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The present study was undertaken to determine the role of several variables (signal duration, frequency, and noise intensity) in producing the masking-level difference (MLD). A further rationale was to suggest clarifying evidence for discrepancies reported in the literature regarding low frequency signals. MLD was defined as the difference between threshold (75-80% correct responses) values for two listening conditions. Both listening conditions consisted of binaural noise (NO) with either a monaural (SM) or binaural (SO) signal. The MLD (measured in dB) represented the difference obtained in a comparison between threshold values for NO SO and NO SM.

Data were collected using the two-alternative forced choice procedure (2ATFC) in a repeated measures design. Two males and one female (ages: 21-33 yrs.), who were trained and unpaid, served as the subjects. S's task was to indicate (by pushing a response button) which of the two noise intervals contained a randomly presented signal. The experimental parameters of interest were: 1) signal frequency: 150 and 200 cps; 2) noise spectrum level: 5 and 35 dB; and 3) signal duration: 20, 60, and 100 msec. Each S received a different random schedule of all possible combinations of these parameters (for NO SO and NO SM). The dependent variable was MLD.

Significant relations were found for frequency, intensity, and the frequency-intensity interaction. Duration was not significant. More specifically the results indicated that the magnitude of the MLD at low frequencies is strongly dependent on the spectrum level of the masker. It was also clear that the MLD resulting from a high (35 dB) spectrum level was different from the MLD at a low (5dB) masker and the difference was strongly related to frequency. At the high spectrum level, the MLD at 200 cps exceeded those at 150 cps by about 5 dB; whereas, the difference was approximately 1 dB for the low spectrum level. Duration was not shown to be an important variable for predicting the MLD at the frequencies and masker levels studied.

The results were discussed in terms of: 1) the internal noise hypothesis; 2) masked thresholds for duration; and 3) two theories of binaural hearing. Two general conclusions were offered. First, MLD probably decreases as the frequency is lowered below 200 cps (although this is strongly dependent on the masker spectrum level). Second, the internal noise hypothesis was shown to be inadequate as a plausible interpretation of the present results.

Masking-Level Difference (MLD) as
a Function of Noise Spectrum
Level, Frequency, and
Signal Duration

by

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APPROVAL SHEET

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CHAPTER I

INTRODUCTION

This thesis deals with a psychophysical phenomenon known as "masking-level difference" (MLD). An overview of the research stimulated by this aspect of binaural analysis will be reviewed prior to discussing the methodological procedures and results of the present study. The review emphasizes MLD as a function of: signal frequency, duration, noise intensity, and interaural correlation. The two prevailing theoretical accounts of MLD will also be examined.

Binaural analysis is the ability, according to Green and Henning (1969), to analyze complex waveforms depending on the differences in the waveforms arriving at the two ears. This functional ability consists in the selection of some specific acoustic signal out of the other unwanted sounds ("cocktail party effect"). In other words, binaural analysis allows a listener to concentrate on speech from one talker, suppressing that of others in his environment. Carhart, Tillman, and Johnson (1967), for instance, have indicated two factors enabling the two-eared listener to cope with conversational chaos more effectively than a monaural listener. First, he is not forced sporadically to depend on an adversely shadowed (by the head) ear, resulting in a 13 dB advantage. Second, the release from masking due to two ears (binaural unmasking) provides a continuous advantage of from 3 to 7 dB.

If the waveform that a person wants to hear is considered the "signal" and all additional acoustic stimuli "noise", various binaural conditions can be delineated. Research in this area has outlined two basic experimental conditions in terms of the phase of the signal and the noise. First, the homophasic condition consists of the noise and the signal both having the same interaural phase relations. The antiphasic condition, on the other hand, consists of the noise and signal having different interaural phase relations. Interaural phase is the relation (in terms of lead or lag) of a sound wave in one ear to a corresponding sound wave in the other.

In general, the difference between the threshold of the signal in the antiphasic versus the homophasic condition has been found to be as much as 25 dB for narrow band width noise (7 cps wide) and short duration (10 msec) signal (Green and Henning, 1969). The difference between signal levels necessary for constant detectability is the masking-level difference (MLD), where the detection of a signal is generally found to be less difficult in the antiphasic than the homophasic conditions.

The various phase conditions found throughout the literature (and used in this paper) can be summarized as follows:

SO - signal in-phase at the two ears

SM - signal monaural, no signal at the other ear

Sπ - signal at one ear 180° out-of-phase with signal at the other ear

NO - noise in-phase at the two ears

Nπ - noise waveform at one ear is inverted with respect to waveform at the other ear

NU - noise uncorrelated at the two ears

Thus, SO NO (or NO SO) is homophasic, while Sπ NO (or NO Sπ) is antiphasic. The MLD is simply the difference between these two conditions (expressed in decibels) for a constant detectability level. Similarly, comparisons between conditions, such as: NU Sπ-NU SO, Nπ SO-NO SO, and NO SO-NO SM, etc., have also been studied in terms of MLD. It is to be emphasized, then, that while MLD is most obviously evident in a comparison between antiphasic and homophasic conditions, other combinations of the above conditions have been researched. An additional phase condition, the heterophasic, concerns uncorrelated noise (NU) and a signal in or out-of-phase.

The accepted distinction between a masker and a maskee will be maintained throughout the paper according to the following definitions. Masking is the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. Thus, masking represents the inability of an individual to analyze a sound into its components. The masker, then, is that sound (typically "white noise") against which an individual is asked to make detectability judgments concerning the maskee, a signal (typically a sinusoid).

Most of the research in this area has been undertaken using one of several basic methods. They may be categorized as follows: 1) the method of constant stimuli; 2) the method of limits; 3) the signal detection method (Green and Swets, 1966); and 4) the two-alternative temporal forced choice procedure (2ATFC).

A study by Robinson and Jeffress (1963) and data from Blackwell (1953) show that, in general, the 2ATFC method yields data which agree in the main with those obtained by the method of constant stimuli; furthermore, the former is less variable. All studies discussed in this paper use one of these standard methods to determine the constant detectability level of the listener (with one noted exception).

<u>MLD as a Function of Signal Frequency</u>

Before discussing the specific results of studies relating MLD to signal frequency, perhaps it is useful to outline two general findings: 1) from about 250 cps MLD is large at low frequencies and grows smaller as the frequency of the signal increases; 2) below about 250 cps MLD seems to decrease as the signal frequency also decreases (Green and Henning, 1969).

The first systematic approach to the relationship between frequency and masking appeared with the publications of Licklider (1948a) and Hirsh (1948a, 1948b) on the masking of signals by white noise. Both of these studies, one for speech (Licklider) and the others for pure tones (Hirsh), demonstrated that the detection of a binaural signal could be greatly improved if the phase of either the signal or noise (but not both) were reversed at one ear relative to the other.

Hirsh was attempting, at the time, to investigate interaural summation and inhibition as they related to signal phase. Threshold meausures were obtained using the method of adjustment. The signal was presented on every trial against a wide band noise (spectrum level = 59.1 dB). Signal (tonal) frequencies were: 100, 200, 500, 1000, 2000, and 5000 cps. Threshold values for the listening conditions (NO SM, Nπ SM, NO SO, Sπ Nπ, NO Sπ) were then found at all six of the frequencies. The results indicated that when a signal and a noise are presented to both ears, and when one or the other is reversed in phase (antiphasic), the signal could be detected at a level of approximately 15 dB lower than when both are in phase (homophasic). This result has been repeatedly reported by a larger number of investigators (Green, 1965; Jeffress, Blodgett, Sandel, and Wood, 1956; Schenkel, 1960; Webster, 1951). Although Hirsh did not discuss these results in terms of MLD, based on the previous definition, MLD was largest at low frequencies (except below

200 cps) and decreased as signal frequency increased to approximately a constant 3 dB difference above 2000 cps. Further, this homophasic-antiphasic difference (MLD) reached a maximum of about 15 dB for a tone of 250 cps.

It was not until 1951 that the term masking-level difference entered the literature. The term was introduced by Webster (1951) who felt that previous research which had discussed changes in audibility with shifts of interaural phase in terms of summation, facilitation, inhibition, or interference, tacitly implied a baseline from which to make the measurements. He felt that an unequivocal definition of a baseline was necessary and chose to use the difference in level of masking (i.e., the difference in the measured level of the maskee at masked threshold in dB) between NO Sπ and NO SO conditions to operationalize the difference found between homophasic and antiphasic conditions.

Webster also found that the effects of the masker declined with increased signal frequency using the constant method with two types of signals: tonal and narrow band noise. He summarized the relation he found between frequency and masker as follows: 1) a peak occurred in the neighborhood of 250 cps; 2) from 250 to 1420 cps (for narrow band signals) and from 250 to 1900 cps (for tonal signals) MLD declined progressively; 3) below 250 cps MLD tended to decline; 4) from 1420 (or 1900) cps to 6600 cps, MLD was small (2-5 dB for most observers).

The effects of wide band and narrow band noise maskers at high intensity (96 dB overall) were studied by Hirsh and Burgeat (1958). The dependence of binaural masked thresholds on the interaural phase relations of both the signal and noise was already known. The question was whether this dependence extended to the remote masking of low frequency tones by a high frequency band of noise. They demonstrated that a phase reversal of the tone at the two ears had the same effect in remote masking (a high frequency band of noise masks tones that are below and remote from the lower cutoff frequency of the band of noise) as in ordinary masking. However, a phase reversal of the high frequency band at the two ears produced changes in the masked threshold midway between those encountered in ordinary masking and no change at all.

Wilbanks and Whitmore (1968) extended the findings of previous investigators by using monaural signals. Two variables were manipulated: signal frequency, and noise correlation. They found that the functions relating the size of the MLD to the magnitude of the noise correlation and frequency were quite similar to those found with binaural signals, with the largest difference at 250 cps and decreased MLD on either side of 250 cps. These results for monaural signals in addition to those of previous investigators for binaural signals demonstrate that the inverse functional relationship between MLD and signal frequency (from 250 cps to 2000 cps) is well established.

