

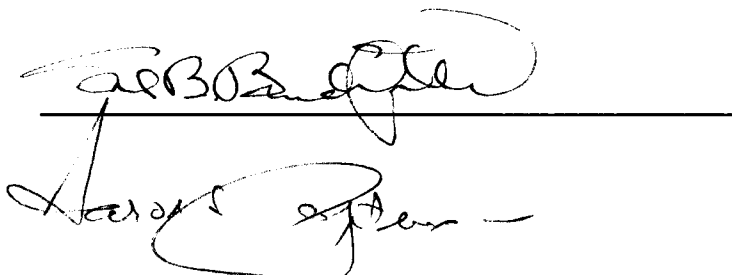
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**EFFECTS OF CLICK POLARITY ON AUDITORY BRAINSTEM
RESPONSES IN MAN USING HIGH-PASS NOISE MASKING**

**A Thesis
Presented for the
Master of Arts
Degree
The University of Tennessee, Knoxville**

**Lisa Lynn Cunningham
December 1991**

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DEDICATION

This document is dedicated to my mother, Gayle Grady
Cunningham, who taught me to pursue knowledge and excellence,
and then supported, encouraged, and put up with me while I did so.

ACKNOWLEDGMENTS

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ABSTRACT

Auditory brainstem responses (ABRs) are used clinically to measure neural activity in the acoustic nerve and in the pathways of the auditory system. ABRs are commonly elicited with 100 microsecond click signals which can be presented in any of three modes: condensation polarity, rarefaction polarity or alternating (condensation and rarefaction) polarity. In normal-hearing subjects, there is little or no effect of click signal polarity (Terkildsen et al., 1973; Borg and Lofqvist, 1981; Tietze and Pantev, 1986; Beattie, 1988). However, inversion of signal polarity has been shown to significantly affect wave V of the ABR in subjects with high-frequency hearing losses (Coats and Martin, 1977; Borg and Lofqvist, 1981, 1982; Pijl, 1987; Schwartz et al., 1990).

Gorga et al. (1991) used single-cycle sinusoids of various frequencies in both polarities to determine if polarity could be shown to affect wave V latencies in ABRs elicited from normal-hearing subjects. They reported significant effects of polarity on wave V latencies for low-frequency signals, with the effects decreasing as signal frequency increased. With the single-cycle sinusoids used by Gorga et al., the ABR depends upon the spectrum of the signal plus a contribution from higher-frequency regions of the cochlea. The present study utilized high-pass masking to precisely limit the regions of the cochlea contributing to the ABR, and a derived response technique which has been described by Don

and Eggermont (1978, 1980) to obtain the ABR elicited from octave regions of the cochlea.

Click polarity was shown to significantly affect wave V latency only when the ABR is restricted to frequencies below 500 Hz. The effect was found for all subjects; its magnitude was predictable ($1.1 \text{ ms} \pm 0.4 \text{ ms}$), but its direction was not predictable. Inversion of signal polarity was shown to occasionally produce substantial changes in waveform morphology, but these changes did not occur on a predictable manner within or between subjects.

The absolute wave V latency was shown to systematically decrease as the response was extended to more basal regions of the cochlea. The results obtained indicate that wave V latency decreases when the contribution of signal energy above 8000 Hz is added. While ABRs can be obtained from every region of the cochlea, the latency of wave V depends primarily upon the highest frequencies contributing to the response.

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I. RATIONALE

Auditory brainstem responses (ABRs) are used clinically to measure neural activity in the acoustic nerve and in the pathways of the auditory brainstem. The ABR is most readily elicited by transient signals which produce synchronous firing of large numbers of neurons (Don and Eggermont, 1978). One commonly used signal for eliciting the ABR is the 100-microsecond click. Though this signal activates nearly the entire cochlea, the ABR in normal-hearing listeners is believed to be dominated by the signal energy in the frequency region from 2000-4000 Hz, which arises from the basal portion of the cochlea (Jerger and Mauldin, 1978; Gorga et al., 1985; Laukli and Mair, 1986; van der Drift, 1987). In clinical protocols it has been common practice to use alternating condensation clicks (initial movement of the earphone diaphragm is toward the tympanic membrane) and rarefaction clicks as a means of cancelling electrical signal artifact which can contaminate the ABR (Borg and Lofqvist, 1981). For normal-hearing listeners, most investigators have reported little or no effect of signal polarity on the latencies of the individual waves which comprise the ABR (Terkildsen et al., 1973; Borg and Lofqvist, 1981, 1982; Tietze and Pantev, 1986; Beattie, 1988).

However, there are two conditions for which significant polarity effects have been reported: 1) in click-evoked ABRs of subjects with high-frequency sensorineural hearing loss (Coats and Martin, 1977; Borg and Lofqvist, 1981, 1982; Pijl, 1987; Schwartz

et al., 1990), and 2) in ABRs using low-frequency signals with normal-hearing subjects (Gorga et al., 1991). In both conditions, it has been proposed that the polarity effects result from ABRs generated in the apical region of the cochlea.

The present investigation was conducted to study the effects of click signal polarity on ABR wave V latency. The effects were studied for specific regions of the cochlea using high-pass noise masking and a derived response procedure which has been described by Don and Eggermont (1978) . Two specific questions were addressed in the study: 1) Does the latency of wave V depend on the polarity of the click signal in normal-hearing listeners? 2) If so, do the latency differences depend upon the region of the cochlea contributing to the response?

II. REVIEW OF LITERATURE

Signal Polarity Effects in Normal-Hearing Subjects

Dependence of Polarity Effects on Signal Intensity

Peake and Kiang (1962) recorded compound action potentials from the auditory nerve in the internal auditory canal of the cat using condensation and rarefaction clicks over a wide range of intensities. They reported no effects of signal polarity on the latency of the N1 peak at low intensities. However, latency differences were seen with reversal of click polarity at high intensities. High level effects were obtained at 60 dB or more above the visual detection threshold for the response. These results were interpreted in terms of a model in which separate excitatory mechanisms respond to low- and high-level signals. There was the implication that these mechanisms may be outer and inner hair cells. Salt and Thornton (1984) studied similar phenomena using ABRs. However, they were not able to find the polarity differences with levels reported by Peake and Kiang to support the hypothesis of low- and high-level excitatory mechanisms.

The majority of studies on the effects of signal polarity discussed in the following section were done with relatively high intensity signals -- 60-90 dB above a laboratory norm for hearing level (dB nHL). The present study was conducted using 65 dB nHL click signals.

Polarity Effects at High Signal Intensities

In normal-hearing subjects, the inversion of click signal polarity produces relatively small (typically less than 0.1 ms) latency differences in the waves which comprise the ABR (Gorga et al., 1991). Some investigators have reported no significant polarity effects on ABR wave latencies (Terkildsen et al., 1973; Borg and Lofqvist, 1981, 1982; Tietze and Pantev, 1986; Beattie, 1988). In studies where latency differences were found with polarity inversion, the direction of the latency effects has not been systematic. Kevanishvili and Aphonchenko (1981) reported shorter Wave V latencies for condensation signals than for rarefaction signals. Other researchers have reported shorter latencies for rarefaction signals (Stockard et al., 1979; Borg and Lofqvist, 1981, 1982; Emerson et al., 1982; Schwartz et al., 1990; Zerlin, 1988; Gorga et al., 1991). Even within a given study, 15-20% of the subjects may demonstrate latency shifts in the opposite direction from the other subjects (Coats and Martin, 1977; Stockard et al., 1979; Borg and Lofqvist, 1981, 1982; Emerson et al., 1982; Schwartz et al., 1990). In the studies discussed above, it cannot be determined if the polarities of the signals used were correctly identified. Despite possible confusion in the labeling of signal polarities, the reversals in polarity effects obtained within studies provide evidence that the direction of polarity effects may differ among individuals.

Borg and Lofqvist (1982) have proposed that inversion of the condensation-rarefaction latency difference can be explained in

terms of the vibratory pattern of the ossicular chain altering the waveform of the stimulus during transmission from earphone to hair cell. If their hypothesis is correct, then ABR latencies may depend complexly on middle ear mechanics in listeners with normal middle ears. Though this hypothesis may account for polarity effects, its validity could not be evaluated in the present study.

Signal Polarity Effects in Hearing-Impaired Subjects

While inverting click polarity has little effect on ABR latencies for normal listeners, response latencies can be significantly affected by signal polarity in subjects with high-frequency sensorineural hearing loss. Borg and Lofqvist (1982) studied 29 ears with steeply-sloping high-frequency cochlear losses. They reported increasingly larger polarity effects as the hearing became confined to lower frequencies. They suggested that the magnitude of the polarity effect could be used as an indicator of the locus of the generation of the ABR in the cochlea. Pijl (1987) reported similar findings: "Latencies of Waves I and V were relatively stable with inversion of stimulus phase in ears with normal hearing and mild degrees of high-frequency hearing loss, but the incidence of substantial phase-induced latency shifts increased in proportion to pure tone deficits" (p. 89).

Signal Polarity Effects with Band-Limited Signals in Normal-Hearing Listeners

The data from listeners with high-frequency hearing loss suggest that this type of impairment causes the click-evoked ABR to

be dominated by low-frequency energy which activates the apical region of the cochlea rather than the basal region which dominates the response in normal-hearing subjects. The effective bandwidth of a click signal may be limited to the lower frequencies by the sensory impairment. However, it is possible that the relatively large effects of click polarity that have been seen in hearing-impaired subjects are also due to ear pathology. If the polarity effects are due to the effective bandwidth of the signal, then similar effects should be observable when the ABR is obtained from neural activity in apical regions of normal cochleas. If polarity effects are not observable in the ABRs generated from the apices of normal cochleas, then it could be reasoned that the effects seen in hearing-impaired subjects are due in part or in whole to ear pathology rather than to the restricted population of neurons activated.

Gorga et al. (1991) addressed this issue by using band-pass signals to activate specific regions of the cochlea. ABRs were recorded from normal-hearing subjects in response to single-cycle sinusoids at octave intervals from 250 to 2000 Hz. They reported that signal polarity affected wave V latencies for low-frequency stimuli, with the effect decreasing as stimulus frequency increased. The presence of low-frequency polarity effects for normal-hearing individuals provides evidence that high-frequency hearing loss polarity effects are due at least in part to the limiting of the effective bandwidth of the signal caused by the sensory impairment.

