time at the periphery and subsequently analysed as interaural time differences (David, Guttman, and Van Breegeijk, 1959; Harris, 1962; Jeffress, 1948). The ultimate representation of Δt was variously described as difference in place (Jeffress, 1948), or numbers of excited and inhibited units (von Békésy, 1960; Van Breegeijk, 1962). The finding that the

time-intensity trade was less than perfect, however, led to the alternative theory that intensity is independently represented in the central auditory nervous system (CANS) (Babkoff and Sutton, 1969; Moushegian and Jeffress, 1959; Whitworth and Jeffress, 1961). The model proposed by Sayers and Cherry (1957), for example, assumes a running cross correlation between the inputs from the right and left ears, and provides for the separate representation and analysis of interaural intensity differences.

Binaural Masking Level Difference. The improvement in a listener's ability to detect a signal in the background of noise is another attribute of binaural hearing. The binaural masking level difference (BMLD), as this phenomenon is called, was first described by Licklider (1948) and Hirsh (1948b). The BMLD is typically demonstrated by presenting tones and noise binaurally. The greatest improvement in threshold is found for low frequency tones (15 dB at 250 Hz) with an interaural phase relationship of 180 degrees when presented against a background of correlated noise. Levitt and Rabiner (1967) have demonstrated a similar improvement in the detection of single words which are presented in a background of gaussian noise. The 13 dB improvement in threshold for speech was attributed to the interaural phase opposition in the low frequency region of the speech spectrum.

While several models have been proposed to explain the BMLD, the Equalization and Cancellation model by Durlach (1972) is considered to be the most comprehensive (Levitt and Voroba, 1974). The model assumes a central processor which performs two transformations on the incoming signal. The E-transformation equalizes the noise components of the signal arriving from the two ears. The C-transformation, then subtracts the complete signal of one side from the complete signal of the other side. The result is the elimination of the interfering noise, allowing improved detection of the signal.

Studies of psychoacoustic binaural phenomena assume a central mechanism which receives, analyses, compares, and transforms the neural inputs arising from the right and left ears as a result of binaural stimulation. The location and operation of these mechanisms can only be inferred based upon information provided by anatomical and electrophysiological studies of the CANS. Jeffress (1948) for example, speculated that the interaural comparisons described in his model took place within the superior olivary complex (SOC). The choice of the SOC was motivated by the fact that the SOC is the first area of bilateral convergence in the brainstem auditory pathway. While the neuroanatomy of the SOC and higher brainstem structures qualifies them as

sites at which binaural interaction could occur, it was up to electrophysiological studies to confirm the existence of binaural interaction in the brainstem.

Electrophysiological Studies

Electrophysiological studies have uncovered evidence of binaural interaction at every level of the CANS, above the level of the first bilateral convergence. These studies employed recording electrodes placed in or near neuronal units within the CANS. The coincidence of pathways from the right and left ears at each level was evident from the ability to elicit responses to both ipsilateral and contralateral stimulation. Complex patterns of excitation and inhibition among CANS units have been demonstrated throughout the CANS. The ability of individual units to respond to both ipsilateral and contralateral stimuli has been demonstrated in the superior olivary complex (SOC) (Galambos, Schwartzkopff, and Rupert, 1959; Hall, 1965), the lateral lemniscus (Rosensweig and Sutton, 1958), the Inferior Colliculus (Kemp and Robinson, 1937), the medial Geniculate Body (Leqouix and Kayser, 1965, in Altman, 1978) and the auditory cortex (Hall and Goldstein, 1968).

As Altman (1978) points out, however, demonstrating the coexistence of right and left pathways at an electrode site does not necessarily imply right and

left convergence. Altman states:

One of the methods used measured gross responses to ipsilateral, contralateral, and to binaural stimulation. However, the finding that responses occur upon both ipsilateral and contralateral signal presentation indicates only that there are pathways at the recording site connected with both cochleae. However, when at a given level the response to binaural stimulation is less than the algebraic sum of the responses to ipsi- and contralateral stimulation, then there is a real bilateral afferent convergence. Research along such lines has been carried out at various levels of the auditory pathways: in the cochlear nuclei, the trapezoid body, the superior olive, the lateral lemniscus, the inferior colliculus, the medial geniculate, and the auditory cortex (Altman, 1972, p. 50).

In a classic experiment which typifies this type of research, Rosensweig and Sutton (1958) recorded responses from the lateral lemniscus of cats to time delayed monaural and binaural stimuli. These researchers hypothesized that if right and left ear stimuli evoked responses in independent populations of neural elements, then the response to time delayed binaural stimuli would

be equal to the sum of the right ear response and the left ear response which was delayed by the amount of delay present in the binaural stimuli. Results indicated that, on the contrary, the presense of the leading ear (right) response caused the response from the lagging left ear to be significantly attenuated. After subtraction of the right response from the binaural response, only the modified left ear response remained. The amplitude of the remaining left ear response was significantly smaller than the amplitude of left ear response obtained with monaural stimulation. These results were interpreted as evidence for convergence of the right and left pathways at the level of the lateral lemniscus. In a similar manner, evidence of bilateral convergence has been found at all levels of the auditory system, from the superior olive to the auditory cortex (Altman, 1978; Jaffe and Hageman, 1969; Hall, 1965; Hind, Goldberg, Greenwood and Rose, 1963; Mast, 1970; Wernick and Starr, 1968).

Thus, there is strong evidence from electrophysiological experiments that binaural interaction exists in the CANS. Activity of units depends on whether the stimulus is ipsilateral, contralateral, diotic (equal stimulation to each ear) or dichotic (interaural stimulus difference). By creating the stimulus parameters which cause binaural perceptions, and

studying their effects on unit activity at different levels of the CANS, the structures which subserve binaural perception has been inferred.

If structures within the brainstem auditory pathways are responsible for the interactions which give rise to binaural phenomena, then there should be a functional relationship between the integrity of the brainstem and performance on binaural tasks. This relationship has been demonstrated by means of lesion experiments in animals. For example, Cassidy and Neff (1975) and Jenkins and Masterton (1982) tested the localization ability of cats before and after lesioning various points along the brainstem auditory pathway, which were believed to be critical for binaural processing. Results of both studies suggested that binaural cues for localization are first encoded in the superior olive and are then either reflected or refined at higher centers. Similar relationships between brainstem structures and the ability to perform binaural tasks have been implied by studies of human subjects with confirmed brainstem lesions (Lynn, Gilroy, and Taylor, 1981; Nilsson, Liden, and Rosen, 1973; Pinheiro and Tobin, 1969; Snow, Rintlemann, and Miller, 1977).

With the role of brainstem neural activity in binaural interaction firmly established, attention turned to finding a far field correlate of binaural interaction.

The use of surface electrodes to record underlying brainstem activity greatly reduced methodological difficulties and made the procedure applicable to human as well as animal subjects. At the same time, the use of the new technique created problems of interpretation which have not, as yet, been completely resolved.

Auditory Evoked Potentials

The use of surface recorded auditory evoked potentials for investigation of the electrophysiology of the auditory system was made possible by the development of the averaging computer in the early 1950's. The averaging computer allows detection of minute neuroelectric potentials, often only a fraction of a microvolt in size, by superimposing the time locked responses to many acoustic stimuli while simultaneously cancelling random EEG activity. The result is the extraction of the auditory evoked potential from the background noise.

Auditory evoked potentials are recordable from every level of the CNS. These potentials are roughly segmented according to their presumed generator sites--auditory nerve and brainstem, thalamocortical areas and auditory cortex--and are classified according to their post stimulus latencies (Figure 1).

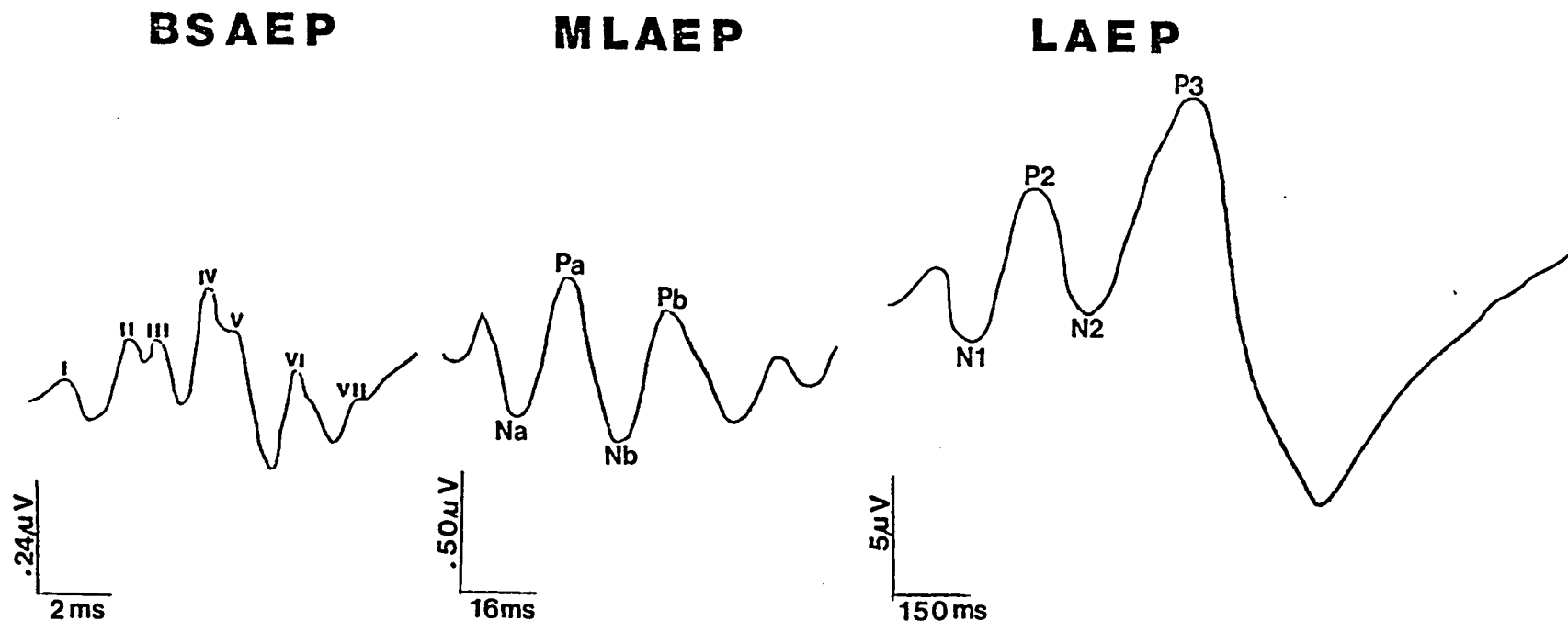


Figure 1. The three primary divisions of the auditory evoked potentials: BSAEP-brainstem auditory evoked potential, MLAEP-middle latency auditory evoked potential, LAEP-late auditory evoked potential.

The Late Auditory Evoked Potential (LAEP) occurs 50 - 300 ms after stimulus onset. The response is a slow, triphasic wave with peak N1 at approximately 90 ms, P2 at approximately 180 ms and N2 at approximately 250 ms. The source of the LAEP is believed to be the primary auditory cortex, the temporal auditory association cortex and the frontal association areas (Picton, Hillyard, Krauz, and Galambos, 1974; Seitz, Jacobson, Weber and Morehouse, 1980; Vaughn and Ritter, 1970).

The Middle Latency Evoked Potentials (MLAEP) occur between 10 and 50 ms. The MLAEP is characterized by a "W" shaped wave with peak Na occurring at approximately 20 ms, Pa at approximately 35 ms and Nb at approximately 45 ms. Although the MLAEP is often subject to myogenic contamination (Bickford, Jacobson, and Cody, 1964), cortical surface recordings from humans (Ruhm, Walker and Flanagan, 1967) and topography studies (Cohen, 1982; Goff, Matsumiya, Allison and Goff, 1977; Streletz, Katz, Hohenberger, and Cracco, 1977) suggest that the MLAEP is neurogenic, arising primarily from thalamocortical areas.

The early, or Brainstem Auditory Evoked Potential (BSAEP) was first described by Jewett and Williston (1971). It consists of a series of 5 - 7 vertex positive waves occurring within the first 10 ms after stimulus onset. Lesion studies performed on cats indicated that the BSAEP arises from multiple generators located within

the brainstem (Allen and Starr, 1978; Buchwald and Huang, 1975; Jewett, 1970; Starr and Achor, 1978). The generator of wave I is, undoubtedly the auditory nerve. The later waves represent successive activation of higher brainstem nuclei (the cochlear nucleus, superior olive, lateral lemniscus and inferior colliculus) with each wave apparently reflecting concurrent activity of several generators (Starr and Achor, 1978).

The auditory evoked potentials, then, represent neuro-electric activity from CNS structures that electrophysiological studies have identified as sites of neural interaction and essential for binaural perceptual tasks. Strengthening the hypothesis that the AEPs are correlated with binaural auditory processing are several recent studies which have examined the relationship between the BSAEP and the ability to perform binaural psychoacoustic tasks in patients with confirmed brainstem lesions. These studies revealed a correlation between abnormal BSAEPs and abnormal performance on tasks of auditory localization (Hausler and Levine, 1980; Russolo and Poli, 1983; Zerlin and Mowry, 1980) and the binaural masking level difference (Hannley, Jerger and Rivera, 1983; Noffsinger, Martinex, and Schaefer, 1982). The implication is that the structures which are necessary for binaural processing are also the generators of the BSAEP. One might reasonably expect, therefore, that the

effects of binaural processing would be detectable by examination of the BSAEP.

The relationship between the monaural and binaural responses is not well understood. If the information present in the binaural response represents a combination of information present in each monaural response, then, given knowledge of the monaural responses, it should be possible to predict the binaural response. Failure to predict the binaural response by means of a simple linear combination of monaural responses may indicate one of the following situations:

- 1) The binaural response is predictable from a knowledge of the monaural responses but the model for combining the monaural responses is inappropriate (perhaps too simple), and does not accurately represent the way in which the auditory system combines right and left auditory tract information.

- 2) The binaural response is not predictable from a knowledge of the monaural responses because,

- a) the monaural and binaural responses reflect activation of different populations of neurons depending upon whether the stimulus is monaural or binaural, or

- b) differences between monaural and binaural responses merely reflect an artifact of the far field recording process, or

c) the binaural response represents the effects of neural activity which occur only when the stimulus is binaural.

Most of the current research has adopted the last position, assuming that failure to predict the binaural response by simply adding together two monaural responses indicates the presence of binaural interaction. The sections which follow outline the way in which the relationship between monaural and binaural responses has been handled in the literature, some of the problems associated with the assumptions underlying these approaches, and finally, present an alternative approach for studying monaural/binaural relationships.

The search for an electrophysiological correlate of binaural interaction in the auditory evoked potentials has proceeded along two routes. One method involves documenting the differences between binaural and monaural evoked potentials; the second method, borrowed from electrophysiological research, subtracts the binaural response from the sum of the right and left monaural responses and examines the resulting difference trace.

Monaural vs. Binaural Evoked Responses. The focus of early investigations of binaural interaction in the auditory evoked potentials was limited to comparisons between responses obtained to monaural and binaural

stimuli. The most notable difference between monaurally and binaurally recorded auditory evoked responses is the difference in amplitude between the two responses. In general, it has been found that binaural responses are larger in amplitude but equal in latency when compared to monaural responses. The increase in binaural response amplitude has been attributed to binaural summation of loudness, a binaural phenomena which accounts for a 3-10 dB increase in the perceived loudness of the signal when the mode of stimulation is changed from monaural to binaural (Reynolds and Stevens, 1960).

Differences between monaurally and binaurally recorded responses have been demonstrated for evoked responses in all three latency categories. In 1968, Allen reported that binaural stimulation produced larger amplitude cortical potentials than did monaural stimulation. Although there was a great deal of intersubject variability, on average, binaural responses were approximately 21% larger than monaural responses. This figure agreed well with that reported by Davis and Zerlin (1966) who found that the binaural cortical response was 20% larger than the monaural response.

Skinner and Shimota (1968) reported that binaural middle latency evoked potentials (MLAEP) were significantly larger than monaural MLAEPs. Unlike Allen (1968) who found no correlation between binaural

summation and stimulus level for the vertex potential, Skinner and Shimota found that the greatest amount of binaural summation was present at threshold while the least amount of binaural summation was present at higher sensation levels. This result was interesting because it was the reverse of the binaural summation pattern found in psychophysical studies.

Dobie and Norton (1980) and Hood, Martin and Berlin (1983) reported results which indicated that, while amplitude differences did exist between monaural and binaural MLAEPs, binaural MLAEP amplitudes were considerably less than twice the monaural MLAEP amplitudes. Hood et al. state that binaural summation in the MLAEP appeared to be governed by different rules from those governing the BSAEP, where the binaural response is proportionately larger than the monaural response.

There is general agreement that binaural summation exists in the the early AEPs. Blegvad (1975) compared the amplitudes and latencies of waves I - V and the FFP7 (negative wave following wave V) using monaural and binaural stimulation at 6 different intensities ranging from 90 - 10 dB SL. Binaural responses were found to be 60% larger than monaural responses on average while latency was unaffected by stimulus condition. Unlike the binaural summation in the MLAEP which appeared to be related to stimulus level, binaural summation in

the brain stem potential was found to be independent of stimulus intensity. Blegvad's results were in good agreement with those of other researchers who invariably reported larger amplitudes for binaural than monaural BSAEPs, while latencies remained unaffected by stimulus mode. (Jewett and Williston, 1971; Starr and Achor, 1975; Van Olphen, Rodenburger, and Verwey, 1978).

Considering that the binaural response represents the contribution of two neural pathways as compared to one neural pathway when the stimulus is monaural, the increase in response amplitude which occurs as a result of binaural stimulation is not surprising. Assuming equal and independent contributions from the the right and left ears, one would expect the binaural response to be equal to two times the monaural response. However, while the degree of summation and the interaction with stimulus parameters appears to differ depending on which latency region of the auditory evoked potentials is being examined, at no level does the binaural response reflect a linear addition of two independent monaural responses. It has been assumed that the fact that the binaural amplitude is invariably less than twice the monaural amplitude indicates a non-linear summation of the activity from the right and left auditory pathways due to neural interaction between the right and left pathways.

Evidence that the binaural response is not

necessarily a reflection of underlying binaural interaction, however, has recently been reported. For example, Howe and Decker (1984) have suggested that the binaural BSAEP is unrelated to binaural loudness perception. Previous to this study, only a handful of studies have attempted to correlate loudness perception with the AEPs. Results indicated that the growth in amplitude of the AEPs follows a power function analogous to the power function described by Reynolds and Stevens (1960) for growth in perceived loudness. This pattern has been documented for the monaural LAEP (Keidel and Spreng, 1965) and the monaural BSAEP (Pratt and Sohmer, 1977), but not for the MLAEP (Madell and Goldstein, 1972).

Only one study has attempted to correlate changes in the binaural AEPs with perception of loudness. Howe and Decker (1984) found that the latency-intensity functions for the BSAEP can be described as a power function. Unlike the psychophysical results, however, the exponents for both monaural and binaural latency-intensity functions were nearly identical. The failure to find a significant difference between the exponents which describe the rate of latency change in the monaural and binaural conditions, comparable to that found in psychophysical studies, caused these authors to speculate that the binaural response is not a reflection of underlying binaural loudness perception.

It should be noted that the analysis in the Howe and Decker (1984) study was limited to latency. Nevertheless, results of this study weakened the argument that the binaural BSAEP is correlated with binaural perception and posed a serious challenge to claims that effects of binaural interaction can, somehow, be extracted from the binaural BSAEP.

$$\underline{(\text{Right} + \text{Left}) - \text{Binaural} = \text{BIC.}}$$

Monaural/binaural comparisons suggested a difference in the way monaural and binaural stimuli are processed, however, they shed little light on the way in which the contribution of each ear combines to form the binaural response. In order to study the relationship between the monaural and binaural responses, Dobie and Berlin (1979a) adopted the algebraic addition and subtraction techniques which were used to demonstrate binaural interaction in the gross electrical responses in the CANS of animals. Dobie and Berlin defined binaural interaction in the auditory evoked potentials as "any deviation from the predictions of a noninteractive linear model" (Dobie and Berlin, 1979a, pg. 391). That is, if the algebraic addition of the right and left monaural responses fails to equal the binaural response, binaural interaction was implied. The Dobie and Berlin procedure was applied to human auditory evoked potentials in an attempt to

demonstrate the presence of binaural interaction in the BSAEP (Dobie and Berlin, 1979a; Dobie and Norton, 1980; Wrege and Starr, 1981) the MLAEP (Dobie and Norton, 1981; Hood, Berlin, and Hughes, 1983) and the LAEP (Hood et al., 1983).

Dobie and Berlin's technique has found wide spread acceptance in spite of the fact that its appropriateness for analysis of evoked potentials has never been firmly established. The auditory evoked potentials are complex events representing a far field summation of activity from a variety of generators. The potentials which are recorded at the scalp, then, bear little resemblance to the single unit spikes which are recorded with depth electrodes. It is probably an oversimplification to expect addition and subtraction of these complex potentials to yield the same kind of information which is derived from adding and subtracting single unit activity. On a purely technical level, algebraic manipulations of complex waveforms may result in the introduction of artifact. Claims that Dobie and Berlin's "binaural interaction component (BIC)" is the result of artifact already exist in the literature. Ainslie and Boston (1980), for example, attributed the BIC to acoustic cross talk. In addition, Decker and Howe (1981) discovered that the presence of small inter-ear asymmetries in the monaural responses had a pronounced

effect on the BIC. Waveforms which are different with respect to phase are more appropriately combined by means of vector addition rather than algebraic addition. Apart from these technical problems associated with deriving a BIC, there are, as yet, no data which demonstrate a strong correlation between the BIC and psychoacoustic measures of binaural interaction. If the BIC is to be of any value, this type of correlation must be established.

Focus of The Present Study

The present study was motivated by an interest in binaural phenomena and the neurophysiology which subserves it. Dobie and Berlin's binaural interaction component appeared, at first glance, to be a promising device for representing binaural interaction in the auditory evoked potentials. Too many theoretical and technical problems remain unsolved, however, for its wholesale acceptance as a true neurophysiological correlate of binaural interaction. Until these problems are addressed, it is recommended that the term "binaural interaction component" be replaced with a more neutral term. For that reason, the result of subtracting the binaural from the summed monaural waveforms will be referred to in this study as the "Residual Component" (RC).

The premise here is that current knowlege does

not permit one to assume that the residual component represents neural interaction. It does, however, represent the extent to which the binaural response can be predicted from a combination of the monaural responses. A null residual component, $(R + L) - Bin = 0$, indicates perfect prediction of the binaural response from a linear addition of the right and left monaural responses. The presence of a residual component, on the other hand indicates less than perfect prediction of the binaural response from the sum of the two monaural responses. The residual component, then, may prove to be a valuable tool for the examination of the relationship between monaural and binaural processing.

In order to gain insight into the relationship between monaurally and binaurally evoked BSAEPs, the present study was designed to examine various ways of combining monaural responses and their ability to predict the binaural response. Considering the importance of interaural time and intensity relationships to binaural perception, an issue which appears to be particularly relevant to a study of this type is the presence of small inter-ear asymmetries in the monaural responses. Do inter-ear asymmetries preclude accurate prediction of the binaural response by means of linear addition of the right and left monaural responses? Data reported by Decker and Howe (1981) suggest that this is true. If so,

then would the prediction become more accurate if the right and left responses were equalized? It was expected that linear summation of symmetrical right and left responses would provide a better predictor of the binaural response than linear summation of asymmetrical right and left responses. This study, therefore, focused on three major issues: first, the determination of the presence of inter-ear asymmetry; second, the efficacy of offsetting asymmetry by means of an interaural intensity difference; and finally, the relationship between naturally occurring asymmetry and the ability to predict the binaural response by means of a linear combination of monaural responses.

CHAPTER 2

REVIEW OF THE LITERATURE

The search for an electrophysiological correlate of binaural interaction has concentrated on comparisons between the binaural and monaural auditory evoked responses. The assumption underlying this approach is that the binaural response reflects a summation of activity which is represented in each monaural response. To the extent that this is true, such comparisons may provide insight into the neural mechanisms of binaural interaction. However, at present, there is insufficient evidence to support this position and an increasing amount of evidence which argues against it.

The precedent for comparing the binaural response to the sum of two monaural responses was set in neurophysiological research, and was reviewed in the previous chapter. Part I of the literature review which follows deals with efforts of researchers to apply this method of examining binaural interaction to the BSAEP. Part II is concerned with auditory tract asymmetry and its relationship to studies of binaural interaction. Part III discusses asymmetry which is induced by means of interaural time or intensity differences in the response eliciting stimulus, and the relationship of these

stimulus manipulations to measures of binaural interaction.

PART I

Binaural Interaction in the BSAEP

The first section of part I examines efforts to demonstrate the presence of binaural interaction in evoked potentials of animal subjects; the second section examines binaural interaction studies of human subjects. The third section focuses on methodological problems with binaural interaction studies and associated questions which have emerged regarding the validity of their results.

Binaural Interaction--Animal Subjects

The first reference to binaural interaction in far field potentials appeared in Jewett (1970). BSAEPs were recorded from electrodes placed in rostral brain locations and on the scalps of 18 anesthetized cats. The volume conducted response which could be recorded from a variety of locations, consisted of four positive waves (P1, P2, P3, and P4). The location of the generator of each wave was inferred from depth electrodes which were moved, stereotaxically along tracts in the vicinity of the classical auditory pathways. Results suggested that

while the scalp recorded P1 represents first order neurons, P2, P3 and P4 are each a composite of activity from several successively activated generators.

Comparing responses to monaural and binaural stimuli, it was found that monaural P1, P2 and P3 added algebraically to equal the binaural P1, P2 and P3. However, the amplitude of the binaural P4 was smaller than expected based on summation of the monaural responses. When the click to one ear was delayed relative to the click to the other ear, P4 of the first response added algebraically to P1 of the delayed response. This phenomenon was considered consistent with recording of two separate generators in a volume conductor. The reduced amplitude of P4 in binaural recordings, however, suggested the possibility of either convergence at the level of the P4 generator or mutual inhibition from the two ears.

Jewett's demonstration of neural interaction was later confirmed by Huang and Buchwald (1978) in a study intended to show the effect of parametric changes in stimuli (eg. intensity, repetition rate, duration) on the BSAEP. In this study, BSAEPs were recorded from an active surface electrode placed at A7 (just off midline) and referred to the pinna on 17 cats. Comparison of responses to binaural stimulation to the sum of responses to monaural stimulation resulted in no difference for waves

P1, P2, or P3 (ie. $R_m + L_m = Bin$). The binaural P4, however, was smaller than predicted based on the summed monaural response (ie. $R_m + L_m \neq Bin$). Huang and Buchwald interpreted this finding as evidence for convergence of crossed and uncrossed input to the generators of wave P4. The apparent lack of occlusive effect on P3, which Huang and Buchwald associated with activity in the superior olive where the first binaural representation occurs, was unexpected. It was, however, consistent with lesion studies in which P3 disappeared as a result of lesions which interrupted crossed fibers but left uncrossed fibers intact (Buchwald and Huang, 1975).

Both Jewett (1970) and Huang and Buchwald (1978) inferred the existence of binaural interaction based on differences in peak amplitudes when summed monaural and binaural responses were compared. This comparison was limited, however, to interactions which manifested themselves as peak amplitude differences between the summed monaural and binaural responses.

Another approach which appeared sensitive to both amplitude and latency differences throughout the entire BSAEP was originally described by Wernick and Starr (1968) and adapted by Dobie and Berlin (1979a) for the purpose of studying binaural interaction in scalp recorded brainstem potentials. The procedure involved computer addition of two monaural responses to form a

"predicted binaural response" from which the true binaural response was subtracted. Binaural interaction was operationally defined as "any deviation from the predictions of a noninteractive linear model" (Dobie and Berlin, 1979a, p. 391). That is, assuming that there are two independent sets of generators, one for each ear, a right and a left monaural response should algebraically sum together to equal a binaural response. Subtraction of the binaural response from the summed monaural response would equal zero and, according to the authors, indicate no binaural interaction.

In order to test this model, Dobie and Berlin recorded the BSAEP from 10 guinea pigs. A midline (nuchal) reference was chosen in order to equalize the contribution of each auditory tract. Contrary to the predictions of the noninteractive, linear model, summation of the left and right monaural responses did not produce a waveform equal to the binaural response. The peak to peak amplitude of wave P4 of the true binaural response, in fact, was smaller in amplitude than the predicted binaural response. In addition, the latency of the negative peak following P4 was shorter (approx. 2 ms) in the true binaural as compared to the predicted binaural response. Subtraction of the true binaural response from the predicted binaural response resulted in a "difference trace" corresponding in latency to peak P4

and the following negative trough of the brainstem response. Dobie and Berlin consistently found this difference trace in the latency region corresponding to waves P4 and the negative peak following P4, the presumed generator of which is the inferior colliculus (Buchwald and Huang, 1975; Jewett, 1970). These authors, therefore, speculated that the BIC reflected neural interaction from third order neurons above the level of the first bilateral convergence (SOC). The difference trace, which was called the "derived binaural interaction component" (BIC) was interpreted by Dobie and Berlin as evidence for binaural interaction in the BSAEP.

Binaural Interaction--Human Subjects

Dobie and Berlin (1979a) had clearly demonstrated that the binaural BSAEP of guinea pigs was not predictable from a linear summation of the right and left monaural BSAEPs. Their claim that the result of subtracting the binaural from the sum of two monaural BSAEPs (BIC) is an indication of binaural interaction motivated other researches to demonstrate a similar occurrence in the BSAEPs of human subjects. The BIC is interesting from a purely scientific view point, as a device for examining CANS processing. In addition, an electrophysiological correlate of binaural interaction which is easily and objectively obtained is a potentially

powerful clinical tool for assessing brainstem function. The potential usefulness of such a measure for evaluation of children with learning disabilities, children with chronic otitis media and stutterers has been suggested (Dobie and Berlin, 1979a, 1979b; Decker et al., 1982).

Attempts to demonstrate binaural interaction, as described by Dobie and Berlin, in human evoked potentials were initially unsuccessful. Gerken Moushegian, Stillman and Rupert (1975) examined the effects of binaural stimulation on the frequency following response recorded from five human subjects. The frequency following response, or FFR, is a series of sinusoidal waves with a period equal to the period of the eliciting stimulus occurring approximately 6ms after stimulus onset. In this study the FFR was elicited by 500 Hz tone bursts presented diotically (identical stimuli to each ear) or dichotically (interaural stimulus difference) with respect to phase and intensity. Gerken et al. concluded that binaural interaction was not present in the FFR based on the finding that the sum of two monaural responses equalled the binaural response. The relationship between responses produced by monaural stimuli and binaural stimuli was consistent with the predictions of the authors' proposed model which assumed that the FFR was generated by independent populations of spatially compact neurons within each auditory tract.

Huang (1980) was similarly unsuccessful in his experiments with human subjects. Although he found evidence of what he considered to be binaural interaction in the brainstem potentials of rats, guinea pigs, cats and dogs, he failed to find any evidence of binaural interaction in the brainstem potentials of his six human subjects. Interspecies differences in brainstem anatomy including size of the fiber tracts, orientation of the generators and conductivity of the brain, require that caution be exercised when making cross species generalizations. Nevertheless, a great deal of similarity is known to exist in brainstem physiology among mammals (Kiang, Pfeiffer and Warr, 1965; Rupert and Moushegian, 1970). The inability to demonstrate binaural interaction in human evoked potentials in spite of clear evidence of this phenomenon in the evoked potentials of other mammals was, therefore, unexpected.

Dobie and Norton (1980), using a vertex to midline neck derivation and two click intensities (97 and 67 dB peSPL) were the first experimenters to claim that binaural interaction could be demonstrated in the auditory evoked potentials of human subjects. These authors recorded the brainstem and middle latency components simultaneously to monaural and binaural stimuli. BICs for the brainstem auditory evoked potentials were obtained using the same procedure

employed by Dobie and Berlin (1979a). Although comparison of mean peak latency and amplitude values for the summed monaural (predicted) and binaural brainstem responses failed to reveal any significant difference between the predicted and true binaural response, a small binaural interaction component corresponding in latency to waves V and V' (approximately 6ms post stimulus, equivalent to wave P4 in cat) was evident after computer subtraction of the two responses.

These results were consistent with those obtained from the earlier study on guinea pigs performed by Dobie and Berlin (1979a) which indicated that binaural interaction was greatly underestimated when comparison of predicted and true binaural responses was limited to measurements of peak latencies and amplitudes. In the case of human brainstem evoked potentials (Dobie and Norton, 1980) and the human FFR (Gerken et al., 1975) this approach not only underestimated binuaural interaction, but missed the phenomenon entirely. Gerken et al. (1975) conceded that their method of comparing peak measurements may not have been sufficiently sensitive to subtle interactions in the FFR. The subtraction procedure as proposed by Dobie and Berlin (1979a), on the other hand, was sensitive to amplitude and latency differences that occurred at points other than at the wave peaks, and initally appeared to be a

robust method for demonstrating the phenomenon which was generally accepted as evidence of binaural interaction in human auditory evoked potentials.

Methodological Considerations in Binaural Interaction Studies

Although Dobie and Norton were the first researchers to demonstrate what they defined as binaural interaction in the BSAEP, the subtleness of the effect in comparison to the large, clear BICs recorded from guinea pigs was disappointing. As Dobie and Norton pointed out, differences in the BIC components in guinea pigs and human subjects may be attributed to relative size of the responses. In guinea pigs large (several microvolts) brainstem responses can be recorded with a comparatively small amount of averaging due to the superficial anatomical arrangement of the auditory tract. Thus, demonstration of the BIC is facilitated. Anatomical differences between the guinea pig and human brainstem, and different morphological features of the brainstem responses account for the latency differences in the BICs of humans and guinea pigs; the human BIC occurs at approximately 6ms corresponding to waves V and V' of the human BSAEP while the guinea pig BIC occurs at 3.5-4ms corresponding to waves P4 and the negative trough following P4 of the guinea pig BSAEP.

Aside from anatomical differences between guinea pig and human subjects, certain technical differences in the evoked potential recordings must be considered. Guinea pigs in the Dobie and Berlin study (1979) were anesthetized which undoubtedly reduced movement related background noise, increasing the stability and reducing the variability of the animal recordings. Spectrum differences in the stimulus used in the guinea pig and human studies may have also contributed to different results. The earbars used for the guinea pigs produced resonances at 750 and 1500 Hz resulting in a much different stimulus spectrum than that used in human studies. While it is unknown to what extent stimulus spectrum affects binaural interaction, evidence has been offered in support of binaural interaction being primarily a high frequency phenomenon (Gardi and Berlin, 1981) and, conversely, primarily a low frequency phenomenon (Wrege and Starr, 1981).

Hosford-Dunn, Mendelson and Salamy (1981) suggested another methodological variable which may have an affect on the demonstration of the BIC in human subjects. In this study, BICs were obtained using the Dobie and Berlin method from ten healthy neonates. BICs appeared similar to those found in adult subjects except that the latency of the BIC was longer in the infant responses corresponding to the expected increased latency

of wave V in these subjects. Similar to previous studies in adults, the BIC was confined to the latency period following the occurrence of wave III. In contrast to the results of Dobie and Norton, however, Hosford-Dunn and her colleagues found significant peak amplitude differences between the binaural and predicted waveforms. The authors attributed this to their filter setting (30-3000 Hz as compared to 100-3000 Hz used by Dobie and Berlin) which they believed to be optimal for teasing out the effects which they attributed to binaural interaction. While inherent differences between infant and adult binaural interaction may have also been offered as an explanation for this finding, comparison of infant responses with the responses from 6 adults in this study failed to support this hypothesis.

The contention that binaural interaction was present in the BSAEPs of human subjects was seriously challenged by Ainslie and Boston (1980). Using the Dobie and Berlin procedure to derive binaural interaction components, these authors were able to demonstrate binaural interaction in responses elicited by high intensity (110 dB peSPL) stimuli, but failed to find binaural interaction in responses elicited by lower stimulus levels (90, 70 and 50 dB peSPL). Acoustic crosstalk was suspected as being responsible for producing an artifact which was misinterpreted as

evidence of binaural interaction. In order to test this hypothesis, monaural responses were re-recorded using insert receivers or contralateral masking in order to reduce or eliminate acoustic cross-over. Binaural interaction components were not observed under these conditions. Ainslie and Boston concluded that the BIC was merely an artifact of cross hearing.

Gardi and Berlin (1981), claimed that their guinea pig data were free from cross talk artifact and argued that lowering of the stimulus spectrum as a result of using insert receivers was responsible for Ainslie and Boston's failure to find evidence of binaural interaction in their low intensity conditions. As for the use of contralateral masking, no data is presently available to assess the effects of masking on the binaural interaction components. Hosford-Dunn et al. (1981), however, did describe results of a pilot study of the effects of masking on the BIC as inconclusive. The presence of masking may have had a significant effect on the monaural waveform apart from eliminating the effects of acoustic cross talk. Chiappa et al. (1979), while claiming no amplitude or latency effects on the BSAEP as a result of using contralateral masking, stated that masking can result in morphological differences in the waveforms. In any case, the presence of masking in the monaural but not in the binaural condition complicates the situation by

making the recording conditions less comparable. The effects of masking on the BSAEP are not well understood and, since the presence of contralateral masking may add a confounding variable, it is probably best avoided in studies of binaural interaction.

A perhaps more significant methodological problem may have contributed to Ainslie and Boston's (1980) negative results. Ainslie and Boston used a model of binaural interaction which differed from Dobie and Berlin's model in an important way. Dobie and Berlin (1979a) and Dobie and Norton (1980) stressed the necessity of using a midline reference in order to equalize the contributions from each auditory tract. Since all responses were recorded using the same electrode configuration, these authors stated that any difference between the monaural and binaural conditions could be attributed to neural interaction and not to differences in the responses as a function of electrode location. The Ainslie and Boston model, in contrast, called for a reference electrode on the right mastoid. Thus, binaural interaction was defined as $K(t) = B(t) - [M_i(t) + M_c(t)]$. That is, the BIC is equal to the binaural response minus the sum of the right (ipsilateral) and the left (contralateral) responses. Several studies, including the Ainslie and Boston study, have reported significant differences between

ipsilaterally and contralaterally recorded responses (Hashimoto, Ishiyama, and Tozuka, 1979; Prasher and Gibson, 1980; Thornton, 1975). If, as Ainslie and Boston point out, the contralateral wave V is only 67% of the ipsilateral wave V, then adding together the ipsilateral and contralateral responses obviously does not result in an equal weighting of the right and left monaural responses.

