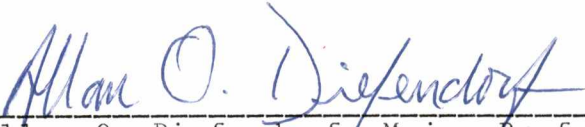
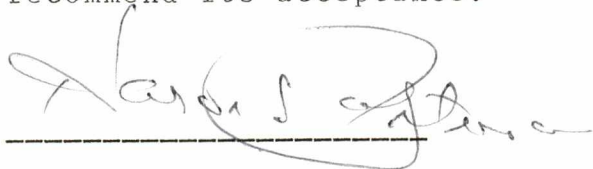


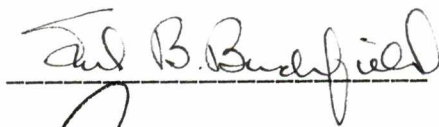
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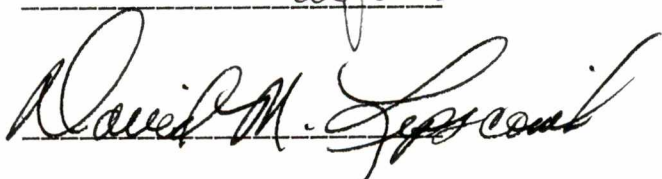
I am submitting herewith a dissertation entitled "The Relationship Between Auditory Brainstem Response Intensity Functions and Loudness." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Hearing and Speech Sciences.

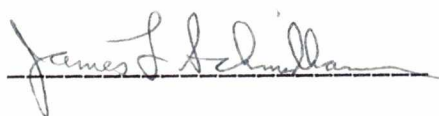

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We have read this
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recommend its acceptance:









Accepted for the Council:



Vice Provost
and Dean of The Graduate School

THE RELATIONSHIP BETWEEN AUDITORY BRAINSTEM
RESPONSE INTENSITY FUNCTIONS AND LOUDNESS

A Dissertation
presented for the
Doctor of Philosophy
degree
The University of Tennessee.

Patricia Wojciak Earl

August 1987

DEDICATION

This dissertation is dedicated to Dr. Larry J. Lovering who taught me to strive for excellence in clinical audiology.

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ABSTRACT

ABR wave I and wave V intensity-latency and intensity-amplitude functions and loudness estimation functions were obtained from eight normally hearing and eight hearing impaired listeners in a sound field situation. Data were collected from the hearing impaired listeners under three conditions of amplification: none, amplification with compression circuitry, and linear amplification. ABR and loudness functions were examined to determine if a relationship existed between the electrophysiological and psychophysical data. It was also determined if the use of compression amplification caused intensity functions generated by hearing impaired listeners to normalize.

When comparisons of F values were made, none of the ABR data produced the same statistical results across amplification conditions as the magnitude estimation data and no clear relationship was inferred. Although data from compression aided hearing impaired listeners tended to approach mean values of the normally hearing group, analysis of variance revealed that statistically significant differences existed between groups for three of the dependent variables. In the case of the other two dependent variables, no statistically significant differences existed, but statistical non-significance also occurred when the hearing impaired listeners were

unaided. Correlational analysis revealed high correlations between magnitude estimation and wave V amplitude ($r=.73$) for normally hearing listeners and between magnitude estimation and wave I amplitude ($r=.73$) for compression aided hearing impaired listeners. The strength of these correlations, however, would not permit the use of either ABR intensity-amplitude function to predict loudness growth.

Although this study did not rule out the use of the ABR test procedure to fit hearing aids, assumptions about aided loudness perception should not be made based on information from the intensity functions. In a few cases, the ABR intensity functions appeared to be related to audiometric contour rather than to loudness perception.

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CHAPTER I

INTRODUCTION

The use of auditory brainstem response audiometry has been advocated in hearing aid assessment to provide information relevant to loudness restoration (Cox and Metz, 1980; Kiessling, 1982; Hecox, 1983; McPherson and Clark, 1983; and Mahoney, 1985). Various investigators (Kiessling, 1982; Hecox, 1983; and Mahoney, 1985) have examined auditory brainstem response (ABR) wave V intensity-latency (I-L) and intensity-amplitude (I-A) functions of hearing impaired subjects, and from that data, have suggested electroacoustic characteristics thought to be necessary for adequate loudness perception. However, different investigators (Pratt and Sohmer, 1977; and Wilson and Stelmack, 1982) have cautioned against the use of electrophysiological data to predict loudness growth. Since restoration of loudness is a goal in hearing aid assessment, continued research is required to determine if features of the ABR are related to the loudness growth function.

Hecox (1983) examined suprathreshold auditory function to characterize dynamic range of hearing by recording ABR wave V I-L functions. Data were obtained from hearing impaired adults and children in unaided and aided

conditions. It was suggested that appropriate amplification caused aided wave V I-L functions to approach normal values. Hecox assumed that when abnormally steep I-L functions were made to approach normal values, loudness growth and loudness perception would become normalized.

Kiessling (1982) examined ABR wave V I-A functions in the unaided condition to estimate dynamic range of hearing in normal and various pathologic ears. In this study projection diagrams were used to determine dynamic range of hearing and in the cases of impairment, specify certain amplification characteristics. The author assumed that wave V amplitude was correlated with loudness growth and loudness perception and that an appropriate hearing aid would allow near normal amplitude values to be recorded.

In a review of current literature in the area of ABR application to hearing aid selection, Mahoney (1985) stated that wave V threshold information is of limited value and did not advocate this measure. He suggested assessment of gain at a suprathreshold level and generation of I-L functions using various frequency and compression settings to establish those which bring the I-L function closest to normal values. Although he included the use of the I-L function in his hearing aid selection procedure, Mahoney noted that the basic premise that normal I-L slope suggests normal dynamic loudness

function has not been demonstrated.

Different investigations (Pratt and Sohmer, 1977 and Wilson and Stelmack, 1982) have suggested that there is no correlation between electrophysiological responses and subjective responses to changes in intensity. These investigations were performed to determine if Steven's power law (1956) which applies to psychophysical phenomenon also applies to electrophysiological responses. If some feature of the electrophysiological response changes in the same manner as the subjective response when stimulus intensity increases, then the electrophysiological response could be considered the neural correlate of the psychophysical response.

Pratt and Sohmer (1977) examined correlations between intensity functions of the auditory evoked responses and psychophysical magnitude estimation (ME) functions for normally hearing young adults. While subjects made ME judgements of the loudness of various click intensities, auditory brainstem and cortical responses were recorded. As click intensity increased ME judgements increased, ABR latencies for waves I through V decreased and amplitudes increased. No systematic change in the cortical responses was noted. Exponents of the electrophysiological and psychophysical functions were examined to determine if correlations existed. Although the exponents for the I-A functions of the ABR waves I and II were similar to the

exponent for the ME function, none of the electrophysiological exponents showed significant similarity to the psychophysical exponent. The authors concluded that the electrophysiological responses which were examined in this study were not the neural correlates of the loudness estimate. Referring to a study by Carmon, Mor and Goldberg (1976), however, they suggested that a means of determining a better correlation between electrophysiological and psychophysical measures of intensity would have responses categorized and averaged according to the loudness estimate given by the subjects.

Wilson and Stelmack (1982) recorded ABR I-L and I-A functions for waves I, II, III, V and VI and loudness estimation functions of normally hearing subjects listening to click stimuli. Latency decreased while amplitude and loudness estimates increased at different rates with increasing stimulus intensity. Exponent values for the functions of individual subjects were used to determine correlations, however, none were significant. The authors concluded that the loudness function was not reflected in the ABR intensity functions, but noted that the reliability of their loudness estimates and the appropriateness of their statistical analyses "may be open to some question".

Although results of some investigations (Pratt and Sohmer, 1977; Wilson and Stelmack, 1982) suggest that

there is no correlation between psychophysical and electrophysiological intensity functions, other investigators (Kiessling, 1982; Hecox, 1983; and Mahoney, 1985) assume that electrophysiological intensity functions are related to loudness growth. This assumption may have originated from the work of Galambos and Hecox (1978). These authors reported that hearing impaired individuals exhibiting abnormally steep ABR wave V I-L functions also had positive signs for recruitment on various psychoacoustic tests.

It should be noted that no investigation of the relationship between electrophysiological data and subjective loudness growth has been performed with normally hearing and hearing impaired subjects. The use of hearing impaired individuals exhibiting abnormal psychophysical and electrophysiological intensity functions would provide more information about the relationships between these functions. Variations in the growth of the responses caused by the introduction of amplification could be compared to functions obtained in the unaided condition or to functions of those with normal hearing.

The purpose of this investigation was to examine the relationships between ABR wave I and V, I-L and I-A functions and the ME function of loudness. Specifically, it was determined if the use of amplification with and

without compression circuitry caused the intensity functions generated by hearing impaired individuals to more closely approximate the functions generated by normally hearing persons. Correlations between ME, I-L and I-A functions were also examined for normally hearing and hearing impaired groups.

CHAPTER II

EXPERIMENTAL QUESTIONS

The experimental questions were:

1. Was there a significant difference between the ABR wave I intensity-latency functions of normally hearing and hearing impaired individuals?
2. Was there a significant difference between the ABR wave V intensity-latency functions of normally hearing and hearing impaired individuals?
3. Was there a significant difference between the ABR wave I intensity-amplitude functions of normally hearing and hearing impaired individuals?
4. Was there a significant difference between the ABR wave V intensity-amplitude functions of normally hearing and hearing impaired individuals?
5. Was there a significant difference between the loudness growth functions of normally hearing and hearing impaired individuals?
6. Was there a significant difference between the ABR wave

I intensity-latency functions of normally hearing individuals, and hearing impaired individuals using compression and linear amplification?

7. Was there a significant difference between the ABR wave V intensity-latency functions of normally hearing individuals, and hearing impaired individuals using compression and linear amplification?

8. Was there a significant difference between the ABR wave I intensity-amplitude functions of normally hearing individuals, and hearing impaired individuals using compression and linear amplification?

9. Was there a significant difference between the ABR wave V intensity-amplitude functions of normally hearing individuals, and hearing impaired individuals using compression and linear amplification?

10. Was there a significant difference between the loudness growth functions of normally hearing individuals, and hearing impaired individuals using compression and linear amplification?

11. Was there a significant correlation between ME and I-A (Wave I and/or wave V) data for normally hearing subjects?

12. Was there a significant correlation between ME and I-L (Wave I and/or wave V) data for normally hearing subjects?

13. Was there a significant correlation between ME and I-A (Wave I and/or wave V) data for hearing impaired subjects?

14. Was there a significant correlation between ME and I-L (Wave I and/or wave V) data for hearing impaired subjects?

15. Was there a significant correlation between ME and I-A (Wave I and/or wave V) data for hearing impaired subjects using compression amplification?

16. Was there a significant correlation between ME and I-L (Wave I and/or wave V) data for hearing impaired subjects using compression amplification?

17. Was there a significant correlation between ME and I-A (Wave I and/or wave V) data for hearing impaired subjects using linear amplification?

18. Was there a significant correlation between ME and I-L (Wave I and/or wave V) data for hearing impaired subjects using linear amplification?

CHAPTER III

REVIEW OF THE LITERATURE

A. The auditory brainstem response

With the development of computer averaging techniques which improve signal-to-noise ratio when recording electrophysiological events, it has become possible to record the human ABR (Sohmer and Feinmesser, 1967). The ABR, a characteristic pattern of voltage changes representing neural activity from the cochlea to the medial geniculate body, has been shown to be stable, especially the latency of its components (Buchwald, 1983). This neural response is generated by presentation of a stimulus which has a very rapid onset or rise time. This abrupt stimulation causes the nerve fibers within the auditory nerve to respond in synchrony which gives rise to the characteristic voltage display. The voltage pattern has been described as a series of waves which occur within 10 milliseconds after stimulus onset and is labeled with Roman numerals from I to VII (Jewett and Williston, 1971).

This voltage pattern can be changed with respect to time (latency) and amplitude as the nature of the stimulus is manipulated. With increases in stimulus intensity more neural elements begin to fire and this is reflected in the ABR by decreases in latency and increases in amplitude.

The latency decrease occurs because a larger number of neural elements can carry the impulse more quickly. Amplitude increases because the larger the number of neural elements activated, the greater the voltage produced. It has been observed that the intensity effect is more variable on amplitude than latency (Picton, et al, 1974; Schwartz and Berry, 1985). When rise time of the stimulus is prolonged, a shift in latency, but not in amplitude of the ABR components is observed (Hecox, Squires and Galambos, 1976). A synchronous neural firing is necessary to record an ABR and this cannot occur when rise time is slow. Fall time has no effect on the ABR. The duration of the stimulus can effect ABR latency and amplitude, but only if there is insufficient neural recovery time before the onset of the next stimulus (Hecox, Squires and Galambos, 1976). Polarity of the stimulus has been shown to effect ABR latency and amplitude. Kevanishvili and Aphonchenko (1981) reported that for high intensity levels, the amplitude of waves II and IV were greater with rarefaction clicks while wave V amplitude was greater with condensation clicks. The latency of wave I was shorter with rarefaction clicks while the latency of all other waves was shorter with condensation clicks. These effects were very small and Kevanishvili and Aphonchenko (1981) concluded that neural triggering with rarefaction and condensation clicks

happens almost instantaneously. The repetition rate of the stimulus effects both latency and amplitude of the ABR. As rate increases the latencies of the component waves increase and the amplitudes, with the exception of wave V, decrease (van Olphen, Rodenburg and Verwey, 1979). If increased repetition rate prohibits sufficient neural recovery time, then asynchrony leads to increases in latency and decreases in amplitude of the ABR.

Because of the stable nature of the ABR and its systematic change with changes in stimulus characteristics, much research and subsequent clinical application have been carried out. Clinical procedures utilizing the ABR are used for hearing threshold assessment, differential diagnosis of hearing disorders, and otoneurological evaluation (Jacobson, 1985). The ABR test technique requires minimal patient cooperation and has been successfully used with patient populations, such as new born babies or the multiply handicapped, who might otherwise be regarded as untestable if behavioral test procedures were employed (Appendix 1).

A recent application of ABR has been made in the area of hearing aid evaluation. Since recording of the ABR is not contingent upon patient cooperation, use of this technique in hearing aid evaluation would allow for objective measurement of the effects of amplification in difficult to test patients. To date no definitive ABR

test paradigm for examining aided performance has been established, however, certain procedures have been proposed. Characteristics of the ABR which have been used to make comparisons between hearing aids include changes in wave V threshold, wave V latency and wave V amplitude.

Cox and Metz (1980) attempted to correlate wave V latency values and speech discrimination scores of eight hearing impaired subjects wearing behind-the-ear instruments. Wave V latency at 75 dB dial and speech discrimination scores for N.U. 6 words were obtained with subjects wearing their hearing aids at a comfortable listening level. Measurements were repeated with various frequency response adjustments. These data suggested that the hearing aid frequency response setting which produced the highest speech discrimination scores also produced the shortest wave V latency. Wave V threshold was also examined and the correlation with speech discrimination data was poor. It should be noted that subjects were separated into groups according to audiometric configuration and results were not identical between groups. An interesting finding in this study concerned the change in wave V latency when preferred gain setting was increased 10 decibels. No latency change was measured and the authors concluded that gain setting could be determined by finding the point where an increase in gain did not result in a further decrease in wave V latency.

Kileny (1982) presented case studies illustrating the effect of amplification on the auditory brainstem responses of children. He stated that a hearing aid could be considered effective if it caused an ABR to appear at stimulus intensity levels where there had not previously been a response. He noted in one case that after a certain hearing aid gain level was exceeded, no further decrease in wave V latency was observed. Since the ABR is thought to reflect a response from the high frequency basal end of the cochlea when moderate to high levels of stimulation are employed, Kileny suggested that damage to this area would prohibit further wave V latency change after all existing hair cells in that region had been stimulated.

Kiessling (1982) examined a procedure utilizing unaided wave V intensity-amplitude functions to determine hearing aid gain and compression characteristics. He assumed that the amplitudes of the ABR waves were correlated with loudness perception. Wave V amplitudes of a hearing impaired individual were recorded at several intensity levels and compared to amplitude norms. The differences between amplitude values for a hearing impaired individual and normative amplitude data were used in an equation to determine hearing aid gain and amount of compression. It was noted that the amount of compression derived from the equation was not always available in

commercially made hearing aids.

Hecox (1983) presented several case studies to demonstrate the use of the ABR to quantify dynamic range. Wave V intensity-latency functions were recorded in unaided and aided conditions. In the aided condition, subjects wore their hearing aids at their preferred gain settings. Hecox used the wave V latency values and descriptive slope of the intensity-latency function to suggest amount of improvement provided by the hearing aid. From illustrated case studies several conclusions were made regarding hearing impaired listeners and their amplification needs. These were:

1. The longer the wave V latency values, the greater the gain requirements for the hearing aid.
2. The steeper the intensity-latency function, the greater the chance that compression amplification will be needed.
3. In the aided condition, wave V latencies should be recorded at approximately 6 milliseconds with stimulus presentation level at 60 decibels.

McPherson and Clark (1983) examined suprathreshold measures which they felt to be important in hearing aid selection. They recorded behavioral and auditory brainstem responses in normally hearing adult subjects with simulated conductive hearing losses. Behavioral and ABR data were recorded at threshold, maximum comfort level

and loudness discomfort level in three sound field conditions: ears free from occlusion, ears occluded and ears occluded and aided. Changes in behavioral data between conditions were not necessarily seen in the ABR data. For example, a substantial behavioral threshold shift was seen between the first two conditions while the wave V latency shift was minimal. This may suggest that comparison of certain behavioral and electrophysiological measures cannot be made. Although McPherson and Clark recognized the limitations of their study, they proposed that with appropriate amplification, wave V latency at threshold would occur at 7.5 milliseconds and wave V latency at maximum comfort level would occur at 6.5 milliseconds. Average wave V latency was at 5.3 milliseconds with clicks presented at loudness discomfort level and it was suggested that a compression circuit limit hearing aid output so that wave V latency never occur at less than that value. These suggested values were considered inappropriate to use with infants and neurologically impaired individuals.

Mahoney (1985) summarized various ABR hearing aid evaluation procedures and suggested an approach which combined aspects of several procedures. In the suggested approach gain is set at the point where wave V latency stabilizes. With the gain adjusted, wave V intensity-latency functions are recorded at various

compression settings to determine the amount of compression which causes the intensity-latency function to approach normal values.

It was not the clinical procedure described by Mahoney (1985) that was the most interesting feature of his chapter, but rather certain clinical observations which merited his comments. He noted a rollover effect in the aided condition in which wave V latency decreased with increased amplification only up to a point, after which further increase in gain not only stabilized, but caused wave V latency to increase. Two reasons were given to explain this observation: As hearing aid output became saturated, increased gain produced distortion which degraded the click signal. Degradation caused prolonged rise time and resulted in increased wave V latency (Hecox, Squires and Galambos, 1976). This wave V latency shift might have also been due to electrophysiological degradation. The cochlea's output might have become saturated with high intensity stimulation and produced cochlear overload and reduced neural output. This, too, would be reflected in increased wave V latency.

In summary, several procedures utilizing the ABR to fit hearing aids have been suggested, but conclusions regarding a definitive approach cannot be made at this time. This is due to limitations of published studies to date. In all the studies a very small number of subjects

was used. In fact, Kileny (1982) and Hecox (1983) used only case studies to illustrate their procedures. The use of descriptive rather than experimental research designs limited conclusions made. Descriptive statistics reveal differences between subjects, but cannot ascertain if differences are statistically significant or due to sampling error. In cases where interesting observations were noted, subsequent studies which would permit statistical analyses of differences have not been found.