The area along the low frequency end of the function is not so clear. It has been discovered that the size of the MLD does not continue to increase as the frequency of the signal is lowered. The increase continues down to approximately 250 cps. Below about 200 cps some investigators report that MLD seems to decrease as a function of signal frequency (Dolan, 1968). However, agreement on the extent of the decrement is not particularly uniform. For instance, in the region of 100 cps Hirsh (1948b) found an MLD of about 5 dB, as has Schenkel (1964). On the other hand, evidence gathered by Webster (1951) suggests an MLD of approximately 15 dB at 100 cps. Finally, Rabiner, Laurence, and Durlach (1966) measured an MLD of 8 dB at 160 cps.

Green and Henning (1969) suggest a number of possibilities for these discrepancies at low signal frequencies.

First, the intensity of the noise may be an important variable at low frequencies. Dolan (1968) has obtained data at signal frequencies of 150 cps and 300 cps as a function of the intensity of the background noise level (signal duration = 150 msec). He found MLDs (re NM SM for NO $S\pi$) of about 10 dB at 300 cps and 5 dB at 150 cps when a low noise level (20 dB spectrum level) was used. At higher noise levels, for example a spectrum level of 65 dB, both signal frequencies resulted in MLDs of approximately 15 dB. The results indicate that the dependence of MLD size on spectrum level varies as a function of the signal frequency. The size of the MLD at 150 cps was much more sensitive to changes in the masker spectrum level than was the MLD at 300 cps. An additional finding concerned the size of the MLD in the NO SO condition relative to NM SM at 150 cps and 300 cps as a function of spectrum level (20, 35, 50, and 65 dB). At a signal frequency of 300 cps, the MLD at NO SO was negligible (less than 1 dB) at all spectrum levels. At 150 cps, however, the MLD increased to about 3.5 dB when the spectrum level was decreased to 20 dB.

Second, Dolan (1968) suggests a source of difficulty when comparing binaural signal detection at low frequencies. Large changes in interaural intensity and phase can easily occur at low frequencies with slight changes in the position and seal of the headphones on the ears. These changes necessarily lead to an increased variance and poorer performance as signal frequency is lowered. Obviously, then, in addition to differences in spectrum level of the masker, laboratories, and psychophysical procedure, a portion of the variance in the findings of different researchers at these low frequencies can be attributed to this factor.

Third, it is clear that size of MLD may vary within a certain range depending on the various conditions (homophasic, antiphasic, heterophasic, monaural, binaural, etc.) that are compared. A hierarchy of these various conditions based on the data of Hirsh (1948b) and Jeffress, Blodgett, Sandel, and Wood (1956) is the following. In descending order of difficulty, the conditions can be ordered thus: NM SM (most difficult detection), NU SM, $N\pi$ $S\pi$, NO SO, NU $S\pi$, $N\pi$ SM, NO SM, $N\pi$ SO, and NO $S\pi$ (easiest detection).

A simplified explanation for this hierarchy is offered by Diercks and Jeffress (1962). First, the homophasic conditions provide no interaural interaction to improve the signal detection. The same is true of the condition where both noise and signal are monaural (NM SM). These are, therefore, the worst conditions. Second, $N\pi$ and NU make for more difficult detection than NO because the noise is more diffuse and thus locating the signal is more difficult. Third, the conditions in which the signal is monaural and the noise is either in-phase (NO), reversed in-phase ($N\pi$), or uncorrelated (NU), provide some, but not much, interaural assistance in signal detection. They are the poorest of the non-homophasic conditions. Fourth, the antiphasic condition NO $S\pi$ provides the greatest interaural assistance in signal detection of all conditions involving a tonal signal and a noise masker. $N\pi$ SO provides similar interaural assistance.

MLD as a Function of Signal Duration

Finally, signal duration may be a contributing factor in the decrement of MLD at low frequencies, although this role is uncertain. Jeffress, Blodgett, and Deatherage (1952), for instance, have found somewhat larger (3.5 dB)

MLDs than Hirsh (1948b) using a 500 cps, 150 msec signal. Hirsh's signal was 1000 msec in duration. Later data (Jeffress, Blodgett, Sandel, and Wood, 1956) presented to implicate signal duration in this discrepancy was the following. They found an MLD (re NO SO for NO Sπ) of 13 dB for a 500 msec signal and 16 dB for a 25 msec signal (spectrum level = 58 dB). These results, taken at 500 cps and those to follow, are merely suggestive of the influence of signal duration on MLD in general since data are lacking at the lower frequencies.

A systematic study of the effects of signal duration on MLD was performed by Blodgett, Jeffress, and Taylor (1958). This study represented an extension of a finding by Garner and Miller (1947) that showed (for the NO SO paradigm) a linear relationship between the logarithm of the signal duration and the masked threshold through a range from 12.5 msec to 200 msec. In other words, an increase in duration by a factor of 10 was associated with a 10 dB decrease in threshold.

Blodgett, et al. (1958) employed a 500 cps signal (rise-decay time 0.5 msec and 60 dB spectrum level for a wide band noise) for these conditions: NO SO, Nπ Sπ, NM SM, NU SO, NU Sπ, NO SM, Nπ SO, and NO Sπ. The method of constant stimuli was used. The signal durations examined were: 5, 10, 15, 20, 25, 50, 100, 200, 300, and 500 msec. The results indicated a hierarchy of conditions where the data, when plotted as a logarithmic function of duration, were roughly parallel for each condition and negative in slope. Rather sharp changes in slope were noted at 15 and 50 msec, although in general, MLD increased (2-5 dB) as duration decreased from 500 to 5 msec.

Green (1966a) has reported similar findings. Using the NM SM, NO SM, and NO $S\pi$ paradigms, the duration for a 250 cps signal (rise-decay time of 2.5 msec) was 10, 100, or 1000 msec. A wide band noise with a spectrum level of 55 dB served as the masker. The data were collected in a 2ATFC procedure. The results showed that the signal level needed to obtain about 75% correct detection was some 9 dB higher in the NM SM condition than the NO SM and about 16 dB higher in the NM SM than in the NO $S\pi$. Even though the signal duration was varied by a factor of 100, the change in magnitude of the interaural phase effects was small. Specifically, the MLD is about 2 dB larger at 10 msec than at 100 msec and 1000 msec. These results are consistent with those of Jeffress, Blodgett, and Taylor (1958), in so far as MLD tended to increase with decreases in signal duration.

Both studies, however, have failed with extreme values to find the simple linear relationship suggested by Garner and Miller (1947) and indicated that the same spread of energy (signal energy/noise power density) does not affect the listening conditions NO $S\pi$, NO SM as much as the homophasic (NM SM). In other words, in Green's (1966a) study, both former conditions demonstrated almost perfect power summation from 100 msec to 10 msec. In the homophasic condition, however, about 2 dB more energy was needed at 10 msec than at 100 msec to maintain the same level of detectability. This departure from perfect power summation for short duration signals is well established (Garner, 1947; Green, 1957; Hamilton, 1957) and presumably due to the spread of energy caused by gating the signal for a very short duration.

Wightman (1969) has examined the effects of signal duration (10, 124, and 500 msec) for S0 and Sπ 250 cps signals under the following conditions: 1) gated masking: the narrow band masker (a 250 cps sinusoid; 12 msec rise-decay time; SPL = 70 dB) was turned on and off with the signal (i.e., phase locked); 2) phase difference (α) between the signal and masker was 0° and 90° (as computed from measurements of the amplitude of the signal-plus-masker waveforms at the left and right earphone under Sπ conditions). The 2ATFC method was used. The results indicated the following. At all three durations MLD was essentially zero in the $\alpha = 90^\circ$ condition. For $\alpha = 0^\circ$, however, a negative MLD was observed at each duration. At 120 msec, the MLD was -10 dB, while it was -6 dB at 10 msec and -1 dB at 500 msec. It appears then, that a negative MLD also decreases (becomes more positive) as duration increases, although the form of this function is not altogether clear, being based on only three values.

Additional findings using continuous maskers (the masking tone, 250 cps, was on continuously throughout a session) and gated maskers (the masking tone was turned on and off with the signal, only during the two observation intervals of each trial) were also obtained. Seven values of α were studied: $0°$, $15°$, $30°$, $45°$, $60°$, $75°$ and $90°$. The signal duration was 124 msec. For the continuous masker condition MLD was 12 dB at $\alpha = 90°$ and decreased as α approached $0°$ (MLD = -3 dB). In the gated condition, negative MLDs were found for all values of signal-masker phase between $0°$ and $90°$ with -10 dB at $\alpha = 0°$ and negligible effect at $\alpha = 90°$. Thus in contrast with the bulk of the literature, with continuous and particularly gated tonal maskers, of the same frequency as the signal, $S\pi$ signals were more difficult to detect than SO signals. In gated masking conditions, cues associated with interaural time and intensity differences for $S\pi$ appear to degrade performance. McFadden (1966) has similarly demonstrated performance that is degraded by 4-6 dB when gated masking conditions are compared with continuous ones for NO $S\pi$, $N\pi$ SO, NO SM, and $N\pi$ SM.

<u>MLD as a Function of Noise Intensity</u>

Research in this area of the MLD phenomena has concentrated upon the dependence of MLD on the relative and absolute levels of sound in the two ears. Considering first, relative level of sound (both signal and noise are attenuated by the same amount for a given ear), we find that research has concentrated on binaural noise and monaural signal listening conditions. Typically, investigators have varied the attenuation level of the nonsignal ear, with the general result that as the noise level decreased so did MLD in a nearly linear fashion.

The data reported, in general, reflect back to the original results found by Hirsh (1948a) that detectability was greatest when the level of the noise masker at the two ears was equal, and decreased as the level of the masker at the nonsignal ear was attenuated.

Since various investigators have done basically the same thing (i.e., contrast NO SM with Nπ SM while ranging the noise level in the nonsignal ear), employed similar methods (2ATFC or constant method), and found similar results, a study by Egan (1965) will serve to characterize their findings. These discoveries will then be compared with the binaural experiments on absolute noise level of McFadden (1968).