Wrege and Starr (1981) also examined the effects of stimulus intensity on the BIC in humans. Reducing stimulus intensity to 50 dB SL resulted in a reduction in the amplitude of the BIC in relation to the amplitude of binaural Wave V. Latency change in the BIC was always constant relative to the latency change of wave V. This essentially replicated the findings of Dobie and Norton (1980) who reported an attenuated, but otherwise identical BIC pattern in response to lower intensity stimuli (67 dB peSPL). Since the lower intensity levels used in these two studies were safely below levels at which acoustic cross-over may have occurred, these results clearly contradicted those of Ainslie and Boston (1980) and further strengthened the argument that the BIC is not merely an artifact of cross hearing.

In an attempt to further elucidate the effect of stimulus parameters on binaural interaction, Wrege and Starr (1981) also examined the sensitivity of binaural

interaction in the brainstem auditory evoked potentials to the phase of the stimulus. It had been previously shown that the morphology of waves IV through VI were affected by initial phase of the stimulus and, since waves IV through VI were also the purported sites of binaural interaction, it was expected that stimulus phase would affect binaural interaction in the BSAEP. Binaural interaction components were derived from BSAEPs elicited from eight normal hearing subjects with either rarefaction or condensation clicks. Morphological and latency differences in the vicinity of waves IV, V and VI were observed with change of click phase. The amplitude of the binaural interaction components reflected both amplitude and latency differences between the predicted and binaural waveform. Peaks 1 and 2 of the binaural interaction component were always larger in response to condensation clicks. They were also consistently later in latency, occurring after wave V, while interaction in response to rarefaction clicks preceded wave V. The latency difference between the interaction produced by rarefaction and condensation clicks was greater than could be accounted for by the expected latency difference of BSAEPs produced as a result of different polarity stimuli.

In addition to examining the effects of stimulus polarity, Wrege and Starr (1981) attempted to isolate the

portion of the click spectrum which was responsible for the BIC. Gardi and Berlin (1981) had argued that the BIC was dependent primarily on the high frequency portion of the click spectrum. This conclusion was based on the observation that lower frequency stimuli produced by insert receivers (Ainslie and Boston, 1980) failed to yield the expected BIC in human subjects.

Wrege and Starr also used indirect methods for deriving information about the relationship between spectral content of the stimulus and the BIC. Three sources were used for deriving this information: 1. responses obtained from hearing impaired subjects, 2. comparison of responses obtained with different polarity stimuli, and 3. responses obtained from stimuli presented with an interaural time delay. Unlike Gardi and Berlin, Wrege and Starr interpreted their results as evidence that the BIC is dependent on low frequency components in the stimuli. Examination of BICs obtained for subjects with low frequency and/or high frequency hearing loss, led Wrege and Starr to conclude that high frequency hearing loss had no affect on binaural interaction while low frequency hearing loss did affect binaural interaction. The results of different stimulus polarity and interaural time delay, furthermore, suggested that binaural interaction was dependent on a stimulus frequency at approximately 500-550Hz. Considering that

polarity inversion results in a latency difference equal to one half the period of the stimulating tone, the latency differences in the binaural interaction components found in this study indicated an effective frequency of 500 Hz. In addition, 900 μ s (.9ms), the time delay which produced the smallest binuaral interaction component, was equal to 1/2 period of a 550 Hz tone. A 900 μ s interaural difference would cause the 550 Hz component of the broad band click to be in counterphase between the ears and, according to the authors, become ineffective in producing the binaural interaction component.

Wrege and Starr admit that the arguments for a low frequency component based on the results of polarity inversion and interaural time difference were tentative and required more precise control of stimulus parameters. Their argument based on results from the hearing impaired listeners was also weak. While it can be argued that hearing loss interacts with stimulus spectrum, it is unknown what effects, other than spectral, hearing loss may have on binaural interaction. In addition, Wrege and Starr's conclusions concerning the effect of hearing impairment are based on results from only three subjects. Considering the large amount of intersubject variability found in this and other studies, and the fact that there is no information on the effects of hearing loss on

binaural interaction components available in the literature, it would appear premature to offer conclusions based on so small a sample.

Thus, few definitive conclusions can be drawn from the relatively small body of existing literature on the BIC, the presumed electrophysiological correlate of binaural interaction. Important issues concerning the effects of stimulus, recording and subject parameters on the BIC remain unresolved. However, an even more fundamental issue remains inadequately explored: is the BIC truly a measure of binaural interaction or is it merely an artifact which results from the algebraic manipulations of complex waveforms? When waveforms are subjected to the additions and subtractions which are called for by the Dobie and Berlin procedure, any small, albeit insignificant variability in amplitude and or latency between responses will contribute to a difference trace. In reference to response variability, Picton et al. (1983) state:

One of the assumptions of the averaging technique is that the evoked potential waveform remains constant with each presentation of the stimulus. The amplitude and/or latency of the evoked potential components can vary during the averaging process. When only the amplitude varies, the average response has an amplitude

that is the average amplitude of all the individual responses. When the latency varies, the amplitude can become quite distorted and may even show cancellation. (p. 332)

Sources of small amounts of variability in the BSAEP have been identified. Differences in signal to noise ratio attributable to the level of background EEG during recording contributes to latency and amplitude variability in the resulting evoked potential. While the signal to noise ratio is enhanced by averaging high numbers of responses, varying amounts of residual background noise are, inevitably, left in the averaged response (Picton et al., 1983). Thus two BSAEPs, recorded from the same subject under identical conditions, may contain slight differences. Subtraction of these two responses would result in a difference trace which reflects variability in the residual noise level and not a real difference between the two evoked potentials. Thus, a serious problem inherent in the Dobie and Berlin procedure is the potential for artifactual contamination. Inspection of human BICs indicates that they are often low amplitude components which barely exceed the noise floor of the response. It is apparent, then, that the derivation of artifact-free BICs requires minimally two controls: 1) recognition and control of sources of variability which are not related to binaural interaction, and 2)

establishment of a criterion against which the significance of a difference trace can be tested.

In addition to the run to run variability encountered in the BSAEP, another potential source of error has been identified which could significantly affect the BIC. Observing that the polarity of the BIC was reversed for some subjects, Decker and Howe (1981) hypothesized that slight phase shifts between the true binaural and predicted binaural responses were responsible. These authors discovered that small latency shifts between the right and left monaural responses resulted in the creation of an artificial mean latency when the two monaural responses were summed, causing the predicted binaural response to be slightly phase shifted in relation to the true binaural response. They found that the polarity of the difference trace, which remained after subtraction of the binaural from the predicted response, was a mathematically predictable function of the phase relationship between these two responses.

According to Decker and Howe (1981), the reason for the small latency shifts between right and left monaural responses was auditory tract asymmetry. That is, in spite of equal pure tone sensitivity and equal sensation level stimulation, the response from one ear was unequal in latency and/or amplitude to the response from the other ear. Auditory tract asymmetry, as Decker

and Howe termed this phenomenon, was found in 4 out of 8 of their subjects. Subjects demonstrating auditory tract asymmetry had responses to binaural, diotic stimuli (equal dB SL) which mirrored the monaural response from the "preferred" auditory tract. Diotic stimulation, then, did not necessarily result in equal output from each auditory tract.

Decker and Howe's findings have important implications for research which is directed towards establishing a relationship between binaural interaction and the BIC. These authors state that the existence of auditory tract asymmetry may have been overlooked by previous authors due to the convention of analysing mean data in which small latency differences between "preferred" and "non-preferred" auditory tract responses tend to cancel. Consistent right-left differences are only apparent upon inspection of individual data. Since artifactual difference traces may result from applying the Dobie and Berlin procedure to responses from a subject who demonstrates auditory tract asymmetry, Decker and Howe proposed an alternative method of analysis in order to eliminate this source of error. Instead of adding together the two monaural responses, each monaural response was individually subtracted from the binaural response. For the asymmetrical subject, the result was a difference trace when the non-preferred response was

subtracted from the binaural, and a null when the preferred response was subtracted from the binaural. This method had the advantage of not only purporting to demonstrate binaural interaction, but also indicated the presence and direction of inter-ear asymmetry in the BSAEP.

Dobie (1982) criticized Decker and Howe's technique stating that by presenting stimuli at equal sensation levels (SL) re the monaural and binaural thresholds, obtaining a difference trace was assured by virtue of the different intensities used in the monaural and binaural conditions. By presenting the stimuli at equal SLs, loudness was equalized among conditions. Dobie contended that loudness was not a key issue although he was unable to offer any data or appropriate references to support his view. Decker and Howe argued that demonstration of binaural interaction in spite of eliminating the binaural summation of loudness factor actually strengthened the theory. Allen (1982) subsequently demonstrated auditory tract asymmetry via the Decker and Howe procedure using equal dB pe SPL stimulation. Dobie also rejected the notion of auditory tract asymmetry based on his failure to find any significant left-right differences in his data, a prerequisite for the auditory phenomenon. As Decker and Howe (1982) pointed out, however, Dobie analysed mean

data in which small latency differences can be expected to cancel. Only in the analysis of individual data are interaural differences revealed.

Clearly, inter-ear response asymmetry which Decker and Howe (1981) attribute to auditory tract asymmetry is an important phenomena which, in and of itself, deserves further study. Its effect on the BIC is problematic. Interear response asymmetry has emerged as a variable which must be accounted for in binaural interaction studies.

Summary

In summary, the procedure of subtracting the summed monaural response from the binaural response [$(R_m + L_m) - B_{in} = BIC$], has been offered as a method for demonstrating binaural interaction in the brainstem auditory evoked potentials. The method, which results in a difference trace indicating non-equality between $R_m + L_m$ and the binaural response, has yielded positive results when applied to both animal and human BSAEPs. Although the procedure has been gaining acceptance as a useful tool for revealing the effects of binaural processing, serious questions about the legitimacy of the procedure have been raised. Does the BIC represent neural interaction between auditory tracts which occurs when the auditory system is stimulated binaurally, or does it

represent some other, as yet unknown phenomenon? It has been suggested that the BIC is seriously contaminated by artifact. One of the factors which has been singled out as a confounding variable is the presence of small inter-ear asymmetries in the monaural responses. The phase shifts between right and left monaural responses which result from these asymmetries make the practice of algebraic summation appear inappropriate. Thus, asymmetry is an important variable which must be examined in connection with studies which attempt to demonstrate binaural interaction by means of non-equality between $R_m + L_m$ and the binaural response.

PART II

Auditory Tract Asymmetry

Part II reviews evidence of asymmetry in auditory evoked potentials. The first subsection discusses asymmetries which have been observed at the cortical level, while the second section deals with evoked potentials arising from lower levels of the auditory system, primarily the BSAEP.

Evidence of Asymmetry at the Cortical Level

Cortical asymmetry has been associated with left hemisphere specialization for speech. The right ear advantage for processing of speech stimuli has been demonstrated in the BMLD for speech (Licklider, 1948) and in dichotic listening tasks (Broadbent, 1958; Kimura, 1961; Studdert-Kennedy and Shankweiler, 1970). The anatomical basis for asymmetry in speech processing has been attributed to the prepotency of the contralateral auditory pathway to the speech dominant, left hemisphere (Truex and Carpenter, 1964).

Investigation of neural asymmetries which are believed to underly the right ear advantage by means of electrophysiological techniques has yielded mixed results. Some electroencephalographic studies showed

clear right/left differences in alpha activity recorded from the two hemispheres which were correlated to the task in which the subject was engaged. Suppression of left hemisphere alpha activity was observed when subjects performed verbal tasks, while suppression of right hemisphere alpha activity was observed when subjects performed spatial, or non-verbal tasks (Butler and Glass, 1974; Doyle et al. 1974; Galin and Ornstein, 1972; Glass and Butler, 1973). Attempts to demonstrate speech related asymmetries in cortical evoked potentials have focused on detecting differences in evoked potentials elicited by speech stimuli and those elicited by non-speech stimuli. These studies, however, have been fraught with methodological difficulties and have led to conflicting results (Davis and Wada, 1974; Friedman, Simpson, Ritter and Rapin, 1975; Grabow and Elliot, 1974; Morrell and Salamy, 1971).

The expectation that the late evoked potentials would reveal asymmetry was motivated by previous studies which had documented a right ear advantage for speech (eg. Kimura, 1965; Studdert-Kennedy and Shankweiler, 1970). Nonetheless, demonstration of these asymmetries in the cortical evoked potentials has been elusive. The functional significance of asymmetries in the early potentials (BSAEP and MLAEP) is less clear. Recording of these early potentials is dependent upon rapid onset,

short duration stimuli which bear no resemblance to speech. Since the right ear advantage has only been demonstrated for speech-like stimuli, there is no reason to believe that click stimuli should give rise to asymmetry which is related to the right ear advantage for speech. Thus, it seems reasonable to assume that the small inter-ear asymmetries which are now being recognized in the early potentials are probably not related to hemispheric specialization for speech, but to some other, as yet unknown, function.

Evidence of Asymmetry at the Brainstem Level

Until recently, few reports of right/left asymmetries in the early evoked potentials existed in the literature. It had been assumed that a normal individual with symmetrical hearing would produce identical responses as a result of equal stimulation of the right and left ears. Analysis of mean data supported this view (Ainslie and Boston, 1980; Dobie, 1981; Dobie and Norton, 1980; Starr and Squires, 1982). Rowe (1978), for example, studied monaural BSAEPs recorded from young and old, normal hearing subjects. He failed to find any significant inter-ear latency¹ differences in his analysis of mean data. In contrast, Levine and McGaffigan

¹Amplitude measurements were considered too variable for meaningful analysis.

(1983) reported statistically significant right/left asymmetries in the baseline to peak amplitudes of the negative wave following wave I and wave III in their group data. These asymmetries, furthermore, favored the right ear in all cases. Similar inter-ear asymmetries have also been found in the middle latency auditory evoked potential (Hood, Berlin and Hughes, 1983). Studies which painstakingly controlled for possible contamination of imperfectly matched amplifiers and earphones, day to day recording variability, and the effect of electrode derivation have confirmed that inter-ear response asymmetry was unrelated to equipment or methodological artifact (Berlin, Allen and Parrish, 1982; Berlin, Allen and Hughes, 1983).

In addition to inter-ear latency and amplitude asymmetries, the responses obtained from the right and left ears may differ in shape. Chiappa et al. (1979) identified six different morphological patterns² which could occur in the brainstem auditory evoked potentials of normal subjects. These authors found, furthermore, that the right and left responses from one individual could fall into two different categories. Chiappa et al. found morphological asymmetry in 42% of their normal subjects. Similarly, Rowe (1978) reported

²Categorization of BSAEPs depended on shape of the wave IV-V complex.

morphological asymmetry in 40% of his normal subjects.

The available information concerning inter-ear response asymmetry in the BSAEP is scanty. With the exception of negative wave I and wave III amplitudes (Levine and McGaffigan, 1983), statistically significant inter-ear asymmetries have not been reported. Decker and Howe (1981) attributed this lack of evidence for inter-ear asymmetry to the fact that previous researchers analysed mean data in which small right/left differences are likely to cancel. According to Decker and Howe, significant inter-ear response asymmetry is revealed only in the analysis of individual data. As discussed above, inter-ear morphological asymmetry has been documented and classified by analysing individual data. To date, no study has similarly documented and classified inter-ear latency or amplitude asymmetry in the monaural responses of individual subjects.

Early studies concerned with binaural interaction in the brainstem response have either reported no difference between the responses from the right and left ears (Ainslee and Boston, 1980; Dobie, 1981; Dobie and Norton, 1981) or have failed to make inter-ear comparisons (Prasher, Sainz, and Gibson, 1981; Wrege and Starr, 1981). Hosford-Dunn et al. (1981), however, suggested the presence of a morphological asymmetry in several of their infant subjects. As discussed in the

previous section, Decker and Howe (1981) were the first to suggest that small inter-ear asymmetries could have an effect of the BIC. In order to examine binaural interaction free of the contaminating effects of auditory tract asymmetry, they individually subtracted monaural responses from the binaural response thus avoiding the phase shifts associated with addition of unequal right and left monaural responses. The BICs derived in this fashion were distinctly different for asymmetrical and symmetrical subjects. Decker and Howe did not, however, show how the BIC derived by means of the Dobie and Berlin procedure compared between groups.

Inter-ear response asymmetry, regardless of its origin or functional significance, creates a technical problem in the derivation of the BIC by means of the procedure described by Dobie and Berlin (1979a). In addition to potentially confounding the measure which many researches have associated with binaural interaction, the presence of response asymmetry raises questions concerning the relationship between monaural asymmetries and the binaural response. Decker and Howe suggested that the binaural response from an asymmetrical auditory system is dominated by one auditory tract. Presumably, the binaural response from a symmetrical auditory system represents equal contributions from the right and left auditory tracts. In this case, $R_m + L_m$

might be an adequate model for describing the binaural response from a symmetrical system, but would be inadequate in describing the binaural response from an asymmetrical system. Thus $(R_m + L_m) - B_{in}$ could potentially equal zero if the equation was applied to symmetrical monaural responses. Application of the equation to asymmetrical monaural responses, however, will result in a BIC. Thus the BIC may be more useful as a measure for studying the relationship between monaural and binaural processing than as a measure of binaural interaction per se. The BIC is an indicator of the extent to which the binaural response is predictable from an algebraic summation of two monaural responses. According to the speculations stated above, the more asymmetrical the monaural responses are, the greater will be the difference between B_{in} and $R_m + L_m$. Examining the effects of inter-ear response asymmetry on the BIC may, perhaps shed further light on this issue. The section which follows is devoted to studies which have addressed the question of asymmetry and the effects of asymmetry on measures of binaural interaction.

Summary

Functional asymmetry of the auditory system has been observed in the form of a right ear advantage for speech. Small asymmetries in the early auditory evoked

potentials (MLAEP and BSAEP) have been observed, however, the significance of these asymmetries remains unclear. Recently, it has been suggested that inter-ear asymmetry in the BSAEP may have a significant effect on methods which are currently being used to study binaural interaction. Given the potentially confounding effects of inter-ear asymmetry on the BIC, it was suggested that the BIC may be more useful as a means of studying the relationship between monaural and binaural BSAEPs rather than as a measure of binaural interaction per se.

PART III

Interaural Stimulus Differences

Conceptual models of binaural interaction have assumed that equal stimulation (time of arrival or intensity) gives rise to equal neural activity in the right and left auditory pathway (von Békésy 1960, Hall, 1965; Van Bergeijk, 1962). The discovery of asymmetry in the BSAEP and MLAEP in approximately 50% of normal hearing subjects when stimuli are presented equally and simultaneously to the two ears, then, appears contradictory to this view. Does response asymmetry indicate unequal neural conduction through the auditory pathways inspite of equal stimulation? The neurophysiology underlying the asymmetry or its functional significance is as yet unknown. Also unknown is how the asymmetry would behave under varying stimulus conditions. As noted in Chapter 1, asymmetries caused by inter-ear stimulus differences are known to underlie binaural psychoacoustic phenomena such as sound lateralization and the masking level difference. Furthermore, these perceptions can be dramatically changed by small changes in the interaural intensity or time relationships. Are these changes detectable in the binaural BSAEP? The manipulations of time or intensity will effect the latency and/or amplitude of the monaural

BSAEP. When stimuli are presented binaurally with a time or intensity difference it seems likely that the relationship between the monaural and binaural response would be affected. It also seems likely that inter-ear stimulus differences would affect symmetrical subjects in a different way than they would affect asymmetrical subjects: in the first case the stimulus difference would create asymmetry, in the later case it would either offset or enhance asymmetry.

Motivated by the belief that the BIC represents the electrophysiological correlate of behavioral binaural phenomena which have their basis in interaural differences, several studies have investigated the effects interaural stimulus differences on the BIC. The studies presented in the next two sections examined the effect of interaural time differences and interaural intensity differences on the BIC. Note that these studies, with the exception of the one performed by Allen, Berlin and Parrish. (1982), assumed response symmetry when stimuli were presented without interaural difference. The last section deals with the effects of interaural stimulus differences on BSAEPs which are naturally asymmetrical.

Interaural Time Difference

Jewett (1970), who was the first to report the existence of binaural interaction in the BSAEP as mentioned earlier, was also the first to explore the effects of dichotically presented stimuli on binaural interaction in the BSAEP. In experiments performed on cats, Jewett found that when binaural clicks were delivered with a 3ms interaural time difference that P4 of the response elicited by the first click summed algebraically with P1 of the response elicited by the delayed click. This result was interpreted as evidence that the binaural response represented the outputs of two separate generators in a volume conductor. In other words, binaural interaction, which was observable when the stimulus was diotic, was no longer apparent when the stimulus was presented dichotically.

Dobie and Berlin (1979a) recorded brain stem evoked potentials from guinea pigs using dichotic stimuli. Largest binaural interaction difference traces were found for stimuli with the smallest amount of interaural difference, however, introduction of interaural time differences up to 3,000 us still resulted in recognizable binaural interaction components. Larger interaural differences resulted in two separate monaural traces without evidence of binaural interaction. Perhaps, Jewett's failure to find binaural interaction in response

to time delayed stimuli was due to his use of an interaural difference (3ms) which was too large to produce binaural interaction.

Wrege and Starr (1981) obtained similar results in an experiment in which brain stem evoked potentials were recorded to time delayed binaural stimuli in 2 human subjects. Binaural interaction difference traces were obtained by artificially delaying two monaural responses by the amount of the interaural delay and then adding them together. The binaural response elicited by the dichotic stimuli was subtracted from the summed monaural response. The amount of binaural interaction as evidenced by the resulting difference trace was inversely related to the size of the interaural difference. With an interaural difference of 900 μ s, the amplitude of the difference trace was at a minimum.

In contrast, Arslan, Prosser and Michelevi (1981) found little evidence of binaural interaction in responses elicited by time delayed stimuli. Using the same method employed by Wrege and Starr, Arslan et al. added together two time delayed monaural responses creating a template with which dichotic binaural responses could be compared. Instead of deriving difference waveforms as had been done in previous studies of binaural interaction, the binaural responses were cross correlated with monaural responses in order to

determine whether or not the binaural responses represented a simple algebraic summation of two monaural components. It was found that the templates could predict the dichotic binaural response for every value of Δt . When the monaural response was subtracted from the dichotic response leaving only the second, time delayed response, a cross correlation between the monaural and derived time delayed response revealed great similarity between the two waveforms. The authors concluded that the primary mechanism underlying the binaural brainstem response was algebraic addition of two, independent monaural responses.

Arslan et al. observed that as the interaural time delay increased from 0 to 3.5ms, the morphology of the binaural brainstem response changed. At delays greater than 2ms, the normal peaks of the brainstem response were no longer identifiable. This observation was consistent with Wrege and Starr (1981) who also found distortion of binaural responses beginning at .5ms interaural delay. In order to determine if there was a delayed pattern within the dichotic binaural response, Arslan et al. performed a cross correlation between the monaural and dichotic binaural responses. Significant correlations between secondary peaks in the cross correlation functions to Δt indicated the existence of a second delayed pattern in the dichotic response.

Lack of correlation at two delta t values (2.5ms and 3.5ms), however, indicated the presence of some other process besides simple linear addition of two time delayed monaural responses. Therefore, the presence of some small interaction component could not be completely ruled out.

The results obtained by Arslan et al., however, may not be directly comparable to results obtained by other researchers who found evidence of binaural interaction in dichotic responses. Two methodological peculiarities in this study may have been responsible for their negative results:

- 1) Arslan et al. used an unusual electrode derivation, Cz toinion, in order to maintain a non-preferential midline reference while avoiding an electrode site which would be sensitive to muscle artifact. The effect of choosing the inion as the reference site was to change the morphology of the brainstem response. Specifically, there was an increase in the amplitude of waves III and VI and a decrease in the amplitude of waves II and IV. The morphological changes created by using the inion as reference affected precisely those waves of the brainstem response where binaural interaction is said to occur. It is likely, therefore that electrode derivation significantly affected the results.

2) Stimulus polarity may have also affected the results. Wrege and Starr (1981) demonstrated significant amplitude and latency differences in binaural interaction difference waves produced by rarefaction and condensation clicks. Arslan et al., in using alternating polarity, may have confounded their results.

Interaural Intensity Difference

Only two binaural interaction studies have dealt with stimuli with interaural intensity differences. In their 1979 study of binaural interaction in the BSAEP of guinea pigs, Dobie and Berlin used stimuli which differed in intensity by 0, 20 and 40 dB between ears. They found that, like results for interaural time differences, the size of the BIC was inversely related to the size of the interaural difference. BICs were obtained for BSAEPs in responses to dichotic stimuli with interaural differences up to 20 dB.

Prasher, Sainz and Gibson (1981) performed the only published study of binaural interaction as it relates to interaural intensity differences in human subjects. Comparing monaural to diotic binaural responses, it was found that binaural stimulation resulted in a 68.7% increase in wave V amplitude. Reducing the intensity to one ear had the effect of decreasing the amplitude of wave V. With an interaural

difference greater than 10 dB, the size of wave V was equal to that of the monaural response. The increase in wave V amplitude which would be expected as a result of a simple linear summation of individual responses to sounds differing by more than 10 dB was not observed. In fact, it appeared as though the ear receiving the lower intensity stimulus did not contribute to the binaural response at all.

Prasher et al. rejected the theory that the increase in wave V amplitude in the binaural condition was related to binaural summation of loudness. They found that adding 3 dB (the presumed amount of binaural loudness summation) to the intensity delivered to one ear did not noticeably affect the amplitude of the monaural response. They found, instead, that their results were related to the subject's subjective sensation of lateralization. While no methodological information or lateralization data were presented, the authors claimed that subjects perceived diotic stimuli at the midline, a 10 dB interaural difference half way between midline and the ear, and a 20 dB interaural difference completely lateralized at the ear. These perceptions, then, corresponded to binaural wave V amplitude which was maximum for diotic stimuli when the image was perceived at the midline, and equal to the monaural response when the image was completely

lateralized, ie. perceived as monaural.

Intriguing as these results appear, they are difficult to accept for a number of reasons:

1) The question as to whether the binaural response is related to binaural loudness summation was inadequately tested. While approximately 3 dB of loudness summation is expected for binaural sounds presented at threshold, a greater amount of summation has been observed for sounds presented above threshold. Since Prasher et al. were using stimuli between 70 and 90 dBHL, an approximation of loudness summation closer to 10 dB may have been more appropriate (Reynolds and Stevens, 1960;). In order to properly answer this question the precise amount of binaural loudness summation should have been determined by loudness balancing. Comparing responses to loudness matched monaural and binaural stimuli would then indicate the extent of the role of loudness summation in the binaural response.

2) The relationship between binaural interaction and sound lateralization was inadequately examined. Prasher et al. claimed that their subjects perceived the binaural image as being half way between midline and the ear when the interaural intensity difference equalled 10 dB, and completely lateralized when the interaural intensity difference equalled 20 dB. These figures were at odds with some of the psychoacoustic literature which

indicated that a short duration sound will be completely lateralized when the interaural difference reaches 10 dB or less (von Békésy, 1960; Flanagan, David and Watson, 1964; Pinheiro and Tobin, 1969). On the other hand, the interaural difference needed to completely lateralize a sound has also been reported by some authors as greater than 10 dB (Guttman, 1962; Moushegian and Jeffress, 1959; Whitworth and Jeffress, 1961). Clearly, a careful and precise mapping of image trajectory would be required to draw any meaningful relationship between lateralization and evoked potentials. Prasher et al., however, gave no details concerning their methods of measuring lateralization.

3) The methodology employed by Prasher et al. was also problematic. It is generally agreed that binaural responses must be recorded in such a way as not to favor one auditory tract over the other. In spite of this, Prasher et al. placed the active electrode on the left mastoid (M1) and the reference electrode on the vertex. This derivation presumably favored the left auditory tract. In order to create interaural intensity differences, the stimuli to the right ear was decreased. Thus, the diminishing effect of the right ear to the binaural response with increasing interaural difference was confounded by the electrode asymmetry which favored the left ear.

Interaural Stimulus Difference as it Relates to Asymmetry

The foregoing studies, which predated Decker and Howe's description of auditory tract asymmetry, were performed without regard to naturally occurring asymmetry which may be present during equal stimulus conditions. These studies did not consider the possibility of an interaction between response asymmetry and interaural stimulus differences. The introduction of interaural intensity difference causing the right ear to receive a lower level signal than the left ear, for example, would be expected to produce a right ear response which is longer in latency and smaller in amplitude than the left ear response (Prasher et al. 1981). This expectation is based on the well documented principle that intensity is directly related to response amplitude and inversely related to response latency (Davis, 1976; Picton et al. 1974). If, however, the response from the right ear is leading in latency and larger in amplitude than the response from the left ear under equal stimulus conditions (diotic), introduction of the interaural intensity difference may not have the anticipated affect. The interaural difference may, in fact, cause a balancing of the two responses, that is, simulate symmetry. Considering further that available evidence indicates that the degree of asymmetry varies from one individual to another (Allen et al., 1982; Decker and Howe, 1981),

the effect of introducing an interaural stimulus difference may produce unpredictable results if one does not account for both the direction and degree of response asymmetry.

To date, only one study has examined interaural stimulus differences in relation to their effects on naturally occurring response asymmetry and the BIC. Using Decker and Howe's (1981) technique to determine auditory tract asymmetry and ear dominance, Allen, Berlin and Parrish (1982) found that 4 out of 9 of their subjects demonstrated varying degrees of inter-ear brainstem response asymmetry. Introducing predetermined interaural time differences ($\pm 100, 300, 1000, 3000$ microseconds) during binaural stimulation had the effect of "balancing" the responses from the two ears, thus making the responses of these asymmetrical subjects similar to the responses of symmetrical subjects.

There is clearly lacking sufficient information which would provide a link between naturally occurring response asymmetry and artificially induced asymmetry by means of interaural stimulus differences. While it is possible that the two types of asymmetry are manifestations of different phenomena and are governed by different principles, evidence that naturally occurring asymmetry can be offset by means of an interaural time difference (Allen et al., 1982) suggests that the two

types of asymmetry are related.

Allen et al. (1982) also examined the BICs which were derived from the responses of symmetrical subjects and asymmetrical subjects before and after the asymmetry was offset. Both symmetrical subjects and asymmetrical subjects produced the largest BICs when the responses from the two ears were equal. Restating the results of Allen et al. (1982) in terms of the relationship between monaural and binaural BSAEPs, these authors indicated that the monaural combination formula which best predicted the binaural response was the addition of right and left monaural responses in their natural, asymmetrical state. That is, when natural asymmetry was present, subtracting the binaural response from the sum of the asymmetrical right and left responses produced the smallest BIC, indicating good prediction of the binaural response from a simple algebraic addition of the monaural responses. The prediction of the binaural response, according to these authors, became poorer when the right and left monaural responses were equalized by means of an interaural time difference.

These results, however, appeared at odds with the expectations based on Decker and Howe's theory of naturally occurring asymmetry and its effect on the BIC (Decker and Howe, 1981). According to Decker and Howe, the phase shift between the summed monaural response and

the binaural response, which occurs because of naturally occurring asymmetry, causes the algebraic combination of the monaural responses to be a poor predictor of the binaural response. This is evidenced by the presence of a difference trace (BIC) when the binaural response is subtracted from the summed monaural response. It follows then, that the more asymmetrical the monaural responses are, the more pronounced this effect would be. This would occur because summation of a right and left response with a relatively large latency difference would cause the resulting summed response to have a large phase shift relative to the binaural response (which, according to Decker and Howe, will mirror the monaural response from the "preferred" ear). When the binaural response is subtracted from the summed monaural response, a large BIC can be expected. At the other extreme is the case of naturally symmetrical responses where summation of equal right and left responses can be expected to very nearly approximate the latency of the binaural response. Summation of symmetrical monaural responses, therefore, should yield a better predictor of the binaural response. Subsequent subtraction of the binaural from the summed monaural response, then, can be expected to yield a smaller BIC.

The results of studies using interaural stimulus differences conflicted with these expectations. Studies

using both interaural intensity and interaural time differences consistently showed that the size of the interaural difference was inversely related to the amplitude of the BIC. One explanation for these findings might be failure to control for naturally occurring asymmetry, which, as pointed out above, could confound results. Allen et al., however, did account for naturally occurring asymmetry and still found the largest amplitude BICs associated with response symmetry. Their practice of presenting stimuli at equal dB peSPL instead of at equal dB SL to the right and left ears, however, may not have insured equal stimulation if the click thresholds of the right and left ears were slightly different in some of their subjects.

If Decker and Howe were correct in their assertion that the BIC is related to response asymmetry, and if the BIC is accepted as a measure of the extent to which the binaural response can be predicted from a combination of monaural responses, then, clearly, algebraic combination of monaural responses from symmetrical subjects should be a better predictor of the binaural response than algebraic combination of monaural responses from asymmetrical subjects. Following this line of reasoning, if the monaural responses of asymmetrical subjects could be made symmetrical by means of an interaural stimulus difference, then the ability to

predict the binaural response from a combination of monaural responses should be improved. No study to date has directly compared the monaural/binaural relationship in symmetrical subjects and asymmetrical subjects. Only one study (Allen et al., 1982) has attempted to compare BICs from asymmetrical subjects using equal stimulus conditions, and BICs from the same subjects with the asymmetry offset by means of an interaural time difference. No study has examined asymmetry offset by means of an interaural intensity difference.

Summary

The current knowlege concerning binaural interaction and auditory tract asymmetry leaves the following questions unanswered:

1) How does response asymmetry affect the ability to predict the binaural response from a combination of monaural responses?

2) Can response asymmetry, when it is present, be offset by means of an interaural intensity difference?

3) When asymmetry is offset by means of an interaural intensity difference, will the ability to predict the binaural response from a combination of monaural responses be improved?

4) Will the ability to predict the binaural response from a combination of monaural responses change

as a function of intensity level?

5) Does an alternative monaural combination formula (for example, multiplying the monaural response from the "preferred ear" by two) provide a better predictor of the binaural response than an algebraic combination of the right and left monaural responses?

CHAPTER 3

EXPERIMENTAL DESIGNPART IStatement of Problem and Hypotheses

In the BSAEP, we have a potentially useful tool for viewing the neural mechanisms which underlie binaural processing. Based on observations of the monaural responses, a prediction can be made about the relative amplitude, wave morphology and latency of the binaural response. The most simple hypothesis is that the auditory system merely adds the neural activity in the right and left auditory pathways, represented in the two monaural responses, to form the binaural response. This can be easily tested by means of Dobie and Berlin's procedure, $(R_m + L_m) - B_{in} = B_{IC}$. The extent to which the combination of monaural responses fails to predict the binaural response is evident in the relative amplitude of the BIC. Stating that the BIC represents binaural interaction *per se*, however, may be an overstatement of the case for the reasons outlined below.

The difference component (BIC) which remains after a binaural BSAEP is subtracted from the sum of the right and left monaural BSAEPs has been interpreted by several researchers as evidence of binaural interaction

(Dobie and Berlin, 1979a; Dobie and Norton, 1981; Wrege and Starr, 1981). Although the technique of adding and subtracting waveforms has a long history in electrophysiological research, the appropriateness of using this technique for the study of binaural interaction in scalp recorded, auditory evoked potentials, is questionable for the following reasons:

1. Unlike the spatially compact neural activity which is recorded from individual neurons or small groups of neurons by depth electrodes, the BSAEP represents synchronous onset activity from multiple, concurrently active generators within the brainstem. The electrical potential, which reaches the scalp electrode through the process of volume conduction, undergoes extensive modification due to the algebraic summation of fields produced by each generator (Vaughn, 1982). Considering the complex patterns of excitatory and inhibitory activity of units within the brainstem nuclei as a result of auditory stimulation (Galambos et al., 1959; Hall, 1965; Hind et al., 1963; Kemp and Robinson, 1937; Rosensweig and Sutton, 1958) the algebraic summation of activity from many units within multiple generators may result in cancellation of the effects of binaural interaction in a far field recording.

2. It is a well known fact that algebraic addition or subtraction of two sine waves which are

different in phase or frequency will result in a waveform which no longer resembles a sine wave. In order to combine or subtract dissimilar sine waves without distorting the wave morphology, the waveforms must be added vectorially. An analogous situation exists in relation to the BSAEP. The BSAEP, consisting of seven waves spaced at approximately 1 ms intervals, resembles a sine wave. The problems involved with performing algebraic operations on sine waves also apply to performing algebraic operations on the BSAEP. Assuming that two BSAEPs are identical in phase, linear addition or subtraction will not introduce morphological distortions. Evidence that right and left ear BSAEPs may be phase shifted as a result of small inter-ear asymmetries, however, suggests that computer algebraic addition and subtraction of monaural responses may not be an appropriate operation. As discussed in the previous chapter, Decker and Howe (1981) found that asymmetrical monaural responses combine to form a summed response ($R_m + L_m$) with a latency equal to the mean of the latencies of the two component responses. As a result, $R_m + L_m$ is phase shifted in relation to the binaural response. According to Decker and Howe, subtraction of these misaligned waves results in a difference trace which is a mathematically predictable function of the phase relationship between the binaural and summed monaural

responses.

3. It has been suggested that monaural and binaural BSAEPs reflect the activity of two different populations of neurons (Howe and Decker, 1984). Support for this hypothesis comes from electrophysiological research which has demonstrated the existence of units within the auditory pathway which are specifically sensitive to either ipsilateral, contralateral or binaural stimuli (Galambos et al., 1959; Hall, 1965). The difference trace which is left after subtraction of the binaural response from the summation of the right and left monaural responses may be merely the result of adding together monaural BSAEPs which arose from one population of neurons and subtracting them from a binaural response which arose from a second population of neurons. The difference trace, in this case would reflect differences in activity between the two populations of neurons rather than neural interaction per se (Howe and Decker, 1984).

4. To date, the BIC has not been correlated with any psychoacoustic measure of binaural interaction. There is, in fact, little data relating the BSAEP to psychophysical measures. Based on their inability to find a correlation between subjective loudness growth and BSAEP amplitude growth, Pratt and Sohmer (1977) speculated that the neural parameters which are recorded

in the BSAEP are not the same as those which subserve subjective loudness judgements. Howe and Decker (1984) reached a similar conclusion when they failed to find monaural/binaural latency-intensity functions in the BSAEP which corresponded to loudness judgements obtained psychophysically. Thus, there is no evidence as yet to support the view that the BIC represents underlying neural interaction which subserves any psychoacoustic binaural phenomena.