B. Magnitude estimation

Magnitude estimation (ME) is a procedure for measuring the relationship between the intensity of a stimulus and the perception of its magnitude. Prior to the development of this procedure by Stevens (1956, 1955) the assessment of perceptual magnitudes was accomplished by having subjects determine when a stimulus appeared half as or twice as great as a standard stimulus, or at some ratio with the standard (Kling and Riggs, 1971). It was Stevens who introduced a procedure which was the inverse of the method just described. In ME the levels of stimulus characteristic to be studied are predetermined and the subject specifies the ratio between them. Although Stevens applied ME to the measurement of various perceptions, much of his work was in the area of loudness perception.

From results of various experiments Stevens (1956,

1955) determined that when subjective responses were plotted on a log/log plot they formed a straight line. This indicated that loudness is a power function of intensity. It has been demonstrated that other perceptual magnitudes are also power functions. A general description for these functions is $P = kI^n$, where P equals perceived magnitude, k equals a constant, I equals intensity and n or the exponent indicates slope (Goldstein, 1980). This relationship is referred to as Stevens' Power Law.

Stevens (1956) described variations in experimental procedure, such as the use of only one presentation of a standard, no use of a standard or presentation of a standard at the extremes of an intensity range, which always resulted in the same outcome, that loudness was a power function of intensity. A later investigation (Stevens and Guirao, 1964) found that although the exponent may differ from person to person, the form of the psychophysical function remained invariant.

The loudness of click stimuli has been investigated because electrophysiological research using click stimulation has revealed certain relationships between neural events and intensity level. A magnitude estimation study of the loudness of clicks was performed by Raab and Osman (1962). Subjects listened to presentations of a single click over a range of intensities from 40 dB to 90

dB sensation level. It was found that the loudness of clicks was a power function of intensity, but click loudness grew less rapidly than loudness of sustained stimuli.

In studies of the growth of N1 amplitude, Taub and Raab (1969) and Charlet de Sauvage and Aran (1976) reported plateaus in intensity-amplitude functions at moderate levels. Cazals and Stephens (1975) examined the loudness of clicks to see if there was a psychophysical correlate to the N1 amplitude plateau. Loudness functions were obtained for clicks and tone bursts in normally hearing subjects using four measurement techniques: loudness estimation, loudness balancing, loudness production and reaction time. All four procedures revealed that the slopes of the loudness functions were similar. Only the loudness production experiment yielded some limited evidence of the plateau observed in electrophysiological tests.

Initially, ME procedures were used to quantify the perception of loudness in normally hearing individuals. More recent applications involve the hearing impaired. For example, Penner (1986) used a ME procedure to evaluate the loudness of tinnitus in individuals with sensorineural hearing loss. Another recent application of this procedure has been made in the area of amplification.

Geller and Margolis (1984) questioned the usefulness

of maximum comfort level (MCL) and loudness discomfort level (LDL) in hearing aid evaluation procedures. They cited literature which found that MCL and LDL values established by a listener could be changed depending upon the type of stimuli, psychophysical method or instructions used during testing and that these measures varied considerably between subjects. They stated that MCL and LDL were highly variable and represented a limited range of listening conditions.

Geller and Margolis (1984) assumed that amplification should restore normal perception for all auditory stimuli and suggested that a loudness scaling procedure, such as magnitude estimation, be employed in hearing aid evaluation procedures. Through a series of experiments with normally hearing subjects, the relationships between MCL, LDL and ME for loudness of tonal stimuli were examined. It was noted that a deviation from classical ME procedure was used in these experiments. Subjects were instructed to use a range of numbers between zero and 100 when estimating loudness. It was demonstrated that LDL was highly variable, changing as much as 26 dB within a subject and by as much as 44 dB between subjects. It was also demonstrated that MCL and LDL characterize loudness perception at isolated points along the continuum of the loudness experience, while ME data provided information along a broader range.

In two experiments Knight and Margolis (1984) examined the use of a magnitude estimation procedure to detect abnormal loudness growth. In the first experiment, normally hearing subjects and subjects with asymmetrical sensorineural hearing loss performed ME and alternating binaural loudness balance (ABLB) tasks. In the second experiment, the ME functions of normally hearing and presbycusic subjects were compared.

In experiment 1, abnormal loudness growth was demonstrated by both ABLB and ME procedures in subjects with asymmetrical hearing loss. In experiment 2, the presbycusic group had steeper ME functions than the normally hearing group, but statistically significant differences were observed at 6000 Hz only. It was suggested that ME be used to evaluate recruitment in subjects with bilateral hearing loss.

In ME data analysis slope estimates of the loudness growth functions were used. These estimates were calculated from the ME curves using the first derivative of the best-fit third degree polynomial at 30 decibels. The authors stated that slope estimates are not clinically useful because the analysis involved is time consuming and requires computer support. Instead, they suggested visual inspection of loudness growth functions to determine the presence of recruitment.

Margolis (1985) reported the results of a descriptive

study in which he obtained loudness growth functions of normally hearing and hearing impaired listeners for narrow bands of noise. The hearing impaired group was tested with and without hearing aids. Data for each hearing impaired listener were compared to data for the normally hearing group. Visual inspection of the loudness growth functions led the author to these conclusions:

1. All hearing impaired listeners had abnormal loudness functions whether aided or unaided.
2. At the lower intensities, aided loudness functions were shifted toward their unaided responses by a constant amount.
3. For some hearing impaired individuals, the aided loudness function showed more deviation from normal than the unaided function.
4. In some instances the aided functions showed smaller loudness values than the unaided function for narrow bands of noise in frequency regions where ear canal resonance provides gain.

The use of ME in hearing aid selection, like ABR testing, is a relatively new procedure. Magnitude estimation data appears to provide considerable information about an individual's loudness perception when using amplification, but interpretation of this information seems unclear. Margolis (1985) has demonstrated that hearing impaired listeners have abnormal

loudness growth functions even when wearing their hearing aids. Characteristics of these aided loudness functions need to be studied more thoroughly to see if certain features can predict hearing aid performance.

C. Studies correlating loudness and evoked potentials

Madell and Goldstein (1972) examined the relationship between loudness and the amplitudes of the middle latency auditory evoked responses. Amplitude functions for three waves, P0-Na, Na-Pa and Pa-Nb, and a loudness function were recorded for normally hearing listeners. Correlations between the slopes of the functions were low. High correlations were found between loudness and amplitude at each sensation level and those correlations were significant at or beyond a 0.05 alpha level.

Botte, Bujas and Chocholle (1975) examined the relationship between the slow cortical potential and loudness estimation in normally hearing subjects. Psychophysical and electrophysiological data were recorded simultaneously since the cortical potential varies with degree of alertness. Peak-to-peak amplitudes of N1-P2 waves and the latencies of N1 and P2 were recorded along with direct loudness estimates determined by paired ratio comparisons. No clear relationship was found between the slow cortical potential and loudness estimation.

Pratt and Sohmer (1977) examined magnitude estimates and simultaneously recorded brain stem and cortical

responses to clicks in normally hearing subjects. It was reported that as intensity increased magnitude estimates increased, ABR latencies decreased and ABR amplitudes increased. No clear cut change in the cortical response was observed. Although amplitude functions of ABR waves I and II were most similar to the magnitude estimation functions, magnitude estimates showed intersubject and intersession variability which the ABR data did not.

Wilson and Stelmack (1982) examined power functions of loudness estimations and auditory brainstem responses in normally hearing subjects. The exponent of the power function for loudness was similar to that reported by Raab and Osman (1962). Power functions for magnitude estimation and amplitude data were positive while power functions for latency data were negative. Although amplitude functions more closely resembled the loudness function, exponents of the power functions for ABR amplitudes were smaller than the exponent of the power function for loudness. Since amplitude functions appeared to grow more slowly than the loudness function, it was not concluded that the electrophysiological correlate of loudness was ABR amplitude.

Investigations of the relationship between the loudness of clicks and auditory evoked response intensity functions have demonstrated that characteristics of various auditory potentials change in response to changes

in intensity just as loudness perception changes. However, when these changes are quantified and compared, statistically significant information has not been obtained. A relationship between loudness and auditory evoked responses may exist, but, as Pratt and Sohmer (1977) suggest, perhaps a different means of data analysis would provide a better correlation.

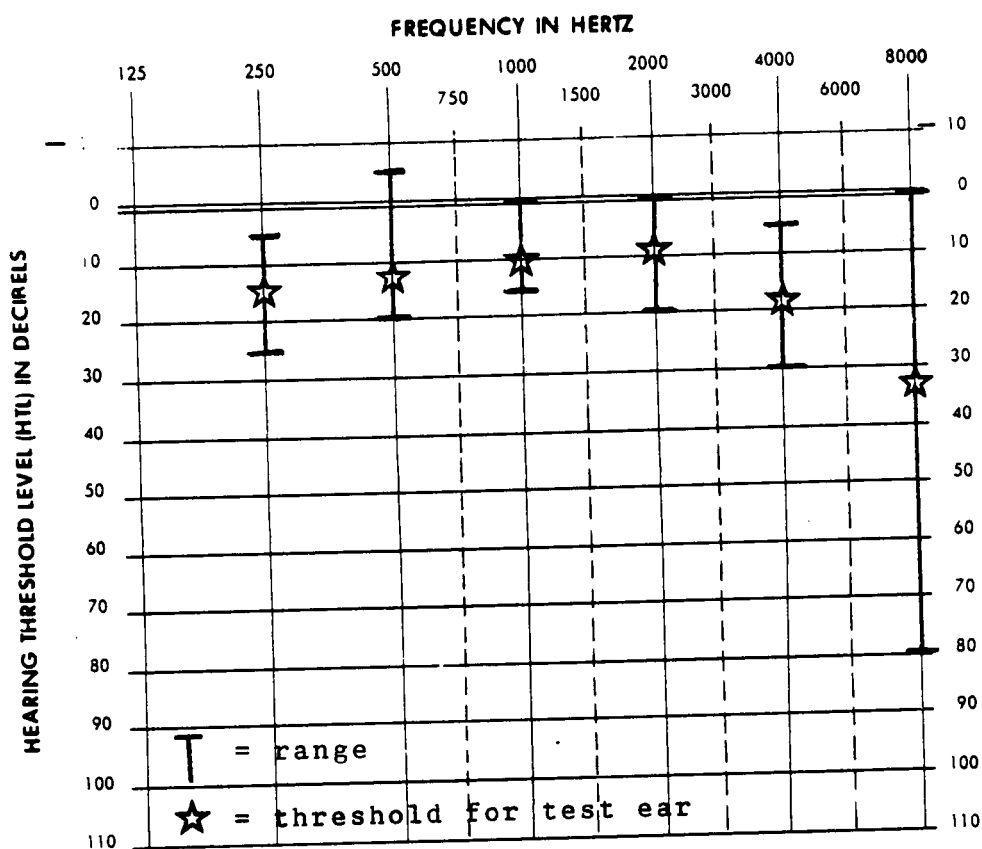
CHAPTER IV

METHOD

The purpose of this investigation was to compare electrophysiological and psychophysical intensity functions of normally hearing and hearing impaired adults. Auditory brainstem response audiometry was utilized to obtain wave I and wave V intensity-latency and intensity-amplitude functions. Loudness data was obtained by the method of magnitude estimation. An analysis of variance was employed to examine the relationships between the intensity functions. Correlation coefficients were used to examine the degree of strength between magnitude estimation data and the other four dependent variables.

A. Subjects

Eight adults (four males and four females) with an average age of 63 years served as normally hearing listeners. Mean audiometric information is presented in Figure 1. None of these listeners demonstrated positive retrocochlear signs during the Suprathreshold Adaptation Test (Jerger and Jerger, 1975) performed at 500 Hz and 1000 Hz. Corrected TEC scores from the Staggered Spondaic Word Test (Katz, 1979) for these listeners were indicative of normal hearing and no central auditory processing problems.



Audiometer Madsen OB 822

Standard ANSI 1969

AVERAGE HEARING LEVEL FOR
500, 1000 & 2000 Hz

10 dB

AVERAGE
SPEECH DISCRIMINATION SCORE

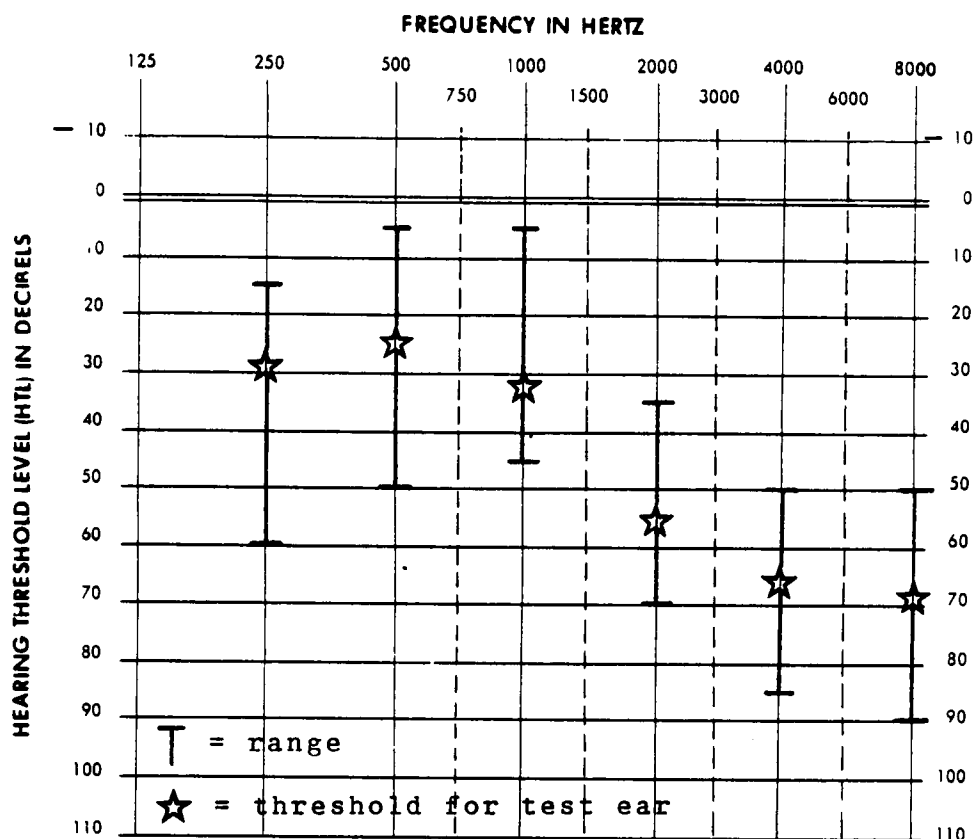
98 % @ - dB HTL
Stimuli CCT

Figure 1. Audiometric data from normally hearing subjects.

Eight adults (seven males and one female) with an average age of 61 years served as hearing impaired listeners. These listeners had previously been diagnosed as having bilateral sensorineural hearing loss when tested in the Audiology Clinic at the University of Tennessee. Mean audiometric information is presented in Figure 2. None of these listeners demonstrated positive retrocochlear signs during the Suprathreshold Adaptation Test performed at 500 Hz and 1000 Hz. Corrected TEC scores from the Staggered Spondaic Word Test for all listeners were indicative of cochlear involvement and no central auditory processing problems.

The hearing impaired listeners had previously been fit with Phonic Ear 805 CD behind-the-ear hearing aids in the Audiology Clinic at the University of Tennessee. Individual data regarding the hearing aid adjustments preferred by this group are presented in Table 1.

The hearing impaired listeners were considered successful hearing aid users since they reportedly used their hearing aids (with activated compression circuitry) for a minimum of eight hours each day. When aided communication function was assessed by these individuals with the Hearing Handicap Inventory for the Elderly (Weinstein and Ventry, 1982), six listeners had scores of less than 16% which indicated no communication problems. Two listeners had slightly higher scores (18% and 21%)



Audiometer Madsen OB 822

Standard ANSI 1969

AVERAGE HEARING LEVEL FOR

500, 1000 & 2000 Hz

37 dB

AVERAGE

SPEECH DISCRIMINATION SCORES

73 % @ - dB HTL

Stimuli CCT

Figure 2. Audiometric data for hearing impaired subjects.

Table 1. Individual settings for the Phonic Ear 805 CD hearing aid.

Volume	Amount of Compression	Tone
2.00	115	H1
1.75	115	N
3.50	111	H3
2.00	115	N
1.75	115	N
3.00	118	H2
2.00	103	N
2.75	118	N

which indicated mild communication problems.

During data collection, hearing impaired listeners were tested with and without their hearing aids. In the aided condition, data were collected with and without activation of the compression circuit in the hearing aid. The use of a hearing aid with activation of compression circuitry was referred to as a compression aided listening condition while hearing aid use without activation of the circuit was referred to as a linear aided condition (Appendix 2).

Prior to participation in the experimental procedures, electroacoustic analyses were obtained for each hearing impaired subject's hearing aid. The analyses were performed according to ANSI specifications for hearing aid characteristics (Acoustical Society of America, 1982) and used to verify that each device was functioning.

B. ABR recording procedures

To obtain the ABR latency and amplitude information a Nicolet Compact 4 electrodiagnostic test unit was used. Square waves of 100 μ s duration presented at a rate of 11.4 per second were used as the stimuli (clicks). A rate of 11.4 was selected because this rate causes better definition of the ABR waveform and clicks at this rate can be transduced by a hearing aid receiver without an accompanying ringing (Kileny, 1982). The clicks were generated by the Nicolet Compact 4, led to an attenuator

(custom) and delivered to a subject's ear via a loudspeaker (custom) placed 10 centimeters (cm) away from the external auditory meatus. Placement away from the external canal was used so that measurements could be obtained when the hearing impaired subjects were wearing their hearing aids. A distance of 10 cm was selected because click intensity reaching the ear was less subject to variation in level than clicks presented at positions closer to the ear. Silver cup electrodes were used to pick up EEG activity from the scalp and deliver it to the preamplifier for initial amplification. The active electrode was placed on the vertex with reference electrodes placed on the ipsilateral and contralateral mastoids. The forehead served as ground. Resistance at the electrode-skin interface was less than 5000 ohms. Upon reaching the Compact 4, the EEG activity was amplified 100,000 times, filtered from 150 to 1500 Hz and led to an averager. Response time was 10 milliseconds (ms) and each waveform (tracing) generated consisted of 1600 averaged responses. Instrumentation for stimulus delivery and recording of the ABR is presented in Figure 3.

To obtain the ABR data from each subject, electrodes were applied, the subjects was seated in a reclining chair located in a quiet room and clicks were presented through the loudspeaker. ABR wave I and wave V, I-L and I-A

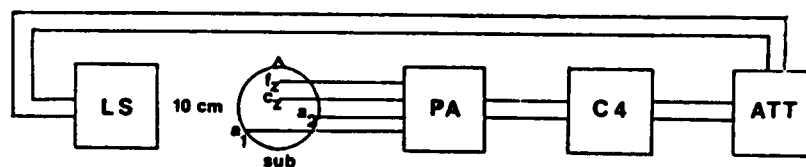


Figure 3. Instrumentation for stimulus delivery and recording of the ABR. LS = loudspeaker; sub = listener; fz = electrode; cz = electrode; a1 = electrode; a2 = electrode; PA = preamplifier; C4 = Nicolet Compact 4; ATT = attenuator.

functions were recorded for each subject from 100 to 50 dB SPL in 10 dB steps. Two tracings were recorded for each subject at each intensity level. To obtain latency and amplitude measures at each level, the tracings were overlaid. If the tracings overlapped, a latency value in milliseconds was recorded at the point where the right sided slope of the wave broke away from the peak and an amplitude value was measured as the difference in microvolts from the point where latency was measured to the trough of the wave.