Egan (1965) employed the 2ATFC procedure and a monaural signal of 500 cps presented to the right ear. The masker was binaural noise with a spectrum level of 45 dB. The noise in the left, nonsignal ear (NL) was systematically decreased from an intensity equal to the noise in the right ear (NR) down to an intensity of zero (NM SM). Thus, the independent variable was the ratio NL/NR. The ratios used for NO were: 0, -10, -20, -30, -40, and -∞ dB; for Nπ they were: 0, -15, and -30 dB. The experimental question involved how much release from masking would be obtained when the noise in the nonsignal ear was weaker than in the signal ear.

The results showed that when the correlation of the binaural noise was 1.0 (NO), an MLD of 5.8 dB was obtained even when the amplitude of NL was 1/10th of NR. An MLD was found even when the noise in the left ear was 40 dB down from that in the right ear. The MLD for Nπ SM was less than for NO SM, and that for NU SM nearly zero. In other words, MLD reached a maximum when the level of the masker at the nonsignal (left) ear was the same as the level of the masker at the signal ear, but steadily decreased in a near linear manner as the masker at the signal ear was attenuated. Several studies (Blodgett, Jeffress, and Whitworth, 1962; Dolan Deatherage, and Hafter, 1965; Weston and Miller, 1965) have reported similar findings.

McFadden (1968) examined the MLD for the NO Sπ condition as a function of the overall intensity of the masker. This is the absolute noise level condition. Both ears received the same level of stimulation, but this level was varied.

McFadden decided to use the NO Sπ condition so that the MLD could be followed over a greater range before binaural detection was confounded with monaural detections. The spectrum level of noise (45 dB) in one of the ears was held constant, while the level in the other ear was varied systematically. For all conditions: NM SM, NO Sπ, and NO' Sπ' (interaural differences in noise spectrum level), the S/N ratio was held equal in the two ears. That is, if the noise level in the left ear was 6 dB less than in the right ear, then the signal in the left ear was attenuated by that same amount. The signal was 400 cps (duration = 250 msec) and the 2ATFC procedure was used.

The results showed that for the conditions in which there was an interaural disparity in masker intensity (NO' Sπ'), there was no decrease in the magnitude of the MLD until the disparity became greater than about 10 dB. The maximum MLD (about 15 dB) was found when the sound in the weaker ear was within 10 dB of the stronger. For NM SM, the detectability of the signal was unchanged over a range of about 40 dB as long as a constant S/N ratio was maintained. This is in agreement with the linear relationship obtained by previous researchers. A nonlinear relationship was found for NO Sπ until relatively high (35 dB) noise levels were reached.

McFadden's data suggested that the auditory system could tolerate interaural disparities in masker intensity of about 10 dB before detectability was affected. Previous investigators had implied that this disparity was about 6 dB.

The discrepancy found can probably be attributed to the binaural noise and monaural signal conditions (used previously) which produced a relatively small MLD, while the largest MLD occurred with NO Sπ where monaural detections were minimized.

In general, then, MLD increased with increased spectrum level of the noise. McFadden (1968) has argued that internal noise causes a "decorrelation" of the external masker and that the contribution of the internal noise varies with the level of the external masker. The contribution of internal noise, it is argued, is inversely related to the intensity of the external noise. MLD should thus decrease with decreases in masker intensity as it does. Differences between the two ears, in the absence of an external masker, thus become an important consideration.

Shaw, Newman, and Hirsh (1947) reviewed the findings of previous researchers who had concluded that the two ears of a typical observer commonly differed in their sensitivity at any given frequency by an amount between zero and 10 dB in either direction. They found that the average difference was about 5 dB.

Early studies on binaural summation concerned absolute thresholds (i.e., thresholds for stimuli presented in the absence of a masker). A summary of the results of a number of investigations (Hirsh, 1948a) indicated that the binaural threshold was approximately 3 to 4 dB lower than the monaural threshold. Similarly, Shaw, Newman, and Hirsh (1947) reported results that showed that the difference between binaural and equated monaural thresholds for speech was approximately 3 dB. In general, the difference was interpreted as suggesting an equivalent power summation at the two ears.

Pollack (1948), however, found that a difference between monaural and binaural conditions was generally less than 3 dB for either a pure tone (1000 cps) or for "white noise". By both equating and "mismatching" the two ears in sensitivity, Pollack discovered that the difference between the binaural threshold and the threshold of the better ear decreased as the difference in the effective stimulation at the two ears increased. The difference between the binaural threshold and the threshold of the better ear was found to be not statistically significant when the two ears were stimulated at sensation levels more than 6 dB apart. This was taken as disconfirming the hypothesis that the auditory threshold is constant and equal to the sum of the effective powers at the two ears.

Another more recent attack on the power summation hypothesis has been extended by Diercks and Jeffress (1962). Since earlier workers had employed in-phase signals when they found a 3 dB advantage for the binaural threshold, they hypothesized that delaying the signal to one ear would reduce this advantage and thus raise the binaural threshold.

It was argued that because in-phase signals arrive simultaneously (no time difference) at the two ears, this had served to lower the binaural threshold in past studies.

A 250 cps tone was used with the phase reversed at one ear ($S\pi$); this produces a 2 msec time difference between the ears. Nine intensities were randomly presented for both binaural and monaural conditions. Contrary to their hypothesis, Diercks and Jeffress (1962) found that the out-of-phase condition yielded a lower threshold (MLD = 3.7 dB) than the in-phase condition (2.8 dB). Thus, reversing the interaural phase of the signal lowered the absolute threshold for the binaural condition even further than previously reported (3 dB). The explanation which they offered (alternative to the power summation hypothesis) centered on the physiological findings of Lorente de Nó (1939) on the spatial summation of nerve impulses. The fact that the binaural absolute thresholds are generally lower than the monaural threshold is to be accounted for in terms of binaural masking phenomenon rather than in terms of energy power summation.

Green and Henning (1969) have suggested that in the absolute threshold condition it is probable that the limit of detectability for a low frequency signal is physiological or "neural noise" or both. This notion was first introduced by Sivian and White (1933). Since then, this idea has been systematically studied by Piercy and Shaw (1962), who measured low frequency noise of physiological origin in the external auditory meatus. They found that the level in a 1/3-oct band centered at 250 cps and averaged over 6 Ss was 12 dB sound pressure level. At 125 cps, the noise level was 34 dB and continued to increase at lower frequencies. Watson, Franks, and Hood (1967) estimated the level of noise at 125 cps to be about 19 dB greater than at 250 cps.

Diercks and Jeffress (1962) were the first to present data to support the assumption that determinations of absolute sensitivity (threshold) were actually determinations of masker sensitivity where the masker was "internal noise." McFadden (1968) has also argued that the "internal noise" component adds to the neural activity caused by the external masking noise. He has suggested that when the intensity of external noise is decreased, the relative contribution of the "internal noise" increases until some point at which the external noise ceases to be effective and the "internal noise" becomes the primary masking component. Dolan and Robinson (1967) have upheld this view in terms of interaural correlation.

MLD as a Function of Interaural Correlation

MLD has also been studied in terms of the manipulation of interaural noise correlation. In general, up to this point in the discussion, it has been assumed that the noise waveforms at the two ears (when binaural) have been perfectly correlated (NO), i.e., the noise source has been the same for both ears. Briefly, two basic methods have been used to systematically vary this correlation: 1) adding two uncorrelated noises (one source to each ear) to correlated noise already present; 2) imposing a time-delay on the noise arriving at one of the ears.

The noise-addition method proceeds, in general, as follows. Unitary (1.00) correlation (NO) is obtained by using a single noise source for both ears. Uncorrelated noise (NU) consists of employing independent noise generators— one for each ear. Correlations between 0.00 and 1.00 are obtained by mixing the outputs of the two noise generators (adding the output of one generator to another) in the channel to one ear, while the noise at the other ear is supplied by an independent generator. Expressed in another way, Licklider and Dzendolet (1948b) have shown with oscillographic scatterplots, that if the power level of the mixture is held at a constant level, the correlation between the noise waveforms present at the two ears is the power of the common source squared divided by the sum of the squared powers of the common plus the uncorrelated source. Jeffress and Robinson (1962) have restated Licklider's formulas for two and three noise source conditions following some confusion in the literature concerning the appropriate uses for the formulas. They suggested, as had Licklider, that where three noise sources are used, one for one ear, one for the other, and one for both (the standard procedure), the formula for the coefficient is: $r_{xy} = ec^2/(ec^2 + eu^2)$ where ec is the voltage common to the two ears, and eu is unique voltage to each ear. This correlation coefficient squared is employed for two sources and had been mistakenly used in a three source condition by one investigator.

Robinson and Jeffress (1963) used the standard procedure in investigating the effects of varying the interaural correlation for noise on the detectability of a 500 cps tonal signal (spectrum level = 50 dB for wide band noise). The noise correlation conditions were as follows: $\pm$ 1.00, $\pm$ .99, $\pm$ .97, $\pm$ .95, $\pm$ .90, $\pm$ .80, $\pm$ .65, $\pm$ .50, $\pm$ .25, and 0.00. The signal conditions were SO and $S\pi$; both the constant and 2ATFC methods were used. They found that the MLD changed from essentially zero at a noise correlation of unity and the same phase as the signal (NO SO or $N\pi$ $S\pi$), to about 3 dB when the noise waveforms are uncorrelated (NU SO or NU $S\pi$), to about 12 to 15 dB in the antiphasic condition (NO $S\pi$ or $N\pi$ SO). The reference condition was NO SO. Further, MLDs obtained with the 2ATFC method were smaller than those with the constant method— as was the variability. Variability was also less in the antiphasic conditions.

Some investigators have attempted to assess detection of a signal in one ear as a function of the level of perfectly correlated noise at both (NO SM). Blodgett, Jeffress, and Whitworth (1962), for instance, have reported that for perfect noise correlation at the two ears (NO), the masked threshold for a monaural tone increased as the level of noise at the opposite ear was decreased from a level equal to that of the masking noise down through low levels to "off" (no noise).

An actual measure of the signal-to-noise ratio necessary to eliminate one ear from masking was made by Weston and Miller (1965). They indicated the following findings: 1) if a tonal signal mixed with noise was received at one ear, the addition of a noise to the other ear slightly reduced the threshold for the tone if the noises were statistical independent (NU); 2) the noise added to the nonsignal ear reduced the threshold for the tone if the noises were perfectly correlated (NO); 3) if identical tones were presented to the two ears (SO), and if the S/N ratio was about 25 dB lower in one ear than in the other, the effect of the signal at the ear with the lower S/N ratio was eliminated.

