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BINAURAL MASKED THRESHOLDS WITH REPRODUCIBLE NOISE BURSTS

by

BARRY VOROBA

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

1973

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

5-14-73 Harry Levitt

date

Chairman of Examining Committee
Harry Levitt, Ph. D.

May 22, 1973 Norma S. Rees

date

Executive Officer
Norma Rees, Ph. D.

James K. Lang
James K. Lang, Ph. D.

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Eli Osman, Ph. D.
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The City University of New York

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ABSTRACT

BINAURAL MASKED THRESHOLDS WITH REPRODUCIBLE NOISE BURSTS

by

BARRY VOROBA

Advisor: Dr. Harry Levitt

Binaural masked threshold levels were obtained at 250 and 500 Hz from three subjects for the $S0N_{\tau}$-$S0N0$ and $S\pi N_{\tau}$-$S\pi N0$ listening conditions. An interaural time delay was introduced to the binaural noise waveforms by means of a precision delay line. In previous experiments, some form of thermal noise source provided the masking stimulus to the listener. Such noise is a random, admixture of components, forever changing in instantaneous amplitude, and quantifiable only in terms of statistical averages. An experimenter could not, therefore, specify the precise noise and tone burst waveforms presented to a subject from trial to trial. In this study, however, a digital noise generator provided the identical noise waveform to the listener during each test trial.

A number of similarities were observed, between the threshold level functions derived from this experiment and those reported in the literature—notably, the re-demonstration of the familiar cyclic MLD pattern for a number of test situations. Some striking differences between past and present findings were also observed. These included: an absence of the classic MLD pattern when the test tone burst occurred within particular portions of the noise waveforms and an actual elevation of the MLD peaks as τ_n increased, rather than the expected damping that is typically observed.

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CHAPTER I

BINAURAL HEARING - AN OVERVIEW*

Binaural hearing refers to hearing with two ears. Several phenomena are associated with binaural hearing, including: binaural fusion, localization, masking level differences, enhanced intelligibility of speech, the precedence effect, binaural beats, and other forms of binaural interaction. These effects are not only of interest in themselves as perceptual phenomena, but also because they provide considerable insight into the underlying hearing process, monaural or binaural. The purpose of this chapter is to provide a broad overview of the major effects of binaural hearing.

In a normal listening situation, the signals reaching our ears are similar, but not quite identical; yet, we typically hear one sound. This phenomenon, in which a single sound is heard for two separate inputs, is known as binaural fusion. In the laboratory, a binaurally fused sound image may be created by means of headphone listening. In the most basic case, two identical stimuli are applied, one to each ear, i.e. diotically.** Under these conditions, a normal-hearing listener almost

---

*Portions of this chapter are based on Levitt and Voroba (1973).

**A monaural (monotic) listening situation involves the use of one ear only. Binaural listening utilizes two ears, but a distinction should always claims to hear a single fused sound image within or near his head and close to or on the median plane (i.e. roughly in line with his nose).

Early workers (Boring, 1942; von Bekesy, 1930; von Hornbostel and Wertheimer, 1920) found that the introduction of an interaural time difference between signals reaching the two ears produced a shift in the lateral position of the fused image. Von Bekesy (1930) introduced the interaural time delays by transmitting signals to the ears via brass tubing of different lengths. He employed a stream of air directed at the subject's head as a pointing device for locating the lateral position of the sound image. Modern studies have used electronic techniques. In one procedure (Teas, 1962) observers controlled the degree of interaural time difference between pairs of test pulses. They were asked to graph the perceived location of the sound image. Figure 1 displays the change of apparent lateral image position as a function of the time delay between the input stimuli. The 20 dBSL curve is linear to an interaural delay of about 500 µsec (Hornbostel-Wertheimer constant) after which it flattens out sharply. That is, for interaural delays greater than 500 µsec, the change of apparent lateral position with increased

---

be made between the terms <u>diotic</u> and <u>dichotic</u>. In a diotic listening situation, the identical signal is applied to each ear of the listener. Dichotic listening also involves both ears, but different stimuli are applied to each ear. The terms <u>monophonic</u> and <u>stereophonic</u> are typically used to describe listening situations employing, respectively, one and two sound sources where the output of each sound source reaches both ears.

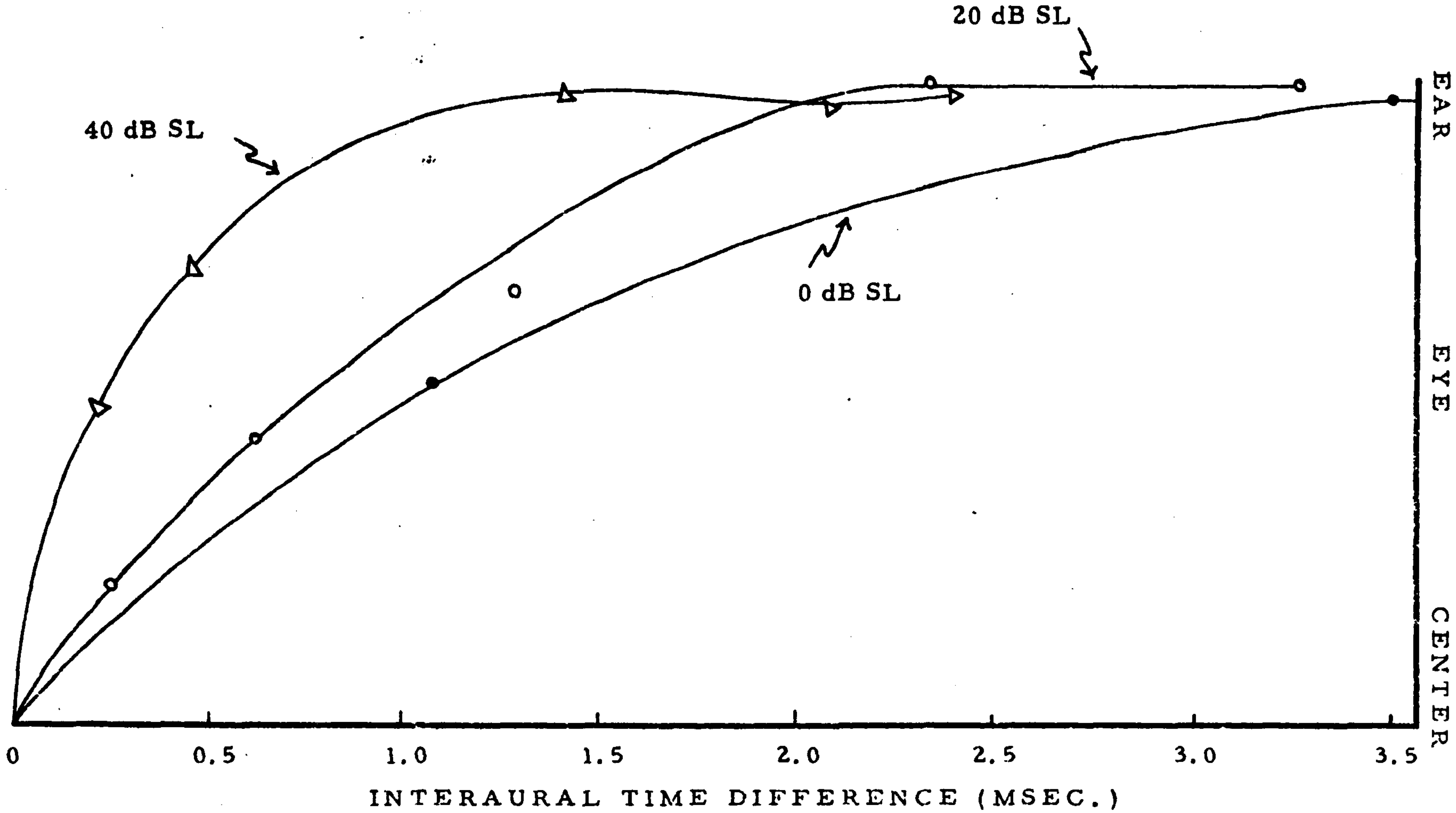


Fig. 1.--The change of apparent lateral image position as a function of the time delay between the input stimuli (after Teas, 1962).

delay is relatively small. For click-like stimuli, delays greater than three to five msec, will begin to break up the image and two percepts will be heard -- one at each ear (Guttman, 1962).

For speech signals, however, a larger time delay reaching up to fifteen msec. can be tolerated (Cherry and Taylor, 1954). For tones, an obvious split of the image does not occur. Since tones are periodic, an interaural time delay equal to the period will bring the tone back to its median plane position. The effect of systematically increasing interaural time delay in this case is to produce cyclic changes in apparent lateral position, from the center of the head to one or the other extremity and back again (Sayers and Cherry. 1957). In the extreme condition, corresponding to a time delay of 1/2 period of the signal (which is equivalent to a 180° or π radians interaural phase difference) the auditory percept appears to differ between individuals. Some claim to hear a single fused image emanating from all directions; while others have claimed to hear the image split into two parts, one at each ear.

The smallest detectable interaural time delay (the just noticeable difference or jnd) varies with the type of signal employed. Jnds as low as 10 μsec have been reported when wide band noise bursts (Tobias and Zerlin, 1959) or continuous speech (Levitt, 1964) are used as the test stimuli. For tones the jnd in interaural time delay varies as a function of frequency. Zwislocki and Feldman (1956) have observed a minimum jnd of the order of fifteen μsec at a frequency of 1kHz, rising to about twice this value for the test tone frequency of 250 Hz (see Figure 2). Similar

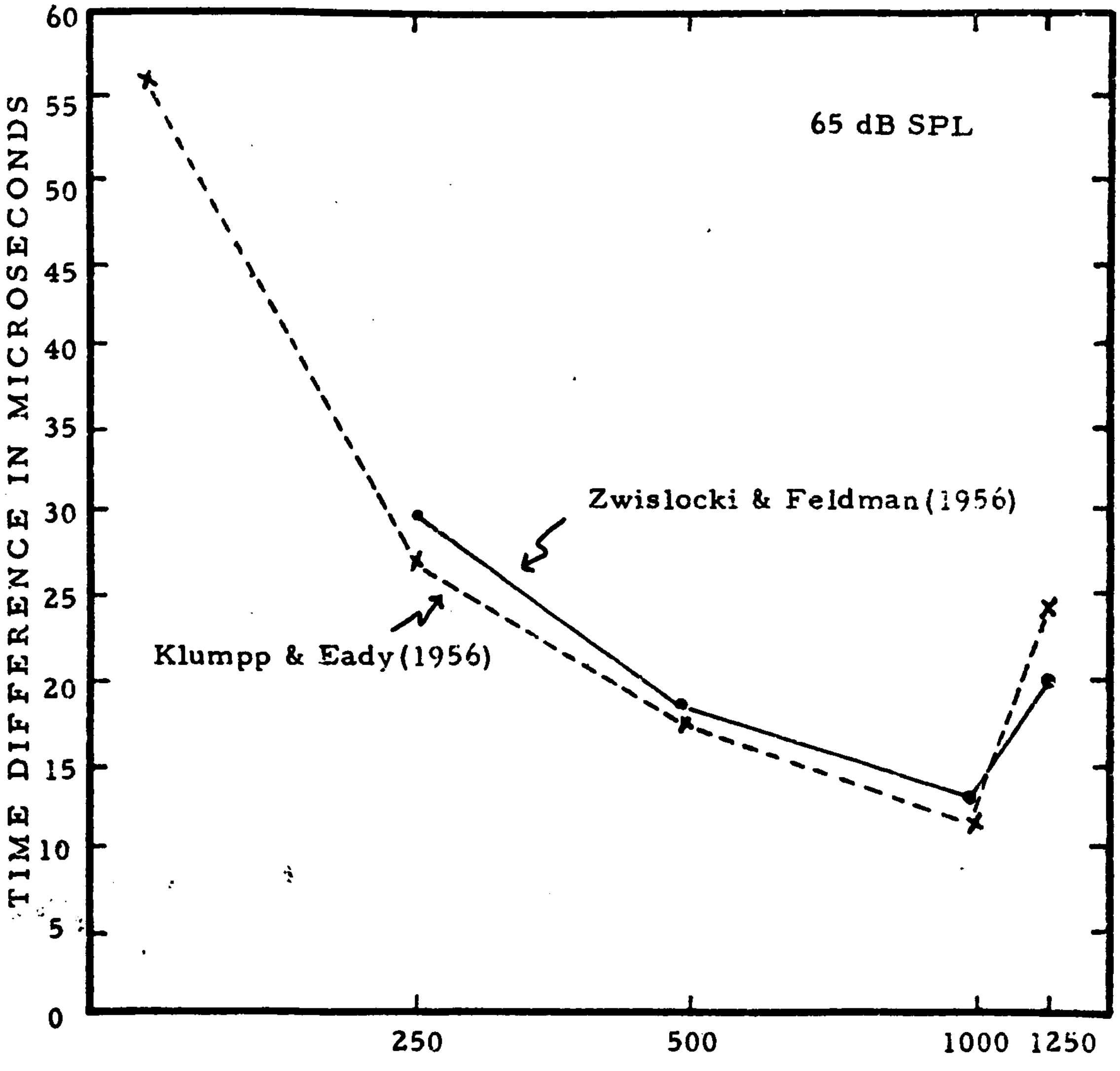


Fig. 2.--The jnd for interaural time as a function of the test tone frequency (after Zwislocki and Feldman, 1956).

4

data have been reported by Klumpp and Eady (1956) for narrow bands of noise.

An important consideration in experiments of this type is the manner in which the binaural signals are switched on and off. One approach is to have a sharp onset for the tone burst (see Figure 3a). Another approach is to switch the signals synchronously, but with an interaural time delay between the ongoing signals (Figure 3b). Transients in switching have a substantial effect on lateralization judgments and the effect is likely to be most severe when there is a period of silence at one ear while there are switching transients at the other ear (as in Figure 3a). In this case, the judgment of apparent position may be critically dependent on the switching transients. Switching transients also occur for the condition depicted by Figure 3b, but they occur at both ears simultaneously and should influence judgments of apparent position to a lesser extent. A preferred method of switching is to use synchronous switching, as shown in Figure 3b but with a relatively long rise time ($>$ 25 msec.) superimposed on the tone burst, as shown in Figure 3c. The long rise time substantially reduces the effects of switching transients. These effects are further reduced by having both signals switched off synchronously. Because of the crucial role of transients in lateralization, care should be taken to check such details when comparing lateralization data.

Interaural intensity differences also produce a change of the apparent lateral position of the fused sound image (Moushegian and Jeffress, 1959;

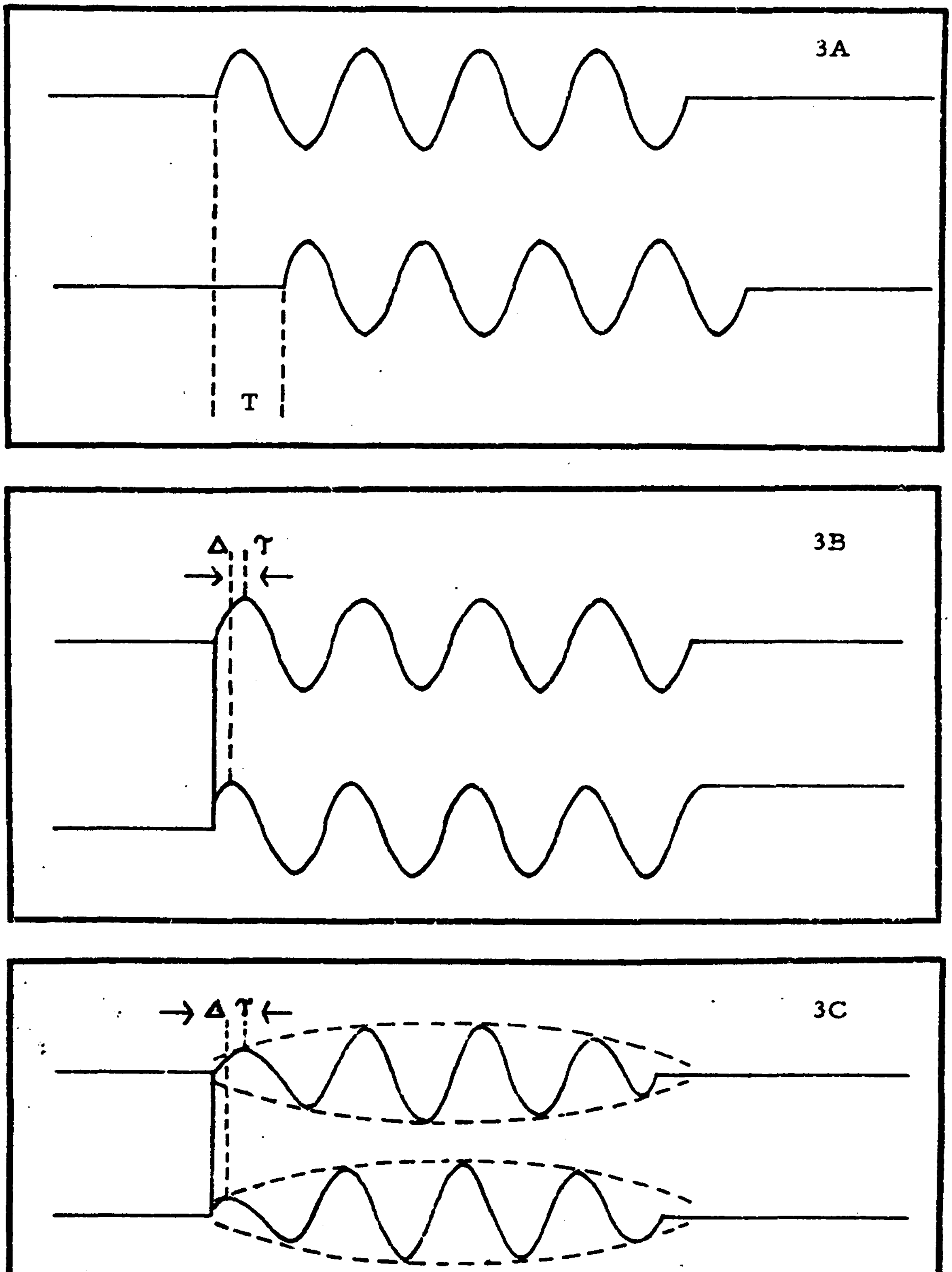


Fig. 3. --Tone bursts switched on (a) asynchronously (b) synchronously with interaural time delay (c) synchronously with time delay plus long rise and decay time.

Whitworth and Jeffress, 1961). In this case, there is a simple monotonic relationship for all stimuli (including pure tones) between apparent lateral position and intensity difference. The larger the interaural intensity difference, the greater the degree of laterality. In the limiting condition (i.e. extremely large interaural intensity difference) the signal will be well below threshold at one ear and heard only at the opposite ear. The jnd for interaural intensity difference is about 1.0 dB at 1000 Hz, decreasing to 0.5 dB at lower and higher frequencies (Mills, 1960).

The relative importance of interaural time and intensity differences upon apparent lateral position is very much a function of frequency. For low frequency tones, both time and intensity differences are important. Interaural time differences become progressively less important with increasing frequency, and is not a measurable effect above approximately 1500 Hz. A number of workers (Guttman, 1962; Harris, 1960; Whitworth and Jeffress, 1961) report that temporal and magnitude cues tend to compensate for each others' effects in a highly complex trading relationship. The compensation is incomplete, however, for the resulting sound image is more diffuse. Also, there is not necessarily a unique trading relationship between intensity and time differences. David, Guttman and van Bergeijk (1959), for example, found two separate trading relationships with tonal stimuli.

The use of additional factors which appear to shift lateral image position include: head turning and jaw clenching (Bowles, 1960); rotation or acceleration of the subject's head (Arnoult, 1952; Graybiel and Niven, 1951); interaction with visual stimuli (Jackson, 1953; Arnoult, 1952); unilateral masking (Butler and Naunton, 1962; Raab and Osman, 1962); unilateral fatigue (Wright, 1960); and the spectral content of the stimulus itself (Mouzon, 1955).

Binaural fusion can also occur when non-identical stimuli are used, so long as the signal envelopes are the same. Figure 4 depicts two sine waves of differing frequency but identical envelopes (i.e. the gradual change with time of the amplitudes of the two sine waves is the same). Large differences between signals reaching the two ears need not cause a breakdown in fusion, provided the signals have a common envelope and the envelope frequency itself does not exceed 1500 Hz. This effect has been demonstrated in a number of experiments using such disparate stimuli as: identically modulated sine waves of different frequency as shown in Figure 4 (Leakey, Sayers and Cherry, 1958); the oscillatory responses of two different resonant circuits pulsed in synchronism (Broadbent and Ladefoged, 1957), and also simultaneous bursts of uncorrelated noise (David et al., 1959). Binaural fusion has also been produced with differentially filtered clicks by presenting the low frequency components to one ear and the high frequencies to the other ear (Deatherage, 1961).

Yet another means of creating a fused image is to present subjects with a speech signal that alternates from ear to ear (Cherry, 1953). With a switching period less than 0.1 second, the listeners reported hearing a fused sound image. For slower switching rates, they observed one lateral image that fluctuated from side to side. The intelligibility

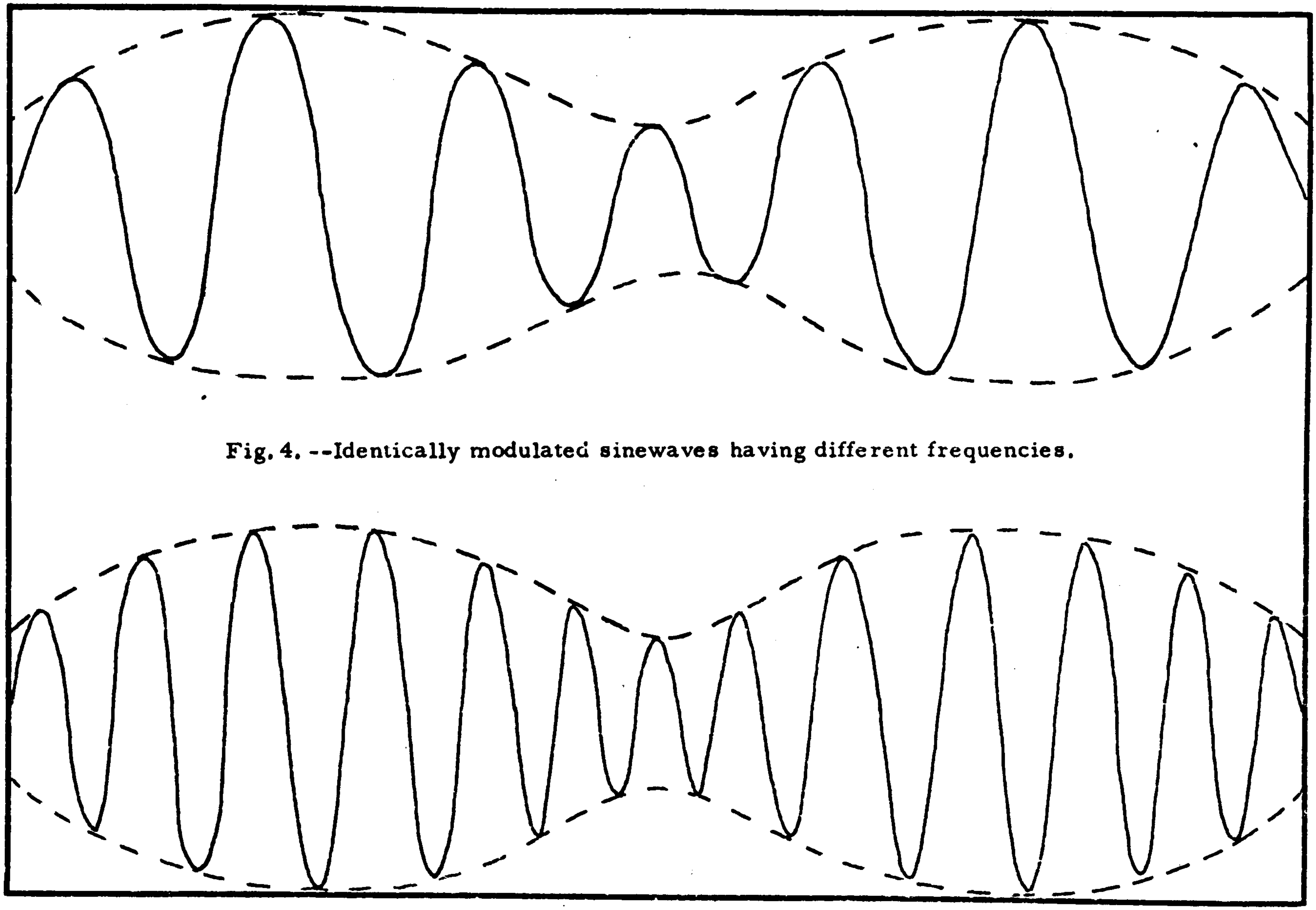


Fig. 4. --Identically modulated sinewaves having different frequencies.

of the switched speech reaches a minimum when the switching rate is 6 per second, which is roughly the critical switching rate for the transition from an alternating to a centrally fused image (Cherry and Taylor, 1954).

The illusion of a single sound image may also occur to listeners under free space listening conditions. A common example is the Stereophonic Effect which is produced when the stimuli are derived from two or more sources, e.g., two loudspeakers in the free sound field. Localization, rather than lateralization, is the term commonly used to describe the apparent position of the stereophonic sound image. The reason for the difference in terminology is that the binaural fused image under headphone listening is internalized (i.e. it is heard either in or near the head) and by far the most prominent spatial co-ordinate of this internally fused image is its apparent lateral position. In the case of free space listening, the sound is heard externally and, in this instance, all three spatial co-ordinates are needed to specify the location of an external sound image. The perception of the third co-ordinate, distance from the sound source, is relatively imprecise, however.

The mechanism underlying the difference between internal and external sound images is not clear. Several investigators suggest that in an everyday, non-free sound field, the constant tiny movements of the human head provide additional cues to form and locate an external sound image (see, e.g. Franssen, 1960). An experiment by DeBoer (reported by Franssen, 1960) provided data which support this hypothesis.

Microphones were mounted at ear level upon an artificial head, and the amplified outputs fed dichotically through headphones to a listener. If the dummy-head was placed upon a fixed object, such as a table, an internal sound image was perceived. If the dummy-head was attached atop the subject's own head, an external sound image was reported.

The signals reaching the listener's ears are more complex under stereophonic listening than for dichotic (headphone) listening. As shown in Figure 5, for the basic two-loudspeaker situation without reflections off walls or other surfaces, there are two signals reaching each ear. The signal reaching the left ear is the sum of the signals from the left channel, over the path AB, and the signal from the right channel, over the path CB. The time delay and attenuation resulting from travelling the path AB may be represented as T (in msec.) and I (in dB) respectively, while the delay and attenuation resulting from travelling the path CB is $T+\Delta T$ and $I+\Delta I$, respectively. ΔT is an additional time delay and ΔI is an additional attenuation, both incurred by travelling the greater distance CB. The signal reaching the right ear similarly consists of two components, a signal from the right channel and a delayed, slightly attenuated signal from the left channel. Either loudspeaker alone would produce a binaural sound image with values of interaural time and intensity differences that would place the sound image at the loudspeaker. When the two loudspeakers produce identical stimuli, simultaneously, the combination of the two sets of signals balance each other out, resulting in the equivalent of one signal and its "echo" at each ear.

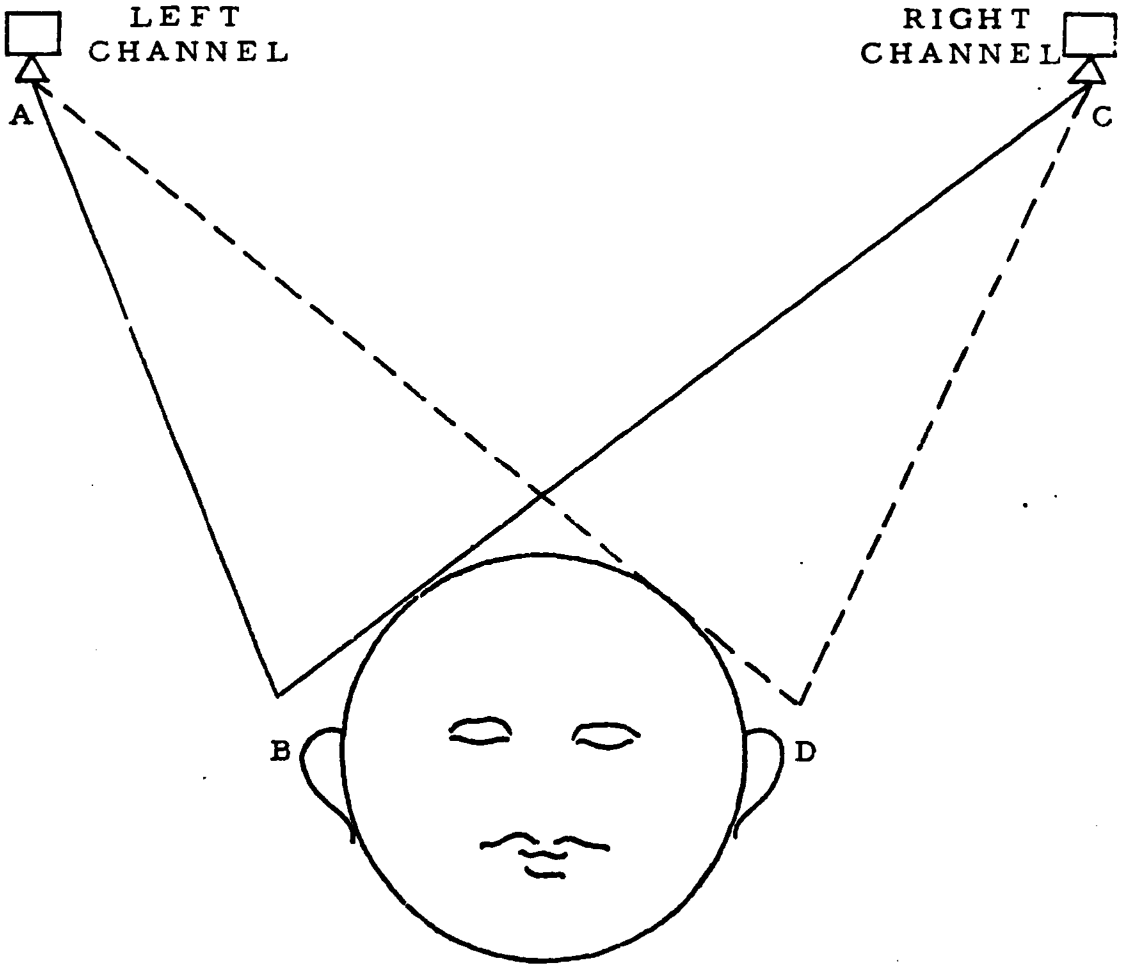


Fig. 5.--A stereophonic listening situation.

The resulting sound image appears to emanate midway between the speakers and has an altered quality due to the echo. If an interchannel time or intensity difference is introduced, the balance will be disturbed and the image will be localized at some other point in space.

Quantitative measures of the degree of accuracy with which a listener can localize a sound have been obtained by several workers (Mills, 1958; Leakey, 1959; Sandel et al., 1955; Snow, 1954; Stevens and Newman, 1936). For free sound field listening conditions, the average error in azimuth made by a subject listening to sinusoidal sounds, varies from about 10° at the extremes of the frequency range of human hearing to about 20° for tones within the 2000 to 5000 Hz zone. Localization improves to errors of about 5° for complex stimuli such as clicks and noise bands, presumably because of the presence of a wide range of intensity and time information within the stimulus. It should be noted that jnds and changes in position for stereophonic sound images require four to five times as much temporal or intensity disparity between the channels as do similar effects for binaural images produced with headphones.