The data from each subject were used to construct wave I and wave V, I-L and I-A functions showing the means and standard deviations for each group.

C. ABR test unit calibration

Loudspeaker output was verified by measurement with a Knowles Electronic Mannequin for Acoustic Research (KEMAR) and associated microphone (Bruel and Kjaer 4165), preamplifier (Bruel and Kjaer 2619) and measuring amplifier (Bruel and Kjaer 2807). The loudspeaker was placed 10 cm from KEMAR's ear and dial settings on the Compact 4 were noted which corresponded to the following levels on the measuring amplifier: 100 dB, 90 dB, 80 dB, 70 dB, 60 dB and 50 dB SPL. Instrumentation for calibration of output is presented in Figure 4. Output readings were taken prior to the testing of each subject. The spectrum of the click stimulus was measured

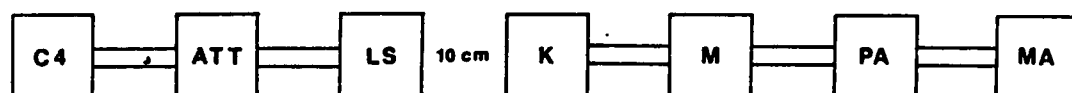


Figure 4. Instrumentation for calibration of ABR stimulus output. C4 = Nicolet Compact 4; ATT = attenuator; LS = loudspeaker; K = KEMAR; M = microphone; PA = preamplifier; MA = measuring amplifier.

periodically to verify spectral stability. Loudspeaker output was directed to a spectrum analyzer (Nicolet UA5000) via KEMAR. Instrumentation for verification of spectrum is presented in Figure 5.

D. ME recording procedures

To construct a loudness estimation function the method of magnitude estimation was used. Each subject was instructed to listen to pairs of click stimuli and judge the loudness of the comparison click stimulus relative to the standard one (Appendix 3). The intensity of the standard stimulus was 80 dB SPL and the comparison stimuli varied from 50 to 100 dB SPL in 10 dB steps. Each subject presented the stimuli to himself via a three position switch. This method of stimulus presentation allowed a subject to work at his own pace and attend properly when the stimulus came on (Stevens, 1956). The subject was told that the loudness of the standard stimulus would not change, but the loudness of the comparison stimuli would. The loudness of the standard stimulus was assigned a value of "10". The subject was free to choose whatever numbers he felt represented the magnitudes of the comparisons. The comparison stimuli were presented in random order and the subjects made five magnitude estimations for each of the six comparison stimuli (Richards, 1976). A practice trial consisting of five loudness estimations was performed prior to testing to familiarize the subject with

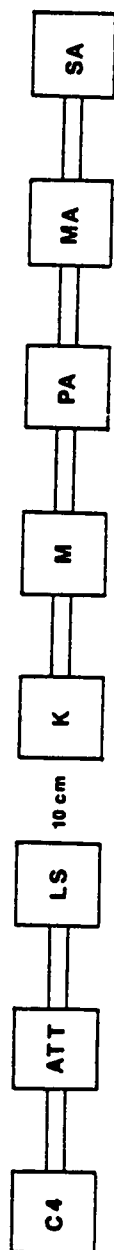


Figure 5. Instrumentation for verification of ABR stimulus output spectrum. C4 = Nicolet Compact 4; ATT = attenuator; LS = loudspeaker; K = KEMAR; M = microphone; PA = pre-amplifier; MA = measuring amplifier; SA = spectrum analyzer.

the task. Psychoacoustic and electrophysiological testing were completed during separate test sessions. The data from each subject were used to construct magnitude estimation functions showing the means and standard deviations for each group.

The stimuli used in this task were clicks presented at a rate of 10 per second. Clicks were selected because they were also used to obtain the ABR I-L and I-A functions.

The clicks were generated by a Tycon 0133 MMD-1 processor. The output of the processor was split and directed to a two channel power amplifier (SAE 2200 amplifier). By splitting the output, two identical signals were generated and independently controlled. The output from each channel was led to an attenuator (custom). Attenuator outputs were directed to a three-position switch (custom) and, depending on switch position, were then delivered to a loudspeaker (custom). The loudspeaker was positioned 10 cm from the opening of the listener's external auditory meatus. An electronic voltmeter (Hewlett-Packard 350D) was placed in parallel with one of the attenuators to monitor voltage of the comparison stimuli. Instrumentation for the delivery of the standard and comparison click stimuli is presented in Figure 6.

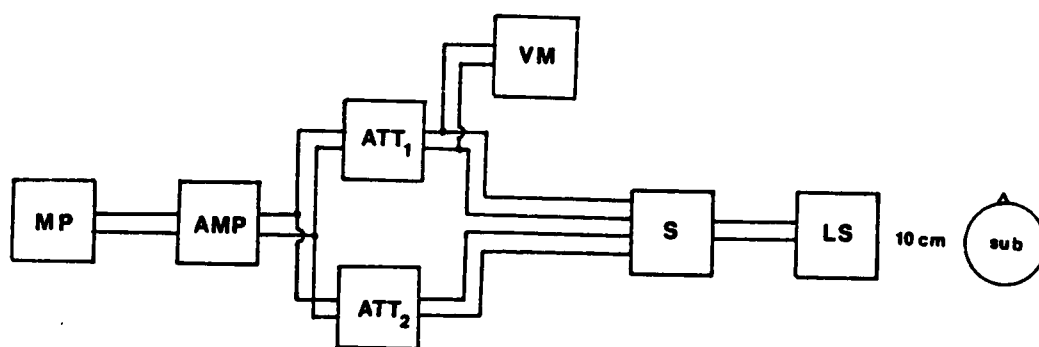


Figure 6. Instrumentation for stimulus delivery used to obtain loudness estimations. MP = microprocessor; AMP = amplifier; ATT₁ = attenuator; ATT₂ = attenuator; VM = voltmeter; S = switch; LS = loudspeaker; sub = listener.

E. ME calibration

Loudspeaker output was verified prior to each test session by measurement with a KEMAR and associated microphone (Bruel and Kjaer 4165), preamplifier (Bruel and Kjaer 2619) and measuring amplifier (Bruel and Kjaer 2807). Instrumentation for the calibration of output is presented in Figure 7. The loudspeaker was placed 10 cm from KEMAR's ear and dial settings on the attenuators were noted which corresponded to the level of the standard and to the levels of the comparison clicks. Output for the standard channel was fixed at 80 dB SPL and output for the comparison channel was noted from 50 dB to 100 dB SPL in 10 dB steps. The spectrum of the click stimulus was measured periodically to verify spectral stability by directing the loudspeaker output to a spectrum analyzer (Nicolet UA5000) via KEMAR. Instrumentation for verification of spectrum is presented in Figure 8.

F. Reliability

ABR wave I and wave V latency and amplitude measurements for a 90 dB SPL signal were repeated for each subject at the end of the test session. The initial and repeated ABR measurements were used to compute test-retest reliability coefficients from the computation of Pearson product-moment correlations. Likewise, a magnitude estimate for an 90 dB SPL signal was repeated for each subject and the data were used to compute a test-retest

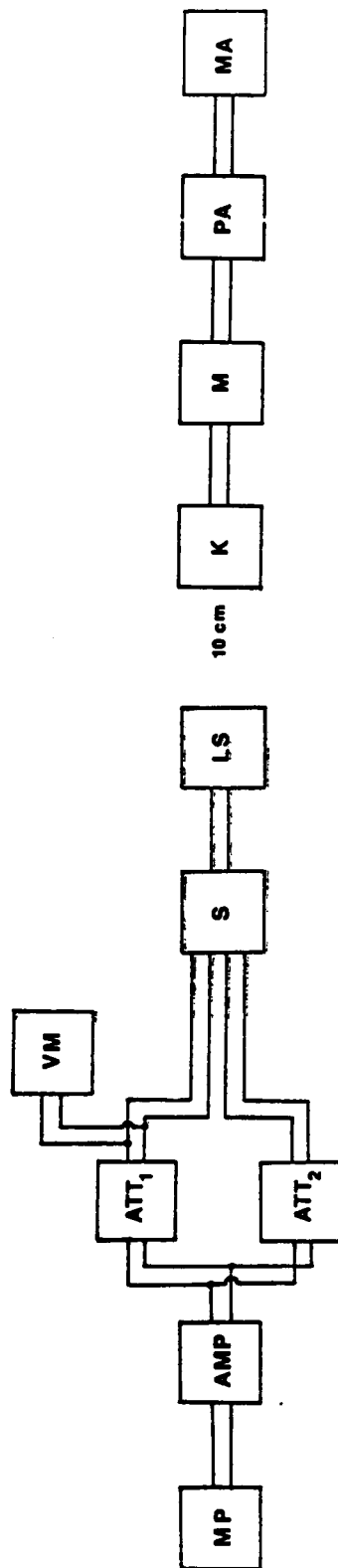


Figure 7. Instrumentation for the calibration of stimulus output used to obtain magnitude estimations. MP = microprocessor; AMP = amplifier; ATT₁ = attenuator; ATT₂ = attenuator; VM = voltmeter; S = switch; LS = loudspeaker; K = KEMAR; M = microphone; PA = preamplifier; MA = measuring amplifier.

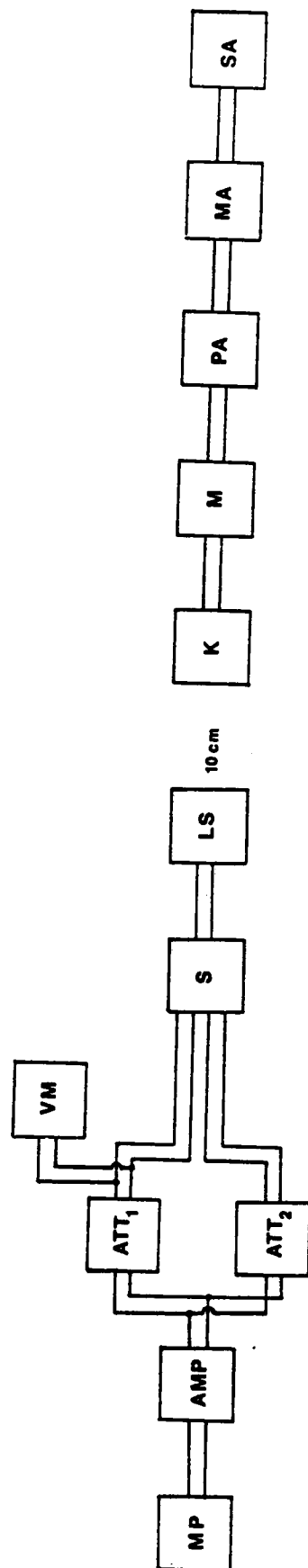


Figure 8. Instrumentation for verification of stimulus spectrum used to obtain magnitude estimations. MP = microprocessor; AMP = amplifier; ATT1 = attenuator; ATT2 = attenuator; VM = voltmeter; S = switch; LS = loudspeaker; K = KEMAR; M = microphone; PA = preamplifier; MA = measuring amplifier; SA = spectrum analyzer.

reliability coefficient. These coefficients are presented in Table 2.

G. Statistical design

This was a three factor repeated measures design. Factor A was group, factor B was intensity level and factor C was amplification. There were two levels of factor A (normally-hearing vs hearing impairment), six levels of factor B (50, 60, 70, 80, 90 and 100 dB SPL) and three levels of factor C (no amplification, compression amplification and linear amplification. Both groups were exposed to all intensity levels with no amplification, but only the hearing-impaired group was exposed to all intensity levels under conditions of compression and linear amplification. Statistical analysis of the data was performed using analysis of variance. Planned comparisons were used to answer experimental questions 1 through 10. Pearson product-moment correlations were used to answer experimental questions 11 through 18.

Table 2. Test-retest reliability coefficients calculated from data recorded at 90 dB SPL.

	WI lat	WV lat	WI amp	WV amp	Mag est
Normally hearing	.99	.99	.39	.85	.94
Hearing impaired	.99	.92	.99	.78	.90

CHAPTER V

RESULTS

The purpose of this study was to examine relationships between ABR wave I and wave V intensity functions and the magnitude estimation function of loudness in normally hearing and hearing impaired listeners. ABR intensity-amplitude, ABR intensity-latency and ME functions were recorded for eight normally hearing and eight hearing impaired listeners. Additionally, responses were recorded for the hearing impaired listeners wearing hearing aids equipped with compression and linear amplification. Intensity functions of normally hearing and hearing impaired listeners were compared to determine if the introduction of amplification caused responses of the hearing impaired group to approximate responses of the normally hearing group.

A. Means and standard deviations

ABR data were not available from all subjects at all intensity levels because wave I and wave V were not always reproducible. For each group in one amplification condition, it was expected that eight observations of wave I and wave V would occur at each intensity level, but sometimes fewer than eight observations per level occurred. The absence of an observation was due to

waveform morphology which was not readable. In addition to means and standard deviations presented in the following tables, the number of observations or readable ABR responses is noted under the column N.

The means and standard deviations for ABR wave I latency are presented in Table 3. Only those values recorded at four intensity levels from 100 dB to 70 dB are presented because the number of empty data cells at the 60 dB and 50 dB levels precluded the use of these levels in any statistical analyses. There were several general trends in these data. An inverse relationship existed between mean wave I latency values and intensity levels. Shorter wave I latency values were recorded for normally hearing subjects at all intensity levels. The number of observations was largest for the normally hearing group in three out of four intensity levels. The hearing impaired group in the compression aided condition had mean values which most closely resembled those of the normally hearing group at 100 dB, 90 dB and 80 dB levels. The largest standard deviations at each intensity level were recorded for the hearing impaired group whether aided or unaided.

The fact that standard deviations were larger for the hearing impaired group was not surprising. In general, hearing impaired individuals show a greater range of performance on various auditory tasks than normally hearing individuals. This variability in performance is

Table 3. Means and standard deviations for wave I latency data at four intensity levels.

Level	Normally hearing		Hearing impaired (unaided)		Hearing impaired (compression)		Hearing impaired (linear)					
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.			
100	6	1.99	0.29	7	2.24	0.21	5	2.19	0.16	4	2.42	0.67
90	8	2.14	0.22	8	2.34	0.23	5	2.31	0.19	2	2.38	0.20
80	7	2.19	0.19	6	2.72	0.43	3	2.43	0.29	2	2.54	0.14
70	6	2.44	0.22	2	3.00	0.40	2	2.80	0.23	3	2.60	0.12

probably due to the effects of hearing loss which, at the present time, cannot all be identified with traditional audiological tests. For example, it is a common clinical observation that hearing impaired individuals with similar audiometric configurations will often have very different speech recognition ability.

The means and standard deviations for ABR wave V latency data are presented in Table 4. There were several general trends in these data. An inverse relationship existed between mean wave V latency values and intensity levels. Mean latency values for the normally hearing group were shorter than those for the hearing impaired amplification conditions in five out of six intensity levels. The number of observations in the normally hearing group was equal to or exceeded those for the hearing impaired whether aided or unaided at all intensity levels. The mean latency values for the hearing impaired group in the unaided condition most closely resembled the mean values of the normally hearing group at the four highest intensity levels.

Means and standard deviations for wave I amplitude data are presented in Table 5. There were several notable features in these data. Wave I amplitude values for both groups decreased as intensity level decreased. The largest mean values were recorded for the normally hearing group at 90 dB, 80 dB and 70 dB levels. At 100 dB the

Table 4. Means and standard deviations for wave V latency data at six intensity levels.

Level	Normally hearing		Hearing impaired (unaided)		Hearing impaired (compression)		Hearing impaired (linear)		
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.
100	8	6.32	0.29	8	6.44	0.20	8	6.58	0.18
90	8	6.33	0.28	8	6.56	0.29	8	6.90	0.43
80	8	6.47	0.28	8	6.80	0.41	8	6.90	0.35
70	8	6.75	0.26	7	7.08	0.62	8	7.31	0.57
60	8	7.11	0.39	3	7.85	0.81	7	7.56	0.68
50	8	7.60	0.48	0	----	----	3	7.82	0.85
							4	7.53	0.81

Table 5. Means and standard deviations for wave I amplitude data at four intensity levels.

Level	Normally hearing		Hearing impaired (unaided)		Hearing impaired (compression)		Hearing impaired (linear)					
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.			
100	6	0.25	0.20	7	0.25	0.19	5	0.49	0.46	4	0.16	0.08
90	8	0.17	0.09	8	0.15	0.11	5	0.15	0.09	2	0.10	0.05
80	7	0.14	0.06	6	0.08	0.05	3	0.11	0.10	2	0.09	0.07
70	6	0.13	0.12	2	0.06	----	2	0.10	----	3	0.09	0.66

largest mean value was recorded for the hearing impaired group in the compression aided condition. The number of observations in the normally hearing group was equal to or exceeded those for the hearing impaired group whether aided or unaided in three out of four intensity levels. The standard deviation values for the three hearing impaired amplification conditions tended to be greater than those for the normally hearing group at 100 dB, 90 dB and 80 dB levels

Means and standard deviations for wave V amplitude data are presented in Table 6. There were several notable features in these data. With one exception, the mean amplitude values decreased as intensity level decreased. The number of observations for the normally hearing group was equal to or exceeded those of the hearing impaired group whether aided or unaided at all intensity levels. The normally hearing group had the largest mean amplitude values in four out of six intensity levels. The largest standard deviations were observed for the normally hearing group in three out of six intensity levels.

Means and standard deviations for loudness estimations are presented in Table 7. There were several notable features in these data. The mean loudness estimation values decreased as intensity level decreased. The results for the normally hearing group most closely resembled Stevens' data (1956). The largest differences

Table 6. Means and standard deviations for wave V amplitude data at six intensity levels.

Level	Normally hearing			Hearing impaired (unaided)			Hearing impaired (compression)			Hearing impaired (linear)		
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.
100	8	0.52	0.36	8	0.46	0.12	8	0.41	0.19	8	0.37	0.16
90	8	0.34	0.21	8	0.26	0.09	8	0.27	0.13	8	0.29	0.12
80	8	0.26	0.16	8	0.23	0.11	8	0.21	0.12	8	0.24	0.04
70	8	0.20	0.08	7	0.15	0.09	8	0.18	0.09	8	0.23	0.09
60	8	0.22	0.05	3	0.12	0.04	7	0.15	0.05	5	0.18	0.11
50	8	0.09	0.05	0	-----	-----	3	0.10	0.04	4	0.15	0.11

Table 7. Means and standard deviations of loudness estimations at 6 intensity levels.

Level	Normally hearing		Hearing impaired (unaided)		Hearing impaired (compression)		Hearing impaired (linear)					
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.			
100	8	33.91	15.80	8	73.95	38.51	8	57.27	29.24	8	62.97	31.33
90	8	18.22	04.44	8	27.12	14.84	8	24.85	13.56	8	29.92	17.17
80	8	09.72	00.40	8	09.97	00.17	8	09.95	00.59	8	10.22	00.83
70	8	04.62	00.76	8	05.21	01.49	8	05.61	01.97	8	06.32	01.94
60	8	01.95	01.20	8	02.32	01.18	8	03.07	01.48	8	03.92	02.02
50	8	01.03	00.99	8	00.61	00.73	8	01.20	00.74	8	02.05	01.33

between the normally hearing and hearing impaired listeners occurred at 90 dB and 100 dB levels. The hearing impaired group utilizing linear amplification had the largest loudness estimation values in five out of six intensity levels. At 100 dB, 90 dB, 80 dB and 50 dB levels, the hearing impaired group utilizing compression amplification most closely resembled the normally hearing group. The hearing impaired group whether aided or unaided had larger standard deviation values than the normally hearing group.