Mulligan (1965) has shown that detection of a tonal signal at one ear improved in a nearly constant proportion to the level of correlated noise in the "off" ear up to the point of equal noise levels in the two ears. A given level of uncorrelated noise at the "off" ear has the opposite effect in that it produced a nearly constant decrease in detection over the monaural condition for various S/N ratios in the "on" ear.

Wilbanks and Whitmore (1968), as has already been mentioned (see MLD as a Function of Frequency), studied detection in terms of six interaural noise correlations: +1.00, +.90, +.75, +.50, +.25, and 0.00. Considering a 250 cps signal, it was found that NO SM was superior to NU SM by about 9-10 dB. Likewise, although the difference between NU SM was small, purely monaural detection appeared to be slightly superior to detection under noise correlations approaching zero (at 250 cps). These findings have been replicated (Egan, 1965; Whitmore and Wilbanks, 1965b). Whitmore and Wilbanks (1965a) also demonstrated that NO SM was superior to NU SM by 7 dB at 225 cps and 4 dB at 200 cps.

Wilbanks and Whitmore (1965, 1967) extended this work with a 135 cps narrow band noise signal centered at 250 cps. Signal correlations were: +1.00, +.81, +.56, +.25, +.06, and 0.00. The masker was wide band noise under two correlational conditions: +1.00 and 0.00. When the masker was uncorrelated (NU), increasing the correlation of the signal from zero to +1.00 resulted in an improvement in detection of about 2 dB. With a correlated masker (NO), however, detection improved approximately 8 dB as the correlation of the signal was reduced from unity to zero. An uncorrelated signal (SU) was about 14 dB more detectable with a correlated masker than with an uncorrelated masker, and about 16 dB more detectable than the monaural condition (NM SM). The difference between NO SM and NM SM was about 2 dB more with a noise signal than a tonal (250 cps) signal and the small detectability advantage of a tonal signal usually found of NM SM over NU SM was reversed for a noise signal.

Another way of changing the interaural correlation of the noise is to delay the noise in one ear (thereby imposing a time difference). After Hirsh, et al., had shown the improvement in detectability for the antiphasic conditions as compared with the homophasic, the effects of systematically manipulating interaural noise and signal phases were first studied by Jeffress, Blodgett, and Deatherage (1952). They shifted the interaural phases of the masking component and of the tone (500 cps) by various amounts (36° steps) between 180° and -180°, and also shifted the noise in time by amounts up to 4 msec. Briefly summarized, they found that MLD decreased as the positive values of the correlation were reduced and increased with reduction of negative correlations. In addition, the masking effect of the noise was at least at 1.0 msec and 3.0 msec. The greatest masking effect occurred at 0, 2.0, and 4.0 msec, and these values were approximately the same.

Langford and Jeffress (1964) have extended this work with greater noise delays. Besides using positively and negatively correlated antiphasic and homophasic conditions, they also used two heterophasic conditions: NU SO and NU Sπ. Nineteen interaural time differences in noise ranging from 0.0 to 9.0 msec in 0.5 msec steps were used. The signal was 150 msec, 500 cps. The masker was wide band noise. The additional conditions were: NO SO, N$\pm$ SO, and N$\pm$ Sπ, where $\pm$ refers to the noise correlation (+ = in-phase; - = out-of-phase). The MLDs (re non-NU correlations) obtained (NO Sπ = 14.1 dB; NO SO = 11.1 dB; 1 msec delay and 8.5 dB; 3 msec) showed a close correspondence with those of several investigators (Jeffress, Blodgett, and Deatherage, 1952; Rabiner, Laurence, and Durlach, 1966; and Robinson and Jeffress, 1963).

The graph relating MLD to non-zero noise correlations for SO and Sπ signals indicated a periodic function decreasing with time delay such that MLDs were maximal at odd multiples of 1 msec for Sπ signals and even multiples for SO. With the heterophasic conditions, however, results for SO and Sπ were indistinguishable, being best represented by a non-periodic, negatively decreasing function where MLD was 10.5 dB at 0.5 msec and 2.0 dB at 8.5 msec. Langford and Jeffress concluded that: 1) reducing the correlation by adding a time delay produced more masking than reducing the correlation to the same degree by adding random noise; 2) the neural mechanism responsible for binaural masking phenomena appears to be capable of matching time delays in the stimulus at least up to 9 msec.

Blodgett, Wilbanks, and Jeffress (1956) attempted to assess the maximal interaural time difference that could be introduced into one channel without loss of a judgment of sidedness (lateralization) as a function of narrow or wide band noise. S's task was to adjust the setting of a micrometer down from maximal delay (24 msec) until he was able to judge the side on which the randomly presented sound (noise) was located. Their data indicated that when noise was presented binaurally with a delay in the channel to one earphone, the maximal delay that could be added without loss of sidedness was optimally 20 msec. Maximal delay values, computed as thresholds, varied across Ss ranging from 7.5 to 20.7 msec and 2.5 to 14.2 msec for narrow and wide band noise respectively. Clearly, the length of delay can be greater with narrow than wide noise bands.

Further measurements of interaural time difference thresholds have been made by Klumpp and Eady (1956) and Zerlin (1966). The former indicated the following thresholds for the detection of interaural time difference: 1) for wide band noise (9 msec), 2) for a 1000 cps tone (11 msec), and 3) for a 1 msec click (28 msec). Zerlin has studied MLD as a function of increased interaural time and intensity differences between members of a click pair. Briefly, he found that MLD (re NO SO) increased with increases in the time separation between (SO) clicks, reaching a maximum of 13 dB at 1 msec. Further, as signal interaural intensity differences increased, MLD approached a limiting value of about 7 dB for SM. An interaural intensity difference of 24 dB yielded an MLD of 6 dB.

A series of experiments by Carhart, Tillman, and

Johnson (1967, 1968) and Carhart, Tillman and Greetis (1969) have pursued the effects of interaural time disparities to include speech. A brief summary of their results indicates the following findings. First, interaural time disparities do not produce as large an MLD as does antiphasic presentation. The MLD for antiphasic presentation was 5.8 dB while that for 0.8 msec time delay was 4.8 dB. This finding, it will be recalled was also demonstrated for tones by Langford and Jeffress (1964). Second, the MLD produced by varying the interaural timing of either the masking sound or the speech signal became larger as the time difference was increased from 0.1 to 0.8 msec, but they were always smaller than the MLD during the antiphasic presentation. Finally, insofar as the reception of speech was concerned, the advantage for antiphasic presentation was maintained whether the masker was white noise, speech alone, or speech plus noise.

Clearly, the second method, of altering the interaural correlation by delaying the noise, is closely related to the phenomenon of localization, where localization is distinguished from lateralization as follows: a sound is localized when S can "point" to it, i.e., give its azimuth angle. Lateralization refers to the indication of where the sound is on a left-right line connecting the ears (Jeffress and Taylor, 1961).

Two studies on lateralization by Robinson and Egan (1967) and Egan and Benson (1966) showed that for a tonal signal (high or low frequency), the listener required only slightly greater signal energy (1-2 dB) in order to lateralize as well as he could detect when the noise was uncorrelated (NU). With perfectly correlated noise (NO) the slope of the function for lateralization was much smaller than for detection at 250 cps, still less at 1000 cps, and equal at 2000 cps.

MLD and Theoretical Positions

There are two major theoretical accounts of MLD extant in the literature. In this section the models upon which these theories are based will be discussed in simplified form. The two theories advanced attempt to explain how binaural analysis occurs and to predict the MLD. The models are: 1) the time difference model (TD) of the Webster-Jeffress theory, and 2) the equalization and cancellation model (EC) in Durlach's theory.

The description which follows relies primarily on the explanations found in Green and Henning (1969) and Wightman (1969).

The time difference (or interaural difference) model is a synthesis of two hypotheses. The first is the time deviation hypothesis of Webster (1951). Webster proposed this hypothesis to account for the improvement in signal detectability which occurs under antiphasic conditions. Briefly stated, he suggested that the decline in level of NO $S\pi$

masking with increasing frequency is determined by a fixed minimum interaural time deviation. In other words, the important variable in accounting for changes in MLD with changes in signal frequency is the difference in time created between the two ears as a result of the phase relationship of the signal and masker. This time difference is conceptualized as follows: each ear is looked upon as a filter of a certain narrow bandwidth whose center frequency is considered (for short intervals— 10-20 msec) as identical in frequency to that of the signal. In homophasic conditions, the phase change at both ears is in the same direction, while under antiphasic conditions it is not; therefore, reversing the phase of the signal at one ear acts to retard the phase at that ear while advancing it at the other one. Consequently, a time difference in the arrival of neural messages from the two ears is introduced and subsequently interpreted by a central mechanism which in turn leads to a judgment of detection (if the interaural time difference exceeds the minimum fixed interval). Therefore, according to Webster, a change in interaural phase produces the MLD. Since a given change in phase results in a small time difference at high frequencies and a large one at low frequencies, MLD should be large at the lower frequencies and small at high frequencies— as it is.

The second hypothesis, that of Jeffress, et al. (1952) incorporated Webster's hypothesis that the basis for detection in MLD conditions is the interaural time shift between the signal plus noise in one ear and the signal plus noise in the other ear. This notion has been extended, however, in terms of physiological localization and conceptual neural processing. The Jeffress hypothesis (Wilbanks and Whitmore, 1967) proposes that the basis for improved detection under binaural conditions is the change in the correlation between neural events subsequent to the cochlea. Before considering the physiological aspect of the theory, the manner in which Jeffress represents MLD conditions through vector constructions is important.

Jeffress' typical procedure for representing the various interaural conditions (by vector diagrams) also suggests his manner of quantitative analysis. The two typical conditions of an MLD experiment are NO SO and NO $S\pi$. The noise masker is usually portrayed as a single vector since it is the same for both ears. Typically, the masker is noise, and thus the length of the vector at any time is subject to random change. In the NO SO condition, the signal is added to the masker in random phase (α) producing a resultant signal-plus-masker complex that is the same for both ears. For NO $S\pi$, because the signal is inverted at one ear, the resultant signal-plus-masker complex is different for both ears; there are interaural amplitude and phase differences.