With the single-cycle sinusoids used by Gorga et al., the pattern of excitation in the cochlea is determined by the shape of the traveling wave. Moderate- to high-intensity low-frequency stimuli can cause an upward spread of excitation to basal (high-frequency) regions of the cochlea (Gorga and Worthington, 1983). Therefore, it is possible that the region of excitation is greater than the bandwidth of the signal. With this procedure, the cochlear regions that contribute to the ABR are known approximately but not precisely.

The present study utilized a method which has been described by Don and Eggermont (1978) which permits more precise determination of the cochlear regions contributing to the ABR. This technique involves masking the basal regions of the cochlea with high-pass noise, thus eliminating this region's contribution to the ABR. The contributions of specific regions of the cochlea can be determined by the use of a derived-response technique. Waveforms which are obtained with successively lower high-pass cutoff frequencies are algebraically subtracted from one another. For example, the derived response for the frequency region between 1000 and 2000 Hz is obtained by subtracting the response from 0-1000 Hz (masking at 1000 Hz and above) from the response from 0-2000 Hz (masking at 2000 Hz and above). The derived response represents the contribution to the overall response from the cochlear region between the two masker cutoff frequencies.

The validity of the derived response technique has been verified in studies in which the ABR results obtained with the

derived response technique were very similar to results obtained using notched noise of the same frequencies (Parker and Thornton, 1978). Behavioral studies in hearing-impaired listeners have shown that the ABR response thresholds obtained with the derived technique are very close to behavioral thresholds (Don et al., 1979). The derived response technique was used in the present study as the means of describing the contributions of octave-band frequency regions to the ABR.

III. METHODS AND PROCEDURES

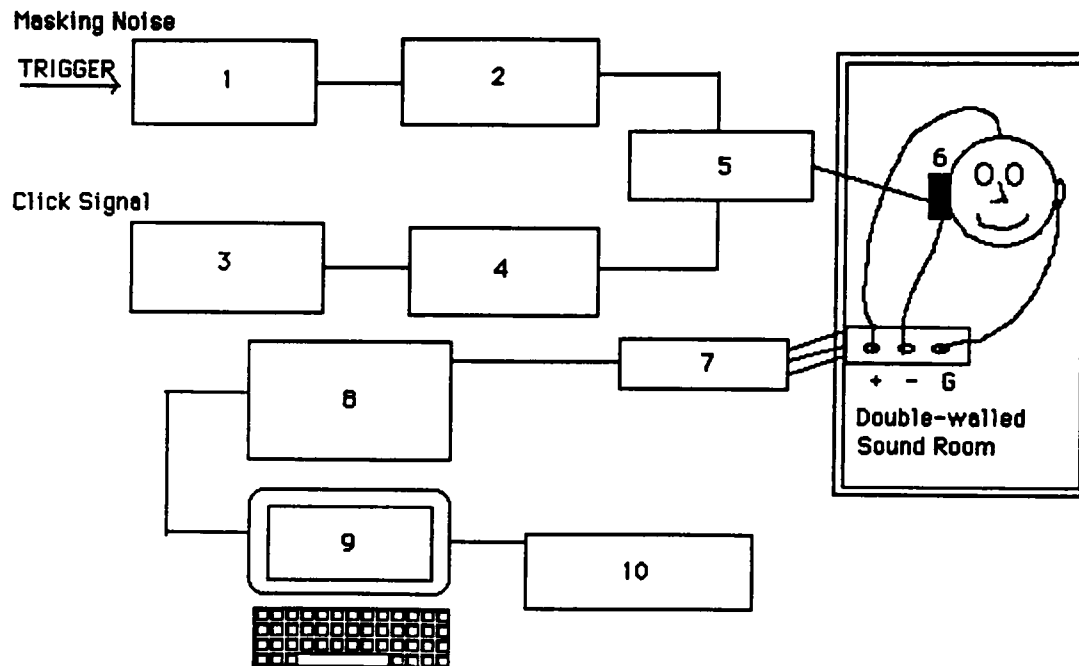
Subjects

This study involved eleven subjects ranging in age from 20 to 25 years (mean = 22.7); data for two of the subjects were not reported for reasons explained in the Results. The remaining nine subjects were one male and eight females. The subjects were volunteers (see Appendix A for subject consent form), and each received a standard clinical hearing test as a qualifying procedure. Puretone air-conduction and bone-conduction thresholds, tympanometry, and otoscopy were performed. Each subject participating in the study had normal auditory sensitivity at 250 Hz and at half octave intervals from 500 to 8000 Hz (see Appendix B), normal tympanometry, no history of neurologic disorders, and good overall health.

Instrumentation

Signal and Masker Generation

Figure 1 is a simplified block diagram of the signal generating and data collecting equipment. Click signals were generated and controlled by an auditory waveform generation system (Modular Instruments, NI2) which was interfaced to a microcomputer (Everex, 386/25). The click generator (Modular Instruments, M312) was controlled by a timer (Modular Instruments, M214). Signal parameters were controlled by the microcomputer using menu-driven stimulus generation and control software (WAVE).



1. Noise Generator
2. Filter
3. Timer
4. Click Generator
5. Mixer
6. Earphone
7. Pre-amplifier
8. Signal Averaging Software
9. Monitor
10. Plotter

Figure 1. Signal Generating and Data Collecting Equipment

Signal polarity was determined using a method which has been described by Gorga et al. (1985).

The wide-band noise output of the program control module (Modular Instruments, M300) was routed to the input of the filter (Rockland Series 2000 filter). The wide-band noise was high-pass filtered and routed to a mixer (Modular Instruments M300), where it was electronically mixed with the output of the click generator. The click and masker signals were finally delivered to the ear by an earphone (Telephonics, TDH-50; Telephonics MX, 41/AR ear cushion).

Response Recording and Processing

The ABR was recorded using EEG-type electrodes placed on the vertex and on the ipsilateral earlobe. Another electrode placed on the contralateral earlobe served as the common ground. The electrical activity from the scalp electrodes was amplified 200,000 times by a pre-amplifier (Grass, P5115), filtered (response passband 30 to 3000 Hz), and then routed to the input of the analog-to-digital module of the Modular Instruments data acquisition system which was interfaced with the microcomputer. An enhanced color monitor was used to display the ABRs both as they were recorded on-line and later for inspection and analysis. The Modular Instruments software (S-215) was used for response averaging and manipulation of recorded data. Routines within the software serve application functions such as data analysis, stimulus control, spectrum analysis and data plotting. A plotter (Hewlett-

Packard 7475A) connected to the computer was used to plot data off-line.

Test Room

During data collection, subjects were reclining inside a custom-manufactured double-walled sound room (Suttle). The ambient noise levels inside the sound room are provided in Appendix C. For the octave band centered at 250 Hz the noise level in the room was 27.5 dB SPL. For all higher frequencies, it was less than 19 dB SPL.

Experimental Signals

Click Signals

In all conditions for all subjects, the signals were 100 microsecond condensation and rarefaction clicks which were equal in sound pressure but opposite in signal polarity. The level of the click signals was 65 dB nHL and 96.5 dB peak SPL. The acoustic spectra of the rarefaction and condensation clicks are shown superimposed upon one another in Figure 2. It can be seen that the frequency responses of both clicks are identical. ABRs were recorded separately for condensation and rarefaction clicks in the unmasked condition and in all masking conditions.

Noise Maskers

The broad-band noise was a computer-generated Gaussian noise with a lower cutoff frequency of 125 Hz. The upper cutoff of this signal was shaped by the frequency response of the earphone.

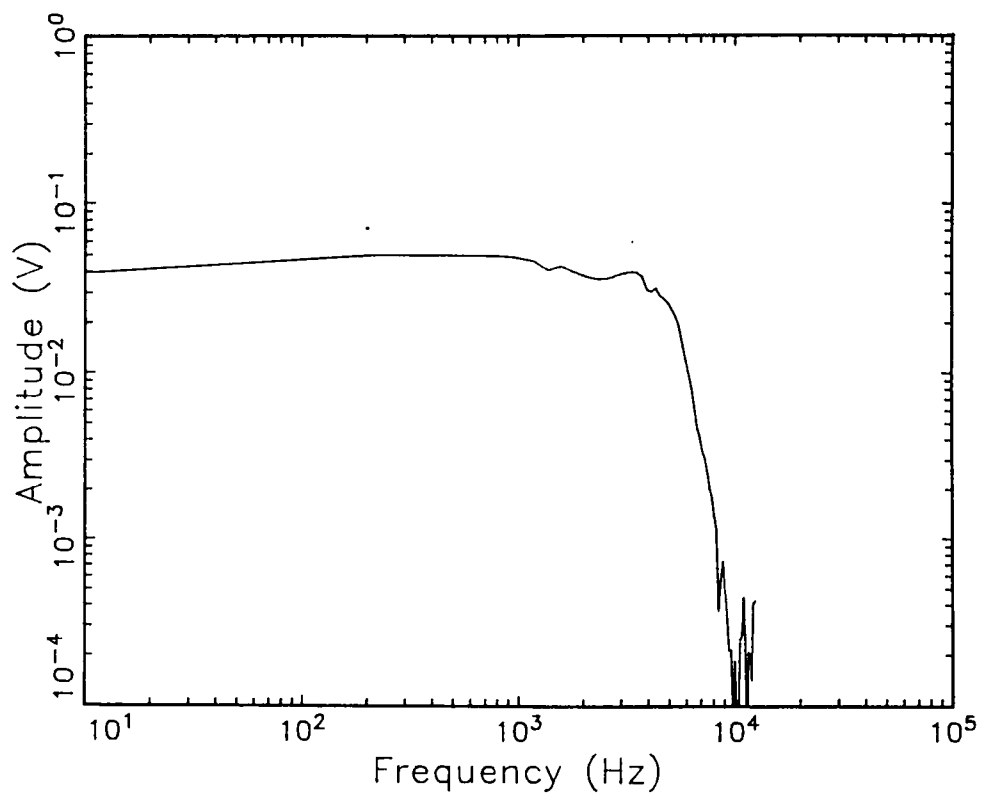


Figure 2. The acoustic spectra of the condensation and rarefaction click signals are shown superimposed upon one another.