Additional temporal and magnitude localization cues may arise from the reflective properties and tiny movements of the human head. Sound waves may be reflected from, or pass around, an object depending upon the relationship between the obstacle's dimensions and the frequency of the incident wave. As shown in Figure 6, sounds with small wavelengths that encounter large objects will cast a sound shadow, while those signals with wavelengths that are large compared with the size of the obstacle

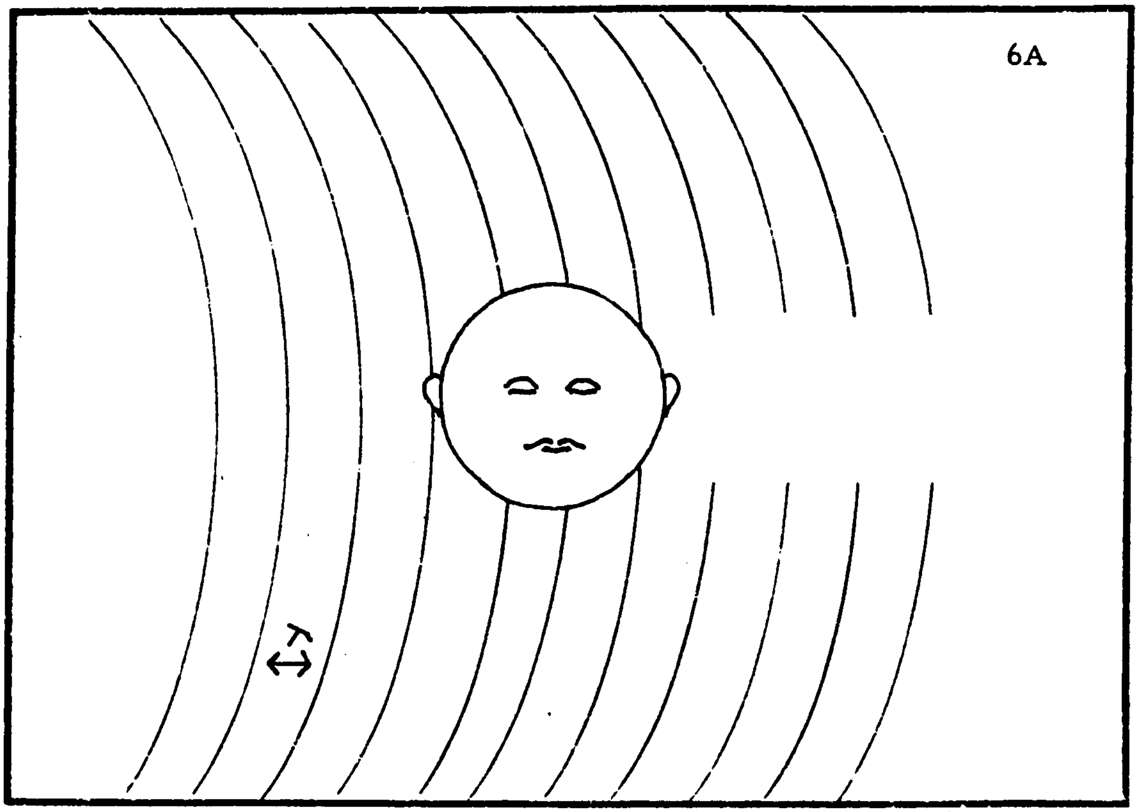
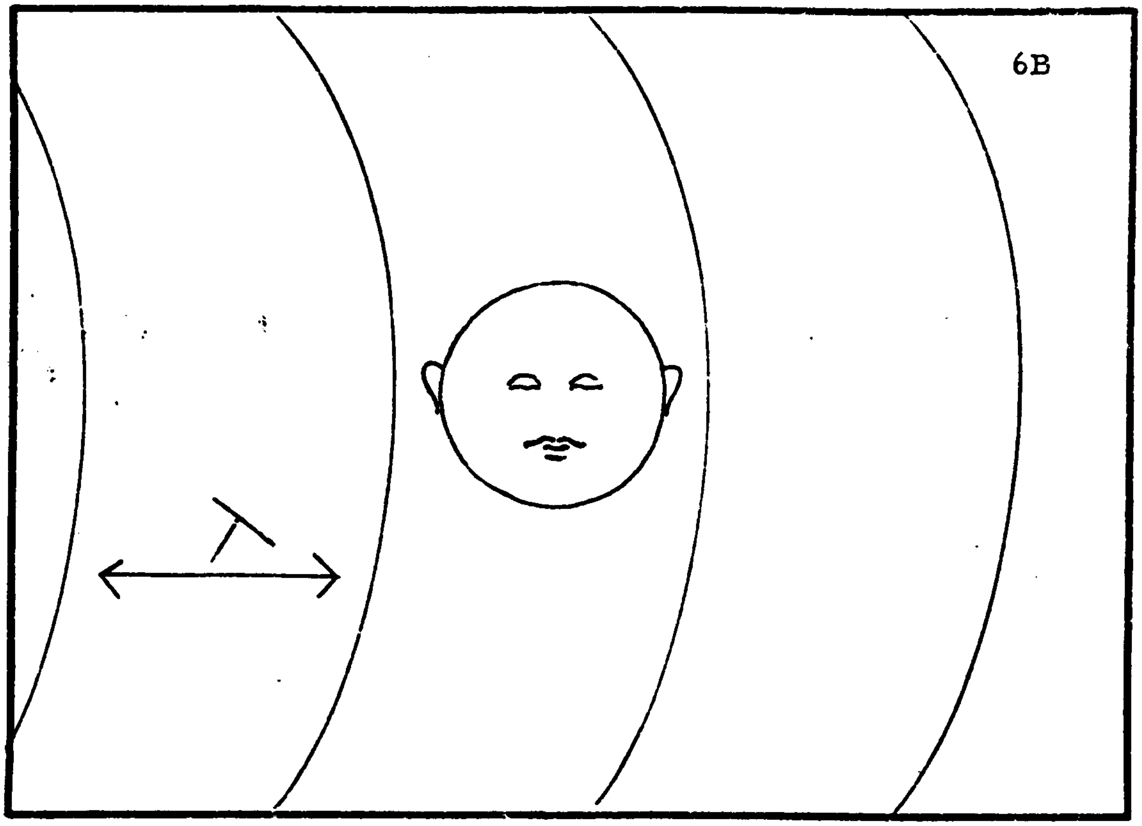


Fig. 6.--The obstacle effect:(a)sound shadow formed when λ is small compared to size of obstacle (b) no shadow when λ is relatively big.



will readily pass around the object.

An object the size of a human will cast a substantial sound shadow above 2000 Hz. Interaural intensity differences between subject's ears have been reported to be as large as 10 dB for a 4000 Hz tone presented in a sound field (Firestone, 1930; Nordlund, 1962). The value of this magnitude difference varies in a complex fashion as a function of both the frequency and azimuth of the arriving stimulus. Interaural level and time of arrival differences reach a maximum when the incident sound wave has a 90° azimuth (0° being the front of the head). This maximum time difference is slightly less than one msec. for a head-sized object. Because of the diffractive and reflective properties of the external ear, it is possible to make very crude localizations of sounds using only one ear (Franssen, 1960; Mathes, 1955; Mouzon, 1955).

A related phenomenon important to localization of sounds is the precedence effect (Wallach et al., 1949). The effect may be demonstrated by first creating a fused sound image with identical dichotic stimuli, followed very shortly afterwards by yet another pair of signals differing from the first set by small interaural time or intensity disparities(see Figure 7). Subjects report hearing a single image with an apparent position corresponding to the <u>initial</u> stimulus pair. Precedence will take place when two conditions are met (according to Wallach, Newman and Rosenzweig, 1949):

a) The second pair of dichotic stimuli should not lag the first by more than a few milliseconds. Critical values range from one or two to over 40 milliseconds depending upon

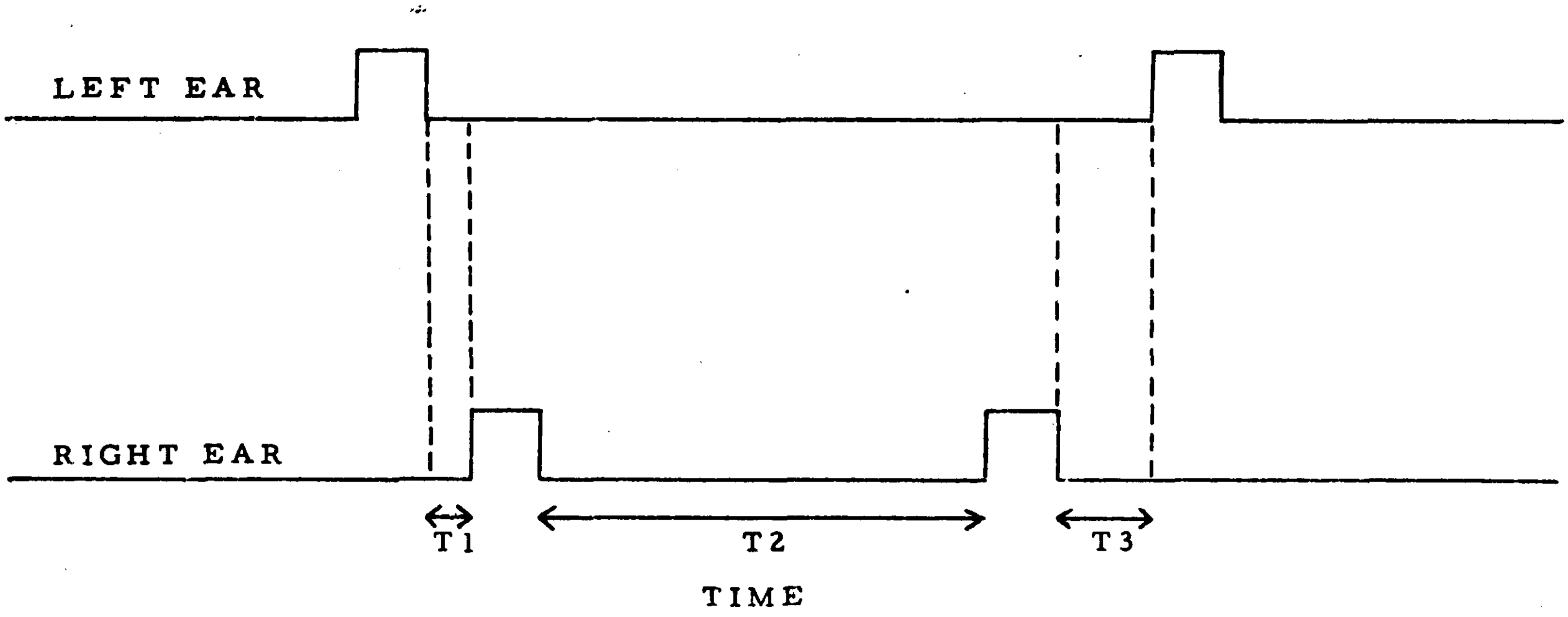


Fig. 7.--The precedence effect. Listeners perceive the fused sound image associated with the initial stimulus pair.

the nature of the test stimuli.

b) The second stimulus pair should not exceed the first by more than 15 dB in level.

In the real world, we rely upon those stimuli arriving first at our ears for the determination of the direction of a sound source. Without this effect one would be confused as to a sound's location even in moderately reverberant surroundings, such as a classroom or office.

Precedence and lateralization effects are most apparent when the test stimuli employed are impulsive. It seems that the auditory system makes use of and is highly sensitive to the wide range of frequency components within transient cues. When a binaural signal is presented which contains conflicting lateralization information, then the cues contained in the initial or transient portion of the waveform will dominate. It has been estimated that the effect of a brief transient cue may persist for several hundred milliseconds after its occurrence (Franssen, 1960; Tobias and Schubert, 1959).

The binaural hearing mechanism assists the listener with more than the lateralization and localization of sounds. Indeed, for almost every psychoacoustical effect there appears to be a corresponding, often enhanced, binaural counterpart. For example, the binaural auditory threshold appears to be from 3 to 6 dB lower than the monaural threshold (Hirsh, 1948a, 1948b; Keys, 1947; Shaw et al., 1947). The loudness of a binaural sound image is also greater than that for monaural stimulation and the difference in loudness appears to increase with the stimulus level (Reynolds and Stevens, 1960). Improvement in the just noticable differences for frequency have been reported (Pikler and Harris, 1955) although this enhanced frequency discrimination may be linked to the increased loudness of the binaural sound image. In addition, a sharpening of the ear's ability to filter out particular noise frequencies appears under binaural listening conditions (French and Steinberg, 1947).

There is also the binaural counterpart of the beat phenomenon. When two pure tones of differing frequency are presented dichotically, the presence of a single tone that is fluctuating in magnitude is often reported. This phenomenon, called binaural beats, should be distinguished from objective beats perceived by either or both ears due to the interaction of two tones outside the head. Early studies (Lane, 1925; Rayleigh, 1907) reported the occurrence of binaural beats only when frequencies below 1000 Hz were employed. Subsequent research (Licklider et al., 1950; Loesch and Kapell, 1948; Wever, 1949) has provided data which extend this frequency limit to about 1500 Hz and suggests that the effect is linked to the complex synchrony of neural firings.

Binaural listening facilitates the rejection of unwanted spurious noises that interfere with the desired acoustic signal. This improvement of a subject's detection performance for a signal within noise as a consequence of dichotic rather than monotic listening has been investigated by numerous researchers since Licklider (1948) and Hirsh (1948c) first reported the effect. The present dissertation will focus upon several aspects of this phenomenon.

Nomenclature

A great many studies have been undertaken in this area of binaural hearing, and it would be helpful to summarize the terminology and binaural listening configurations that have been employed (See Table I).

A classification may also be made of the variety of noise and signal combinations which have been researched. If both noise and signal are in-phase or both are out-of-phase (viz. S0N0 and SπNπ) they are said to be homophasic listening conditions. When the signals are out-of-phase and the noise waveforms are in-phase or vice versa (viz. SπN0 and S0Nπ) an antiphasic condition is said to occur. Other possibilities include the so-called heterophasic (S0Nu, SπNu) the mixed (SmN0, SmNπ) and the monotic (SmNm) listening conditions. The differences in detectability between these separate listening conditions have been variously labeled: binaural release from masking, binaural unmasking, binaural analysis, binaural masking level differences (BMLD), and masking level differences (MLD). Masking level differences are typically specified in terms of the signal level (in dB) required for a fixed level of detection for the experimental condition relative to the signal level for the S0N0 or SmNm conditions.

A review of the major empirical findings for various listening conditions and research parameters follows.

Table I- MLD Nomenclature

Symbol	Binaural Phase Relationship
Sm	Signal, monaural, no signal presented to opposite ear.
S0	Signal in phase at the two ears.
$S\pi$	Signal at one ear 180° (π radians) out of phase with the signal at the opposite ear.
Nm	Noise, monaural, delivered to one ear only.
N0	Identical noise presented to each ear.
$N\pi$	Noise waveform at one ear is 180° out-of-phase with noise waveform at the other ear.
$N\mu$	Uncorrelated noise (i.e. arising from two statistically identical but separate sources) at the two ears.
N_τ	The noise waveform at one ear is time delayed with respect to the noise waveform in the opposite ear. Both waveforms are, however, identical.

CHAPTER II

REVIEW OF THE LITERATURE - MLD

The parameter of signal frequency

The influence of frequency upon binaural release from masking was first examined by Hirsh (1948c). Three subjects were presented with a tone which remained on for one second and off for three seconds in a background of white noise (flat spectrum to 7000 Hz). Six experimental conditions were examined: (1) SmN0 (2) SmNπ (3) S0N0 (4) SπNπ (5) S0Nπ (6) SπN0. The spectrum level of the noise was varied from -10.9 dB to 59.1 dB for each condition. Hirsh found that for the test frequencies employed (viz. 100 to 5000 Hz) the subject's detection performance was improved by about 10 to 12 dB for antiphasic conditions over those values obtained for homophasic conditions. Figure 8 is a composite display of Hirsh's findings. In the original study, Hirsh had regarded the SmN0 and SmNπ listening conditions to be monotic ones. The addition of the test signal to the opposite ear (i.e. S0N0 and S0Nπ conditions) produced a noticeable reduction in signal detectability and led him to suggest that some form of binaural inhibition had occurred. The issue is clarified, however, when one compares the thresholds obtained by Hirsh with the data taken by French and Steinberg (1947)

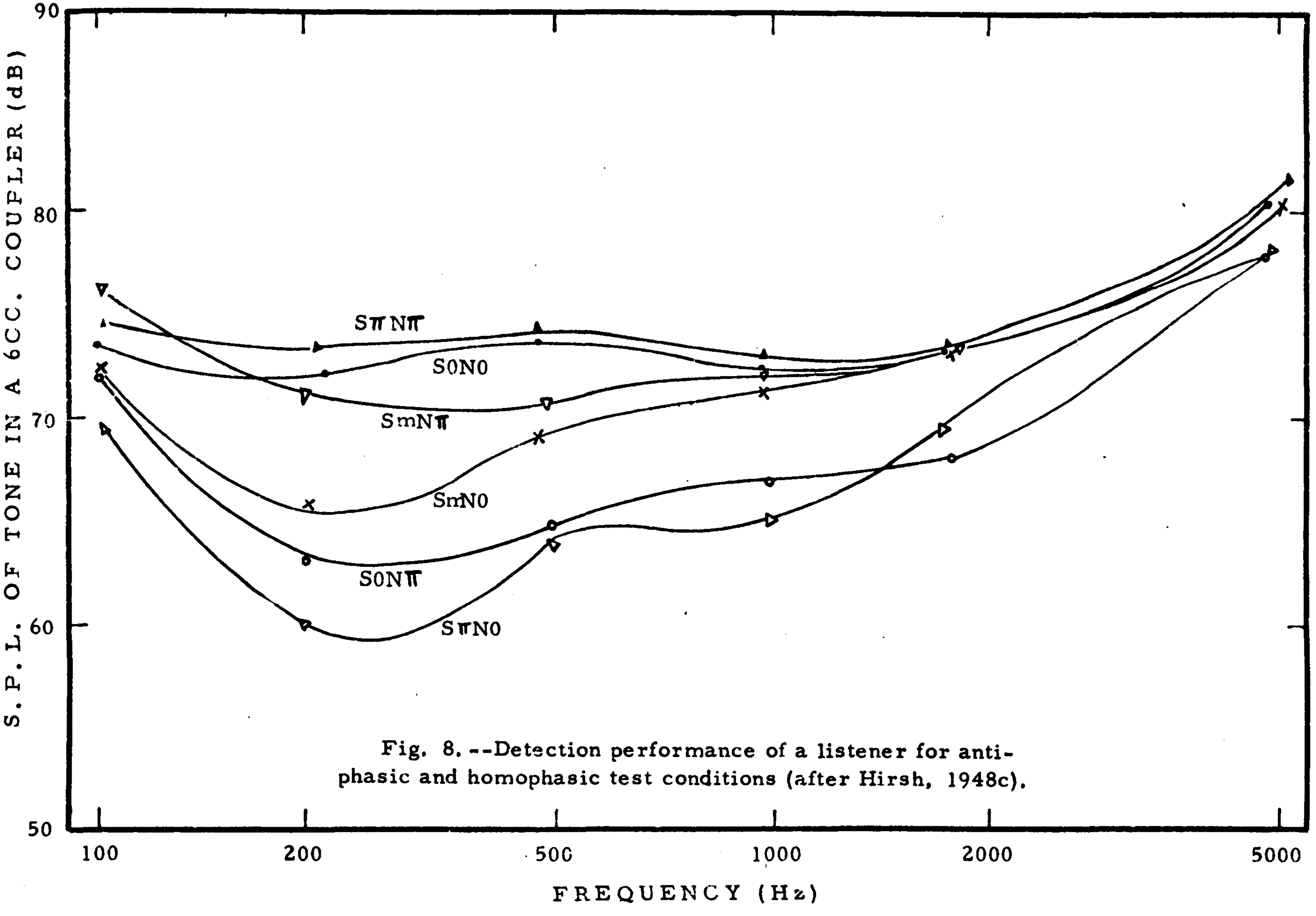


Fig. 8.--Detection performance of a listener for antiphasic and homophasic test conditions (after Hirsh, 1948c).

for a truly monotic listening condition (viz. SmNm). All of Hirsh's listening conditions are then seen to yield improved detection thresholds over the monotic case. With the SmNm condition as the reference, a hierarchy of detection improvements emerges from the data, ranging from the poorest to the best detectability, they are: SπNπ, S0N0, SmNπ, SmN0, S0Nπ, and SπN0. A comparison between the SπN0 and the S0N0 situations as a function of the test signal frequency appears in Figure 9. In this display of the data from several studies one may see that above 250 Hz, MLD values decrease from a maximum of 15 dB to a low of 3 or 4 dB (Hirsh, 1948c; Webster, 1951; Hirsh and Burgeat, 1958; Durlach, 1972; Schenkel, 1964; Wilbanks and Whitmore, 1968). Below 250 Hz, however, discrepancies between MLD data are evident. Webster (1951); Jeffress, Blodgett and Deatherage (1962) and Durlach (1972) have reported MLD values below 250 Hz to be essentially constant whereas Schenkel (1964); Hirsh (1948c) and Rabiner, Laurence and Durlach (1966) found a tendency for MLDs to decrease below 250 Hz. These disparities have not yet been fully resolved and questions arise as to the influence of procedural differences upon the test results. In Webster's study, for example, the noise level was adjusted while the magnitude of the sinusoidal signal was kept constant. This is in contrast with Hirsh's technique which utilized a fixed noise level and varying signal level.

The manner or sequence in which the signals are presented to the listener might be another factor that affects detection performance. Rosenblith and Miller (Cited by Hirsh, 1952) in another experimental

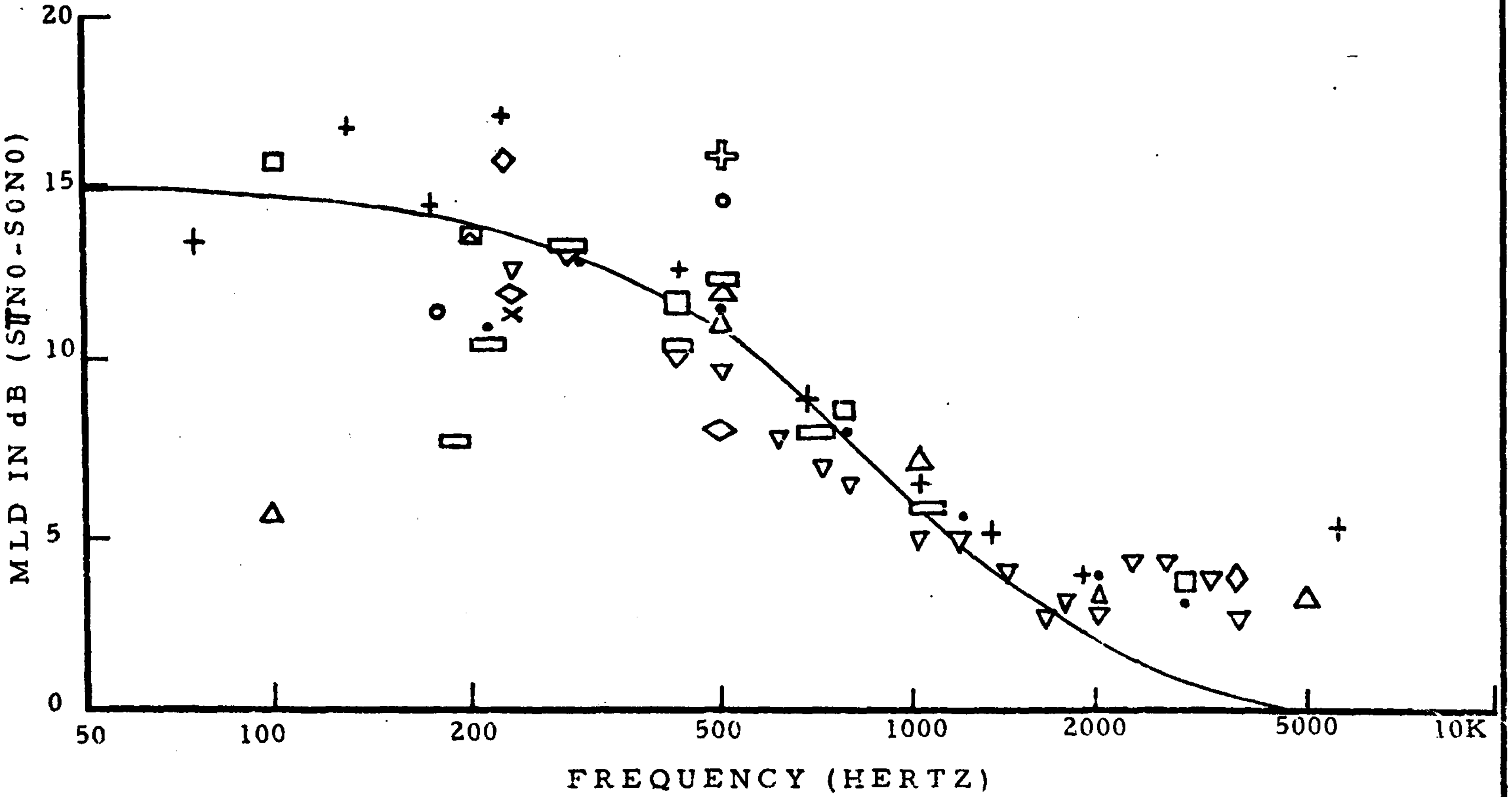


Fig. 9.--The change in MLD values as a function of tone frequency. The data points represent the diverse results of many studies (after Durlach, 1972).

context, found substantial threshold differences (as high as four dB) to occur when they employed a descending as opposed to ascending method of limits procedure. In the same fashion, different modes of signal delivery might conceivably give rise to different MLD results. One might consider, for example, the clear contrast between Hirsh's (1948c) straightforward tone-on, tone-off procedure with the more elaborate sequence of signal bursts used by Webster (1951) and the disparate results of these two workers below 250 Hz. Webster, himself, noted that even slight changes in the interruption pattern of his stimuli gave rise to "...higher levels of masking, sometimes by six or seven dB, and greater inter-observer variability."

Signal duration and MLD

Jeffress, Blodgett and Deatherage (1952) and Jeffress et al. (1956) cited substantially greater MLD values for the SπN0 versus S0N0 conditions than those reported by Hirsh (1948c). These workers have related such differences in MLD results to disparities in the duration of the test signal presented to the listener. For a 500 Hz tone of 500 msec. duration, Jeffress et al. (1956) found an MLD value of 13 dB. For a signal of only 25 msec. duration these workers reported an MLD of 16 dB. The noise spectrum level, in all cases, was 58 dB. Blodgett, Jeffress and Taylor (1958) varied the signal duration between 5-500 msec. and found that subjects required about 3 dB more sound magnitude per doubling of duration in order to maintain a fixed level of detection performance. McFadden and Pulliam (1971) reported similar findings for the SmN0 condition. A related phenomenon had been reported earlier for the masking of a tone by noise in one ear only (Garner and Miller, 1947; Gales and Wilcott, 1954). McFadden and Sharpley (1972) extended the research for the binaural case by utilizing a narrow band noise (50 Hz wide) as both masker and test signal. Four of their five subjects displayed improved detection performance as duration of the test signal was increased. One subject, however, clearly displayed no dependence upon the parameter of signal duration.

The parameter of noise intensity

The levels of masking noise delivered to a listener appears to be a variable of major significance in MLD research. Experiments which have examined this parameter have had several basic formats.

In one procedure, McFadden (1968) determined MLD values as a function of masking noise levels, while maintaining a fixed signal to noise ratio between the two ears for all listening conditions. He contrasted the $S\pi N0$, SmNm and $S\pi' N0'$ * listening conditions rather than the SmN0-SmNm test situations used by previous workers. He suggested that the conditions he chose yielded larger MLD values which could be "...followed over as great a range as possible before binaural detection

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* McFadden defined $S\pi' N0'$ to be a special instance of the $S\pi N0$ condition wherein *differences* in interaural noise level were used.

became 'contaminated' by monaural detections." Figure 10 shows a plot of subjects' thresholds as a function of the noise spectrum level employed (data from McFadden, 1968; Hirsh, 1948c). McFadden noted that the masking influence of the noise increased linearly as the spectrum level was raised for the SmNm test condition. This is in agreement with the classic relationship determined by Hawkins and Stevens (1950). Such linearity, however, is not evident for the SπN0 condition and McFadden alerts the reader to the possible existence of other nonlinear relationships for other MLD and noise configurations. He cites, as an example, the report of Canahl and Small (1965) who found that MLD values actually decrease at extremely high noise spectrum levels. Figure 11, shows MLD values for the SπN0 versus SmNm and S0N0 conditions as a function of the spectrum level of noise employed. Even though Hirsh and McFadden used very different test procedures and conditions, the functional relationships they obtained were similar. Hirsh, for example, compared the SπN0 to S0N0 test situation using a 200 Hz tone(one second duration) and a method of adjustments test procedure. McFadden used the different test conditions described above, a 250 msec., 400 Hz tone in a two alternative forced choice procedure. One may see from Figure 11 that at high spectrum levels (Above about 35 dB spectrum level) the MLD values rise as high as 15 dB. As the level of the masking noise is lowered, the MLD values decrease to an assymptotic three or four dB.*

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*In this extreme case there is no audible noise and one is essentially "comparing the detectability of a monaural signal, Sm, with the detect-

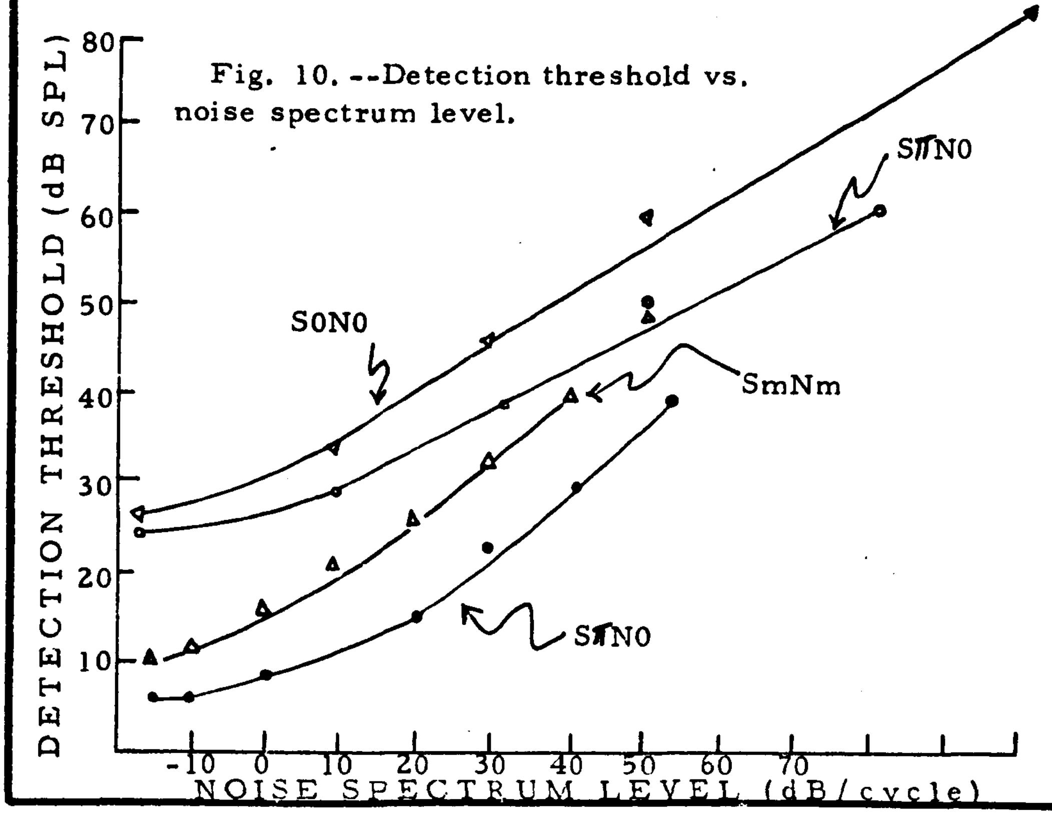

Fig. 10. --Detection threshold vs. noise spectrum level.

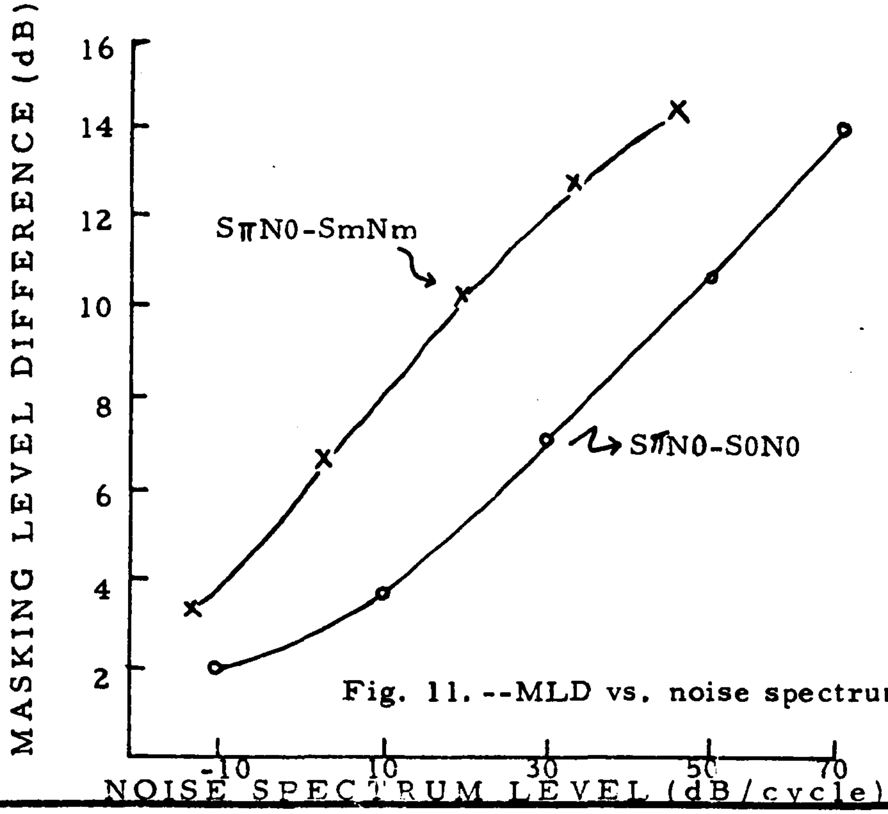

Fig. 11. --MLD vs. noise spectrum level.