Jeffress suggests that the basis of binaural detection is the interaural phase (time) difference, symbolized by the angle θ ($\theta = \phi L + \phi R$). Once again it should be noted that when the masker is noise and the angle α which results from the summation of signal and masker is constantly changing, a corresponding change in θ occurs. This is important since the detectability of signals in any binaural condition is determined by the average value of θ in that condition. For example, if $\theta = 0^\circ$ (NO SO), the binaural system is assumed to be inoperative, and detection determined monaurally.

Turning to the physiology of this model, Jeffress suggests a set of 2 filter systems, one at each ear. The filters are identical, except for location (right or left), in their ability as frequency analyzers. A center (the median plane) for higher order neurons is conceptualized as a temporal detector of the arrival of neural impulses from the right and left ears. The outputs from the filter systems of the two ears converge on the higher order neurons only when simultaneously excited; i.e., when the waveforms are identical at the two ears. If the sound in one ear leads the other, it is assumed that the neural impulses will travel to that side (right or left) of the median plane which is lagging. In other words, maximal neural excitation will occur on the side of the median plane which is lagging. It is this system of temporal localization which makes detection in the antiphasic condition easier than the homophasic. Random variation in the timing of signals is assumed in order to avoid the logical, but not empirical, prediction that an antiphasic signal could be detected no matter how small the difference. Comparison of the time difference between the ears allows prediction of the MLD.

The equalization and cancellation (EC) model of Durlach (1960a) was originally discussed by Kock (1950). In contrast to the TD model, it is not physiological, but rather represents a quantitative, "black box" approach to binaural analysis.

According to Durlach (1961) the basic idea of equalization and cancellation is the following:

> 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 equalization process), and then subtracting the total signal in one ear from the total signal in the other ear (the cancellation process) (p. 1207).

Binaural signals are processed in three stages: 1) initial filtering, 2) equalization-cancellation, and 3) decision. After initial filtering, the signals are fed to the inputs of both EC and decision mechanisms. Monaural processing involves the two inputs to the decision device, bypassing the EC mechanism. Binaural processing, however, occurs through the EC mechanism. The decision device functions as a signal detector and operates only on the input with the largest signal-to noise (S/N) ratio. The MLD, then, is looked upon as the result of the fact that in some binaural conditions the EC mechanism provides a higher S/N ratio at the input to the decision device than either monaural input.

The EC mechanism, however, will improve the S/N ratio only when the signal and masker are not in the same interaural relation. This is done by the cancellator which eliminates the masker leaving the signal. For example, with Nπ SO, the cancellator supposedly adds the two waveforms, which makes noise zero and doubles the signal level. If the interaural relationships are the same, the S/N ratio is not improved. Rather, the equalization process would equate both signal and masking components of the input waveforms.

Durlach has avoided the theoretical implications of perfect processing by the binaural system, and infinite improvement in the S/N ratio, by assuming (as does Jeffress) the operation of processing errors. He suggests two: 1) a random time difference between the waveforms as processed by the respective ears, and 2) a slight instability in processing the amplitude of the signal.

<u>Summary and Conclusions</u>

It should be obvious at this point in the discussion that the study of binaural analysis regarding MLD has generated a considerable volume of research. To summarize the many results obtained is particularly difficult because there is no completely successful theoretical account to serve as a convenient organizational scheme (Green and Henning, 1969). In spite of this situation, a brief overview of the subsections just considered will be presented, emphasizing substantiated findings as well as discrepant or insufficient data.

Fig. 1 (adapted from Dolan, 1968) presents a summary of the research relating MLD (NO Sπ re NO SO) to signal frequency. Agreement is quite uniform across a number of researchers that MLD decreases in a near linear fashion from 300 cps to 2000 cps, leveling off at about 3 dB beyond 2000 cps (to 8000 cps). Below 300 cps, however, experimental results are often contradictory, although if one were forced to suggest a trend, it would be that MLD appears to decrease with further frequency decreases. More data are obviously necessary before this suggestion can be presented with more assurance.

The function relating signal duration to MLD is similarly in need of clarifying data, as Fig. 2 demonstrates. Although it is fairly well established that MLD increases (slightly: 2-5 dB) as duration decreases, the shape of this function is not completely clear. Blodgett, Jeffress, and Taylor (1958) note, for example, that a "best fit" is obtained by three different lines for data from 50-500, 15-50, and 5-15 msec. Research manipulating smaller values within these three ranges would perhaps be helpful, although certainly not critical.

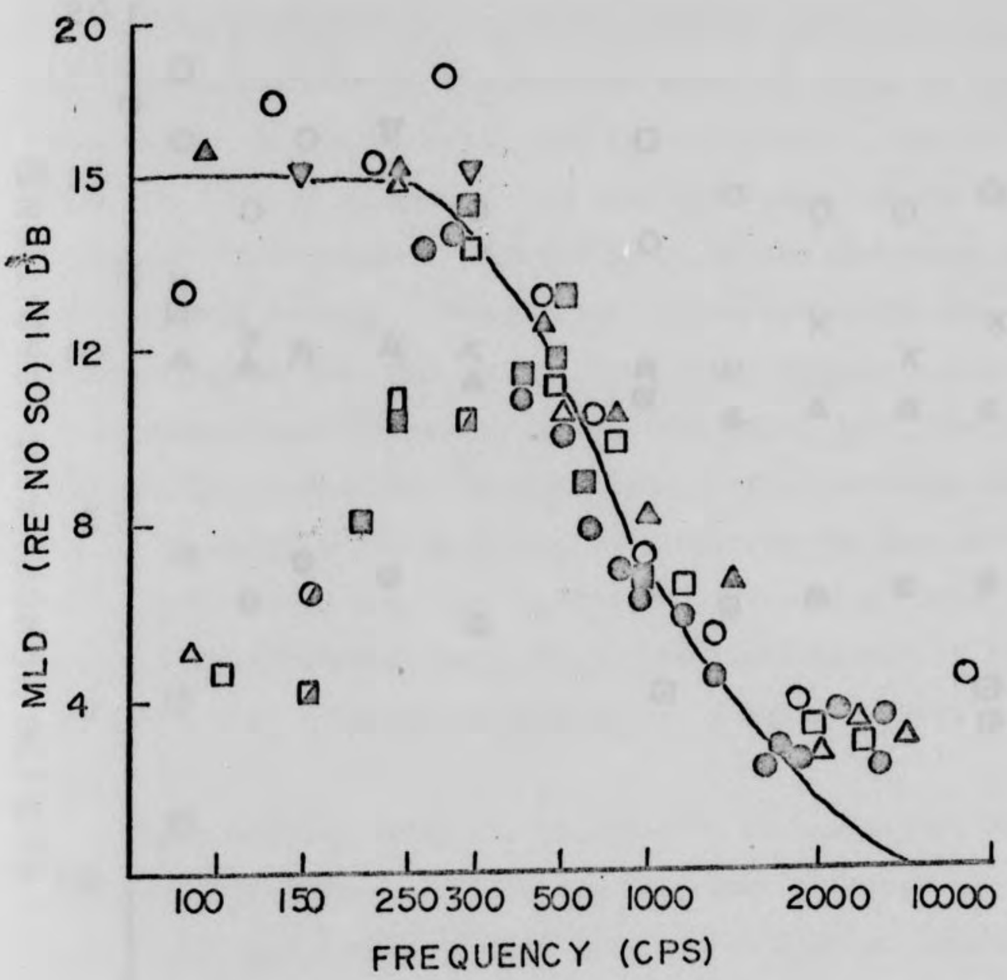

Figure 1. Results of several experiments in which the MLD at NO Sπ relative to NO SO was measured as a function of frequency (adapted from Dolan, 1968). The results were obtained employing different psychophysical methods and spectrum levels of the masker. The solid line represents a prediction of the size of the MLD as a function of frequency based on the EC model. ○: Webster, 1951; ▲ : Hirsh, 1948a; □ : Rabiner, Laurence & Durlach, 1966; ● : Hirsh & Burgeat, 1958; ■ : Schenkel, 1964; △ : Durlach, 1963; Dolan, 1968: ▽: 35 (300 cps), 50,65, &75 dB spectrum level; ■ : 20 dB spectrum level; ● : 35 dB spectrum level (150 cps).