High-pass masking signals were generated by passing this noise through two filters, each with a rejection rate of 48 dB per octave. The response characteristics of the filters were analyzed in two ways. First, the filters were driven with 100 microsecond clicks. The resulting output is plotted in Figure 3, which shows amplitude as a function of cutoff frequency. The nominal cutoff frequencies of the high-pass masking signals are 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz; the nominal attenuation rate at each cutoff frequency is 96 dB per octave. Second, an octave band analysis was performed on the noise maskers using a sound measurement system (Bruel and Kjaer: sound level meter, 2203; octave filter set, 1613; one-inch pressure condenser microphone, 4144; artificial ear, 4152 with NBS 9A artificial ear; and pistonphone, 4220). The results of these measurements are shown in Appendix D. The overall level of the broad band noise was 90.8 dB SPL, and the pressure spectrum level (PSL) in the six one-octave bands with center frequencies from 125-4000 Hz was 53 dB SPL + 2 dB. When the filters were used to reject noise in any or all of these bands, the average PSL in the band was at least 38 dB below the PSL in the passband.

The level of the masking signal was determined in a preliminary experiment in which the click signal was presented simultaneously with the broad band masking noise. In a series of trials, the PSL of the broad-band noise masker was increased until the ABR (based on 8000 responses) had no identifiable response that could be attributed to unmasked energy from the click signal. The

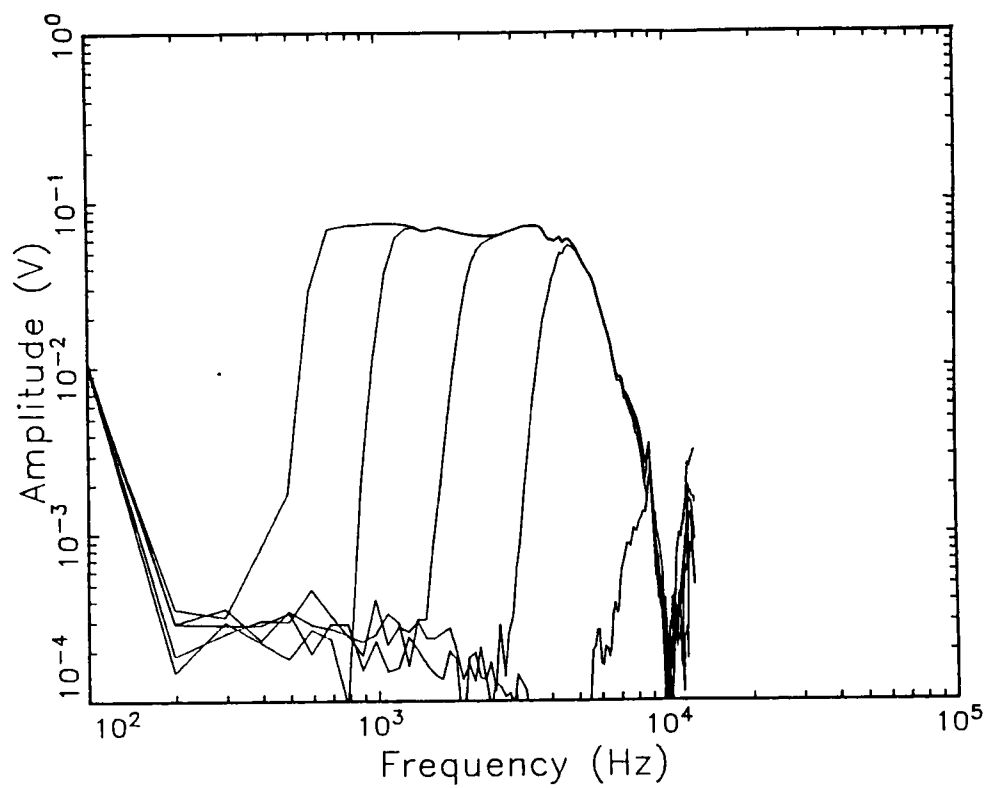


Figure 3. The characteristics of the filters are shown in response to $100\ \mu$ click signals.

presentation level of the masker which produced no identifiable response was 90.8 dB SPL. This masking level was used for all subjects in all experimental conditions. Each subject was tested to determine that this masker level produced no identifiable response in the broad band masking condition.

Experimental Procedures

The procedures for this experiment were the accepted audiological procedures for the measurement of ABR in clinical patients. Three EEG-type surface electrodes were placed on the head. The skin was abraded mildly with a commercial preparation prior to electrode placement. Electrodes were held in place with plastic tape. Testing was conducted in a sound-treated room with the subject seated in a reclining chair for maximum comfort. The subject wore standard audiometric earphones through which test signals were delivered. Experiments proceeded as follows:

1. ABRs With Unmasked Click Signals

ABRs were obtained to the two 65 dB nHL experimental clicks (condensation and rarefaction) without masking noise present.

2. ABRs With Broad-Band Noise Masking

ABRs were recorded using condensation clicks in the presence of the 90.8 dB SPL broad-band masking signal to verify that the response was eliminated.

3. ABRs With High-Pass Noise Masking

ABRs were recorded using the experimental condensation

and rarefaction click signals with high-pass noise maskers presented simultaneously. The PSL of the noise maskers was held constant at 53 dB SPL, and high-pass cutoff frequencies were varied as shown below:

8000 Hz

4000 Hz

2000 Hz

1000 Hz

500 Hz

The order in which high-pass masking conditions were presented was randomized within and across subjects. In each high-pass masking condition, ABRs were recorded separately for condensation clicks and rarefaction clicks. Click stimuli were presented at a rate of 21.1 clicks per second, and each experimental condition was replicated once to insure stability of responses. Each trial lasted from 1.5 to 9 minutes. Inter-trial intervals of 30 to 90 seconds were used to minimize the possible effects of auditory fatigue. Data were collected for each subject in one session lasting approximately two hours. Data were stored in the computer and analyzed after the experimental session.

Each ABR waveform was composed of 800 data points over a response epoch of 20 ms. Each ABR waveform for high-pass masking conditions of 2000, 4000, and 8000 Hz was the average of 2000 responses. In the 500 Hz high-pass masking condition it was necessary to average 8000 responses to obtain waveforms that

were interpretable and repeatable. The stimuli were presented in four sets of 2000 presentations each; the four sets were compared for replicability and then added together. In order to keep the number of stimulus presentations constant within each derived response band, it was also necessary to collect responses for 8000 stimulus presentations in the 1000 Hz high-pass masking condition.

Data analysis for derived bands involved the subtraction of response waveforms representing contributions from different regions on the cochlea. For example, the responses obtained in the 4000 Hz high-pass masking condition were subtracted from those obtained in the 2000 Hz condition. This procedure determined the portion of the overall response attributable to energy in the frequency region from 2000-4000 Hz.

Audiometric thresholds were measured again within five minutes of completion of experimental procedures to assess the possibility of temporary threshold shift (Appendix B). Post-test thresholds ranged from 5 dB better to 10 dB poorer than pre-test thresholds of audibility. The temporary threshold shifts (TTSs) were + 1 dB except at 6 kHz, where there was a 4 dB shift. This amount of TTS was not believed to have affected the results obtained using the 65 dB nHL click signals.

IV. RESULTS

The experiments with high-pass masking were conducted to restrict the regions of the cochlea which were contributing to the ABR. For example, when click signals were presented simultaneously with 500-Hz high-pass masking noise, the ABR was obtained from the unmasked apical region of the cochlea, which responds to low-frequency stimulation. As masker cutoff frequency was increased to 1000, 2000, 4000, and 8000 Hz, responses were progressively changed by the contributions from increasingly more basal regions of the cochlea. The high-pass masking experiments simulated steeply-sloping, high-frequency sensory hearing loss.

On each subject's data record, wave V latencies were measured at the highest peak appearing just before the steep slope of the Slow Negative 10 (SN 10) component. In instances in which waveform morphology made it difficult to determine the latency of wave V, decisions were based upon comparison with the response obtained in the same condition with the opposite polarity and with those in the adjacent masking conditions. For two of eleven subjects it was not possible to accurately determine the latencies of the waves due to responses contaminated by noise that was probably myogenic in origin. Data from these two subjects were eliminated from the analysis. Results are presented here for the remaining nine subjects. Wave V latencies for each subject in the unmasked condition and in each high-pass masking condition

appear in Appendix E; wave V latencies for each of the derived response conditions appear in Appendix F.

Broad Band Noise Masking Condition

The results obtained with simultaneous presentation of the click signal and the broad band masking noise are shown in Appendix G. This condition was used as a means for ensuring that the broad-band noise was capable of effectively masking the response to the click signal. In all cases, the ABR had no identifiable response which could be attributed to unmasked energy from the click signal.

Latency Effects

High-Pass Masking Conditions

Figure 4 shows ABRs obtained from Subject 5 in the 8000, 4000, 2000, and 500 Hz high-pass masking conditions. Figure 5 shows mean wave V latency as a function of high-pass masking condition. The range of response latencies within each condition is indicated by vertical bars. It can be seen in Figures 4 and 5 that wave V latency increased very systematically each time the cochlear portion contributing to the response was limited to more apical regions (i.e., each time the masking noise was extended into lower frequencies). There was no instance in which lowering of the masking noise produced a decrease in wave V latency, and only one instance in which the latency did not increase (Subject 3 showed a wave V latency of 6.88 ms in both the 8000 Hz and 4000 Hz high-pass masking conditions). A highly significant effect of masker

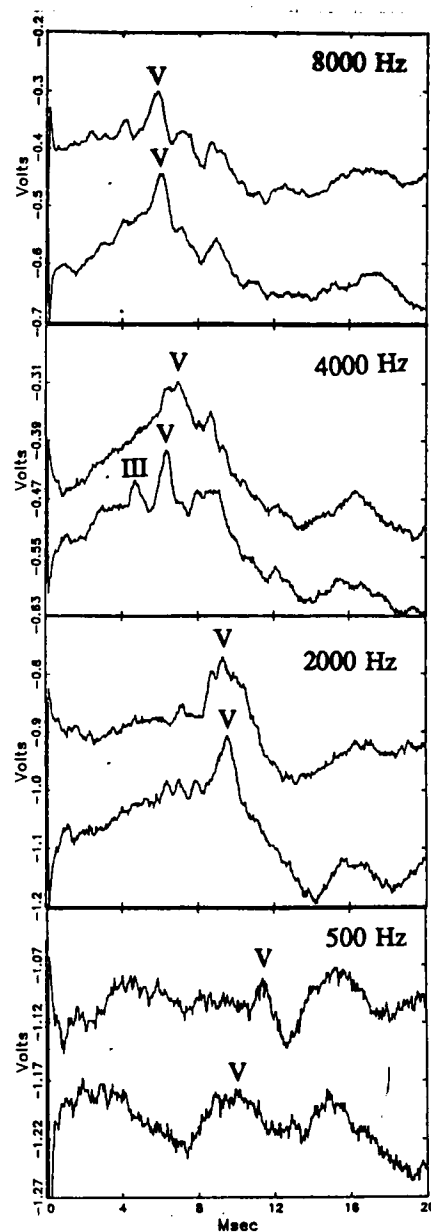


Figure 4. ABRs obtained from Subject 5 in the 8000, 4000, 2000, and 500 Hz high-pass masking conditions. For each condition, the ABR obtained with condensation clicks appears above that obtained with rarefaction clicks. Note the systematic shift in wave V latency as the response becomes limited to more apical regions of the cochlea. The 4000 Hz condition illustrates a typical morphology difference in that wave III is present with rarefaction polarity and absent with condensation polarity. The opposite is true for wave IV. The 500 Hz condition shows a condensation-rarefaction latency difference of 1.2 ms. (Note that the amplitude scale varies from one condition to another).