Considering the lack of firm evidence to support the association of binaural interaction and the difference trace which results from $(R_m + L_m) - B_{in}$, it seems inappropriate to use the term BIC, which implies that this difference trace is related to binaural interaction. For this reason, a more neutral term "Residual Component" (RC), was introduced in Chapter 1 and will be used in this study instead of BIC, to designate the result of subtracting the binaural response from the sum of the monaural responses.

The residual component may prove useful as a measure of the relationship between the monaural and binaural response. When the right and left monaural responses are added and subsequently subtracted from the binaural response, the residual component can take on one of two forms:

- 1) $RC = 0$. In this case, the residual component

equals zero indicating perfect prediction of the binaural response from a linear combination of the monaural responses.

2) $RC \neq 0$. In this case, the presence of a residual component indicates less than perfect prediction of the binaural response from a linear combination of the monaural responses. If the amplitude of RC is large, this indicates that the difference between $R_m + L_m$ and B_{in} is large, and the prediction of the binaural response is poor. If, on the other hand, the amplitude of RC is small and approaches zero, this indicates that the difference between $R_m + L_m$ and B_{in} is small and, although the prediction of the binaural response is not perfect, it may be considered a reasonably good approximation of the binaural response. The accuracy with which the linear combination of $R_m + L_m$ predicts the binaural response, therefore, is inversely related to the amplitude of the RC.

As stated above, Decker and Howe (1981) have suggested that $R_m + L_m$ does not equal B_{in} because of the presence of inter-ear asymmetries. The inadequacy of $R_m + L_m$ as a binaural predictor is reflected in the amplitude of the RC, as explained above. Thus, the presence of an RC may be attributable to one or more of the following situations concerning the relationship between the right and left monaural response:

a) The right and left monaural responses may be unequal with respect to latency. Latency is generally associated with neural conduction time through the brainstem auditory pathways, and is inversely related to stimulus intensity, ie. the higher the intensity, the shorter the latency, and vice versa.

b) The right and left monaural responses may be unequal with respect to amplitude. Amplitude of the response is generally associated with the number of neural units firing synchronously in response to the stimulus, and is directly related to the intensity of the stimulus, ie. the higher the intensity, the larger the amplitude, and vice versa.

The relationship between the latency and amplitude in the BSAEP is revealed by comparison of the latency-intensity function with the amplitude-intensity function. In general, shorter latencies are associated with larger amplitudes, while longer latencies are associated with smaller amplitudes.

c) The right and left monaural responses may be different with respect to morphology, ie. the BSAEP from each ear may be different in terms of number of waves, width of peaks, steepness of slope, presence or absence of multiple components, fusion or separation of components (particularly waves IV and V).

Right/left response asymmetries may reflect

external differences related to the interaural differences in the stimulus. For example if intensity is held constant but the stimulus presented to the right ear is presented earlier than the stimulus presented to the left ear, the right ear response will have a shorter latency than the left ear response³. If, on the other hand, time is held constant, but the intensity of the stimulus presented to the right ear is greater than the intensity of the stimulus presented to the left ear, the right ear response will not only have a shorter latency, but will also have a larger amplitude than the left ear response. Even when the stimuli transduced by the right and left earphones are perfectly equated with respect to time, phase, and intensity, natural asymmetries related to peripheral differences could still exist due to any number of anatomical and physiological differences between the ears such as ear canal volume and resonance, middle ear impedance, and sensitivity of the cochleae.

If the response asymmetry is limited to simple amplitude and/or latency differences which are associated with stimulus differences or peripheral auditory system differences, the asymmetry should be "correctable" by means of an interaural stimulus difference designed to compensate for the asymmetry. If asymmetries are

³Similarly, rarefaction clicks produce shorter latencies than condensation clicks.

congruent, ie. shorter latencies accompany larger amplitudes and longer latencies accompany smaller amplitudes, then the following hypothetical situation might be expected:

Situation #1. (Congruent Asymmetry). The right BSAEP is shorter in latency and larger in amplitude than the left BSAEP. In this situation, delaying the time of stimulus onset to the right ear would offset the latency asymmetry by delaying the waveform of the right ear response, but would not resolve the amplitude asymmetry. A reduction in intensity to the right ear, however, would eliminate the latency asymmetry by delaying the right ear response, and, at the same time, eliminate the amplitude asymmetry by reducing the amplitude of the right ear response.

Alternatively, right/left asymmetries could reflect a real difference in the way in which the right and left auditory tracts process acoustic information. Differences in wave morphology, for example, may indicate differences in the synchrony of neural firing between tracts. Several studies have documented right/left morphological asymmetries (Chiappa et al., 1979; Rowe, 1978) in the BSAEPs of normal hearing subjects. The nature of these asymmetries, however, has precluded quantification and they have been described in purely qualitative terms. Complex asymmetries, such as those due

to morphological differences, would not be expected to yield to simple manipulations of interaural time or intensity relationships. The following situation illustrates this point.

Situation #2. (Morphological Asymmetry). The right BSAEP has a fused wave IV-V complex and the left BSAEP has distinctly separated waves IV and V. D.)) Interaural time or intensity manipulations may succeed in aligning wave V of the left ear response with the IV-V complex of the right ear response, however, a significant asymmetry would remain by virtue of the different wave shapes which would not be expected to change as a function of interaural stimulus manipulations. It was anticipated that time and intensity manipulations would be equally ineffective in offsetting asymmetries due to morphological differences.

Latency and amplitude asymmetries may also be complex and unyielding to manipulations of interaural time or intensity. A shorter latency may indicate faster neural conduction through the brainstem auditory pathways while a larger amplitude may indicate more neural units responding in one tract as compared with the other. Such latency or amplitude differences, could, conceivably, exist independently of each other creating a situation in

⁴Other types of morphological asymmetries are described in Appendix D.

which, for example, the response from one ear has a shorter latency but also a smaller amplitude in comparison to the response from the opposite ear. Incongruent asymmetry such as this, in which the expected amplitude/intensity relationship does not occur, would be difficult to offset by means of interaural stimulus manipulations. The following hypothetical situations illustrate this point:

Situation #3. (Type A Incongruent Asymmetry).

The right BSAEP leads in latency but is smaller in amplitude than the left BSAEP. In this situation, a delay in the onset of the right ear stimulus would correct the latency asymmetry, but the amplitude difference would remain uncorrected. A decrease in the intensity to the right ear would offset the latency asymmetry, but increase the amplitude asymmetry by further reducing the amplitude of the right ear response.

Situation #4. (Type B Incongruent Asymmetry).

The right BSAEP leads in latency but is equal in amplitude to the left BSAEP. In this situation an interaural time difference may be effective in eliminating the asymmetry. Delaying the onset of the right ear stimulus relative to the left ear stimulus would be expected to delay the right ear response until the latencies of the right and left ears matched. Decreasing intensity to the right ear, on the other hand

would correct the latency asymmetry, but, by reducing the amplitude of the right ear response, would also create an amplitude asymmetry.

Situation #5. (Type C Incongruent Asymmetry).

The right BSAEP is equal in latency but is unequal in amplitude to the left BSAEP. In this situation an interaural time difference would be ineffective in offsetting the amplitude difference and would introduce an inter-ear latency difference. An interaural intensity difference may correct the inter-ear amplitude disparity, but, like the time difference, would introduce a latency difference which did not exist in the equal SL condition.

The decision as to which stimulus variable, time or intensity, to manipulate for the purposes of maximizing the elimination of response asymmetry was motivated by expectations concerning the type of asymmetry which would be most frequently encountered. As mentioned above, neither time nor intensity manipulations were expected to be effective in eliminating morphological asymmetries. Congruent asymmetries were expected to be offset most successfully by intensity manipulations, while some incongruent asymmetries would probably respond to time manipulations. Although several studies have documented inter-ear latency and amplitude differences in normal subjects (Levine and McGaffigan, 1983; Rowe, 1978; Seltzers and Brackmann, 1977), no study

to date has examined the relationship between amplitude and latency in inter-ear BSAEP asymmetries. There were, therefore, no available data to support an a priori assumption that inter-ear latency and amplitude asymmetries would be anything other than congruent. Assuming that larger amplitudes would be associated with shorter latencies and, conversely, that smaller amplitudes would be associated with longer latencies, situation #1, described above, was expected to be encountered most frequently when amplitude and latency asymmetries were present. For this reason, the decision was made to use intensity as the stimulus variable for the purposes of offsetting asymmetry. Whereas manipulation of interaural time relationships may compensate for latency asymmetries, manipulation of interaural intensity relationships may compensate for both latency and amplitude asymmetries. It was expected that this manipulation would be only partially successful in eliminating asymmetry for situations in which right/left morphology differences existed.

The threefold purpose of this study was first, to determine the frequency of occurrence of natural asymmetry in a group of normal hearing subjects, second, to examine any right/left asymmetries that were found in the BSAEPs of normal hearing subjects and third, to examine the relationship between monaural and binaural

auditory processing by means of observing the differences between monaural and binaural BSAEPs. It was hypothesized that the binaural response represents a combination of information which is available in the right and left monaural responses. It was further hypothesized that, under conditions of binaural stimulation, the auditory system combines right and left auditory tract information in a manner which can be best described by a model based on an algebraic combination of monaural responses. Because of the previously described problems associated with algebraic combinations of waveforms in which differences exist, it was proposed that the right/left asymmetries which may exist in the BSAEPs would have a pronounced effect on the ability of these models to predict the binaural response. A linear combination of right and left responses was, therefore, expected to be a good predictor of the binaural response only under conditions in which the right and left ear responses were symmetrical. In cases in which responses to equal stimulation were naturally asymmetrical, two alternative models for predicting the binaural response by means of combining the monaural responses were proposed. Under conditions in which response asymmetry existed, it was proposed, that Decker and Howe's (1981) method of subtracting the preferred monaural response from the binaural response ($[2 \times \text{Preferred monaural}] - \text{Bin}$) was

expected to be a better predictor of the binaural response. The third alternative, was to eliminate the right/left asymmetry by means of an interaural intensity adjustment. After asymmetry was eliminated, $(R_m + L_m) - B_{in}$ was expected to be a good predictor of the binaural response, as was the case for naturally symmetrical responses. The following summarizes the three models which were tested in this study:

Model 1. Algebraic summation of the right and left monaural responses which were obtained under conditions of equal dB SL stimulation. This is $R_m + L_m$, as described in the noninteractive linear model by Dobie and Berlin (1979a).

Model 2. Multiplying by 2 the monaural response (right or left) which, when doubled, was most similar to the binaural response in phase, amplitude and morphology. This is the "preferred" response as described by Decker and Howe (1981).

Model 3. Algebraic summation of the right and left monaural responses after any existing right/left asymmetry had been offset by means of an interaural intensity difference. This is a stimulus manipulation specifically designed for this study.

The following results were anticipated:

- 1) If monaural responses are naturally symmetrical, equal right and left monaural responses will

sum to equal the binaural response. Algebraic summation of the right and left responses would be a good predictor of the binaural response, therefore, the residual component (RC), if any, would be small.

2) If monaural responses are asymmetrical, algebraic summation of the right and left responses would provide a poor predictor of the binaural response. The residual component would, in this case, be large. A better predictor of the binaural response might be provided by simply doubling the preferred monaural response and eliminating the other response (non-preferred response) from the calculation.

3) If monaural responses are naturally asymmetrical but can be made more or less symmetrical by means of an interaural intensity difference, the monaural responses could be combined to form a good predictor of the binaural response. The RC, in this case would be small and approximate the RCs of naturally symmetrical subjects.

The foregoing speculations regarding inter-ear asymmetry, its nature and its effect on the prediction of the binaural response, are important only if asymmetry does, in fact, exist in the BSAEPs of a significant number of normal hearing subjects. An important issue which needs to be addressed, therefore, is, determination of the proportion of normal hearing subjects that will

exhibit right/left asymmetries in the BSAEP. Available data suggest that approximately 40 to 50% of normal hearing subjects will have asymmetrical monaural BSAEPs under conditions of equal stimulation to the right and left ears, while the remaining 50% will have naturally symmetrical responses (Allen et al., 1982; Chiappa et al., 1979; Decker and Howe, 1981; Rowe, 1978). The first experimental question deals with this fundamental issue:

1. What proportion of normal hearing subjects will have significant right/left asymmetries in the Brainstem Auditory Evoked Potential when equal sensation level stimuli are presented to each ear?

It is hypothesized that natural asymmetry exists in a significant number of normal hearing subjects. Assuming that this hypothesis is correct, the following questions will be addressed:

- a) Are there significant differences in the incidence of asymmetry at different intensity levels (70 vs. 50 dB SL)?

- b) Does the direction of the asymmetry, ie. right leading or left leading, consistently favor one ear?

2. Is there any relationship between the amount of right/left asymmetry present and the ability to predict the binaural response by linear addition of the right and left monaural responses?

It is hypothesized that the ability to predict

the binaural response by means of a linear addition of the right and left monaural responses will be inversely related to the degree of asymmetry present in the monaural responses of a given subject, ie. the more asymmetry present, the poorer the predictions of $R_m + L_m$ will be.

3. Given that asymmetry will be found in the BSAEPs of a significant number of subjects, can it be eliminated or significantly reduced by manipulating interaural intensity? That is, can the magnitude of the right/left difference be reduced by systematically varying the intensity presented to one ear relative to the intensity presented to the other ear?

The hypothesis is that response asymmetry, when present, can be eliminated or significantly reduced by means of an interaural intensity manipulation.

4. Three monaural combination models were proposed. Which model will best predict the binaural response?

Model 1. Linear summation of the right and left monaural responses which result from equal sensation level stimuli?

Model 2. Doubling of the preferred monaural response.

Model 3. Linear summation of the right and left monaural responses after any existing asymmetry has been

offset by means of an interaural intensity difference ($R_m + L_m'$).

It is hypothesized that linear summation of the right and left monaural responses is a good predictor of the binaural response when the right and left responses are symmetrical, either naturally or by means of an interaural intensity difference. When responses are asymmetrical the binaural response is best predicted by means of doubling the preferred monaural response.

PART II

Criterion for Significant Right/Left Difference

The experimental design required the grouping of subjects into two categories: symmetrical and asymmetrical. It was necessary, therefore, to develop a method and a criterion for the classification of subjects into these two categories. A review of the current literature concerned with response asymmetry revealed a variety of ways in which the problem of determining the presence of significant response asymmetry has been handled.

Time Series ANOVA. Berlin, Allen and Hughes (1982) described a statistical procedure for determination of response asymmetry. A computer program was designed which performed a point by point analysis of the 256 points which comprise the evoked potential. The procedure involved off-line digitization of the waveform and subsequent computer analysis. According to Hood, Martin and Berlin (1983), who used this program to determine the existence of asymmetries in the MLAEP and LAEP, "Non-parallel amplitude differences at each of the respective points provide quantification and significance of differences between waveforms" (Hood et al., 1983, p. 2).

Binaural - Monaural Subtraction. This

procedure was introduced by Decker and Howe (1981) for the purpose of examining difference traces which these authors associated with binaural interaction, free from the confounding effects of response asymmetry. Secondly, the procedure revealed the presence and direction of response asymmetry. This method required the individual subtraction of each monaural response from the binaural response which was scaled by a factor of two (Binaural / 2). Decker and Howe assumed that, if both ears contribute equally to the binaural response, then $\text{Binaural} - \text{Right} = \text{Binaural} - \text{Left}$. The presence of response asymmetry was revealed in the form of a larger amplitude difference trace when the response from the "non-preferred" ear was subtracted from the binaural response. This method has been used to examine response asymmetry in the BSAEP (Allen et al., 1982; Decker and Howe, 1981; Garcia, 1983), and the MLAEP (Hood, Berlin and Hughes, 1983).

Right-Left Monaural Subtraction. Hood, Martin and Berlin (1983) subtracted the left monaural response from the right monaural response in order to assess asymmetry. The results of this manipulation were not quantified, but were used primarily as pictorial representations of asymmetry (Hood, 1984).

Since this experiment required an immediate classification of a subject's responses as symmetrical or

asymmetrical, each of the methods outlined above were unsuitable for this purpose for one or more reasons. The time series ANOVA used by Berlin et al. (1982), for example, was not applicable to this experiment since it did not provide for immediate, on-line analysis of the data. The binaural - monaural subtraction described by Decker and Howe (1981) was also judged to be inappropriate because it was too time consuming for use as an on-line method of analysis. Implementation of Decker and Howe's procedure would have required the recording of binaural responses for every interaural intensity condition. In an experiment in which the running time per subject often exceeded three hours, the addition of 12 - 16 extra runs, lasting 3 minutes each, was not practical.

More importantly, Decker and Howe's procedure called for a two step subtraction procedure (1. $\text{Bin} - \text{Rm}$; 2. $\text{Bin} - \text{Lm}$) which could easily be reduced to a one step procedure, $\text{Rm} - \text{Lm}$. The advantage of using $\text{Rm} - \text{Lm}$ as a measure of asymmetry is that it is a direct assessment of the equality of Rm and Lm in the equation $(\text{Rm} + \text{Lm}) - \text{Bin} = \text{BIC}$. According to Decker and Howe, it is the inequality of the Rm and Lm terms in the equation which causes the BIC to be an inaccurate representation of binaural interaction. Decker and Howe, therefore, proposed separate monaural subtractions from the binaural

response. According to these authors, if $Bin - Rm = Bin - Lm$, symmetry could be assumed. If, however, $Bin - Rm \neq Bin - Lm$, then asymmetry could be assumed. Since both sides of Decker and Howe's equation contain a common term (Bin), the equation can be simplified to $Rm - Lm = 0$. Thus, if one merely wishes to demonstrate the presence of asymmetry between monaural responses, it can be directly accomplished by means of subtracting the left from the right response. There is a high correlation between results of $Rm - Lm$ procedure and measurements of asymmetry based on right/left differences in wave V latency (see Appendix A) indicating that $Rm - Lm$ is a useful measure of asymmetry. This method was employed by Hood et al. (1983). Their procedure, however, did not provide a method for quantifying or determining the significance level of the right/left difference.

In order to use $Rm - Lm$ as a measure of asymmetry in this experiment it was necessary to develop a decision criterion in order to make on-line judgments as to whether or not the results of $Rm - Lm$ represented a significant right/left asymmetry, or merely represented random fluctuations due to uncanceled background noise in the BSAEP. The following describes the way in which the criterion for evaluation of the amplitude of the $Rm - Lm$ difference trace was developed.

The null hypothesis predicted no significant

difference between the right and left monaural responses. In order to provide a stringent test of the null hypothesis and thus minimize the possibility to Type I errors, a conservative criterion of significant difference was developed for this study. The criterion, which was calculated individually for each subject, was based on the amplitude of the uncanceled, random noise which remained in the no stimulus control run (NSC) after averaging. The peak to peak (p-p) amplitude of the residual noise was multiplied by a factor of 1.5 in order to establish a conservative criterion against which the peak to peak amplitude of the Rm - Lm difference trace was compared. If the peak to peak amplitude of the Rm - Lm difference trace exceeded the criterion, the null hypothesis could be rejected at the .01 level of confidence. The rationale for this criterion is described in Appendix B. The following operational definitions for asymmetry and symmetry were based on the the criterion described above and used in this study:

Naturally Occurring Asymmetry was defined as a significant right/left response difference which was determined by subtracting the left (average of 2 runs) from the right (average of two runs) response and measuring the peak to peak amplitude of the resulting difference trace. The positive and negative peaks within the 5 - 8 ms latency region with the largest interpeak

amplitude were selected for this measurement. This window encompasses waves IV - VI and is the latency region on which previous studies of response asymmetry and binaural interaction have focused. Criterion for asymmetry was a difference trace which exceeded an estimate of the peak to peak amplitude of the noise floor by a factor of 1.5.

Naturally Occurring Symmetry was defined as the situation in which the peak to peak amplitude of the right minus left difference trace fell below the criterion for significant right/left difference when stimuli were presented at equal dB SL to each ear.

Induced Symmetry, which was brought about as a result of an interaural intensity manipulation, was defined according to the following criteria:

a. Right response minus left response yields a difference trace which is less than criterion for asymmetry, or

b. Right response minus left response yields a difference trace which exceeds the criterion for asymmetry, but is smaller than the difference trace obtained under the equal SL condition (best possible, although imperfect, match).

The criterion described was employed for two reasons: 1) it provided a conservative criterion for

determining the presence of significant inter-ear response asymmetry, and 2) it was a relatively quick and simple technique which provided immediate, on-line information concerning the relationship between the right and left ear responses. An alternative method had been suggested, however which was felt to provide a more rigorous criterion for determining inter-ear asymmetry (Levitt, 1985). Briefly, this method required that an estimate of the run-to-run measurement variability be determined. In order to do this the standard errors of the mean for three measurements (run-to-run wave V latency differences, run-to-run wave V amplitude differences, and run-to-run $R_m - L_m$ amplitude differences) were calculated. The null hypothesis stated that measurement of Right - Left difference would not exceed the estimate of the standard error of the mean. A pilot study was performed in which this method of determining significant right/left difference was employed. Appendix B presents a description of this criterion and a comparison of the results of using this statistical criterion with the results of using the empirical on-line criterion. Results indicated that the on-line method of determining significant right/left difference which was used in the main experiment was, indeed, very conservative.

PART III

Method

Subjects

Twenty-four subjects with pure tone thresholds not greater than 15 dB HL at any audiometric frequency, volunteered for this study. As a control for latency and amplitude differences between BSAEPs of males and females (Seitz and Morehouse, 1979; Seitz, Weber, Jacobson and Morehouse, 1979; Stockard, Stockard, and Sharbrough, 1979), subjects consisted of equal numbers of males and females. In order to control for ear differences, subjects were required to have symmetrical audiograms, i.e. the right and left ear thresholds could not differ by more than 5 dB at any frequency. Mean thresholds and standard deviations for all frequencies are shown in Table 1. In addition, acoustic immittance measurements (tympanograms and contralateral acoustic reflex thresholds) had to be within normal limits for all subjects.

Subjects ranged in age from 12.6 to 35 years. It is through this age range that the BSAEP is most stable, since it is not likely to be effected by changes due to maturation (Hecox and Galambos, 1976; Salamy and McKean, 1976) or to aging (Rowe, 1978). The mean age for all

TABLE 1

Mean right and left ear thresholds (dB HL) and standard deviations for 24 subjects used in this study.

		Frequency Hz					
		<u>250</u>	<u>500</u>	<u>1K</u>	<u>2K</u>	<u>4K</u>	<u>8K</u>
Right (dB HL)	- x	4.2	2.9	1.7	1	0.0	5.0
	S.D.	5.8	5.2	6.0	7.1	7.5	7.1
Left (dB HL)	- x	4.0	3.5	2.5	1.0	0.4	3.5
	S.D.	6.4	5.4	5.5	6.5	7.5	7.0

subjects was 22.2 years. The mean age for male subjects was 22.3 years and for female subjects was 22.2 years.

Equipment

Inclusion of subjects in the study was determined on the basis of behavioral pure tone thresholds which were measured using the Grason Stadler model 1701 or GSI-10 clinical audiometer. Acoustic immittance measurements were made on the Electromedics 83 clinical impedance bridge.

A four channel clinical evoked response unit (Nicolet CA-1000) with associated click generator (model NIC-1007A) and physiological amplifiers (model HGA-200A) with a 12 dB per octave roll off, was used to record the BSAEPs. The model DC-2000 (Nicolet) disk controller was used to store waveforms on floppy diskettes for off-line analysis. The add, subtract, and invert functions of the DC-2000 were used for addition and subtraction of waveforms. Stimuli were transduced through matched Telex (1470A) earphones mounted in standard MX41/AR cushions.

Calibration

1. A 100 microsecond click was transduced through the right and left earphones and displayed on an oscilloscope in order to check for differences in the responses of the two earphones. The earphone responses

are shown in Figure 2. Visual inspection indicated no significant difference between the two earphones. The difference in amplitude of the major pulse transduced by the right and left earphones was .03 microvolts for the 70 dB click, and .01 microvolts for the 50 dB click.

2. The equality of the right and left earphones was also checked by reversing the earphones on four subjects and comparing the responses obtained in this manner to those obtained with the earphones in their normal position. Results from one such subject are displayed in Figure 3. An overlay of responses recorded with earphones reversed and responses recorded with earphones normal revealed that both earphone positions yielded virtually identical results.

In order to quantify the differences between responses obtained with earphones reversed and responses obtained with earphones in their normal position, the amplitudes and latencies of waves I, III, V and VI were measured for three response conditions: Right ear/Left earphone (Reversed), Right ear/Right earphone (Run 1) and Right ear/Right earphone (Run 2). The amplitude and latency differences between the Reversed condition and Run 1, were compared to the amplitude and latency differences between Run 1 and Run 2. These data are presented in Appendix C. Amplitude and latency differences between the Reversed condition and Run 1 at

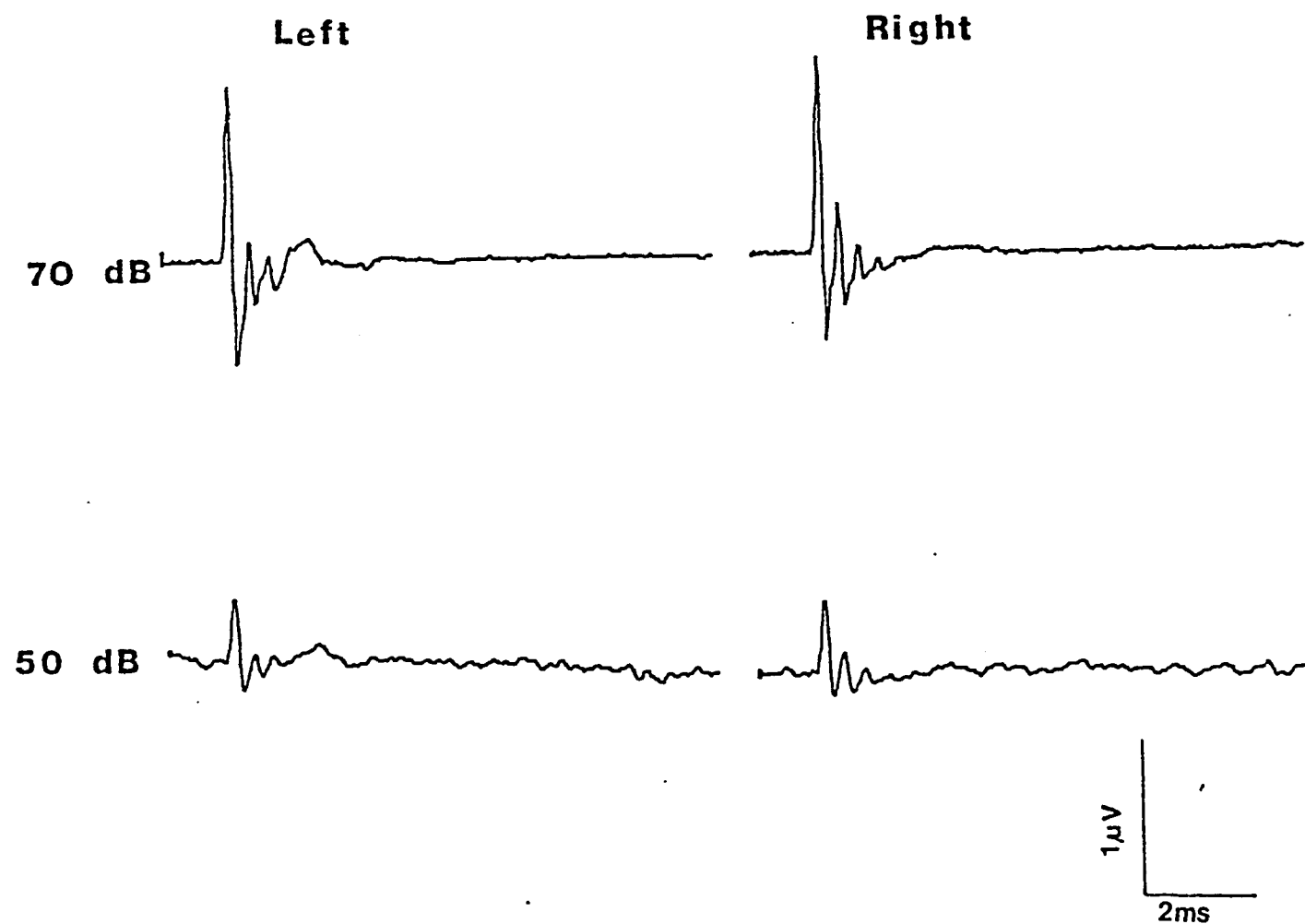


Figure 2.- Oscilloscope display of 100 us pulse transduced through Telex 1470A earphones.

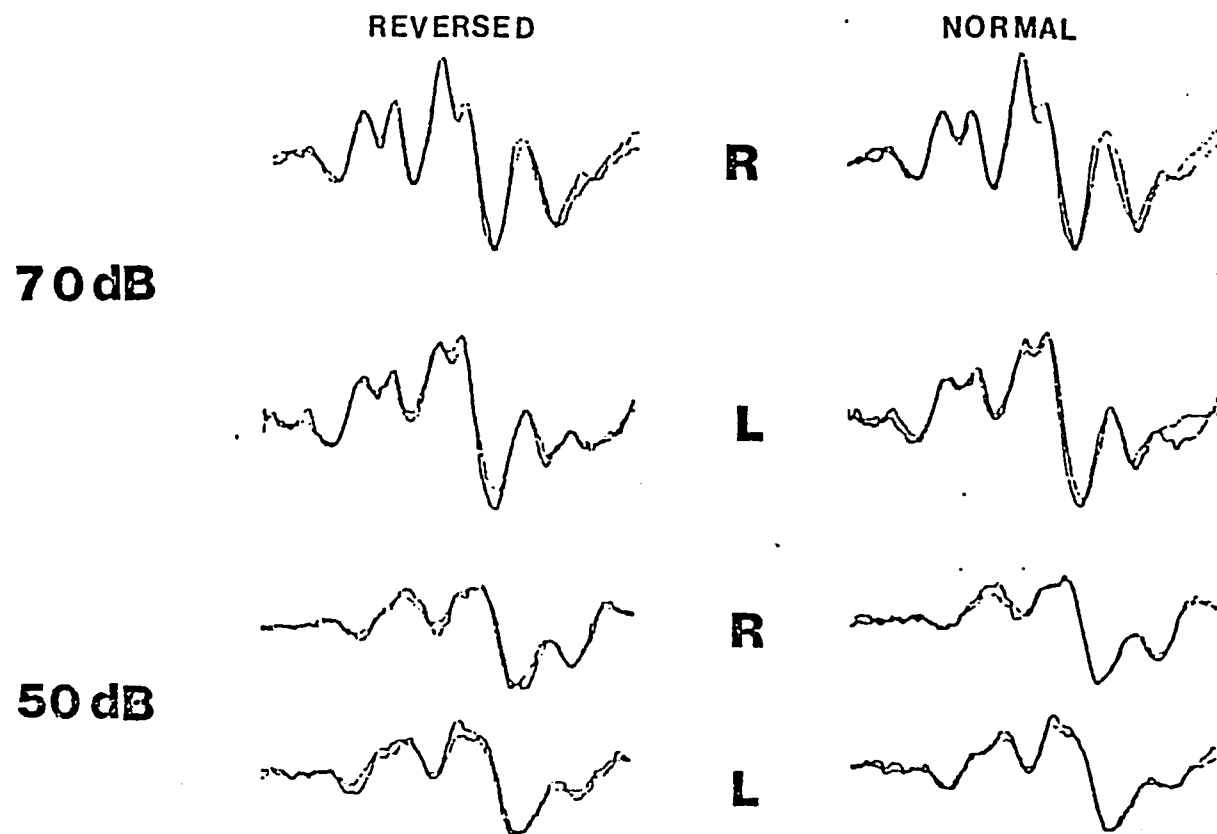


Figure 3. BSAEPs recorded from the right (R) and left (L) ears of one subject at two sensation levels. The left half of the figure shows BSAEPs recorded with earphones reversed (right earphone on left ear) and the right half of the figure shows BSAEPs recorded with earphones in their normal position.

no time exceeded the amplitude and latency differences between Run 1 and Run 2. Thus, it was concluded that small differences in responses which might be attributable to changing earphones (Reversed - Run 1), did not exceed the observed run-to-run variability (Run 1 - Run 2).

3. The equality of the right and left channel attenuators was checked by displaying a 100 microsecond pulse on an oscilloscope and measuring, in microvolts, the decrease in amplitude of the pulse as the attenuation was increased in 2 dB steps. A 2 dB decrease in intensity produced an equal decrease in the amplitude of the pulse for the right and left channel. These measurements for a 70 dB and 50 dB click are shown in table 2.

4. In order to estimate the level at which acoustic crossover may begin to affect the BSAEPs, BSAEPs were recorded from the deaf ear of a unilaterally deaf subject. The interaural attenuation of the system was found to be in excess of 80 dB HL. That is, the intensity of the click delivered to one ear could be raised to 80 dB HL without causing a BSAEP attributable to stimulation of the opposite ear by means of acoustic cross-over (Figure 4).

5. The integrity of the system was checked immediately before each recording session with the Nicolet calibration unit (NIC-100). The amplitude and

TABLE 2

The effect of reducing intensity in 2 dB steps on the amplitude of a 100 microsecond pulse.

dB HL	RIGHT μ V	LEFT μ V
70	29.4	29.0
68	21.6	21.4
66	19.6	19.2
64	14.8	14.4
62	12.2	12.0
50	5.0	5.0
48	4.2	4.2
46	3.8	3.8
44	3.4	3.4
42	2.6	2.8

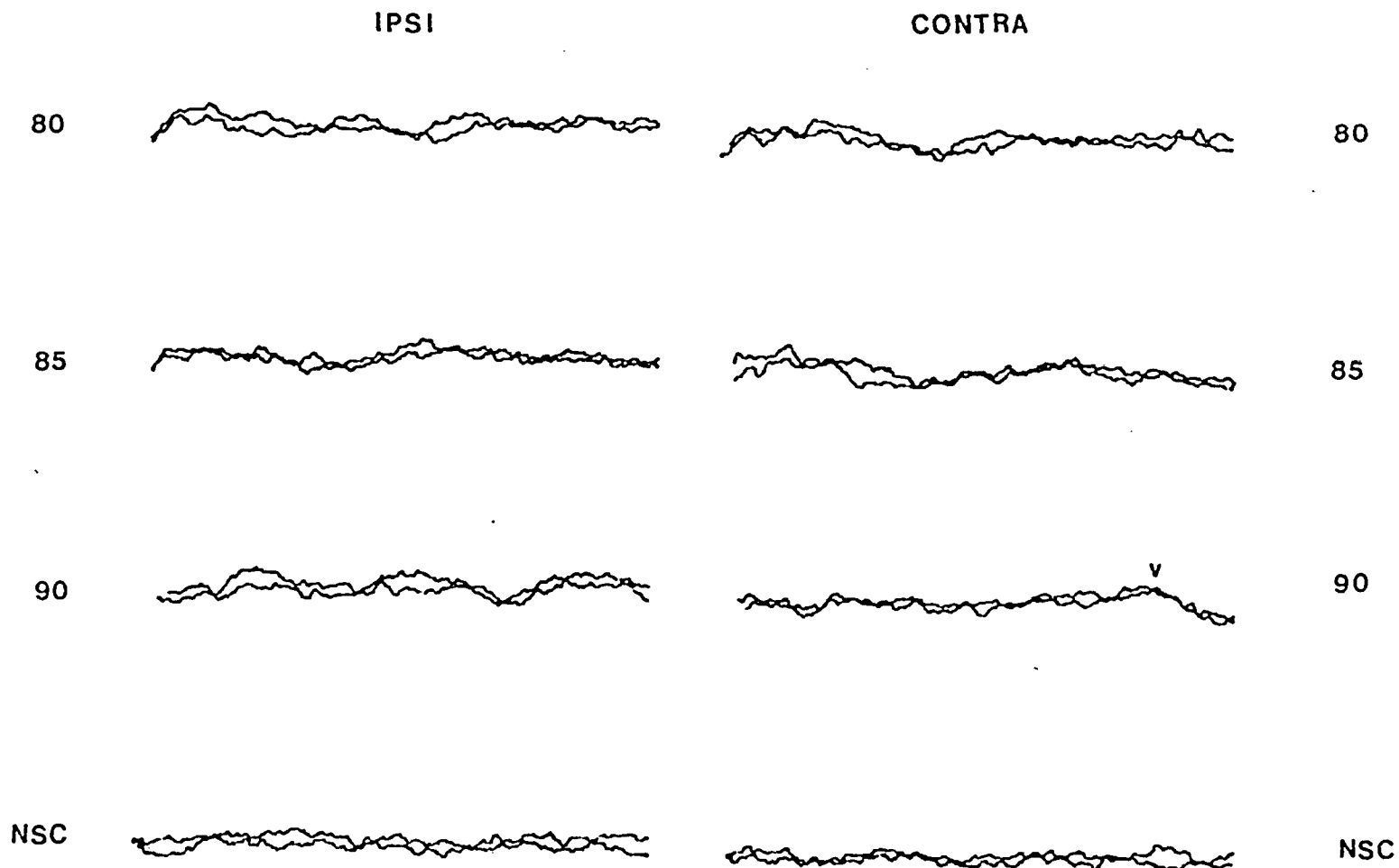


Figure 4. Ipsilateral (IPSI) and contralateral (CONTRA) recordings upon stimulation of the deaf ear of a unilaterally deaf subject. The level of the stimulus is indicated in dB HL for each recording. A no stimulus control run (NSC) is included for comparison. Note the appearance of wave V on the contralateral side in response to 90 dB.

duration of the averaged pulse were measured to insure that they measured .5 microvolt in amplitude and 2 ms in duration.