In another procedure, Blodgett, Jeffress and Whitworth (1962) and Weston and Miller (1965) delivered a fixed spectral level of white noise (41 dB/cycle) and a test tone of 500 Hz to one of a listener's ears and then varied the noise level in the opposite non-signal ear. In Figure 12, the subjects thresholds for the tone in the right ear are seen to increase from about 52 dB S. P. L. to about 62 dB S. P. L. in a relatively linear fashion as the noise in the non-signal ear is decreased from 41 dB/cycle to total attenuation (i.e. as the SmN0 condition approaches the SmNm condition). Several other experimenters employing these listening conditions (viz. binaural noise and monaural signal) have reported essentially similar findings (Egan, 1965; Mulligan and Wilbanks, 1965; and Dolan and Robinson, 1967).

The link between noise-signal lateralization and MLD

Several workers have discussed the similarities between the phenomena of binaural release from masking and binaural lateralization (e. g. Egan and Benson, 1966; Robinson and Egan, 1967; Green and Henning, 1969; Hafter, 1971). In this regard, Hirsh and Burgeat (1958) have pointed out that most listeners perceive binaural in-phase tone, or noise, waveforms, to be lateralized in the center of the head while out-

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ability of a binaural signal, $S\pi$, (180° out of phase)." From Green and Henning, 1969. These writers remind us that this phenomenon had been demonstrated quite early (see Hirsh, 1948b; Licklider, 1951; Pollack, 1948) and that it might also be easier to detect for the $S\pi$, as opposed to S0, interaural signal condition (see Diercks and Jeffress, 1962).

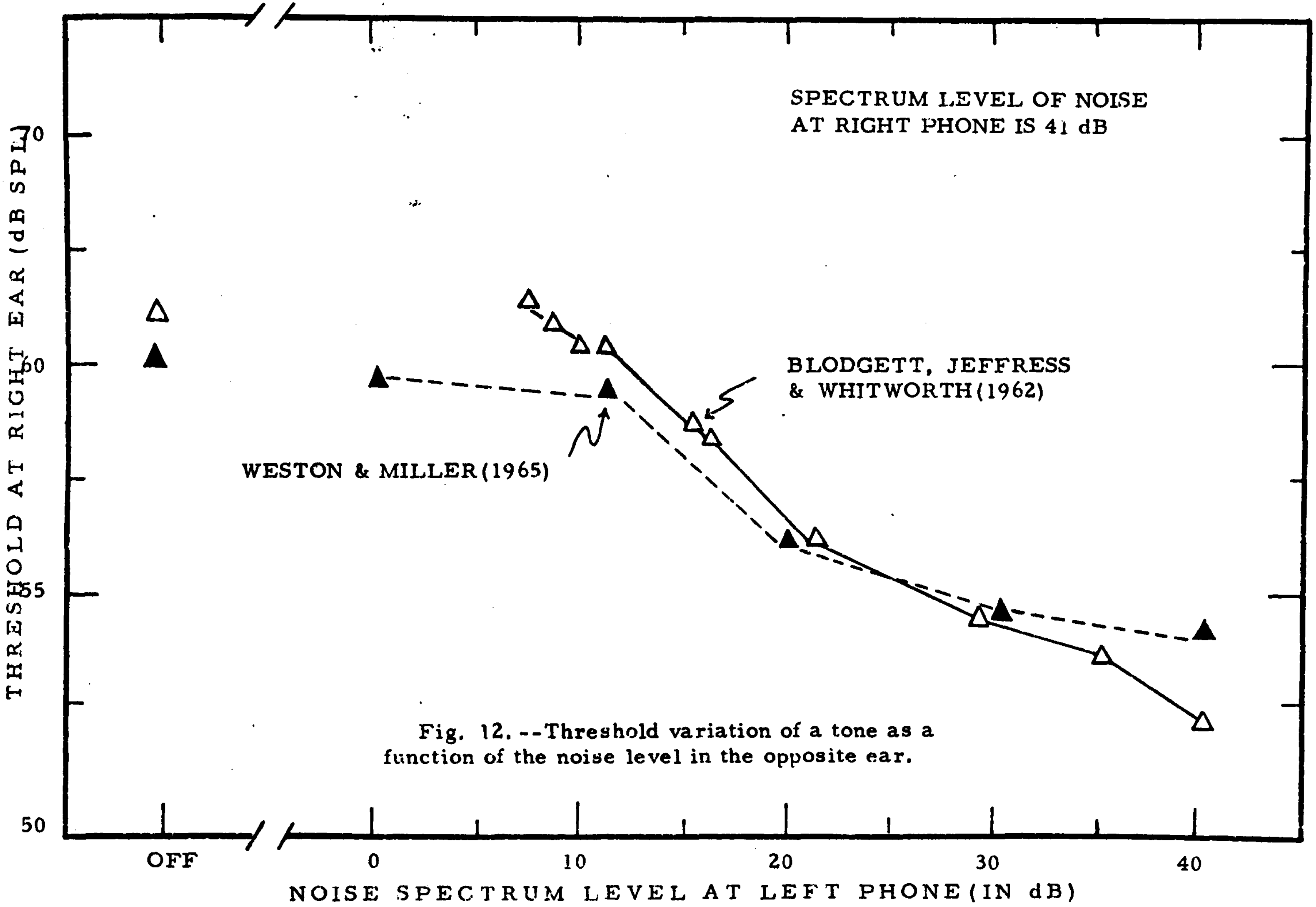

Fig. 12.--Threshold variation of a tone as a function of the noise level in the opposite ear.

of-phase stimuli appear"...either spread throughout the head or concentrated at the two ears." The addition of interaural phase changes to either noise or tones gives rise to shifts in both the lateralization and threshold detection performance of the listener.

Some comment and data has been reported which suggest that lateralization and binaural release from masking are separate and distinct phenomena arising from different binaural mechanisms (see Licklider, 1948; Egan and Benson, 1966; Robinson and Egan, 1967; and Colburn and Durlach, 1965). Egan and Benson (1966), for example, compared the psychometric functions for monaural signal lateralization as well as monaural signal detection thresholds within backgrounds of perfectly correlated and uncorrelated binaural noise.[*] These workers found the psychometric functions for lateralization and detection to be nearly equal (only one or two dB apart) in a background of uncorrelated noise. For correlated noise, however, the functions for lateralization and detection were displaced toward smaller signal levels than for the uncorrelated noise. The lateralization function also possessed a lower slope in the background of correlated, as opposed to uncorrelated noise. See Figure 13. Jeffress and McFadden (1971); McFadden, Jeffress and Ermy (1971); and McFadden, Jeffress and Lakey (1972) measured subjects' lateralization and detection performance for the S0N0 and SπN0 conditions. The test signal employed was the same narrow band noise (50 Hz wide, centered around 500 Hz) that was used as the masking stim-

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[*] See Appendix I for a description of Short-Term Correlation Analysis.

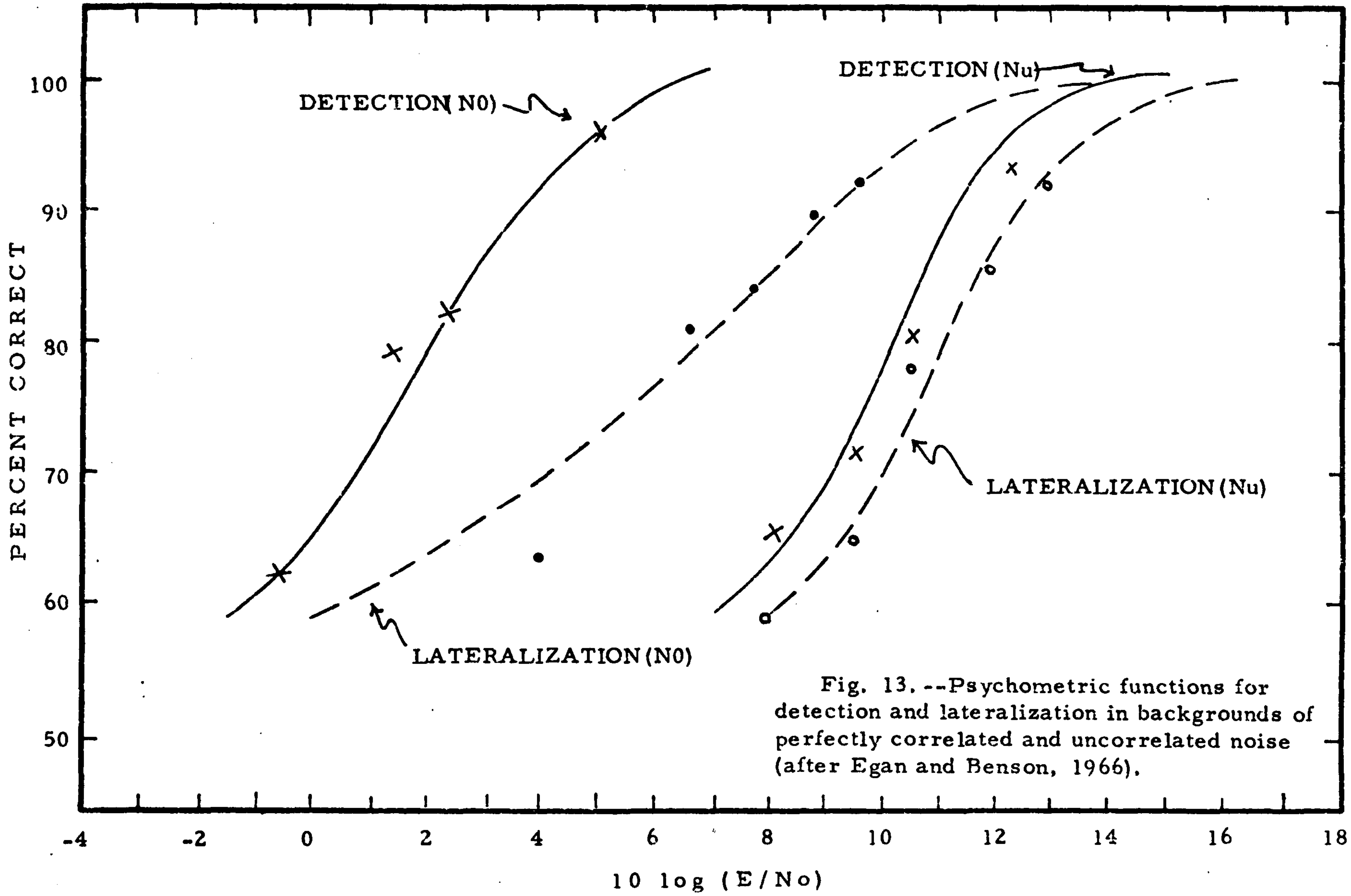

Fig. 13.--Psychometric functions for detection and lateralization in backgrounds of perfectly correlated and uncorrelated noise (after Egan and Benson, 1966).

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ulus. The authors found that for all of the test frequencies explored (viz. 250, 500, 1000, and 2000 Hz) listeners did not appear to rely upon lateralization cues for improving their detection performance. The major influence upon both detection and lateralization was the size of the phase angle introduced between the signal and noise channels by a phase-shifting network.

Noise correlation and MLD-Technique I(adding uncorrelated noise)

Licklider (1948), working with speech as the test signal, found that a listener's intelligibility score improved by about three dB for binaural antiphasic listening conditions over the homophasic cases. He determined that the addition of uncorrelated noise at the two ears reduced the improvement obtained by reversing the interaural phase of either the noise or signal. Jeffress, Blodgett, and Deatherage (1953a) explored the effects of such noise decorrelation upon the masking of tonal signals and obtained considerably larger MLDs than did Licklider (1948). These workers assumed that a zero correlation for the noise would lead to no release from masking and that the S0N0 situation would be the most appropriate reference condition. Subsequent research, however, has contraindicated these assumptions. Jeffress, et al. (1956) found MLDs (using tonal stimuli) for the S0N0 versus S0Nu conditions. Values of 4.7 dB and 6.1 dB were obtained when, respectively, 100 and 25 msec. duration test signals were employed. Robinson and Jeffress (1963) found an MLD of about three dB between the heterophasic (S0Nu, SπNu) and the monotic (SmNm) listening conditions. The latter results were obtained in a background of wide band masking noise (100-3000 Hz) at a rather high spectral level of 50 dB. A 500 Hz tone of 150 msec. duration and 25 msec. rise and decay time comprised the tonal stimulus. For antiphasic, as well as, homophasic test conditions, these authors found a clear drop in MLD size as the interaural noise correlation was reduced by the addition of uncorrelated noise. Wilbanks and Whitmore (1968) extended this type of experiment over a wide range of frequencies (150-4000 Hz). They examined the detectability of monaurally presented, 200 msec.duration, tones as a function of the following interaural noise correlations: 1.00, 0.90, 0.75, 0.50, 0.25, and zero. The correlated noise was obtained by using one generator for both ears whereas the various decorrelated noise stimuli were produced by adding the noise from two additional, independent, generators. Figure 14 shows that as the noise correlation is decreased from unity, (N0), to zero, ($N\mu$), the MLD values diminish sharply (SmNm is taken as the reference condition). At 150, 200, 3000, and 4000 Hz, little or no change in detection performance occurs.

Internal noise and Correlation

As mentioned in an earlier footnote (p.30), Diercks and Jeffress (1962) have reported that when the binaural versus monaural detection of a signal are compared, the $S\pi$ rather than the S0 interaural phase condition yields slightly improved detection thresholds when no external noise is applied to the subject's ears. Presumably, in this situation,

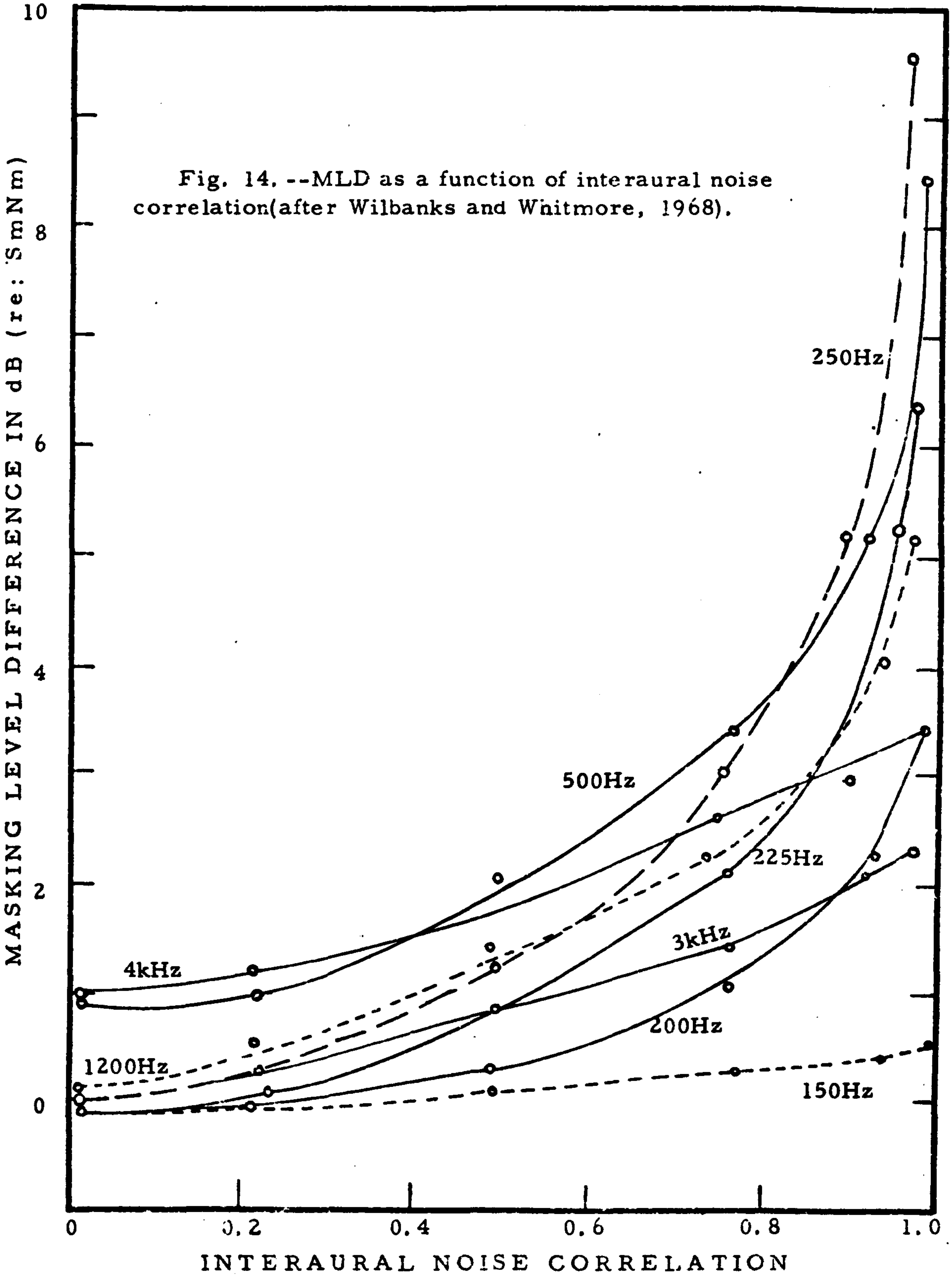

Fig. 14. --MLD as a function of interaural noise correlation(after Wilbanks and Whitmore, 1968).

only the individual's own physiological noise is present. The improvement for $S\pi$ listening over the S0 condition was reported to be only about one dB better and the question arises as to how reliable or significant this figure might be. Two workers have been unable to detect any difference between the conditions (Chocholle, 1959; Levitt, 1973). Several writers have suggested that any such enhancement for the $S\pi$ phase condition might be linked to the presence of noise in the ear canal which has a slight positive correlation (Diercks and Jeffress, 1962; Dolan and Robinson, 1967; McFadden, 1968). It has been suggested that this correlation arises from the fact that the vascular flow is synchronized with the heartbeat (Green and Henning, 1969).

Noise correlation and MLD-Technique II(Interaural time delay)

Another way of producing decorrelated noise is to introduce a substantial time delay between the noise waveforms delivered to each ear (Jeffress, Blodgett, and Deatherage, 1952, 1962; Rabiner, 1964). This listening condition is portrayed in Figure 15. The subject listens to the identical band of noise in each ear. In one ear, however, the noise waveform is delayed by some time, τ. The variation in MLD values due to interaural time delay of the noise waveform (as reported by Jeffress, Blodgett, and Deatherage, 1952) is shown in Figure 16. The relationship is cyclic in nature with successively damped maxima and minima occurring, respectively, at the half and full period times for the particular tone employed (in this instance, 500 Hz). The manner

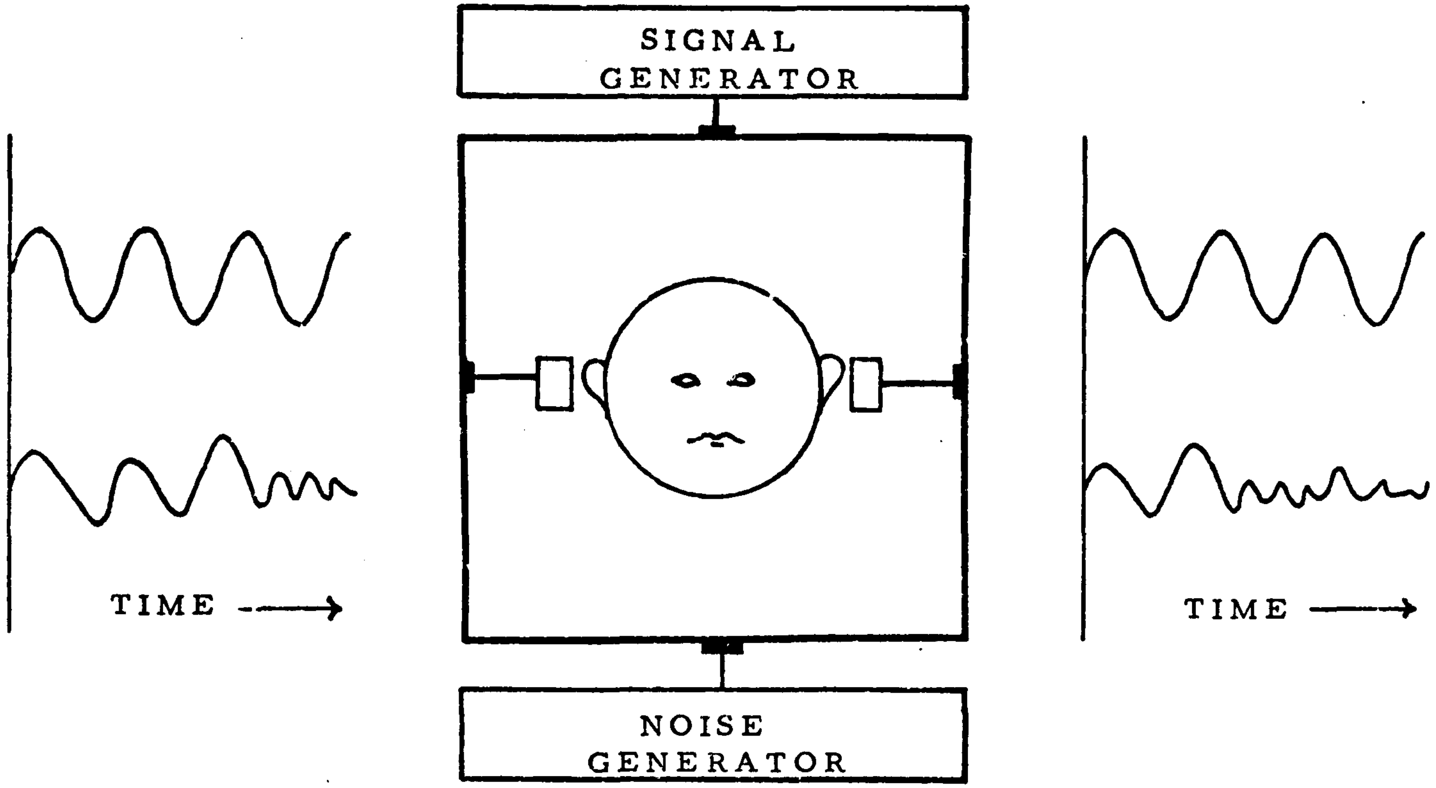

Fig. 15.--The S0Nτ listening condition (signals binaurally in phase, noise delay to one ear). The signal detectability varies with the interaural delay.

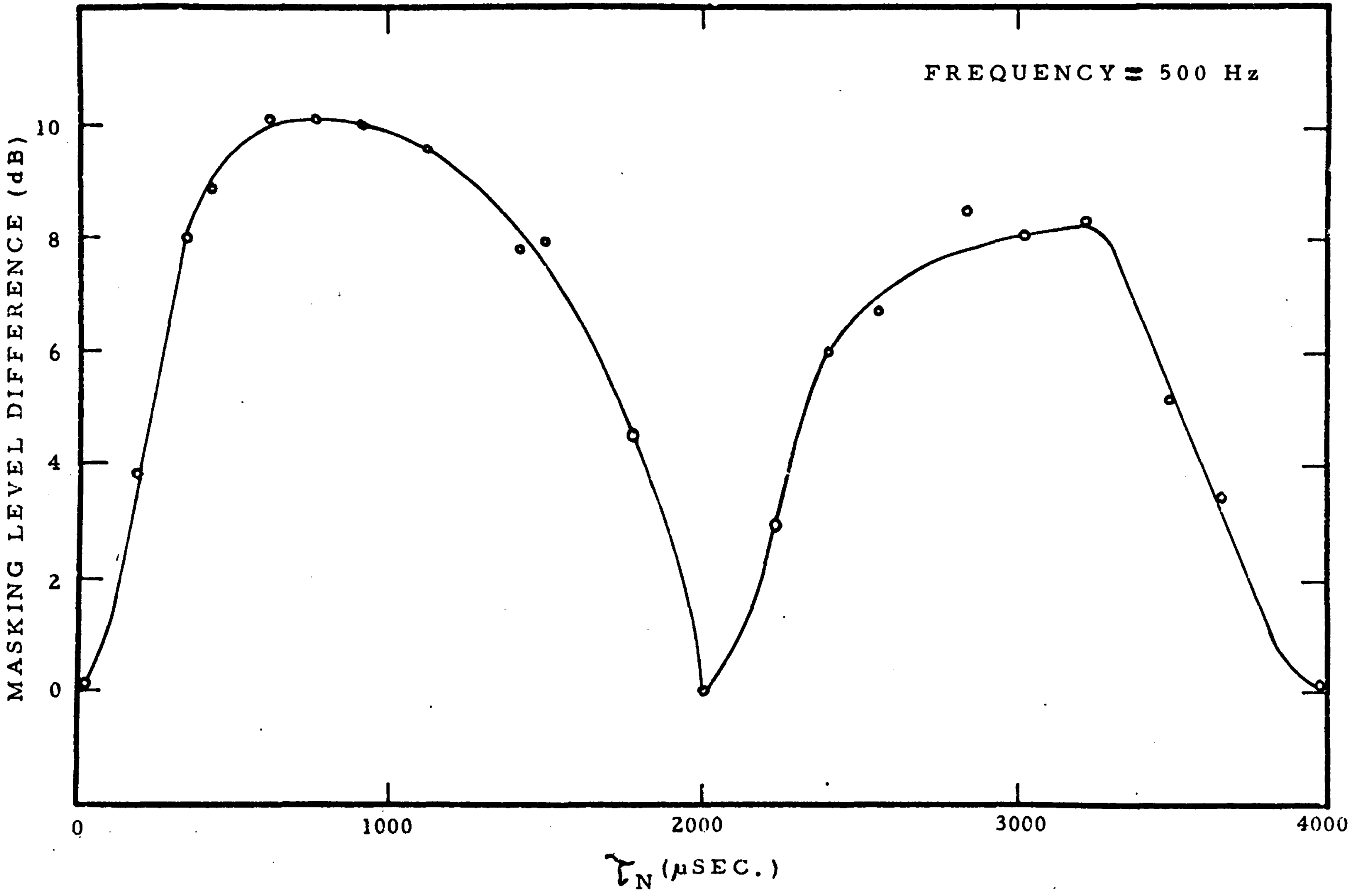

Fig. 16.--MLD vs. interaural time delay between the noise waveforms.

in which these authors introduced the interaural time delay for the noise waveforms has prompted some critical comments (Rabiner, 1964). In their first procedure they employed an R-C phase network to shift the 500 Hz component of the noise. This technique would be appropriate for shifting tonal stimuli but is incapable of uniformly altering the phase of all components in a band of noise, as required. Their second approach was to delay the noise waveform to one ear by means of a binaural tape reproducer. The noise was first recorded in-phase on both channels and then one tape head was moved laterally to introduce the desired noise phase shift. Even though this rough technique was prone to error, essentially similar data have been obtained by subsequent workers using different techniques (Rabiner, 1964; Rabiner, Laurence, and Durlach, 1966; Langford and Jeffress, 1964). These later investigators found that for extremely large interaural delays, the short-term correlation between the noise waveforms reaching the two ears, was negligible, and a steady MLD of about three dB is obtained (see Figure 17).

For the low frequency test signal of 167 Hz, Jeffress, Blodgett, and Deatherage (1962) published a curve with no apparent cyclic relationship between MLD and τn. After $\tau n = 0.6$ msec. the curve is seen to "flatten out" at MLD values near four dB. This result has been explored for larger values of τn (up to six msec., Rabiner, Laurence, and Durlach, 1966) and the extended curve reported, shows diminishing MLD values as the six msec., full period, point is approached. Both sets of data are displayed in Figure 18.

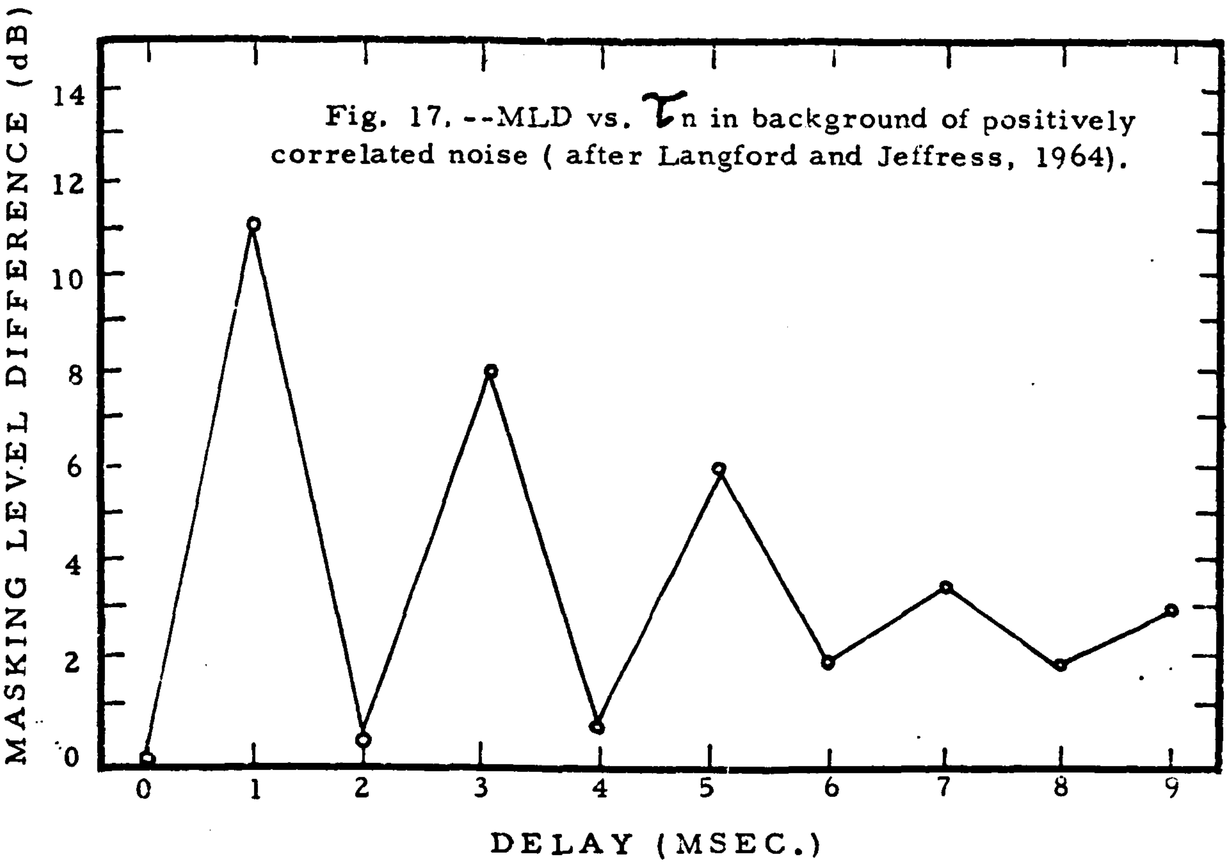

Fig. 17. --MLD vs. τn in background of positively correlated noise (after Langford and Jeffress, 1964).