B. Research question 1

An analysis of variance was performed to determine if statistically significant differences existed among the ABR wave I latency means of the normally hearing group and the hearing impaired group in an unaided listening condition. An F value for group of 10.28 was statistically significant at the 0.05 alpha level. An F value for intensity of 11.47 was statistically significant at the 0.05 alpha level. An F value of 1.13 for a group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 8.

It was not necessary to use Bonferroni planned comparisons to examine differences between group means because there were only two levels of group. It should be noted that the hearing impaired group had a greater mean wave I latency value. Comparisons were made between

Table 8. ANOVA table of wave I latency data for normally hearing and hearing impaired groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	1.34776348	10.28	0.0063
S (Group)	14	1.83532392		
Intensity	3	0.88655053	11.47	0.0001
Grp * Intensity	3	0.08718739	1.13	0.3545
Int * S (Group)	28	6.72124304		

intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used with an alpha level determined by the number of comparisons divided into 0.05. With six comparisons, the alpha level was 0.008. With respect to intensity, a statistically significant differences was found only between means at 100 dB and 70 dB. These results are presented in Table 9. Interaction means were not examined because there was no statistically significant interaction effect.

The results of these tests for significance provided an affirmative answer to research question 1: There was a statistically significant difference between mean wave I latency values of normally hearing and hearing impaired groups with hearing impaired individuals exhibiting longer wave I latencies.

C. Research question 2

An analysis of variance was performed to determine if statistically significant differences existed among the ABR wave V latency means for the normally hearing group and the hearing impaired group in an unaided listening condition. An F value for group of 3.39 was not statistically significant. An F value of 29.36 for intensity was statistically significant at the 0.05 alpha level. An F value of 2.01 for a group by intensity interaction was not statistically significant. The ANOVA

Table 9. The results of Bonferroni planned comparisons of intensity levels using wave I latency data from normally hearing and hearing impaired groups. t = t value and α = significance level.

Levels		100	90	80	70
100	t =	--	-1.2034	-2.2117	-3.3031
	α =	--	0.2393	0.0368	0.0037
90	t =	--	--	-1.4648	-2.7824
	α =	--	--	0.1599	0.0109
80	t =	--	--	--	-0.8380
	α =	--	--	--	0.4125
70	t =	--	--	--	--
	α =	--	--	--	--

table is presented in Table 10.

Comparisons were made between intensity levels to determine where statistically significant differences existed between levels. With fifteen comparisons by the Bonferroni planned comparison approach, the alpha level was set at 0.003. Statistically significant differences were observed between means at 100 dB and 70 dB, 100 dB and 60 dB, 100 dB and 50 dB, 90 dB and 60 dB, 90 dB and 50 dB, 80 dB and 60 dB, 80 dB and 50 dB and 70 dB and 50 dB levels. These results are presented in Table 11. It was not necessary to examine differences between group means or interaction means because neither effect was statistically significant.

The results of these tests for significance provided a negative answer for research question 2: There was no statistically significant difference between mean wave V latency values of normally hearing and hearing impaired groups.

D. Research question 3

An analysis of variance was performed to determine if statistically significant differences existed among the ABR wave I amplitude means of the normally hearing group and the hearing impaired group in an unaided listening condition. An F value of 0.37 for group was not statistically significant. An F value of 4.51 for intensity was statistically significant at the 0.05 alpha

Table 10. ANOVA table of wave V latency data for normally hearing and hearing impaired groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	1.29015477	3.39	0.0869
S (Group)	14	5.32790230		
Intensity	5	10.34461042	29.36	0.0001
Grp * Intensity	4	0.56657303	2.01	0.1053
Int * S (Group)	57	4.01678054		

Table 11. The results of Bonferroni planned comparisons of intensity levels using wave V latency data from normally hearing and hearing impaired groups. t = t value and α = significance level.

Levels	100	90	80	70	60	50
100	t = --	-0.6301	-2.2154	-3.7906	-4.9070	-6.7614
	α = --	0.5334	0.0345	0.0011	0.0003	0.0001
90	t = --	--	-1.5742	-3.2482	-4.4790	-7.2950
	α = --	--	0.1259	0.0029	0.0006	0.0001
80	t = --	--	--	-1.7480	-3.3649	-5.3737
	α = --	--	--	0.0910	0.0013	0.0001
70	t = --	--	--	--	-1.9625	-3.3281
	α = --	--	--	--	0.0614	0.0032
60	t = --	--	--	--	--	-1.0990
	α = --	--	--	--	--	0.2871
50	t = --	--	--	--	--	--
	α = --	--	--	--	--	--

level. An F value of 1.83 for a group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 12.

Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.008 alpha level. No statistically significant differences were found between any comparisons of interest. These results are presented in Table 13. It was not necessary to examine differences between group means or interaction means because neither effect was statistically significant.

The results of these tests for significance provided a negative answer for research question 3: There was no statistically significant difference between mean wave I amplitude values of normally hearing and hearing impaired groups.

E. Research question 4

An analysis of variance was performed to determine if statistically significant differences existed among the ABR wave V amplitude means of the normally hearing group and the hearing impaired group in an unaided listening condition. An F value of 1.41 for group was not statistically significant. An F value of 10.32 for intensity was statistically significant at the 0.05 alpha level. An F value of 0.27 for a group by intensity

Table 12. ANOVA table of wave I amplitude data for normally hearing and hearing impaired groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.00765209	0.37	0.5513
S (Group)	14	0.28744765		
Intensity	3	0.16220836	4.51	0.0105
Grp * Intensity	3	0.06580462	1.83	0.1643
Int * S (Group)	28	0.33532156		

Table 13. The results of Bonferroni planned comparisons of intensity levels using wave I amplitude data from normally hearing and hearing impaired groups. t = t value and α = significance level.

Levels		100	90	80	70
100	t =	--	1.5258	2.4832	1.8799
	α =	--	0.1450	0.0259	0.0755
90	t =	--	--	1.5052	1.1091
	α =	--	--	0.1439	0.2794
80	t =	--	--	--	0.0298
	α =	--	--	--	0.9765
70	t =	--	--	--	--
	α =	--	--	--	--

interaction was not statistically significant. The ANOVA table is presented in Table 14.

Comparisons were made between intensity levels to determine where statistically significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were observed between means at 100 dB and 80 dB, 100 dB and 70 dB, 100 dB and 60 dB, 100 dB and 50 dB, 90 dB and 50 dB, 80 dB and 50 dB and 60 dB and 50 dB levels. These results are presented in Table 15. It was not necessary to examine differences between group means or interaction means because neither effect was statistically significant.

The results of these tests for significance provided a negative answer for research question 4: There was no statistically significant difference between mean wave V amplitude values of normally hearing and hearing impaired groups.

F. Research question 5

An analysis of variance was performed to determine if statistically significant differences existed among the magnitude estimation means for the normally hearing group and the hearing impaired group in an unaided listening condition. An F value of 7.32 for group was statistically significant at the 0.05 alpha level. An F value of 43.24

Table 14. ANOVA table of wave V amplitude data for normally hearing and hearing impaired groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.08219807	1.41	0.2548
S (Group)	14	0.81616820		
Intensity	5	0.88031667	10.32	0.0001
Grp * Intensity	4	0.01860955	0.27	0.8945
Int * S (Group)	57	0.97279548		

Table 15. The results of Bonferroni planned comparisons of intensity levels using wave V amplitude data from normally hearing and hearing impaired groups. $t = t$ value and $\alpha =$ significance level.

Levels	100	90	80	70	60	50
100	$t =$ $\alpha =$	-- 2.4673 0.0195	3.3072 0.0031	4.5510 0.0002	4.4323 0.0003	5.9668 0.0001
90	$t =$ $\alpha =$	-- --	1.0180 0.3168	2.6857 0.0131	2.4942 0.0210	4.8292 0.0001
80	$t =$ $\alpha =$	-- --	-- --	1.7066 0.0986	1.4831 0.1518	4.1542 0.0005
70	$t =$ $\alpha =$	-- --	-- --	-- --	-0.4027 0.6907	2.6062 0.0165
60	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	3.6836 0.0018
50	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-- --

for intensity was statistically significant at at the 0.05 alpha level. An F value of 6.65 for a group by intensity interaction was statistically significant at the 0.05 alpha level. The ANOVA table is presented in Table 16.

With respect to the group factor, Bonferroni planned comparisons to detect differences between means were not necessary since there were only two levels of group. Magnitude estimation means for the hearing impaired group were greater than means for the normally hearing group.

Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferrone planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were observed between the mean at 100 dB and means at all other intensity levels. Statistically significant differences were observed between the mean at 90 dB and means at 70 dB, 60 dB and 50 dB levels. Alpha levels are presented in Table 17.

Comparisons of interest for the group by intensity interaction were between each group at each intensity level. Bonferroni planned comparisons were used to determine statistical significance at a 0.008 alpha level. The only statistically significant difference was observed between groups at the 100 dB level. Alpha levels are presented in Table 18.

Table 16. ANOVA table of ME data for normally hearing and hearing impaired groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	1648.46662604	7.32	0.0171
S (Group)	14	3152.71862292		
Intensity	5	33058.68167188	43.24	0.0001
Grp * Intensity	5	5083.25743021	6.65	0.0001
Int * S (Group)	70	10703.91731458		

Table 17. The results of Bonferroni planned comparisons of intensity levels using magnitude estimation data from normally hearing and hearing impaired groups. α = significance level.

Levels	100	90	80	70	60	50
100 α =	--	0.0001	0.0001	0.0001	0.0001	0.0001
90 α =	--	--	0.0045	0.0001	0.0001	0.0001
80 α =	--	--	--	0.2630	0.0821	0.0426
70 α =	--	--	--	--	0.5270	0.3518
60 α =	--	--	--	--	--	0.7638
50 α =	--	--	--	--	--	--

Table 18. The results of Bonferroni planned comparisons of interest for the group by intensity interaction using magnitude estimation data from normally hearing and hearing impaired groups.

Comparison between groups at:	Pr > /t/
100 dB	0.0001
90 dB	0.1545
80 dB	0.9679
70 dB	0.9241
60 dB	0.9531
50 dB	0.9464

The results of these tests for significance provided an affirmative answer to research question 5: There was a statistically significant difference between mean magnitude estimation values of normally hearing and hearing impaired groups, but this difference only occurred at a high intensity level.

G. Research question 6

An analysis of variance was performed to determine if statistically significant differences existed among the wave I latency means of the normally hearing group and the hearing impaired group in a compression aided listening condition. An F value of 7.89 for group was statistically significant at the 0.05 alpha level. An F value of 11.21 for intensity was statistically significant at the 0.05 alpha level. A group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 19.

It was not necessary to use Bonferroni planned comparisons to examine differences between group means because there were only two levels of this factor. It should be noted that the hearing impaired group utilizing compression amplification had a greater mean latency value. With respect to intensity, comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons used to determine statistical significance at

Table 19. ANOVA table of wave I latency data for normally hearing and compression aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.55257257	7.89	0.0158
S (Group)	12	0.84042039		
Intensity	3	1.01854950	11.21	0.0001
Grp * Intensity	3	0.04662333	0.51	0.6775
Int * S (Group)	22	0.66646541		

a 0.008 alpha level. Statistically significant differences were observed between means at 100 dB and 70 dB and at 90 dB and 70 dB levels. These results are presented in Table 20. It was not necessary to examine differences between interaction means because this effect was not statistically significant.

An analysis of variance was performed to determine if statistically significant differences existed among wave I latency means of the normally hearing group and the hearing impaired group in a linear aided condition. An F value of 3.44 for group was not statistically significant. An F value of 13.75 for intensity was statistically significant at the 0.05 alpha level. An F value of 0.84 for a group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 21.

Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.008 alpha level. A statistically significant difference was observed between 90 dB and 70 dB levels. These results are presented in Table 22. It was not necessary to examine differences between group means or interaction means because neither effect was statistically significant.

These tests for significance provided an answer to research question 6: There was a statistically

Table 20. The results of Bonferroni planned comparisons of intensity levels using wave I latency data from normally hearing and compression aided hearing impaired groups. t = t value and α = significance level.

Levels		100	90	80	70
100	t =	--	-1.2766	-1.6273	-3.7522
	α =	--	0.2151	0.1201	0.0016
90	t =	--	--	-0.5420	-3.0542
	α =	--	--	0.5936	0.0065
80	t =	--	--	--	-2.3016
	α =	--	--	--	0.0351
70	t =	--	--	--	--
	α =	--	--	--	--

Table 21. ANOVA table of wave I latency data for normally hearing and linear aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.61989068	3.44	0.0905
S (Group)	11	1.98032958		
Intensity	3	0.80401809	13.75	0.0001
Grp * Intensity	3	0.04892679	0.84	0.4904
Int * S (Group)	19	0.37037925		

Table 22. The results of Bonferroni planned comparisons of intensity levels using wave I latency data from normally hearing and linear aided hearing impaired groups. t = t value and α = significance level.

Level		100	90	80	70
100	t =	--	0.0225	-0.4032	-1.7197
	α =	--	0.9824	0.6934	0.1114
90	t =	--	--	-0.7241	-3.0941
	α =	--	--	0.4789	0.0066
80	t =	--	--	--	-2.2471
	α =	--	--	--	0.0391
70	t =	--	--	--	--
	α =	--	--	--	--

significant difference between mean wave I latency values for normally hearing and hearing impaired groups when the latter used compression amplification, but no statistically significant difference was observed for normally hearing and hearing impaired groups when the latter used linear amplification.

H. Research question 7

An analysis of variance was performed to determine if statistically significant differences existed among the wave V latency means of the normally hearing group and the hearing impaired group in a compression aided listening condition. An F value of 5.07 for group was statistically significant at the 0.05 alpha level. An F value of 22.11 for intensity was statistically significant at the 0.05 alpha level. A group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 23.

It was not necessary to use Bonferroni planned comparisons to examine differences between group means. It should be noted that the hearing impaired group using compression amplification had longer wave V latencies. With respect to intensity, comparisons were made between intensity levels to determine where statistically significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level.

Table 23. ANOVA table of wave V latency data for normally hearing and compression aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	2.62694976	5.07	0.0410
S (Group)	14	7.25986792		
Intensity	5	13.60589848	22.11	0.0001
Grp * Intensity	5	0.16635638	0.27	0.9277
Int * S (Group)	64	7.87637478		

Statistically significant differences were observed between 100 dB and 70 dB, 100 dB and 60 dB, 100 dB and 50 dB, 90 dB and 70 dB, 90 dB and 60 dB, 90 dB and 50 dB and 80 dB and 50 dB levels. These results are presented in Table 24. Interaction means were not examined because there was no statistically significant interaction effect.

An analysis of variance was performed to determine if statistically significant differences existed among wave V latency means of the normally hearing group and the hearing impaired group in a linear aided listening condition. An F value of 4.60 for group was statistically significant at the 0.05 alpha level. An F value of 24.67 for intensity was statistically significant at the 0.05 alpha level. A group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 25.

It was not necessary to use Bonferroni planned comparisons to examine differences between group means. It should be noted that the hearing impaired group using linear amplification had longer wave V latencies. With respect to intensity, comparisons were made between intensity levels to determine where statistically significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were observed

Table 24. The results of Bonferroni planned comparisons of intensity levels using wave V latency data from normally hearing and compression aided hearing impaired groups. $t = t$ value and $\alpha =$ significance level.

Levels	100	90	80	70	60	50
100	$t =$ $\alpha =$	-- -0.8785 0.3867	-2.0461 -2.0461 0.0496	-4.0993 -4.0993 0.0003	-5.4945 -5.4945 0.0001	-6.7085 -6.7085 0.0001
90	$t =$ $\alpha =$	-- --	-1.3867 -1.3867 0.1757	-3.3521 -3.3521 0.0022	-4.7967 -4.7967 0.0001	-6.6468 -6.6468 0.0001
80	$t =$ $\alpha =$	-- --	-- --	-1.5261 -1.5261 0.1375	-2.8931 -2.8931 0.0072	-4.1986 -4.1986 0.0003
70	$t =$ $\alpha =$	-- --	-- --	-- --	-1.5200 -1.5200 0.1393	-3.0125 -3.0125 0.0059
60	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-1.4877 -1.4877 0.1499
50	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-- --

Table 25. ANOVA table of wave V latency data for normally hearing and linear aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	2.19887096	4.60	0.0501
S (Group)	14	6.69666638		
Intensity	5	13.31354028	24.67	0.0001
Grp * Intensity	5	0.28400347	0.53	0.7555
Int * S (Group)	63	6.79888225		

between 100 dB and 70 dB, 100 dB and 60 dB, 100 dB and 50 dB, 90 dB and 60 dB, 90 dB and 50 dB, 80 dB and 50 dB and 70 dB and 50 dB levels. These results are presented in Table 26. Interaction means were not examined because there was no statistically significant interaction effect.

These tests for significance provided an affirmative answer to research question 7: There was a statistically significant difference between mean wave V latency values of normally hearing and hearing impaired groups when the latter utilized either compression or linear amplification.

I. Research question 8

An analysis of variance was performed to determine if statistically significant differences existed among the wave I amplitude means of the normally hearing group and the hearing impaired group in a compression aided listening condition. Group was not statistically significant. An F value of 3.59 for intensity was statistically significant at the 0.05 alpha level. A group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 27.

Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.008 alpha level. No statistically significant differences were observed

Table 26. The results of Bonferroni planned comparisons of intensity levels using wave V latency data from normally hearing and linear aided hearing impaired groups. $t = t$ value and $\alpha =$ significance level.

Level	100	90	80	70	60	50
100	$t =$ $\alpha =$	-1.2285 0.2288	-2.0213 0.0522	-4.0221 0.0004	-4.3763 0.0005	-6.3406 0.0001
90	$t =$ $\alpha =$	-- --	-0.4933 0.6254	-2.1812 0.0371	-3.2964 0.0028	-4.9807 0.0001
80	$t =$ $\alpha =$	-- --	-- --	-1.8672 0.0717	-3.1253 0.0042	-4.9650 0.0001
70	$t =$ $\alpha =$	-- --	-- --	-- --	-1.7062 0.0995	-3.3727 0.0024
60	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-1.1842 0.2484
50	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-- --

Table 27. ANOVA table of wave I amplitude data for normally hearing and compression aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.03260754	2.75	0.1233
S (Group)	12	0.14239088		
Int	3	0.29780965	3.59	0.0299
Grp * Intensity	3	0.13010536	1.57	0.2253
Int * S (Group)	22	0.60826445		

between any comparisons of interest. These results are presented in Table 28. It was not necessary to examine differences between group means or interaction means because neither effect was statistically significant.

An analysis of variance was performed to determine if statistically significant differences existed among the wave I amplitude means of the normally hearing group and the hearing impaired group in a linear aided listening condition. Group, intensity and group by intensity interaction effects were not statistically significant. The ANOVA table is presented in Table 29.

The results of these tests for significance provided a negative answer to research question 8: There were no statistically significant differences between the wave I amplitude means of normally hearing and hearing impaired groups when the latter utilized either compression or linear amplification.

J. Research question 9

An analysis of variance was performed to determine if statistically significant differences existed between wave V amplitude means of the normally hearing group and the hearing impaired group in a compression aided listening condition. Group effect was not statistically significant. An F value of 12.87 for intensity was statistically significant at the 0.05 alpha level. A group by intensity interaction was not statistically

Table 28. The results of Bonferroni planned comparisons of intensity levels using wave I amplitude data from normally hearing and compression aided hearing impaired groups. t = t value and α = significance level.