Recording

Brainstem auditory evoked potentials were recorded from gold, cup electrodes affixed to the vertex (active), base of the neck (mid-line reference placed equidistant between the two ears) and forehead (ground). Electrode impedances were maintained below 4K ohms; interelectrode impedances were maintained below .5K ohms. The EEG was amplified by 10^4 and band passed between 150-3000 Hz. The recording window was set to analyse the first 10 ms of the evoked response. Sensitivity was set at ± 10 microvolts. Responses to 2,048 stimuli were averaged and constituted one run. Each run was replicated for a total of two runs per condition. Responses for each stimulus condition, right monaural, left monaural, and binaural were individually recorded on the same channel utilizing the same amplifier. By using only one of four available amplifier channels, instrumental variability was eliminated. The system's automatic artifact reject program was in operation throughout the recording sessions. Any EEG activity exceeding ± 10 microvolts was automatically excluded from the average.

Stimulus

Stimuli consisted of 100 microsecond rarefaction clicks presented via earphones at a rate of 11 clicks per second. This rate was selected because it was the most commonly used rate in research of this kind and would allow for cross study comparisons. Intensity of the clicks was expressed in dB SL re each subject's monaural click threshold. In order to examine the effect of stimulus level on the experimental conditions, two intensity levels were used, 70 dB SL (high intensity) and 50 dB SL (moderate intensity). 70 dB SL was chosen as the high intensity level because it was safely below the estimated cross-over point of the system (80 dB) and it was a reasonably comfortable level for subjects. The 50 dB SL level was considered to be sufficiently below the high intensity level to show any differences which might be related to intensity level, while at the same time, high enough in intensity so that waveform definition would not be sacrificed.

Stimulus Presentation

One ear was randomly selected to be the "variable" ear; the intensity to the opposite ear was held constant (70 dB SL or 50 dB SL). The stimulus presentation proceeded in the manner described below. In this illustration, the standard ear was the left ear and

the variable ear was the right ear. Numbers to the left of each stimulus presentation indicate the order in which conditions were recorded.

MONAURAL

BINAURAL

- | | |
|---|---|
| 1. Right (standard) 70 dB | |
| 2. Left (variable) 70 dB | 3. L70/R70 |
| 4. Left (raise or lower in
2 dB steps until $R_m - L_m$
is less than criterion) | 5. L (balance dB ⁵ /
R/70 |
| 6. Right (standard) 50 dB | |
| 7. Left (variable) 50 dB | 8. L50/R50 |
| 9. Left (raise or lower in
2 dB steps until $R_m - L_m$
is less than criterion) | 10. L (balance dB/
R50 |

Procedures

Behavioral click thresholds for monaurally presented clicks were determined for each ear in 2 dB steps using an ascending-descending procedure. Subjects reclined comfortably on a cot in a semi-darkened, double

⁵The intensity to the variable ear required for induced symmetry.

walled, IAC booth. Subjects were instructed to close their eyes and relax.

Brainstem auditory evoked potentials were recorded under three stimulus conditions: 1. Monaural, 2. Binaural diotic (equal sensation level to each ear) and, 3. Binaural dichotic (interaural intensity difference required to produce symmetrical responses according to the definition of symmetry discussed previously).

Monaural Stimulation. 1. Responses to 70 dB SL stimuli were recorded from the right and left ears of each subject.

2. Two silent (no stimulus) control runs (NCR) were recorded in order to estimate the level of the uncanceled background noise. In order to achieve a conservative estimate of the background noise, the NCR with the largest peak-to-peak amplitude was selected for analysis. The amplitude of the NCR was determined by choosing the highest positive and lowest negative peaks within the analysis window and measuring the difference in microvolts between them. This measurement was used in determining the criterion for judging significant difference between right and left responses as explained above (on-line method).

3. On-line comparison of the right and left responses ($R_m - L_m$) was made in order to determine the presence or absence of response asymmetry.

4. If the left and right responses met the criterion for asymmetry, the direction of the asymmetry, ie. right leading or left leading, was determined on the basis of wave V latency (or wave V amplitude if latencies were equal). The intensity of the stimulus to one ear was either increased (to the lagging ear) or decreased (to the leading ear) in 2 dB steps in an attempt to find the intensity level which would elicit a response from the variable ear which was symmetrical with the response from the standard ear.

The following example illustrates the way in which asymmetry was offset by means of an interaural intensity difference:

- a. Right response (70 dB SL) - Left response (70 dB SL) = difference trace exceeding criterion.
- b. The left ear is randomly chosen as the variable ear. Wave V of the left ear response leads wave V of the right ear response in latency, therefore, the intensity to the left ear is reduced in 2 dB steps.
- c. Right response (70 dB SL) - Left response (68 dB SL) = difference trace which is smaller than the difference trace obtained in "a", however, it still exceeds criterion for significant right/left difference. Intensity to

the left ear is reduced 2 dB.

d. Right response (70 dB SL) - Left response (66 dB SL) = difference trace which falls below criterion for significant right/left difference. Intensity to the left ear is reduced 2 dB.

e. Right response (70 dB SL) - Left response (64 dB SL) = difference trace which, once again, exceeds criterion for significant right/left difference.

In the above example, the two monaural responses were considered symmetrical (induced symmetry) when the intensity to the right ear was 70 dB SL and the intensity to the left ear was 66 dB SL.

5. If 70 dB SL stimuli to the right and left ears resulted in naturally symmetrical responses, step 3 was omitted.

Binaural Stimulation

Equal SL. Responses were recorded to 70 dB SL stimuli presented simultaneously to the right and left ears.

Interaural Intensity Difference (IAID).

Binaural responses were recorded with the interaural stimulus difference which produced symmetrical monaural responses, as explained above. Dichotic binaural

recordings were omitted when monaural responses were judged to be naturally symmetrical.

The procedures outlined above were repeated for the 50 dB SL click stimuli. All BSAEPs were stored on floppy diskette for later, off-line analysis.

PART IV

Data Analysis

The amplitude and latency of Waves I, III, and V were measured using the cursor of the Nicolet CA-1000. Amplitude was measured from the positive peak of each wave to the following negative trough. Latency was measured from stimulus onset to the positive peak.

Asymmetry Ratio (AR)

In order to provide a measurement of the degree of asymmetry present in each subject's monaural responses, a ratio was calculated between the amplitude of the Rm - Lm difference trace under the equal sensation level condition and the criterion which, as described in Part II of this chapter, was obtained by multiplying NSC by a factor of 1.5. If the amplitude of the Rm - Lm difference trace exceeded the criterion, thereby meeting the requirements for asymmetry, the asymmetry ratio (AR) was greater than unity and indicated the presence of significant right/left response asymmetry. The degree to which an individual subject's right/left asymmetry differed from the level of background noise, was indicated by the size of the AR. If, on the other hand, the amplitude of the Rm - Lm difference trace was smaller than or equal to the criterion, the AR was less than

unity and, According to the definition for naturally occurring symmetry, response symmetry was indicated. The following hypothetical example illustrates the determination of the presence of response asymmetry based on the AR.

The peak-to-peak amplitude of the NSC for subject X is .15 uV. The criterion for significant difference for this subject, therefore, is .23 uV:

$$.15\text{uV NSC} \times 1.5 = .23 \text{ uV}$$

The Rm - Lm difference trace under the equal SL condition is .44 uV. The AR, which is the ratio between the Rm - Lm difference trace and the NSC, is equal to 1.91:

$$.44\text{uV} / .23 \text{ uV} = 1.91 \text{ AR}$$

Since the AR exceeds unity ($2.17 > 1.0$), this subject's responses are classified as asymmetrical. Figure 5 shows, in graphic form, how the presence or absence of response asymmetry is determined on the basis of the AR. The AR, therefore, provided a single number representation of the presence and degree of response asymmetry.

The following algebraic manipulations of responses were performed using the add, subtract and invert functions of the DC-2000. These operations were

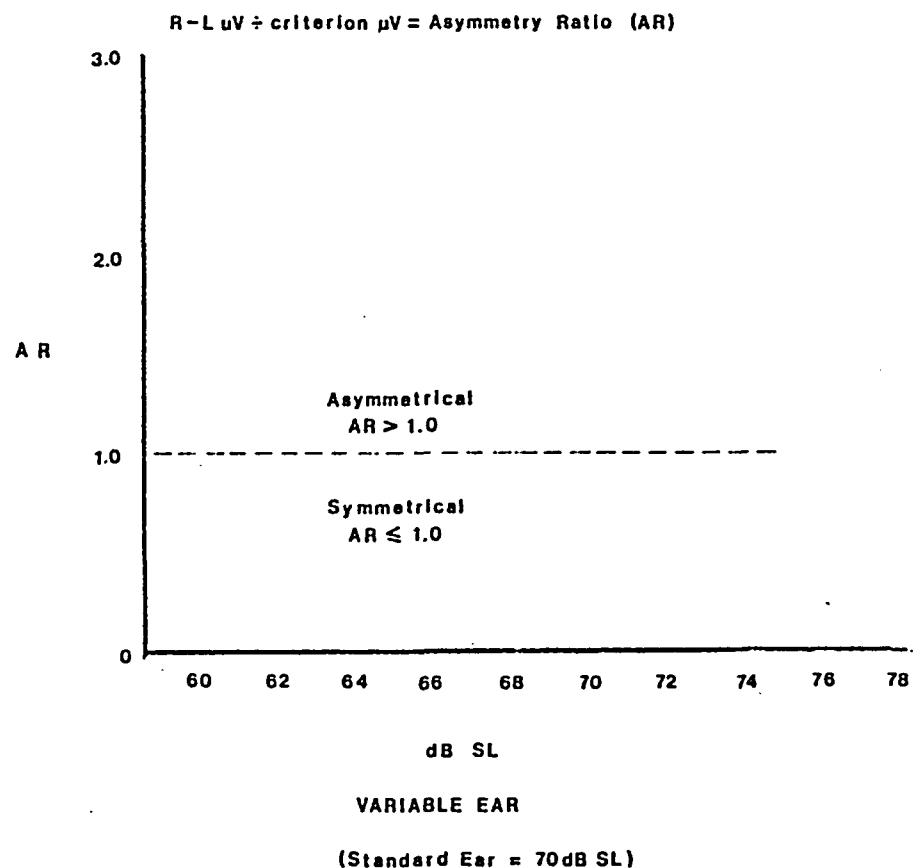


Figure 5 . Determination of asymmetry by means of the asymmetry ratio (AR). When $R_m - L_m$ divided by the Ss criterion falls below unity (dashed line), responses are classified as symmetrical.

applied to the mean of two runs (4,096 stimuli) for each stimulus condition.

Residual Component (RC)

The Dobie and Berlin procedure for determining the presence of binaural interaction was applied to two sets of responses at each intensity level (70 and 50 dB SL):

70 dB

1. Equal SL. $(Lm^6 70 + Rm 70) - B 70/70 =$

Residual Component (RC)

2. IAID. $(Lm \text{ balance dB} + Rm 70) - B \text{ balance dB}/70 = RC$

50 dB

1. Equal SL. $(Lm 50 + Rm 50) - B 70/70 = RC$

2. IAID. $(Lm \text{ balance dB} + Rm 50) - B \text{ balance dB}/70 = RC$

Where $Lm 70$ or 50 is the left monaural response from the midline electrode to 70 dB or 50 dB SL stimuli; $Rm 70$ or 50 is the corresponding right monaural response; $B 70/70$ or $50/50$ is the binaural response to diotic stimuli; balance dB is the intensity applied to the left ear which elicited a left monaural response equal to the 70 dB or 50 dB right monaural response; $Lm \text{ balance dB}$ is the left monaural response which equals either the 70 dB or 50 dB right monaural response; $B \text{ balance dB}/70$ or 50 is the binaural response to IAID stimuli; RC is the difference trace.

⁶The variable ear will differ from subject to subject.

Binaural/Monaural Difference Trace

The Decker and Howe (1981) method for determining binaural interaction was applied to the two sets of responses at each intensity level (70 and 50 dB SL):

70 dB

1. Equal SL. $B_{70/70} - 2 \times (Rm_{70}) =$
Binaural/Monaural Difference Trace-Right Ear (B - MR).

2. Equal SL. $B_{70/70} - 2 \times (Lm_{70}) = B - ML.$

50 dB

1. Equal SL. $B_{50/50} - 2 \times (Rm_{50}) = B - MR.$

2. Equal SL. $B_{50/50} - 2 \times (Lm_{50}) = B - ML.$

Preferred (B - P) vs. Non-preferred (B - N)Binaural/Monaural Difference Traces

As previously defined, the preferred response was the monaural response which, when doubled, was most similar in phase, morphology, and amplitude to the binaural response. The preferred response (right preferred or left preferred) was determined by comparing the amplitudes of the B - MR and the B - ML. The monaural response which produced the smaller difference trace after being subtracted from the binaural response was considered to be the preferred response. Since it was

anticipated that the responses of some subjects would be right preferred and the responses of other subjects would be left preferred, analysis of the data in terms of right vs. left was expected to nullify any differences which may have existed between the right and left responses. For this reason, difference traces for all subjects were arranged according to classification as preferred (P) or non-preferred (NP). Although, theoretically, $B - MR$ should equal $B - ML$ for subjects with symmetrical responses, there were, in fact, small differences between these two difference traces which allowed them to be arranged in terms of $B - P$ and $B - N$. This arrangement of symmetrical responses into $B - P$ vs. $B - NP$ facilitated comparison of results from symmetrical subjects with results from asymmetrical subjects.

CHAPTER 4

RESULTS

Data were collected and analysed in order to test the four hypotheses posed in chapter 3. These hypotheses are briefly restated here:

1. Natural response asymmetry exists in a significant number of normal hearing subjects.

2. The ability to predict the binaural response by algebraic combination of the monaural responses is inversely related to the degree of interear response asymmetry present.

3. Response asymmetry, when present, can be eliminated or reduced by means of an interaural intensity difference.

4. Algebraic combination of the right and left monaural responses is a good predictor of the binaural response when monaural responses are symmetrical. The alternative model, 2 x the preferred response, is a better predictor of the binaural response when monaural responses are asymmetrical.

Results will be discussed as they pertain to the experimental questions associated with each of these hypotheses.

The first experimental question asked what proportion of normal hearing subjects will demonstrate significant right/left asymmetries in the BSAEP when equal sensation level stimuli are presented to each ear. The expectation under the null hypothesis was that no subjects would have asymmetrical monaural responses under conditions of equal dB SL stimulation. In order to test this hypothesis, subjects were grouped into categories of symmetrical or asymmetrical, at each intensity level, according to the criteria described in Chapter 3.

At 70 dB SL, 71% of subjects were found to have significant right/left response asymmetry. Assuming that there is no asymmetry, the probability of exceeding the asymmetry criterion because of random variability is .01. The cumulative binomial probability for $N = 24$ and $p = .01$ indicated that the null hypothesis could be rejected if the criterion for asymmetry was exceeded on 2 or more occasions. Had the criterion for asymmetry been less stringent, the cumulative binomial probability for $N = 24$ and $p = .05$ would require that the criterion for asymmetry be exceeded on 4 occasions in order to reject the null hypothesis. Thus, the obtained proportion of asymmetrical subjects far exceeded the minimum proportion needed in order to reject the null hypothesis.

The distribution of asymmetrical and symmetrical subjects did not remain constant when sensation level was

decreased. At 50 dB SL, 42% of the subjects were classified as asymmetrical and 58% of the subjects were classified as symmetrical. Once again, the obtained proportion of asymmetrical subjects significantly exceeded the predictions of the null hypothesis.

The difference in the distribution of subjects between the two sensation levels reflected the fact that 28% of the subjects changed categories as a function of the reduction in sensation level. Seven subjects who had been categorized as asymmetrical at 70 dB SL, were categorized as symmetrical at 50 dB SL. One subject who had been categorized as symmetrical at 70 dB SL, was categorized as asymmetrical at 50 dB SL. A summary of the distribution of subjects by category and sensation level is presented in Table 3.

Confidence intervals for the proportions of asymmetrical subjects were determined and are shown in Table 4. There was little overlap between the confidence intervals for observed proportions of asymmetrical subjects at 70 dB SL and 50 dB SL. This suggested that, given the expected frequency of asymmetrical subjects at 70 dB SL ($.71 \pm .19$), the probability of obtaining a proportion of asymmetrical subjects equal to .42, as was obtained at 50 dB SL, was less than .05. The McNemar test for difference between correlated proportions confirmed that there was a

TABLE 3

Proportion of subjects categorized as asymmetrical
or symmetrical

		<u>ASYMMETRICAL</u>		<u>SYMMETRICAL</u>	
		<u>number</u>	<u>proportion</u>	<u>number</u>	<u>proportion</u>
70 dB	17	.71		7	.29
	(7 M, 10 F)			(5 M, 2 F)	
50 dB	10	.42		14	.58
	(5 M, 5 F)			(7 M, 7 F)	

TABLE 4

Confidence intervals for frequency distributions
of asymmetrical subjects.

SL	Proportion Asymmetrical	S.D.	95% Confidence Intervals
70 dB	.71	.093	.52 to .90
50 dB	.42	.100	.21 to .63

significant difference in the frequency of asymmetrical subjects at the two sensation levels, $\chi^2 (1) = 4$, $p < .05$. On the basis of these results it must be concluded that stimulus level significantly affected the number of asymmetrical subjects found in a given sample of normal hearing subjects, ie. as sensation level decreases, the frequency of asymmetrical subjects decreases.

In order to further explore the nature of response asymmetry, the data obtained from subjects classified as asymmetrical were examined for evidence of significant ear effects (ie. right leading vs. left leading), and differences related to sex of the subjects.

The direction of asymmetry for 17 asymmetrical subjects at 70 dB SL, and 10 asymmetrical subjects at 50 dB SL, was determined on the basis of wave V latency and is summarized in Table 5. The leading ear was defined as the ear which produced the shortest wave V latency. At 70 dB SL subjects were more or less evenly divided between right leading and left leading monaural responses, with 9 out of 17 (53%) subjects producing right leading responses, and 8 subjects (47%) producing left leading responses. Of the 10 subjects who demonstrated response asymmetry at 50 dB SL, 3 subjects (30%) had right leading responses and 7 subjects (70%)

TABLE 5

Distribution of males and females with right leading^a or left leading BSAEPs.

RIGHT LEADING					LEFT LEADING		
	Male	Female	Total		Male	Female	Total
70 dB	3	6	9		4	4	8
50 dB	2	1	3		3	4	7

^aLeading ear was determined on the basis of wave V latency.

had left leading responses. The binomial test revealed that there was no significant difference between the proportions of right leading or left leading asymmetrical subjects at 70 dB SL ($p > .05$) or at 50 dB SL ($p > .05$).

Equal numbers of male ($n = 12$) and female ($n = 12$) subjects participated in this study in order to control for any possible differences in incidence or direction of asymmetry which might exist as a function of sex of the subject. In order to confirm that there were no such differences, the data were further subdivided into categories of male and female for each intensity level (Table 4-3). The 17 asymmetrical subjects at 70 dB SL consisted of 7 males and 10 females. The 10 asymmetrical subjects at 50 dB SL consisted of 5 males and 5 females. The binomial test revealed no significant difference in the proportions of males and females at 70 dB SL ($p > .05$) or 50 dB SL ($p > .05$).

Of the 9 right leading subjects at 70 dB SL, 3 subjects were males and 6 subjects were females. The 8 left leading subjects were evenly divided between males and females. At 50 dB SL, 3 right leading subjects were comprised of 2 males and 1 female, and seven left leading subjects were comprised of 3 males and 4 females. The data from each sensation level were arranged separately into 2×2 contingency tables and tested by means of the

chi-square test for significant difference. Chi-square revealed no significant difference in the proportions of male and female subjects classified as either right leading or left leading subjects at either 70 dB SL ($p = .67$) or at 50 dB SL ($p = .31$).

As anticipated, male and female subjects were not significantly different with respect to incidence or direction of asymmetry at either intensity level. Therefore, data from male and female subjects were combined for the analyses which follow.

It was expected that auditory tract asymmetry would manifest itself in varying degrees among subjects. This variation was reflected in the wide range of asymmetry ratios (AR) which resulted when the stimuli were presented monaurally to the right and left ears at equal sensation levels. Figures 6 and 7 show the frequency distribution of asymmetry ratios among subjects at the 70 dB SL and 50 dB SL sensation levels.

The second hypothesis predicted that the ability to predict the binaural response from an algebraic sum of the right and left monaural responses (RC) would be inversely related to the amount of right/left asymmetry present. The accuracy with which a simple linear combination of $R_m + L_m$ predicts the binaural response is reflected in the amplitude of the RC. A perfect

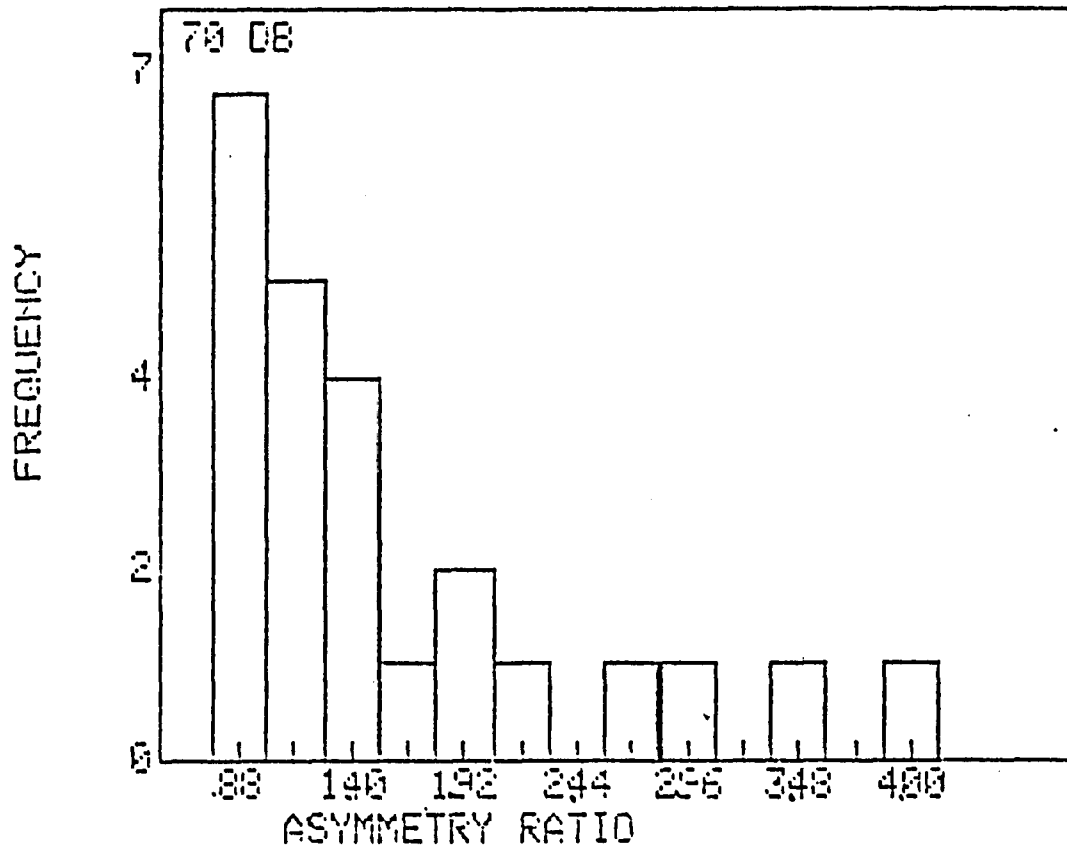


Figure 6. Frequency distribution of asymmetry ratios obtained at 70 dB SL.

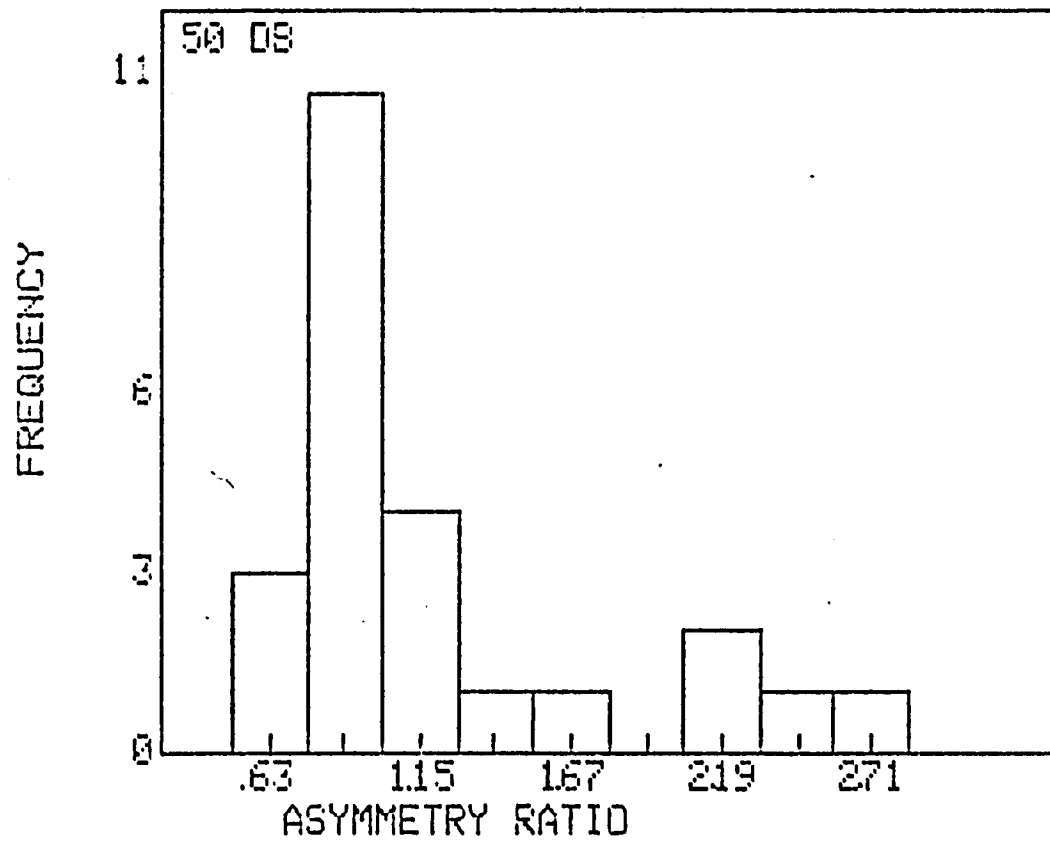


Figure 7. Frequency distribution of asymmetry ratios obtained at 50 dB SL.

prediction is evidenced by $RC = 0$. It was expected, therefore, that if the prediction was not perfect, $RC \neq 0$. The amplitude of the RC was expected to increase as the degree of asymmetry increased. That is, small asymmetries would be associated with small RCs, while large asymmetries would be associated with large RCs.

The relationship between the degree of asymmetry, represented by the AR, and the accuracy of the binaural prediction, represented by the amplitude of the RC, was examined by computing the Pearson product moment coefficient of correlation between the RC and the AR for 24 subjects at each sensation level. Pearson product moment coefficients of correlation revealed a positive correlation, $r = .58$, between the amplitude of the RC and the AR at 70 dB SL. The correlation was significant beyond the .01 level of confidence. A similar positive coefficient of correlation, $r = .57$, $p < .01$, was found between the amplitude of the RC and the AR at 50 dB SL. The relationship between the amplitude of the RC and AR at both sensation levels is represented in the scatter diagrams in Figures 8 and 9. The lines through the data points were determined by a least-squares regression analysis.

Having established that right/left asymmetry exists in the monaural BSAEPs of a significant proportion

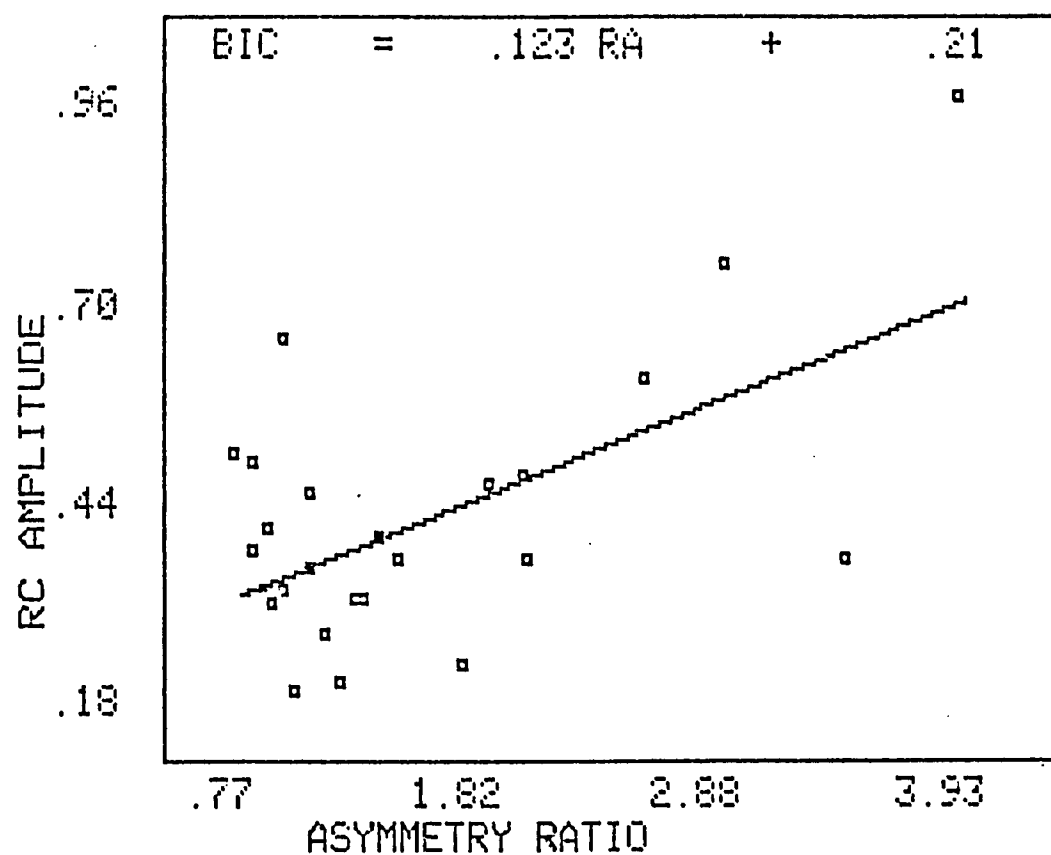


Figure 8 . Scatter plot and regression line showing the correlation between RC amplitude and the asymmetry ratio ($r = .58$) for the 70 dB SL data.

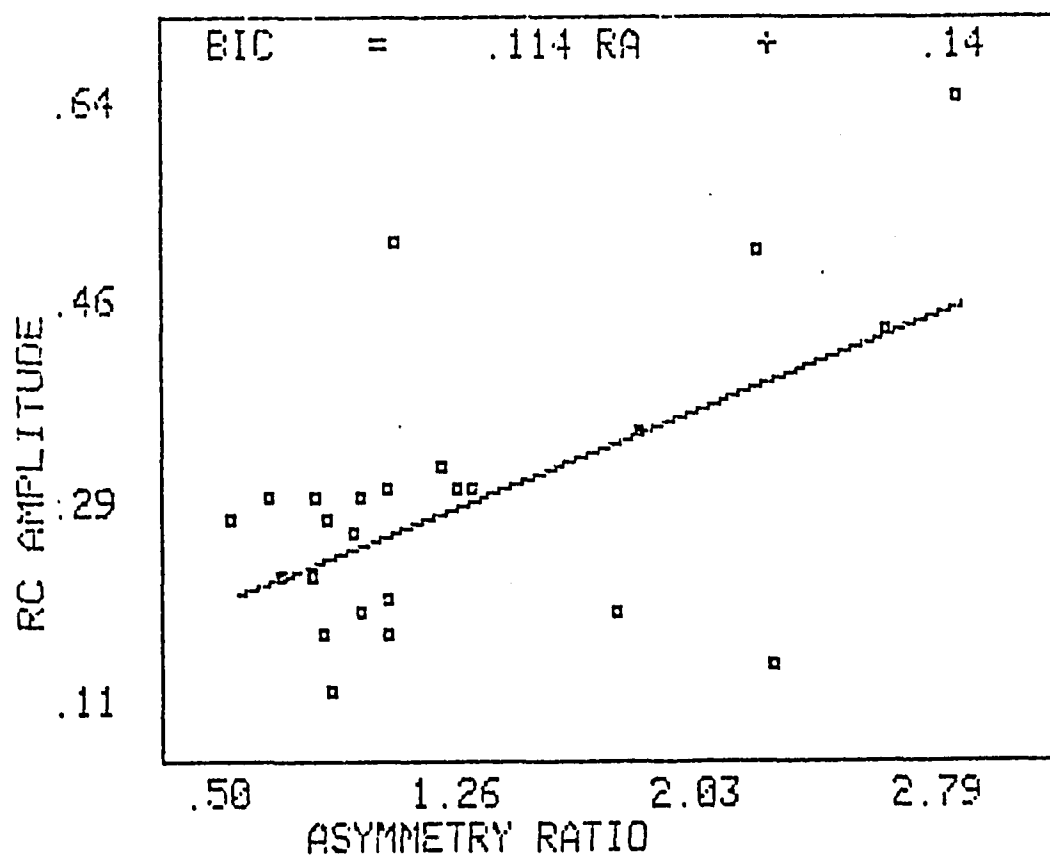


Figure 9 . Scatter plot and regression line showing the correlation between RC amplitude and the asymmetry ratio ($r = .57$) for the 70 dB SL data.

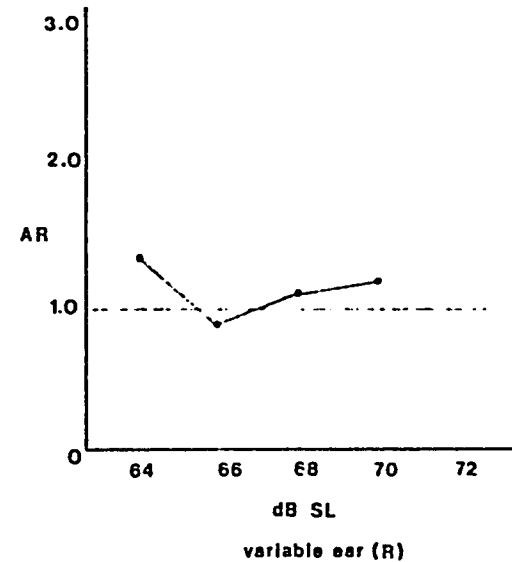
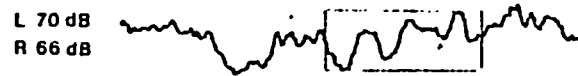
of normal hearing subjects, the effect of interaural intensity manipulations in offsetting the asymmetry was examined. The third experimental hypothesis stated that asymmetry, when it occurred, could be offset by means of an interaural intensity difference (IAID). According to the operational definition of asymmetry, the $R_m - L_m$ amplitude under equal dB SL conditions must exceed the subject's criterion. This situation was reflected in an asymmetry ratio (AR) which exceeded unity. The effectiveness of the IAID in reducing asymmetry was determined by comparing the amplitude of the AR under conditions of equal sensation level and interaural intensity difference. By systematically manipulating interaural intensity it was expected that the amplitude of the AR would diminish until it fell below unity, the criterion for asymmetry.

As anticipated, introduction of an interaural intensity difference had the effect of reducing the size of AR for all asymmetrical subjects. Reduction of the intensity to the ear with the leading response, or increase in the intensity to the ear with the lagging response was effective in offsetting the asymmetry between the right and left responses.

A T test for correlated pairs was performed comparing the size of the ARs in the equal sensation level condition and the size of the ARs in the interaural

intensity difference condition at each sensation level. A T test revealed that the AR in the interaural difference condition was significantly smaller than the AR in the equal SL condition at both 70 dB SL, $t(16) = 5.68$, $p < .001$, and 50 dB SL, $t(9) = 3.42$, $p = .007$. This indicated that the interaural intensity difference significantly reduced the asymmetry between ears. The effectiveness of this stimulus manipulation in producing symmetry, however, varied among subjects. According to the criteria for determining when response symmetry had been achieved, the interaural intensity difference was considered to be completely successful in creating symmetry when the AR was reduced to a value less than or equal to unity. This usually coincided with the condition which produced the best wave V latency match between the right and left responses (see Appendix A). Interaural intensity difference produced "complete" symmetry in 7 asymmetrical subjects at 70 dB SL (41%) and 4 asymmetrical subjects at 50 dB SL (40%). The data for one representative subject in which the AR was reduced below unity is shown in Figure 10. Short of achieving complete symmetry, the interaural difference which produced the smallest possible AR, or best match, was accepted. The ARs of nine asymmetrical subjects at 70 dB SL (53%) and 5 asymmetrical subjects at 50 dB SL (36%) were reduced in the interaural intensity difference

RIGHT - LEFT



Subject: L.K. asymmetrical

Figure 10 . The amplitude of $R_m - L_m$ was reduced below criterion for asymmetry with an interaural intensity difference of 4 dB (70 dB left, 66 dB right).

condition, although not below unity. An example of this situation is shown in Figure 11.

By definition, the ARs of symmetrical subjects were at their minimum and below unity when the stimuli presented to the two ears were equal in sensation level. Introducing an interaural intensity difference by increasing or decreasing the intensity to one ear caused the amplitude of $R_m - L_m$ and the asymmetry ratio to increase. The data from a symmetrical subject exemplifying this pattern is shown in Figure 12.