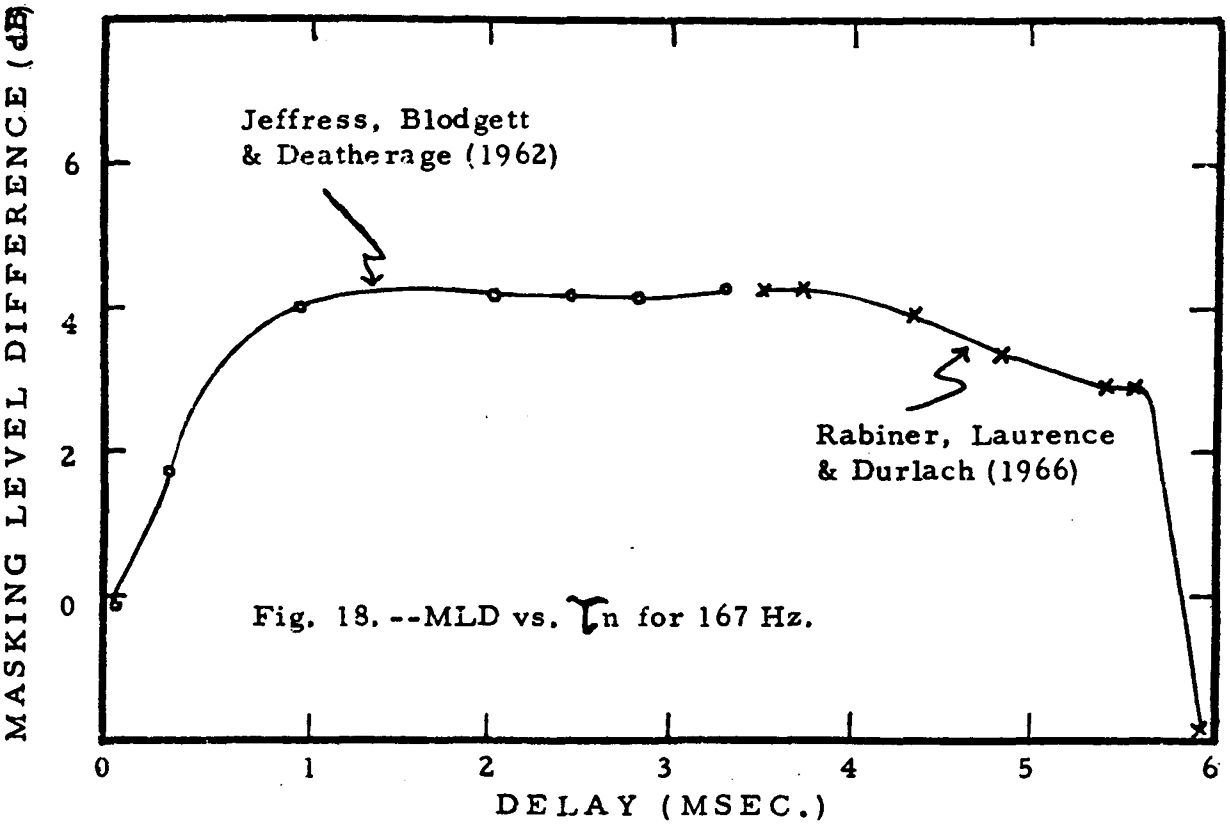

Fig. 18. --MLD vs. τn for 167 Hz.

Phase differences between test tones and resulting MLDs

Several researchers have examined the change in MLD values due to various phase differences between the tonal stimuli at the two ears within backgrounds of in-phase noise. See, for example, Hirsh (1948c) and Jeffress, Blodgett, and Deatherage (1952, 1962). Figure 19 shows how MLD values diminish sharply when a slight phase shift is introduced to the two test tones. As the $S\pi N0$ point is approached, this decrease is less abrupt.

MLDs for speech stimuli

Masking level differences for speech stimuli have also been studied. It is important to distinguish between binaural release from masking for the detection of speech (MLD), and the release from masking for a specific level of speech intelligibility. For the latter case, the term, binaural intelligibility difference (ILD)* has been suggested (Levitt and Rabiner, 1967a). The data on the binaural enhancement of speech in noise are quite disparate. ILDs as low as three dB (Licklider, 1948) and as high as twelve dB (Kock, 1950) have been reported. The magnitude of the ILD, however, appears to depend on the intelligiblity level, a greater ILD being observed for low levels of intelligibility. It has been determined that the low frequency region of the speech signal (around 300 Hz) is of

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*The nomenclature BMLD and BILD was originally used in the Levitt and Rabiner paper, but was shortened to MLD and ILD in order to be consistent with nomenclature used in this chapter and elsewhere.

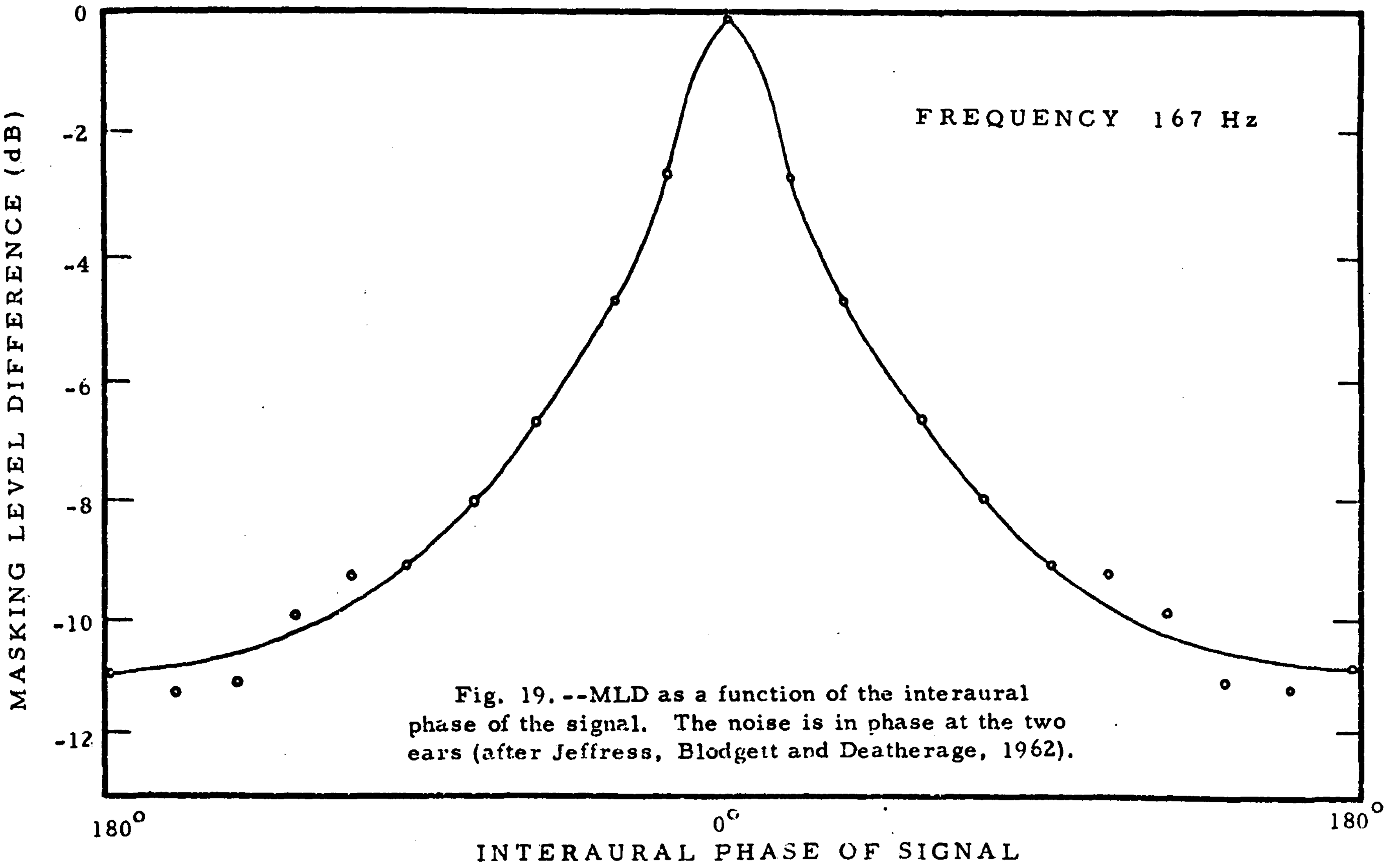

Fig. 19.--MLD as a function of the interaural phase of the signal. The noise is in phase at the two ears (after Jeffress, Blodgett and Deatherage, 1962).

primary importance in release from masking (MLD) while both the high and low portions of the speech spectrum play a significant role in binaural gain in intelligibility (ILD), although the lower frequencies are relatively more important. Levitt and Rabiner (1967b) have provided a simple numerical procedure for predicting the ILD and MLD values for speech using the Articulation Index (Kryter, 1962a). These predictions indicate that ILD values become progressively larger as one moves from high intelligibility levels to low intelligibility levels, until zero intelligibility is reached. At this point, speech is just detectable but no longer intelligible and a maximum improvement, equal to the MLD, is achieved. The MLD for speech may be thought of as a limiting case of the ILD.

Theoretical Viewpoints

Webster-Jeffress (time difference) framework

Webster (1951) has proposed the essential factor in MLD phenomena to be ". . . .the time-divergence between the two ears that is produced by the signal whenever it is neither exactly in-phase with the masking tone, nor exactly out of phase with it." His characterization of the masking stimulus as a tone becomes meaningful in view of the fact that an extremely narrow band noise masker (e.g. as derived from the critical bandwidth filtering of the ear) may be considered analogous to a modulated sine wave slowly varying in amplitude and frequency. Indeed, Webster suggests that over short intervals (e.g. 10-20 msec.) one might

"...consider the signal and masker to be identical in frequency." Operating under this assumption, Webster (and subsequently, Jeffress, et al., 1956) were able to depict MLD listening conditions in a vector format. Figure 20 is such a display of the $S\pi N0$ case at one instant in time. The horizontal vector represents the in-phase masker at the two ears. The two signal components (S_{left} and S_{right}) are clearly seen to be supplementary (i.e. 180° phase separation). The dashed vector lines show the resultant signal-noise voltages at the two headphones. The diagram reveals that for this particular moment in time, the left ear signal leads the combined noise vector by a phase angle, α, of 45°. The value of α is cited by Jeffress (1972) as a convenient midvalue while one unit along each of the vectors is taken as the rms voltage of the noise. Appropriate trigonometric computations give rise to an interaural phase difference between the resultants at the ears of 17.5°. This is equivalent to a time difference between the signals of 97 μsec. (for---500 Hz) and it is this time difference that is purported to be the principal cue for binaural release from masking.

Jeffress (1965, 1972) incorporated and extended Webster's basic concept into a more complex neuro-physiological framework which relates release from masking to localization-lateralization phenomena. Jeffress' concept was that the two ears act as a matched pair of filter banks with the component filters in each bank possessing a width roughly that of a critical band. Myriads of neural links from the right and left ear filters were envisioned as merging at, and triggering "higher

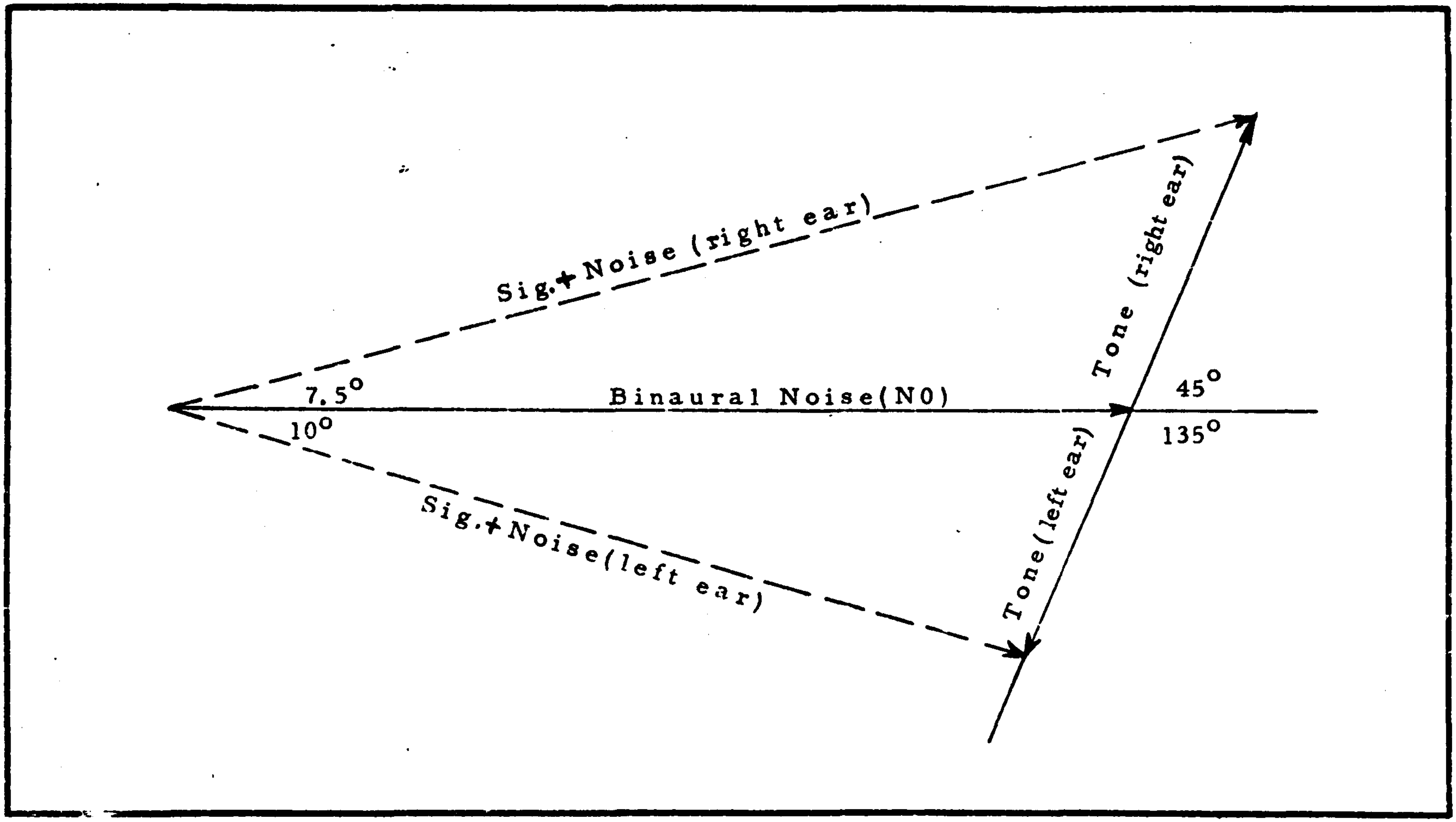

Fig. 20.--Vector diagram for the SπN0 listening condition (after Jeffress, 1972).

order neurons." This triggering action would occur only when the left and right neural branches would simultaneously stimulate the particular "higher order neuron." If, for example, the identical waveform is delivered to each ear, the electrical impulses would tend to meet at and excite one of those neurons which reside in the median plane of the listener's head. Jeffress suggests that for those instances wherein the signal to one ear lagged, in time, behind the stimuli sent to the contralateral ear, the neural activity would tend to converge upon the vicinity of some neural locus that represents the ear that is lagging. Such a description provides a link between the locus of the neural activity and the location of the sound source itself.

The Equalization and Cancellation Model

Durlach (1960; 1963; 1972) has developed a "black box" rather than neuro-physiological model of the masking level difference mechanism. He postulates that the binaural mechanism performs a limited number of operations upon the input stimuli in order to enhance the detection process. Durlach (1963) has reduced these operations into two basic steps:

> "........when the subject is presented with a binaural-masking stimulus, the auditory system attempts to eliminate the masking components by transforming the total signal in one ear relative to the total signal in the other ear until the masking components are exactly the same in both ears (the E process), and then subtracting the total signal in one ear from the total signal in the other ear (the C process). If this operation is performed with complete precision, the masking signal will be completely eliminated."

After the initial equalization of the noise waveform amplitudes, cancellation of the masking stimuli is achieved through the simple algebraic summation of the two inverted noise waveforms. In this idealized case, a doubling of the signal magnitude accompanies the elimination of the noise -- giving rise to perfect detection. Perfect performance is, of course, not realized in the human listener and Durlach postulates the presence of two types of signal processing errors to account for this less than ideal detection. The first being some form of temporal instability or "jitter" in the processing of the signals at the two ears. This "jitter" is random in nature and considered to be quite small in magnitude -- about 105(μsec.^{2}). At low frequencies (e.g. 250 Hz) this "jitter" has little effect upon the phasic relationship between the two inputs. At high frequencies, however, there is significant altering of the coherence between the waveforms that are presented to the two ears -- hence poorer detection performance and a lower MLD. An ever present amplitude variance comprises the second type of processing error. This variance is estimated to be on the order of $(0.25)^2$ in magnitude.

Criticism of the T-D and E-C models

A number of authors have commented upon the predictions made by the Webster-Jeffress and Durlach models. Hafter (1971) has endorsed that aspect of the time difference model which relates MLDs to lateralization phenomena as it is in agreement with his own recent research findings. He points out, however, that the T-D model cannot account for MLD values which have been obtained at frequencies "...where interaural time is known to be ineffective for localization" (see, for example, Hirsh and Burgeat, 1958). Dolan and Robinson (1967) have noted that the T-D model "...predicts no change in detectability as the level of the masker at the non-signal ear is varied." This would seem to be contraindicated by the data obtained by numerous workers (see pages 27-30, above). Green and Henning (1969) suggest that both the T-D and E-C models do not address themselves to the influences of transient cues in the binaural listening situation. These writers have posed the question of whether the T-D and E-C predictions might not be based upon an unrealistic conception of the process of release from masking. Specifically, the predictions are based only upon "... static quantities, quantities that represent the average over some interval of time."

The E-C model has successfully accounted for much of the MLD data but it too has drawn critical comment on several issues. Hafter (1971) draws our attention to the fact that the E-C model:

> "...does not explain the relation between detection and signal to noise phase. Since noise is presumed canceled in the E-C process, the energy of the difference, and hence detection, should be independent of the phase angle between the signal and the masker. Yet, Hafter and Carrier (1970), using tonal maskers in order to fix the signal-to-mask phase, have found that dichotic detection is very dependent on this phase relation."

New Developments

Hafter (1971) has proposed a model of binaural release from masking in which a single theoretical quantity(related to lateralization of the binaural fused image) serves as the underlying factor in the MLD mechanism. The test quantity, $\bar{\Delta}$, is believed to be the weighted average of the instantaneous interaural time and intensity disparities between the stimuli reaching the two ears. Variations in the magnitude of $\bar{\Delta}$ are thought to produce displacements of the fused auditory image along the median plane of the subject's head. This shift is detected by the listener and it is the difference in detection performance for the various test situations which comprise the MLD values.

Osman (1971) has recently proposed a model of the MLD process "....which provides a description of a large mass of results, simply organized with regard to interaural correlation." Osman has postulated that the receiver utilizes a single decision variable that is derived from a linear combination of three basic quantities: the magnitude of the energy levels at the two ears, plus the interaural cross correlation of the waveforms at the two ears.

The Proposed Study

The focal point of much of the research into MLD phenomena has been upon the role which interaural correlation of noise and signal waveforms plays in the detection performance of a listener. To this author, the data reported in the literature and cited in this review, suggest that interaural correlation is the pivotal, underlying factor in the MLD process. See the work of Osman, 1971. Indeed, it is possible to translate each of the major theoretical viewpoints into the framework of interaural correlation.

The vector model of masking level differences may be described in terms of correlation when it is considered over some continuous time period rather than for an instant in time (as portrayed above). In Figure 21, the tonal signals are represented as vectors of fixed length (displaying their invariant amplitudes). For the narrow band noise waveform at each ear, however, the vector will change in length from moment to moment. This is because band limited noise approximates a sinusoid that is slowly varying in magnitude. The resultant noise and signal vector for each ear is then seen to fluctuate as the angle between the noise and signal varies between 0-360.° The resultant noise and signal vectors will alternately wax and wane in size. As greater time delays are introduced, the maxima of each cycle will diminish. This may be likened to the decorrelation that occurs between noise waveforms to which an interaural time delay has been introduced. This relationship is displayed in Figure 23.

Rabiner, Laurence, and Durlach (1966) expanded the Equalization and Cancellation theory to include a discussion of the influence which noise decorrelation has upon both the empirical evidence they obtained and the theoretical considerations they have offerred. In the earlier version of the model, complete cancellation of the noise waveforms was assumed. In the expaned theory, however, the cancellation is thought to be only partial. In Figure 22a, two perfectly correlated, identical,

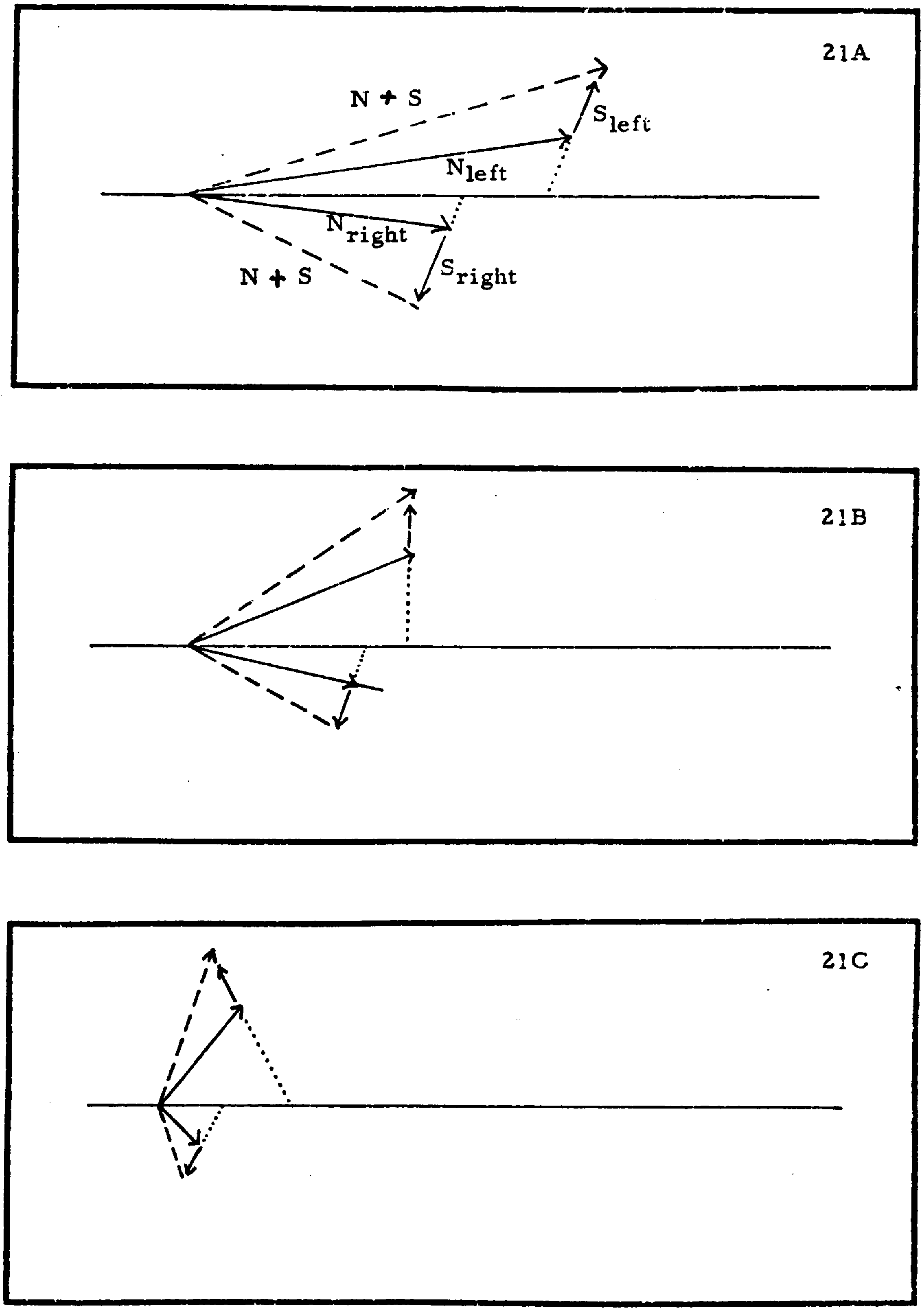

Fig. 21. -- Vector representation of narrow band noise and signal at the two ears. The signal is invariant but the noise fluctuates in magnitude as the signal-and-noise vectors rotate around each other with the passage of time.

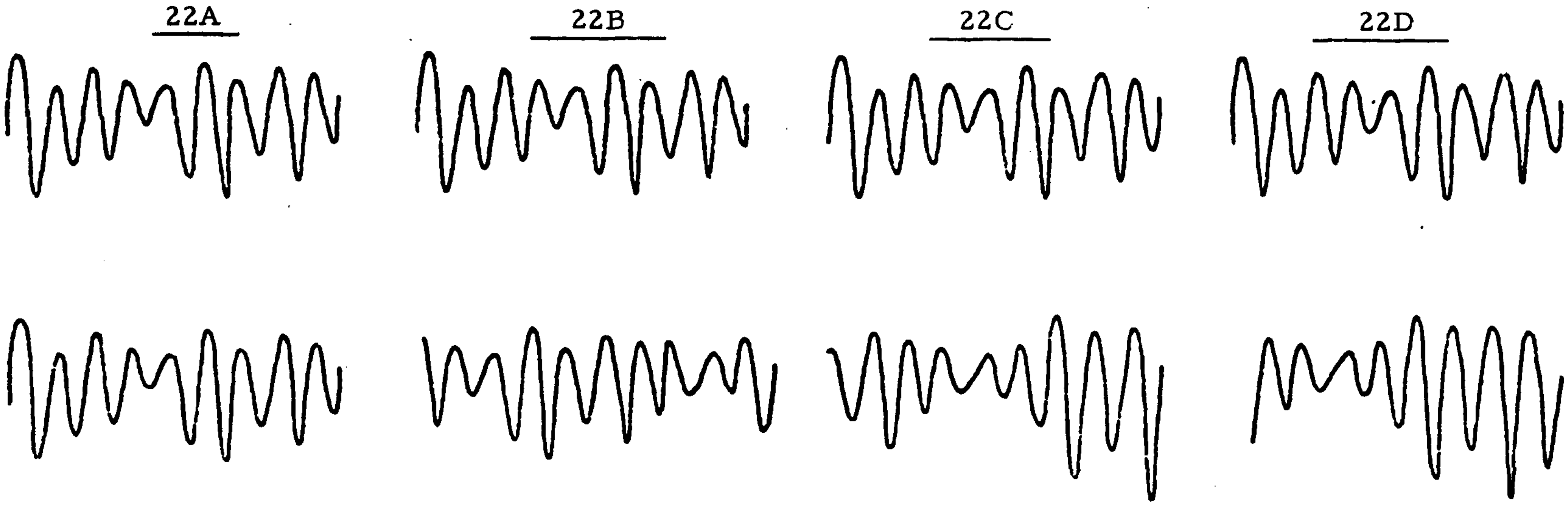

Fig. 22. -- Binaural narrow band noise waveforms. The identical waveforms are at each ear in fig. 22A. Fig. 22, B, C, D, show the waveform to one ear with different time delays introduced.

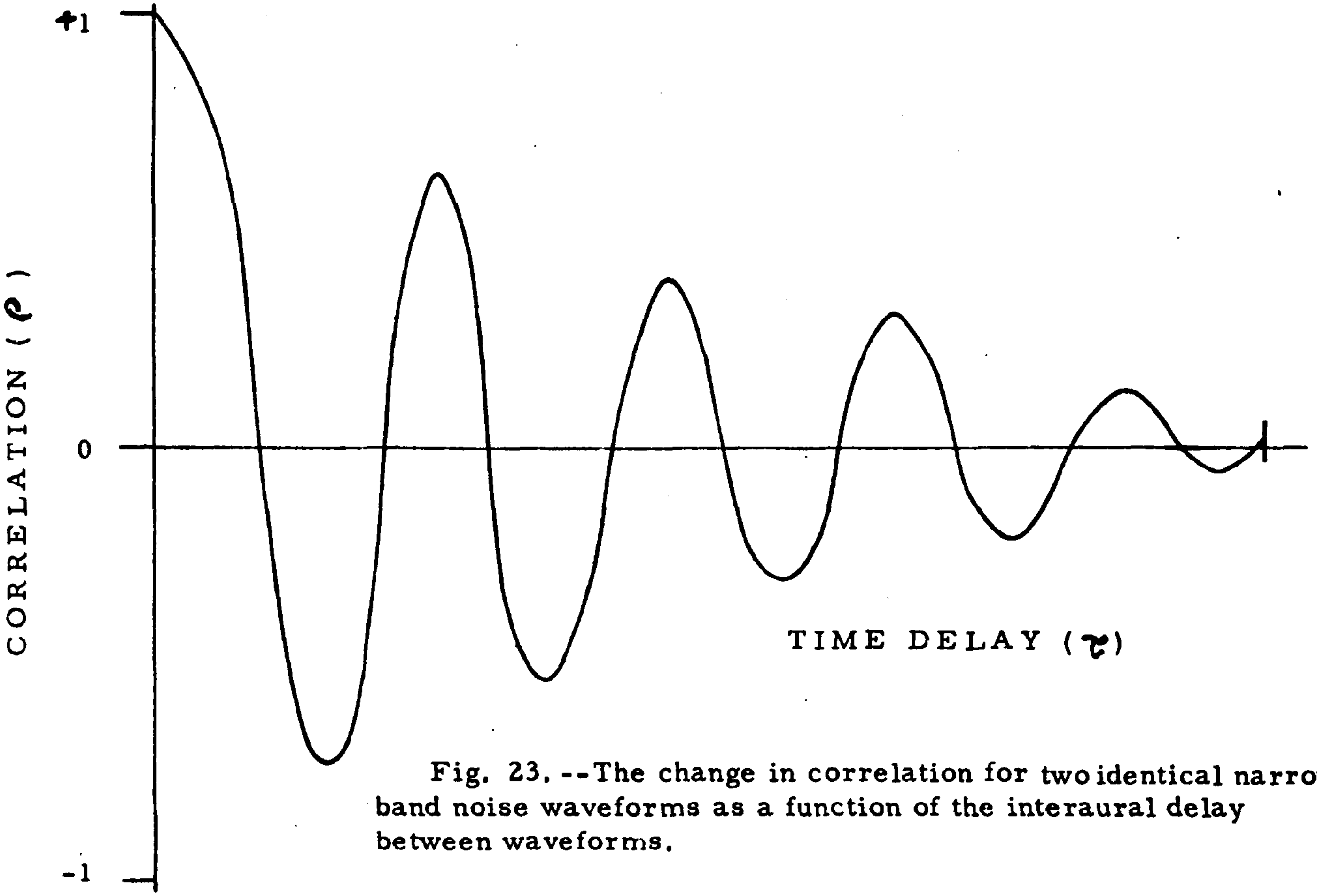

Fig. 23.--The change in correlation for two identical narrow band noise waveforms as a function of the interaural delay between waveforms.

narrow band noise waveforms are displayed. In Figure 22b, c, d, one may see that the resultant noise waveform would change as greater time delays, τ_n, are introduced between the component waveforms. For those instants wherein peaks on the two component waveforms coincide, the resultant will exhibit a "local" maximum amplitude. These maxima become progressively smaller as the decorrelation of the noise waveforms increases. This relationship is shown in Figure 23. The cyclic nature of this curve is reminiscent of the function observed for MLD values and interaural time delay of noise waveforms(Figures 16-17). For very large values of τ_n, no maximum is obtained and there is zero correlation between the noise waveforms. In the revised E-C model, the MLD mechanism may be characterized as shifting one noise waveform, in time, with respect to the waveform at the other ear (perhaps to the nearest meshing of the waveform peaks). Subsequent subtraction of the waveforms would not, then, lead to complete cancelation of the masking noise. Such a description(emphasizing the role of noise correlation in MLD phenomena) along with the previously described temporal and amplitude variances, aid the model in accounting for the real world situation of less than perfect detection.

To confirm the nature and extent of the influence which noise decorrelation exerts upon detection performance, one must specify the characteristics of the noise waveform that a subject listens to during each test trial. It is not yet possible to determine the exact nature of a subject's own internal, physiological, noise. Recent advances, however, in digitally produced waveforms offer the experimenter a degree of control and repeatability over masking stimuli that is unattainable with conventional thermal noise sources. Pfafflin and Mathews (1966) and Pfafflin (1968) have employed an IBM 7094 computer to generate a series of 240 random numbers which a digital to analog converter then transformed to electrical impulses at a sampling rate of 2500 samples per second. This wide band noise was then passed through a low pass filter and delivered to subjects as the masking stimulus for the detection of computer generated sinusoids. The applicability of such reproducible noise to research in psychoacoustics, and the superiority of digital noise generators over tape recorded stimuli (with its inherent distortion due to wow and flutter) are clear.

The limiting factor in detection and the size of MLD values is probably due to some form of internal listener error (viz. internal noise). The use of random noise sources, in previous experiments, compounded with the listener's own internal noise has led to theoretical interpretations of MLD data which are quite complicated. This is because the model must account for the role of both the external and internal noise in the experiment. It is the goal of the proposed study, however, to eliminate the fluctuations of external noise through the use of rigorously specified, digitally generated masking stimuli. This, it is hoped, might lead to a more direct interpretation of internal noise.

CHAPTER III

EXPERIMENTAL METHOD

Subjects

Three sophisticated listeners (two men and one woman, ranging in age from 23 to 27 years) were the subjects for this study. Pure tone hearing threshold levels for each individual were determined and found to be within normal audiological limits. The frequencies examined included: 125, 250, 500, and 1000 Hz. The test tone, itself, was of the same duration and rise-decay time as the experimental tones employed in this research and described below.

Psychometric Procedure

In this research, the subject's basic task was to detect a binaurally presented tone burst within a background of binaural noise. The psychophysical procedure used to determine threshold values was the two interval, forced choice (2IFC) technique. With this type of procedure, the listener is exposed to two consecutive observing intervals--both containing the noise masker but only one containing the binaural test signal. The subject decides within which of these two intervals the tone was delivered, and reports his choice to the experimenter.