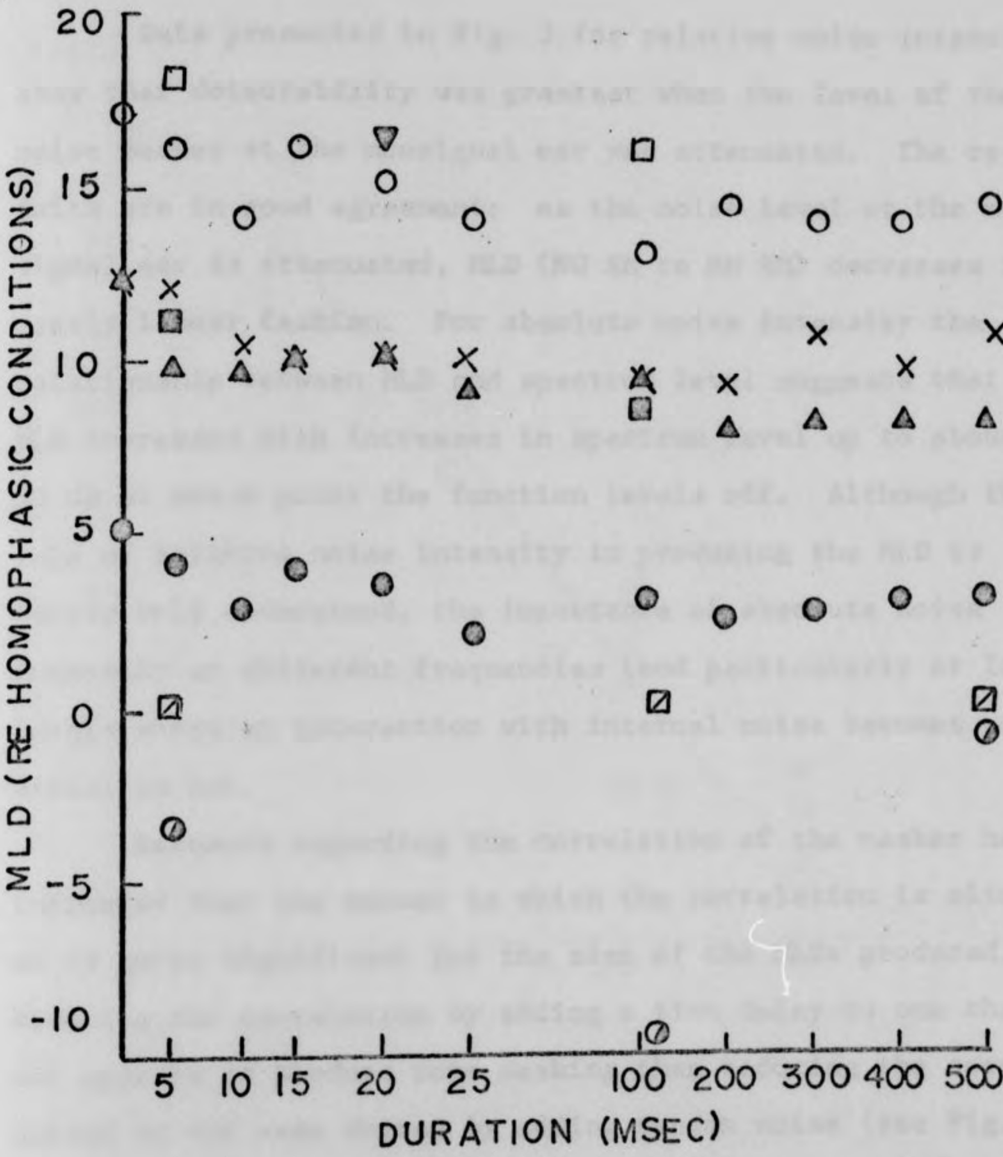

Figure 2. Results of a number of experiments in which the MLD at several conditions relative to the homophasic conditions (NO SO, Nπ Sπ, and NM SM) was measured as a function of signal duration. The results were obtained using different methods, maskers, and frequencies. Blodgett, Jeffress, and Taylor, 1958: ◎ : NU Sπ, NU SO; △ : NO SM; × : Nπ SO; ○ : NO Sπ. Green, 1966: ⊡ : NO SM; ⊡ : Nπ SO. Jeffress, Blodgett, Sandel, and Wood, 1956: ▽ : NO Sπ. Wightman, 1969: ⊘ (phase difference α = 0; gated masker; Sπ signal); ⊠ : (phase difference α = 90).

Data presented in Fig. 3 for relative noise intensity show that detectability was greatest when the level of the noise masker at the nonsignal ear was attenuated. The results are in good agreement: as the noise level at the nonsignal ear is attenuated, MLD (NO SM re NM SM) decreases in nearly linear fashion. For absolute noise intensity the relationship between MLD and spectrum level suggests that MLD increases with increases in spectrum level up to about 35 dB at which point the function levels off. Although the role of relative noise intensity in producing the MLD is fairly well understood, the importance of absolute noise intensity at different frequencies (and particularly at low levels where an interaction with internal noise becomes possible) is not.

Research regarding the correlation of the masker has indicated that the manner in which the correlation is altered is quite significant for the size of the MLDs produced. Reducing the correlation by adding a time delay to one channel appears to produce more masking than reducing the correlation to the same degree by adding random noise (see Fig. 4). One area concerning the correlation of the masker requiring further experimental elaboration is the internal noise hypothesis (McFadden, 1968).

This thesis investigated the role of several variables on MLD and replicated some previous investigations which were concerned with low frequency signals. In so do-

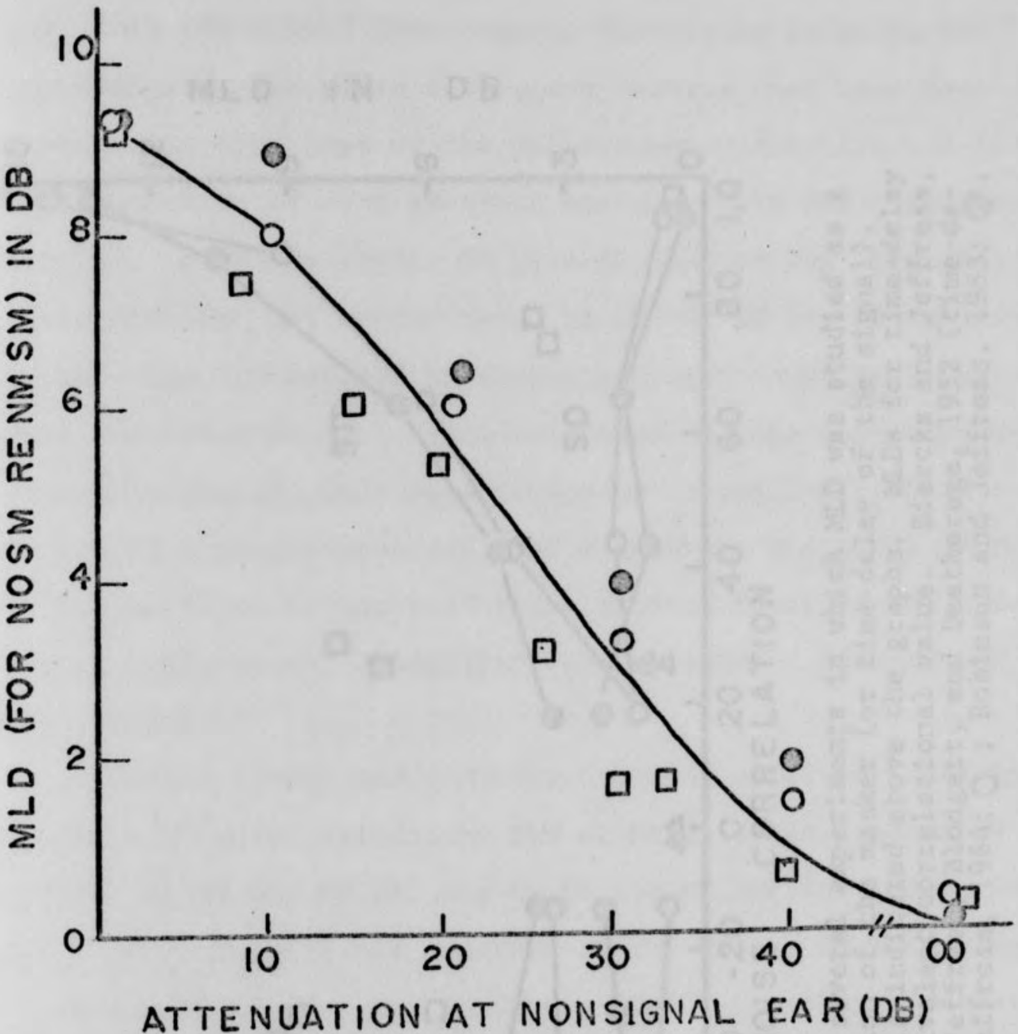

Figure 3. Results of three experiments (using different methods) which relate relative noise to MLD. The solid line represents a visual "best fit" of these results. □ : Blodgett, Jeffress, and Whitworth, 1962; ● : Dolan and Robinson, 1967; ○ : Egan, 1965.

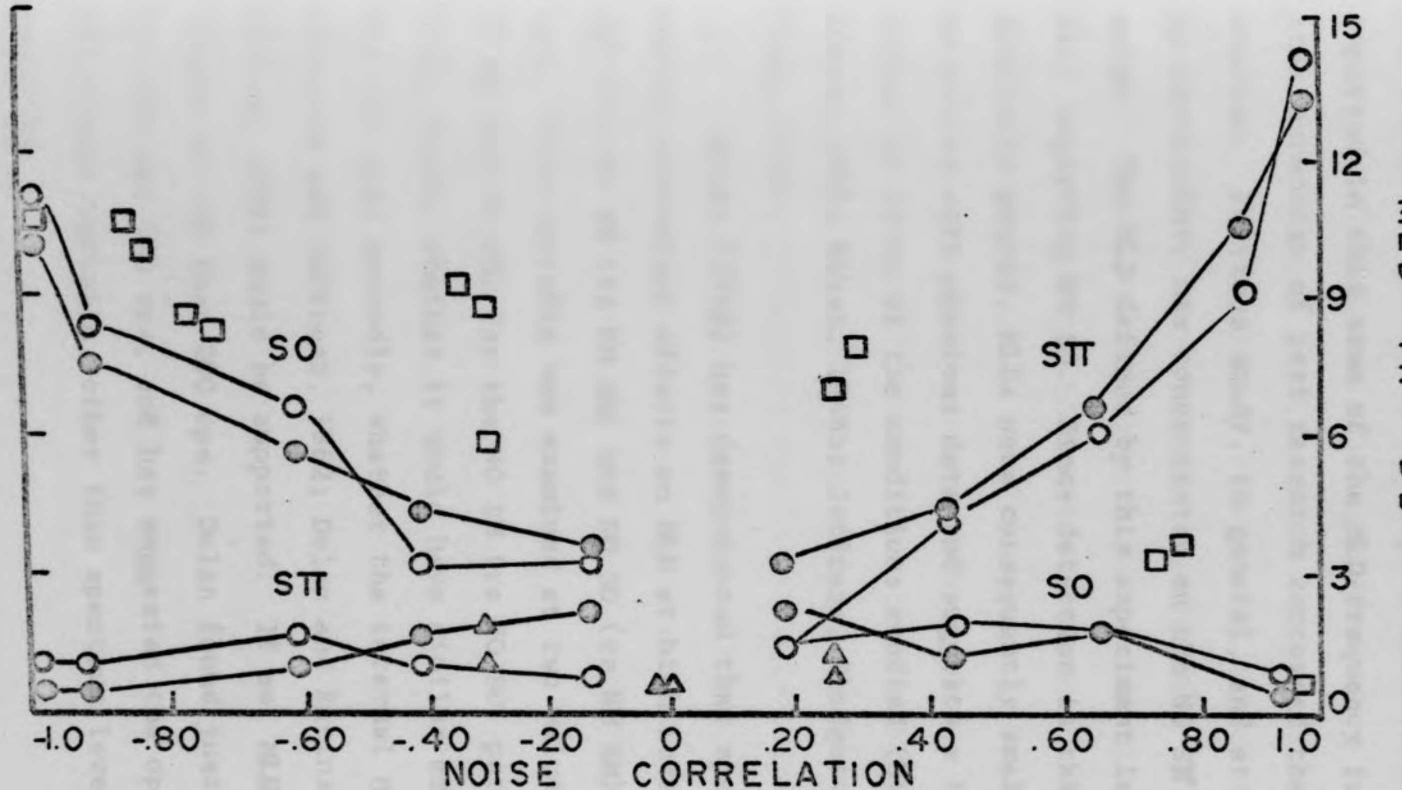

Figure 4. Results of several experiments in which MLD was studied as a function of the correlation of the masker (or time-delay of the signal). The phase of the signal is indicated above the graphs. MLDs for time-delay are converted to the equivalent correlational value. Diercks and Jeffress, 1962; △ : SO; △ : Sπ; Jeffress, Blodgett, and Deatherage, 1952 (time-delay): □ ; Langford and Jeffress, 1964: ○ ; Robinson and Jeffress, 1963: ● .