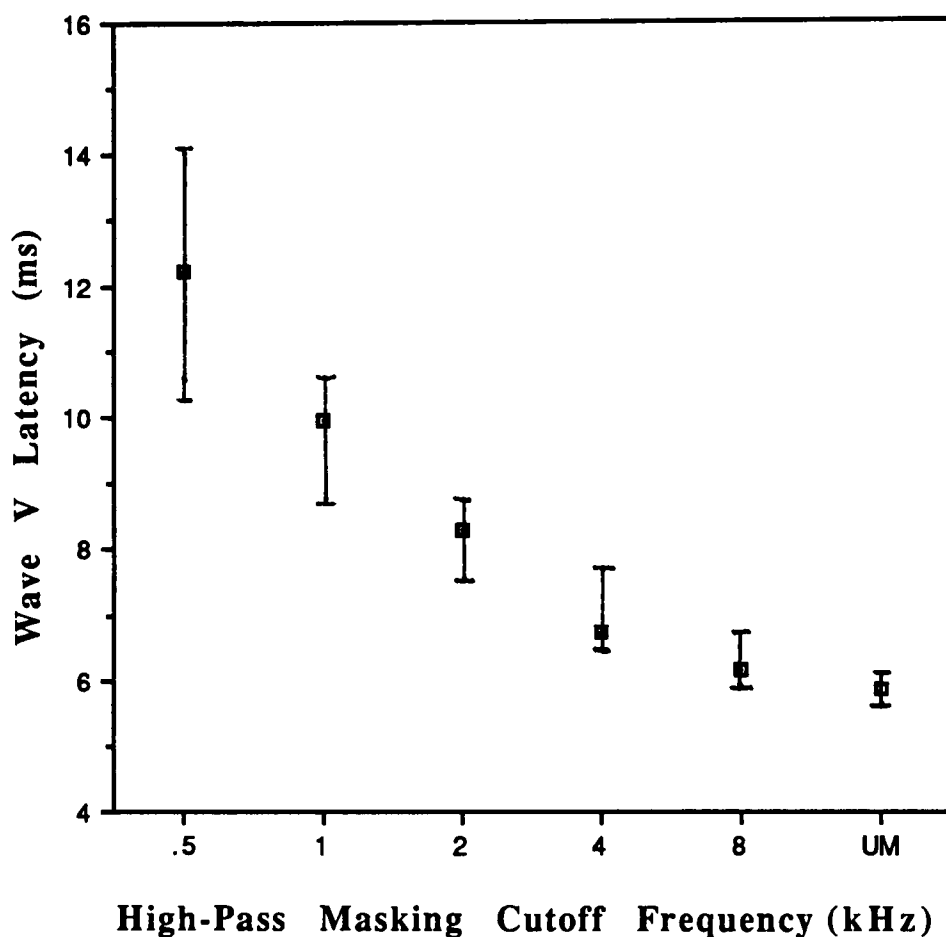


Figure 5. Mean wave V latencies (condensation and rarefaction in each of six conditions for a total of 12 data points per subject) are shown for each high-pass masking condition and for the unmasked condition. Vertical bars indicate the range of wave V latencies in each condition. For each subject in both polarities, wave V latency increased systematically as high-pass masking cutoff frequency decreased.

cutoff frequency on wave V latency was shown using a repeated measures analysis of variance (ANOVA) ($F(4, 5)=128.49, p<0.0001$). These systematic shifts in latency are similar to those reported by Don and Eggermont (1978) and Gorga et al (1991).

The results for the 8000 Hz high-pass masking condition were compared to the results for the unmasked condition to determine whether the addition of signal energy above 8000 Hz altered the wave V latencies significantly. Every subject demonstrated a longer wave V latency for the 8000 Hz high-pass masking condition than for the unmasked condition. ANOVA indicated that the latency difference was significant ($F(1, 8)=12.14, p<0.0083$). This indicates that frequencies above 8000 Hz contribute significantly to the overall response. This increase in wave V latency with the masking noise occurred despite the fact that the SPL and frequency spectrum of the 8000 Hz masker and the click signal in the present study were limited by the frequency response of the earphone (see Figure 3). Examination of the data presented by Don and Eggermont (1978) reveals that they obtained similar results using the same procedure.

Derived Response Conditions

The derived response technique was used to determine the contribution of octave-band regions of the cochlea to the overall response. Figure 6 shows mean wave V latency as a function of derived band cutoff frequencies. The format of Figure 6 is similar to that of Figure 5 except that the 500 Hz condition is not

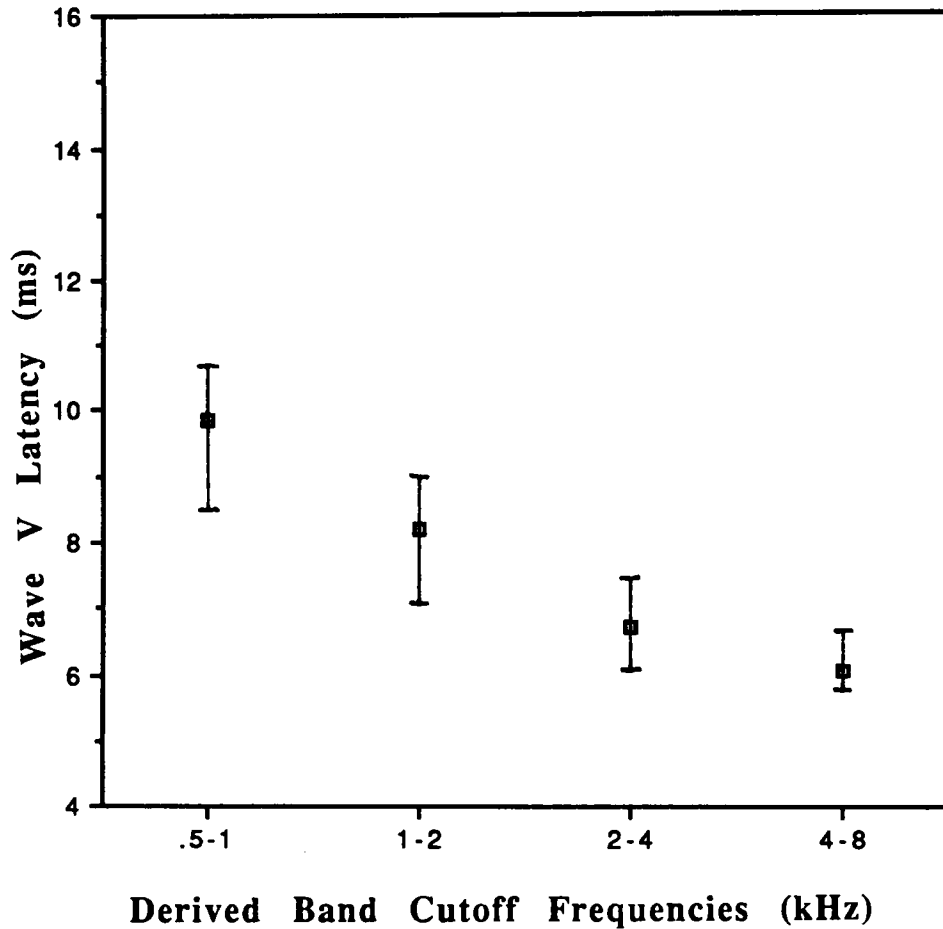


Figure 6. Mean wave V latencies (condensation and rarefaction in each of four derived response bands for a total of 8 data points per subject) are shown for each derived response condition. Vertical bars indicate the range of wave V latencies in each derived condition. For each subject in both polarities, wave V latency increased systematically as derived response cutoff frequencies decreased.

represented here, as it was a high-pass condition (not a derived band). As in the high-pass conditions, the derived conditions produced very systematic increases in the latencies of wave V based on derived response cutoff frequency. The effect of derived band frequency on wave V latency was also found to be statistically significant using ANOVA ($F(3, 6)=121.26, p<0.0001$). The systematic latency shifts seen in the derived responses are again similar to those reported by Don and Eggermont (1978) using similar signals and derived responses, and those reported by Gorga et al. (1991) using single-cycle sinusoids.

Comparison of High-Pass Masking and Derived Response Data

A comparison was made between the wave V latencies obtained with the high-pass masking noise and the derived band having the same upper cutoff frequency (e.g., the 4000-Hz high-pass masking condition was compared to the 2000-4000 Hz derived band). The mean wave V latency for each set of derived responses was 0.03 to 0.1 ms earlier than the mean wave V latency for the high-pass condition which corresponded to the upper cutoff frequency of that derived band (Table 1). These effects are small, but they occurred in the same direction, and approximately the same magnitude, for each set of responses. These results indicate that the addition of lower frequency energy to a higher frequency signal slows the latency of wave V slightly.

Table 1. Comparison Between Wave V Latencies for the High-Pass Masking Conditions and the Derived Response Data With the Same Upper Cutoff Frequency. Data for condensation and rarefaction clicks were pooled.