Stimulus magnitudes were varied according to an adaptive test procedure. In an adaptive method, the stimulus values are dependent upon the subject's responses. In general, when a correct detection or error is made, the tone is, respectively, attenuated or increased in magnitude. The specific adaptive technique used for these experiments was a transformed up-down procedure (Levitt, 1971). For each two consecutive, correct, interval identifications achieved by the listener, one dB of attenuation(the increment or step size) was applied to the signal. Any incorrect response gave rise to an automatic one dB increase in the signal level. Errors occurring after attenuation of the signal constituted reversals and marked the beginning of an upward series of steps known as a run. Twelve such upward runs completed one experimental test condition. Figure 24 depicts a hypothetical subject's response pattern showing several reversals and runs. With this particular up-down procedure, it is possible to obtain an estimate of the 70% probability of response point along the subject's psychometric function. The operational definition of threshold , as used in this study, was taken to be this point.

The test tone bursts

Tone bursts of 250, and 500 Hz were chozen as the signals for this study. MLD values are most pronounced for frequencies within and near this frequency range (see chapter II). The tone bursts had a duration of 12 msec. (equivalent to a total of six periods at 500 Hz and

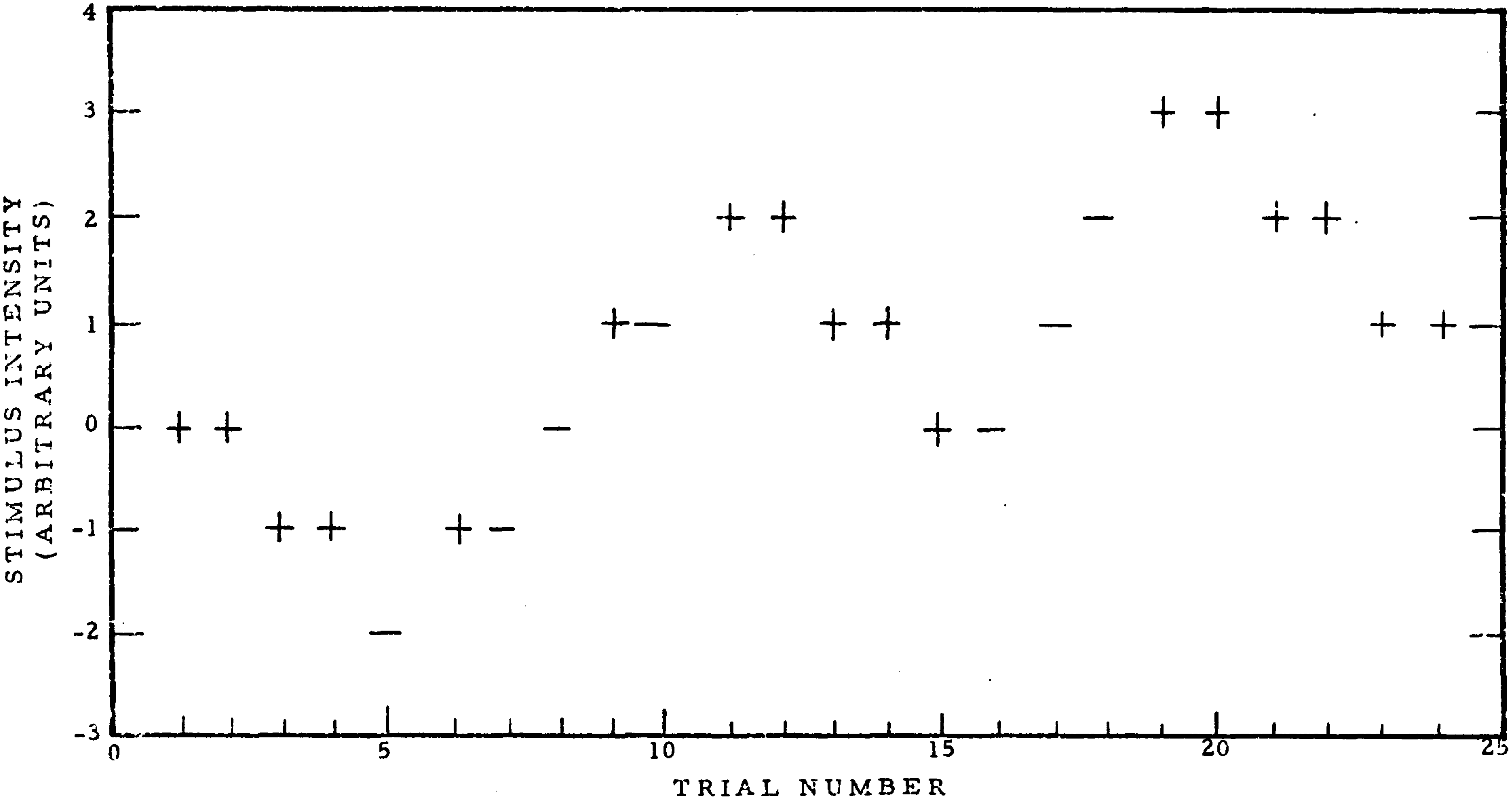

Fig. 24.--Typical response pattern for the transformed up-down procedure used in this study (after, Levitt, 1971).

three periods at 250 Hz. See Appendix II for oscillograms of all the waveforms used in this study. Such brief duration signals have been found to yield relatively large MLD values (see chapter II). The signal was presented on a random schedule to one of the two observation intervals (followed, in turn, by a one second listener response period).

Binaural test conditions

Differences between detection performance for the $S0N_\tau$ and $S\pi N_\tau$ listening conditions were examined (the S0N0 and SπN0 cases are obtained when $\tau = 0$). As discussed in chapter II, experimental conditions such as these typically give rise to substantial differences in subject detection performance.

Masking Stimuli

The noise stimuli for this study were produced by means of a digital noise generator which could be programmed to repeat the identical waveform for each presentation. The wide band output of the noise generator was passed through a narrow band filter (50 Hz bandwidth) whose center frequency was that of the test signal itself. Four different narrow band waveforms (two for each frequency) were employed as masking stimuli. Waveforms with differing auto-correlation functions were selected in order to explore the influence of such waveform disparities upon the threshold performance of the listener. An examination of the relative positions of the tone bursts within the different noise waveforms reveals that for noise conditions I and III, the tone burst is located within a portion of the noise waveform that contains less amplitude variability than is evident for noises II and IV (contrast Plate I with Plate III, and Plate V with Plate VII). One may see from Plates II and IV as well as VI and VIII, that as greater interaural time delays are introduced to the binaural listening conditions, the tone burst is displaced into portions of the waveforms that are more and more like a sinusoid.

The magnitude of the noise masker was fixed at a value of 90 dB SPL. In chapter II it was noted that MLD values are largest within high intensity noise backgrounds. It is important to describe the magnitude of noise stimuli in terms of the overall bandwidth of the noise itself. The spectrum level of noise , which is the noise per unit cycle, is a valuable measure of noise intensity. The computed spectrum level of the masking stimuli used in this study was 73 dB/cycle for a bandwidth of 50 Hz.

An interaural time delay, τ_n, was introduced between the noise waveforms by means of three precision L-C delay lines (totalling seven msec. delay, with taps every 40 μsec.). Values of τ_n were selected with two basic criteria in mind:

1) A number of delay times should center around multiples of the half period and full period points for each frequency, so that the influence of noise decorrelation upon the maxima and minima MLD values might be revealed. Of particular interest was the flattening of the MLD vs. τ_n function observed by some workers (see chapter II).

2) Time delays should extend for several periods for the 500 Hz tone burst to better contrast the

> typically smaller MLD values obtained for such long time delays with the diminished cross-correlation product of the noise waveforms at the two ears.

On this basis, the following test points were selected:

Frequency 500 Hz Period 2000 μsec.

0, 400, 800, 1000, 1200, 1800, 2000, 2200, 2800, 3000, 3200, 3800, 4000, 4200, 4800, 5000, 5200, 5800, 6000, and 6200 μsec.

Frequency 250 Hz Period 4000 μsec.

0, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000, and 4500 μsec.

Calibration procedures

A tone burst was introduced to the delay line and both the input and output waveforms for each delay setting were examined upon an oscilloscope to insure the precision and accuracy of the delay line's performance. Photographs were taken at the beginning and end of each test session, comparing the electrical noise input to one headphone with its delayed counterpart on the opposite channel (see Plates XIII-XVIII) as well as the tone burst, alone, on one channel versus the delayed noise on the other (see Plates I-XII). This was done so that the stability of the delay times throughout the entire experiment might be monitored. These oscillograms have a time base of 10 msec. / division.

Before and after each test session, the magnitudes of the noise masker and tone burst stimuli were monitored so as to ascertain the stability of these waveforms from day to day. The selected values of 90 dB SPL for the noise stimuli, and 92 dB SPL for the tone bursts (at an attenuator setting of 40 dB) were measured upon a Bruel and Kjaer type 2203 sound level meter, 1613 octave filter set, and a type 4152 artificial ear equipped with a special cuff (made from an MX 41/AR cushion) to accommodate the Koss PRO -50 headphones used in this study.

Apparatus

Figure 25 displays a block diagram of the experimental equipment employed in this research. The heavy lines represent the audio paths which the noise and signal follow, whereas the thin lines demark the stimulus control circuitry. Of special note is the manner in which the tone bursts were added to the noise waveforms. The typical sequence of steps were as follows. The control logic circuitry initiates the first observing interval during which , switch #1 is turned on for the duration of the interval. Within this interval, the tone passed by switch #1 is pre-shaped and gated by another switch in series with the first. Switch #2 was added in series with #1 to insure that no signal would feed through to the subject during the wrong interval. Switch #2 gates the actual tone "packet" submitted to the listener , only during the interval chosen by the experimenter with the interval selection switch. In addition, a timer within the tone burst switch unit, insures that the tone burst will be gated at the identical zero crossing of the waveform from trial to trial. This was done to maintain the same phasic relationship between noise and signal during each test condition.

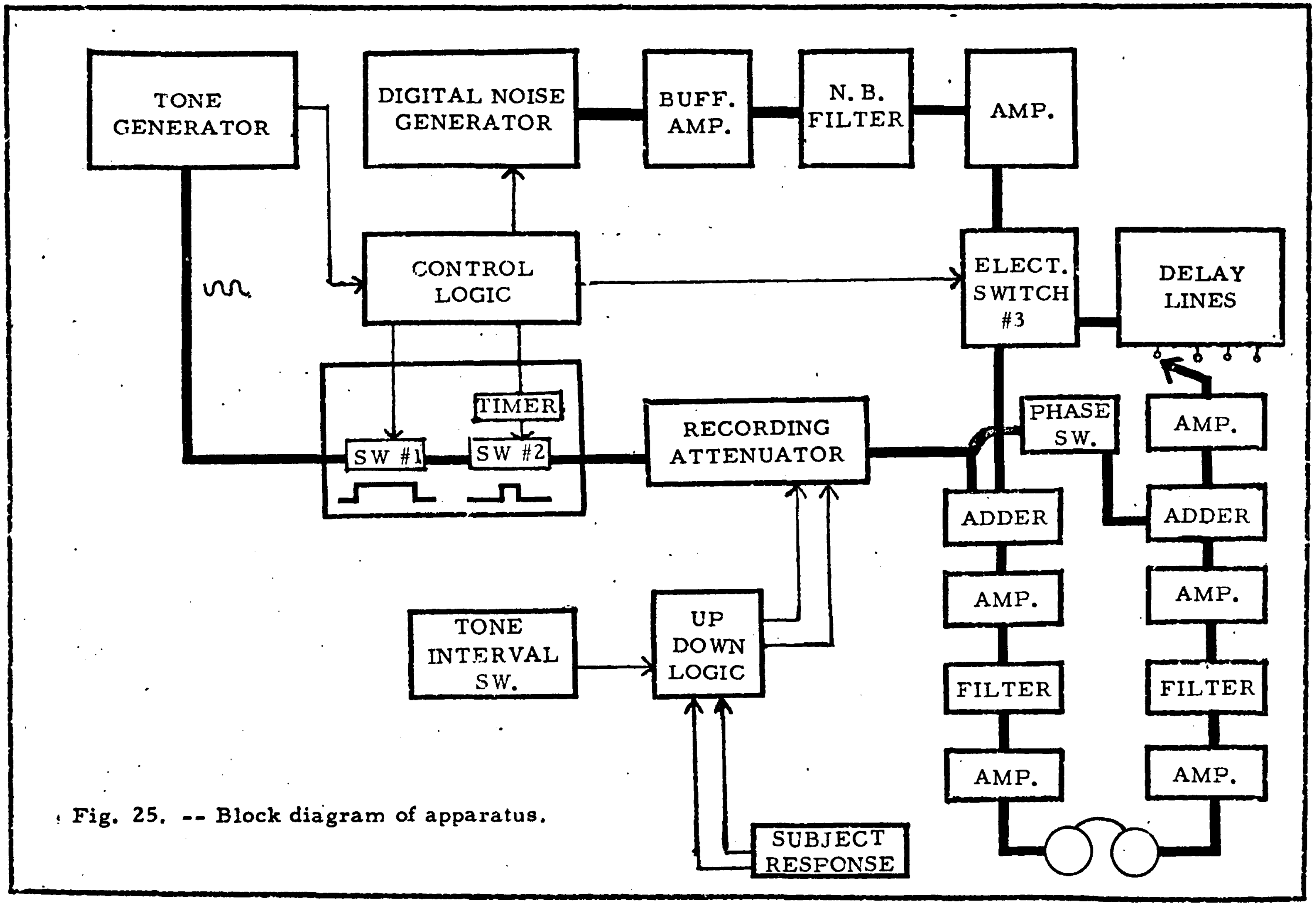

Fig. 25. -- Block diagram of apparatus.

CHAPTER IV

RESULTS

Coding and Processing of Threshold Data

A subject's threshold* for the different test conditions was determined by encoding the levels of the peaks and valleys appearing upon the recording attenuator chart onto punched cards. An IBM 1130 computer was employed to calculate the subject's threshold from the average of twelve such pairs of peaks and valleys on each card. In addition, a four factor analysis of variance for these mean threshold values was performed by the computer.

General characteristics of the test results

One prominent feature of the data obtained in this study, and plotted in figures 26-43,are the great intersubject differences. In a number of instances (particularly for the case wherein 500 Hz was the signal frequency) intersubject thresholds differed by more than ten to fifteen decibels. These disparities were relatively fixed, with one listener

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*In this study, the 70 % locus on the individual's psychometric function was chosen as the operational definition of threshold. This point corresponds to a d' value of 0.74.

having a higher threshold than another, over most test conditions. The question remains, however, as to whether or not the variability of these data is so great, that the resulting curves fail to fit any meaningful pattern. A statistical method is available which gives the expected variability of a mean for a set of data with a given range (Lord, 1947). This procedure employs the range of the data as the measure of a subject's in-session variability. The average range within test conditions was obtained for the all three subjects and found to be approximately: 5 dB for subject I (represented by x-x, data points on each graph); 10 dB for subject II (0-0 data points); and 10 dB for subject III (Δ -Δ data points). The maximum acceptable deviation for a test value may be computed from the relationship:

$$T = \frac{\bar{X} - A}{W}$$

Where:

T = critical values which have been tabulated for different levels of statistical significance (Lord, 1947).

$\bar{X}$ = the average magnitude of a number of experimental observations.

A = the value of a point on some known curve which has been fitted to the experimental function.

W = the magnitude of the range.

Subject I, as an illustrative example, had a typical intrasession range of 5 dB and a value for T, of 0.3 (with ten threshold observations and at the .01 level of significance). The value of $\bar{X}$ - A, which is the expected deviation of the data points from the estimated curve, would be:

$$\bar{X} - A = (0.3)\,(5\text{ dB}) \text{ or } 1.5\text{ dB}$$

In a similar fashion, the computed values for subjects II and III would be 3 dB each. Figure 23 (pg. 54, above) displayed the correlation coefficient for two identical narrow band noise waveforms as a function of τ_n. This curve has the similar cyclic, damped, characteristics as the typical MLD vs. τ_n functions which have appeared in the literature. Figure 23 is not necessarily identical to the curves which have been reported in the literature, but the correlation function is probably responsible for the cyclic characteristics of the real data. The half-cycle components in Figure 23 may be regarded as bell shaped functions and can be fitted to the plotted results of this study (see figures, 38-43). From the calculation made above, one is alerted to any data points on the experimental curves that deviate from the fitted bell curve by more than 1.5 dB for subject I and by more than 3 dB for subjects II and III. A scan of the plotted results reveals that the bulk of the data points appear to lie within the permissible limits of deviation and may, therefore, be considered to fit some meaningful, rather than random pattern.

Specific characteristics (250 Hz, tone leads noise)

Figure 38, a-f, depicts the listening condition wherein the 250 Hz binaural tone bursts were in-phase. One may see that the expected pattern of a valley at 0 and 4 msec.; and a peak at the half-period point of 2 msec., are clearly present for subject I and roughly in evidence for the other two listeners. Also, subjects I and II display somewhat better thresholds for the first noise waveform condition than for the second. This effect is present for subject III only for delays beyond about 2.5 msec. For the listening situation wherein the binaural tone bursts were out-of-phase ($S\pi$, figure 39 a-f) one finds all three subjects displaying the expected pattern of peak at zero delay, valley at half-period point, and peak, again, at the full period point. In these instances , however, there is relatively little difference in sensitivity between the two noise waveform conditions.

Specific characteristics (500 Hz)

In figure 40, a-c(noise III, signals in-phase) one finds the familiar cyclic MLD pattern, with peaks and valleys occurring in a number of test situations. There are some differences, however, between these curves and the already published data. One fails to notice, for example, any significant dimunition of the threshold peaks as the time delay is increased (with the exception of peak three, subject II). Indeed, for subjects I and III, the peaks actually ascend in magnitude.

For noise waveform IV, only a few peaks and valleys occur at their appointed time delays. The cyclic pattern possesses far less regularity and symmetry than for the third noise waveform condition. In addition, there is a tendency for thresholds to be a little poorer for this waveform condition than for the noise III cases.

When the binaural tones are antiphasic (figure 41, a-f) one , again, finds waveform III test results to be far more symmetrical than those of noise IV (with the exception, perhaps, of subject III, fig. 41f).

As with the 250 Hz data, one finds several instances of ascending crests, with increased time delay for the 500 Hz cases (note, fig. 41, b, c, e). And, as with the S0 case mentioned above, for 500 Hz, thresholds are generally poorer for noise waveform condition IV than for noise III.

Specific characteristics (250 Hz, tone in noise)

In figure 42, a-d, one finds the basic, expected, pattern for the S0 condition. Here, again, there is evidence that thresholds for noise I are somewhat better than those for noise II.

The antiphasic condition shown in fig. 43, a-d, shows the basic pattern, for noise I, with the valley curiously displaced to the left by about 500 μsec. For noise waveform II, there does not seem to be much of a meaningful pattern at all. A comparison of figures 39 with 42, for the 250 Hz conditions reveals slightly better thresholds when the tone was embedded in the noise (for the Sπ condition). This result is surprising, in light of the fact that when (in an initial pilot experiment) subject I was presented with a 250 Hz tone burst which extended beyond, but at no point overlapped with, the noise waveform, thresholds were enhanced by 30 to 40 decibels. It was therefore anticipated that an additional durational cue might be obtained by allowing the tone burst to lead the noise slightly -- thereby yielding more sensitive thresholds.

Analysis of Variance for Thresholds

A computer printout of the analyses of variance for the three experimental conditions appears in tables II, III, and IV. As was expected from the wide variability of the data points, there was a clearly significant difference between subjects at the .005 level for each test frequency used. For the case wherein the 250 Hz tone burst led the noise there were also significant differences between the two phases (.025 level) and between the noise waveforms (.01 level). For the 500 Hz tone, there were significant differences between phases (.01 level); delays (0.1 level); subject-noise interactions (.01 level); phase-noise interactions (.005 level) and phase-delay interactions(.05 level). The final test condition, wherein the 250 Hz tone was embedded in the noise, displayed significant differences between : phases (.005 level); noises (.1 level); delays (.1 level); phase-noise interactions (.1 level); and subject-phase-noise interactions (.025 level).

Noise I.