ing, this additional data suggest clarifying evidence for the ambiguous and often discrepant results that have been reported in this area of the MLD-frequency function. A further extension of past research concerned the MLD conditions studied. Previous study, in general, and at low frequencies in particular, has concentrated on the NO Sπ (re NO SO) paradigm. The MLD defined by this experiment is NO SM (right ear) regarding NO SO. Since detection in this condition is generally poorer, MLDs were consequently smaller. This is in accord with previous data and suggests a hierarchy of MLD values in terms of the conditions studied (Diercks and Jeffress, 1962; Hirsh, 1948b; Jeffress, Blodgett, Sandel, and Wood, 1956).

Dolan (1968) has demonstrated that spectrum level has nearly equivalent effects on MLD at high levels (beyond 50 dB) for NO Sπ (re NM SM) and NO SO (re NM SM) for 150 or 300 cps. This variable was examined at two values in this study (5 dB and 35 dB) for the NO SM (re NO SO) paradigm to determine, first, whether it would have similar effects for 150 and 200 cps; secondly, whether the internal noise hypothesis (Diercks and Jeffress, 1962; Dolan and Robinson, 1967; McFadden, 1968) would be supported. If so, MLDs should be larger at 150 than 200 cps. Dolan found just the reverse for 150 and 300 cps, and has suggested the operation of an additional variable, other than spectrum level, at low frequencies.

One possibility is that signal duration (he used 150 msec) may be important. Shorter signals may be correlated with greater internal masking effects than long signals. This could result in MLDs which increase with decreases in duration and frequency. Dolan's failure to find MLDs that increased with decreases in frequency may be attributable to the signal duration he used. This thesis investigated this possibility and extended the study of duration to low signal frequencies.

The experiment, then, systematically explored the respective roles of several variables known or presumed implicated with MLD in the following conditions: 1) signal frequency: 150 and 200 cps; 2) signal duration: 20, 60, and 100 msec; 3) noise spectrum level: 5 and 35 dB; and 4) binaural masking condition: NO SO and NO SM.

CHAPTER II

METHOD

Design

A 2x2x3 repeated measures design was used to investigate three experimental parameters: 1) masker spectrum level: 5 and 35 dB SPL re 0.0002 dynes/cm^2; 2) frequency of the signal: 150 and 200 cps; 3) signal duration: 20, 60, and 100 msec. The various experimental conditions were thus defined by all possible combinations of these parameters. Each S received a different random schedule of the twelve experimental conditions. The dependent variable was the MLD which occurred between NO SO and NO SM conditions when detectability was constant (75-80%). Figure 5 shows the experimental design.

Procedure

Three unpaid and trained Ss (two males and one female, ages 21-33) with clinically normal hearing were the listeners. Each S was provided with a pair of calibrated earphones and seated in a sound attenuated room before a panel of indicator lights and response buttons.

A two-alternative temporal forced choice (2ATFC) method was used. Each S was instructed to respond on each trial indicating (by pressing one of two buttons) his deci-

Intensity	5 dB						35 dB					
Frequency	150 cps			200 cps			150 cps			200 cps		
Duration	20	60	100	20	60	100	20	60	100	20	60	100
S 1												
S 2												
S 3												

Figure 5. A schematic representation of the 2x2x3 repeated measures design used in this study.

sion regarding the interval with the signal. "Feedback lights" informed S after each trial which of the 2 observation intervals contained the signal. A schematic representation of a trial (where the signal is in the first interval) can be seen in Fig. 6. Each trial was 5.5 sec long and consisted of the following sequence: intertrial time (ITI) of 1 sec, 2 sec noise interval, 2.3 sec response period, and .2 sec feedback light. The noise was divided into two equal observation intervals by a dim light flash (.1 sec). Thus each of the two observation intervals were 1 sec duration. The signal occurred at random in the middle of one of the two observation intervals.

Each one and a half hour session consisted of 5 blocks of 100 trials each. A rest period of 3-5 min followed each 100 trial block. Fifteen warm-up trials begun 15-20 dB above the signal level where S was run preceded each 100 trial block. For the first 100 trials the signal was attenuated in 1 dB steps (beginning at the warm-up level) until a point was reached where S began to miss some signals. In short, the first 100 trials were used to estimate a value for threshold to be used during the remaining 400 trials. Although S responded during the warm-up trials his data were not recorded. In addition, the data from the first trial block were not used in the statistical analysis because signal attenuator settings were changed on the basis of S's responding to a level which appeared to yield 75-80%

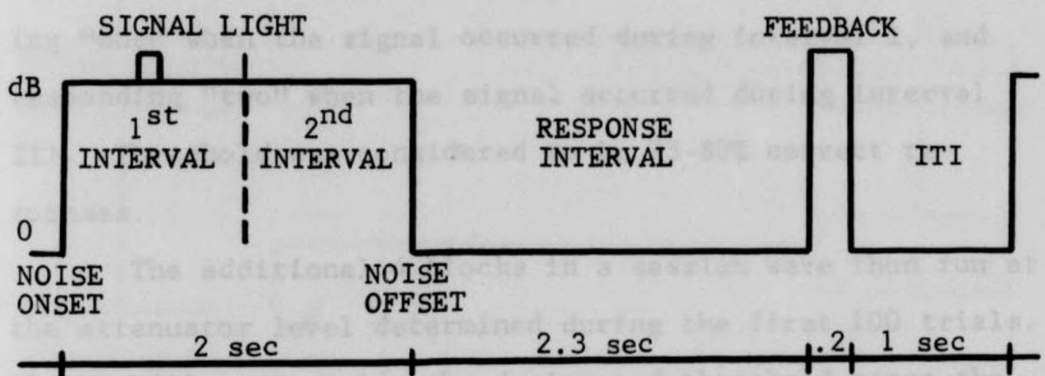

Figure 6. A schematic representation of an experimental trial. The signal is shown in the first interval.

correct responses. Previous research (Blackwell, 1953) has shown that a "settling in" of the S to the task occurs during the first 100 trials or so. By extending the warm-up period, in effect, to 100 trials S's variability was reduced. The performance measure was percentage correct [P(C)] which represented total hits for the two intervals (i.e., responding "one" when the signal occurred during interval I, and responding "two" when the signal occurred during interval II). Threshold was considered to be 75-80% correct responses.

The additional 4 blocks in a session were then run at the attenuator level determined during the first 100 trials. If the P(C) was outside the designated threshold range the signal level was attenuated accordingly. A threshold value was based on at least 200 trials with additional trial blocks occasionally necessary to obtain a better measure for a particular condition.

Apparatus

A block diagram of the apparatus is presented in Fig. 7. The masker in this experiment was white gaussian noise with a band width (15-5000 cps) determined by a 3100 Krohn-Hite band pass filter. The masker was generated by a Grason-Stadler 455-C noise generator and had a spectrum level (5 and 35 dB) controlled by two Hewlett-Packard 350-D attenuators. An additional attenuator of the same model regulat-