Level		100	90	80	70
100	t =	--	1.8639	2.1503	2.1519
	α =	--	0.0890	0.0550	0.0522
90	t =	--	--	0.8639	0.8890
	α =	--	--	0.3974	0.3851
80	t =	--	--	--	0.1951
	α =	--	--	--	0.8477
70	t =	--	--	--	--
	α =	--	--	--	--

Table 29. ANOVA table of wave I amplitude data for normally hearing and linear aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.01386096	1.16	0.3044
S (Group)	11	0.13137899		
Intensity	3	0.06431460	1.89	0.1647
Grp * Intensity	3	0.00545282	0.16	0.9215
Int * S (Group)	19	0.21495060		

significant. The ANOVA table is presented in Table 30.

Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were observed between these levels: 100 dB and 70 dB, 100 dB and 60 dB, 100 dB and 50 dB, 90 dB and 50 dB, 80 dB and 50 dB, 70 dB and 50 dB, 60 dB and 50 dB. These results are presented in Table 31. It was not necessary to examine differences among means for group or interaction effects because neither was statistically significant.

An analysis of variance was performed to determine if statistically significant differences existed between wave V amplitude means of the normally hearing group and the hearing impaired group in a linear aided listening condition. Group was not statistically significant. An F value of 12.83 for intensity was statistically significant at the 0.05 alpha level. A group by intensity interaction was not statistically significant. The ANOVA table is presented in Table 32.

Comparisons were made between intensity levels to determine where statistically significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were

Table 30. ANOVA table of wave V amplitude data for normally hearing and compression aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.05979646	1.00	0.3342
S (Group)	14	0.83685904		
Intensity	5	1.14795909	12.87	0.0001
Grp * Intensity	5	0.01111869	0.12	0.9864
Int * s (Group)	64	1.14141067		

Table 31. The results of Bonferroni planned comparisons of intensity levels using wave V amplitude data from normally hearing and compression aided hearing impaired groups. $t = t$ value and $\alpha =$ significance level.

Level	100	90	80	70	60	50
100	$t =$ $\alpha =$	-- 2.0023 0.0544	2.9567 0.0073	3.7784 0.0014	3.9442 0.0011	5.2784 0.0001
90	$t =$ $\alpha =$	-- --	1.1999 0.2396	2.3199 0.0301	2.5727 0.0189	4.6719 0.0002
80	$t =$ $\alpha =$	-- --	-- --	1.0963 0.2817	1.3333 0.1973	3.8534 0.0010
70	$t =$ $\alpha =$	-- --	-- --	-- --	0.2208 0.8268	3.5607 0.0015
60	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	4.5137 0.0001
50	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-- --

Table 32. ANOVA table of wave V amplitude data for normally hearing and linear aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	0.01914591	0.32	0.5799
S (Group)	14	0.83464973		
Intensity	5	1.06749444	12.83	0.0001
Grp * Intensity	5	0.04170556	0.50	0.7740
Int * S (Group)	63	1.04803433		

observed between these levels: 100 dB and 60 dB, 100 dB and 50 dB, 90 dB and 50 dB, 80 dB and 50 dB, 70 dB and 50 dB. These results are presented in Table 33. It was not necessary to examine differences among means for group or interaction effects because neither was statistically significant.

The results of these tests for significance provided a negative answer to research question 9: No statistically significant differences were observed in mean wave V amplitude values between normally hearing and hearing impaired groups when the latter utilized either compression or linear amplification.

K. Research question 10

An analysis of variance was performed to determine if statistically significant differences existed between magnitude estimation means of the normally hearing group and the hearing impaired group in a compression aided listening condition. An F value of 4.38 for group was statistically significant at the 0.05 alpha level. An F value of 46.87 for intensity was statistically significant at the 0.05 alpha level. An F value of 3.36 for a group by intensity interaction was statistically significant at the 0.05 alpha level. The ANOVA table is presented in Table 34.

With respect to group, it was not necessary to use Bonferroni planned comparisons to detect differences among

Table 33. The results of Bonferroni planned comparisons of intensity levels using wave V amplitude data from normally hearing and linear aided hearing impaired groups. $t = t$ value and $\alpha =$ significance level.

Level	100	90	80	70	60	50
100	$t =$ $\alpha =$	1.6015 0.1198	2.6188 0.0165	3.1449 0.0057	3.3543 0.0036	4.6101 0.0002
90	$t =$ $\alpha =$	-- --	1.3168 0.1979	2.0971 0.0477	2.4213 0.0243	4.3408 0.0002
80	$t =$ $\alpha =$	-- --	-- --	0.8833 0.3841	1.2595 0.2186	3.6362 0.0012
70	$t =$ $\alpha =$	-- --	-- --	-- --	0.5163 0.6098	3.5117 0.0017
60	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	3.0308 0.0060
50	$t =$ $\alpha =$	-- --	-- --	-- --	-- --	-- --

Table 34. ANOVA table of ME data for normally hearing and compression aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	704.05833750	4.28	0.0576
S (Group)	14	2303.23702917		
Intensity	5	23178.68582083	46.87	0.0001
Grp * Intensity	5	1663.99150000	3.36	0.0088
Int * S (Group)	70	6923.70764583		

the means. Magnitude estimation means for the hearing impaired group using compression amplification were greater than those for the normally hearing group. Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were observed between 100 dB and all other levels and between 90 dB and all other levels. Alpha levels are presented in Table 35. Comparisons of interest for the group by intensity interaction were between each group at each intensity level. The only statistically significant difference occurred between groups at the 100 dB level. Alpha levels are presented in Table 36.

An analysis of variance was performed to determine if statistically significant differences existed between magnitude estimation means of the normally hearing group and the hearing impaired group in a linear aided listening condition. An F value of 6.70 for group was statistically significant at the 0.05 alpha level. An F value of 46.15 for intensity was statistically significant at the 0.05 alpha level. An F value of 4.48 for a group by intensity interaction was statistically significant at the 0.05 alpha level. The ANOVA table is presented in Table 37.

Bonferroni planned comparisons to examine group means

Table 35. The results of Bonferroni planned comparisons of intensity levels using magnitude estimation data from normally hearing and compression aided hearing impaired groups. α = significance level.

Level	100	90	80	70	60	50
100	$\alpha =$ --	0.0001	0.0001	0.0001	0.0001	0.0001
90	$\alpha =$ --	--	0.0014	0.0001	0.0001	0.0001
80	$\alpha =$ --	--	--	0.1838	0.0409	0.0155
70	$\alpha =$ --	--	--	--	0.4617	0.2590
60	$\alpha =$ --	--	--	--	--	0.6919
50	$\alpha =$ --	--	--	--	--	--

Table 36. The results of Bonferroni planned comparisons of interest for the group by intensity interaction using magnitude estimation data from normally hearing and compression aided hearing impaired groups.

Comparison between groups at:	Pr > /t/
100 dB	0.0001
90 dB	0.1871
80 dB	0.9640
70 dB	0.8426
60 dB	0.8227
50 dB	0.9720

Table 37. ANOVA table of ME data for normally hearing and linear aided groups.

Source	df	Type IV SS	F value	Pr > F
Group	1	1408.29100104	6.70	0.0214
S (Group)	14	2941.32715625		
Intensity	5	26279.50952188	46.15	0.0001
Grp * Intensity	5	2550.12178021	4.48	0.0013
Int * S (Group)	70	7972.25138125		

were not necessary. The hearing impaired group using linear amplification had larger magnitude estimation values. Comparisons were made between intensity levels to determine where significant differences existed between levels. Bonferroni planned comparisons were used to determine statistical significance at a 0.003 alpha level. Statistically significant differences were observed between 100 dB and all other intensity levels and between 90 dB and all other intensity levels. Alpha levels are presented in Table 38. Comparisons of interest for the group by intensity interaction were between each group at each intensity level. The only statistically significant difference occurred between groups at the 100 dB level. Alpha levels are presented in Table 39.

The results of these tests for significance provide an affirmative answer to research question 10: There was a statistically significant difference between mean magnitude estimation values of normally hearing and hearing impaired groups when the latter utilized either compression or linear amplification.

L. Analysis of amplification conditions

Separate analyses of variance were performed using each dependent variable to determine if statistically significant differences existed between the three amplification conditions: unaided, compression aided and linear aided. Statistically significant differences

Table 38. The results of Bonferroni planned comparisons of intensity levels using magnitude estimation data from normally hearing and linear aided hearing impaired groups.
 α = significance level.

Level	100	90	80	70	60	50
100	α = --	0.0001	0.0001	0.0001	0.0001	0.0001
90	α = --	--	0.0004	0.0001	0.0001	0.0001
80	α = --	--	--	0.2368	0.0664	0.0286
70	α = --	--	--	--	0.5042	0.3008
60	α = --	--	--	--	--	0.7117
50	α = --	--	--	--	--	--

Table 39. The results of Bonferroni planned comparisons of interest for the group by intensity interaction using magnitude estimation data from normally hearing and linear aided hearing impaired groups.

Comparison between groups at:	Pr > /t/
100 dB	0.0001
90 dB	0.0317
80 dB	0.9256
70 dB	0.7505
60 dB	0.7131
50 dB	0.8482

between groups were not obtained for any dependent variable. The ANOVA tables are presented in Tables 40 through 44.

M. Research questions 11 through 18

Pearson product moment correlations were determined to examine correlations between the magnitude estimation data and the ABR data. Results are presented in Table 45. The results of these statistical tests provided answers to research questions 11 through 18 which dealt with correlations between magnitude estimation and intensity-amplitude or intensity-latency data. The magnitude of the correlations were described using guidelines suggested by Guilford (1956).

Between groups and across amplification conditions there was a low/moderate negative correlation between magnitude estimation and wave I latency data. The correlations between magnitude and wave I latency data for the normally hearing group and the hearing impaired group using compression amplification were significant at the 0.05 alpha level. Compared to these correlations, correlations between magnitude estimation and wave V latency data were slightly stronger. Correlations between magnitude estimation and wave V latency data were statistically significant at the 0.05 alpha level for both groups and whether the hearing impaired were aided or unaided. Moderate correlations between magnitude

Table 40. ANOVA table of wave I latency data for all levels of amplification.

Source	df	Type IV SS	F value	Pr > F
Subjects	7	1.33007912		
Amplitude	2	0.35893333	1.60	0.2547
Amp * Subjects	9	1.01060290		
Intensity	3	0.98371244	15.29	0.0001
Int * Subjects	15	0.32165145		
Amp * Intensity	6	0.06851111	0.41	0.8491
Amp * Int * S	6	0.16723586		

Table 41. ANOVA table of wave V latency data for all levels of amplification.

Source	df	Type IV SS	F value	Pr > F
Subjects	7	8.43761401		
Amplitude	2	0.31411138	0.62	0.5528
Amp * Subjects	14	3.55475929		
Intensity	5	6.38487619	7.46	0.0001
Int * Subjects	30	5.13375508		
Amp * Intensity	9	0.89233585	1.13	0.3597
Amp * Int * S	49	4.29583924		

Table 42. ANOVA table of wave I amplitude data for all levels of amplification.

Source	df	Type IV SS	F value	Pr > F
Subjects	7	0.16062223		
Amplitude	2	0.07913981	0.92	0.4344
Amp * Subjects	9	0.38872536		
Intensity	3	0.35926912	21.92	0.0001
Int * Subjects	15	0.08195830		
Amp * Intensity	6	0.30438194	4.56	0.0435
Amp * Int * S	6	0.06670408		

Table 43. ANOVA table of wave V amplitude data for all levels of amplification.

Source	df	Type IV SS	F value	Pr > F
Subjects	7	0.429062663		
Amplitude	2	0.00980663	0.41	0.6683
Amp * Subjects	14	0.16546938		
Intensity	5	0.48413571	11.01	0.0001
Int * Subjects	30	0.26372471		
Amp * Intensity	9	0.03525614	0.43	0.9109
Amp * Int * S	49	0.44376893		

Table 44. ANOVA table of ME data for all levels of amplification.

Source	df	Type IV SS	F value	Pr > F
Subjects	7	6171.40515486		
Amplitude	2	218.79005139	1.53	0.2516
Amp * Subjects	14	1004.00135972		
Intensity	5	71585.96142014	1.89	0.0001
Int * Subjects	35	16922.42560764		
Amp * Intensity	10	1058.10252361	0.16	0.0821
Amp * Int * S	70	4180.62746528		

Table 45.

Correlations between magnitude estimation and all other dependent variables with data separated by group and amplification condition. r = value from the Pearson product moment correlation. α = significance level. n = number of observations. * denotes statistical significance at a .05 alpha level.

Dependent variables	Normally hearing	Hearing impaired (unaided)	Hearing impaired (compression)	Hearing impaired (linear)
ME and W I lat	$r = -0.45380$ $\alpha = 0.0070 (*)$ $n = 34$	-0.34659 0.0765 27	-0.42767 0.0531 21	-0.34722 0.2048 15
ME and W V lat	$r = -0.57516$ $\alpha = 0.0001 (*)$ $n = 60$	-0.41120 $0.0062 (*)$ 43	-0.52024 $0.0001 (*)$ 53	0.44238 $0.0012 (*)$ 51
ME and W I amp	$r = 0.59832$ $\alpha = 0.0002 (*)$ $n = 34$	0.41227 $0.0326 (*)$ 27	0.73272 $0.0002 (*)$ 21	0.50924 0.0525 15
ME and W V amp	$r = 0.73349$ $\alpha = 0.0001 (*)$ $n = 60$	0.64966 $0.0001 (*)$ 43	0.66273 $0.0001 (*)$ 53	0.60670 $0.0001 (*)$ 51

estimation and wave I amplitude data were observed for the normally hearing group and for the hearing impaired group in unaided or linear aided listening conditions. A high correlation between magnitude estimation and wave I amplitude was noted for the hearing impaired group when compression amplification was used. All correlations between magnitude estimation and wave I amplitude data were statistically significant. The strongest correlations were observed between magnitude estimation and wave V amplitude data. Moderate correlations were noted for the hearing impaired group whether aided or unaided and a high correlation was noted for the normally hearing group.

N. Summary

In summary, statistically significant differences were found between the normally hearing group and the hearing impaired group using no amplification for magnitude estimation and wave I latency data. No statistically significant differences were noted between these groups for wave V latency, wave I amplitude or wave V amplitude data. The linear amplification condition yielded no statistically significant difference between normally hearing and hearing impaired groups with respect to wave I latency. Statistically significant differences continued to be noted between groups for magnitude estimation data when hearing impaired subjects used either compression or

linear amplification. Compression and linear amplification conditions yielded a statistically significant difference between normally hearing and hearing impaired groups for wave V latency when there previously had been no statistically significant difference. When the three amplification conditions were examined, no statistically significant differences were found between unaided and aided conditions. Only two strong correlations existed between magnitude estimation and the other four dependent variables. High correlations were observed between magnitude estimation and wave I amplitude data for the hearing impaired group when compression amplification was used and between magnitude estimation and wave V amplitude data for the normally hearing group.

CHAPTER VI

DISCUSSION

The purpose of this study was to examine the relationships between ABR wave I and wave V intensity-latency and intensity-amplitude functions and the magnitude estimation function of loudness in normally hearing and hearing impaired individuals. Responses were obtained from hearing impaired individuals in unaided and aided (compression;linear) amplification conditions to determine if the use of amplification caused intensity functions generated by the hearing impaired individuals to more closely approximate the functions generated by normally hearing persons. ABR and ME intensity functions were also examined to determine if amplification had similar effects on electrophysiological and psychophysical responses.

The answers to research questions one through ten which used the F statistic to examine the effect of amplification on normalizing the intensity functions of hearing impaired subjects are presented in Table 46. It was assumed that the degree of sensorineural hearing loss exhibited by the hearing impaired group would cause the responses of that group when using no amplification to differ from those with normal hearing, but statistical

Table 46. Answers to research questions one through ten which utilized analysis of variance to examine between group differences.

Dependent variable	Statistical significance between groups with HI unaided	Statistical significance between groups with HI using compression.	Statistical significance between groups with HI using linear.
Wave I latency	yes	yes	no
Wave V latency	no	yes	yes
Wave I amplitude	no	no	no
Wave V amplitude	no	no	no
Magnitude estimation	yes	yes	yes

significance between groups did not occur for all dependent variables. It was also assumed that the use of amplification could cause the intensity functions of the hearing impaired group to approach normal values and result in statistical non-significance when comparisons between groups were made, but this was not always observed. When comparisons of F values were made, none of the ABR data produced the same statistical results across amplification conditions as the magnitude estimation data. No clear relationship between ABR and ME data was inferred from the results of analysis of variance and several factors were considered when interpreting the results of the statistical tests. These factors were subject selection, sample size and variance.

A. Description and analysis of intensity functions

Wave I intensity-latency functions representing normally hearing, unaided and aided (compression;linear) hearing impaired mean data are presented in Figure 9. Hearing impaired curves for all amplification conditions are displaced above the normally hearing curve indicating longer latency values. Data points from the unaided and compression aided amplification conditions for the hearing impaired ran parallel to the intensity function for the normally hearing group with the compression aided condition showing the closest similarity to the normative data. Comparison of these functions suggested that

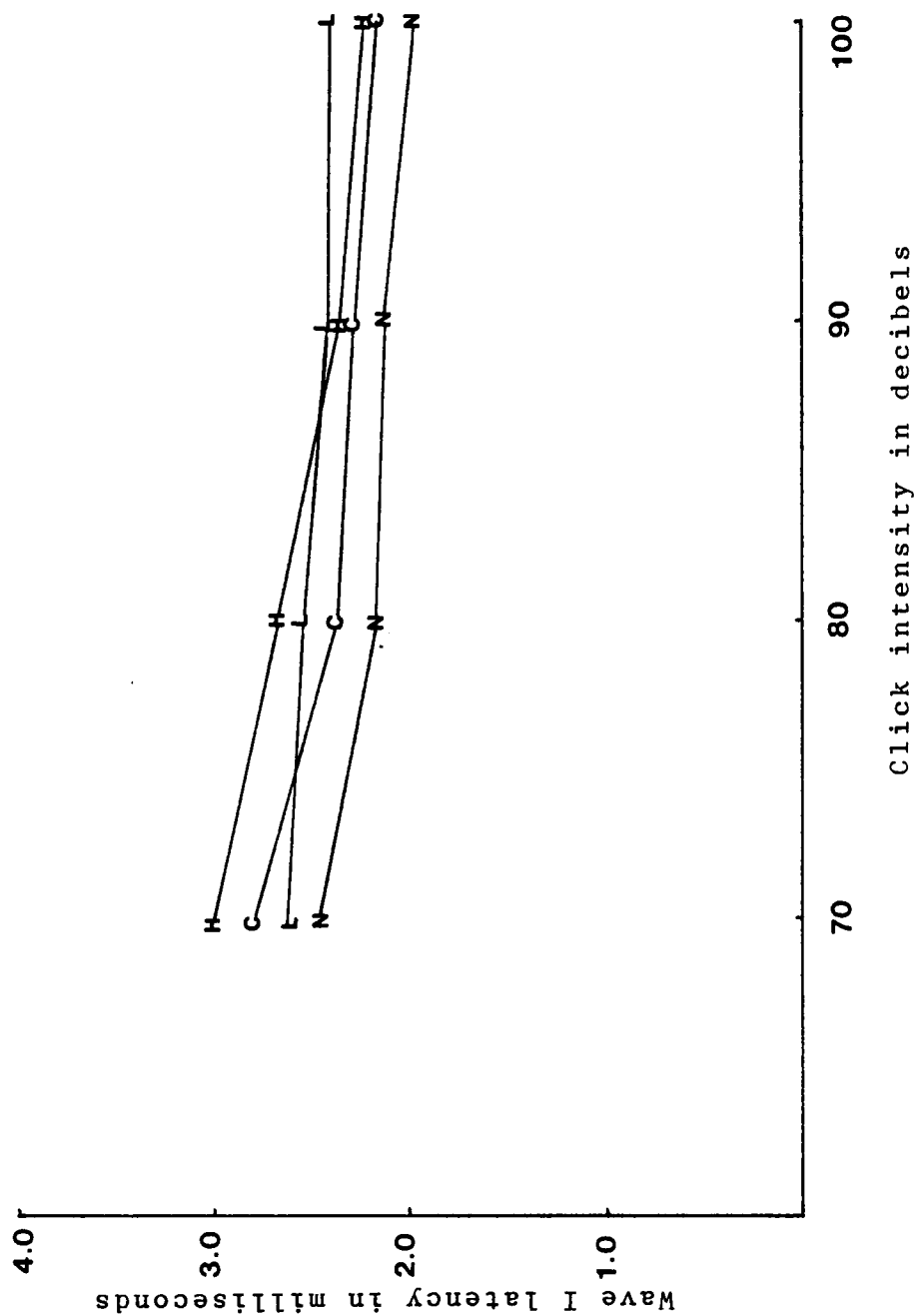


Figure 9. Wave I intensity-latency functions. N = normally hearing; H = hearing impaired; C = hearing impaired using compression amplification; L = hearing impaired using linear amplification.

differences between groups were related to hearing sensitivity and that compression amplification provided partial compensation. This trend was not observed with linear aided data.