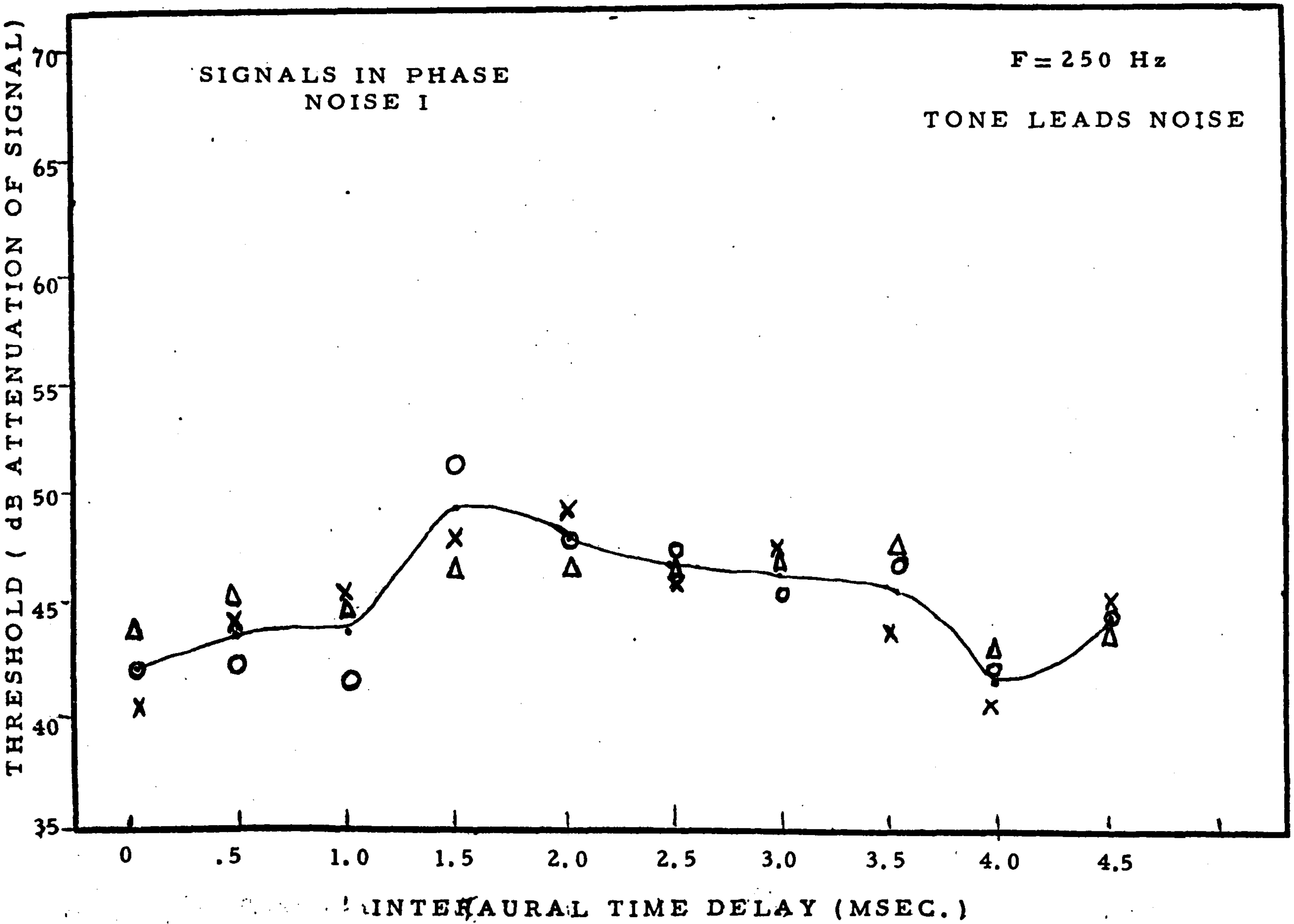

Figure 26

φ, Noise II

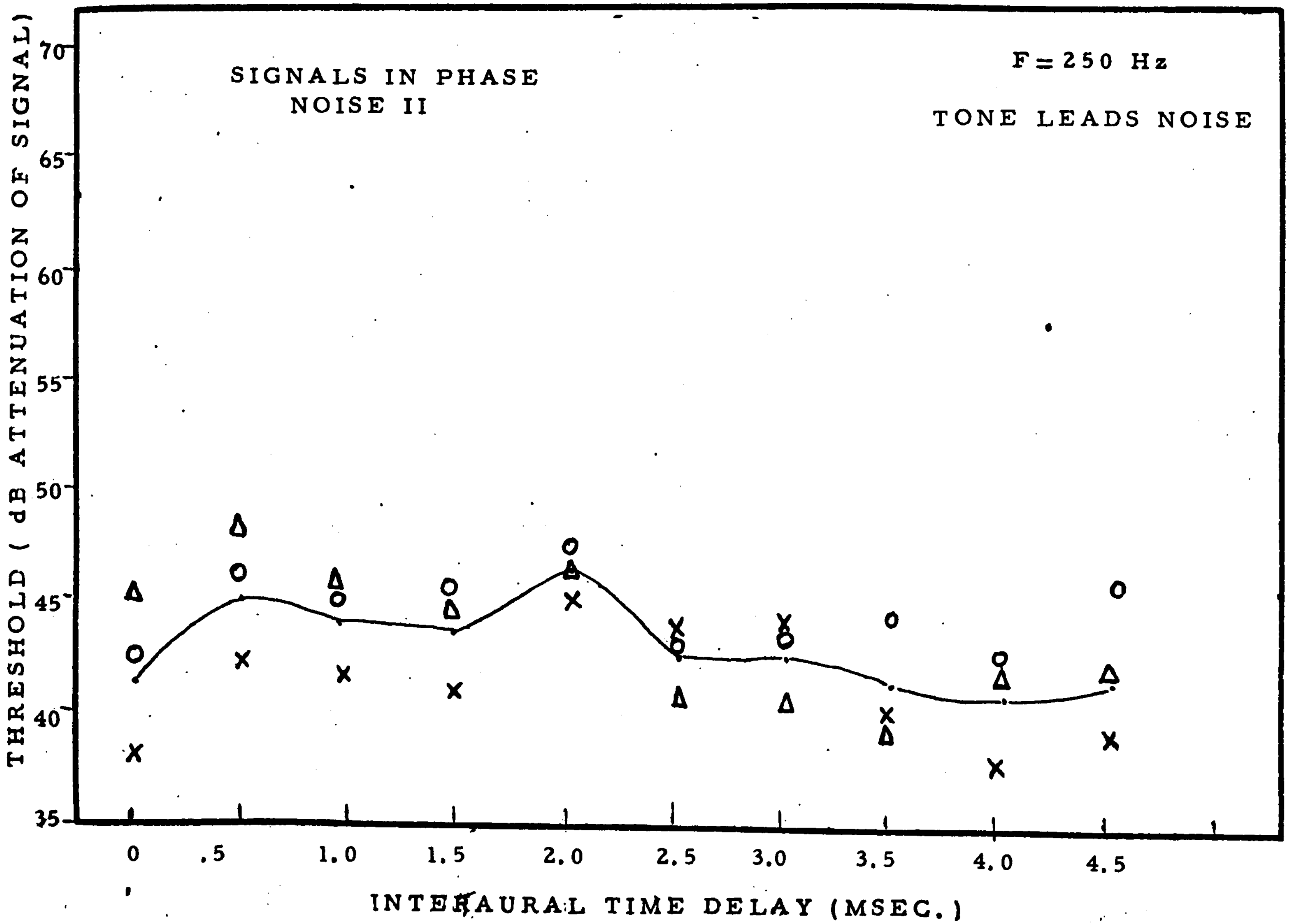

Figure 27

D_c Noise I

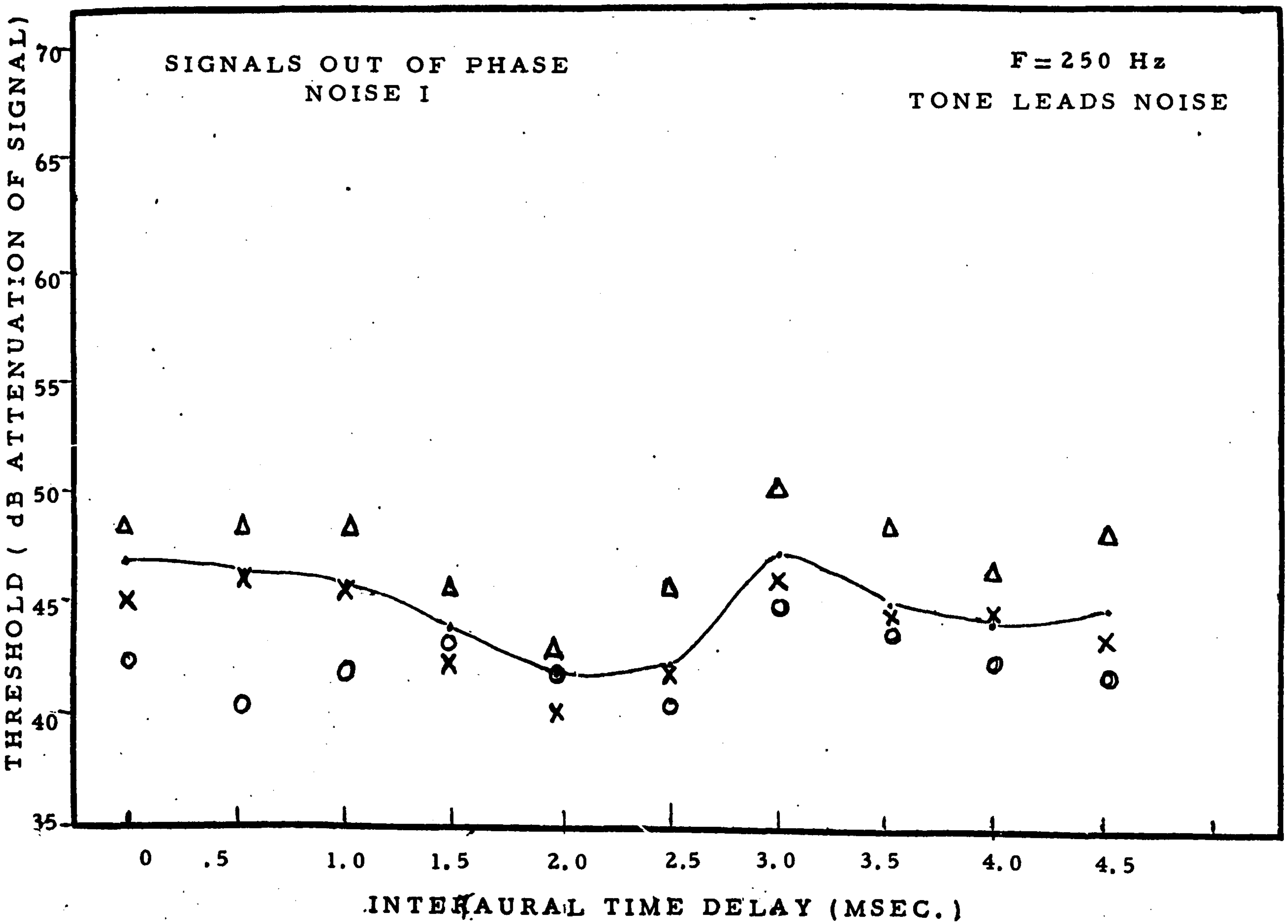

Figure 28

ψ_2 Noise II

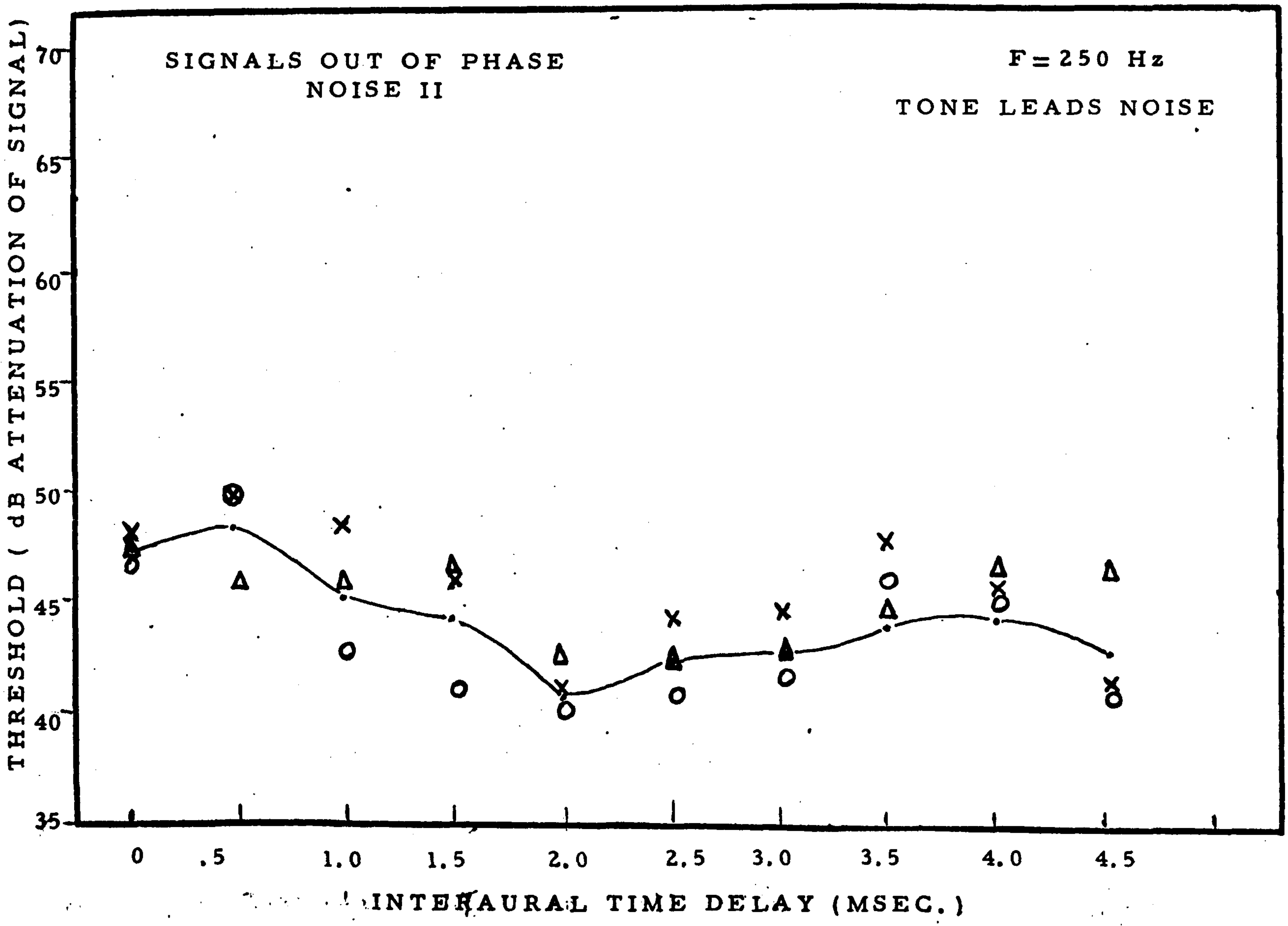

Figure 29

S,N, Noise I

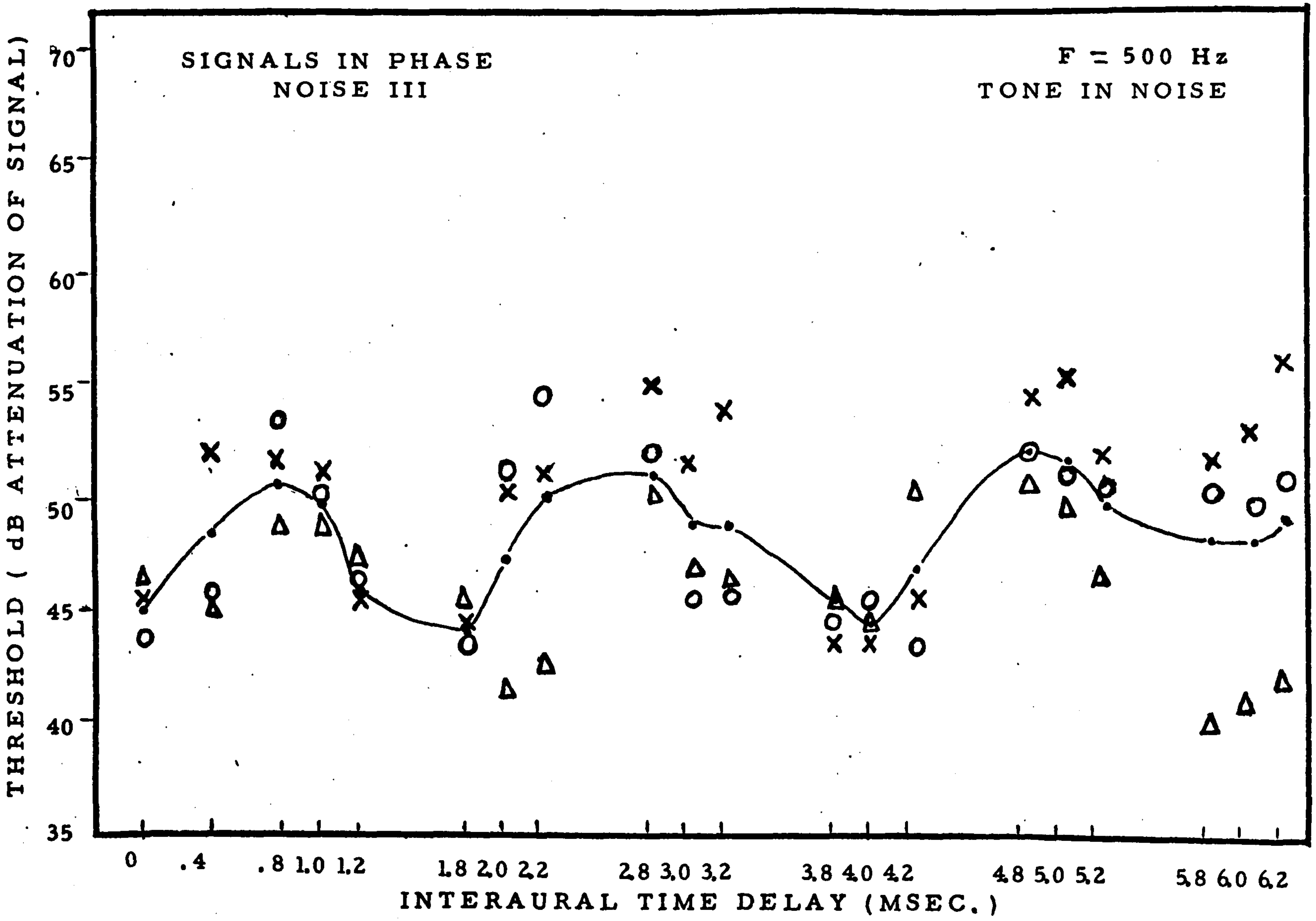

Figure 30

ϕ_1 Noise II

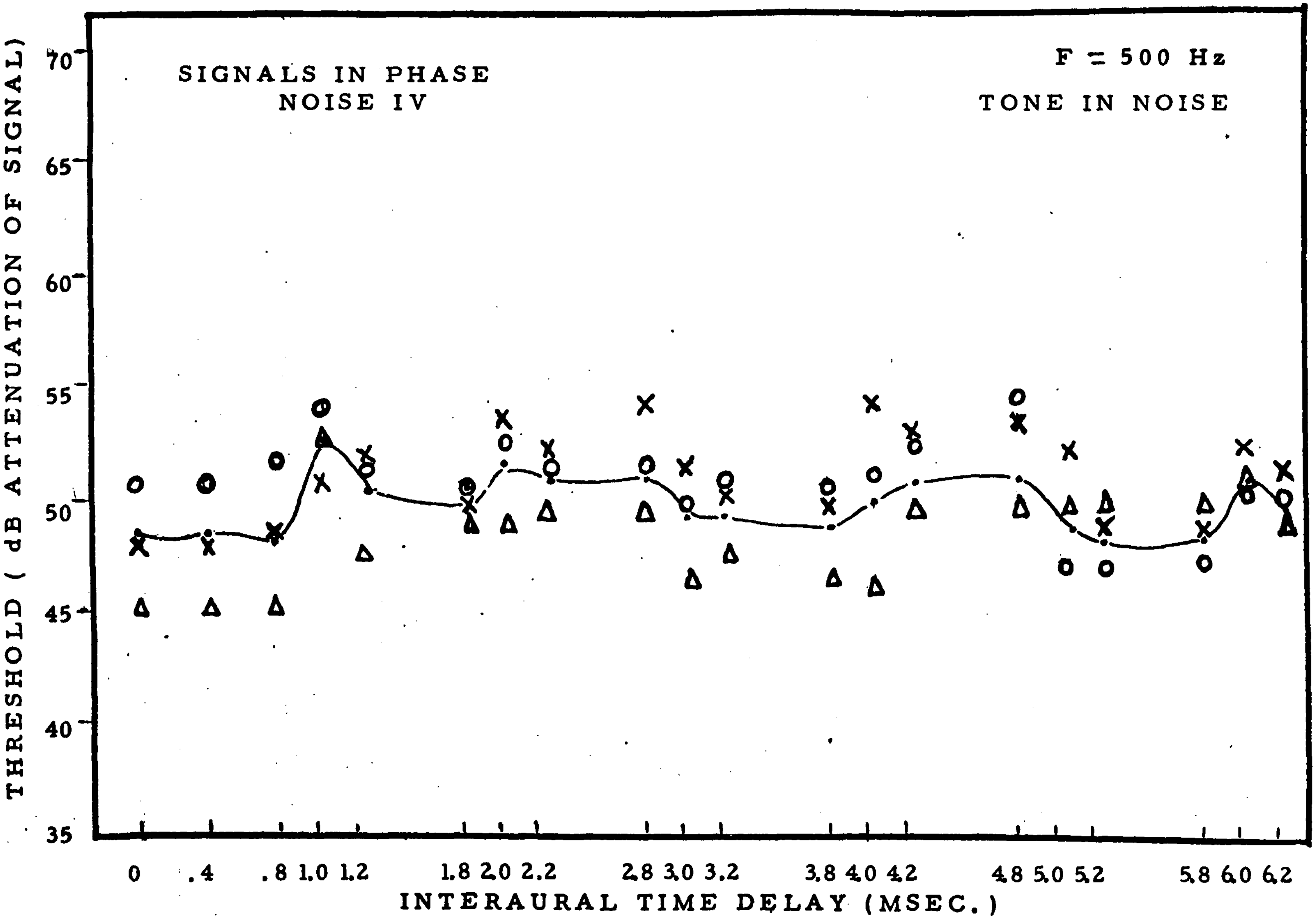

Figure 31

ψ_2 Noise I

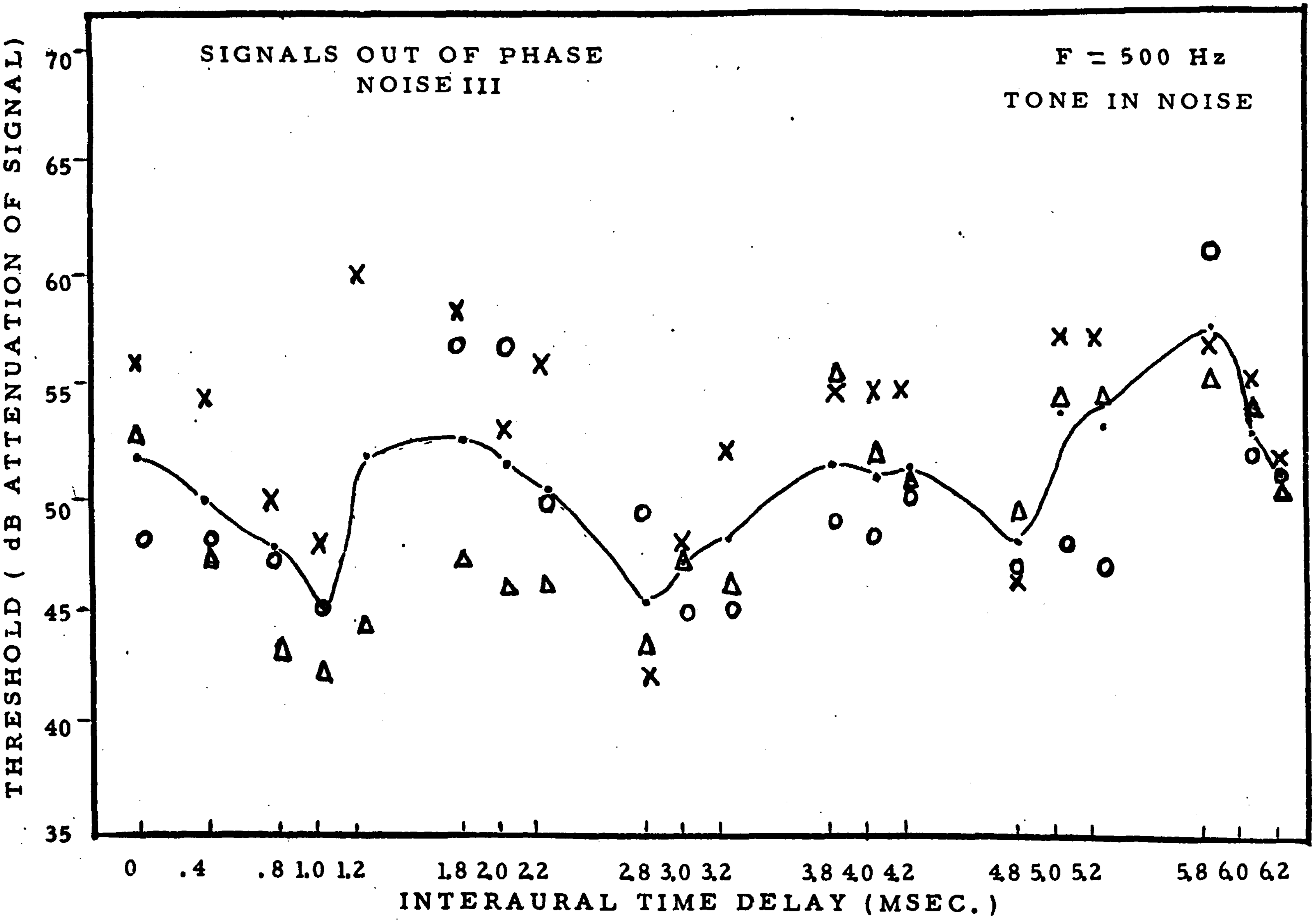

Figure 32

½ Noise II

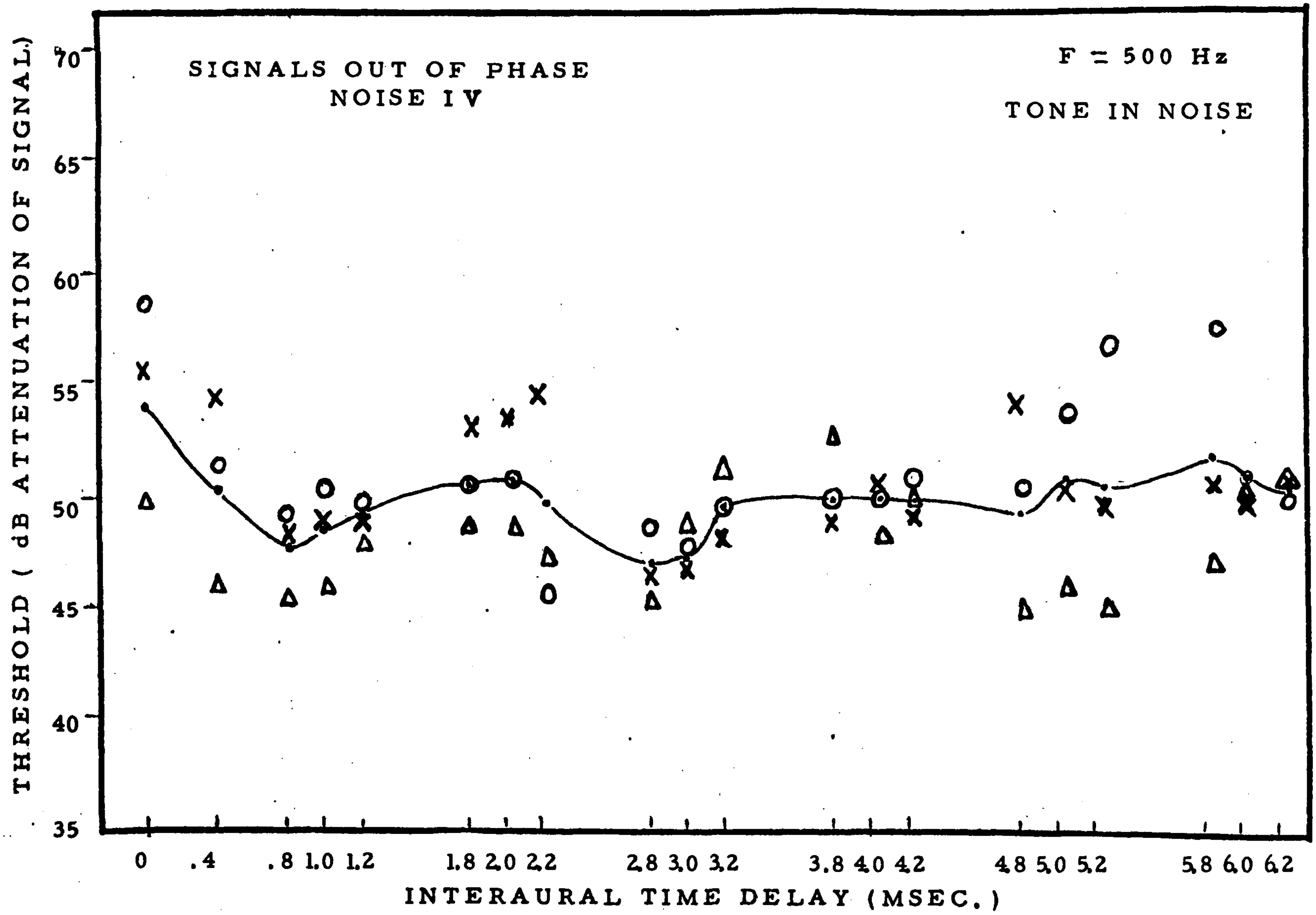

Figure 33

ψ, noise I
special

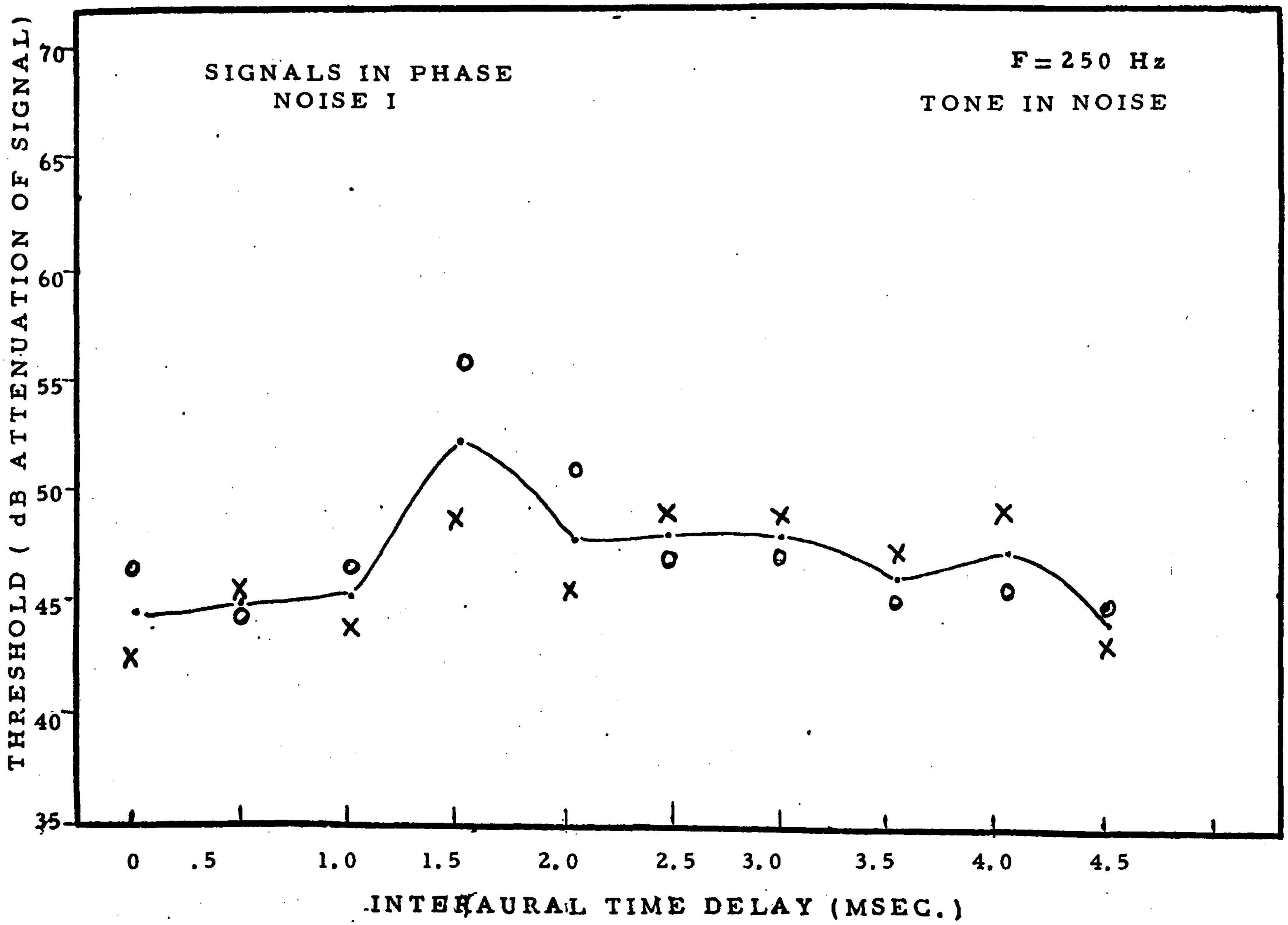

Figure 34

Ψ_1 Noise II
Signals

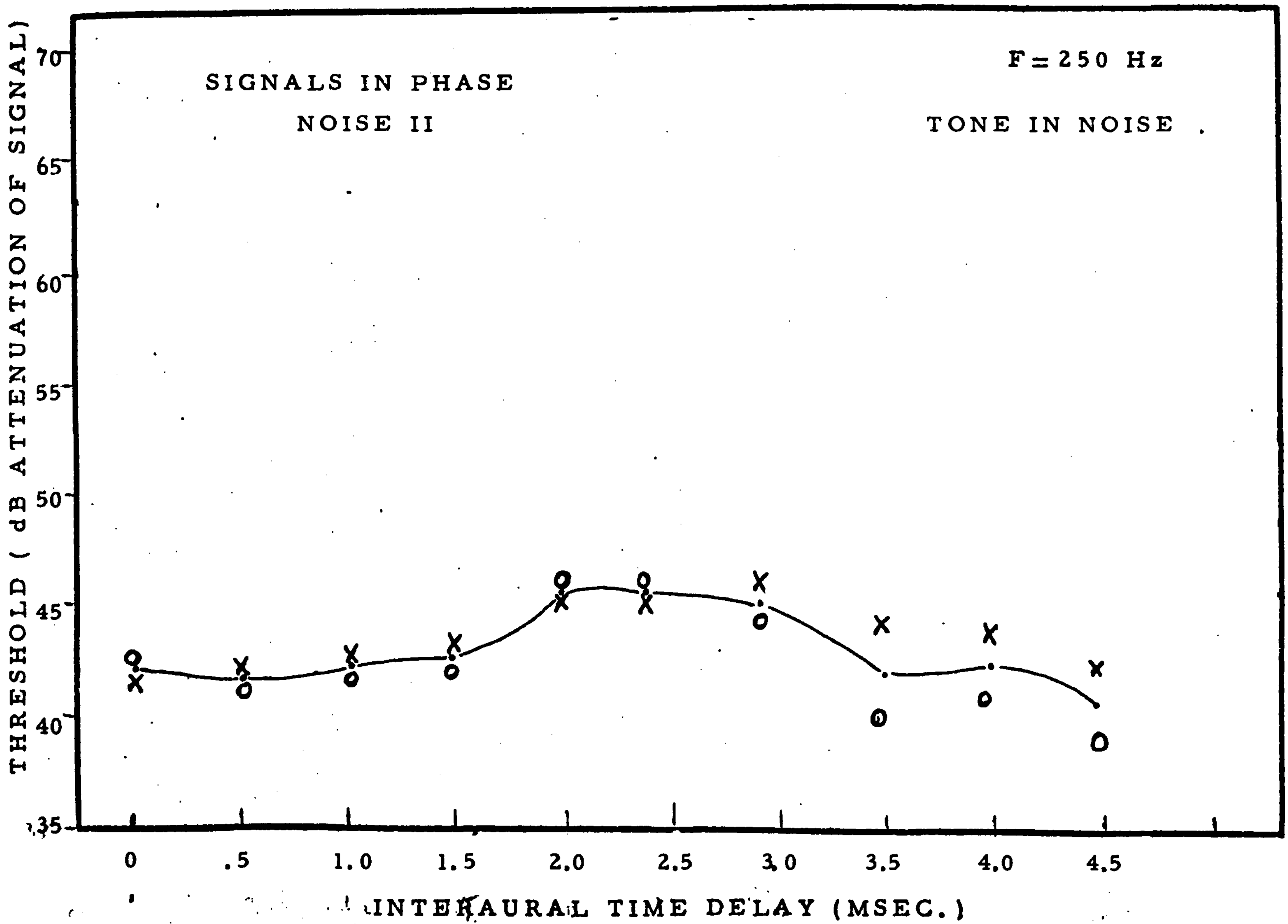

Figure 35

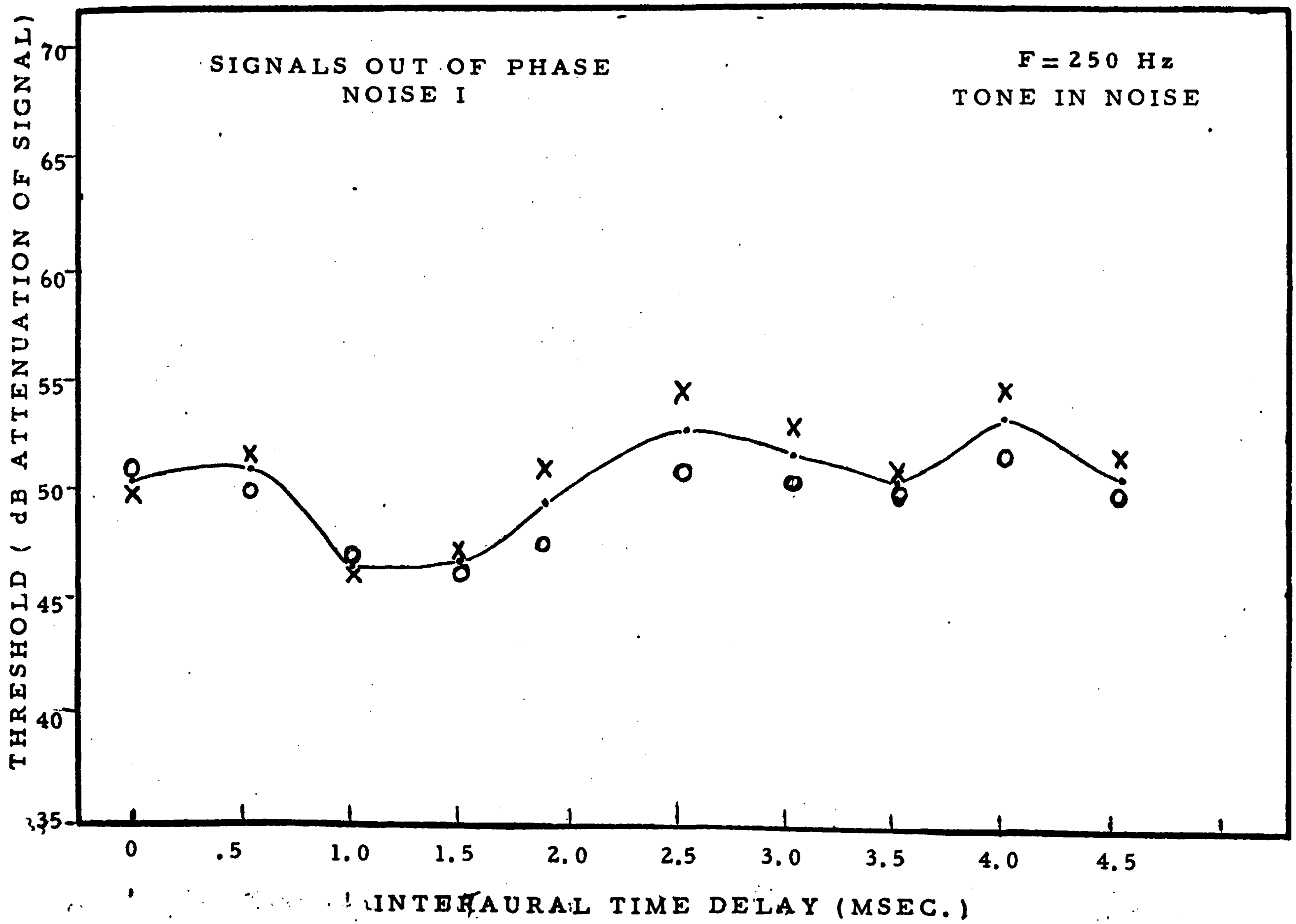
SIGNALS OUT OF PHASE
NOISE I
F = 250 Hz
TONE IN NOISE
THRESHOLD (dB ATTENUATION OF SIGNAL)
70
65
60
55
50
45
40
35
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
INTERAURAL TIME DELAY (MSEC.)

Figure 36

φ_2 Noise II
Special

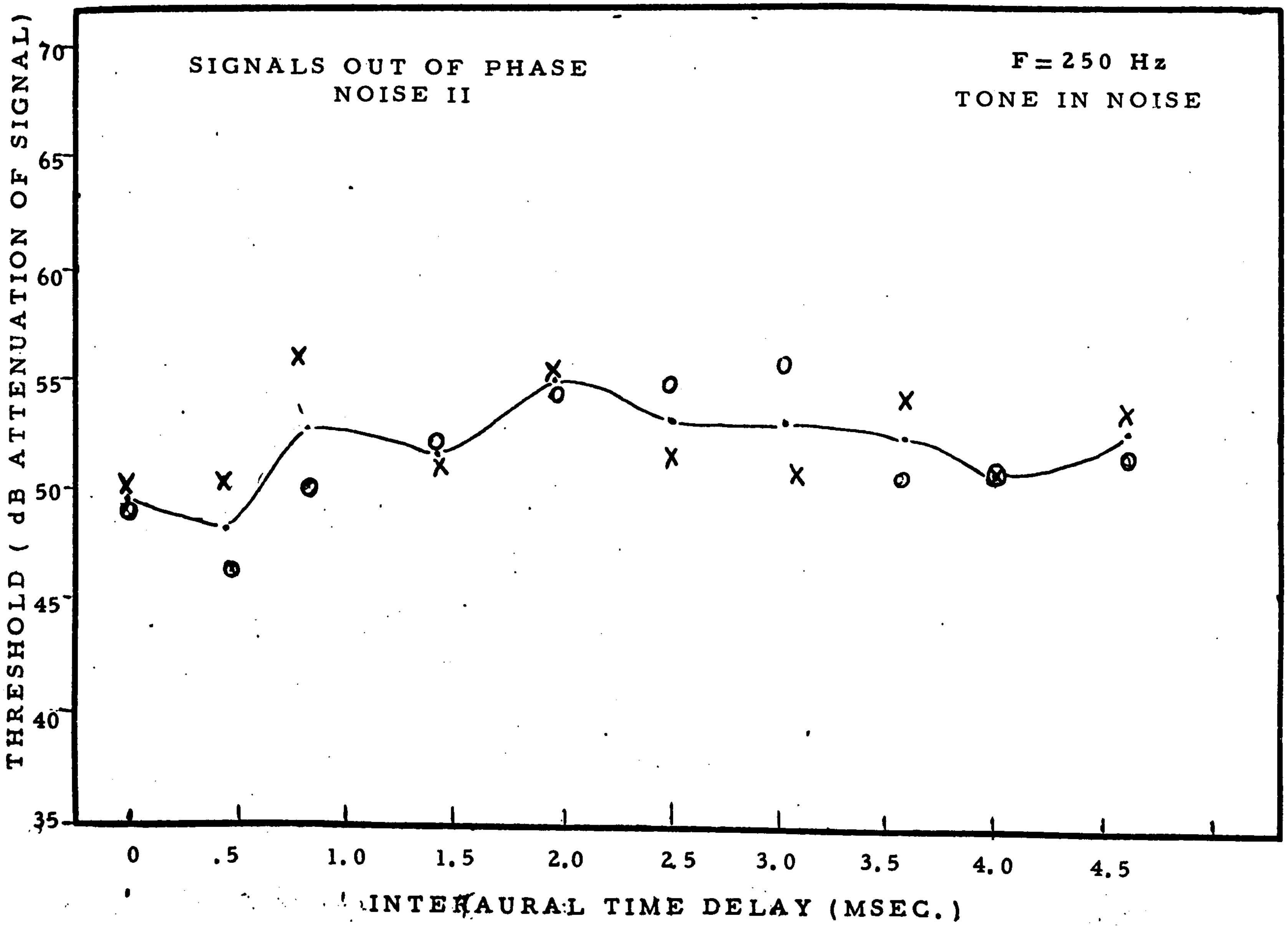

Figure 37

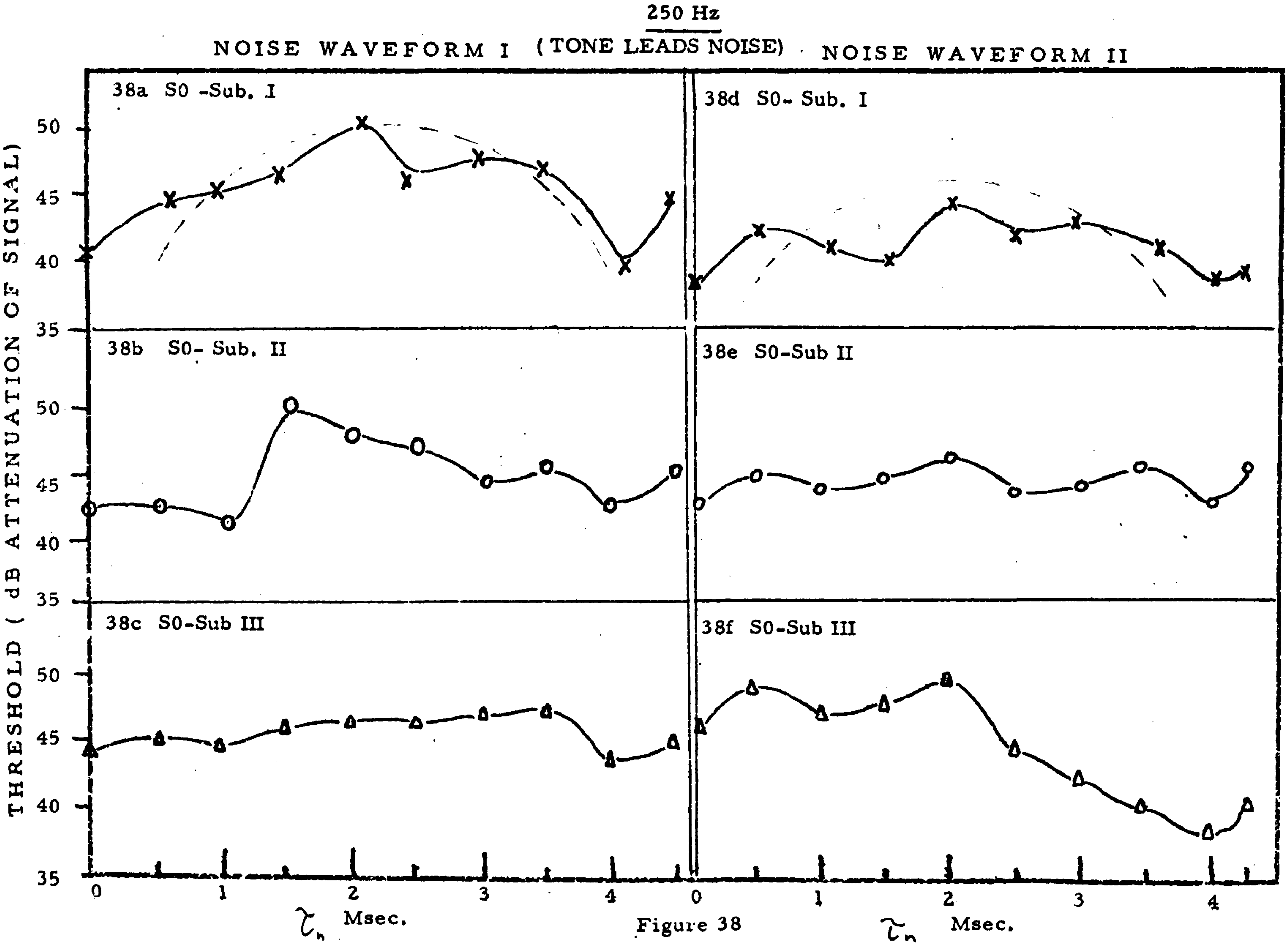
250 Hz
NOISE WAVEFORM I
(TONE LEADS NOISE)
NOISE WAVEFORM II
38a S0 -Sub. I
38b S0- Sub. II
38c S0-Sub III
38d S0- Sub. I
38e S0-Sub II
38f S0-Sub III
THRESHOLD (dB ATTENUATION OF SIGNAL)
50
45
40
35
0
1
2
3
4
τ_n Msec.