HIGH-PASS MASKING CONDITION AND MEAN WAVE V LATENCY	DERIVED RESPONSE CONDITION AND MEAN WAVE V LATENCY
8000 Hz = 6.15 ms	4000-8000 Hz = 6.05 ms
4000 Hz = 6.73 ms	2000-4000 Hz = 6.70 ms
2000 Hz = 8.30 ms	1000-2000 Hz = 8.22 ms
1000 Hz = 9.94 ms	500-1000 Hz = 9.84 ms
500 Hz = 12.10 ms	

Polarity Effects

High-Pass Masking Conditions

Figure 7 shows the magnitude and direction of the condensation-rarefaction latency difference for each subject in each high-pass masking condition and the unmasked condition. The effect of polarity on the latency of wave V was significant for only the 500-Hz high-pass masking condition. ANOVA was performed using the magnitude of the condensation-rarefaction latency difference (ignoring the direction of the difference); the 500-Hz high-pass masking condition was shown to be significantly different from the other four conditions ($F(4, 5)=70.31$, $p<0.0001$).

In the 500-Hz high-pass masking condition, every subject showed a marked difference in the latency of wave V elicited with rarefaction clicks versus condensation clicks. Rarefaction produced earlier wave V latencies in four of nine subjects (indicated in figure 7 by negative values), and condensation produced earlier wave V latencies in five subjects. Latency reversals such as these between rarefaction and condensation signals have been reported by other investigators (Coats and Martin, 1977; Stockard et al., 1979; Borg and Lofqvist, 1982), but the percentage of reversals was greater in the present study than in previous investigations. The mean absolute value of the difference in the latencies in the 500 Hz condition was 1.11 ms (range = 0.76 ms to 1.52 ms). This is very similar to the result reported by Gorga et al. (1991) for their 250 Hz single-cycle sinusoid (a signal which contained energy up to 600 Hz).

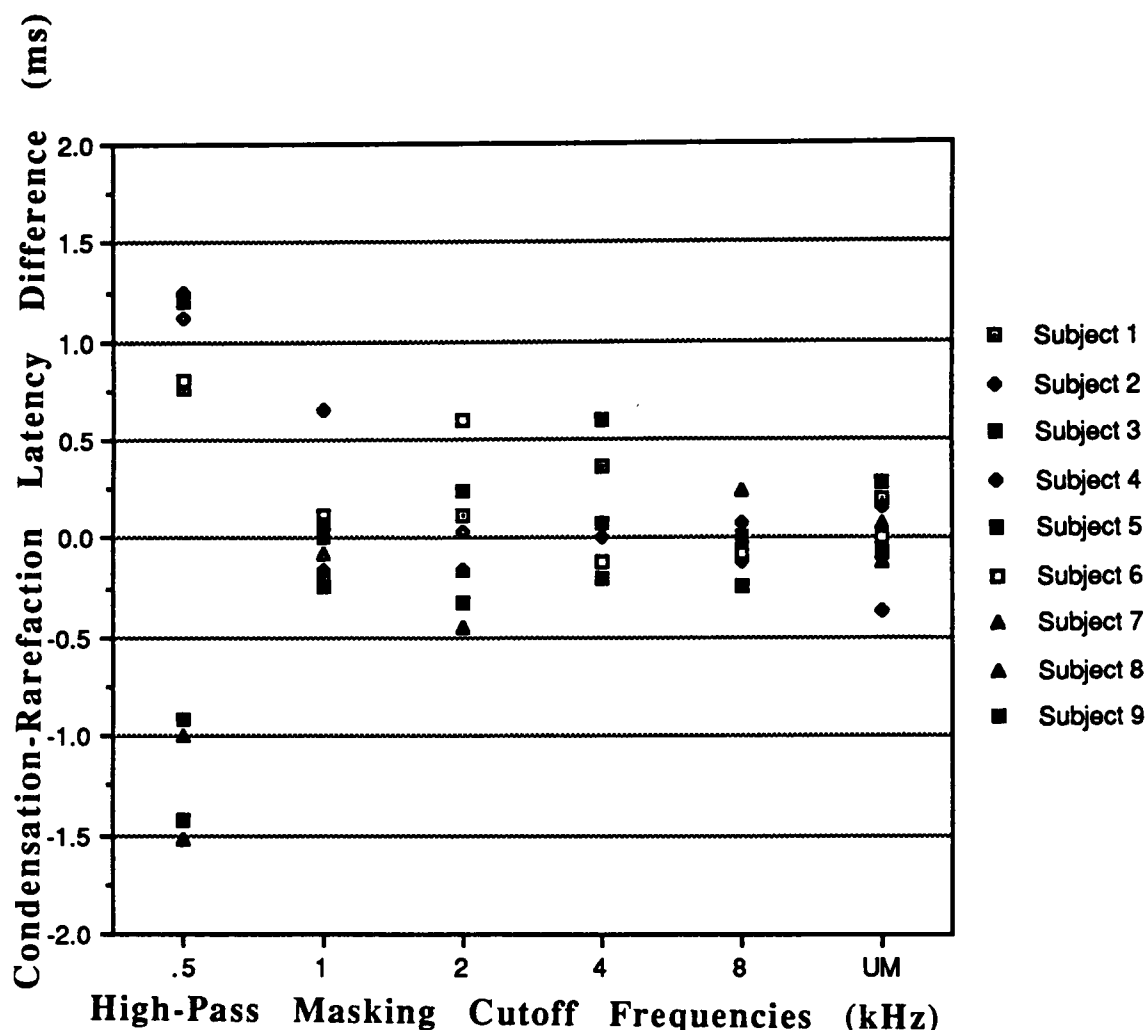


Figure 7. The condensation-rarefaction latency difference is shown as a function of high-pass masking cutoff frequency. The unmasked condition is presented for comparison to the other high-pass masking conditions. Positive values indicate that condensation produced a later wave V latency than rarefaction. Conversely, negative values indicate that rarefaction produced a later wave V latency than condensation. Inversion of stimulus polarity produced a significant difference in the latency of wave V only in the 500 Hz high-pass masking condition. In this condition, the mean absolute value of the condensation-rarefaction latency difference was 1.11 ms.

In all other high-pass masking conditions (cutoff frequencies of 1000, 2000, 4000, and 8000 Hz), the mean condensation-rarefaction latency difference was 0.17 ms (range = 0.10 ms to 0.26 ms). Gorga et al. (1991) reported a significant latency difference for their 500 Hz single-cycle sinusoid. However, in the current investigation, the condensation-rarefaction differences for these four conditions were not significant ($F(3, 6)=0.714$, $p<0.5783$).

Derived Response Conditions

Figure 8 shows the magnitude and direction of the condensation-rarefaction difference in the latency of wave V for each derived response band. This figure corresponds to Figure 7 which represents the latency differences for the high-pass conditions. As with the corresponding high-pass masking conditions (1000-8000 Hz), these derived band responses were not different from each other ($F(1, 8)=0.161$, $p<0.698$).

Effects of Click Polarity on Waveform Morphology

In the 500 Hz high-pass masking condition, wave V was generally the only clearly identifiable wave. Therefore the following discussion of morphology differences applies only to the high-pass masking conditions with cutoff frequencies of 1000 to 8000 Hz and the derived response conditions.

There were numerous instances in which inversion of click polarity, did not produce a significant latency difference but did produce substantial differences in waveform morphology. Each pair

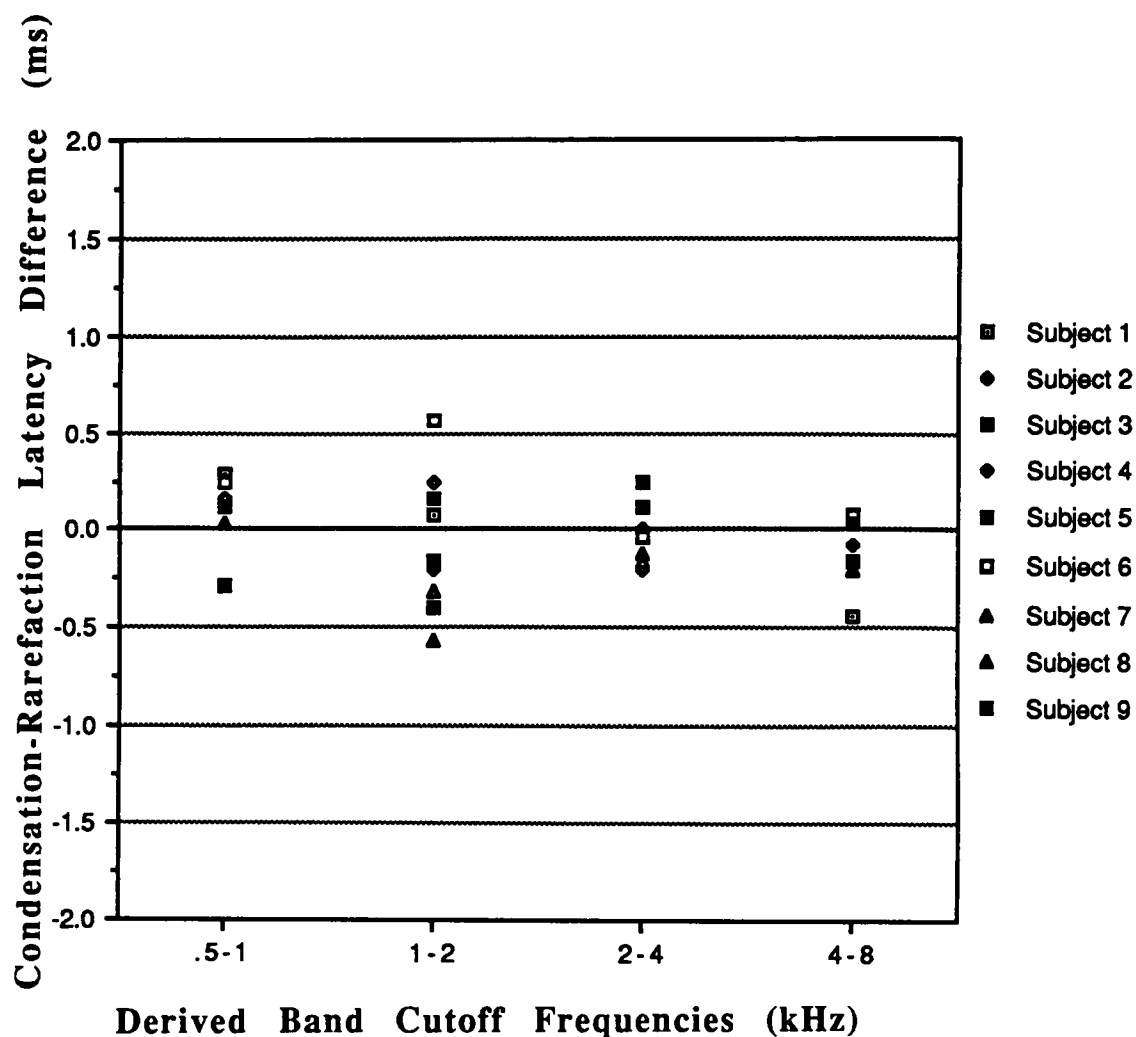


Figure 8. The condensation-rarefaction latency difference is shown as a function of derived band cutoff frequencies. Positive values indicate that condensation produced a later wave V latency than rarefaction. Conversely, negative values indicate that rarefaction produced a later wave V latency than condensation. In no derived band was there a statistically significant difference in the wave V latency produced by condensation versus rarefaction clicks. However, a few individual subjects did have condensation-rarefaction latency differences which exceeded 0.4 ms.

of traces (rarefaction and condensation in each experimental condition) was analyzed for morphology differences caused by inversion of click polarity. A pair of traces was categorized as having polarity-related morphology differences if it exhibited one or more of the following features: 1) marked differences in the relative amplitudes of waves IV and V, 2) wave III was present with one polarity and absent with the opposite polarity, 3) wave IV was present with one polarity and absent with the opposite polarity, 4) waves III and/or IV had much greater amplitude with one polarity than with the opposite polarity. The ABRs in Figure 4 demonstrate some of these morphology differences. For example, in the 4000 Hz condition shown in Figure 4, wave III is present with rarefaction polarity and absent with condensation; the reverse is true for wave IV.