With linear amplification, wave I latency values changed very little across intensity levels and by 100 dB all other conditions exhibited shorter wave I latencies. Linear amplification should cause a hearing aid to reach its saturation level at a lower input intensity than compression amplification. Once saturation is reached, further increases in input level result in peak clipping of the output. Pollack (1975) stated that peak clipping causes more signal distortion than compression amplification. If linear amplification at high intensity levels results in more distortion of the click stimuli, then increased intensity would produce longer ABR latencies.

Analysis of variance revealed a statistically significant difference between the normally hearing group and the hearing impaired group when the hearing impaired used no amplification or compression amplification. No significant difference was estimated for normally hearing and hearing impaired groups when the hearing impaired used linear amplification. Although there was the temptation to interpret these data to mean that the use of linear amplification caused the wave I intensity-latency function

to normalize, it was more likely that large variance caused the statistical results. Figure 9 revealed that mean values for the linear aided condition were displaced farther from the normally hearing means than the means for the compression aided condition at 80 dB, 90 dB and 100 dB. It was concluded that a large variance made it impossible to detect differences which existed between the normally hearing group and the hearing impaired group using linear amplification.

Wave V intensity-latency functions are presented in Figure 10. With the exception of linear aided at 50 dB, mean wave V latencies for hearing impaired whether aided or unaided were longer than the means for the normally hearing group. When mean wave V latencies of the unaided hearing impaired condition were compared to means of the normally hearing group, the largest difference between means occurred at 60 dB. It has previously been reported that the difference in wave V latency between sensorineural and normal ears is greatest at low intensity levels (Galambos and Hecox, 1978). When mean wave V latencies of compression aided and linear aided conditions were compared to the normally hearing data, large differences between means occurred from 60 dB to 90 dB and smaller differences occurred at 50 dB and 100 dB. Small differences between the normally hearing group and the hearing impaired group using either compression or linear

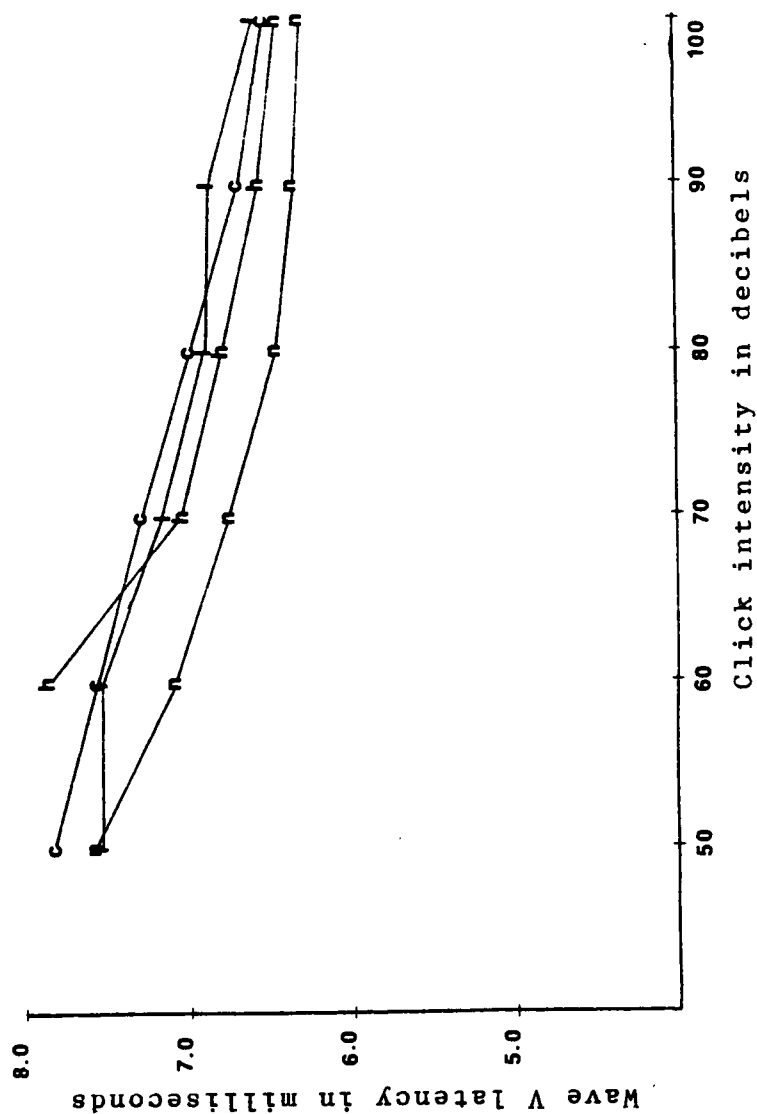


Figure 10. Wave V intensity-latency functions. n = normally hearing; h = hearing impaired; c = hearing impaired using compression amplification; l = hearing impaired using linear amplification.

amplification at 100 dB were expected, but the pattern from 50 dB to 90 dB was surprising. Since the utilization of both compression and linear amplification caused the appearance of wave V at near normal latencies at 50 dB, it was expected that aided wave V latency would have continued to occur at near normal latencies above 50 dB. Instead, compression and linear mean data from 60 dB to 100 dB looked more like unaided hearing impaired data. In the linear aided condition, there was a slower shift in wave V latency as intensity increased and this was attributed to the deleterious effects of peak clipping on signal processing.

Since the unaided hearing impaired data was most similar to the normally hearing data at four out of six intensity levels, it was not surprising that analysis of variance found no statistically significant differences between groups. Statistical significance occurred between groups when the hearing impaired used either compression or linear amplification. These findings were just the opposite of what would be expected if the use of amplification normalized wave V intensity-latency functions.

Although the introduction of amplification did not produce a normalizing effect on wave V latency from 60 dB to 100 dB, at 50 dB the use of either compression or linear amplification by the hearing impaired group

resulted in the appearance of wave V where there had previously been none. Kileny (1982) used wave V threshold to estimate a hearing aid's effectiveness. If wave V threshold could be improved, then a hearing aid was thought to be beneficial. Although the present study did not measure wave V threshold, the appearance of wave V at a level where it had not previously been seen was interpreted to mean that amplification provided improved sensitivity.

Wave I intensity-amplitude functions are presented in Figure 11. Wave I amplitude values for hearing impaired listeners in all amplification conditions tended to be smaller than those for the normally hearing group. With hearing loss the sensation level of the clicks would be reduced causing activation of fewer nerve fibers which, in turn, could account for a reduction in the amplitude of the ABR waves. Comparison of means for normally hearing and hearing impaired (unaided) groups revealed that large differences between means occurred at 70 dB and 80 dB, but means were almost identical at 90 dB and 100 dB. The disparity between groups at the lower intensity levels was consistent with trends observed in wave I and wave V latency data. The introduction of compression and linear amplification had differential effects on wave I amplitude. At 70 dB, 80 dB and 90 dB, wave I amplitude means for the compression aided hearing impaired group

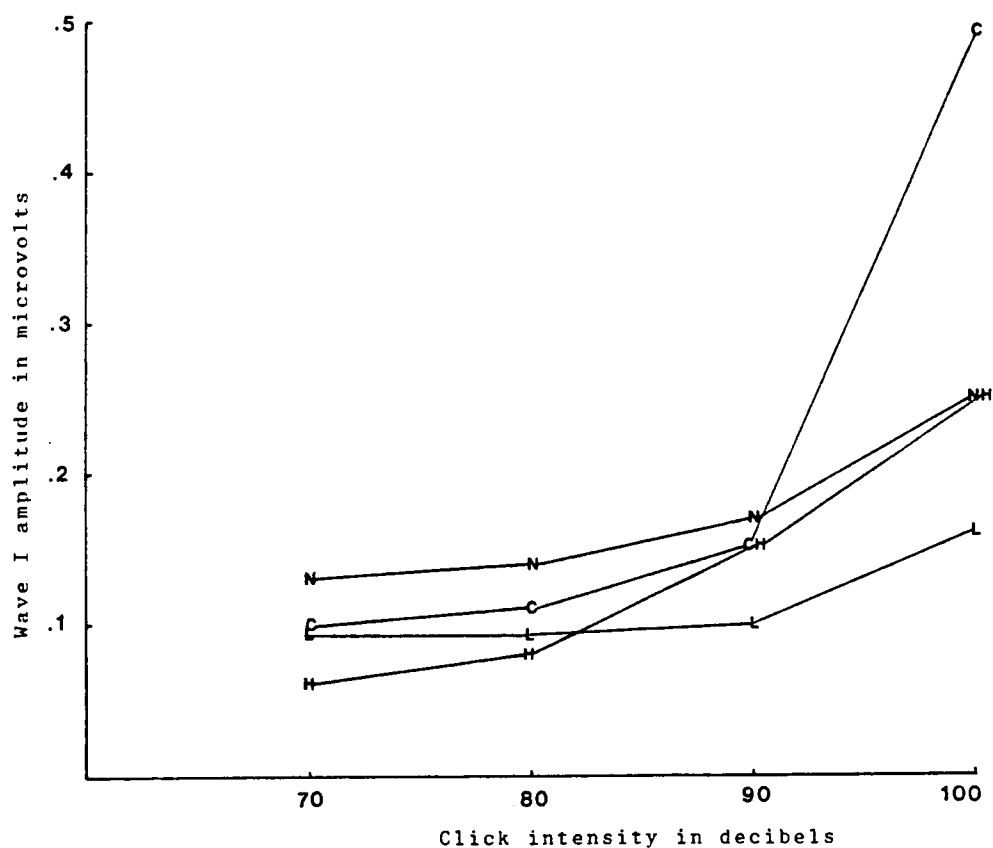


Figure 11. Wave I intensity-amplitude functions. N = normally hearing; H = hearing impaired; C = hearing impaired using compression amplification; L = hearing impaired using linear amplification.

were very close to the means of the normally hearing group. At 100 dB, an extremely large wave I amplitude mean was recorded for the compression aided condition. Two outlier scores (hearing impaired listeners #1 and #3) were responsible for this large difference. With linear amplification, wave I amplitude means were never as close to the normally hearing means as the compression aided condition and showed progressive departure from normally hearing means as intensity increased. Linear aided mean values increased with increases in intensity, but the rate of change was slower than all other conditions. Large ABR amplitudes should occur with high intensity stimulation, but signal distortion would reduce the effect of increased intensity. It was stated previously that linear amplification produces more signal distortion with higher input intensities than compression amplification.

Differences between the normally hearing group and the hearing impaired group whether aided or unaided for wave I amplitude were not statistically significant. Like some of the other non-significant comparisons obtained in this study, these findings were attributed to small sample size and large variance which would obscure between group differences analyzed by analysis of variance.

Statistical analyses of wave V amplitude data revealed non-significance between the normally hearing group and the hearing impaired group in any amplification condition.

Visual inspection of wave V intensity-amplitude functions presented in Figure 12 revealed more overlap between functions than had been observed in wave I and wave V latency and wave I amplitude data. Statistical non-significance could be attributed to either failure of subject selection criteria to differentiate groups or the inherent variability of ABR amplitude which created large variance within the statistical tests.

While intensity functions generated for wave I latency, wave V latency and wave I amplitude by the normally hearing group and the hearing impaired group using no amplification revealed greater disparity at lower intensities, wave V amplitude data revealed large differences between groups at high and low intensities. It was difficult to discern distinctive patterns from the intensity functions in Figure 12. No one amplification condition for the hearing impaired group approximated the normally hearing means across intensity levels. At 50 dB and 70 dB, the means for the compression aided condition were closest to the normally hearing means. At 60 dB, 80 dB and 90 dB, the means for the linear aided condition were closest to the normally hearing means. At 100 dB, the unaided hearing impaired mean was the closest to the normally hearing mean. When the hearing impaired intensity functions were compared to each other, the means generated with compression amplification followed the

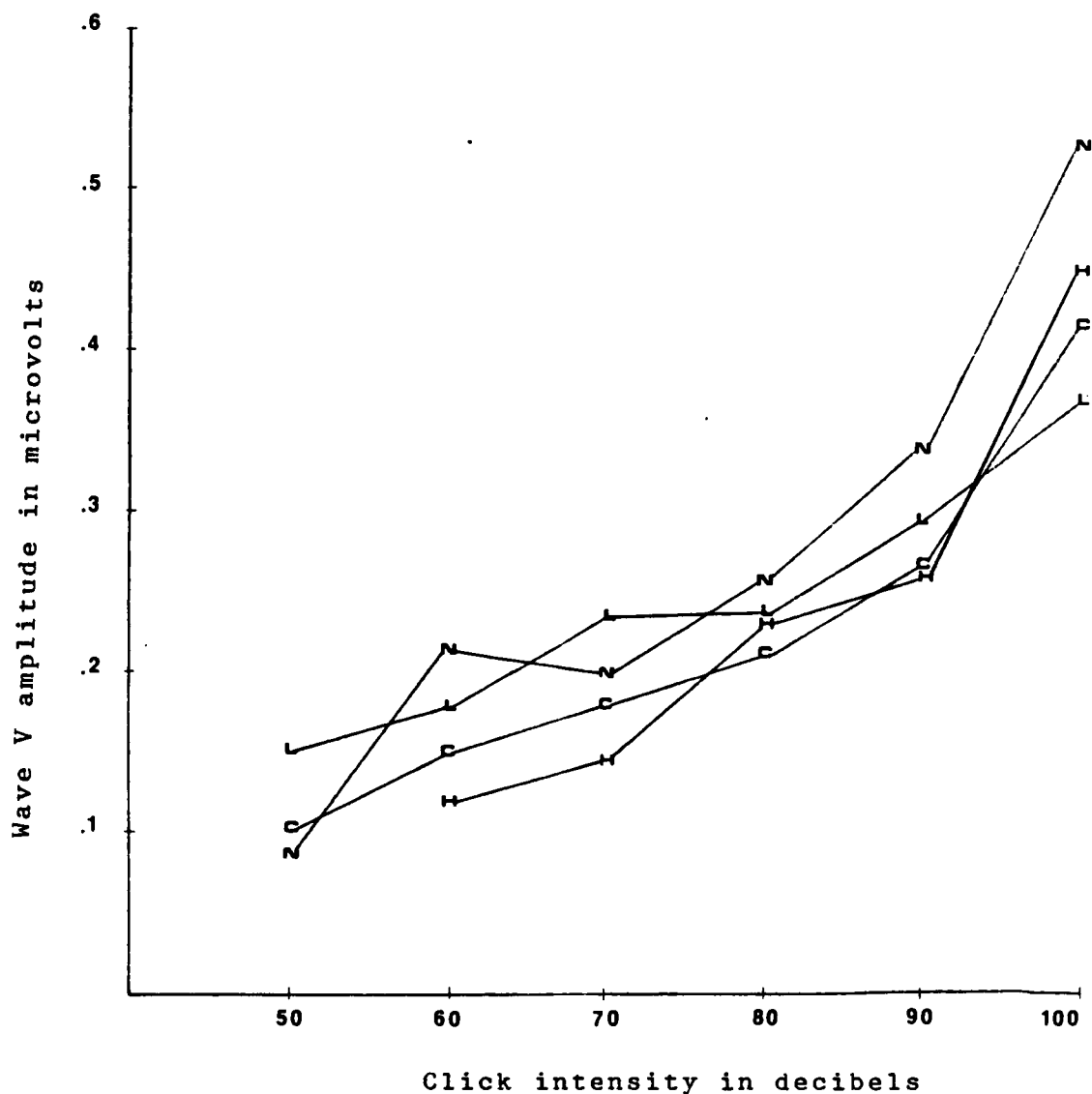


Figure 12. Wave V intensity-amplitude functions. N = normally hearing; H = hearing impaired; C = hearing impaired using compression amplification; L = hearing impaired using linear amplification.

unaided hearing impaired means more closely than the means for the linear aided condition. The use of linear amplification resulted in slower growth of wave V amplitude with increased intensity and this finding was attributed to the deleterious effects of peak clipping.

Statistical analyses of magnitude estimation data revealed significant differences between the normally hearing group and the hearing impaired group whether the hearing impaired were aided or unaided. These data, plotted as intensity functions, are presented in Figure 13. The four functions were remarkably similar at levels below 90 dB with increasingly larger differences at 90 dB and 100 dB levels. The differential effect of group at different intensity levels accounted for the significant interaction effects recorded by analyses of variance.