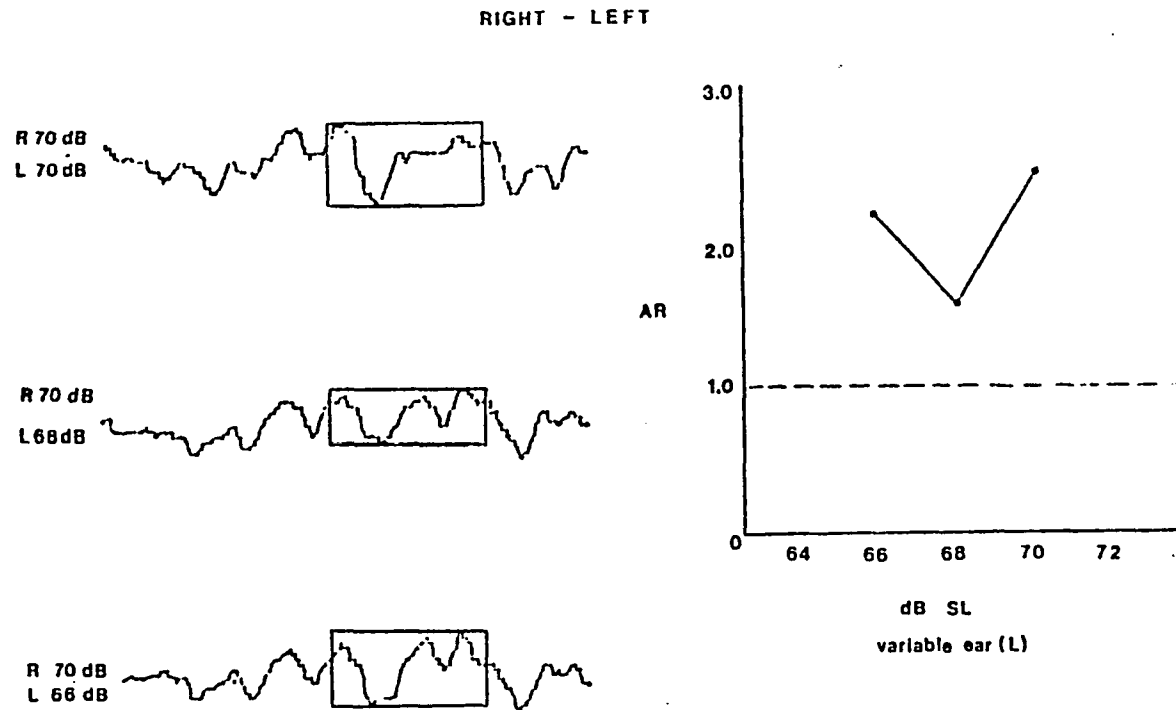
The fourth hypothesis stated that the binaural response is predictable from a combination of the monaural responses. Three alternative models for combining the monaural responses were proposed:

Model #1. Linear addition of the right and left monaural responses which result from equal sensation level stimuli.

Model #2. Doubling of the preferred monaural response.

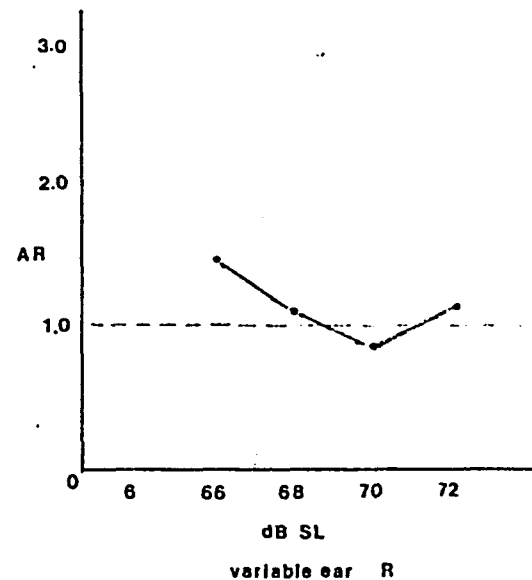
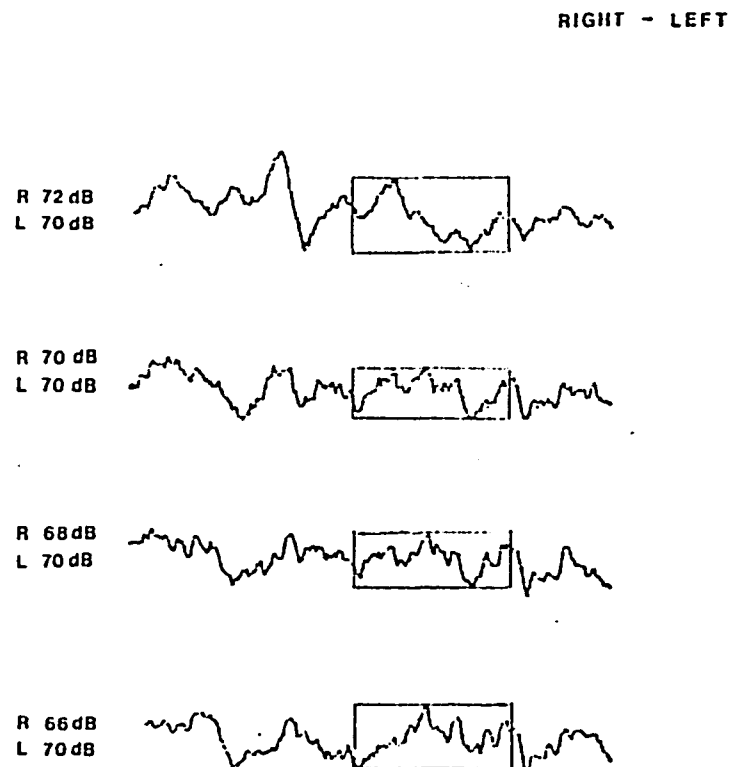
Model #3. Linear summation of the right and left monaural responses after any existing asymmetry had been offset by means of an interaural intensity difference.

As mentioned above, the accuracy of the prediction of the binaural response was inversely related to the amplitude of the component which remained after



Subject: D.R. (asymmetrical)

Figure 11 . The amplitude of $R_m - L_m$ was reduced to a minimum (but not below criterion for asymmetry) with an interaural intensity difference of 2 dB (70 dB right, 68 dB left).



Subject: J.D. (symmetrical)

Figure 12 . The amplitude of $R_m - I_m$ was at a minimum, and below criterion for asymmetry when the stimuli were presented to each ear at equal sensation levels for subjects classified as symmetrical.

the monaural responses were combined and subtracted from the binaural response. The monaural responses of asymmetrical subjects were combined three different ways, according to the models listed above. The monaural responses of symmetrical subjects, which were obtained only under the equal SL condition, were combined two different ways, according to models 1 and 2 listed above. The combined monaural responses were each subtracted from the appropriate binaural response. This subtraction yielded three types of difference traces (or two types of difference traces in the case of symmetrical subjects):

1) The residual component (RC), as previously defined, was the result of $(R_m + L_m) - B_{in}$ under the equal sensation level condition.

2) The Binaural - Preferred difference trace (B - P) was the result of doubling the preferred monaural response obtained under the equal sensation level condition (see chapter 3, part IV) and subtracting it from the binaural response.

3) The Adjusted Residual Component (ARC) was the result of $(R_m + L_m')^7 - B_{in}$, after asymmetry has been reduced by means of the interaural intensity difference. This difference trace was obtained only for asymmetrical subjects.

⁷ $R_m - L_m'$ refers to the condition in which the asymmetry is offset by means of an interaural intensity difference.

Subjects were divided according to their classification as symmetrical or asymmetrical. Data for each group and each intensity level were analysed separately. The model for combining monaural responses which resulted in the smallest difference trace was considered to be the best predictor of the binaural response.

Asymmetrical

Monaural responses from asymmetrical subjects were combined according to the three models and the following difference traces were obtained:

1. $(R_m + L_m) - B_{in} = RC$
2. $2 \text{ (Preferred Monaural)} - B_{in} = B - P$
3. $(R_m + L_m)' - B_{in} = ARC$

Decker and Howe (1981) hypothesized that the binaural response from asymmetrical subjects reflects an unequal weighting of the contributions from the preferred and nonpreferred ears. Therefore, it was predicted that $B - P$ would be significantly smaller than RC , indicating that, when monaural responses were asymmetrical, Model 2 was better than Model 1 as a predictor of the binaural response. After the asymmetry was offset by means of the interaural intensity manipulation, the relative contributions of the right and left ear responses to the binaural response were expected to be equalized. In this

situation, it was expected that the ARC would be significantly smaller than the RC indicating that, when monaural asymmetries were eliminated or reduced, a linear combination of the right and left responses (Model 3) accurately predicted the binaural response.

70 dB SL (n = 17). Mean amplitudes for the difference traces obtained as a result of each combination model (RC, B - P, and ARC) are presented in Table 6.

Inspection of mean data revealed that no monaural combination condition resulted in a difference trace equal to zero, indicating that a perfect prediction of the binaural response was not possible by means of a combination of monaural responses according to the models proposed. Mean amplitudes for B - P and RC were equal, indicating that, contrary to the predictions of hypothesis #4, there was no difference between B - P and RC in their abilities to predict the binaural response. The mean amplitude for ARC was smaller than the mean amplitude for RC. A T test for correlated samples revealed that this difference was significant, $t(16) = 3.25$, $p = .005$. Thus, the hypothesis that an algebraic combination of $R_m + L_m$ would be a better predictor of the binaural response after asymmetry had been reduced (Model 3), was supported. Figure 13 shows combined monaural responses, binaural responses and

TABLE 6

Amplitudes in microvolts and standard deviations
of difference traces obtained for asymmetrical subjects.

	B-P uV			RC uV			ARC uV	
	-			-			-	
	X	S.D.		X	S.D.		X	S.D.
70 dB	.42	.19		.42	.21		.34	.15
n=17								
----- -----								
50 DB	.36	.12		.36	.16		.28	.15
n=10								

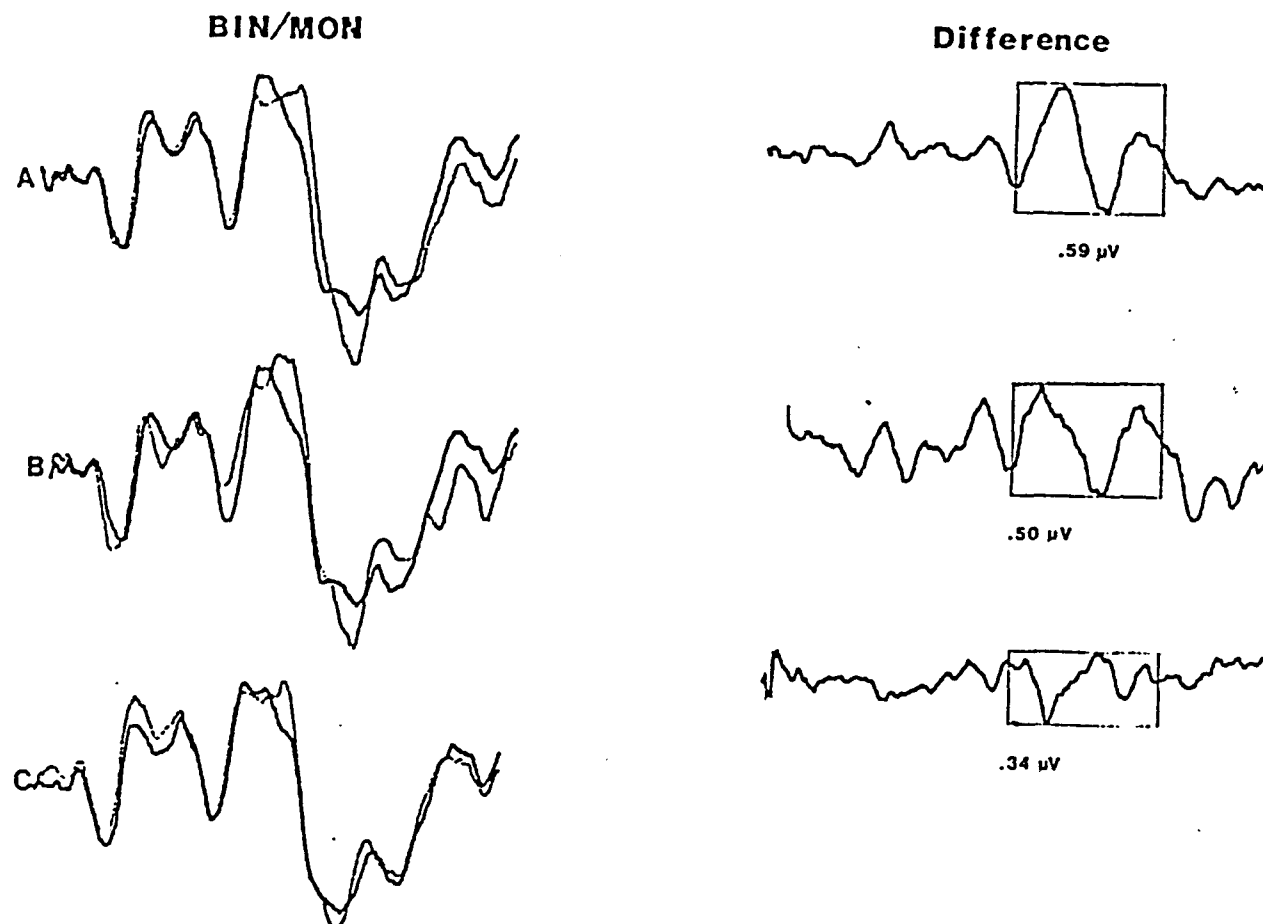


Figure 13 . A: Binaural (dark trace) and $R_m + L_m$ (light trace), 70 dB SL presented to each ear of an asymmetrical subject.
 B: Binaural and 2 x L_m .
 C: Binaural and $R_m + L_m$, IAID condition.
 Traces to the right of each set of waveforms are the results of subtracting the binaural from the combined monaural responses.

difference traces for one subject.

50 dB SL (n = 10). Similar results were obtained for the 50 dB SL data. Once again, no monaural combination model was successful in perfectly predicting the binaural response as evidenced by the fact that difference traces were obtained under each condition. Contrary to the hypothesis, mean amplitudes for B - P and RC (Table 6) were equal, as they were at 70 dB SL. Thus, the expectation that Model 2 would be better than Model 1 as a predictor of the binaural response when monaural asymmetries were present, was not supported. The mean amplitude for ARC was significantly smaller than the mean amplitude for RC, $t(9) = 2.35$, $p = .04$ which supports the hypothesis that Model 3 is a better predictor of the binaural response than Model 1. Combined monaural responses, binaural responses and difference traces obtained for one subject at 50 dB SL are shown in Figure 14.

Mean amplitudes for the difference traces which resulted from all three models were smaller at 50 dB SL than those obtained at 70 dB SL. A two factor analysis of variance was performed to determine if a significant difference existed between the amplitudes of the three difference traces obtained at 70 dB SL and the amplitudes of the three difference traces obtained at 50 dB SL. The ANOVA table is presented in Table 7. The amplitude x

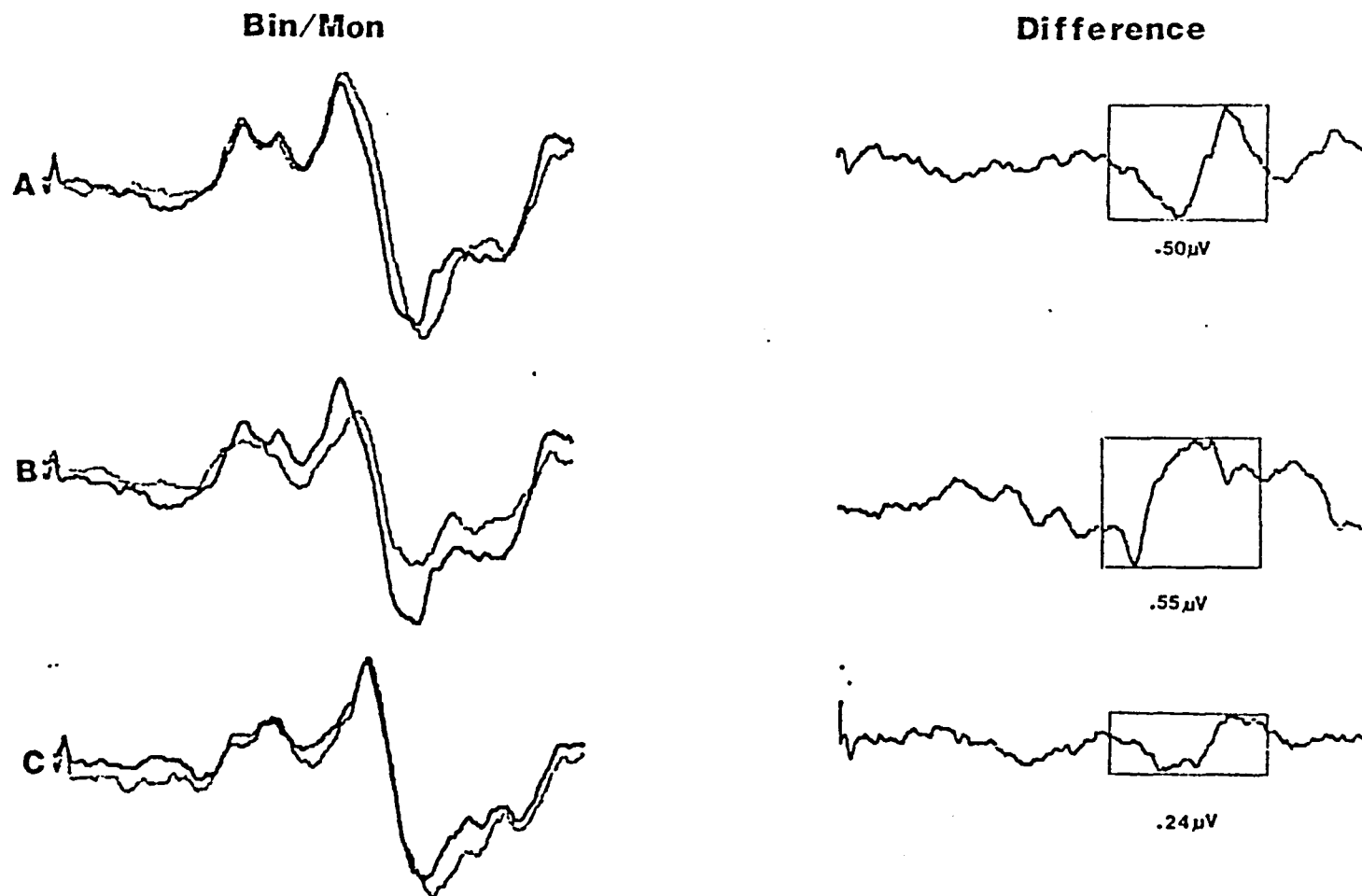


Figure 14. A: Binaural (dark trace) and $R_m + L_m$ (light trace), 50 dB SL presented to each ear of an asymmetrical subject.
 B: Binaural and $2 \times L_m$.
 C: Binaural and $R_m + L_m$, IAID condition.
 Traces to the right of each set of waveforms are the results of subtracting the binaural from the combined monaural responses.

TABLE 14

ANOVA to determine significant difference between amplitudes of difference traces for asymmetrical subjects as a function of sensation level.

SOURCE	SS	DF	MS	F	P
Between Levels	.062	1	.062	.925	>.05
Error	1.677	25	.067		
Within Levels	.112	2	.056	5.6	.006
Interaction	.000	2	.000		>.05
Error	.504	50	.010		

sensation level main effect was not significant, $F(1, 25) = .062, p > .05$, indicating no significant difference in difference trace amplitudes as a function of sensation level. The within blocks difference was significant, $F(2, 50) = 5.6, p = .006$, reflecting the significant differences between the amplitudes of RC, B - P and ARC at both sensation levels, reconfirming the results of the T tests already discussed. There was no significant interaction between sensation level and model $F(2, 2) = 0, p > .05$.

Symmetrical

Monaural responses from symmetrical subjects were combined according to two models and the following difference traces were obtained:

$$1. (R_m + L_m) - B_{in} = RC$$

$$2. 2 (\text{Preferred Monaural}) - B_{in} = B - P$$

The experimental design required that data for symmetrical subjects be collected only under the equal sensation level condition. Since responses were not recorded under the IAID condition, ARCs were not derived for this group. Therefore comparisons were made between the amplitudes of RC and B - P. It was speculated that binaural responses obtained from symmetrical subjects would represent equal input from each ear. Therefore RC and B - P were expected to be equivalent in their

abilities to predict the binaural response, and no significant differences were expected between the difference traces derived under each model.

70 dB SL (n = 7). The presence of difference traces exceeding zero indicated that the binaural response was not perfectly predictable from a linear combination of monaural responses from naturally symmetrical subjects. Means and standard deviations for RC and B - P are shown in Table 8. A T test for correlated samples revealed that the difference between the amplitudes of the two difference traces approached, but did not reach statistical significance, $t(6) = 2.397$, $p > .05$. Thus the expectation that the predictions of Model 1 and Model 2 would not be significantly different for symmetrical subjects was supported. The data from one symmetrical subject are shown in Figure 15.

50 dB SL (n = 14). Means and standard deviations for RC and B - P for symmetrical subjects at 50 dB SL are presented in Table 8. The RC and B - P amplitudes were not significantly different, $t(13) = 1.70$, $p = .110$, supporting the expectation that RC and B - P are equally predictive of the binaural response for symmetrical subjects. Data for one symmetrical subject are shown in Figure 16.

As was the case for asymmetrical subjects, mean

TABLE 8

Amplitude in microvolts and standard deviations
for difference traces from symmetrical subjects.

	B-P uV			RC uV	
	-			-	
	X	S.D.		X	S.D.
70 dB	.51	.17		.38	.08
n=7					
50 DB	.29	.12		.22	.06
n=14					

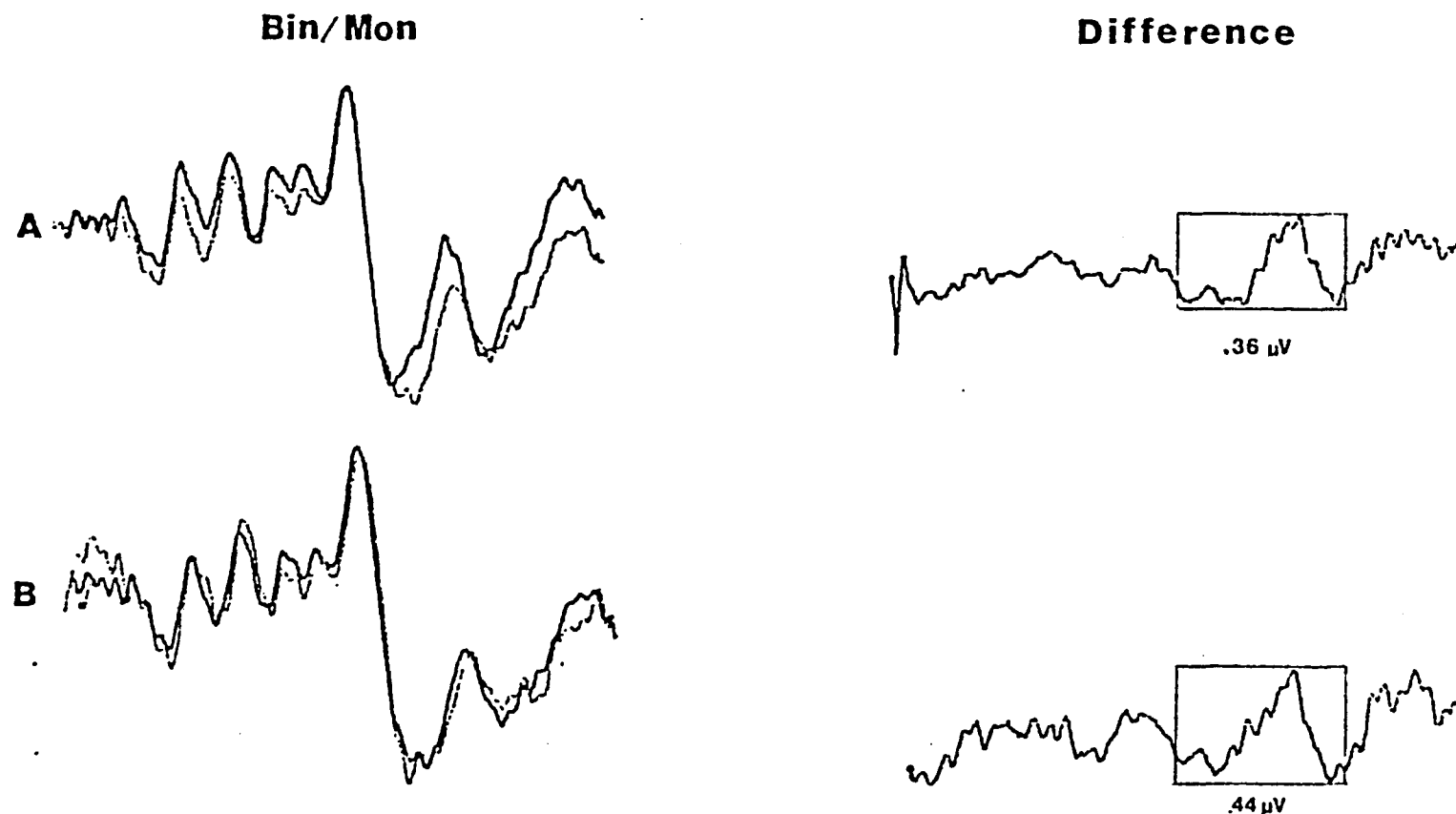


Figure 15. A: Binaural (dark trace) and Rm + Lm (light trace), 70 dB SL presented to each ear of a symmetrical subject.
 B: Binaural and 2 x Rm.
 Traces to the right of each set of waveforms are the results of subtracting the binaural from the combined monaural responses.

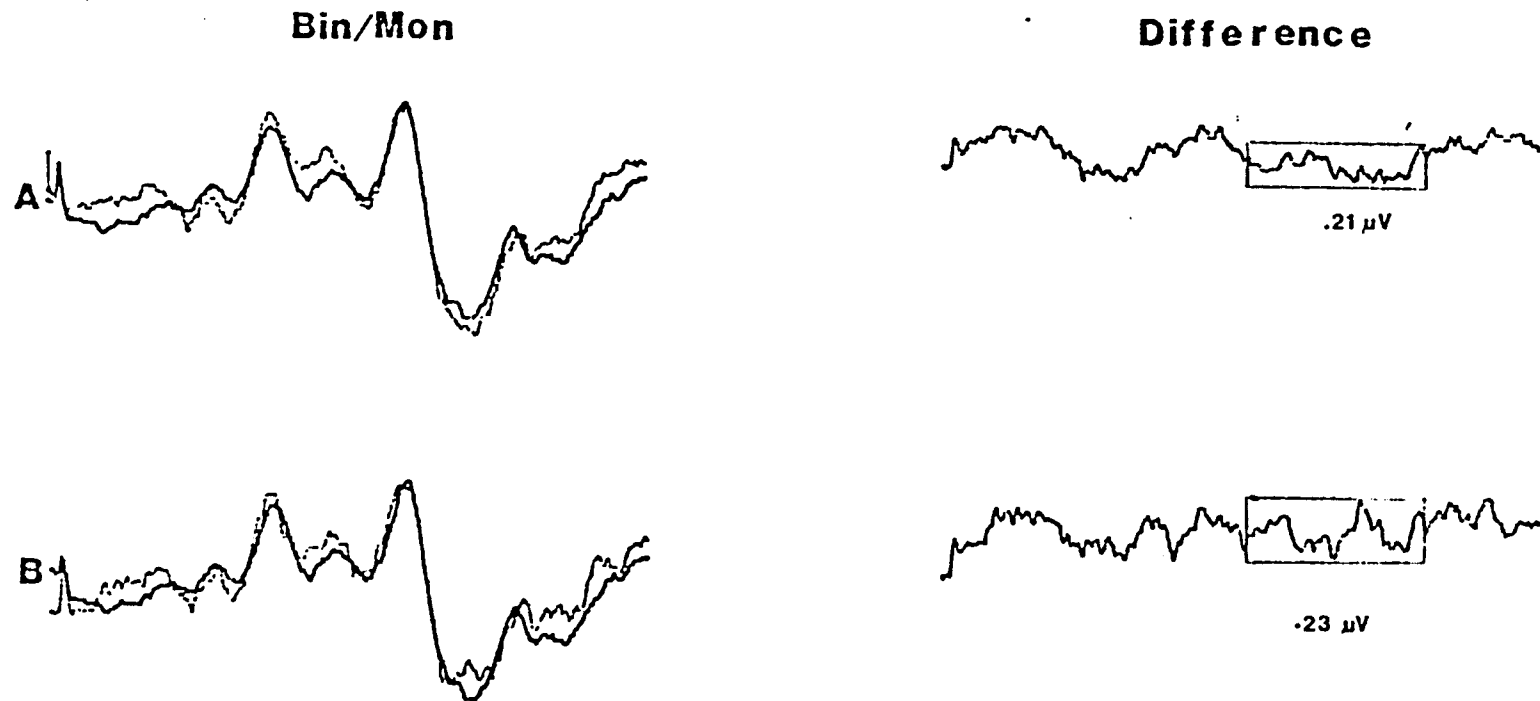


Figure 16. A: Binaural (dark trace) and $R_m + I_m$ (light trace), 50 dB SL presented to each ear of a symmetrical subject.
 B: Binaural and $2 \times R_m$.
 C: Traces to the right of each set of waveforms are the results of subtracting the binaural from the combined monaural responses.

amplitudes for difference traces obtained at 50 dB SL were smaller than those obtained at 70 dB SL. A T test for differences between amplitudes of RC at 70 dB SL vs. amplitudes of RC at 50 dB SL revealed a highly significant difference in RC amplitudes as a function of sensation level, $t_{(19)} = 3.15$, $p < .001$.

Similarly, significant differences were found between amplitudes of B - P at 70 dB SL and B - P at 50 dB SL, $t_{(19)} = 3.15$, $p = .002$. These results were in contrast to results obtained for asymmetrical subjects which showed no significant difference between amplitudes of difference traces as a function of sensation level.

Asymmetrical vs. Symmetrical

It was predicted that symmetrical and asymmetrical subjects would differ with respect to the accuracy with which a linear combination of monaural responses predicted the binaural response. Thus the amplitudes of RCs from symmetrical subjects were expected to be smaller than RCs from asymmetrical subjects. It was shown, however, that asymmetry could be significantly reduced by means of an interaural intensity difference. As a result of this manipulation, the amplitude of the residual components (ARC) were significantly smaller than they were under the equal sensation level condition. Thus, the following predictions were posed regarding the

relationship between the symmetrical and asymmetrical data. First, it was predicted that, under conditions of equal sensation level stimulation, RCs of symmetrical subjects would be significantly smaller than RCs of asymmetrical subjects. Secondly, it was predicted that, once asymmetry was reduced, the difference between the amplitudes of symmetrical and asymmetrical subjects would be reduced or eliminated. In order to test these predictions RCs from symmetrical and asymmetrical subjects were compared for each sensation level. Additionally RCs from symmetrical subjects were compared with ARCs from asymmetrical subjects for each sensation level. The following results were obtained.

70 dB SL. As anticipated, mean RC amplitudes for symmetrical subjects were smaller than mean RC amplitudes for asymmetrical subjects (Table 9). However, a T test for independent samples revealed that this difference was not statistically significant, $t_{(22)} = .461$, $p = .638$. There was, however, a statistically significant difference in the variances between the two groups, $F(16,6) = 46.7$, $p < .01$, indicating that the symmetrical and asymmetrical groups represented samples of two distinctly different populations. The symmetrical group, which had the smaller variance, appeared to be a more homogenous group than the asymmetrical group.

TABLE 9

Comparison of residual component amplitudes from
symmetrical and asymmetrical subjects - 70 dB SL.

	MEAN RC AMPLITUDE	S.D.
	μV	
ASYMMETRICAL	.42	.21
SYMMETRICAL	.38	.08

As reported previously, ARCs were significantly smaller than RCs from asymmetrical subjects, indicating a significant reduction in the amplitude of RC as a result of the interaural intensity manipulation. The mean ARC was, in fact, reduced to the point that it was smaller than the mean RC from symmetrical subjects, suggesting that the IAID may have overcorrected for the differences between symmetrical and asymmetrical subjects. The difference between the means, however, was not statistically significant, $t(22) = .775$, $p = .452$. Although the variance of ARC was reduced, the difference in the variance between ARC and symmetrical RC was still significant, $F(16,6) = 22.7$, $p < .01$.

50 dB SL. Results obtained at 50 dB SL were in better agreement with the predictions stated above. Mean amplitudes of RCs from symmetrical subjects were smaller than mean amplitudes of RCs from asymmetrical subjects Table 10 . This difference was statistically significant, $t(22) = 3.602$, $p = .005$. There was also a statistically significant difference between the variances of the two groups, $F(9, 13) = 3.8$, $p < .05$.

RCs from symmetrical subjects remained smaller than ARCs from asymmetrical subjects, nevertheless, this difference did not reach statistical significance, $t(22) = 1.461$, $p = >.05$. The difference between the

TABLE 10

Comparison of residual component amplitudes from
symmetrical and asymmetrical subjects - 50 dB SL.

	MEAN RC AMPLITUDE	S.D.
	μV	
ASYMMETRICAL	.36	.16
SYMMETRICAL	.22	.06

variances of the two groups was also reduced, however, the difference remained significant at the .05 level of confidence, $F(9, 13) = 3.63$. Thus, in accordance with the predictions stated above, the significant difference between RCs of symmetrical and asymmetrical subjects was reduced by means of interaural intensity manipulations.

Summary

The experimental hypotheses were partly, although not entirely supported by the data. The following summarizes the analysis of the data in relation to each of the experimental hypotheses:

1. Hypothesis #1 was supported by the finding of a significant proportion of subjects which demonstrated response asymmetry, according to a conservative criterion, at both sensation levels. The proportion of asymmetrical subjects was significantly reduced as a function of sensation level. No significant ear effects were found.

2. There was a significant, positive correlation between the degree of response asymmetry and the ability to predict the binaural response by means of an algebraic combination of the right and left monaural responses. This result, which was found for both sensation levels, supported hypothesis #2.

3. It was found that an interaural intensity

manipulation was successful in significantly reducing the amount of right/left asymmetry present in the responses of asymmetrical subjects at both sensation levels, supporting the predictions of hypothesis #3.

4. Hypothesis #4 proposed three alternative models for monaural combinations and predicted their relative success in predicting the binaural response.

a) Contrary to the predictions of the hypothesis, Model 1 was equal to Model 2 in its ability to predict the binaural response at both sensation levels.

b) In agreement with the hypothesis was the fact that Model 3 was a significantly better predictor of the binaural response than Model 1 or 2 at both sensation levels.

c) The expectations that RCs from symmetrical subjects would be significantly smaller than RCs from asymmetrical subjects, and that this difference would be eliminated by means of reducing the asymmetry in the responses of asymmetrical subjects, was only partially supported. The 70 dB SL data demonstrated a trend in the direction predicted by the hypothesis, however, statistical significance was not achieved where it was expected. In contrast, the 50 dB SL data was in a complete agreement with the predictions of the hypothesis.

CHAPTER 5

DISCUSSION

Three major issues were addressed in this study. The first issue concerned the prevalence and the kind of naturally occurring response asymmetry in the BSAEPs of normal hearing subjects. The second issue concerned the relationship between monaural and binaural BSAEPs and the effect that asymmetry has on this relationship. The focus of the third issue was naturally occurring asymmetry and the ability to reduce or eliminate the asymmetry by means of interaural intensity manipulations.

Asymmetry in the BSAEP

Small right/left asymmetries in the latency, amplitude, and morphology of BSAEPs recorded from normal hearing subjects have been reported in the literature (Chiappa et al., 1979; Levine and McGaffigan, 1984; Rowe, 1978), however, these asymmetries have not been associated with any clinical or functional significance. Until Decker and Howe (1981) demonstrated the relationship between response asymmetry and the BIC, studies of binaural interaction assumed symmetry of the right and left monaural responses, ignoring small

asymmetries which may have been present in the responses of individual subjects. Although the functional significance of asymmetry is still not known, the work of Decker and Howe clearly illustrated that the presence of such asymmetries must be accounted for in studies which involve algebraic manipulations of brainstem response waveforms.

The results of this study support previous studies which found that a significant proportion of normal hearing subjects (approximately 40 - 50%) had asymmetrical BSAEPs (Allen et al., 1982; Chiappa et al., 1979; Decker and Howe, 1981; Rowe, 1978). While the proportion of subjects in the present study demonstrating asymmetry at 50 dB SL (42%, $\pm$ 21%) was similar to the proportions of asymmetrical subjects found in previous studies, the proportion of subjects demonstrating asymmetry at 70 dB SL (71%, $\pm$ 19%) was higher than expected based on previous reports. There were two possible reasons for this discrepancy. First, it was difficult to make direct comparisons between this study and previous studies because neither the definition of asymmetry nor the method used for measuring asymmetry were uniform among studies. Secondly, results of this study indicated that the proportion of asymmetrical subjects can change as a function of stimulus level. This issue has not been addressed in any previous study. When

one considers the 95% confidence interval for the frequency distribution of asymmetrical subjects at 70 dB (52% to 90%), however, it is seen that previous reports of the frequency of asymmetrical subjects are in reasonably good agreement with the data obtained in the present study.

Prevalence of Natural Asymmetry in the BSAEP

The operational definition of asymmetry and the method used to measure asymmetry could have a significant effect on the way subjects are classified and, therefore, affect the proportions of symmetrical and asymmetrical subjects that are reported. Methods which have been commonly used for measuring asymmetry in the BSAEP include measuring differences in peak latencies and/or amplitudes (Levine and McGaffigan, 1984; Rowe, 1978; Seltzers and Brachman, 1977), distinguishing between responses on the basis of wave morphology (Chiappa et al., 1979; Rowe, 1978), and measuring amplitude differences in the difference traces remaining after the right and left response have been individually subtracted from the binaural response (Allen et al., 1982; Decker and Howe, 1981). There have been no previous studies which have compared these different methods in order to assure their equivalence. A pilot study which was performed in conjunction with the present study (Appendix

A) indicated that there was a high correlation between two methods of measuring asymmetry at 70 dB SL: right/left wave V latency differences and the Rm - Lm method used in this study. The coefficient of correlation, however, changed as a function of the width of the analysis window. When the analysis window was restricted to the approximately 2 ms time period which encompasses wave V and the following negative trough, the coefficient of correlation between wave V latency differences and Rm - Lm was .75, $p < .001$). The coefficient reduced to .58, $p < .01$, however, when the full analysis window used in this study (5 - 8 ms) was used in the measurement (see Appendix B). The difference between the two correlations was apparently due to the fact that the 5 - 8 ms analysis window encompassed portions of waves IV and VI. Any inter-ear asymmetries in these portions of the waveform would not be reflected in the wave V latency difference since that measurement was restricted to asymmetries associated with the wave V peak only. There was not a significant correlation ($r = .24$, $p > .05$), however, between right/left wave V amplitude differences and results of Rm - Lm using either analysis window (window restricted to wave V: $r = .24$, $p > .05$; 5 - 8 ms window: $r = .39$, $p > .05$). Error terms tended to be considerably larger for amplitude measurements than for latency

measurements (Table 16, Appendix B) indicating that variability in measurements of amplitude is greater than the variability in measurements of latency. Since measurement variability will cause the correlation coefficient to be reduced, it is possible that the low correlation coefficients describing the relationship between $R_m - L_m$ and wave V amplitude asymmetry reflect this measurement variability. These results indicated that equivalence among the methods used to measure asymmetry cannot be assumed.