Changes in morphology with inversion of click polarity varied a great deal from one individual to another, and among conditions for an individual. The majority of subjects demonstrated morphology differences in fewer than half of the ten experimental conditions. However, two subjects had morphology differences in the majority of experimental conditions (Subject 7 had morphology differences in seven experimental conditions; Subject 2 had morphology differences in nine experimental conditions). In instances in which a wave V latency difference of greater than 0.4 ms was seen in conditions other than the 500 Hz high-pass masking condition, this latency difference was consistently accompanied by a morphology difference.

V. DISCUSSION

In this study, ABRs were obtained from normal subjects for click signals that were opposite in polarity using high-pass masking noise to limit the response to specific regions of the cochlea. The dominant effect is the systematic decrease in wave V latency as the response is obtained from successively more basal cochlear regions. The longest wave V latencies are obtained when the response is restricted to the most apical region of the cochlea. The latencies shorten systematically and significantly when the response is derived from solely from the middle and then basal regions of the cochlea. This systematic decrease in wave V latency continues even to the regions of the cochlea stimulated by signal energy above 8000 Hz, indicating that frequencies above 8000 Hz contribute significantly to the overall response. When the response is derived solely from the middle or basal regions of the cochlea, the addition of contributions from more apical regions increases the latency of wave V very slightly. The wave V response latency is determined primarily by the highest frequencies in the signal, or by the most basal region of the cochlea participating in the response.

Polarity Effects

Latency of Wave V and Click Polarity

Peake and Kiang (1962) hypothesized that one polarity (rarefaction) produced an increase in neural firing (depolarization), and the opposite polarity produced a decrease in neural activity

(hyperpolarization). Salt and Thornton (1984) suggested that if this hypothesis were correct, then inversion of stimulus polarity should produce a latency difference equal to one-half the period of the stimulus used to elicit the response. They used clicks of various rise-times to elicit ABRs from normal subjects and reported finding no significant latency differences with inversion of click polarity. Examination of the frequency spectra of the clicks used by Salt and Thornton reveals that the response may not have been restricted to the apical portion of the cochlea. The click with the fastest rise-time (i.e., the lowest frequency spectrum) had significant energy in the 1000 Hz range. Since my data indicate that the response is dominated by the highest frequencies in the signal, I believe that this signal was stimulating the 1000 Hz region of the cochlea, an area where I did not see significant latency differences with inversion of stimulus polarity. The results of this study indicate that stimulus polarity affects wave V latency only when the response is restricted to the apical regions of the cochlea. Since they were presumably stimulating a frequency region in which I did not see significant latency effects based on stimulus polarity, my results are in agreement with those reported by Salt and Thornton.

The results obtained in the present study are also largely in agreement with those reported by Gorga et al. (1991). In both studies latency increased significantly as signal frequency was lowered. Wave V latency was shown to depend on signal polarity for low-frequency signals, and the magnitude of the condensation-

rarefaction latency difference was approximately equal in both investigations.

While the nominal frequency of Gorga et al.'s lowest-frequency signal was 250 Hz, I believe this signal was stimulating regions of the cochlea which respond to signal energy at a higher frequency than 250 Hz because this signal did not produce the 2.0 ms condensation-rarefaction latency difference which would be expected if the response were limited to frequencies of 250 Hz and below. For example, at 80 dB SPL the 250 Hz single-cycle sinusoid produced a mean latency difference of 1.25 ms. If the magnitude of the latency difference is determined by the frequency of the signal, then the effective frequency of this signal was approximately 400 Hz. The 250 Hz single-cycle sinusoid was shown to have significant energy up to 600 Hz. For similar reasons, I believe that the single-cycle sinusoid with a nominal frequency of 500 Hz stimulated regions of the cochlea which respond to frequencies higher than 500 Hz. This may explain why Gorga et al. were able to show the effects of polarity on wave V latency decreasing as signal frequency increased. I was not able to see such a progression since I did not test an intermediate frequency between 500 and 1000 Hz. It is possible that a click signal presented simultaneously with 750 Hz high-pass masking noise would produce results very similar to those reported by Gorga et al. for their 500 Hz single-cycle sinusoid.

A more difficult finding to explain is that of the increase in the magnitude of the latency difference with increased signal intensity which was reported by Gorga et al. One possible explanation for

this finding involves the human audibility curve. As intensity is increased, additional low frequencies fall within the range of human audibility, thus altering the effective spectrum of the signal. It is possible that this additional low-frequency energy caused the increase in the condensation-rarefaction latency difference which was observed with increased signal intensity.

One apparent difference in my results and those reported by Gorga et al. is that they apparently saw latency differences in which the direction of the difference was predictable. In the present study, the direction of the condensation-rarefaction latency difference was unpredictable with condensation producing earlier wave V latencies approximately 50% of the time. It appears that the condensation-rarefaction latency differences reported by Gorga et al. were more systematic, producing mean shifts in the same direction for each condition. I have no explanation for this difference in findings.

The fact that significant polarity effects can be demonstrated in normal ears indicates that these effects can be caused by normal cochlear mechanics as well as by cochlear or neural pathology. Significant latency differences were seen in the present study only when the response was restricted to 500 Hz and below, and these latency differences were consistently on the order of 1.0 ms (one-half the period of the highest frequency in the signal).

For the regions of the cochlea activated by frequencies higher than 500 Hz, I did not obtain significant differences in wave V latency with inversion of signal polarity for the group of nine

subjects. Individual subjects did show latency differences of up to 0.6 ms in these conditions, but these differences were not systematic across conditions. Thus clinical investigators may find latency differences for a particular subject in a particular condition, but those differences might not be seen for the same subject in another condition.

One of the chief goals of this study was to add to the knowledge regarding polarity effects which are seen with high-frequency hearing loss. My data are similar to those which have been reported for high-frequency hearing losses in that I obtained increases in absolute latencies as well as significant polarity effects when the response was obtained from the apical region of the cochlea (the responding region in cases of high-frequency hearing loss). Latency differences with inversion of signal polarity are not to be expected when signals with high-frequency energy are used to elicit ABRs from ears with normal or near-normal high-frequency sensitivity.

Latency differences are expected when low-frequency signals are used to elicit ABRs from normal ears, and when unmasked clicks are used to elicit ABRs from subjects with high-frequency hearing loss. Latency differences can be expected to increase as hearing becomes confined to lower frequencies, i.e., as the response is generated in more apical regions of the cochlea.

Waveform Morphology and Click Polarity

For seven of nine subjects there were occasional differences in waveform morphology with inversion of click polarity. These morphology changes did not appear to be systematic in that they were not related to any particular stimulus condition or region of activity within the cochlea. However, two subjects demonstrated morphological changes with inversion of click polarity in the majority of experimental conditions. Therefore the tendency to demonstrate morphological changes based on signal polarity appears to vary among individuals. It should be noted that when large wave V latency differences were seen in conditions other than the 500 Hz high-pass masking condition, they were consistently accompanied by a significant morphology difference.

The results of this study, like those of previous studies, indicate that the routine clinical use of alternating polarity signals may obscure response components. This is particularly true in cases of high-frequency hearing loss, where responses obtained from opposite polarities may differ in latency, resulting in difficulty determining component latencies. I agree with the recommendation of Gorga et al. (1991) that responses from opposite polarities be kept separate and summed only when it is necessary in order to reduce or eliminate stimulus artifact.

Implications for Future Research

The present results indicate that frequencies above 8000 Hz contribute significantly to the ABR, and that elimination of these

frequencies prolongs the latency of wave V. This effect was significant despite the limiting of the high-frequency energy caused by the frequency response of the earphone. Clinical use of earphones which pass ultra-high frequencies in diagnostic ABRs should be considered since it is possible that the use of standard earphones can obscure response components and artificially prolong the latency of wave V.

Another possible implication for future research is the finding of significant polarity effects below 500 Hz and the absence of these effects at 1000 Hz. It would be of interest to obtain similar ABRs from the 750 Hz region of the cochlea to determine if a consistent latency difference with stimulus polarity can be documented at an intermediate frequency. If such latency differences were found, it would meet Gorga's (1991) expectation that polarity effects progressively decrease as energy is extended into higher frequency regions.

Since it has been shown that ABRs can be obtained from apical regions of the cochlea, it might be possible to perform ABR tests for neurologic purposes on patients with significant high-frequency hearing loss by establishing clinical norms for ABRs using 1000 Hz high-pass masking noise. Many patients referred for retrocochlear studies have high-frequency hearing loss, which can make it difficult to successfully rule out retrocochlear involvement. If these neurologic studies could be performed using 1000 Hz high-pass masking noise, the response could be generated in what for many of these patients is a region of normal sensitivity. It may be

therefore possible to obtain a normal ABR for the regions below 1000 Hz and rule out retrocochlear pathology.