Figure 38

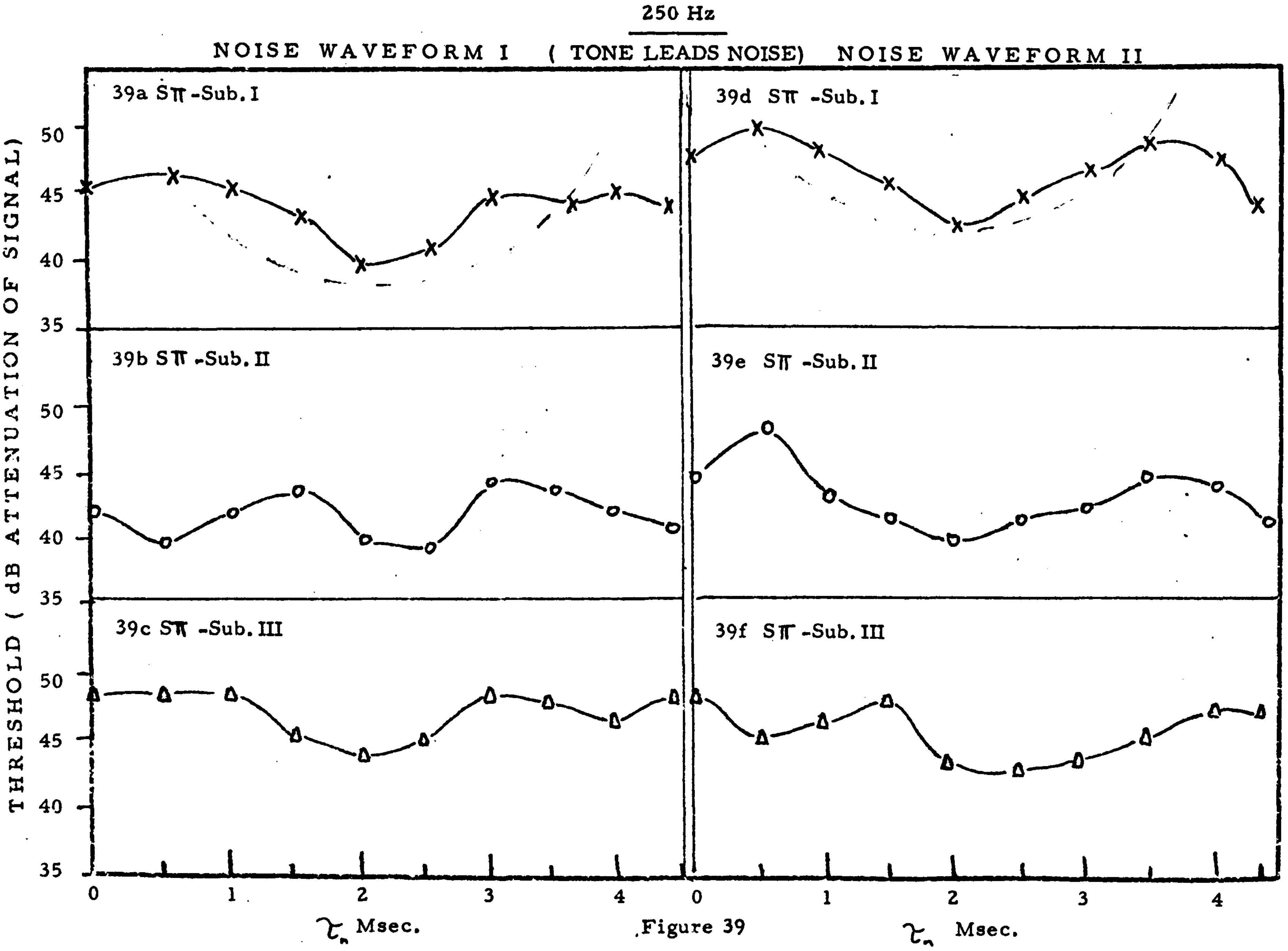
250 Hz
NOISE WAVEFORM I
(TONE LEADS NOISE)
NOISE WAVEFORM II
39a Sπ -Sub. I
39b Sπ -Sub. II
39c Sπ -Sub. III
39d Sπ -Sub. I
39e Sπ -Sub. II
39f Sπ -Sub. III
THRESHOLD (dB ATTENUATION OF SIGNAL)
50
45
40
35
0
1
2
3
4
τₙ Msec.

Figure 39

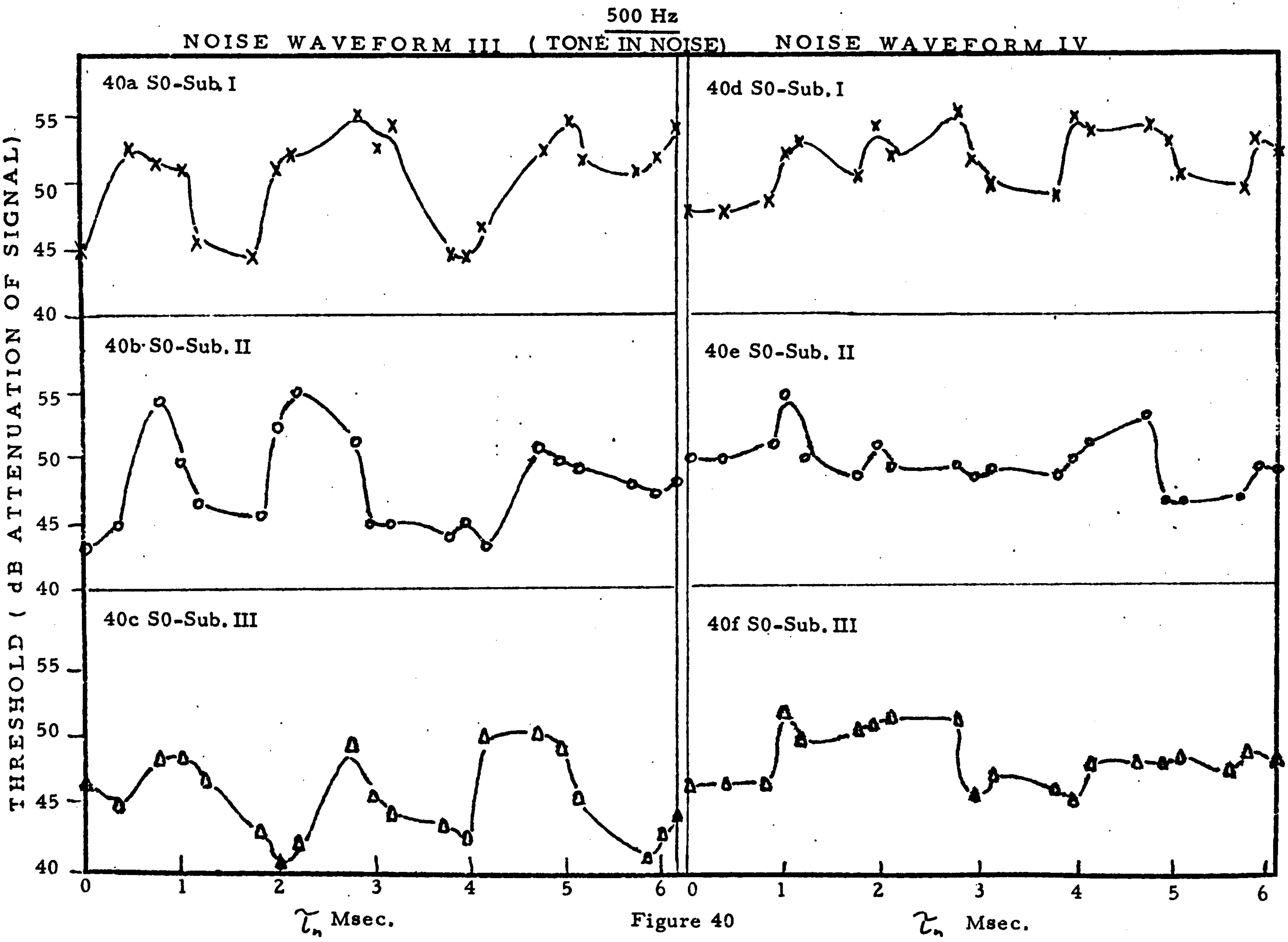
500 Hz
NOISE WAVEFORM III (TONE IN NOISE) NOISE WAVEFORM IV
THRESHOLD (dB ATTENUATION OF SIGNAL)
40a S0-Sub. I
40b S0-Sub. II
40c S0-Sub. III
40d S0-Sub. I
40e S0-Sub. II
40f S0-Sub. III
55
50
45
40
0
1
2
3
4
5
6
τ_n Msec.
τ_n Msec.

Figure 40

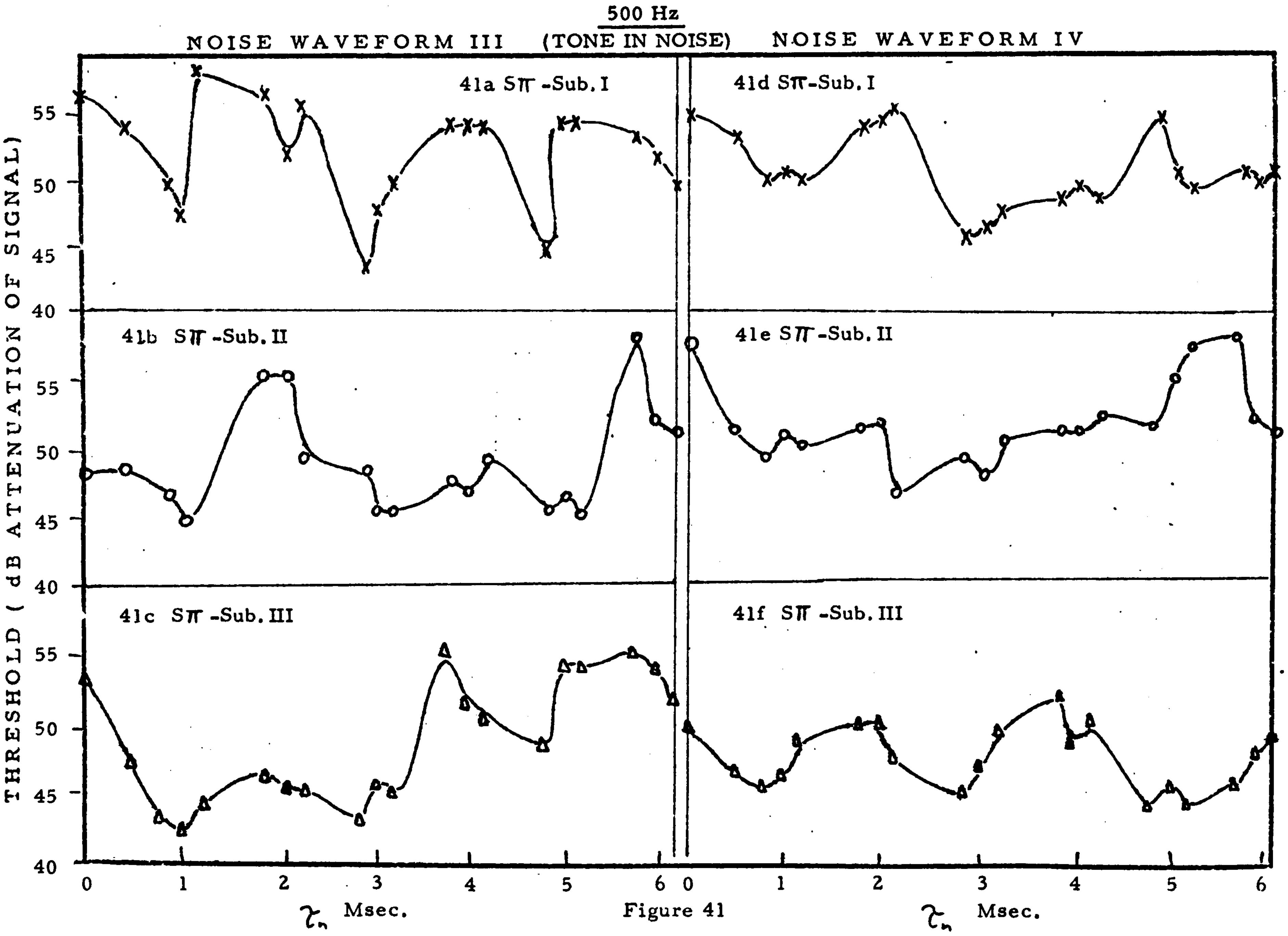
500 Hz
NOISE WAVEFORM III
(TONE IN NOISE)
NOISE WAVEFORM IV
41a Sπ -Sub. I
41b Sπ -Sub. II
41c Sπ -Sub. III
41d Sπ-Sub. I
41e Sπ -Sub. II
41f Sπ -Sub. III
THRESHOLD (dB ATTENUATION OF SIGNAL)
55
50
45
40
0
1
2
3
4
5
6
τ_n Msec.

Figure 41

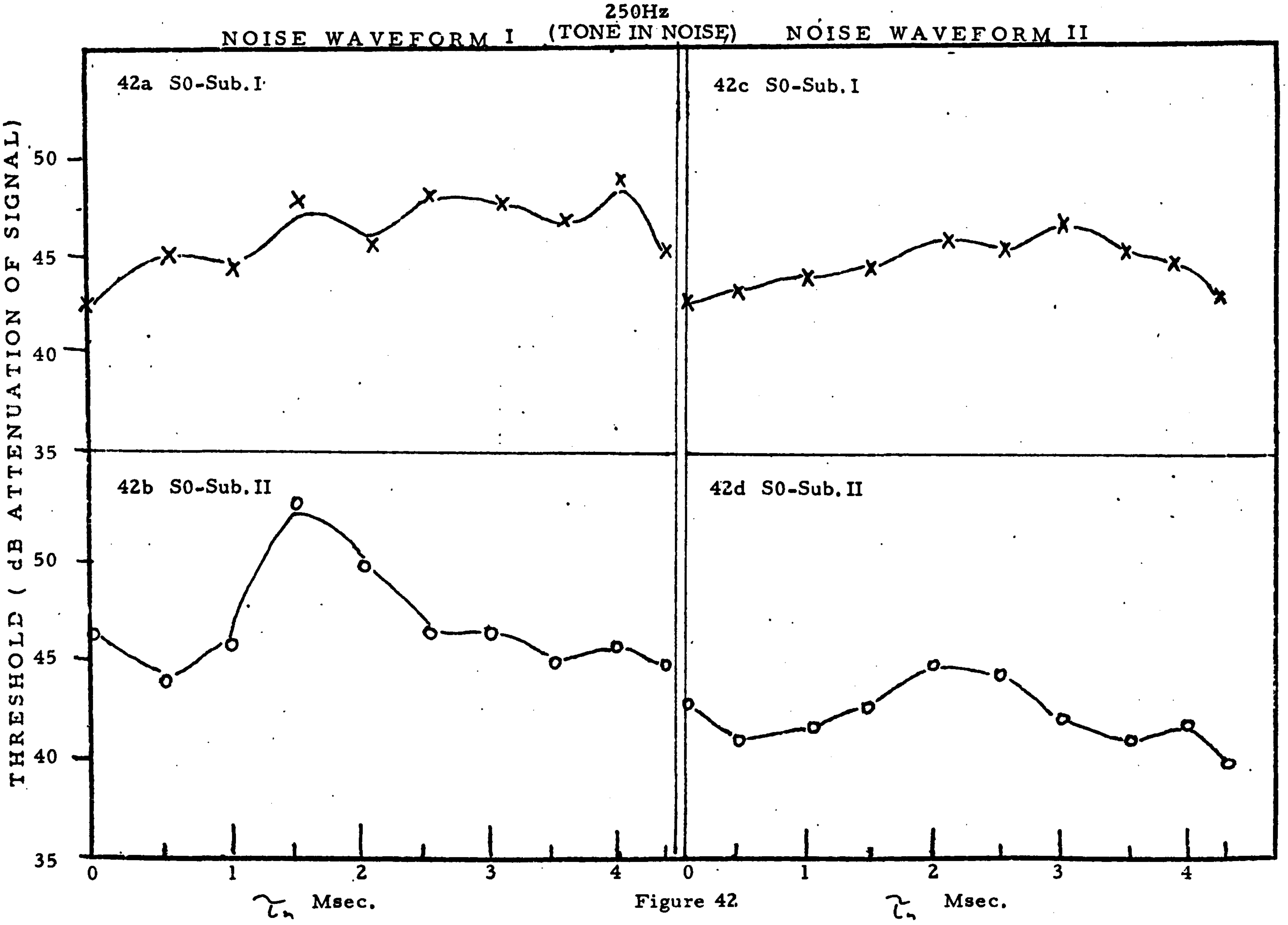
250Hz
(TONE IN NOISE)
NOISE WAVEFORM I
NOISE WAVEFORM II
42a S0-Sub. I
42c S0-Sub. I
42b S0-Sub. II
42d S0-Sub. II
THRESHOLD (dB ATTENUATION OF SIGNAL)
50
45
40
35
50
45
40
35
0
1
2
3
4
0
1
2
3
4
τ_n Msec.
τ_n Msec.

Figure 42

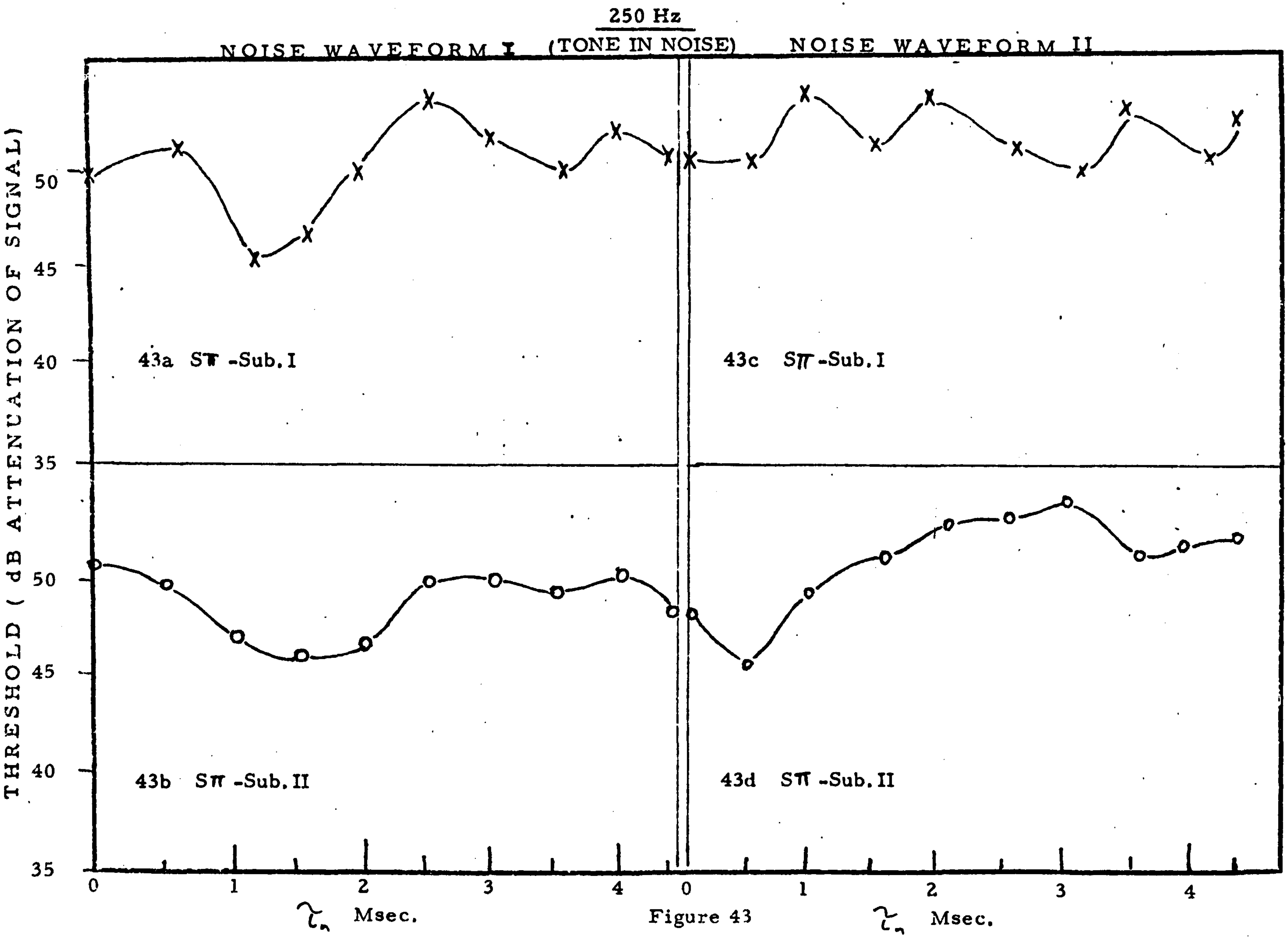
250 Hz
NOISE WAVEFORM I
(TONE IN NOISE)
NOISE WAVEFORM II
THRESHOLD (dB ATTENUATION OF SIGNAL)
50
45
40
35
50
45
40
35
43a Sπ -Sub. I
43c Sπ -Sub. I
43b Sπ -Sub. II
43d Sπ -Sub. II
0
1
2
3
4
0
1
2
3
4
τ_n Msec.
τ_n Msec.

Figure 43

S -- Subjects (3)
P -- Signal Phases (2)

N -- Noise Waveforms (2)
D -- Time Delays (10)

TABLE II

ANALYSIS OF VARIANCE -- 250 Hz (TONE LEADS NOISE)

SOURCE OF VARIATICN	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
S	301.40026	2	150.70013
P	68.81886	1	68.81886
SP	25.20180	2	12.60090
N	95.92892	1	95.92892
SN	21.40937	2	10.70468
PN	19.90636	1	19.90636
SPN	15.27421	2	7.63710
D	92.18945	9	10.24327
SD	103.77783	18	5.76543
PD	30.05110	9	3.33901
SPD	154.32412	18	8.57356
ND	114.66799	9	12.74088
SND	127.77459	18	7.09858
PND	106.83949	9	11.87105
SPND	194.01382	18	10.77854
TOTAL	1471.57715	119	

Fs = 13.98 Fp = 6.38 Fn = 8.89

S -- Subjects (3)
P -- Phases (2)

N -- Noise Waveforms (2)
D -- Time Delays (20)

TABLE III

ANALYSIS OF VARIANCE -- 500 Hz (TONE IN NOISE)

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
S	811.31164	2	405.65582
P	114.81666	1	114.81666
SP	0.26566	2	0.13283
N	5.55109	1	5.55109
SN	160.84835	2	80.42417
PN	178.96887	1	178.96887
SPN	37.52939	2	18.76469
D	477.54138	19	25.13375
SD	737.06787	38	19.39652
PD	535.48217	19	28.18326
SPD	489.37664	38	12.87833
ND	390.46972	19	20.55103
SND	875.88391	38	23.04957
PND	363.00152	19	19.10534
SPND	556.43786	38	14.64309
TOTAL	5734.55079	239	

$F_s = 27.70$ $F_p = 7.84$ $F_{sn} = 5.49$ $F_{pn} = 12.22$

$F_d = 1.716$ $F_{pd} = 1.92$ $F_{snd} = 1.57$

S --Subjects (2)
P --Phases (2)

N -- Noise Waveforms (2)
D --Time Delays (10)

TABLE IV

ANALYSIS OF VARIANCE -- 250 Hz (TONE IN NOISE)

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES
S	111.13649	1	111.13649
P	573.11902	1	573.11902
SP	0.02970	1	0.02970
N	21.91891	1	21.91891
SN	17.22834	1	17.22834
PN	23.06778	1	23.06778
SPN	51.00016	1	51.00016
D	165.04559	9	18.33839
SD	125.44129	9	13.93792
PD	57.84261	9	6.42695
SPD	100.34234	9	11.14914
ND	88.05989	9	9.78443
SND	76.23924	9	8.47102
PND	138.05426	9	15.33935
SPND	52.81018	9	5.86779
TOTAL	1601.33496	79	

$F_s = 18.94$ $F_p = 97.67$ $F_n = 3.73$

$F_{pn} = 3.93$ $F_{spn} = 8.69$ $F_d = 3.12$

CHAPTER V

DISCUSSION

As reported in chapter IV, some similarities exist between the results of this study and the findings of previous researchers. Most notably, the cyclic nature of the threshold curves as a function of interaural time delay between noise waveforms has been re-demonstrated.* Due to several fundamental differences (especially, the use of frozen noise) between the research design of the present study and the methods employed in previous investigations, certain additional effects have been noted which throw light upon the basic mechanism.

Summary of major findings

Tables V and VI comprise a summary of the experimental results reported in chapter IV. A most prominent finding is that there are substantial disparities between the threshold functions for the different noise waveforms used in this study. The familiar, cyclic, MLD vs. τ_n, pattern presented in the literature (e.g. see figures 16-18, above) was, in a number of instances, not in evidence. This result was most apparent

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* The ordinate for the threshold curves in this study may be converted to MLDs by means of an additive constant.

TABLE V

SUMMARY OF EXPERIMENTAL FINDINGS --- 250 Hz

Experimental Result	Signal Phase	Noise I			Noise II		
		Sub. I	Sub. II	Sub. III	Sub. I	Sub. II	Sub. III
Peak #1 occurs at							
(tone leads noise) τ 2 msec.	S0	x			x	x	x
0 msec.	Sπ	x	x	x			x
(tone in noise) τ 2 msec.	S0				x	x	
0 msec.	Sπ		x				
Peak #2 at 4 msec. (tone leads noise)	Sπ				x		
(tone in noise)	Sπ		x				
Valley #1 occurs at							
(tone leads noise) τ 0 msec.	S0	x		x	x	x	x
2 msec.	Sπ	x	x	x	x	x	x
(tone in noise) τ 0 msec.	S0	x			x		
2 msec.	Sπ		x				
Valley #2 at 4 msec. (tone leads noise)	S0	x	x	x	x	x	x
(tone in noise)	S0						
Max. MLD(peak #1 minus valley #1) Range (dB)	S0 leading	10dB	8dB	2dB	7dB	3dB	2 dB
		40-50	42-50	44-46	37-44	42-45	46-48
	Sπ leading	7dB	5dB	5dB	7dB	4dB	5 dB
		38-45	38-43	43-48	40-47	40-44	43-48
	S0 (in noise)	3dB	6dB		2dB	2dB	
		43-46	46-52		43-45	44-46	
	Sπ (in noise)	4dB	5dB				
		46-50	46-51				
Thresholds were better for noise I than II (approx. dB)	S0 leading	higher	higher	similar			
		6dB	4dB				
	Sπ leading	same	same	same			
	S0 (in noise)	higher	higher				
		4dB	6dB				
	Sπ (in noise)	same	same				

TABLE VI

SUMMARY OF EXPERIMENTAL FINDINGS ---500 Hz

Experimental Result	Signal Phase	Noise III Sub. I	Noise III Sub. II	Noise III Sub. III	Noise IV Sub. I	Noise IV Sub. II	Noise IV Sub. III
Peak #1 occurs at τ= 1 msec.	S0	x	x	x	x	x	x
0 msec.	Sπ	x	x	x	x	x	x
Peak #2 occurs at τ= 3 msec.	S0	x					
2 msec.	Sπ		x	x		x	x
Peak #3 occurs at τ= 5 msec.	S0	x					
4 msec.	Sπ	x	x		x	x	
Valley #1 occurs at τ= 0 msec.	S0	x	x		x	x	x
1 msec.	Sπ	x	x	x			
Valley #2 occurs at τ= 2 msec.	S0			x			
3 msec.	Sπ		x			x	
Valley #3 occurs at τ= 4 msec.	S0	x	x	x			
5 msec.	Sπ		x				
Max. MLD(peak#1 minus valley #1) Range (dB)	S0	6 dB 46-52	12 dB 43-55	9 dB 41-50	5 dB 48-53	3 dB 51-54	7 dB 45-52
	Sπ	9 dB 48-57	11 dB 45-56	9 dB 43-54	7 dB 49-56	9 dB 49-58	5 dB 45-50
Peaks rise or fall with greater τ_n dB/x msec.	S0	rise 3dB/5	fall aft. peak#2 2dB/2	rise 2dB/5	rise 2dB/5		
	Sπ	fall 2dB/5	rise 3dB/5	rise 2dB/5			rise 2dB/5
Valleys rise or fall with greater τ_n dB/x msec.	S0	rise 4dB/5	rise 3dB/5			fall 2dB/5	
	Sπ		rise 5dB/5			rise 2dB/5	
Peaks relatively sharp or flat	S0	flat	sharp	flat			
	Sπ	flat	sharp	flat			
Valleys relatively sharp or flat	S0	sharp	sharp	sharp			
	Sπ	sharp	sharp	sharp			
Thresholds were better for noise III than IV (approx. dB)	S0	higher 2dB	higher 3dB	higher 2dB			
	Sπ	higher 4dB	higher 3dB	higher 5dB			

for the threshold functions of noise conditions II and IV. Such an effect could not be attributed to any randomness in the experiment because it was consistently observed for all three subjects. Another experimental finding was that noise waveforms I and III displayed consistently larger MLDs than did, respectively, noises II and IV. Threshold values were, in addition, generally better within noise conditions I and III than for II and IV.