In addition to the lack of methodological uniformity, no study to date has specified what amount of right/left difference (i.e. number of milliseconds or microvolts) constituted a statistically significant difference between the responses of the two ears, nor has any study specified a confidence level associated with the decision to assign subjects to either the symmetrical or asymmetrical group. Thus, classification of subjects as symmetrical or asymmetrical may not be consistent from one study to another. A specified criterion for asymmetry is required in order to insure that insignificant right/left differences due to factors such as run-to-run variability, or variability in the uncanceled background noise are not mistakenly interpreted as evidence for asymmetry. In order to insure that only responses with significant right/left differences were assigned to the

asymmetrical category, a conservative criterion for asymmetry was developed (appendix B) for use in this study. In spite of the fact that the criterion used was conservative, the number of asymmetrical subjects found in this study at 70 dB SL was larger than the number of asymmetrical subjects reported in previous studies.

The affect of criterion on the classification of right/left responses into categories of symmetry or asymmetry was clearly illustrated by a post hoc comparison of response classification using the on-line criterion (employed in this study) and the alternative statistical criterion which was based on the standard error of the mean. As reported previously, the on-line criterion conservatively estimated the percentage of asymmetrical subjects to be 71% at 70 dB SL, and 42% at 50 dB SL. In contrast, utilizing the statistical criterion, all right/left responses at both sensation levels were categorized as asymmetrical.

The second source of difference between this and previous studies was stimulus presentation level. Two sensation levels were used in this study allowing examination of the effects of stimulus presentation level on response asymmetry. The results of this study clearly indicated that the proportion of asymmetrical subjects changed as a function of stimulus level. Multiple stimulus levels were used by Rowe (1978) (60 and 30 dB

SL) and by Chiappa et al. (1979) (60, 50, 40, 30 and 20 dB SL) both of whom studied morphological asymmetries in the BSAEP. The effect of these stimulus manipulations on inter-ear asymmetry, however, was not reported. Levine and McGaffigan (1983) found that their most robust asymmetry, an inter-ear difference in wave III amplitude which favored the right ear, was present and statistically significant at both intensity levels tested (70 dB SL and 40 dB SL). Once again, no information concerning differences, if any, associated with changes in intensity was provided. The two studies (Allen et al., 1982; Decker and Howe, 1981) which examined right/left response asymmetry in conjunction with binaural interaction tested these effects at only one intensity level. These studies reported the incidence of asymmetry among normal hearing subjects to be approximately 50%. Allen et al. (1982) presented stimuli at 100 dB peSPL (roughly 55-60 dB SL) to all subjects regardless of behavioral click threshold. Thus, it is conceivable that data from the Allen et al. study were not collected at a uniform sensation level, making comparisons to the present study difficult. Decker and Howe's (1982) determination of a 50% asymmetry level was based on data collected in response to 60 dB SL stimuli. The sensation levels used in this study were 70 dB SL and 50 dB SL. The different proportions in asymmetrical subjects found in

this study as compared with Decker and Howe's study, then, may be explainable on the basis of the different sensation levels used. Results of the present study indicated that the proportion of asymmetrical subjects will drop from 71% (+/- 19%) at 70 dB SL to 42% (+/- 21%) when the stimulus is lowered to 50 dB SL. Assuming that the decrease in proportions of asymmetrical subjects decreases linearly with decreases in intensity, then, by interpolation, the proportion of asymmetrical subjects that would be expected at 60 dB SL is approximately 56%. This figure is in good agreement with the findings of Decker and Howe. At present, however, there is insufficient information concerning the effect of sensation level on asymmetry, making the assumption of a linear decrease in the proportion of asymmetrical subjects with sensation level purely speculative.

Asymmetry was measured in this study by subtracting the left monaural from the right monaural BSAEP and measuring the amplitude of the resulting difference waveform. Unlike comparisons of peak amplitudes and latencies which are restricted to differences occurring at the wave peaks, $R_m - L_m$ reflects asymmetries which may occur at any point within the time window of interest and, therefore, was considered to be a more robust measure of inter-ear asymmetry. In order to meaningfully compare the results of this study to

previous studies which measured asymmetry on the basis of peak differences, the data were analysed for significant right/left differences in peak latencies and peak to peak amplitudes. The data were arranged in four different ways: 1) Right vs. Left (all subjects), 2) Right vs.. Left (symmetrical only), 3) Right vs. Left (asymmetrical only), 4) Leading ear vs. Lagging ear (asymmetrical only). T tests for correlated pairs (right vs. left or leading vs. lagging) were performed for waves I, III and V at each intensity level.

When all 24 subjects were analysed as a single group, without regard to their classification as symmetrical or asymmetrical, the only statistically significant difference was in wave III amplitude. This difference, which favored the right ear, was significant at both the 70 dB sensation level ($t_{(23)} = 2.5$, $p < .05$) and the 50 dB sensation level ($t_{(23)} = 2.3$, $p < .05$). The significant difference in wave III amplitude was in remarkable agreement with results reported by Levine and McGaffigan (1983). Symmetrical and asymmetrical subjects were analysed separately. Comparison of right vs. left peak measurements for symmetrical subjects, again revealed only one significant difference. Right ear wave III amplitude was significantly larger than left ear wave III amplitude at 70 dB SL ($t_{(6)} = 4.15$, $p < .01$) and 50 dB SL

($t_{(11)} = 2.21, p < .05$). A similar analysis of peak latencies and amplitudes from asymmetrical subjects resulted in no significant difference for any peak measurements. However, it was noted that direction of asymmetry among these subjects was not constant. As reported in the previous chapter, asymmetrical subjects were fairly equally divided between right leading and left leading responders (see Table 3). Thus, any significant difference in peak measurements may have been cancelled by analysing the data in terms of right vs.. left. Therefore, the data were rearranged in terms of leading ear vs.. lagging ear. This analysis revealed significant differences in wave III latency ($t_{(16)} = 6.25, p < .001$) and wave V latencies at 70 dB SL ($t_{(16)} = 7.51, p < .001$) and significant differences in wave V latency ($t_{(9)} = 3.68, p < .01$) and wave III amplitude ($t_{(9)} = 2.84, p < .05$) at 50 dB SL. Means and standard deviations of peak latencies and amplitudes for all subjects are summarized in appendix E.

It was apparent that previous authors who have reported no significant right/left asymmetries in peak latencies (Chiappa et al., 1979; Levine and McGaffigan, 1983; Rowe, 1978; Seltzers and Brackmann, 1977) have not observed the phenomenon for two reasons: 1) they did not recognize the existence of two subgroups among normal

hearing subjects, symmetrical and asymmetrical, and, therefore, failed to analyse the data from each group separately, and 2) data were analysed according to right vs.. left instead of leading vs.. lagging responses. As Decker and Howe (1981) pointed out, mean data have failed to reveal significant asymmetries because small asymmetries tend to cancel when analysed without regard to the direction of asymmetry in individual responses. Only one study (Levine and McGaffigan, 1983) has found a consistent right/left amplitude asymmetry for Wave III. This amplitude asymmetry was also found in the present study and appeared in the data combining symmetrical and asymmetrical subjects, and also in the data from symmetrical subjects alone. Interestingly, the wave III amplitude asymmetry was not present in the data from asymmetrical subjects when the data were analysed in terms of right vs. left. This was apparently due to cancellation of the effect when the analysis was performed in this manner. Re-analysis of the data after it had been reorganized into leading vs. lagging responses, failed to yield a significant difference in wave III amplitude at 70 dB SL, but did reveal a significant wave III amplitude difference at 50 dB SL. It is curious that the only inter-ear amplitude asymmetry was stronger and more consistently found among naturally symmetrical subjects.

There are at least two possible explanations for these seemingly contradictory results. First, this particular asymmetry would not contribute to a subject's classification as asymmetrical in this study because wave III falls outside of the time window (5-8ms) which was examined for inter-ear asymmetry. A wider analysis window which encompassed wave III, would, perhaps, have resulted in more symmetrical subjects being classified as asymmetrical. Second, assuming that the original classification of symmetrical and asymmetrical subjects was appropriate, the differences between groups in terms of wave III amplitude may represent a real difference between the monaural responses of symmetrical and asymmetrical subjects. The analyses of peak measurements suggest that beyond the level of the auditory nerve (Wave I), one monaural response of asymmetrical subjects travels more rapidly than the other through the brainstem auditory pathways. The number of fibers activated in each auditory tract appears to be equal, as evidenced by no significant difference in inter-ear peak to peak amplitudes, with the exception of wave III at 50 dB SL. On the other hand, the right and left monaural responses of symmetrical subjects travel at equal speeds through the brainstem. The significant difference in wave III amplitudes from these subjects, however, suggested a right ear advantage at the level of the primary

generators of wave III, which is thought to represent composite activity from generators up to the level of the superior olive. This advantage, which might, at first glance, appear related to some higher order right ear advantage, is not reflected at higher brainstem levels, as evidenced by the lack of significant difference between Wave V amplitudes. Thus, the functional significance of this amplitude asymmetry was unclear and deserves further investigation.

Effect of Asymmetry on the Relationship Between the Monaural and Binaural Response

The significant, positive correlations found at both sensation levels between the degree of asymmetry, as indicated by the size of the asymmetry ratio, and the amplitude of the residual component supported the hypothesis that naturally occurring asymmetry is related to the ability to predict the binaural response by means of a linear combination of the right and left monaural responses. This finding was consistent with the results obtained by Decker and Howe (1981) which suggested that at least part of the residual component that remained after the binaural response was subtracted from $R_m + L_m$ was related to a misalignment between monaural waveforms which, when added together, formed a summed waveform that was phase shifted in relation to the binaural waveform.

Dobie and Berlin's (1979a) method for demonstrating binaural interaction in the BSAEP was based on the algebraic manipulation of waveforms which, as Decker and Howe pointed out, can lead to spurious results. The fact that asymmetry exists in the monaural BSAEPs of a significant number of normal hearing subjects indicated that the appropriate means of combining waveforms would be by means of vector addition, and argues against combining waveforms by algebraic means. Decker and Howe circumvented this problem by not combining right and left responses, but, instead, individually subtracted right and left monaural responses from the binaural response which was scaled by a factor of two. By doing so, they claimed to demonstrate that, when asymmetry existed, one auditory tract dominated the binaural response. When auditory tracts were symmetrical, on the other hand, each auditory tract contributed equally to the binaural response.

The implication of Decker and Howe's conclusions was that a combination of symmetrical monaural responses would be a better predictor of the binaural response than a combination of asymmetrical monaural responses. The present study supported this assumption by demonstrating that mean RC amplitudes were smaller for symmetrical subjects than for asymmetrical subjects. Although the difference between symmetrical and asymmetrical RC

amplitudes did not reach statistical significance at 70 dB SL, it was statistically significant at 50 dB SL ($p < .01$). Further support for the fourth experimental hypothesis of this study comes from the positive correlation between the degree of asymmetry and the amplitude of the RC. Thus, the ability to accurately predict the binaural response on the basis of a summation of monaural responses was inversely related to the amount of asymmetry present in the monaural responses.

The residual component which occurs in the absence of asymmetry may be a useful measure for studying the relationship between monaural and binaural responses. The correlation between asymmetry and the amplitude of the residual component indicates that asymmetry should be accounted for when the residual component is used as a measure of monaural/binaural relationship. One possible way of controlling for asymmetrical monaural responses, which was utilized in the present study, was to reduce the asymmetry by balancing the left and right monaural responses by means of an interaural intensity adjustment. The effectiveness of this stimulus manipulation is discussed in the following section.

Effect of Interaural Intensity Manipulations

Reduction of the asymmetry ratio. Monaural BSAEPs which were considered to have significant

right/left response asymmetries according to the operational definition of asymmetry used in this study, were subjected to interaural intensity manipulations designed to eliminate, or at least reduce the asymmetry. As the intensity to the variable ear was changed in steps of 2 dB, the asymmetry ratio (AR) was reduced until it reached a minimum. Further changes in the intensity to the variable ear resulted in an increase in the AR (see figures 10 and 11). The interaural intensity difference needed to offset the asymmetry varied from 2 dB to 10 dB. The success of the interaural intensity manipulation in reducing the asymmetry was determined by means of comparing the minimum AR with the criterion for asymmetry ($AR > 1$). When the AR was reduced below the criterion for asymmetry, the interaural intensity manipulation was considered to be successful in eliminating asymmetry according to the operational definition of asymmetry which was used in this study. While the interaural intensity difference was successful in reducing the AR for all asymmetrical subjects, it was successful in eliminating the asymmetry (i.e. reducing the asymmetry below criterion) for only 41% of the subjects at 70 dB SL and 40 % of the subjects at 50 dB SL. Thus, for more than half of the asymmetrical subjects at each intensity level, interaural intensity manipulations were not sufficient for offsetting asymmetry. This suggested that

more than half of the asymmetrical subjects manifested a type of asymmetry which was more complex than that which could be accounted for on the basis of simple asymmetries in the peripheral auditory system (eg. subtle inter-ear sensitivity differences).

As explained in chapter 3, intensity was chosen as the stimulus variable for the purpose of offsetting asymmetry because it was believed that an interaural intensity difference would be most effective in offsetting congruent asymmetries. Two other types of asymmetry (incongruent and morphological asymmetries) were described however, and it was pointed out that, in theory, interaural intensity differences would not be completely effective in offsetting these asymmetries. In order to determine why the interaural intensity manipulation was successful in eliminating the asymmetry in some subjects, but was only partially successful in eliminating asymmetry in others, the responses of asymmetrical subjects were categorized according to the type of asymmetry as described in chapter 3. A criterion based on the standard error of the mean was used to determine significant difference between right and left wave V latency, and right and left wave V amplitude. This procedure for determining significant difference between peak measurements was discussed in detail in Appendix B. The distribution of asymmetrical subjects by category is

presented in Table 11.

The first category described was Congruent Asymmetry (Figure 17). These responses had the expected relationship between latency and amplitude, i.e. shorter latencies were accompanied by larger amplitudes. Although it was expected that this would be the most frequently encountered type of asymmetry, in fact, incongruent asymmetries outnumbered congruent asymmetries at both sensation levels. At 70 dB SL, responses of 14 subjects were classified as incongruent and the responses of 3 subjects were classified as congruent. At 50 dB SL, responses of 7 subjects were classified as incongruent while the responses of the remaining 3 asymmetrical subjects were classified as congruent.

The category of Incongruent Asymmetry was subdivided into three subcategories according to the descriptions of possible types of asymmetry which were outlined in chapter 3. The first subcategory (subcategory A) encompassed monaural responses which violated the expected latency/amplitude relationship. Included in this category were asymmetrical monaural responses in which the response from one ear not only had shorter latencies, but also had smaller amplitudes than the response from the opposite ear (Figure 18). At 70 dB SL, 3 subjects demonstrated this type of asymmetry, while at 50 dB SL no subjects demonstrated this type of asymmetry. The second

TABLE 11

Classification of asymmetrical subjects by type of asymmetry.

dB SL	<u>TYPE</u>				
	Congruent	Incongruent			Morph
		<u>A</u>	<u>B</u>	<u>C</u>	
70 dB	3	3	10	1	7
50 dB	3	0	5	2	5

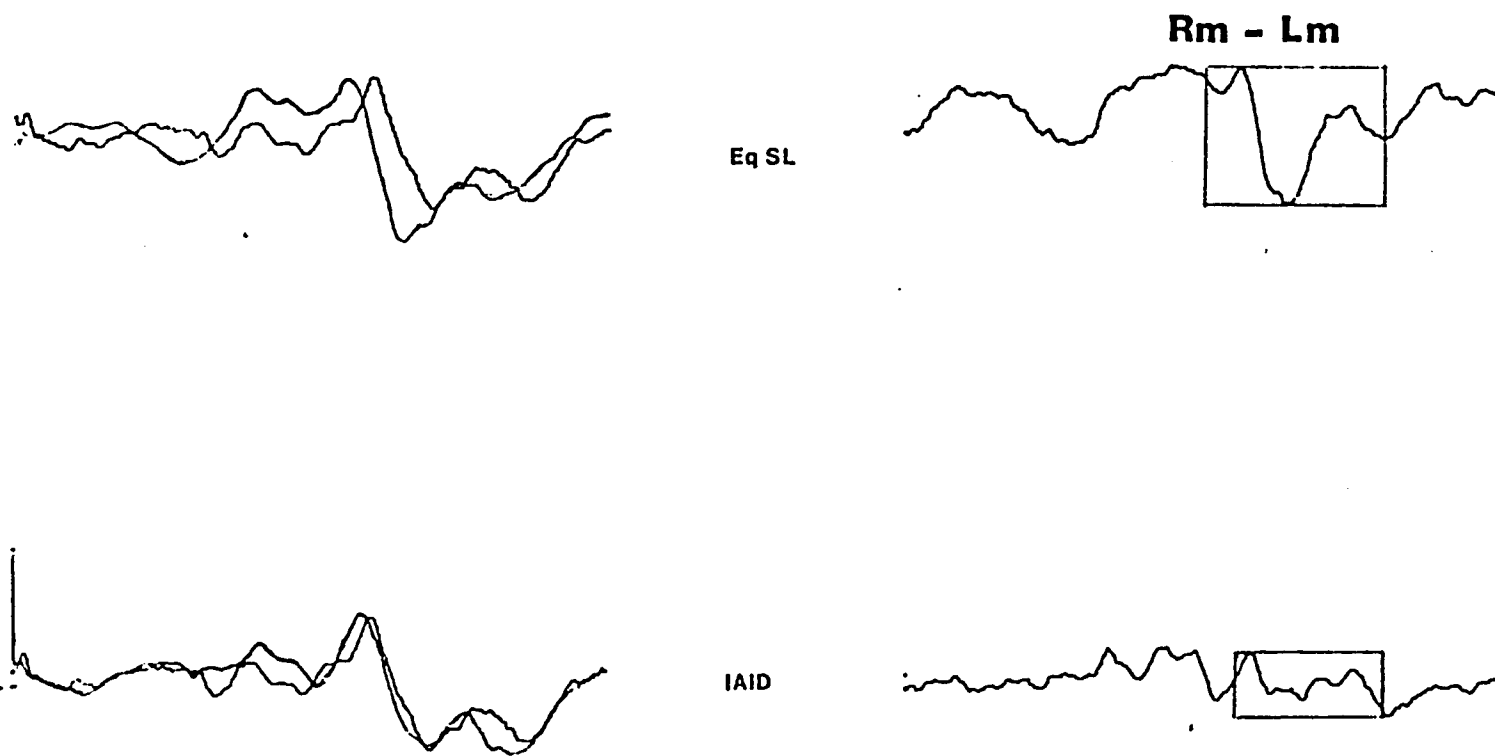


Figure 17. Congruent asymmetry.. Equal dB SL (Eq SL) and the effect of IAID for subject J.K., 50 dB.

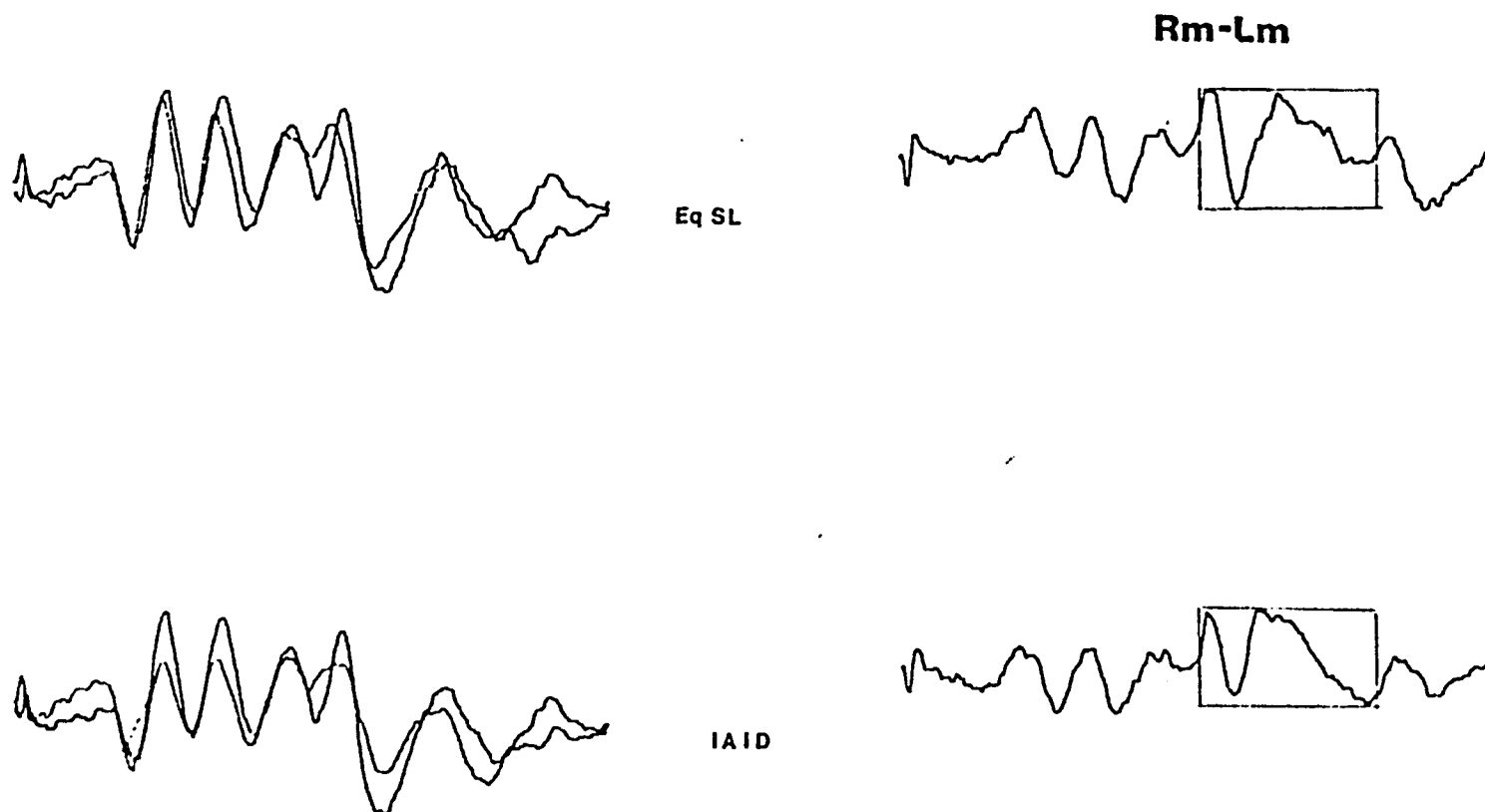


Figure 18 . Incongruent Asymmetry (Type A). Equal dB SL (Eq SL) and the effect of IAID for subject L.G., 70 dB.

and third categories of incongruent asymmetries were characterized by either equal latencies and unequal amplitudes--subcategory B which had 10 subjects at 70 dB SL and 5 subjects at 50 dB SL (Figure 19)--or equal amplitudes and unequal latencies--subcategory C which had 1 subject at 70 dB SL and 2 subjects at 50 dB SL (Figure 20). Although incongruent asymmetries were not expected to be easily offset by means of an interaural intensity difference, 7 incongruent asymmetries at 70 dB SL and 3 incongruent asymmetries at 50 dB SL were completely eliminated by means of the inter-ear stimulus manipulation. Thus, for the 70 dB sensation level, the proportion of incongruent asymmetries which was completely eliminated by the interaural intensity difference (50%) was greater than the proportion of congruent asymmetries (33%) which was completely eliminated. This pattern was also found for the 50 dB SL data where the proportion of incongruent asymmetries (42%) which was completely offset by the interaural intensity manipulation exceeded the proportion of congruent asymmetries (33%) which was completely offset. Thus, the expectation that the interaural intensity manipulation would be most effective in offsetting congruent asymmetries, and least effective in eliminating incongruent asymmetries was not supported.

In addition to asymmetries with respect to

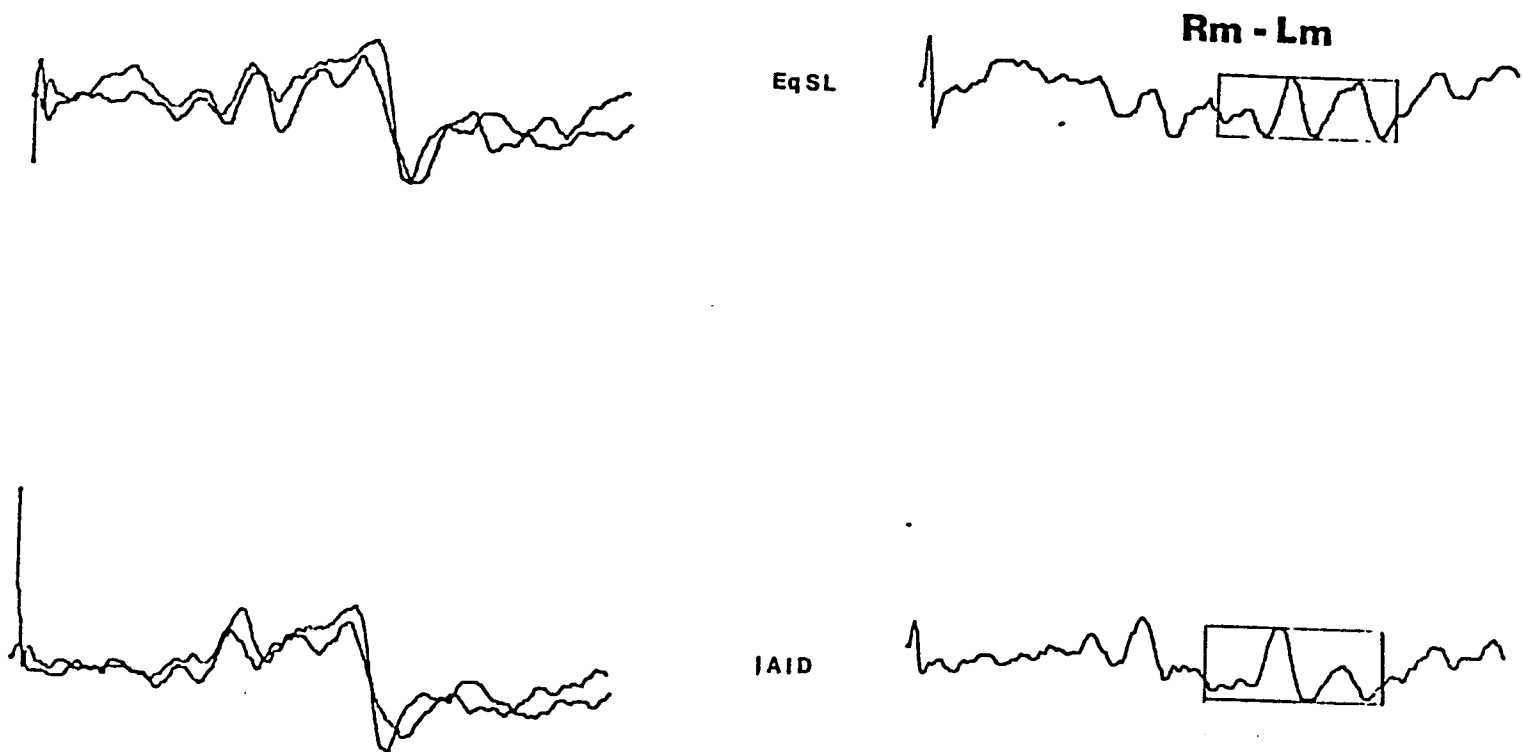


Figure 19 . Incongruent Asymmetry (Type B). Equal dB SL (Eq SL) and the effect of IAID for subject E.A., 70 dB.

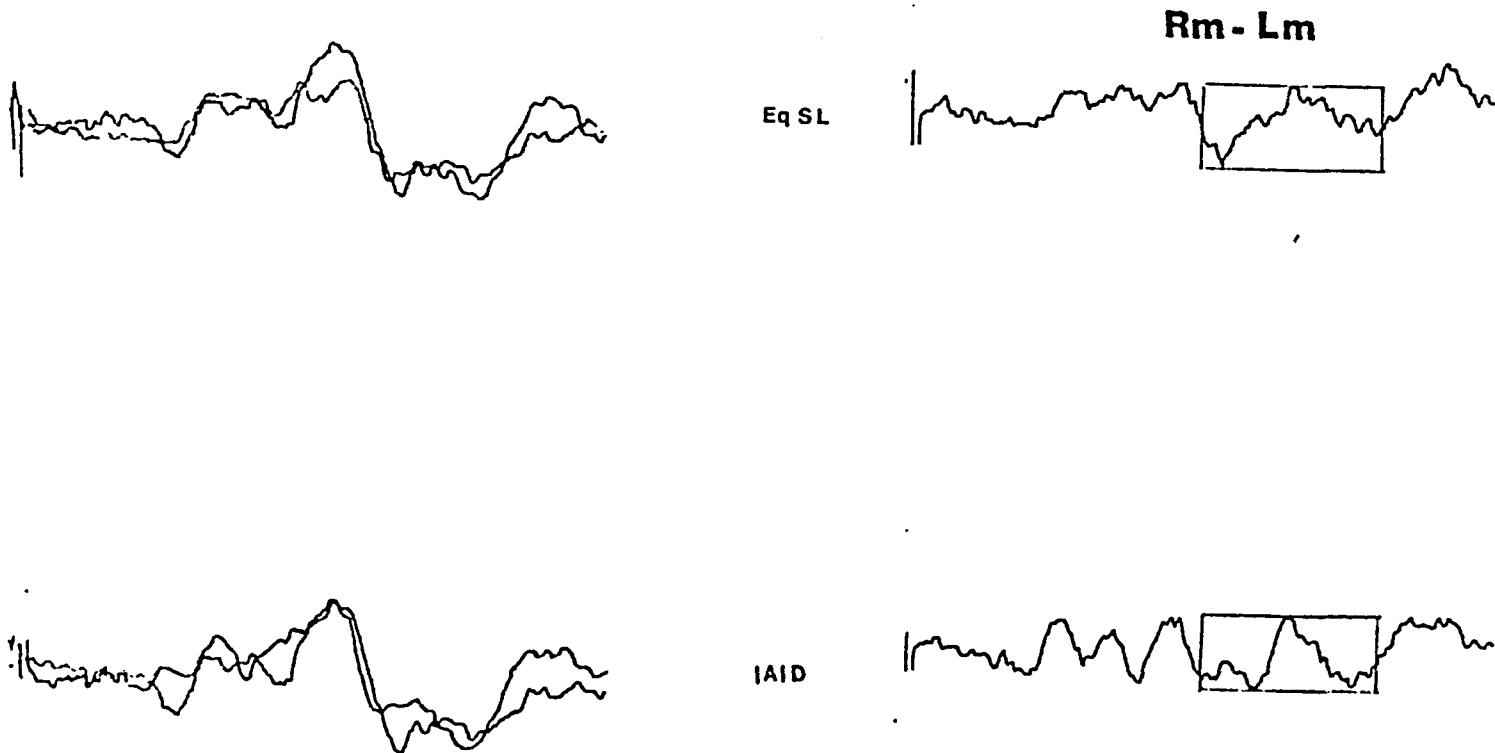


Figure 20. Incongruent asymmetry (Type C). Equal dB SL (Eq SL) and the effect of IAID for subject L.K., 50 dB.

latency and amplitude, many subjects also manifested right/left differences in wave morphology. Morphological asymmetries were determined by classifying the monaural responses of all subjects according to morphological type as described in Chiappa et al. (1979). Chiappa et al.'s six categories of BSAEP morphology are described in Appendix D. The responses from an individual subject were considered morphologically asymmetrical if the right and left responses were placed in different Chiappa et al. categories. For example, the right and left responses of subject LC are shown in Figure 21. The right ear response was categorized as type C while the left ear response was categorized as type F. This subject, therefore, was considered to be morphologically asymmetrical. A total of 7 asymmetrical subjects as well as 2 symmetrical subjects at 70 dB SL (38%) were categorized as morphologically asymmetrical. Five asymmetrical subjects and 2 symmetrical subjects (29%) were classified as morphologically asymmetrical at 50 dB SL. These figures were in reasonably good agreement with figures reported by Rowe (1978) who found marked morphological asymmetry in 40% of his subjects, and with Chiappa et al. (1979) who found morphological asymmetries in 42% of their subjects.

Although it might be expected that morphological asymmetries would be difficult, if not impossible, to

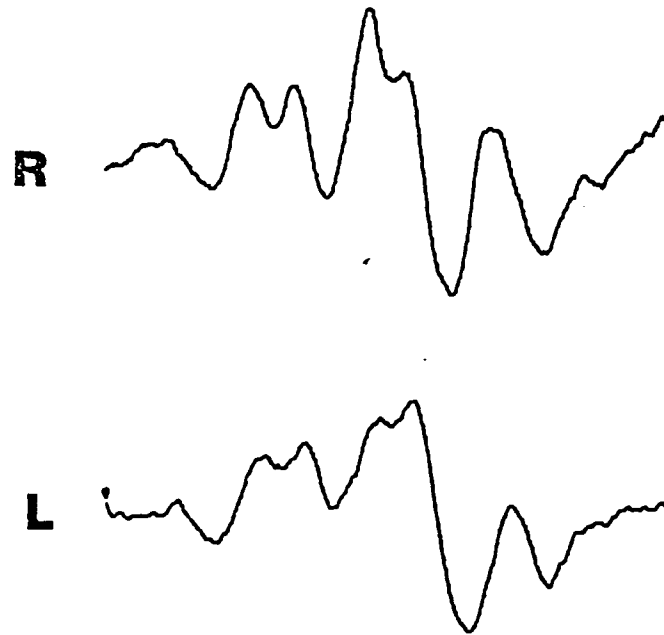


Figure 21 . Right and Left BSAEPs from one subject (L.C.) whose responses were judged to be morphologically asymmetrical. Stimulus level was 70 dB SL.

reduce by means of an interaural stimulus manipulation, this was not the case. The asymmetry ratios of all asymmetrical subjects who were additionally classified as morphologically asymmetrical were reduced as a result of the IAID (Figure 22). Furthermore, 42% of these asymmetries at 70 dB SL, and 40% of these asymmetries at 50 dB SL were completely eliminated by the IAID. Thus, the responses of subjects who were determined to have morphological asymmetries in addition to latency and/or amplitude asymmetry, were not substantially different from responses of subjects who were determined to manifest only one type of asymmetry, in terms of the effectiveness of the IAID in reducing or eliminating asymmetry.

Reduction of wave V latency and amplitude asymmetries. Evaluating the effectiveness of the interaural intensity difference (IAID) in eliminating asymmetry by means of the amplitude of the AR is limited in that it does not indicate how the intensity difference brought about the reduction in the asymmetry. In the case of congruent asymmetry, reduction in the intensity to the leading ear, for example, was expected to bring about a reduction in the asymmetry by increasing the latency and reducing the amplitude of the response from the leading ear until it approximated the latency and amplitude of

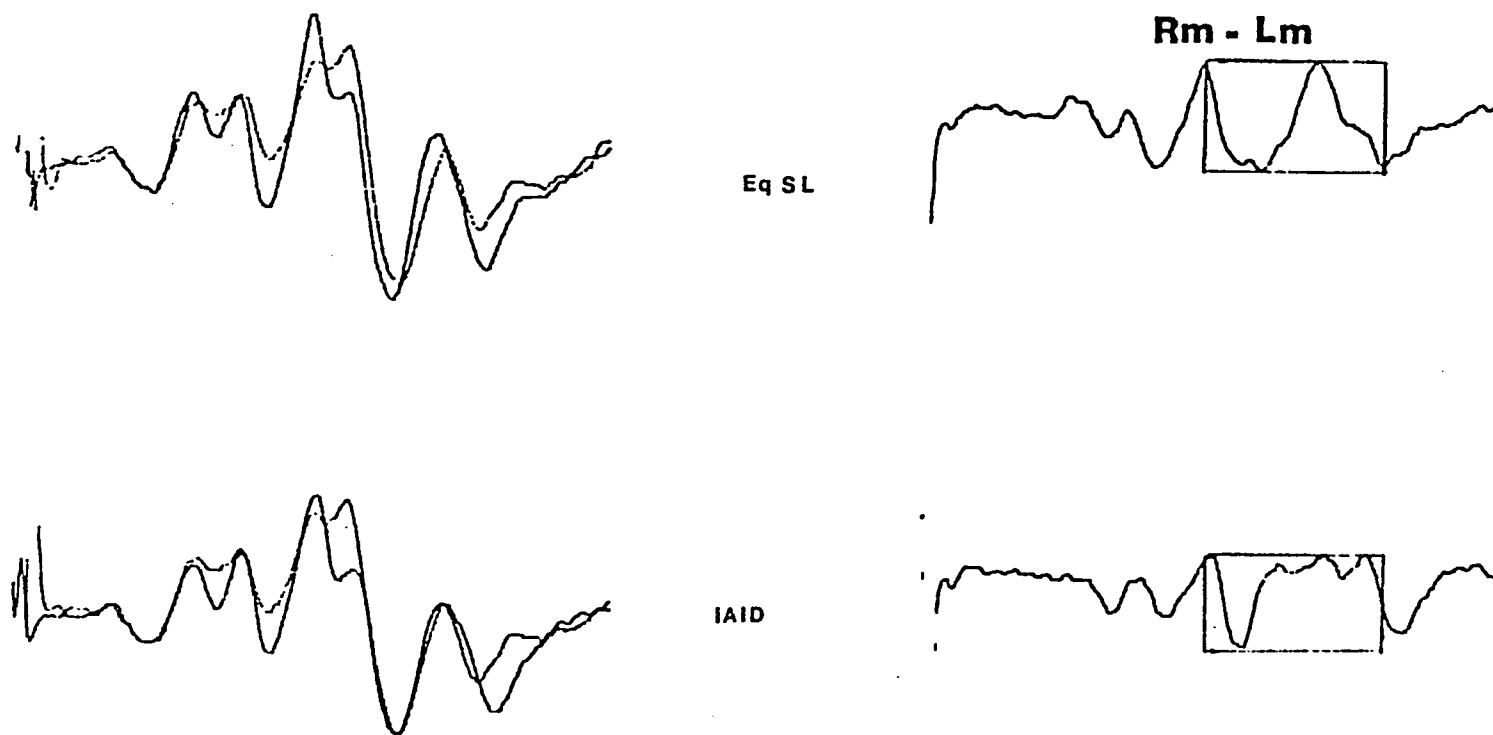


Figure 22 . Morphological Asymmetry. Equal dB SL (eq SL) and the effect of IAID for subject L.C., 70 dB.

the response from the lagging ear. In order to ascertain the effectiveness of the interaural intensity manipulation in reducing the latency and amplitude asymmetries between the right and left ear responses, right/left differences in wave V peak latencies and peak-to-peak amplitudes in the equal sensation level condition were compared to right/left differences in wave V peak latencies and peak-to-peak amplitudes in the IAID condition. It was expected that differences between right and left latencies and amplitudes would be smaller in the IAID condition for congruent asymmetries. In the case of incongruent asymmetries, however, aligning responses on the basis of latency had the potential of increasing the amplitude asymmetry. In order to test these expectations, asymmetrical subjects were categorized according to type of asymmetry and the reduction of the wave V latency and amplitude asymmetries were examined. These data are presented in Tables 12 (70 dB SL) and 13 (50 dB SL).