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APPENDICES

APPENDIX A
SUBJECT CONSENT FORM

INFORMED CONSENT FORM FOR STUDY -- EFFECTS OF CLICK POLARITY ON AUDITORY BRAINSTEM RESPONSES IN MAN USING HIGH-PASS NOISE MASKING

I. Description

You are being asked to participate in an experimental study of the auditory brainstem evoked response to evaluate the contributions of different regions of the inner ear to this response. Should you agree to participate, your hearing sensitivity will be determined initially using a routine clinical test. In this basic test of hearing sensitivity tones of different pitches will be presented to you through headphones and you will be instructed to respond when you hear them. Next, your eardrum and middle ear system will be tested for mobility. This test requires the insertion of a small ear-plug-like probe and the variation of air pressure in your ear canal.

Following completion of the above tests the auditory brainstem evoked responses (ABR) will be recorded using the proposed stimulus paradigm in which a click stimulus is presented repeatedly in the presence of masking noise. The ABR test involves measuring brain waves using small metal discs applied to your scalp with a paste and held in place with plastic tape. This test requires that you merely relax and remain still while reclining and listening to the repetitive sounds presented through earphones.

All of the above tests and procedures are routine clinical procedures that offer no known health risks. However, every effort will be made to minimize any potential risk or discomfort. Although you may not derive direct benefit from this study, you will have contributed usefully to our understanding of the hearing mechanism.

II. Confidentiality

I understand that any information obtained about me for this study will be kept strictly confidential. Information carrying personal identifying material will be kept in locked files. I do understand that my research records, just like hospital records, may be subpoenaed by court order. It has been explained to me that my identity will not be revealed in any description or publication of this research. Therefore, I consent to such publication for scientific purposes.

APPENDIX B
BEHAVIORAL THRESHOLDS BEFORE AND AFTER EXPERIMENTAL
SESSIONS

Frequencies (kHz) at which behavioral thresholds were measured are shown at the top of the table. Subject number appears to the left of the data. Behavioral thresholds (dB HL) for the right (experimental) ear were measured for each subject before the experimental session as part of subject qualifying procedures. Bone conduction thresholds are labeled BC, and air conduction thresholds are labeled AC1. Air conduction thresholds were again measured (AC2) within five minutes of completion of experimental procedures.

		Frequency (kHz)									
		.125	.250	.500	.750	1	2	3	4	6	8
Subject Number	1	BC		15	-5	-5	-5	-5	0		
		AC1	15	15	5	0	0	0	0	0	5
		AC2	15	15	5	0	-5	0	-5	0	10
	2	BC		5	5	0	-5	5	0	0	
		AC1	10	5	5	0	0	0	0	15	5
		AC2	10	5	5	0	0	0	5	20	5
	3	BC		15	0		10	0	-5		
		AC1	5	10	0	-5	-5	-5	0	0	-5
		AC2	5	10	5	0	0	-5	5	0	10
	4	BC			5	0	5	0	0	0	
		AC1	5	5	5	5	5	-5	-10	0	-5
		AC2	5	0	5	5	5	-5	-10	-5	0
	5	BC			5		-10	0	5	0	
		AC1	10	10	5	0	-5	5	5	0	20
		AC2	15	10	5	0	-5	5	0	0	20
	6	BC		10	0	0	0	-5	0	-5	
		AC1	0	10	5	5	0	0	-5	-5	20
		AC2	0	10	0	0	0	0	-5	0	25
	7	BC			5		5	-10		-5	
		AC1	10	10	0	0	0	5	0	0	15
		AC2	10	10	0	0	0	5	5	0	15
	8	BC			5		5	0	5	5	
		AC1	5	5	5	5	5	0	0	5	10
		AC2	5	5	5	5	0	0	0	0	10
	9	BC		10	0		5		-10		
		AC1	10	10	10	5	5	-5	-5	0	15
		AC2	5	5	10	0	0	0	0	5	15

APPENDIX C

AMBIENT NOISE LEVELS IN SOUND ROOM

Ambient noise levels in the double-walled sound room were measured using the Bruel and Kjaer sound measurement system described in the Methods section.

Octave Band Center Freq. (Hz)	Octave Band Pressure Level (dB SPL)
125	46.0
250	27.5
500	less than 19.0
1000	less than 19.0
2000	less than 19.0
4000	less than 19.0
8000	less than 19.0

APPENDIX D

ACOUSTIC MEASUREMENTS OF HIGH-PASS MASKING NOISE

The response characteristics of the filters were measured using the Bruel and Kjaer sound measurement system described in the Methods section. High-pass masking cutoff frequency (Hz) is indicated at the top of each column of data; octave band center frequency on the SLM is indicated to the left of each row. Measured intensities are in dB SPL. Approximate values are indicated by (~). Asterisks (*) indicate instances in which the high-pass masking cutoff frequency was in the center of the octave band filter used to measure the output. The overall SPL of the 125 Hz high-pass masker was measured on 6/24/91 before the experiment began, and again on 10/8/91 after all experiments were completed to insure that the intensity was not variable. On both occasions the overall SPL of the 125 Hz high-pass masking noise was 90.8 dB.

	8000	4000	2000	1000	500	125
31.5	~46	~45	~47	~45	~45	~48
63	~37	~37	~37	~37	~37	~45
125	37.5	37.5	37.4	37.4	~36	*75.5
250	40.1	40.0	40.2	40.6	51.0	81.5
500	35.3	35.7	37.7	54.5	*81.5	85.0
1000	30.7	37.0	56.5	*84.5	87.5	87.5
2000	26.3	59.2	*87.5	90.0	90.0	90.0
4000	44.5	*88.8	92.7	92.7	92.8	92.8
8000	*71.5	83.7	83.8	83.7	83.7	83.7

APPENDIX E

ABSOLUTE WAVE V LATENCIES FOR EACH SUBJECT IN THE UNMASKED CONDITION AND EACH HIGH-PASS MASKING CONDITION

Absolute wave V latencies (ms) are shown for the unmasked condition (UM) and for each high-pass masking condition (8000 Hz through 500 Hz are denoted 8K through .5K, respectively) for both rarefaction (R) and condensation (C) click signals. Subject numbers (1-9) appear above each column of data.

	1	2	3	4	5	6	7	8	9
UM R	6.12	5.76	6.08	5.60	5.72	5.80	6.00	5.84	5.72
UM C	5.92	5.60	5.80	5.68	6.08	5.84	6.00	5.76	5.84
8K R	6.44	5.88	6.80	6.04	5.88	5.92	6.36	6.04	5.88
8K C	6.48	5.80	6.88	6.16	6.12	6.00	6.36	5.80	5.88
4K R	7.76	6.36	6.96	6.96	6.96	6.32	6.68	6.56	6.36
4K C	7.40	6.36	6.88	6.88	6.36	6.44	6.60	6.76	6.56
2K R	8.56	7.36	8.56	8.68	8.72	8.12	8.16	8.52	8.08
2K C	8.44	7.52	8.88	8.64	8.48	7.52	8.60	8.68	7.76
1K R	9.48	9.24	10.68	10.24	9.28	10.00	9.96	10.32	10.40
1K C	9.68	8.59	10.68	10.40	9.52	9.88	10.12	10.40	10.08
.5K R	11.80	11.88	12.16	12.96	11.36	12.40	12.60	12.48	12.76
.5K C	11.04	10.64	13.08	11.84	10.16	11.59	13.60	14.00	14.00

APPENDIX F

ABSOLUTE WAVE V LATENCIES FOR EACH SUBJECT IN EACH
DERIVED RESPONSE CONDITION

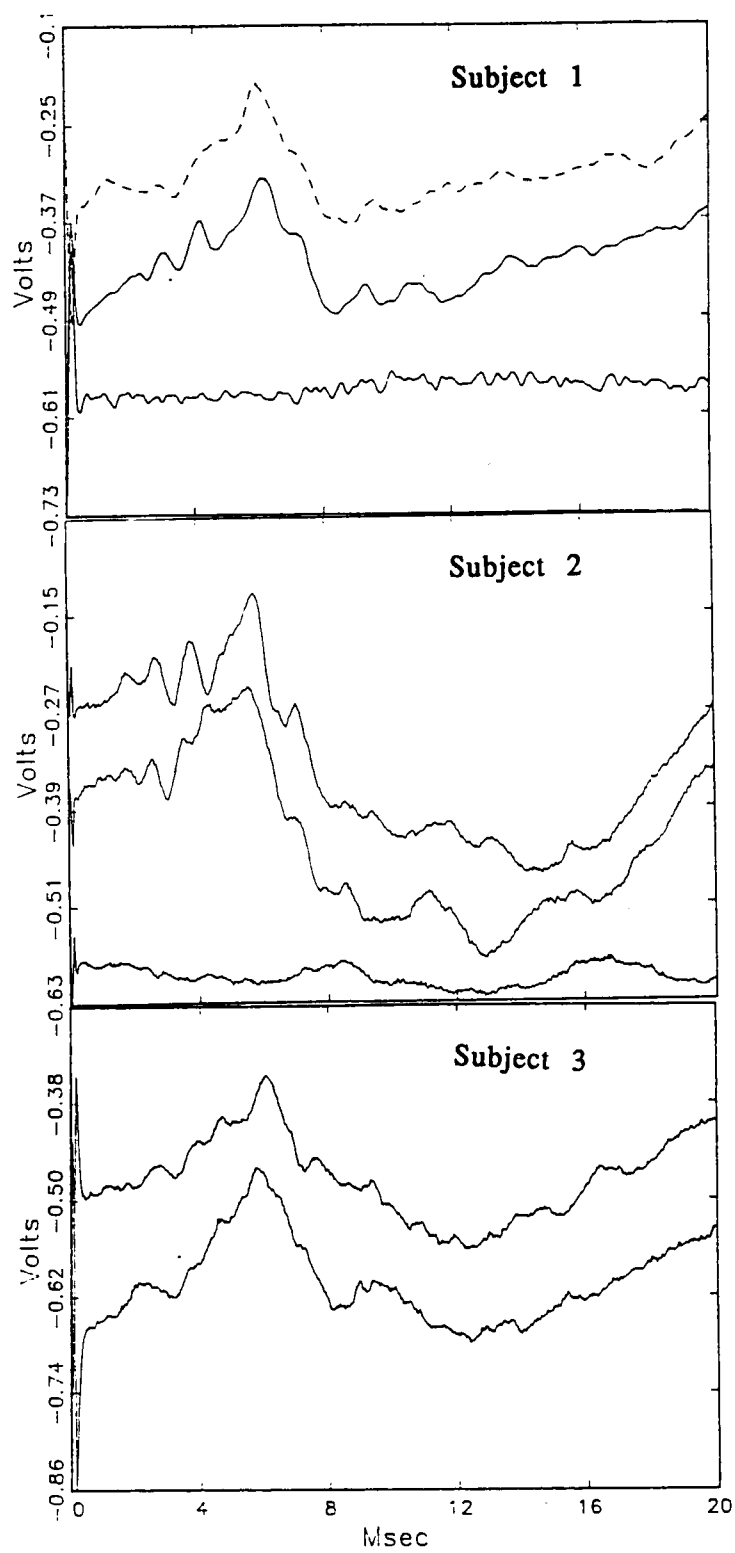
Absolute wave V latencies (ms) are shown for each of the derived response conditions (4000 Hz-8000 Hz through 500 Hz-1000 Hz are denoted 8K-4K through 1K-.5K, respectively) for both rarefaction (R) and condensation (C) click signals. Subject numbers (1-9) appear above each column of data.