For those MLD contours which did display a cyclic pattern (see the in-phase cases for 500 Hz) there was no characteristic gradual reduction in crest amplitudes as interaural time delay was increased. There was, instead, a noticeable rise in peak heights.

The majority of those curves which showed a clearcut presence of threshold valleys, possessed the expected 3 to 4 dB rise in valley height as τ_n increased. This is linked to the fact that the binaural noise is uncorrelated at very large values of τ_n and thresholds are found to be about three decibels better for the Nu condition than for the N0 case.

One final, more qualitative, effect noted in the results was the presence of relatively sharper peaks and valleys upon the MLD functions obtained in this study than evident from those displayed in the literature.

Discussion of findings

The question that arises, and will now be considered, is why differences exist between the results of the present study and previous researches.

The explanation is linked to the type of noise waveform used as the masking stimulus in the experiment.

In the past, some form of thermal noise source has typically served as the masking generator. The noise waveforms produced by such a device are a random admixture of components, forever changing in instantaneous amplitude, and quantifiable only in terms of statistical averages. With this type of noise, an experimenter was unable to specify the particular waveform delivered to a listener from trial to trial. A number of consequences, both theoretical and practical, emerge from this lack of specificity. Since, for example, the narrow band, filtered, output of a thermal noise source is essentially like a sinusoid which is slowly varying in amplitude and frequency, one could expect that for a particular trial, a listener might be presented with a noise and tone burst whose phase configurations were additive and gave rise to an energy increment. The very next trial might contain a tone burst that was out-of-phase with respect to the noise and would thus yield an overall energy decrement. From one observation to the next, the subject might use a simple energy alteration* criterion for detection of the signal. For large numbers of trials, the effects of these instantaneous increments and decrements in energy would be averaged out and experimental test results, as a consequence, would only mirror the operation of the auditory system in average terms. An examination of Plate VII (500 Hz case) reveals that the tone burst signal occurs within a portion of the noise IV waveform that is relatively less sinusoidal in shape than the analogous time delay position

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* Changes in the loudness of the percept arise from these energy changes.

of the tone burst within its noise III counterpart (Plate V). A similar relationship may be seen to exist between the tone burst and noise waveforms I and II (contrast Plate I with Plate III). As mentioned above, such a signal-noise configuration might, using thermal noise, exist solely for one test trial, to be followed by ever changing waveform combinations during subsequent trials. When taken together, these different conditions might average out and obscure the effect of the specific signal-noise pairsupon the auditory system. With the reproducible noise used in this research, however, the subject received the identical waveform for many trials and the observed test results (based upon the use of "frozen noise") showed substantial differences from the predictions and data of previous studies.

Much of the published data suggest some form of linear correlation model to account for the behavior of the binaural mechanism. Such models depend upon statistical averages of the noise and of the signal-plus-noise. One possibility why these models have been effective predictors of MLD data could be that the typical MLD experimental conditions, using random noise, fluctuate between trials. The resulting body of data which is extracted from these trials consists, itself, therefore, of statistical averages of theshold values. The findings of this study tend to indicate that more than a simple linear correlation process may be involved in binaural masking level differences. Consider, for example, the predictions of a linear correlation (averaging) model for the case, described above, wherein the 500 Hz signal occurred in a relatively less periodic portion of waveform IV than it did for waveform III. Such a model would predict little or no difference in performance between these two instances because it is the average over the entire noise burst (and not any individual portion of the waveform) that is important to the linear system. As a demonstration of this principle, consider the following signal and noise waveforms which are represented in binary fashion as a series of zeros and ones:

0110100011010011010010111	← To this random noise burst one ADDS
0000010101000000000000000	← This periodic tone burst.
0110110112010011010010111	The sum of these waveforms is then CORRELATED
0000010101000000000000000	With another tone which is in-phase with respect to the first signal.
0000010102000000000000000	← The resultant correlation value is 4/25.
0110100011010011010010111	
0000010101000000000000000	The process is repeated with the second tone shifted in time by one half period.
0110110112010011010010111	
0000001010100000000000000	
0000000010000000000000000	← The resulting correlation function is now 1/25.

One may see that when the two tones are antiphasic, the correlation function is much smaller than for the in-phase case. The difference between these correlation values is an indication that a signal was, indeed, present within the noise. If one repeats the entire procedure, but assigns the first tone to some other portion of the noise waveform, one observes that there is hardly any difference between the correlation products in this example and the previous signal-noise combination. This is the case because we have averaged over the same noise burst in each case.

Example 2—Tone added to different part of noise.

0 1 1 0 1 0 0 0 1 1 0 1 0 0 1 1 0 1 0 0 1 0 1 1 1

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 1 0 0 0 0 0

---

0 1 1 0 1 0 0 0 1 1 0 1 0 0 1 2 0 2 0 1 1 0 1 1 1

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 1 0 0 0 0 0

---

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 0 2 0 1 0 0 0 0 0 Correlation function $\simeq$ 5/25

0 1 1 0 1 0 0 0 1 1 0 1 0 0 1 1 0 1 0 0 1 0 1 1 1

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 1 0 0 0 0 0

---

0 1 1 0 1 0 0 0 1 1 0 1 0 0 1 2 0 2 0 1 1 0 1 1 1

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 1 0 0 0 0

---

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0

Correlation function $\simeq$ 1/25

One of the major findings of this experiment was that the relative position of the tone burst within the noise does make a difference to the threshold functions. In particular, when the tone occurred during a portion of the noise that was relatively sinusoidal in appearance (as for noises I and III) the MLD function that resulted was similar to the ones which have appeared in the literature. If, however, the tone burst occurred within a relatively aperiodic portion of the noise waveform (as with noise conditions II and IV) the familiar MLD pattern was lost.

These data, the author suspects, indicate that the detection mechanism is heavily dependent upon the shape of the waveform itself, and that a linear averaging process such as correlation may be inadequate to describe the auditory system. It is, perhaps, appropriate for models which are based upon correlation processes to contain some form of non-linear operation.

The Problem of Detection Criteria

Because the waveforms presented to the subjects were invariant from trial to trial, a problem emerged in this study which had not affected prior research and may account, in part, for the high variability in subject performance observed in these experiments. As mentioned above, the typical listening cue in MLD experiments has been some form of energy detection factor. In this research, however, subjects reported the presence of additional cues stemming, undoubtedly, from the fact that the identical waveforms were presented thousands of times to the listener. It became possible to recognize and even memorize, the quality or pattern of each noise burst that was linked to the particular shape of its waveform. In addition, after much exposure, it became possible to detect a slight change in the pitch of the stimulus-plus-noise percept. All three subjects also reported ease in detecting the first test condition(250 Hz, tone leading noise) due to the presence of a duration cue. These diverse factors would occasionally give rise to an abrupt threshold shift (substantially in excess of the range of the data under stable conditions)* If the subject's response pattern consistently

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*Trial to trial fluctuations in criterion or in sensitivity(due perhaps to remained at this new level, it was presumed that the listener had changed his detection criterion. Only the better threshold values were accepted because they represented the limiting performance of the subject. All observers had been uniformly instructed to employ a simple loudness cue, but it was found that maintaining this criterion was far more difficult than at first anticipated.

Areas for Further Investigation

It is clear from the results of this study that two new factors have been isolated and call for further exploration. The instantaneous phase relationships between the signal and noise waveforms are now seen to be important along with the manner in which the noise waveform changes as a function of time. Both of these factors could be better understood if a wide variety of frozen noise bursts with specially selected characteristics were used in future experiments.

It might prove worthwhile for future studies to make a detailed comparison of the results of experiments such as the present study and those in which tone-on-tone masking has been used (e. g. Hafter and Carrier, 1970; Wightman, 1969; and Yost, 1972).

Masking level differences may provide fruitful applications to Audiology. It appears that MLDs are linked to some specific level in the auditory system and there is reason to believe that MLD values would be differentially sensitive to lesions in different parts of the hearing mechanism. The author envisages, however, that the complexity of the listening task and the many criterion difficulties with MLDs may limit its diagnostic effectiveness.

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shifts in attention to different decision variables) may be confounded with other forms of internal noise. This may make interpretation of results difficult.

APPENDIX I

Cross correlation involves the comparison of one signal to a time delayed second signal. Autocorrelation refers to a special case of cross correlation wherein one signal input is compared with a time-delayed version of itself.

The autocorrelation function may be rigorously defined as:

$$C_{AA}(\tau) = \lim_{Ti \to \infty} \frac{1}{2Ti} \int_{-Ti}^{+Ti} f_{A}(t) f_{A}(t-\tau)\, dt$$

Where:

$C_{AA}(\tau)$ = the auto correlation function.

$f_{A}(t)$ = the input signal.

τ = the time delay.

$f_{AA}(t-\tau)$ = the time delayed version of the input signal.

Ti = the time period over which the intergral is computed.

The cross correlation function may be rigorously definedas:

$$C_{AB}(\tau) = \lim_{Ti \to \infty} \frac{1}{2Ti} \int_{-Ti}^{+Ti} f_{A}(t) f_{B}(t-\tau)\, dt$$

Where:

$C_{AB}(\tau)$ = the cross correlation function.

$f_A(t)$ = the first input signal.

$f_B(t-\tau)$ = the second input signal delayed with respect to the first signal.

APPENDIX II

STIMULI WAVEFORMS

Upper trace ---- 250 Hz tone burst signal(note that for 6 msec. delay the tone leads the noise in time).

Lower trace ---- Output of delay line showing narrow band noise delayed with respect to tone on opposite channel.

Noise Waveform I

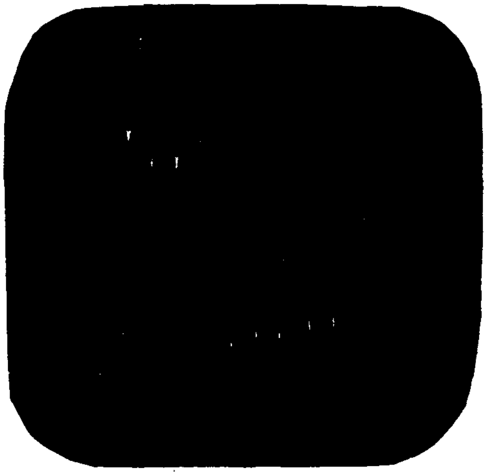

Plate I -- 0 msec. delay

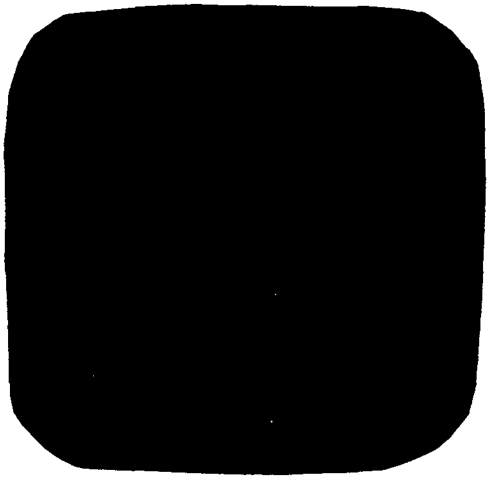

Plate II -- 6 msec. delay

Noise Waveform II

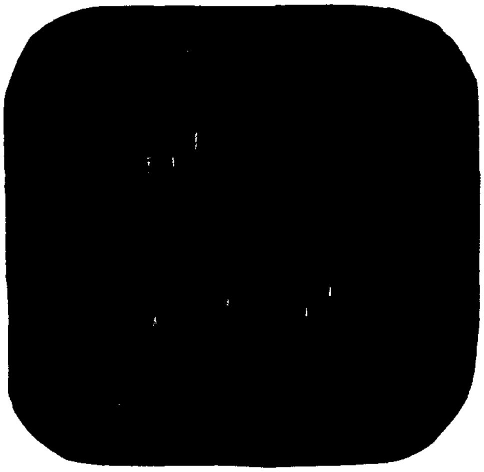

Plate III -- 0 msec. delay

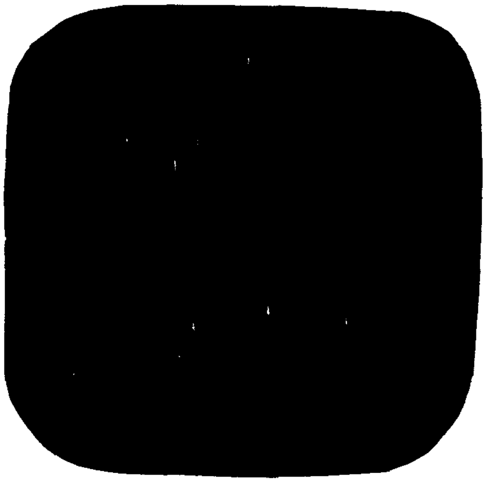

Plate IV -- 6 msec. delay

Upper trace ---- 500 Hz tone burst signal(note that tone is always embedded within noise).
Lower trace ---- Output of delay line showing narrow band noise delayed with respect to tone on opposite channel.

Noise Waveform III

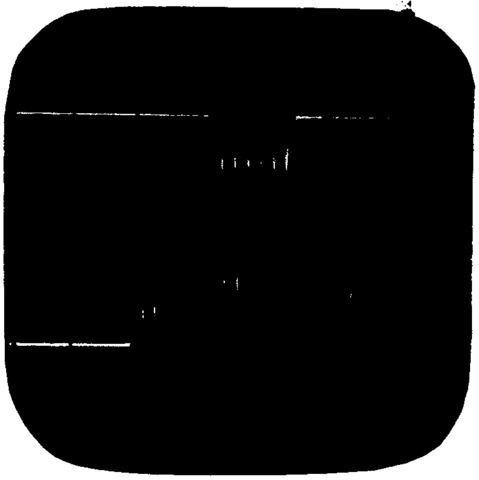

Plate V -- 0 msec. delay

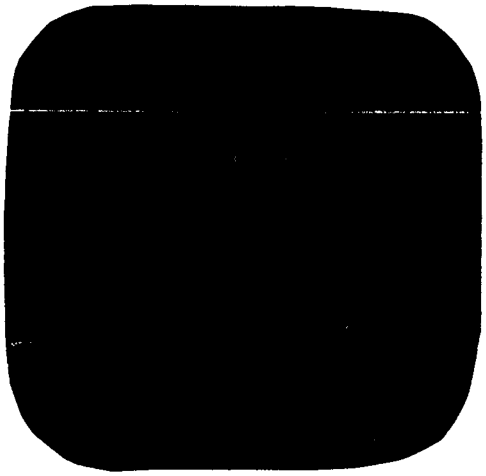

Plate VI -- 6 msec. delay

Noise Waveform IV

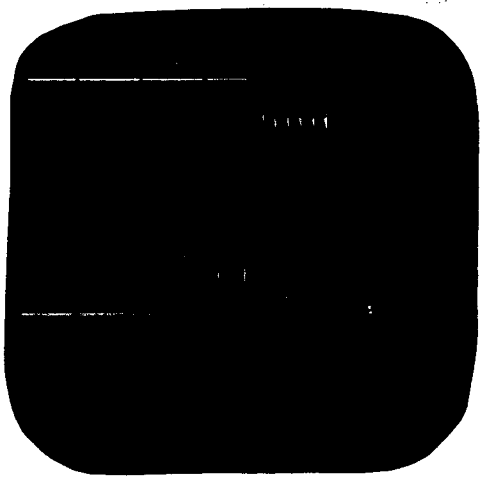

Plate VII -- 0 msec. delay

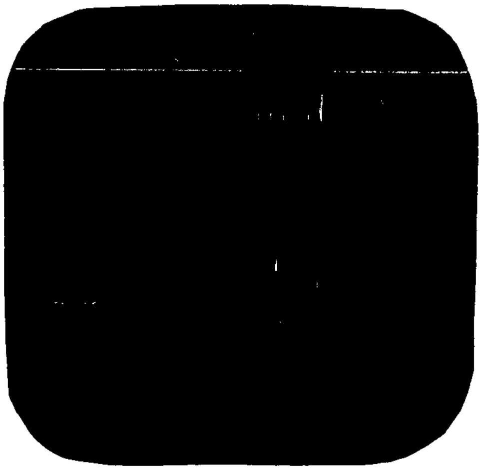

Plate VIII -- 6 msec. delay

Upper trace ---- 250 Hz tone burst signal(note that tone is always embedded within noise).

Lower trace ---- Output of delay line showing narrow band noise delayed with respect to tone on opposite channel.

Noise Waveform I

Noise Waveform II

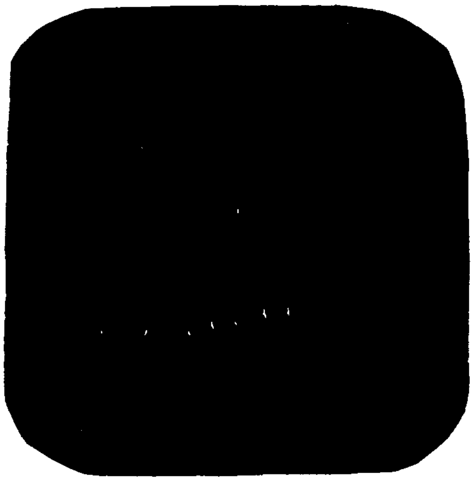

Plate IX -- 0 msec. delay

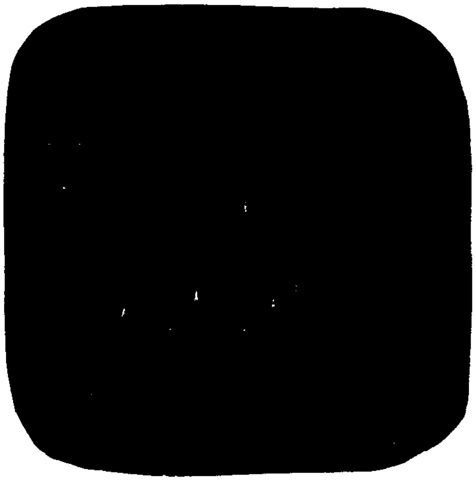

Plate XI -- 0 msec. delay

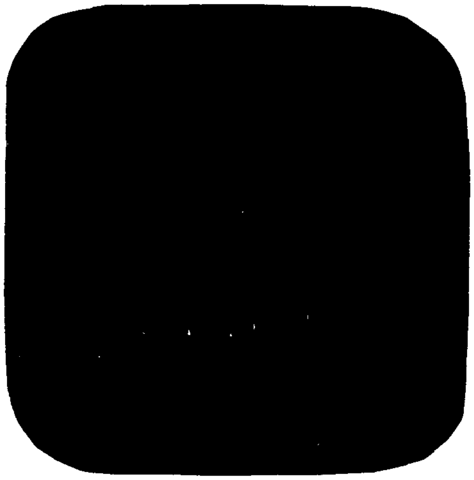

Plate X -- 6 msec. delay

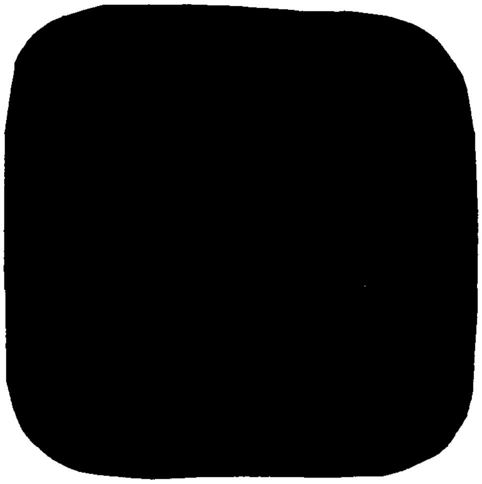

Plate XII -- 6 msec. delay

Upper and Lower traces display the electrical noise inputs to the left and right headphones. No time delay has been introduced to the noise waveforms (note the slight differences between the two channels due to small disparities in the response of the narrow band filters).

Noise Waveform I

Plate XIII -- 250 Hz

Noise Waveform II

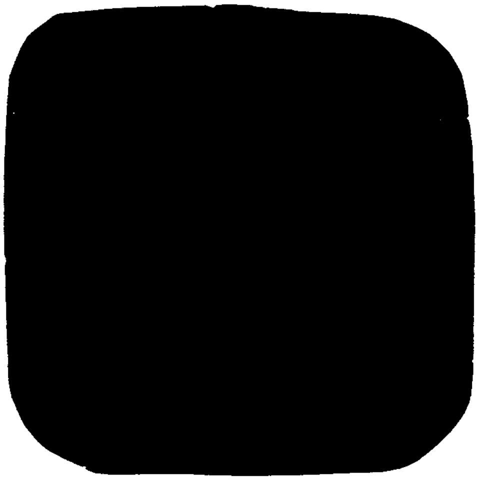

Plate XIV -- 250 Hz

Noise Waveform III

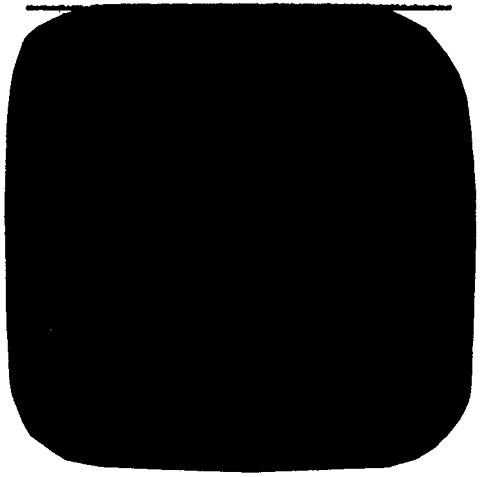

Plate XV -- 500 Hz

Noise Waveform IV

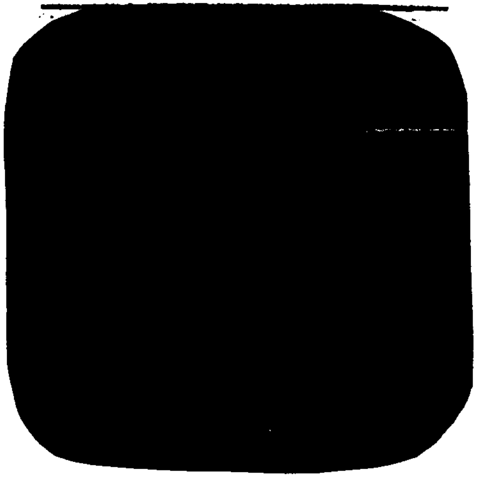

Plate XVI -- 500 Hz

ELECTRICAL INPUT TO HEADPHONES

Lower trace displays noise waveform ($f_c \cong 500$ Hz) to right channel (delayed 6 msec. with respect to waveform in opposite channel).

Noise Waveform III

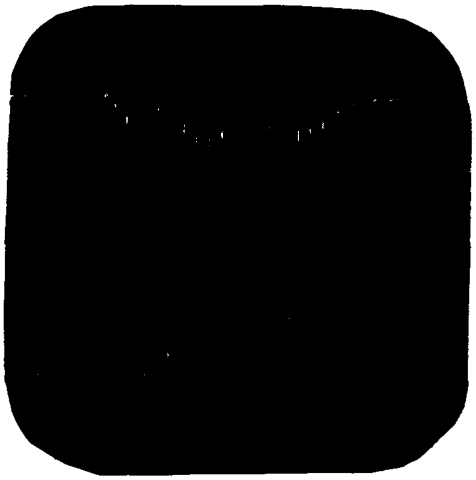

Plate XVII -- 6 msec. delay

Noise Waveform IV

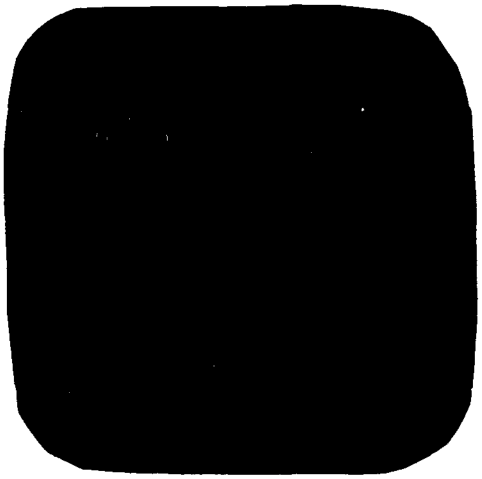

Plate XVIII -- 6 msec. delay

ELECTRICAL INPUT TO HEADPHONES
500 Hz TONE PLUS NOISE

Noise Waveform III

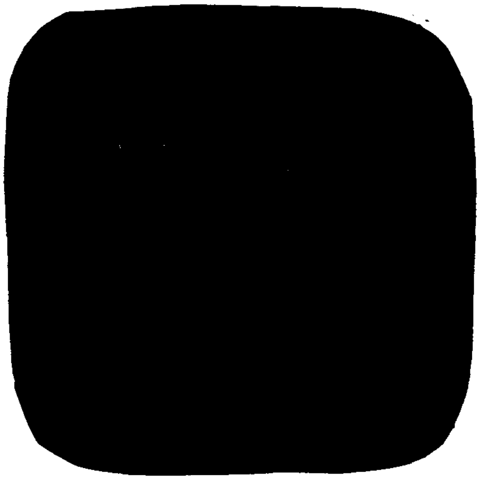

Plate XIX-- 0 msec. delay

Noise Waveform IV

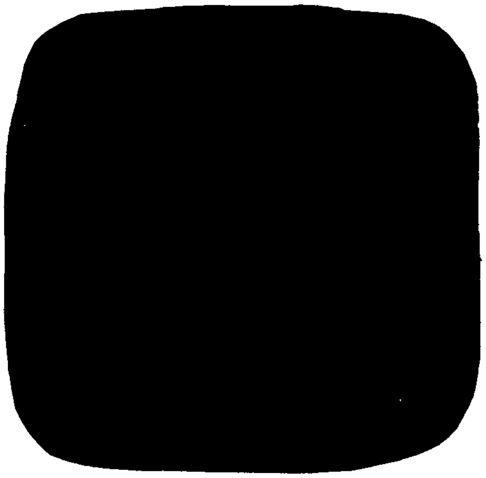

Plate XX -- 0 msec. delay

ACOUSTIC OUTPUT OF HEADPHONES

NOISE WAVEFORM I -- $F_c = 250$ Hz

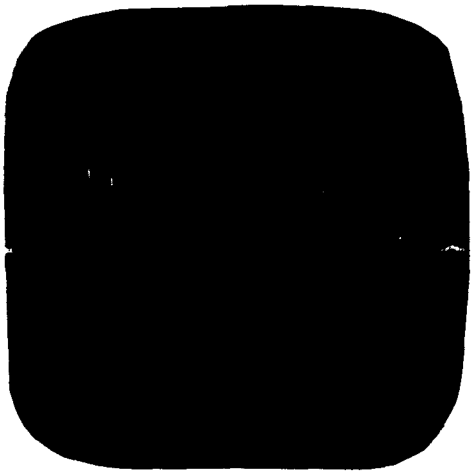

Plate XXI -- Left headphone

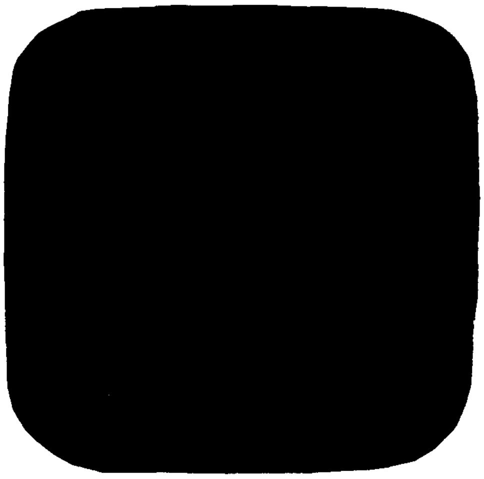

Plate XXII --Right headphone

NOISE WAVEFORM II -- $F_c = 250$ Hz

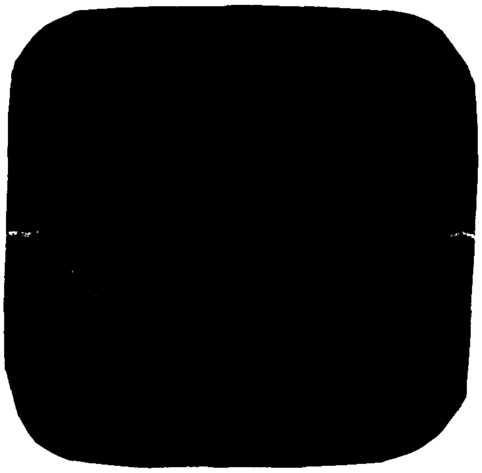

Plate XXIII --Left headphone

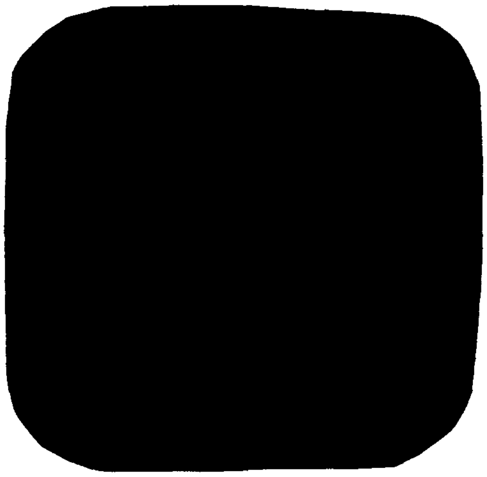

Plate XXIV --Right headphone

ACOUSTIC OUTPUT OF HEADPHONES

NOISE WAVEFORM III -- $F_c = 500$ Hz

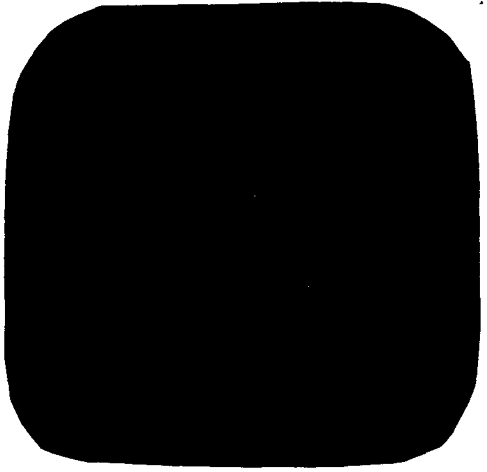

Plate XXV --Left headphone

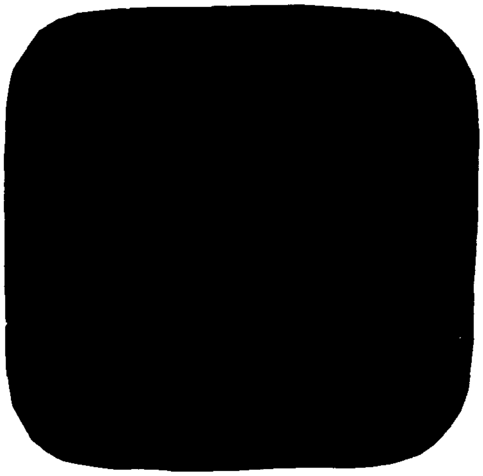

Plate XXVI-Right headphone

NOISE WAVEFORM IV- $F_c = 500$Hz

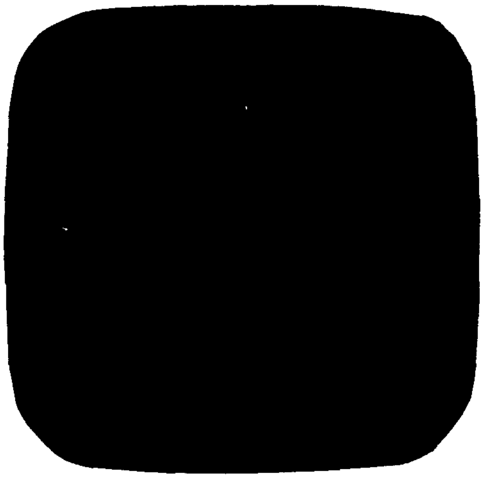

Plate XXVII -Left headphone

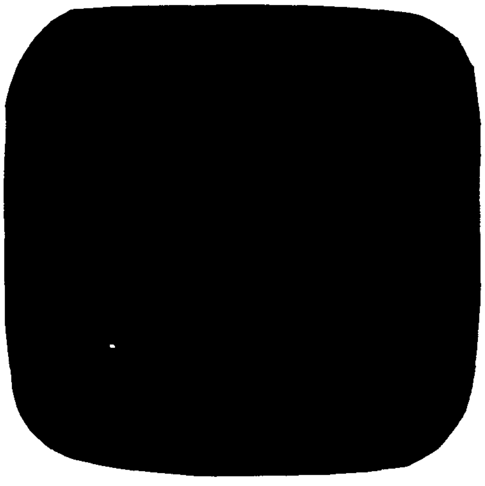

Plate XXVIII-Right headphone

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