With only three exceptions (2 cases at 70 dB SL and 1 case at 50 dB SL), the interaural intensity manipulation was successful in reducing the asymmetry between right and left wave V latencies. This result was not surprising since determination of the leading or lagging ear was made on the basis of wave V latency and the intensity to the variable ear was adjusted in such a way as to cause an alignment between the wave V latencies

TABLE 12

Effect of interaural intensity manipulations on wave V latency and amplitude asymmetries for responses to 70 dB SL clicks that were classified according to type of asymmetry. Positive numbers indicate amount in milliseconds (latency) or microvolts (amplitude) by which asymmetry was reduced. Negative numbers indicate amount by which asymmetry was increased.

SUBJECT	CATEGORY	LATENCY (ms)	AMPLITUDE (uV)
CB	Congruent	.18	.02
JK		.06	.05
DZ		.18	.03
MEAN		.14	.03
LG	Incongruent (A)	.18	-.04
DF		.14	-.05
LK		.04	.01
MEAN		.12	-.03
GG	Incongruent (B)	.18	-.10
JM		.24	-.05
EA		.16	.05
SS		.04	.03
SP		.04	0
KO		0	-.17
HS		.02	.05
SC		.20	-.10
SM		.08	0
DR		.20	-.24
MEAN		.12	-.05
LC	Incongruent (C)	0	-.18
DR	Morphological	.20	-.24
LC		0	-.18
SC		.20	-.10
GG		.18	-.10
CB		.18	.02
JK		.06	.05
KO		0	-.17
MEAN		.12	-.10

TABLE 13

Effect of interaural intensity manipulations on wave V latency and amplitude asymmetries for responses to 50 dB SL clicks that were classified according to type of asymmetry. Positive numbers indicate amount in milliseconds (latency) or microvolts (amplitude) by which asymmetry was reduced. Negative numbers indicate amount by which asymmetry was increased.

SUBJECT	CATEGORY	LATENCY (ms)	AMPLITUDE (uV)
CB	Congruent	.04	-.02
DZ		.06	0
JK		.28	.13
MEAN		.13	.04

DR	Incongruent (B)	.22	-.06
RO		.06	0
SS		.10	.06
SC		.16	.01
DF		.20	-.20
MEAN		.15	-.04

LC	Incongruent (C)	-.02	.01
LK		.04	.15
MEAN		.01	.08

DR	Morphological	.22	-.06
DF		.20	-.20
CB		.04	-.02
LC		0	.01
SC		.16	.01
MEAN		.12	-.07

of the right and left responses. The expected reduction in the latency asymmetry was achieved in all cases of congruent asymmetry at both sensation levels. In two cases of incongruent asymmetry at 70 dB SL (one type B and one type C), the IAID caused a reduction of the amplitude asymmetry, but left the latency asymmetry unchanged. In the case of one subject (Type C) at 50 dB SL, the amplitude asymmetry was slightly reduced, however, the latency asymmetry was increased as a result of introducing the IAID.

The IAID was less successful in reducing wave V amplitude differences. As anticipated, in most cases in which incongruent asymmetry was present, reducing the latency asymmetry brought about an increase in the amplitude asymmetry. This situation occurred in 57% of the incongruent asymmetrical cases at 70 dB SL and in 29% of the incongruent asymmetrical cases at 50 dB SL. In two cases at 70 dB SL and in one case at 50 dB SL, the amplitude asymmetry was unaffected by the intensity difference. As Tables 12 and 13 show, there was a tendency for incongruent asymmetries to show a mean decrease in the right/left latency difference accompanied by a mean increase in right/left amplitude difference. The one exception to this trend was category C at 50 dB SL where both latency and amplitude were decreased. In contrast, results for the congruent asymmetry category

indicated a mean decrease in the right/left latency difference which was accompanied by a mean decrease in right/left amplitude difference. In only one case (50 dB SL) the amplitude asymmetry was increased and in one case (50 dB SL) the amplitude asymmetry was left unchanged by the interaural intensity difference.

By observing the effect of the interaural intensity manipulation on the wave V latency and amplitude asymmetry, it became clear why this manipulation did not consistently produce the expected results. There was a consistent inverse relationship between latency and intensity. The relationship between amplitude and intensity, however, was not consistently maintained. As has been documented by previous studies (Picton et al. 1983; Rowe, 1978; Stockard et al. 1978), amplitude measurements of BSAEP waveforms tend to have a considerable amount of intersubject and intrasubject variability. Thus an increase in peak latency which was brought about by a decrease in intensity was not always accompanied by a predictable decrease in peak-to-peak amplitude. The net effect of the interaural intensity manipulation was, in many cases, to reduce or latency asymmetry while leaving amplitude asymmetry uncorrected.

Predicting the Binaural Response From a Combination of Monaural Responses

The accuracy with which a combination of monaural responses predicts the binaural response was indicated by the amplitude of the residual component which remains after the binaural response was subtracted from the combined monaural responses. If the binaural response was merely a simple summation of the responses from the right and left ears, the addition of the right and left monaural responses would sum to equal the binaural response. Subsequent subtraction of the binaural response from the summed monaural responses would result in a trace which would not exceed the noise floor ($[R_m + L_m] - B_{in} = 0$). Results of past research which compared monaural and binaural responses, however, have repeatedly shown that, while binaural latencies are equal to their monaural counterparts, binaural amplitudes are considerably less than twice the monaural amplitude (Blegvad, 1975; Jewett and Willison, 1971; Starr and Achor, 1975; Van Olphen et al., 1978). This fact alone, would lead one to conclude that the binaural response does not represent a linear combination of activity from each ear. Dobie and Berlin (1979a) as well as other researchers who adopted their methods (Allen et al., 1981; Dobie and Norton, 1981; Hosford-Dunn, 1981; Prasher et al., 1982; Wrege and Starr, 1981) have demonstrated

the fact that the right and left monaural responses do not sum to equal the binaural response. Decker and Howe (1981), however, have demonstrated that, under certain conditions, one monaural response can equal the binaural response which was scaled by a factor of two. According to Decker and Howe, a single monaural response can accurately mirror the binaural response when, because of asymmetry within the CANS, one auditory tract is "preferred" over the other auditory tract during binaural stimulation.

The implications that the central auditory nervous system combines right and left information in some non-linear fashion and, additionally, combines this information differently depending upon whether the right and left auditory systems are symmetrical or asymmetrical, were addressed in the present study. At least two distinct possibilities exist. First, the binaural response represents a combination of information which is available in the right and left monaural responses. If this is true, it should be possible to develop a formula for combining monaural responses which would accurately predict the binaural response. A second possibility is that the binaural response is the result of neural activity which is fundamentally different from the activity which produces the monaural responses. Results obtained by Pratt and Sohmer (1977) and Howe and

Decker (1984) led these researches to speculate that monaural and binaural responses were independent entities. If this is true, then no formula for combining monaural responses will ever accurately predict the binaural response. For the purpose of the present study, the first alternative was tested. Three models for combining the monaural responses were posed. In light of previous research in the area of binaural interaction and the current knowledge concerning the presence of asymmetry in the BSAEP, it was hypothesized that the models which combined monaural responses which were free of asymmetry would be the best predictors of the binaural response. These models included 1) combination of right and left monaural responses from naturally symmetrical subjects ($[R_m + L_m] - B_{in} = RC$), 2) combination of right and left monaural responses from naturally asymmetrical subjects after asymmetry had been reduced by means of an interaural intensity manipulation ($[R_m = L_m]' - B_{in} = ARC$), and 3) doubling of the preferred monaural response from naturally asymmetrical subjects ($2 \times [\text{preferred monaural}] - B_{in} = B-P$).

Asymmetrical Subjects. Mean data from both sensation levels supported the hypothesis that a combination of right and left monaural responses from asymmetrical subjects was a poor predictor of the

binaural response. Doubling of the preferred monaural response was an equally poor predictor of the binaural response. This was unexpected, since it had been reported (Decker and Howe, 1981) that, in the case of asymmetrical monaural responses, one auditory tract would dominate during binaural stimulation. Inspection of data from individual subjects revealed an interesting trend which sheds some light on this result. It was found that, at 70 dB SL, the B-P was a better predictor of the binaural response for 7 asymmetrical subjects while the RC was a better predictor of the binaural response for 10 asymmetrical subjects. The asymmetry ratios (AR) for the 7 subjects for whom B-P was a better binaural predictor tended to be larger than the ARs for the 10 subjects for whom the RC was a better binaural predictor. The differences between the two groups was statistically significant, $t_{(15)} = 2.814$, $p = .01$). This finding indicated that, for subjects with a greater degree of asymmetry, doubling of the preferred monaural response predicted the binaural response more accurately than a combination of right and left monaural responses. For those subjects for whom the degree of asymmetry was small, a linear combination of right and left monaural responses served as the better binaural predictor. This trend in the 70 dB data was also found in the 50 dB data. The difference between mean ARs for 4 subjects for whom

B-P was the better predictor and 6 subjects for whom RC was the better predictor was, however, considerably smaller at 50 dB than it was at 70 dB and failed to reach statistical significance, $t(8) = .65$, $p > .05$).

The model which proved to be most accurate in predicting binaural responses for asymmetrical subjects was a combination of right and left monaural responses after the asymmetry had been reduced or eliminated by means of the interaural intensity manipulation. The mean residual components obtained under this condition (ARC) were significantly smaller than B-P and RC for both sensation levels. Although this result was predicted by the fourth hypothesis, it was inconsistent with reports of previous researchers who studied the effects of interaural differences in intensity or time on the residual component. Dobie and Berlin (1979a) observed that the BIC derived from the BSAEPs of guinea pigs was reduced in amplitude when either interaural time or intensity differences were introduced to the stimuli. These results were replicated in human subjects by Wrege and Starr (1981) who studied the effects of interaural time differences, and by Prasher et al. (1982) who studied the effects of interaural intensity differences. The authors of these three studies assumed that equal stimulation (time and intensity) to the right and left ears resulted in symmetrical monaural responses. The

introduction of the time or intensity differences, therefore, could have served to create inter-ear response asymmetry in these studies. The results of these studies suggested that the residual remaining after the binaural response was subtracted from the sum of the right and left monaural responses was attenuated as a result of introducing asymmetry by means of the interaural stimulus differences. The results of these studies were not directly comparable to the present study, however, for the following reasons:

- 1) The effects of the interaural stimulus difference may have had different effects on the responses of different subjects, depending upon whether they were naturally symmetrical or naturally asymmetrical. Results of this study support previous studies (Allen et al., 1972; Chiappa et al., 1979; Decker and Howe, 1981; Rowe, 1978) that report the presence of response asymmetry in a significant proportion of the normal hearing population inspite of equal stimulation to the right and left ears. Thus, it is likely that the equal stimulus conditions in the studies cited above did not produce symmetrical monaural responses in all subjects. In some subjects, the interaural stimulus difference may have had the intended effect of creating a response asymmetry, while in other cases the interaural stimulus difference may have actually reduced a natural asymmetry.

2) The two studies which employed interaural intensity manipulations (Dobie and Berlin, 1979; Prasher et al. 1981) used relatively large steps of 10 dB. The steps used in this study, for the purpose of offsetting asymmetry, were 2 dB. It was found that naturally occurring asymmetry was effectively reduced or eliminated with interaural intensity differences which ranged between 2 and 10 dB, with the majority of asymmetries being offset with a 4 dB interaural difference. Since the smallest step used in previous studies was 10 dB, it is apparent that the phenomenon which was examined in those studies was different from the phenomenon which was examined in the present study.

Only one study that employed interaural stimulus differences, did so with regard to naturally occurring asymmetry. Allen et al. (1982) examined the change in the amplitude of the BIC as a result of manipulating the interaural time relationship of the stimulus. They found that symmetrical subjects produced the largest BIC when stimuli were presented simultaneously to each ear. BICs for naturally asymmetrical subjects, on the other hand, were largest when the interaural time relationship was such that it caused a reduction in the inter-ear asymmetry. These results were directly opposed to those obtained in the present study. The potential reasons for the differences between the two studies, therefore,

deserve careful consideration and are presented below.

1) The first and most obvious difference between the present study and the study performed by Allen et al. was the stimulus parameter which was manipulated. Thus, the first consideration must be whether or not there is a fundamental difference in the effects of interaural time differences as compared to interaural intensity differences on the residual component. There is, at this time insufficient data to answer this question. The expected effects of each of these stimulus manipulations on response asymmetry were discussed in chapter 3. It was pointed out that, while interaural time differences would be expected to be effective in offsetting right/left latency asymmetries, interaural intensity differences would be expected to be effective in offsetting right/left asymmetries in both the latency and amplitude domains. Furthermore, it was speculated that when inter-ear response asymmetry occurred, the asymmetry would affect both latency and amplitude. The extent to which these expectations were supported in the data was discussed earlier in this chapter. Since Allen et al. present no details regarding the nature of the right/left asymmetries among their subjects, nor do they discuss the effectiveness of the interaural time difference in reducing asymmetries (presumably in latency) between the right and left monaural responses, it is not possible to

compare the relative effectiveness of interaural time and intensity differences in reducing inter-ear latency and amplitude asymmetries.

2) The operational definitions of symmetry and asymmetry differed between the two studies. The present study defined asymmetry on the bases of the amplitude of the difference trace which remained after subtracting the left monaural from the right monaural response. $R_m - L_m$ amplitudes which exceeded a conservative criterion were considered to represent significant right/left asymmetry. Allen et al., in contrast, defined asymmetry on the basis of relative amplitudes of the difference traces which remained after each monaural response was individually subtracted from the binaural response. Inequality of the two difference traces indicated response asymmetry. No criterion or method for determining the significance of the difference between difference traces was reported.

As was discussed in chapter 3, $R_m - L_m = 0$, the definition of symmetry used in the present study, was adapted from $Bin - R = Bin - L$, the definition of symmetry used originally by Decker and Howe (1981) and subsequently by Allen et al. The two methods for defining asymmetry were believed to be equivalent since a the common term on both sides of the second equation (Bin) was eliminated to form the first equation. However, the two equations may not, in fact, produce equivalent

results for the following reasons: 1) The measurement $R_m - L_m$ will have a certain amount of variability which can be described with an error term. The addition of B_{in} to the equation results in the addition of another error term associated with the binaural measurement. Thus $R_m - L_m$ will have less variability than $B_{in} - R = B_{in} - L$. 2) $R_m - L_m$ is a determination of asymmetry between the right and left monaural responses without regard to the relationship of each monaural response to the binaural response. $B_{in} - R = B_{in} - L$, on the other hand, implies more than mere equivalence of the right and left monaural responses, but also implies equivalent relationships between both the right and left monaural response and the binaural response. In other words, $B_{in} - R = B_{in} - L$ indicates that both the right and left monaural responses are equally accurate predictors of the binaural response. This subtle difference in the methods used to determine when symmetry either existed naturally or had been achieved by means of the interaural stimulus manipulation may have contributed to the difference in results. Examination of the data from the present study indicated that the interaural intensity difference which produced the smallest $R_m - L_m$ amplitude, and, thereby the smallest AR, did not always produce the smallest difference between $B_{in} - R$ and $B_{in} - L$. The categorization of responses as symmetrical or asymmetrical, therefore,

differed between the two studies.

3) Methodological differences between the two studies may have also contributed to the different results. As described in Part II of chapter 3, the BSAEPs in this study were recorded using a single, vertex to midline neck electrode derivation. This recording derivation was chosen so as to equalized contributions from the right and left auditory tracts during both monaural and binaural recordings. In contrast, Allen et al. used a vertex to earlobe derivation. Monaural waveforms consisted of ipsilaterally recorded BSAEPs and binaural waveforms consisted of the summation of binaural BSAEPs recorded simultaneously from the right and left side of the head. Little information is available regarding the effects of electrode derivation on studies of response asymmetry. Until such time as the effects of methodological variations on inter-ear response asymmetry are known, the choice of electrode derivation must be considered a potentially significant influence on the results.

Thus, sufficient differences existed in the designs of the two studies which may have accounted for the seemingly contradictory results.

Symmetrical Subjects. Since the right and left responses of symmetrical subjects were, by

definition, identical, it was hypothesized that combining the right and left responses which were naturally symmetrical should provide an accurate prediction of the binaural response. It was found, in fact, that the linear combination of naturally symmetrical monaural responses was a better, although imperfect predictor of the binaural response than the linear combination of monaural responses from asymmetrical subjects. As hypothesized, there was no significant difference between RCs and B-P from this group. This indicated that the binaural response could be predicted equally well with either model.

If response asymmetry was solely responsible for the occurrence of the residual component then the responses of naturally symmetrical subjects as well as the responses of naturally asymmetrical subjects after asymmetry was reduced, should have yielded null residual components. Although symmetrical monaural response, whether natural or induced, consistently combined to produce smaller residual components than did asymmetrical monaural responses, at no time was the residual component entirely eliminated. The persistence of a residual component may have been attributable to several factors. Symmetry between right and left monaural responses may not have insured that they would combine to equal the binaural response. The possible reasons for this are as

follows:

1) A certain amount of jitter may exist within the CANS during monaural and binaural stimulation and may preclude an accurate prediction of the binaural BSAEP from a linear summation of monaural BSAEPs under any condition.

2) The residual component may represent a real difference between monaural and binaural responses which are attributable to binaural interaction. Depth electrode studies of the central auditory system have revealed the presence of neural units which are specifically responsive to or inhibited by ipsilateral, contralateral or binaural stimuli (Galambos et al., 1959; Hall, 1965). Assuming that the BSAEP is robust enough to register these differences in unit responsiveness, differences between summed monaural and binaural responses may indicate binaural interaction.

3) The assumption that the binaural response represents the same underlying neural activity as that which is represented in the monaural responses may be incorrect. If, for example, the binaural response represents neural activity from populations of neurons which are specifically sensitive to binaural stimulation, while the monaural responses represent neural activity from populations of neurons which are specifically sensitive to right or left monaural stimulation, then a

combination of right and left monaural responses would not be expected to equal the binaural response. The differences, furthermore, could not be attributed to binaural interaction, since, in this hypothetical example, no interaction between right and left auditory tracts has taken place.

4) The models which were proposed for predicting the binaural response from a linear combination of monaural responses may not accurately represent the way in which the neural information from each auditory tract is combined. While three models were tested in this study, there exist a virtually infinite number of possible formulae for combining right and left monaural responses, any one of which may prove to accurately predict the binaural response. The failure of the models that were tested in this experiment to perfectly predict the binaural response, therefore, does not necessarily indicate that the binaural response cannot be predicted by combining monaural responses.

Conclusions

The following conclusions were drawn from the results of this study:

1. Asymmetry in the monaural brainstem responses of individual normal hearing subjects was the rule rather

than the exception. The presence and extent of asymmetry observed among normal hearing subjects will vary as a function of the operational definition of asymmetry and the criterion used to measure asymmetry. That is, an individual's classification as symmetrical or asymmetrical could change depending upon which measurement--inter-ear latency, inter-ear amplitude, or $R_m - L_m$ --is being used. This suggested that discrete categories of symmetry and asymmetry do not exist. Inspection of the the frequency distributions of asymmetry ratios (Figures 2 and 3) suggested that subjects' responses fall along a continuum ranging from symmetrical to very asymmetrical.

2. The proportion of asymmetrical subjects also varied with overall stimulus level. At a moderately high intensity (70 dB SL) asymmetry can be expected in the BSAEPs of 71% (+/- 19%) of subjects. Lowering the intensity to 50 dB SL can be expected to significantly reduce the proportion of subjects with asymmetrical responses to 42% (+/- 21%).

The change in proportion of asymmetrical subjects as a function of sensation level is interesting and deserves further study. Out of 17 subjects who were classified as asymmetrical at 70 dB, only 9 subjects remained in the asymmetrical category at 50 dB while one subject who was categorized as symmetrical at 70 dB was

categorized as asymmetrical at 50 dB. The fact that nine subjects switched categories when sensation level was changed suggested that the latency-intensity and/or amplitude-intensity function of the right and left responses are different.

Asymmetries in the latency-intensity functions of asymmetrical responses have been observed by Decker (1983). This hypothesis was further reinforced by the finding that some subjects who were asymmetrical at both sensation levels had right leading⁸ responses at 70 dB but had left leading responses at 50 dB, and vice versa. These two phenomena suggested that latency/amplitude-intensity functions from each ear converge and, in some cases cross. The intensity at which these functions from the right and left ear converge may be a significant measure, representing the intensity level at which right and left monaural responses are symmetrical. The intensity level at which right and left monaural responses are symmetrical may be fairly consistent among subjects or alternatively, may be quite variable. Results of the present study suggested the latter case. Thus, a careful mapping of latency/amplitude-intensity functions in small intensity steps may reveal that there is some intensity at which responses from any normal hearing subject will be

⁸Leading ear was determined on the basis of wave V latency.

asymmetrical or, conversely, may reveal that at some intensity level, responses from any normal hearing subject will be asymmetrical.

3. The operational definition of asymmetry which was used in the present study was an $R_m - L_m$ difference trace which exceeded the level of the background noise. According to this definition, asymmetry in the monaural BSAEPs was present in a significant number of normal hearing subjects. A significant proportion of asymmetrical subjects was also found when asymmetry was defined as a significant difference in Wave V latency and/or Wave V amplitude. Criterion for asymmetry under these definitions was determined statistically. Classification of subjects according to one of these definitions, i.e. statistically significant wave V latency differences, compared remarkably well with the classification which resulted when the empirical definition was applied to the data. Thus, the results of using the on-line method were comparable to results obtained with a more rigorous statistical method which had good face validity. It can be concluded, therefore, that the on-line method can be used as a practical and reliable method of determining the presence of significant asymmetry.

4. Symmetry between right and left wave V absolute and interpeak latencies has been considered, in

the clinical literature, to be one of the hallmarks of normal auditory functioning (Chiappa, 1979; Rowe, 1978; Seltzers and Brackmann, 1977). Some studies, in fact, have suggested that interear wave V latency asymmetry on the order of .2 to .4 ms is a sign of brainstem pathology (Seltzers and Brachmann, 1977; Rowe, 1978). The present study, however, demonstrated the prevalence and variability of interear asymmetries in the BSAEPs of normal subjects. Wave V latency asymmetries for normal subjects, furthermore, often exceeded the so called normal limits for wave V latency differences. Seven subjects at 70 dB and 6 subjects at 50 dB had right/left wave V latency differences which were equal to, or greater than .2ms. The preponderance of interear asymmetries among normal hearing subjects, therefore, seriously challenges the effectiveness of this measurement as a diagnostic indicator of auditory tract pathology.

5. Asymmetry, as it was operationally defined in this study, could be reduced by means of an interaural intensity difference. The interaural intensity manipulation was most effective in reducing both latency and amplitude asymmetries in those asymmetrical responses classified as congruent. The mean asymmetry ratio for all asymmetrical subjects was significantly reduced by means of the interaural intensity manipulation inspite of the fact that the stimulus manipulation was ineffective in

reducing the amplitude asymmetry in the responses of more than half (incongruent) of asymmetrical subjects. This indicated that the amplitude of the asymmetry ratio was primarily governed by interear latency differences.

6. The component which remains after the binaural response is subtracted from the sum of the right and left monaural responses has been interpreted as an indication of binaural interaction. This study has demonstrated, however, that the amplitude of the residual component is positively correlated with the degree of inter-ear asymmetry present. Reduction of the asymmetry caused a corresponding significant reduction in the amplitude of the residual component. Thus, it was apparent that the so-called binaural interaction component was related to processes which were not related to binaural processes. The preponderance of right/left asymmetry in the normal BSAEP and the demonstrated relationship between asymmetry and the residual component indicated that use of this component as a representation of underlying neural processes may not be valid.

Implications For Furture Research

The presence of significant right/left asymmetries in the BSAEPs of normal hearing subjects has

implications for both evoked potential and psychoacoustic research in which symmetry between the two ears has been assumed.

1. Studies of binaural interaction that use the $(R_m + L_m) - Bin$ paradigm must account for naturally occurring asymmetry which exists in a significant proportion of normal hearing subjects. This study has demonstrated a direct relationship between response asymmetry and the amplitude of the residual component. The asymmetry between right and left monaural responses may have been responsible for the variability which is seen in studies of binaural interaction in the auditory evoked potentials. Once trivial asymmetries have been accounted for, the residual component takes on new interest as a measure of the inequality between the binaural response and the summed monaural responses.

2. Before any conclusions concerning the relationship between binaural interaction and the residual component can be drawn, it will be necessary to establish a correlation between the occurrence of this component and some aspect of binaural perception which, supposedly, is subserved by the generators of the BSAEP. The association between the RC and binaural perception has been suggested (Dobie and Berlin, 1979a; Prasher et al., 1981) but has not been adequately investigated. There is a need for research which correlates measures of

binaural phenomena which are believed to be mediated in the brainstem (eg. sound lateralization and the binaural masking level difference) and the RC. The association between the RC and binaural interaction can be investigated in two ways: a) by examining the relationship between measures of psychoacoustic binaural phenomena and the RC in normal hearing subjects and, b) by examining the way in which the RC is affected in subjects demonstrating binaural perceptual deficits.

It has been suggested that the monaural BSAEP is sensitive to confirmed or suspected CANS abnormalities which affect subject performance on binaural perceptual tasks such as sound lateralization, the binaural masking level difference and binaural fusion (Hannley et al., 1983; Hausler and Levine, 1980; Noffsinger et al., 1982; Roush and Tait, 1984; Russolo and Poli, 1983; Zerlin and Mowry, 1980). Interestingly, neither the binaural BSAEP nor the relationship between monaural and binaural BSAEPS have been examined in relation to these organically based deficits in binaural processing. A correlation between the residual component and abnormal performance on binaural perceptual tasks would strengthen the association between the residual component and binaural interaction.

3. Psychoacoustic measures of binaural interaction are affected by small interaural differences.

A small interaural intensity or time difference, for example, causes a sound image to be displaced from the midline and lateralized toward the ear receiving the stimulus which is leading in time or is louder in intensity. Responses from the right and left ears may differ with respect to latency, amplitude, or both. Considering the sensitivity of the auditory system to interear differences related to the stimulus, and their profound affect on binaural perception, it seems reasonable to speculate that interear response asymmetries might similarly affect binaural perception. Given two subjects, one with symmetrical monaural responses and one with significant interear response asymmetry, will their performance on binaural perceptual tasks differ in any consistent way? This question has not yet been addressed in the literature.

Concluding Comment

The results of this study suggested that the population of subjects which is commonly referred to as "normal", is not homogeneous. At least two subgroups can be identified within the normal group: those with symmetrical BSAEPs and those with asymmetrical BSAEPs. Placement in these two subgroups, furthermore, appears to

depend upon the definition of asymmetry and the sensation level of the eliciting stimulus. The variation in the degree of asymmetry which is found among normal subjects suggests that right/left differences might be more properly thought of as existing along a continuum ranging from nearly perfectly symmetrical to very asymmetrical, rather than falling into two discrete categories.

The study of response asymmetry in normal subjects may shed considerable light on brainstem auditory function. Its presence may signify simple interear differences such as small differences in peripheral sensitivity or conduction time through the auditory pathways. These asymmetries would be expected to be in the form of interear latency and/or amplitude differences and should be correctable by means of interaural stimulus manipulations. On the other hand, response asymmetry may signify a more complex difference indicating a fundamental difference in the way in which the right and left auditory tracts process information. In this category would fall morphological asymmetries and incongruent asymmetries, which are less likely to be correctable by means of adjustments in the stimulus.

While the usefulness of right/left asymmetries as a diagnostic measure of brainstem pathology is questionable, their effect on presently used methods of

measuring binaural interaction in the BSAEP is considerable. It has been demonstrated that the binaural BSAEP is poorly predicted by the addition of asymmetrical monaural responses. The inability of the monaural responses to predict the binaural response is, in part, related to response asymmetry, and not necessarily to any fundamental difference in monaural and binaural processing as had been previously suggested. This was demonstrated by the significant decrease in the amplitude of the residual component when asymmetry was reduced by means of an interaural intensity difference. If the relationship between monaural and binaural BSAEPs is to be used as a meaningful measure of binaural interaction, it is clear that the effects of response asymmetry must be recognized and controlled.

APPENDIX A

Suitability of $R_m - L_m$ As a Measure of Asymmetry

Although subtracting left from right monaural responses provided a practical solution to the problem of indicating response asymmetry, it was necessary to firmly establish $R_m - L_m$ as a valid representation of response asymmetry. It was hypothesized that, if $R_m - L_m$ was a true representation of response asymmetry, the results of $R_m - L_m$ would correlate highly with other measurements of asymmetry. In order to test this hypothesis, a pilot study was performed in which the results of $R_m - L_m$ were correlated with two measures of response asymmetry: 1) right/left wave V latency differences and 2) right/left wave V amplitude differences. Peak measurements for wave V were chosen for this comparison because wave V has been found to be the dominant wave occurring within the time window in which the effects of binaural interaction are said to be observed (Decker and Howe, 1981; Dobie and Norton, 1981; Wrege and Starr, 1981). For the purposes of this analysis, the results of the $R_m - L_m$ (equal dB SL condition), within the window encompassing wave V and V' of each subject's right and left responses (N=24), were used.

Results of Pearson product moment correlation indicated that $R_m - L_m$ did not correlate well with

right/left differences in Wave V amplitude ($r = .238$, $p > .05$). $R_m - L_m$ did, however, correlate highly with right/left differences in wave V latency ($r = .75$, $p < .001$).

The low correlation between $R_m - L_m$ and differences in wave V amplitude may be attributed to variability in wave V amplitude over time and between subjects. The variability of wave V amplitude in normal subjects has been well documented in the literature (Starr and Achor, 1975; Rowe, 1978; Chiappa, 1979, among others). Unlike amplitude, wave V latency is a highly stable and replicable measure. Inter-ear differences in wave V latency, therefore, can be considered to be a more reliable measure of response asymmetry than can inter-ear differences in wave V amplitude. Therefore the correlation between $R_m - L_m$ and differences in wave V latency was felt to be the more important of the two correlations. Thus, the high correlation between $R_m - L_m$ and differences in wave V latency supported the argument in favor of using $R_m - L_m$ as a measure of asymmetry.

Figures 23, 24, and 25 demonstrate the close correspondence between differences in wave V latency and $R_m - L_m$. The figures show that, as the value of $R_m - L_m$ decreases, the right/left wave V latency difference also decreases. The shapes of the two functions are remarkably similar. Figure 26 shows data from two subjects in which

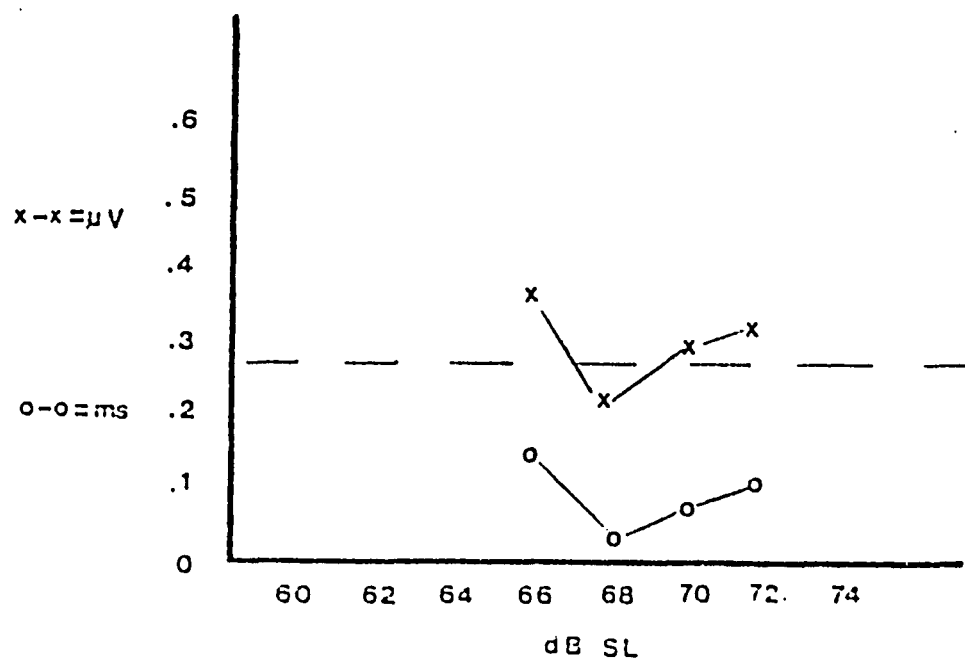
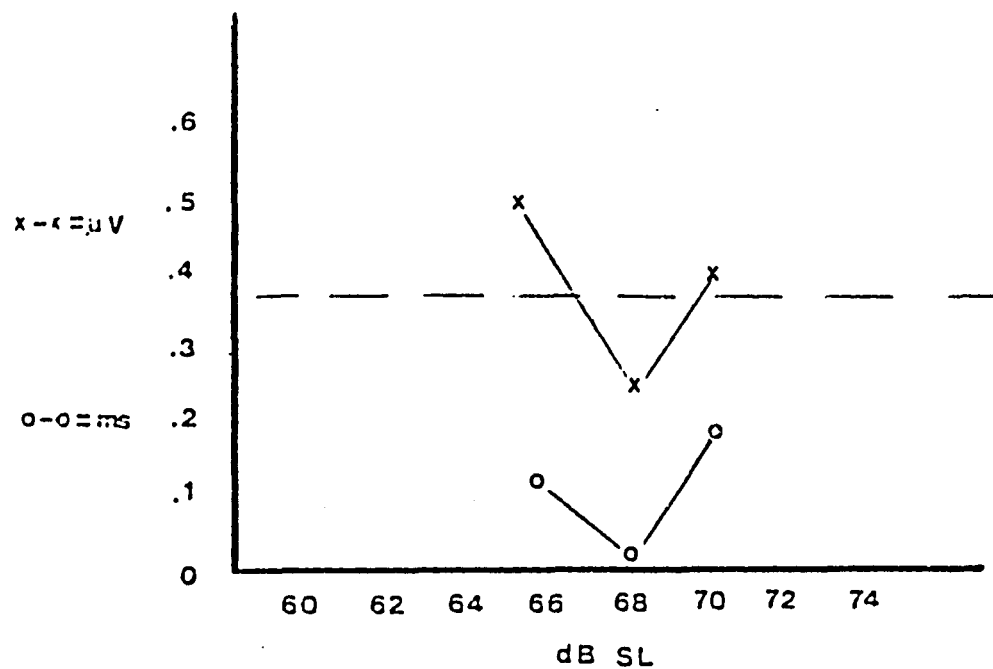


Figure 23. Rm - Im amplitudes (x-x) and wave V latency differences (o-o) for 2 subjects whose Rm - Im was reduced below criterion for asymmetry (dashed line).

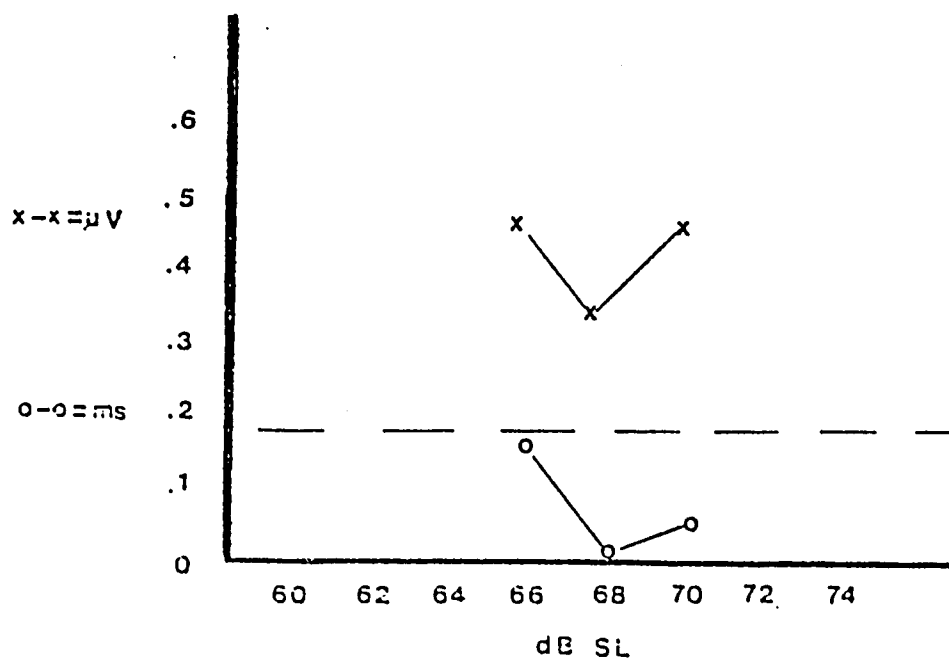
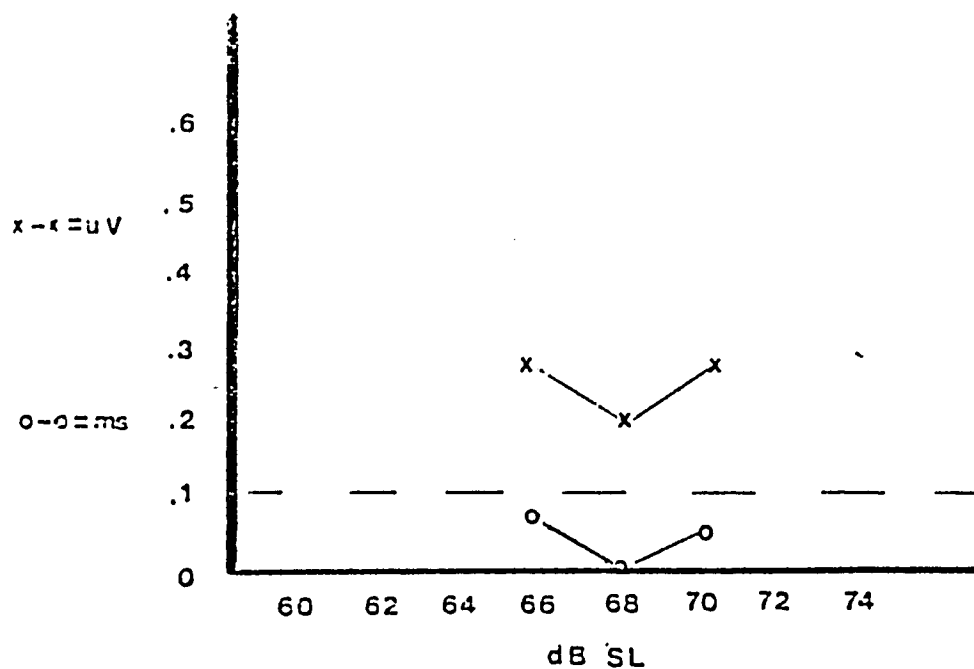


Figure 24. Rm - Lm amplitudes (x-x) and wave V latency differences (o-o) for 2 subjects whos Rm - Lm was reduced, but not below criterion for asymmetry (dashed line).