From 60 dB to 100 dB, mean magnitude estimation values for the hearing impaired group in all amplification conditions were larger than mean values generated by the normally hearing listeners and this difference was attributed to the presence of recruitment. Knight and Margolis (1984) demonstrated that abnormally rapid loudness growth exhibited by some individuals with sensorineural hearing loss caused these individuals to assign larger values to high intensity signals than their normally hearing counterparts. Comparison of mean data between normally hearing and unaided hearing impaired

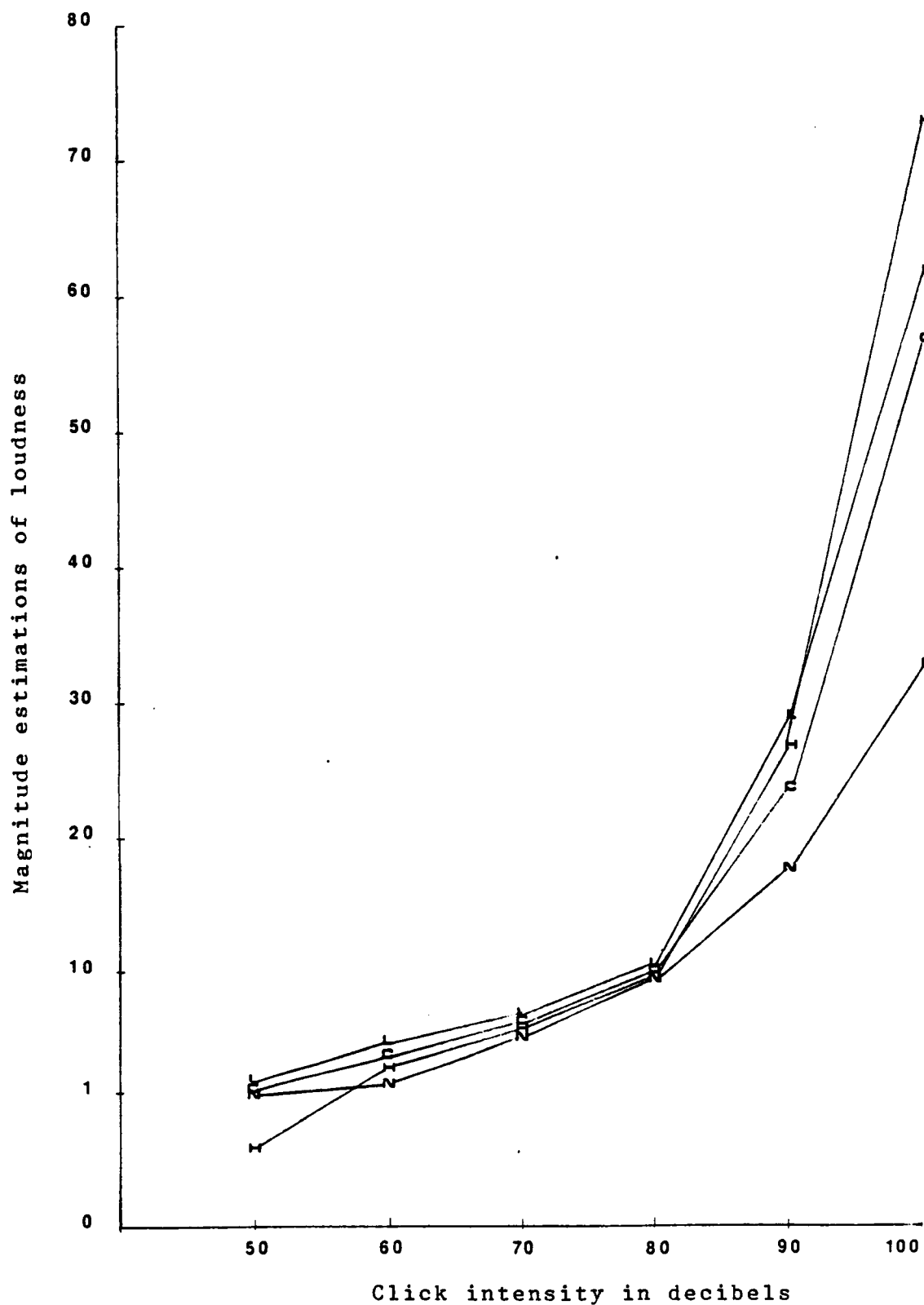


Figure 13. Magnitude estimation functions. N = normally hearing; H = hearing impaired; C = hearing impaired using compression amplification; L = hearing impaired using linear amplification.

groups at 50 dB revealed a larger mean value for the normally hearing group which was attributed to better hearing sensitivity at that level by the normally hearing group. Mean data for the compression aided and linear aided conditions were more similar to the means for the unaided hearing impaired group. With respect to compression, Margolis (1985) reported that magnitude estimation functions obtained from compression aided hearing impaired listeners were often more similar to their unaided responses rather than the normal responses. He attributed this finding to inadequacy of present compression systems to produce appropriate output limiting.

When intensity functions for ABR and magnitude estimation were compared, the differences between them were more obvious than their similarities. While magnitude estimation values increased with increasing intensity, ABR wave I and wave V latencies decreased. When the amplification conditions of the hearing impaired group were compared to the normally hearing data, greater disparity from normal occurred at lower intensities for ABR latencies and at higher intensities for magnitude estimations. When ABR wave I and wave V intensity-amplitude functions were compared to the magnitude estimation functions, all functions tended to increase with increasing intensity, but the effects of

amplification caused very different growth patterns for the electrophysiological data. For example, while the rate of change in ABR amplitude for the linear aided amplification condition was slower than the other conditions, this did not hold true when magnitude estimation functions were recorded. Although these findings should be interpreted with caution because of the effects of large variance, they were in agreement with Wilson and Stelmack (1982) and Pratt and Sohmer (1977) who concluded that loudness information was not reflected in any components of the ABR.

B. Electrophysiological plateaus

A plateau of flattening of slope was observed in several of the ABR intensity functions. The occurrence of plateaus in electrophysiological research has been reported by investigators using electrocochleography (Charlet de Sauvage and Aran, 1976) and ABR audiometry (Kileny, 1982; Cox and Metz, 1980). Examination of the intensity-latency functions revealed that the normally hearing and linear aided hearing impaired groups exhibited plateaus. All groups exhibited plateaus in the intensity-amplitude functions. This plateau or flattening could be explained physiologically or acoustically.

Charlet de Sauvage and Aran (1976) recorded wave I (N1) intensity-amplitude functions and observed plateaus in data from normally hearing individuals and, to a lesser

extent, from individuals with various hearing disorders. It was suggested that the existence of plateaus at moderate intensity levels was related to inner and outer hair cell function. The more sensitive outer hair cells are stimulated by low intensity levels and, in turn, stimulate the neural fibers associated with them. As stimulus intensity is increased, more outer hair cells are stimulated causing an increase in the amplitude of the neural response and a decrease in its latency. When a stimulus level which causes maximum outer hair cell stimulation is increased, no further changes in the neural response will occur until that level is sufficient to stimulate inner hair cells.

Kileny (1982) suggested that if the basal portion of the cochlea, which is the primary response region for an ABR obtained at moderate or high intensities, was maximally stimulated at a given intensity level, increasing that level would not cause further decrease in latency. Although he was referring to wave V latency, this explanation should also apply to wave I latency changes since the entire ABR is initially generated from the same site in the cochlea.

An acoustic explanation for the existence of plateaus in the electrophysiological functions concerned limitations of the transducers. If a loudspeaker which transduces the stimulus is driven maximally at some level,

further increase in signal amplitude would result in distortion of the signal as it is transduced. A distorted signal might have changes in its rise time and duration of sufficient magnitude to cause increase in latency and decrease in amplitude rather than the reverse (Gorga, Abbas and Worthington, 1985; Hecox, Squires and Galambos, 1976). Further signal degradation occurs with the introduction of a hearing aid (Kileny, 1982).

If Kileny's physiological explanation or an acoustical explanation were appropriate then plateaus would have occurred only at higher intensity levels. Most of the plateaus observed in the functions presented in Figures 9 through 12 occurred at moderate intensities and, therefore, could be explained on the basis of inner and outer hair cell function. Three exceptions to this trend of plateaus at moderate intensities revealed plateaus at high intensity levels. These involved wave V latency data of normally hearing and linear aided hearing impaired groups and wave I amplitude data of the unaided hearing impaired group.

When intensity functions were examined for individual listeners, different patterns emerge. For many of the normal hearing listeners, plateaus in wave I and wave V latency occurred between 90 dB and 100 dB, but these plateaus were not observed for wave I and wave V amplitude at those levels. For both groups and under all conditions

of amplification, there were instances where plateaus existed for latency at one level and amplitude at another. In other cases, two plateaus existed within the same function. Perhaps acoustical and physiological explanations were necessary to interpret these data.

Plateaus were not observed in the magnitude estimation functions and this finding was in agreement with the results of Cazals and Stevens (1975). The absence of plateaus in psychophysical functions would support the theory that loudness perception was not reflected in ABR intensity functions.

C. Psychophysical power functions

In Figure 14 magnitude estimation data were plotted on a log/log plot forming straight line functions. These straight line functions demonstrated that loudness grew as a power function of intensity. The exponent of the function for the normally hearing group was 0.6. This value was greater than the exponent value of 0.48 determined by Raab and Osman (1962), but these investigators used single clicks for stimuli rather than a continuous click train. When compared to exponents determined for continuous stimuli, the value of 0.6 agreed favorably with Stevens and Guiaro, 1962; and Stevens, 1956.

The exponents for the hearing impaired under all amplification conditions were larger than 0.6 indicating

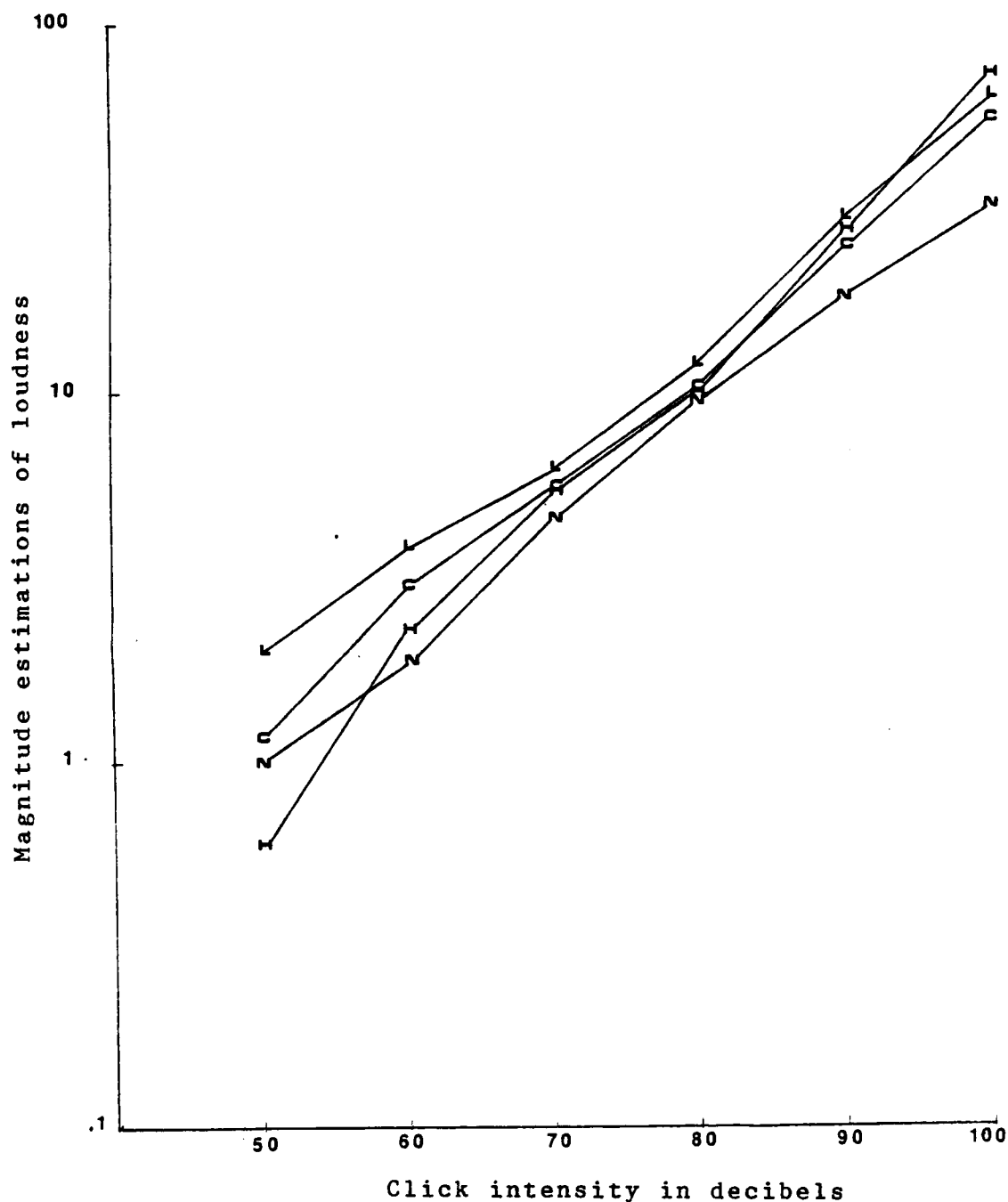


Figure 14. Magnitude estimation data plotted as power functions. N = normally hearing; H = hearing impaired; C = hearing impaired using compression amplification; L = hearing impaired using linear amplification.

steeper slopes. The following values 1.14, 0.91 and 1.01 were obtained for the unaided, compression aided and linear aided data, respectively. Although the exponent of the function for the compression aided condition was the smallest, it was still quite different from the exponent of the function for the normally hearing group.

D. Intensity effects

The most consistent finding from the analyses of variance was a significant main effect for intensity. As intensity decreased, ABR latencies increased and ABR amplitudes, in general, decreased and magnitude estimation values decreased. These findings reflected the characteristic changes which occur in the ABR and loudness perception as stimulus intensity is changed.

The change in latency as a function of intensity has been reported by many investigators and is considered a reliable phenomenon (Schwartz and Berry, 1985). This latency shift with decreasing intensity has been attributed to reduction in neural firing (Picton, Woods, Baribeau-Braun and Healey, 1977). ABR amplitude, on the other hand, is not considered as stable or reliable because it can be influenced by myogenic activity, noise level, and minor alterations in recording technique (Schwartz and Berry, 1985). In the present study, wave I and wave V latencies increased as stimulus intensity decreased, but amplitude, in some cases, fluctuated

slightly between decreasing and increasing. These findings were in agreement with previous literature (Schwartz and Berry, 1985) and suggested that ABR latencies and amplitudes were not the physiological correlates of loudness growth. ABR latency had an inverse relationship with intensity while loudness perception did not. Although ABR amplitude and loudness perception both increased with increases in intensity, the fluctuations which appeared in the ABR intensity-amplitude functions were not present in the magnitude estimation functions.

E. Analysis of amplification conditions

Analysis of variance was also used to determine if statistically significant differences existed between amplification conditions in the hearing impaired group. No statistically significant differences between amplification conditions were observed for any of the five dependent variables. These findings were not interpreted to mean that the introduction of amplification did not provide benefit to the listeners since the listeners were successful hearing aid users as defined by subject selection criteria. Increased distortion of the click stimuli by the hearing aids or less than optimal hearing aid settings might have prevented distinct separation of the intensity functions for unaided and aided conditions.

The addition of stimulus distortion by the hearing aid transducer was thought to contribute to increased latency

and decreased amplitude which would counteract the effects of increased intensity as the clicks were amplified. A change in click spectrum was recorded with KEMAR wearing a Phonic Ear 805 CD hearing aid, so it is not unreasonable to assume that change in stimulus characteristics after amplification would result in effects on ABR latencies and amplitudes. Unaided and aided click spectra are presented in Figures 15 and 16.

Inadequate hearing aid gain could also explain the non-significance between groups. Although the hearing impaired listeners in this study were considered successful hearing aid users, the amount of amplification delivered by the hearing aids did not always bring sensitivity up to within normal limits. The average amount of improvement in warbled tone threshold with hearing aids worn at preferred settings is shown in Figure 17. Although further increases in gain may have been desirable, it was noted that the introduction of amplification at preferred settings permitted the recording of ABR wave V and magnitude estimation values greater than zero at 50 dB where these responses had not been previously observed.

In the case of magnitude estimation, inadequate compression could have prohibited the hearing impaired group from attaining normal loudness estimates at 90 dB and 100 dB levels. Kiessling (1982) reported that the

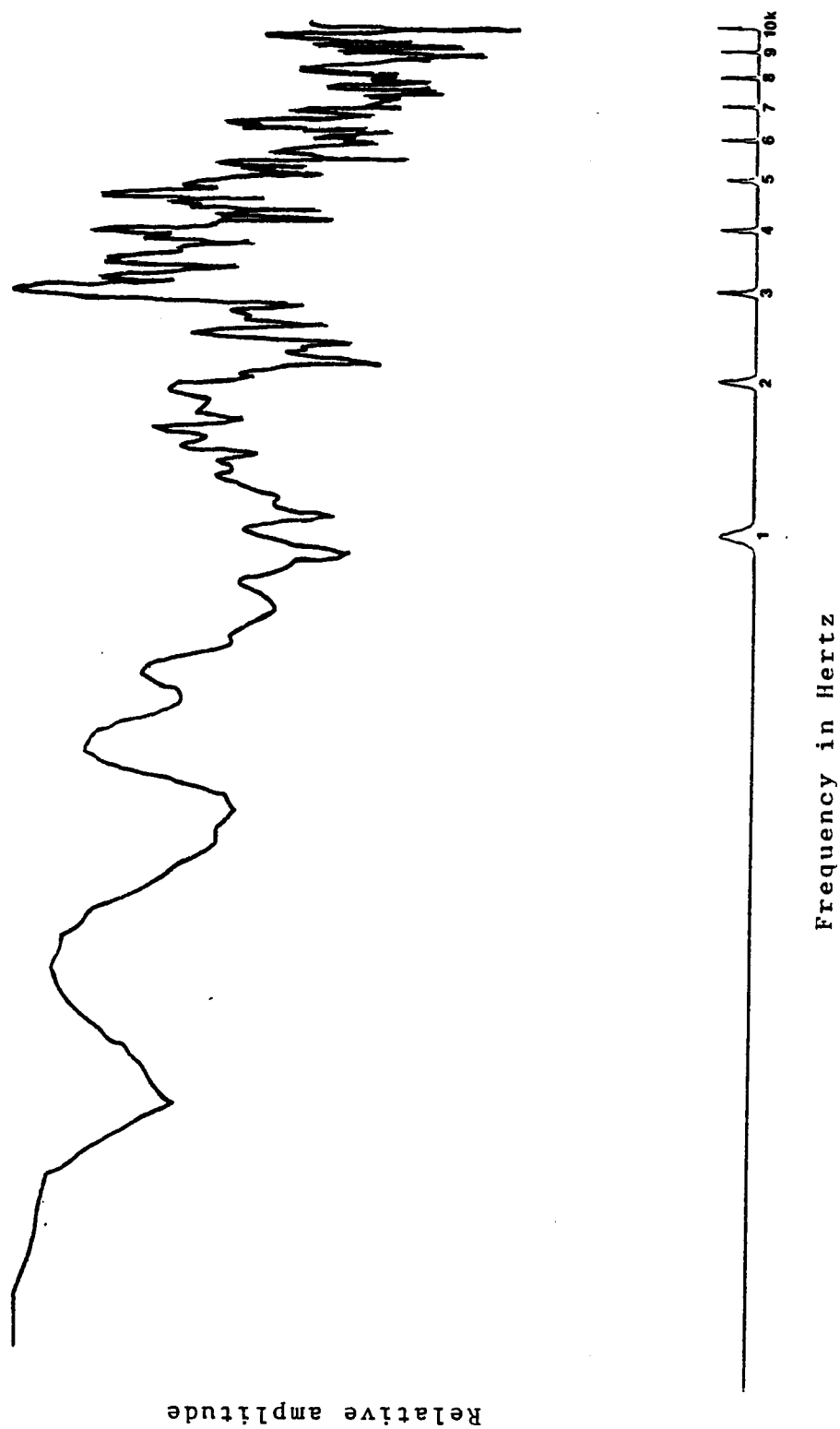


Figure 15. Spectrum of click train produced by Nicolet Compact 4 and recorded through KEMAR.