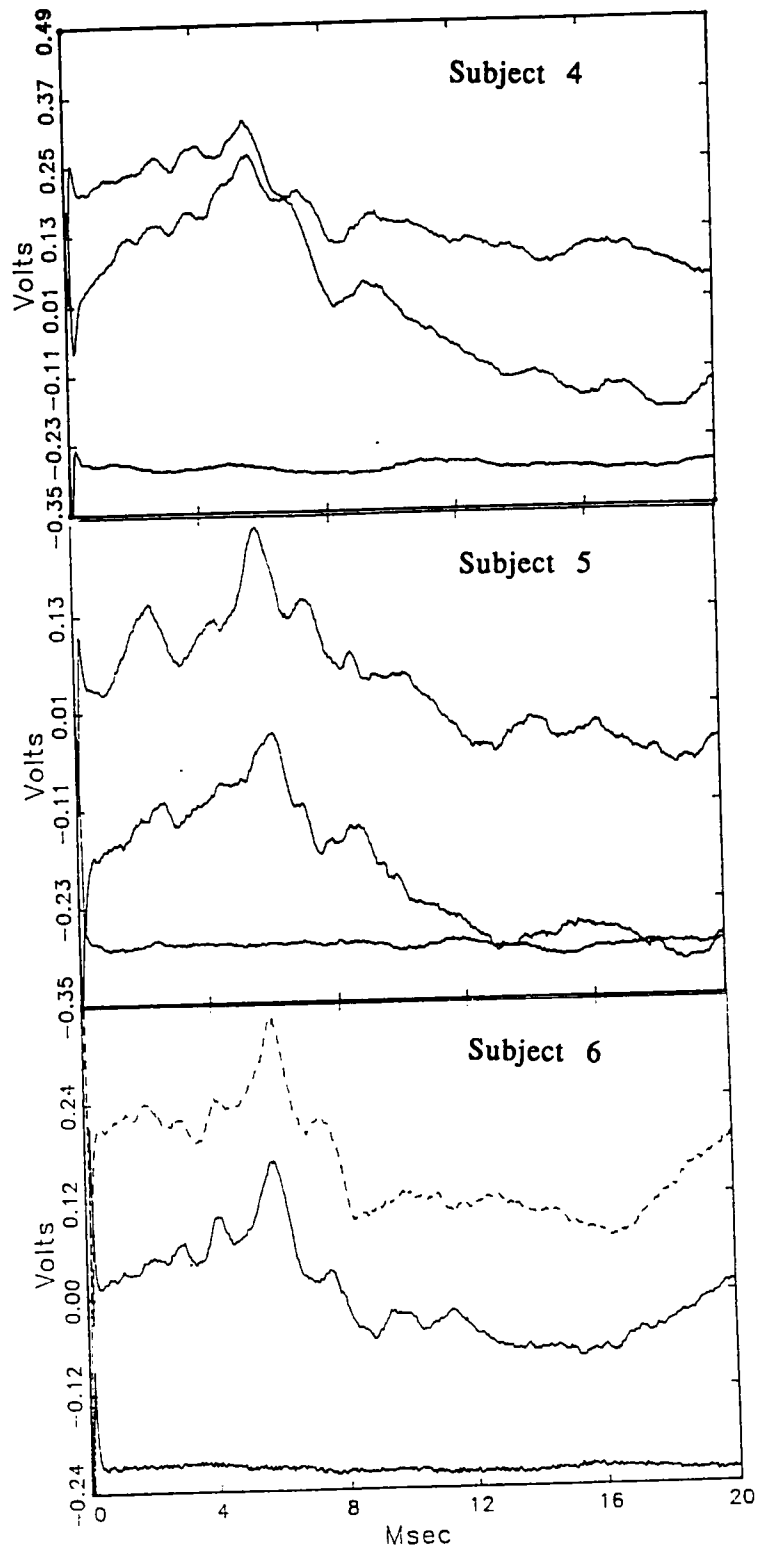
	1	2	3	4	5	6	7	8	9
8K- 4K R	6.04	5.84	6.64	6.00	5.92	5.92	6.04	5.88	5.88
8K- 4K C	6.48	5.92	6.80	5.96	5.88	5.84	6.24	5.84	5.84
4K- 2K R	7.44	6.28	7.12	6.84	6.48	6.44	6.72	6.56	6.48
4K- 2K C	7.32	6.28	6.88	7.04	6.36	6.48	6.84	6.72	6.36
2K- 1K R	8.48	7.36	8.56	8.68	8.16	8.16	8.04	8.64	7.64
2K- 1K C	8.40	7.56	8.96	8.44	8.32	7.60	8.60	8.96	7.48
1K- .5K R	9.64	8.72	10.24	10.24	9.32	9.96	10.16	10.32	10.20
1K- .5K C	9.36	8.59	10.52	10.08	9.60	9.72	10.12	10.20	10.08

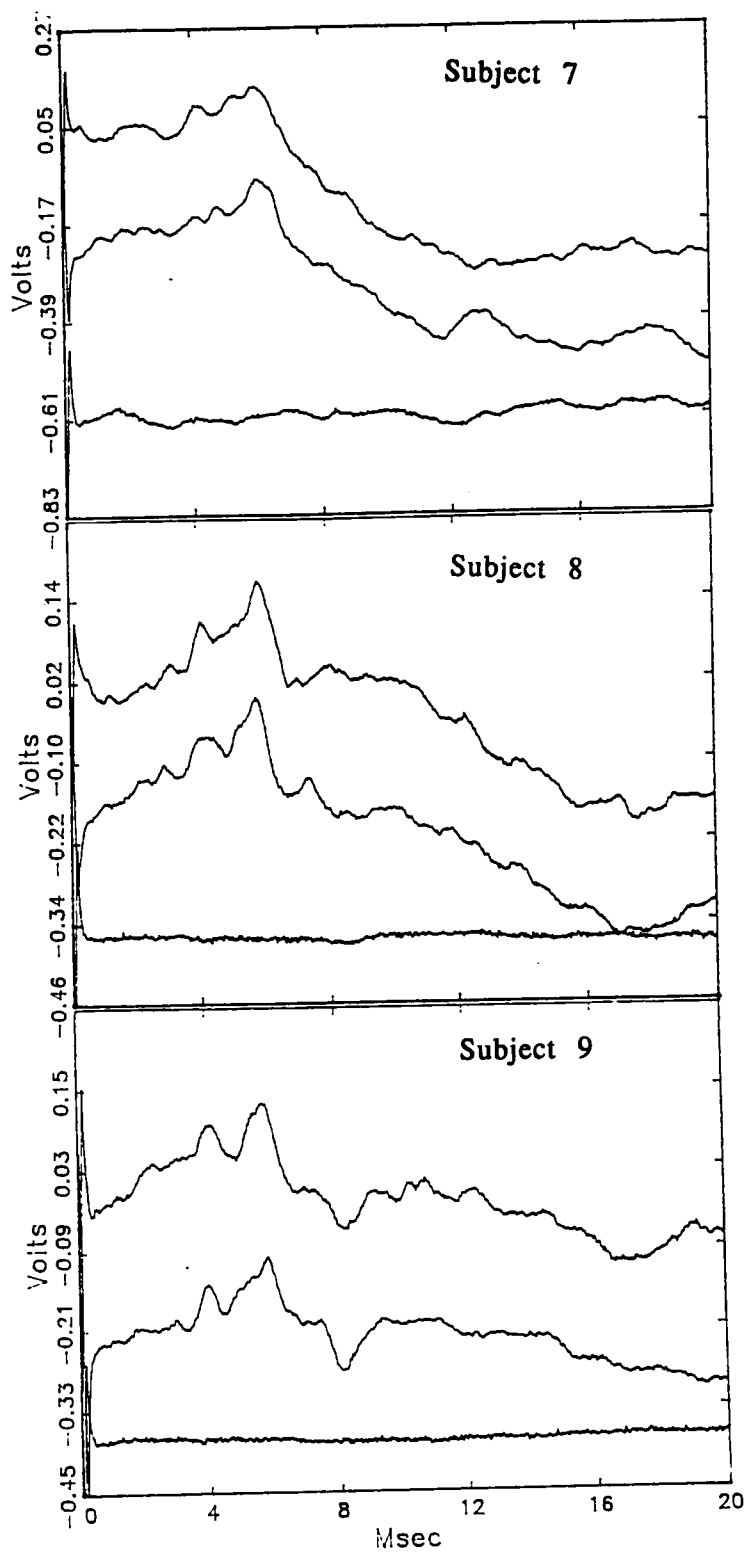
APPENDIX G

ABRs OBTAINED IN THE UNMASKED CONDITION AND IN THE BROAD-BAND MASKING CONDITION FOR EACH SUBJECT

For each subject, three ABRs are shown: the response obtained to 2000 unmasked condensation clicks (top), the response obtained to 2000 unmasked rarefaction clicks (middle), and the response obtained to 8000 condensation clicks presented with ipsilateral broad-band masking noise (bottom). (NOTE: The ABR with broad-band masking noise is not presented for Subject 3; it was lost due to a computer error. It was very similar to the responses obtained from the other subjects in the broad-band noise condition.)







VITA

Lisa Lynn Cunningham was born in Knoxville, Tennessee, on August 2, 1968. She obtained her Bachelor of Arts degree with a major in audiology from the University of Tennessee at Knoxville in May 1990. In December 1991 she received a Master of Arts degree from the University of Tennessee. After completion of a Clinical Fellowship Year in audiology, she intends to pursue a Ph.D. in audiology or speech and hearing science.