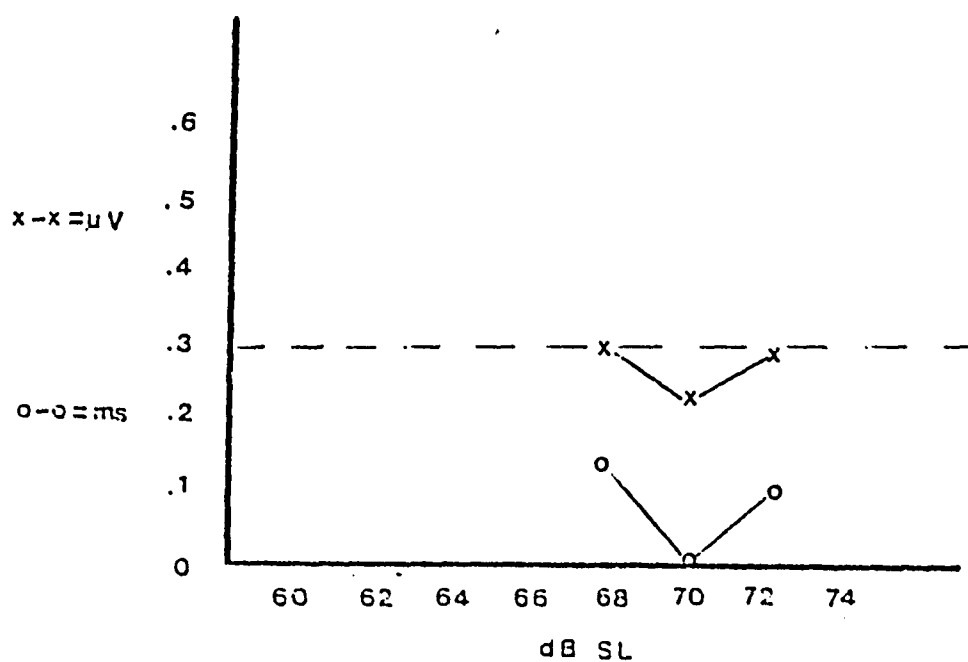
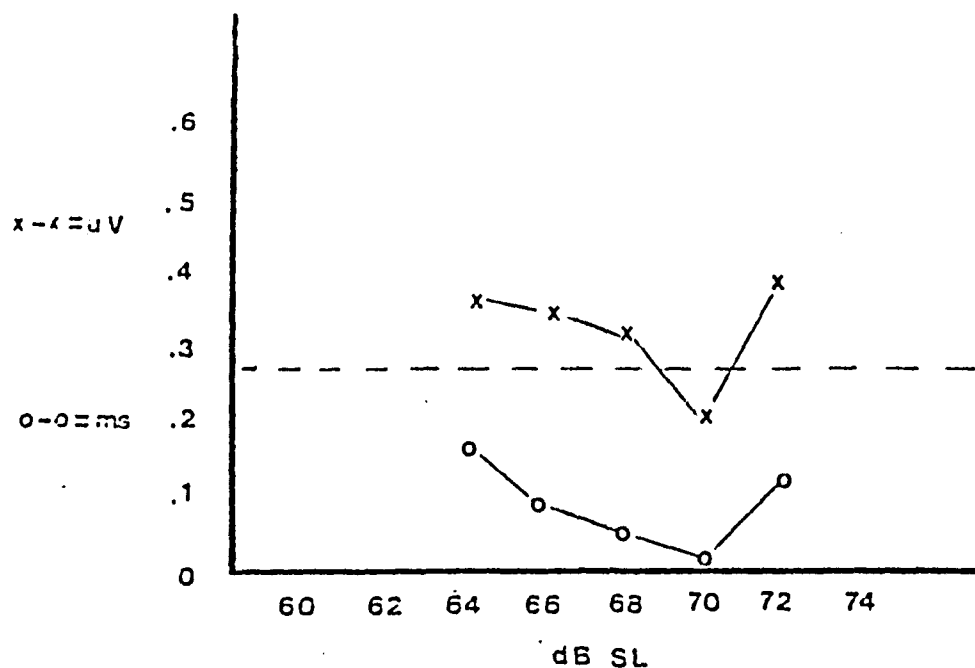


Figure 25. Rm - Lm amplitudes (x-x) and wave V latency differences (o-o) for 2 subjects classified as symmetrical. The dashed line represents criterion for asymmetry.

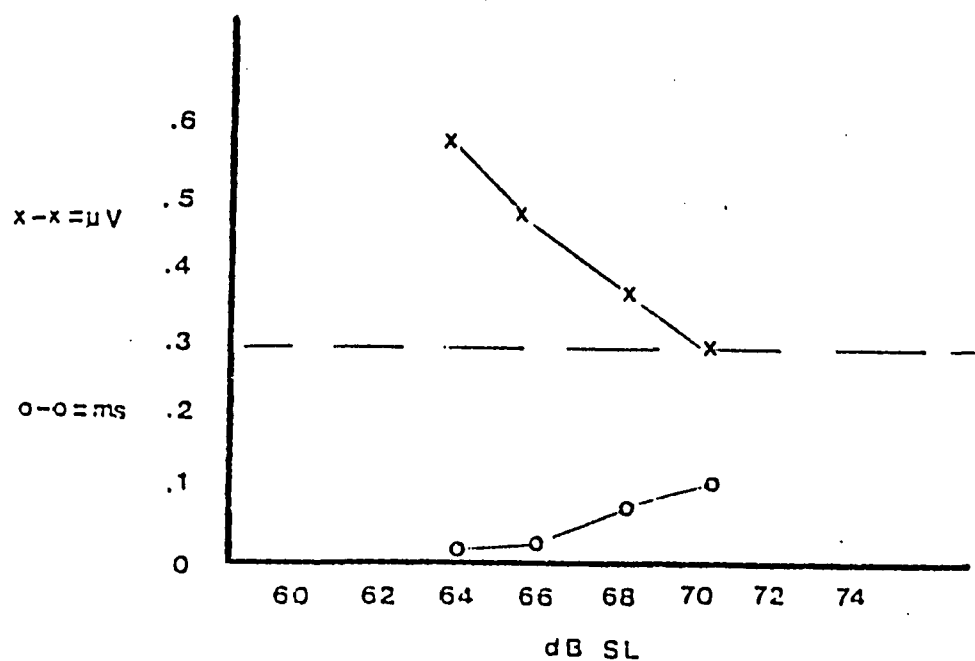
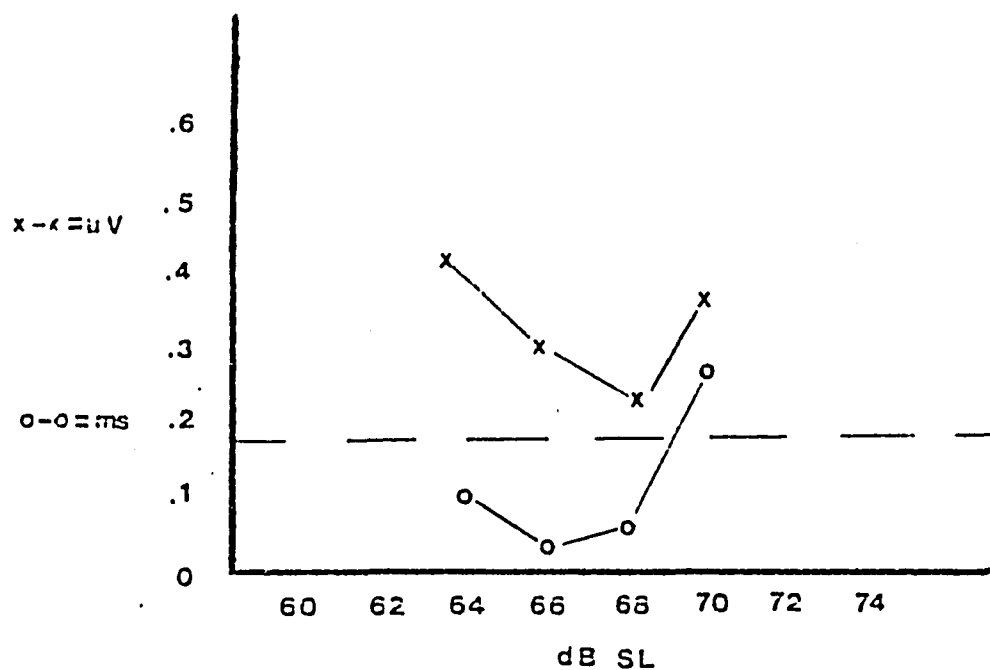


Figure 26 . Rm - Lm amplitudes (x-x) and wave V latency differences (o-o) for 2 subjects. The correlation between the two measures was poor for these subjects.

APPENDIX B

On-Line Criterion For Determination Of Asymmetry

The on-line method was an empirical method based on pilot data which was developed in order to provide a rapid on-line determination of significant right/left difference. The null hypothesis stated that the result of subtracting the left from the right monaural response would be a difference trace which would not exceed the level of the residual noise in the BSAEP. In order to provide a conservative criterion for rejection of the null hypothesis, the noise floor in the BSAEPs of each subject was estimated and multiplied by a factor of 1.5. In order for the $R_m - L_m$ difference trace to be considered significantly different from the background noise, the peak-to-peak amplitude of $R_m - L_m$ must exceed this empirically determined criterion.

The critical value (1.5) was justified in a post hoc analysis (Boothroyd, 1984). The standard deviations of the $R_m - L_m$ difference trace and the background noise (NSC) was estimated from the responses of six subjects on the basis of the interquartile range. The ratio of the standard deviations were evaluated statistically using the F distribution (Picton et al., 1983; Wong and Bickford, 1980). The number of degrees of freedom among the 154 points which comprise the waveform within the 6

ms analysis window were estimated by assuming that points lying one half cycle apart are independent of each other. Since the bandwidth of the system is 2,854 Hz, one cycle is equal to .35 ms. Therefore, the response time is equal to .17 ms. Within a 6 ms window, there are 35 half cycles ($6 / .17$). Thus the estimate of degrees of freedom is 35. The critical F ratio for 35, 35 df = 2.21. The critical ratio of the standard deviations, then is equal to the square root of 2.21, or 1.49 (rounded to 1.5). This method of estimating degrees of freedom in an evoked potential waveform has support in the literature (Wong and Bickford, 1980; Picton et al., 1983).

Thus, in order for the Rm - Lm difference trace to be considered significantly different from the background noise, the standard deviation of the difference trace must exceed the standard deviation of the NCR by a factor of 1.5. The use of the standard deviation for the purpose of determining significant difference, however, was precluded by the length of time involved in calculating the S.D. for each difference trace (an average of 8 difference traces per subject). A practical solution to this problem is to measure the largest peak to peak amplitude in the NCR and compare it to the largest peak to peak amplitude in the Rm - Lm difference trace. The substitution of the peak to peak measurement for the standard deviation requires the

assumption that the peak to peak measurement is proportional to the standard deviation:

$$p-p = k \times S.D.$$

$$\text{ratio of } p-p = p-p_2/p-p_1 = k \text{ SD}_2/k \text{ SD}_1 = \text{SD}_2/\text{SD}_1 = 1.5$$

In order to test the validity of this assumption, the S.D. was estimated from the interquartile range of the NSC from 6 subjects. The equation above was then solved for k : $k = p-p / S.D.$ Table 14 shows the estimated S.D. of the NSC, the peak to peak amplitude (P-P) of the NSC, and value of k for 6 subjects. The range of k values (the ratio of the highest to the lowest value) was found to be small (1.67) indicating that, while there was some variation in k , the $p-p$ measurement could be considered to be proportional to the standard deviation.

In order to protect against variations in k , the criterion of 1.5 can be multiplied by the square root of 1.67 (the range of k). This turns out to be overly conservative, however, for the following reasons.

Protection against variations in k come from two sources:

- 1) Since the NSC represents one run (2,048 samples) and the $R_m - L_m$ represents the average of 2 runs (4,096 samples), the NSC is comprised of 1/2 the number of samples of the $R_m - L_m$. Since the standard deviation of the average decreases by the square root of the number

TABLE 14

Estimated standard deviations (S.D.), peak to peak amplitudes (P-P), and K values for the no stimulus control runs from six subjects.

SUBJ	ESTIMATED S.D.	P-P	K
	NSC (uV)	(uV)	
JK	.044	.21	4.77
LG	.044	.23	5.23
MDS	.030	.18	6.00
SM	.030	.16	5.33
DF	.022	.15	6.81
DR	.022	.09	4.09

of samples in the average, the expected ratio of S.D.s under the null hypothesis is equal to one divided by the square root of 2, or 1.41. Thus, the increase in the critical value in order to account for the range of k, is more than offset by correcting for the differences in numbers of sweeps between $R_m - L_m$ and NSC:

$$1.5 \times \text{SQRT } 1.67 \times 1/\text{SQRT } 2 = 1.37$$

2) Due to the random nature of the background noise, it was expected that the amplitude distribution of the NSC would approximate a gaussian distribution. On the other hand, the amplitude distribution of a real response would be expected to be flatter and broader. Consequently, the standard deviation of the response amplitude distribution has a larger variance than that of the NSC. Thus the ratio of p-p / S.D. in the case of a real response would be reduced. This would have the effect of reducing p-p2 / p-p1.

The critical ratio of 1.5, therefore, is conservative as an estimate of the .01 level of confidence. If the peak to peak amplitude of the $R_m - L_m$ exceeded the peak to peak amplitude of the NCR by a factor of 1.5, then the $R_m - L_m$ was considered to significantly exceed the noise floor and indicate a real difference between the right and left responses.

The validity of the on-line criterion was tested in a

post hoc analysis. The results obtained with the on-line method were compared with the results obtained using a statistical method with good face validity.

Statistical Criterion for Asymmetry

Inter-ear differences in the BSAEP were measured in 3 different ways 1) $R_m - L_m$ (right monaural response minus left monaural response), 2) inter-ear wave V latency differences, 3) inter-ear wave V amplitude differences. The null hypothesis stated that there are no significant differences between right and left ear BSAEPs for any of the above measurements and any observed differences are due to random variability attributable to noise. In order to establish a statistical criterion for rejection of the null hypothesis, an estimate of the error term in each measurement was determined from the difference between the first and second runs of each condition. The difference between these two measurements indicated the amount of run-to-run variability present in the responses of each subject. These data are presented in Table 15. Inspection of these data revealed that the run-to-run variability for the three types of measurements, $R_m - L_m$, wave V latency, and wave V amplitude was small. Inter-run measurement variability tended to increase when the stimulus level was lowered from 70 to 50 dB SL.

Having determined the error term for each of the three measurements for each subject, the standard error of the mean was calculated for each measurement (Table 16). According to the normal distribution, right and left ear responses were significantly different at the .05 level of confidence if the difference exceeded $2.779 \times \sigma_e$. The data from 24 subjects were analysed according to these criteria. When the right - left difference exceeded the criterion, the responses were categorized as asymmetrical. When the right - left difference fell below the criterion, the responses were categorized as symmetrical. Table 17 shows how the responses of each subject were categorized as a function of these criteria.

It was notable that, according to the statistical criterion for a significant $R_m - L_m$ difference, all subjects at both intensity levels fell into the asymmetrical category. This was a strong indication that the on-line criterion ($1.5 \times NSC$) was a very conservative criterion for asymmetry. When inter-ear wave V latency was used to determine asymmetry, the distribution of symmetrical and asymmetrical subjects was identical to the distribution obtained using the on-line criterion (7 symmetrical, 17 asymmetrical). With only 2 exceptions, each subject's responses were categorized the same way in $91.96 \times \sqrt{2}$

TABLE 15

Differences between Run #1 and Run #2

measurements for Rm - Lm amplitude, right and left ear
wave V latency, right and left ear wave V amplitude.

70 dB SL

SUBJ	Rm-Lm (uV)	<u>LATENCY (ms)</u>		<u>AMPLITUDE (uV)</u>	
		R	L	R	L
SS	.14	.00	.08	.10	.01
SM	.05	.00	.00	.04	.07
JD	.01	.08	.08	.04	.05
RO	.14	.00	.04	.10	.06
HS	.01	.00	.00	.03	.06
SC	.05	.00	.00	.05	.08
JM	.01	.00	.00	.00	.08
JS	.01	.06	.08	.10	.03
VV	.01	.04	.00	.06	.02
BD	.02	.00	.00	.02	.03
LC	.03	.04	.00	.09	.01
DR	.14	.00	.08	.10	.00
EA	.13	.00	.00	.01	.09
DF	.00	.04	.00	.02	.11
DZ	.01	.00	.00	.00	.01
MD	.01	.00	.00	.06	.22
MDS	.11	.02	.00	.19	.06
SP	.15	.00	.04	.02	.04
LG	.01	.00	.00	.14	.02
LK	.01	.00	.04	.05	.13
KO	.05	.00	.04	.00	.04
CB	.09	.00	.00	.03	.09
GG	.05	.00	.00	.08	.06
JK	.11	.00	.00	.17	.05

TABLE 15 (cont.)

50 dB SL

	<u>LATENCY (ms)</u>		<u>AMPLITUDE (uV)</u>		
<u>SUBJ</u>	<u>Rm-Lm (uV)</u>	<u>R</u>	<u>L</u>	<u>R</u>	<u>L</u>
SS	.09	.04	.04	.01	.01
SM	.07	.12	.12	.07	.05
JD	.02	.12	.04	.00	.07
RO	.05	.00	.04	.03	.02
HS	.03	.04	.04	.03	.01
SC	.08	.04	.04	.12	.07
JM	.04	.00	.00	.01	.12
JS	.00	.04	.16	.28	.05
VV	.03	.08	.04	.13	.11
BD	.04	.00	.04	.17	.00
DR	.05	.04	.08	.06	.05
EA	.03	.08	.04	.38	.12
DF	.04	.00	.00	.04	.11
DZ	.17	.00	.02	.16	.05
MD	.02	.02	.04	.02	.04
MDS	.03	.08	.04	.03	.06
SP	.00	.04	.02	.01	.02
LG	.09	.06	.04	.01	.06
LK	.05	.04	.00	.05	.25
KO	.01	.00	.04	.04	.08
CB	.03	.00	.04	.04	.01
GG	.03	.04	.08	.08	.05
JK	.11	.00	.00	.03	.02

TABLE 16

The standard error of the mean ($N = 24$) for Rm - Lm, wave V latency difference, and wave V amplitude difference. The criterion for significant right/left difference was determined by multiplying the standard error of the mean by 2.77 ($1.96 \times \sqrt{2}$).

	<u>dB SL</u>	<u>$\bar{\sigma}$</u>	<u>CRITERION</u>
Rm-Lm (uV)	70	.038	.11 uV
	50	.033	.09 uV

Wave V	70	.011	.03 ms
Latency (ms)	50	.029	.08 ms

Wave V	70	.040	.11 uV
Amplitude (uV)	50	.045	.12 uV

TABLE 17

Categorization of right and left BSAEPs as symmetrical (S) or asymmetrical (A) as a function of measurement and criterion. Right - Left measurements are presented for each subject. The parenthesis following the measurement indicates whether the measurement exceeded the criterion for significant right/left difference (A), or did not exceed the criterion for significant difference (S). The second to the last column indicates the subject's original classification using the NSC x 1.5 criterion. The last column indicates the type of asymmetry, when asymmetry is present. Asymmetry was classified as congruent (CON), incongruent type A (IA), incongruent type B (IB) or incongruent type C (IC). An asterisk indicates that morphological asymmetry was also present.

70 dB

SUBJ.	Rm - Lm (uV)	V LATENCY (ms)	V AMPLITUDE (uV)	ORIG.	TYPE
LK	.30 (A)	.06 (A)	.13 (A)	A	IA
DF	.44 (A)	.14 (A)	.13 (A)	A	IA
KO	.44 (A)	.08 (A)	.02 (S)	A	IB*
GG	.40 (A)	.20 (A)	.01 (A)	A	IB*
EA	.41 (A)	.16 (A)	.10 (S)	A	IB
JK	.45 (A)	.12 (A)	.26 (A)	A	CON*
LG	.46 (A)	.20 (A)	.12 (A)	A	IA
DZ	.55 (A)	.20 (A)	.12 (A)	A	CON
SP	.33 (A)	.06 (A)	.03 (S)	A	IB
CB	.49 (A)	.20 (A)	.28 (A)	A	CON*
MD	.23 (A)	.00 (S)	.07 (S)	S	-
MDS	.26 (A)	.00 (S)	.11 (S)	S	-
DR	.36 (A)	.24 (A)	.04 (S)	A	IB*
HS	.14 (A)	.04 (A)	.05 (S)	A	IB
SC	.30 (A)	.20 (A)	.07 (S)	A	IB*
VV	.32 (A)	.10 (A)	.00 (S)	S	IB
LC	.44 (A)	.02 (S)	.14 (A)	A	IC*
SM	.25 (A)	.12 (A)	.11 (S)	A	IB
SS	.31 (A)	.04 (A)	.08 (S)	A	IB
JM	.36 (A)	.24 (A)	.10 (S)	A	IB
BD	.23 (A)	.00 (S)	.07 (S)	S	-
JD	.20 (A)	.02 (S)	.06 (S)	S	-*
JS	.25 (A)	.02 (S)	.01 (S)	S	-
RO	.30 (A)	.02 (S)	.17 (A)	S	IC*

TABLE 17 (cont.)

50 dB

<u>SUBJ.</u>	<u>Rm - Lm</u>	<u>V LATENCY</u>	<u>V AMPLITUDE</u>	<u>ORIG.</u>	<u>TYPE</u>
	(uV)	(ms)	(uV)		
LK	.33 (A)	.06 (S)	.20 (A)	A	IC
DF	.50 (A)	.22 (A)	.07 (S)	A	IB*
KO	.29 (A)	.10 (A)	.11 (S)	S	IB
GG	.18 (A)	.04 (S)	.06 (S)	S	-
EA	.21 (A)	.14 (A)	.09 (S)	S	IB*
JK	.55 (A)	.44 (A)	.14 (A)	A	CON
LG	.23 (A)	.02 (S)	.19 (A)	S	IC
DZ	.39 (A)	.07 (S)	.07 (S)	A	-
SP	.15 (A)	.00 (S)	.04 (S)	S	-
CB	.43 (A)	.14 (A)	.18 (A)	A	CON*
MDS	.24 (A)	.02 (S)	.11 (S)	S	-
MD	.23 (A)	.04 (S)	.18 (A)	S	IC
DR	.36 (A)	.26 (A)	.04 (S)	A	IB*
HS	.11 (A)	.08 (S)	.04 (S)	S	IB
SC	.28 (A)	.40 (A)	.07 (S)	A	IB*
VV	.26 (A)	.08 (S)	.10 (S)	S	-
LC	.19 (A)	.04 (S)	.04 (S)	A	-*
SM	.15 (A)	.06 (S)	.07 (S)	S	-
SS	.15 (A)	.12 (A)	.06 (S)	A	IB
JM	.19 (A)	.04 (S)	.13 (S)	S	-
BD	.23 (A)	.22 (A)	.03 (S)	S	IC
JD	.21 (A)	.28 (A)	.27 (A)	S	CON*
JS	.29 (A)	.02 (S)	.01 (S)	S	-
RO	.31 (A)	.10 (A)	.04 (S)	A	IB

which they were categorized using the on-line criterion. Using wave V amplitude as the determining measure, however, resulted in many more subjects being classified as symmetrical (16 symmetrical, 8 asymmetrical).

Results obtained at 50 dB were similar to those obtained at 70 dB. Categorization of 50 dB responses by means of wave V latency differences resulted in a nearly identical distribution of symmetrical and asymmetrical subjects (13 symmetrical, 11 asymmetrical) as was found using the on-line criterion (14 symmetrical, 10 asymmetrical). It was noted, however, that three subjects who were categorized as asymmetrical according to the on-line criterion, were categorized as symmetrical according to the statistical criterion. Balancing this shift from asymmetrical to symmetrical, however, were four subjects who were classified as symmetrical according to the on-line criterion, but who were classified as asymmetrical according to the statistical criterion for significant inter-ear wave V latency difference. As was the case for the 70 dB data, inter-ear wave V amplitude differences substantially underestimated the number of asymmetrical responses.

The categorization of subjects as either symmetrical or asymmetrical by the on-line method was most closely approximated by the statistical method which

employed wave V latency as the determining measure. This suggested that the amplitude of the Rm - Lm difference trace, which was used as the determining measure in the on-line method, was primarily influenced by wave V latency differences and not by wave V amplitude differences. A Pearson product moment correlation revealed that, in fact, Rm - Lm amplitude (5 - 8 ms window) was positively correlated with wave V latency differences ($r = .58$, $p < .01$ at 70 dB, $r = .54$, $p < .01$ at 50 dB). However, Rm - Lm amplitude was not highly correlated with wave V amplitude ($r = .39$, $p > .05$ at 70 dB, $r = .10$, $p > .05$ at 50 dB). Thus, right and left responses which had significant wave V latency differences were more likely to be categorized as asymmetrical when the on-line criterion was used.

Comparing the incidence of wave V latency asymmetries and wave V amplitude asymmetries, it was found that wave V latency differences accounted for the majority of asymmetries. While wave V latency asymmetries were found in 71% of all subjects at 70 dB and 42% of all subjects at 50 dB, significant wave V amplitude differences were found in only 33% of subjects at 70 dB and 25% of the subjects at 50 dB. Significant wave V latency asymmetries were accompanied by significant wave V amplitude asymmetries in 35% of the subjects at 70 dB

and 18% of the subjects at 50 dB. Wave V amplitude asymmetries occurred without a corresponding wave V latency asymmetry in only 2 subjects at 70 dB (8%) and 3 subjects at 50 dB (13%).

The relationship between wave V amplitude and latency differences has implications for the use of interaural stimulus differences for the purpose of offsetting the asymmetry. Four situations were outlined in Chapter 3 which described the possible combinations of latency and/or amplitude asymmetries. Congruent asymmetries had the expected latency-amplitude relationship, i.e. short latencies accompanied by large amplitudes. These were simple asymmetries which could be explained by slight differences in intensity attributable to the stimulus or to peripheral asymmetries causing a difference in the effective intensity reaching the cochleae. It was predicted that these simple asymmetries would be most easily correctable by means of the interaural intensity manipulations. More complex latency-amplitude relationships that violated the expected relationship between latency and amplitude were called incongruent asymmetries. These were subdivided into 3 categories: A) short latencies accompanied by small amplitudes, B) latency asymmetry with equal amplitudes, C) amplitude asymmetries with equal latencies. The final column of Table 17 indicates the

type of asymmetry present based on the relationship between wave V latency and amplitude differences.

APPENDIX C

In order to insure the equality of the right and left earphones, BSAEPs were recorded from four pilot subjects under the following three conditions. Right ear/ Left earphone (Reversed), Right ear/ Right earphone (Run 1), and Right ear/ Right earphone (Run 2). The stimulus was a 100 microsecond click, presented at 70 dB SL, at a rate of 11 per second. All recording conditions were identical to those described in Chapter 3. Latency and amplitude measurements for waves I through VI under each condition are presented in Table 18. Mean differences between conditions are presented in Table 19.

TABLE 18

Latency in milliseconds and amplitudes in microvolts of waves I through VI for three different conditions: earphones reversed (Revs.), earphones normal (Run 1 and Run 2).

SUBJ	COND.	I		III		V		VI	
		Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp
		-----		-----		-----		-----	
LC	Revs.	1.64	.19	3.80	.45	5.72	.89	7.16	.49
	Run 1	1.60	.18	3.84	.49	5.72	.84	7.20	.49
	Run 2	1.60	.16	3.88	.45	5.76	.79	7.24	.59
		-----		-----		-----		-----	
CB	Revs.	1.72	.18	3.64	.33	5.56	.99	7.28	.14
	Run 1	1.72	.21	3.64	.30	5.52	.96	7.48	.19
	Run 2	1.72	.18	3.64	.41	5.56	1.05	7.32	.35
		-----		-----		-----		-----	
LG	Revs.	1.60	.30	3.60	.49	5.60	.71	7.28	.43
	Run 1	1.60	.40	3.56	.59	5.64	.80	7.24	.33
	Run 2	1.60	.33	3.60	.53	5.64	.78	7.36	.25
		-----		-----		-----		-----	
TN	Revs.	2.32	.16	3.96	.49	5.76	.55	7.32	.35
	Run 1	2.32	.16	3.88	.49	5.76	.54	7.32	.34
	Run 2	2.24	.20	4.00	.49	5.76	.65	7.44	.30

TABLE 19

Mean differences in latency in milliseconds and amplitude in microvolts between Reversed and Run 1, and between Run 1 and Run 2.

COND.	I		III		V		VI	
	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp
Reversed-								
Run 1	.01	.035	.04	.043	.02	.045	.065	.04
Run 1 -								
Run 2	.02	.055	.050	.053	.02	.068	.11	.085

APPENDIX D

CATEGORIES OF MORPHOLOGICAL ASYMMETRY

Chiappa, Gladstone and Young (1979) described six normal variations of BSAEP morphology. They noted that among their 50 normal subjects, almost half had right and left BSAEPs with different morphological patterns. The description of the six patterns focused on variations in the shapes IV-V complex.

Pattern A. Wave IV and V are fused into a single peak in the usual wave V latency range.

Pattern B. Wave IV and V are separated with wave IV amplitude smaller than wave V amplitude.

Pattern C. Wave IV and V are separated with wave IV amplitude larger than wave V amplitude.

Pattern D. Wave V consists of a small shoulder on the downward slope of a large wave IV.

Pattern E. Wave IV consists of a small shoulder on the upward slope of a large wave V.

Pattern F. Wave IV and V are equal in amplitude.

APPENDIX E

Mean peak latency and amplitude data and standard deviations are presented for 24 subjects. Data in Tables 20 and 21 are categorized as follows: male (M), female (F), monaural right ear (R), monaural left ear (L), and binaural (B). Data for 70 dB SL stimuli are contained in Table 20; data for 50 dB SL stimuli are contained in Table 21. Tables 22 through 33 present data which were reorganized according to right vs. left, or leading vs. lagging responses for symmetrical and asymmetrical subjects separately.

TABLE 20
MEAN DATA - 70 dB

LATENCY-MS

	I		III		V	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
M -R	1.70	.11	3.73	.12	5.78	.17
M -L	1.67	.09	3.73	.10	5.75	.15
M -B	1.69	.11	3.75	.11	5.70	.21

F -R	1.71	.10	3.67	.15	5.58	.15
F -L	1.72	.11	3.65	.21	5.57	.23
F -B	1.71	.09	3.67	.19	5.61	.18

=====

AMPLITUDE-uV

M -R	.14	.06	.29	.16	.62	.16
M -L	.12	.04	.22	.11	.58	.17
M -B	.28	.10	.49	.25	.98	.31

F -R	.17	.06	.29	.10	.62	.15
F -L	.19	.05	.27	.14	.67	.18
F -B	.34	.10	.47	.21	1.31	.35

TABLE 21
MEAN DATA - 50 dB

LATENCY-MS

	I		III		V	
	X	SD	X	SD	X	SD
M -R	2.23	.20	4.23	.24	6.29	.25
M -L	2.23	.26	4.30	.25	6.23	.18
M -B	2.23	.28	4.20	.19	6.18	.15

F -R	2.09	.33	4.17	.26	6.08	.25
F -L	2.10	.26	4.07	.32	6.06	.24
F -B	2.18	.21	4.15	.24	6.02	.26

=====

AMPLITUDE-uV

M -R	.07	.04	.15	.09	.43	.19
M -L	.13	.10	.11	.06	.46	.16
M -B	.12	.06	.24	.15	.77	.36

F -R	.11	.06	.13	.07	.57	.12
F -L	.12	.06	.11	.04	.53	.14
F -B	.19	.07	.20	.08	.99	.23

TABLE 22

Mean amplitudes (μV) for right vs. left ear responses for asymmetrical subjects at 70 dB SL ($n = 17$).

	I			III			V		
	X		SD	X		SD	X		SD
R	.16		.08	.27		.13	.62		.17
L	.16		.07	.25		.14	.65		.21

TABLE 23

Mean latencies (ms) for leading vs. lagging ear responses for asymmetrical subjects at 70 dB SL ($n = 17$).

	I			III			V		
	X		SD	X		SD	X		SD
Lead	1.70		.11	3.67		.16	5.60		.20
Lag	1.73		.11	3.77		.16	5.75		.22

TABLE 24

Mean amplitudes (μV) for leading vs. lagging ear responses for asymmetrical subjects at 70 dB SL ($n = 17$).

	I			III			V		
	X		SD	X		SD	X		SD
Lead	.16		.07	.26		.14	.64		.22
Lag	.17		.07	.26		.12	.62		.16

TABLE 25

Mean latencies (ms) for right vs. left ear responses for symmetrical subjects at 70 dB SL (n = 7).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	1.70		.10	3.66		.12	5.69		.20
L	1.68		.11	3.63		.15	5.67		.19

TABLE 26

Mean amplitudes (uV) for right vs. left ear responses for symmetrical subjects at 70 dB SL (n = 7).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	.15		.05	.34		.15	.63		.18
Left	.14		.03	.24		.15	.60		.15

TABLE 27

Mean latencies (ms) for right vs. left ear responses for asymmetrical subjects at 70 dB SL (n = 7).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	1.71		.12	3.72		.15	5.69		.20
Left	1.71		.11	3.71		.18	5.67		.65

TABLE 28

Mean latencies (ms) for right vs. left ear responses for symmetrical subjects at 50 dB SL (n = 14).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	2.17		.30	4.21		.28	6.23		.28
L	2.17		.30	4.21		.30	6.23		.22

TABLE 29

Mean amplitudes (uV) for right vs. left ear responses for symmetrical subjects at 50 dB SL (n = 14).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	.10		.06	.15		.09	.45		.15
L	.11		.06	.10		.05	.43		.12

TABLE 30

Mean amplitudes (uV) for right vs. left ear responses for asymmetrical subjects at 50 dB SL (n = 10).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	.08		.04	.14		.07	.56		.20
L	.11		.04	.12		.06	.59		.17

TABLE 31

Mean latencies (ms) for right vs. left ear responses for asymmetrical subjects at 50 dB SL (n = 10).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
R	2.19		.26	4.20		.24	6.12		.28
L	2.16		.26	4.12		.34	6.04		.22

TABLE 32

Mean latencies (ms) for leading vs. lagging ear responses for asymmetrical subjects at 50 dB SL (n = 10).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
Lead	2.09		.28	4.11		.33	5.99		.23
Lag	2.31		.09	4.21		.24	6.17		.24

TABLE 33

Mean amplitudes (uV) for leading vs. lagging ear responses for asymmetrical subjects at 50 dB SL (n = 10).

	I			III			V		
	$\bar{X}$		SD	$\bar{X}$		SD	$\bar{X}$		SD
Lead	.11		.04	.10		.04	.61		.18
Lag	.09		.05	.15		.08	.54		.18

APPENDIX F

SUMMARY OF OPERATIONAL DEFINITIONS AND TERMS

On-line Criterion for Asymmetry-This was an empirical method for determining significant right/left difference. The peak-to-peak amplitude of the no stimulus control run (NSC) was multiplied by 1.5.

Statistical Criterion for Asymmetry-This was based on the run-to-run measurement variability. The standard error of the mean was calculated for wave V latency and amplitude measurements.

Natural Asymmetry-The peak-to-peak amplitude of $R_m - L_m$ was greater than the on-line criterion which was determined for each subject.

Induced Symmetry-Responses of naturally asymmetrical subjects were made to approximate symmetry by means of an interaural intensity difference.

Natural Symmetry - The peak-to-peak amplitude of $R_m - L_m$ fell below criterion for significant right/left difference when stimuli were presented at equal sensation levels to each ear.

Congruent Asymmetry-Significant right/left difference in which the response with the shorter latency had the larger amplitude (and vice versa).

Incongruent Asymmetry-Significant right/left difference in which the expected latency/amplitude relationship (i.e. congruent) did not exist.

Type A. Shorter latency/smaller amplitude.

Type B. Equal amplitudes/different latencies.

Type C. Equal latency/different amplitudes.

Morphological Asymmetry-Right and left monaural responses from the same subject were classified into different morphological categories, after Chiappa et al., 1979.

Preferred Response-The monaural response which, when doubled, most resembles the binaural response (after Decker and Howe, 1981).

R_m - L_m -Right monaural response minus the left monaural response.

R_m - L_m' - Right monaural response minus the left monaural response after the interaural intensity

manipulation.

IAID- Interaural intensity difference.

Asymmetry Ratio (AR)-The peak-to-peak amplitude of $R_m - L_m$ divided by the subject's criterion for asymmetry.

Residual Component (RC)-The result of subtracting the binaural response from the summed monaural responses.

Adjusted Residual Component (ARC)-The result of subtracting the binaural response from the summed monaural responses after the interaural intensity manipulation.

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