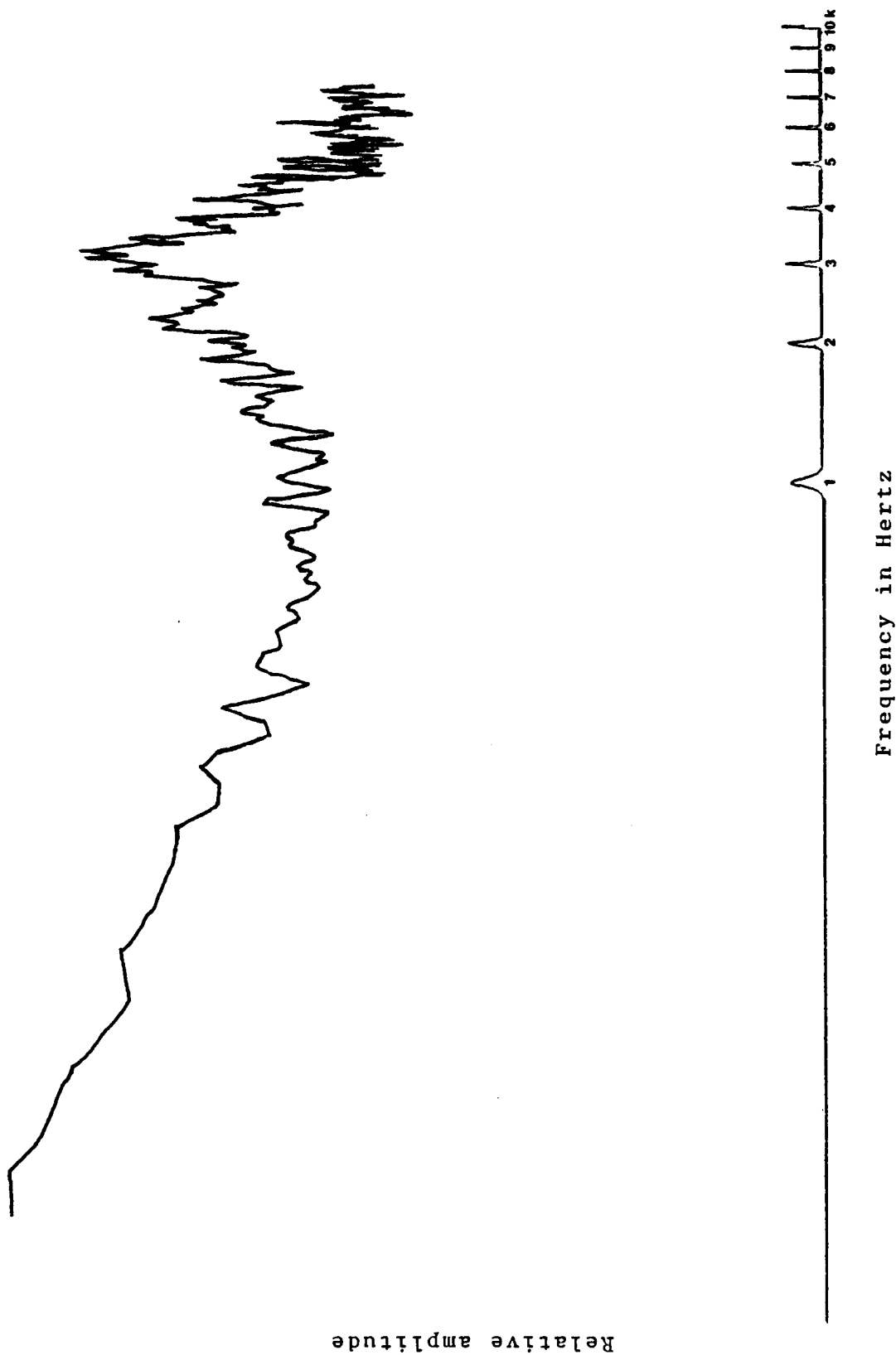


Figure 16. Spectrum of click train produced by Nicolet Compact 4 and recorded through a Phonic Ear 805 CD hearing aid and KEMAR.

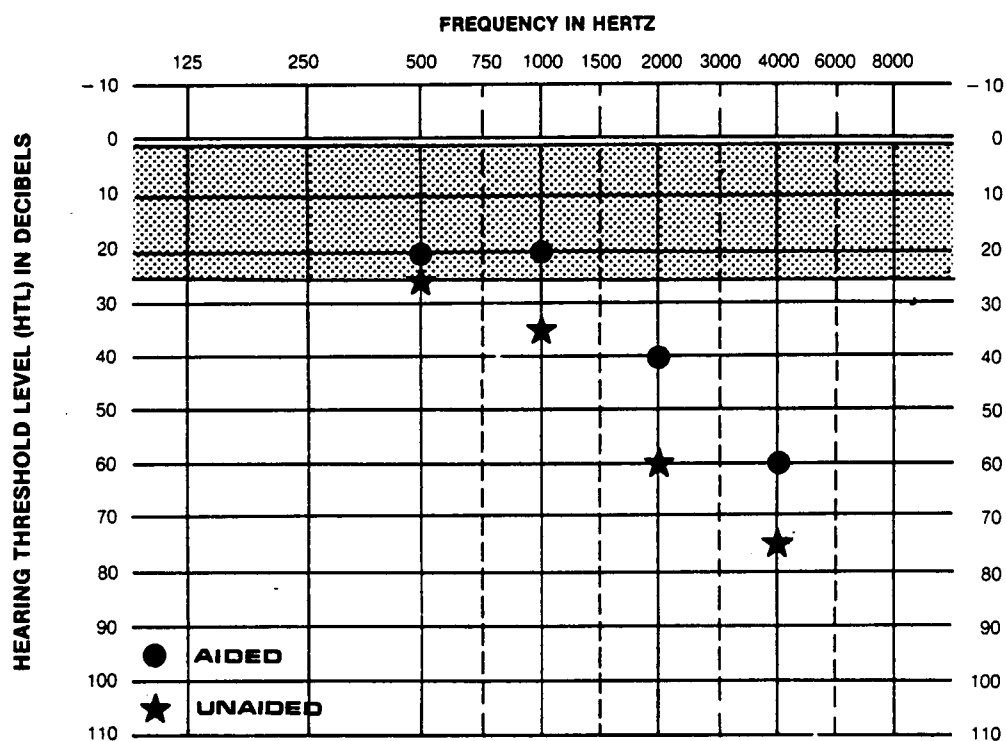


Figure 17. Average values for warbled tone thresholds recorded for the hearing impaired group in sound field.

amount of compression he calculated as necessary to obtain normal wave V intensity-amplitude functions was not always available in commercial hearing aids. In the present study, it was not that the hearing impaired listeners were unable to obtain a greater compression setting because none of the hearing impaired listeners in this study wore their hearing aids at the maximum compression setting.

If data from compression and linear amplification conditions were examined in figures 9 through 13, an interesting pattern emerged. The relationships between these conditions appeared to change at, or slightly above, 80 dB SPL. For example, when wave I amplitude or magnitude estimation data from figures 11 and 13 were examined, mean values for the two conditions were very similar at and below 80 dB, but not above this level. When hearing aid input-output functions were recorded with activation of compression circuits, the 80 dB level corresponded to an average "knee point" where non-linearity began to occur. "Knee points" for individual hearing impaired listeners ranged from 75 dB SPL to 85 dB SPL.

F. Experimental questions 11 through 18

Correlations were determined between magnitude estimation data and each of the other dependent variables for normally hearing and hearing impaired (unaided, compression aided and linear aided). The r values for

each group were ranked by degree of strength and are shown in Table 47. The strongest correlation across groups was between magnitude estimation and wave V amplitude, followed by correlations between magnitude estimation and wave I amplitude, magnitude estimation and wave V latency, and magnitude estimation and wave I latency.

The correlation between magnitude estimation and wave V amplitude suggested a substantial relationship if interpreted with Guilford's (1956) classification table, however, the use of a wave V intensity-amplitude function to predict loudness growth would be inappropriate. Guilford's classification table is presented in Table 48. The use of a variable as a predictor requires a much higher correlation (Williams, 1968). The variability of ABR amplitude as it is presently measured would also preclude the use of the wave V intensity-amplitude function as a predictor of loudness growth.

G. ABR wave V latency

Hecox (1982) suggested that hearing aid gain be set at a level which caused a wave V latency to appear at 6.0 ms when click stimuli were delivered at 60 dB. McPherson and Clark (1983) suggested that gain be adjusted so that wave V latency occurs at 6.5 ms when stimuli were presented at a most comfortable listening level. In the present study, neither normally hearing or aided hearing impaired individuals had wave V latency values at or near 6.0 ms at

Table 47. Ranking of correlation coefficients used to answer research questions 11 - 18.

Correlations between depen- dent variables	Normal		Unaided		Compress		Linear	
	rank	r	rank	r	rank	r	rank	r
ME & W I lat	4	-.45	4	.34	4	.42	4	.34
ME & W V lat	2	.59	2	.41	1	.73	2	.50
ME & W I amp	3	-.57	3	.41	3	.52	3	.44
ME & W V amp	1	.73	1	.64	2	.66	1	.60

Table 48. Guilford's correlation classifications. From J.P. Guilford, Fundamental Statistics in Psychology and Education (New York: McGraw-Hill, Inc., 1956), p. 145.

Classifications	
less than .20	Slight; almost negligible relationship
.20 to .40	Low correlation; definite but small relationship
.40 to .70	Moderate correlation; substantial relationship
.70 to .90	High correlation; marked relationship
more than .90	Very high correlation; very dependable relationship

60 dB. Instead, mean wave V latencies for the normally hearing and aided hearing impaired groups were greater than 7.0 ms at 60 dB. Even increasing click intensity to 70 dB did not cause mean wave V latencies to occur below 7.0 ms.

Procedural differences with respect to loudspeaker placement and signal level measurement most likely account for the disparity between the results of this investigation and previous studies. The loudspeaker used in the present study was placed 10 cm away from each listener's ear, while other studies report placement of a loudspeaker or earphone at 3 to 5 cm from the ear under test. A latency shift of 0.2 ms should occur if a loudspeaker or earphone is moved from a position 3 cm from to ear to 10 cm. This correction factor alone could not account for the differences in wave V latency observed between studies. In the present study, intensity level was measured by placing KEMAR with an associated measuring amplifier 10 cm from the loudspeaker and reading decibel values from the meter on the measuring amplifier. In previous studies it was not clear whether the investigators used a similar measuring technique or simply read the decibel value on the attenuator dial of their ABR test units. Since direct comparison of procedures cannot be made, findings of wave V latency values greater than 6.0 ms at 60 dB cannot be used to discuss conclusions made

by previous investigators.

Galambos and Hecox (1978) suggested that steeply sloping wave V intensity-latency functions were characteristic of hearing impaired individuals who exhibited loudness recruitment. Table 49 revealed that two unaided hearing impaired listeners (#2 and #8) in the present study had normal loudness perception as measured by magnitude estimation, but exhibited a greater than normal wave V latency shift. The latency shift was measured between 100 dB and 80 dB because there were no missing data cells at those levels. Conversely, listeners #3 and #7 had steeply sloping magnitude estimation functions, but lower than or close to normal wave V latency shift. The other four hearing impaired listeners had steeply sloping magnitude estimation functions and greater than normal wave V latency shifts. It was not evident from these data that a clear relationship existed between loudness growth and ABR wave V intensity latency functions.

Table 49 also identified the pure tone threshold shift from 1000 Hz to 4000 Hz which was used to describe audiometric contour. This information was used to examine relationships between audiometric contour, shape of the magnitude estimation function and wave V latency shift. Gorga, Worthington, Reiland, Beauchaine and Goldgar (1985) proposed that steeply sloping wave V intensity-latency

Table 49. Individual data from hearing impaired subjects and mean data from the normally hearing group representing audiometric contour, shape of ME function and wave V latency shifts.

S	Shift in dB from 1k-4k	Shape of ME function	Wave V latency shift
1	45	steep	.32
2	60	normal	.32
3	45	steep	.12
4	25	steep	.40
5	40	steep	.86
6	30	steep	.52
7	35	steep	.04
8	25	normal	.24

9-16	9	normal	.17

functions were related to audiometric configuration rather than loudness perception. The results for hearing impaired listener #2 would support their conclusion. Listener #2 exhibited a sharp slope in audiometric contour, larger than normal wave V latency shift and no abnormal loudness perception for clicks. In contrast listener #3 exhibited a sharp slope in audiometric contour, a steeply sloping magnitude estimation function and a near normal wave V latency shift which suggested that a relationship existed between loudness perception and audiometric contour. Most of the hearing impaired listeners in the present study had greater than normal pure tone shifts from 1000 Hz to 4000 Hz, steeply sloping magnitude estimation functions and greater than normal wave V latency shifts which suggested that a relationship existed between all three factors. Since the number of subjects used in this study was small and conflicting patterns were present in the data with regard to audiometric contour, wave V intensity-latency function and loudness perception, information about the relationship between loudness growth and the wave V intensity-latency function remained inconclusive.

CHAPTER VII

SUMMARY AND CONCLUSIONS

A. Limitations of the study

The subject selection criteria limited the number of listeners eligible to participate in this investigation. The availability of eligible listeners further reduced the number of participants who could be tested and this resulted in a small sample size.

Although all hearing impaired individuals participating in this study used Phonic Ear 805 CD hearing aids, the internal adjustment for amount of compression and the volume control adjustment were slightly different for some subjects. The inconsistency among preferred hearing aid settings was thought to have increased variability.

The inability to record a measurable wave I left many empty data cells and caused simpler statistical analyses to be performed. It also caused a reduction in the number of intensity levels used in the intensity functions for wave I since only a very limited number of responses were recorded at 50 dB and 60 dB.

B. Summary and conclusions

The purpose of this study was to determine if the use of amplification caused intensity functions generated by

hearing impaired individuals to more closely approximate the functions generated by normally hearing persons. Visual inspection of the data revealed that the introduction of amplification had differential effects on the dependent variables. Intensity functions generated by the hearing impaired group utilizing compression amplification tended to approach normal values more often than functions generated with linear amplification, but this trend was not established as statistically significant when analysis of variance was applied. Since correlational analysis revealed no strong correlations between magnitude estimation and any of the other four dependent variables, the use of either ABR intensity-latency or intensity-amplitude functions would be inappropriate to predict loudness growth.

ABR has been used to fit hearing aids in difficult to test patients (Hecox, 1982; Kileny, 1983; Mahoney, 1985). It may continue to have a role in the evaluation of amplification for certain individuals, but it is important for the audiologist using this technique to recognize that information about loudness perception cannot be inferred from the data.

C. Suggestions for further study

The relationship between loudness growth and ABR intensity functions has not yet been clearly determined and further research should be pursued. The following are

suggestions to improve the present design or ideas for future studies:

1. Further examination of wave I intensity-latency and intensity-amplitude functions should be performed with electrocochleography to insure better recording of wave I.
2. Re-examine the intensity functions at levels above 60 decibels to avoid problems with empty data cells.
3. In an effort to reduce within group variance, a strict subject selection criteria should be adhered to with respect to hearing level and word recognition ability.
4. Using a large N, determine correlations between audiometric configuration, loudness growth functions and ABR intensity function.
5. Measure magnitude estimation functions before and after aural rehabilitation or at time of hearing aid fitting and six months later to determine if adjustments made to amplification cause changes in loudness growth.

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APPENDIXES

APPENDIX 1

CLINICAL APPLICATION OF THE ABR

In terms of hearing threshold assessment, the ABR wave V threshold obtained with click stimuli has been found to be a good estimator of pure tone thresholds in the 2000 Hz to 4000 Hz region (Coats and Martin, 1977, Moller and Blegvad, 1976). Wave V is the wave of choice to determine hearing level because it is the most robust wave in the ABR and the last to disappear when stimulus intensity is decreased (Jewett and Williston, 1971; Galambos and Hecox, 1978).

The nature of the stimulus used to elicit the ABR accounts for the good correlation between wave V threshold and behavioral pure tone thresholds between 2000 Hz and 4000 Hz. In order to elicit the ABR, the stimulus must have a very fast rise time and short duration (Hecox, Squires and Galambos, 1976). In the case of clicks which are commonly used in clinical testing, the acoustic spectrum has its peak value in the regions above 2000 Hertz. Other stimuli used in ABR threshold testing include tone bursts and logons which can be made with spectra in other frequency regions. Some of these stimuli have been used to provide an estimate of hearing below 2000 Hz, but correlations with pure tone data have not been very strong.

ABR test procedures have been used for the differential diagnosis of hearing disorders. Galambos

and Hecox (1978) examined wave V intensity-latency functions and found differences between functions generated by individuals with normal hearing, conductive and sensorineural hearing losses. With respect to sensorineural loss, steeply sloping I-L functions were thought to be indicative of recruitment, but other investigators (Gorga, Worthington, Reiland, Beauchaine and Goldgar, 1985) have concluded that steep I-L functions were correlated with audiometric contour. Jerger and Mauldin (1979) proposed the use of bone conducted clicks to estimate the behavioral air-bone gap in the 1000 Hz to 4000 Hz region. To differentiate cochlear from retrocochlear problems the measurement of intra-aural wave V latency differences (Selters and Brackmann, 1977) and wave I/wave V interwave interval differences (Coats, 1978) are commonly used.

In terms of otoneurological evaluation, ABR audiometry has been used in the assessment of demyelinating diseases, differentiation of various types of coma and evaluation of brain death (Starr and Achor, 1975). Auditory brainstem responses have also been used in the diagnosis of pediatric neurologic disease (Hecox, Cone and Blaw, 1981). The use of interwave interval, wave I/wave V amplitude ratio, waveform morphology and changes in morphology with increased rate of stimulation which is appropriate for evaluation of adults has been

applied to detect neurologic disease in children,
although maturational changes in the ABR are taken into
account when results are interpreted.

APPENDIX 2

COMPRESSION AMPLIFICATION

Compression is a form of output limiting used in hearing aids to prevent the amplification of input signals to an uncomfortable level. The compression circuit rapidly lowers the gain when an input signal exceeds a predetermined level and keeps the gain down until the input signal has decreased sufficiently. The predetermined level has been referred to as compression threshold and is usually set so that a listener's threshold of discomfort is not exceeded (Braida, Durlach, Lippman, Hicks, Rabinowitz, and Reed, 1979).

In a hearing aid without a compression circuit (a linear amplifier), an input signal is amplified by the amount of gain provided. The amplitudes of all signals are increased by the gain level unless the input signals become so intense that the output limit of the hearing aid amplifier is reached. After that point, a linear relationship no longer exists between input and output, and distortion at the output occurs as the result of peak clipping.

By using a compression circuit, overamplification and peak clipping can be avoided. A compression circuit monitors the amplitude of either the input signal or the output signal and triggers the gain control so that amplitudes at the output are reduced when input

amplitudes are too high. This is accomplished through the use of a control voltage which is obtained from the signal (Herbst, 1983). Whereas a very high input signal processed by a linear amplifier result in a clipped signal at the output, a compression amplifier is able to preserve the waveform.

The Phonic Ear 805 CD hearing aid was selected for this study because it can be adjusted to provide either linear or compression amplification. When the output limit is set at maximum, the amplifier is linear. When the output limit is set any lower level, the output amplitudes depend nonlinearly on the input amplitudes. Input, gain and output values for the linear and a compression setting are presented in Table A1.

Table A1. Input/output values for two settings on the PE 805 CD.

Output limit at 122 dB SPL		
Input	Gain	Output
50 dB	50 dB	100 dB
60 dB	50 dB	110 dB
70 dB	50 dB	120 dB

Output limit at 118 dB SPL		
Input	Gain	Output
50 dB	34 dB	84 dB
60 dB	34 dB	94 dB
70 dB	30 dB	100 dB

APPENDIX 3

INSTRUCTIONS TO THE LISTENERS

You are going to hear pairs of sounds. The first sound in each pair is the standard and the second sound is the comparison. The loudness of the standard is equal to "10". Your task is to estimate the loudness of the second sound. In other words, if the standard is called "10", what would you call the comparison? Use whatever numbers between 0 and 100 which seem appropriate - fractions, decimals or whole numbers. For example, if the comparison sounds 7 times as loud as the standard, its loudness would be 70. If it sounds $1/5$ as loud, its loudness would be 2.

Try not to worry about being consistent; try to give the appropriate number to each sound regardless of what you may have called the comparison sound in a previous pair.

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