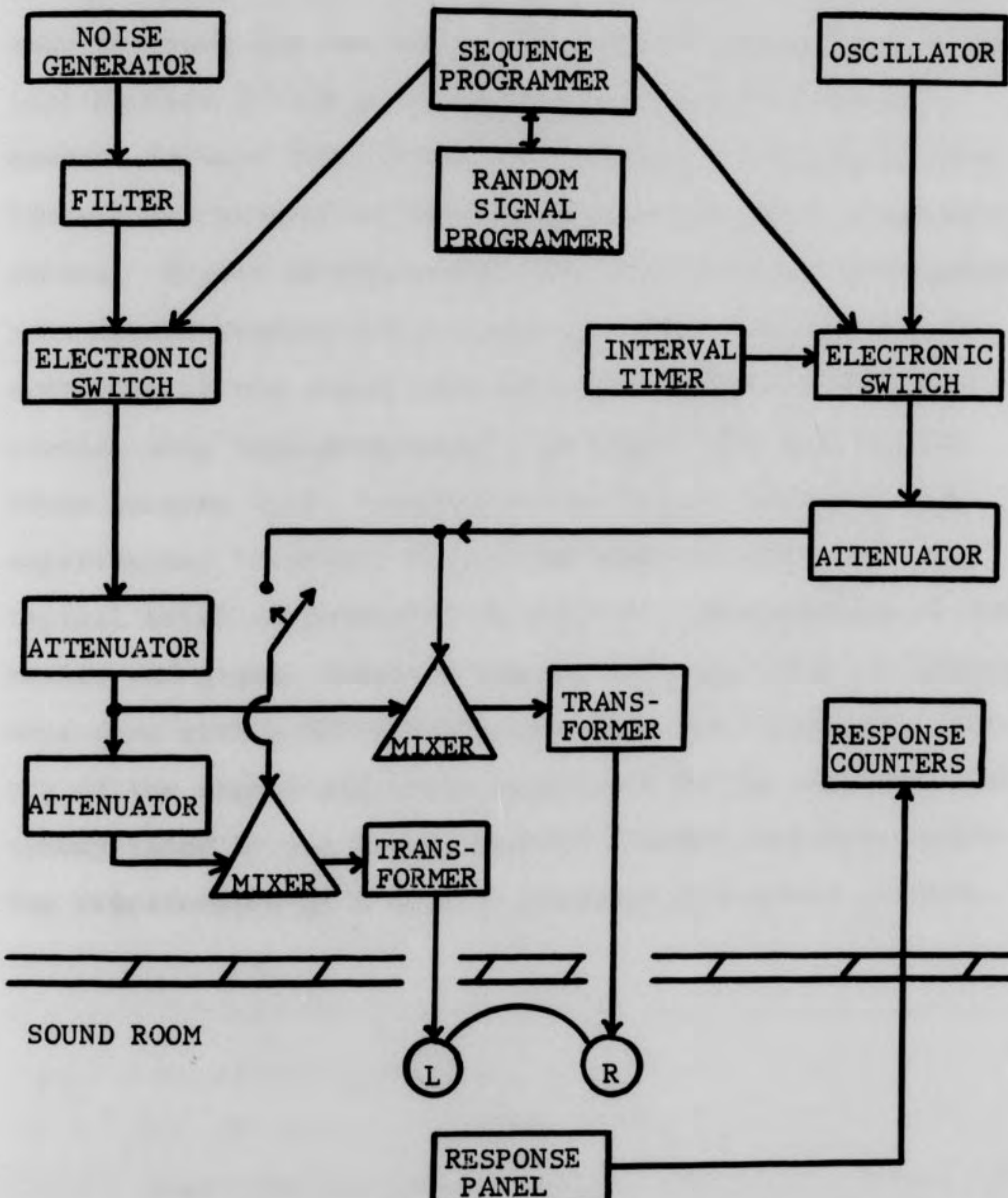

Figure 7. A block diagram of the experimental apparatus used to generate the signal and masker conditions.

ed the signal level. The signal was presented without regard to phase and was 150 or 200 cps and generated by a Hewlett-Packard 201-CR audio oscillator as calibrated by a Hewlett-Packard 5221B electronic counter. Rise-decay time (5msec) was determined by a Grason-Stadler 829-C electronic switch. Signal durations (20, 60, and 100 msec) were gated by a Grason-Stadler 471-1 interval timer. The random presentation of the signal was done by a Lehigh Valley electronic, step tape-programmer. An Eight bank 5431 A Lafayette program timer controlled the overall timing of the experimental intervals (i.e., the temporal character of a typical trial as indicated in Fig. 6). Measurements of the masker and signal levels preceding each experimental session were done with a 320 A Ballantine true RMS voltmeter. Mixing of the signal and noise antecedent to the earphones was accomplished by two Grason-Stadler E10589A impedance matching transformers in a locally produced resistance network.

CHAPTER III

RESULTS

An analysis of variance (repeated measures) was performed on the data presented in Table 1. The dependent measure, MLD was obtained by comparing the attenuator settings for 200 (or more) mean threshold trials [P(C) = 75-80%] for the NO SM condition relative to NO SO. MLD values of 0.5 dB represent estimates based on a linear interpolation between two attenuator (1 dB steps) settings.

The analysis of variance (see Table 2 in Appendix) indicated that the MLDs obtained for a spectrum level of 35 dB were significantly larger than those for 5 dB ($p < .05$). Similarly, MLDs at 200 cps significantly exceeded those at 150 cps ($p < .05$). In addition, the frequency-intensity interaction was significant ($p < .05$). The main effect of duration and the remaining interactions were not significant. A simple effects analysis (see Table 3 in Appendix) on the significant interaction showed all factors significant ($p <$ .01 or $p < .05$) except frequency at the low (5 dB) spectrum level. Under the assumption that all factors are fixed, the estimate of the proportion of variance accounted for (w^2) indicated that the three significant factors accounted for 77% of the total variance in the following manner: frequency (14%), spectrum level (57%), and the interaction of fre-

TABLE 1

MLDs OBTAINED IN THE VARIOUS EXPERIMENTAL CONDITIONS

SPECTRUM LEVEL		35 dB			5 dB		
DURATION		20	60	100	20	60	100
150 cps	S1	6.0	7.5	6.0	-4.5	1.0	-1.5
	S2	1.0	2.5	0	-0.5	-1.5	1.0
	S3	5.5	6.5	3.5	0	1.5	-0.5
	mean	4.2	5.5	3.2	-1.7	0.3	-0.3
DURATION		20	60	100	20	60	100
200 cps	S1	12.0	13.5	11.0	0	1.0	0.5
	S2	9.0	8.0	5.5	1.0	0	0
	S3	10.5	9.0	9.0	-0.5	1.5	2
	mean	10.5	10.2	8.5	0.2	0.8	0.8

quency and spectrum level (6%).

The overall results are shown in Fig. 8 and portray each S's MLD as a function of duration for both signal frequencies and spectrum levels examined. In general, S1 did better (larger MLDs) than the other two Ss at the high noise level although this superior performance did not maintain itself at the lower spectrum level. In addition, larger individual differences appeared at the high (35 dB) spectrum level while the variability was considerably smaller at the low noise intensity (5 dB). The frequency difference for each S was plainly evident with the size of the difference being dependent on the spectrum level of the noise. The shape of the functions in Fig. 8 shows a peak (largest MLD) at 60 msec. This was fairly consistent across Ss, although there were several exceptions, but the magnitude was small and nonsignificant.

One additional observation from the individual data concerns the negative MLDs (NO SO condition better than NO SM) for the low spectrum levels. Negative MLDs in binaural masking experiments are atypical although they do occur (McFadden, 1966; Wightman, 1969). All Ss showed some negative MLDs at the low noise intensity as well as several zero values. The explanation for these results is somewhat elusive. However, plausible reasons can be found and will be discussed in a later section.

The mean values of the data in Fig. 8 for the three

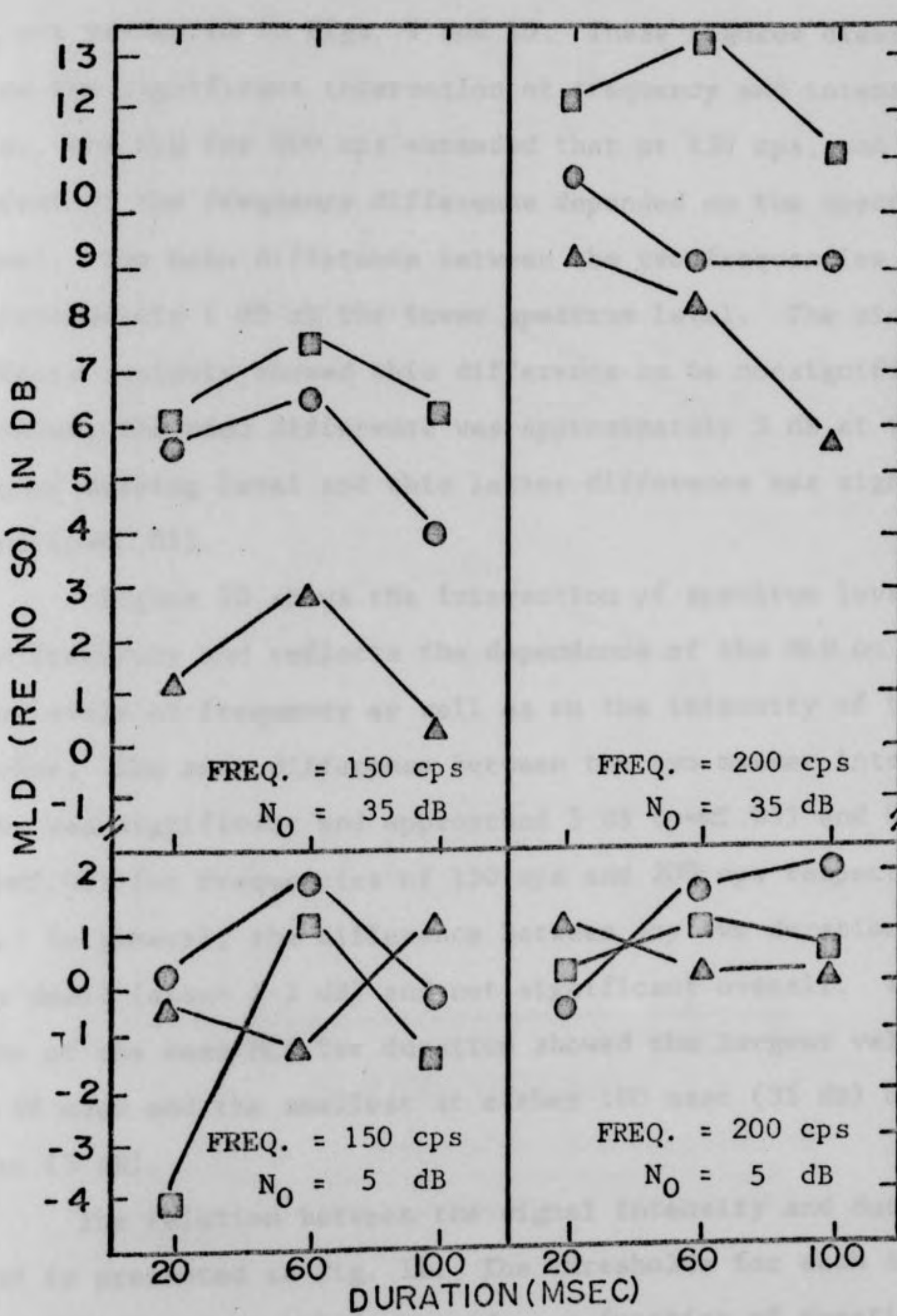

Figure 8. MLD as a function of duration for both signal frequencies and spectrum levels. The subjects are designated as follows: S1: □ ; S2: △ ; S3: ○ .

_S_s are presented in Figs. 9 and 10. These figures clearly show the significant interaction of frequency and intensity, i.e., the MLD for 200 cps exceeded that at 150 cps, and the extent of the frequency difference depended on the spectrum level. The mean difference between the two frequencies was approximately 1 dB at the lower spectrum level. The simple effects analysis showed this difference to be nonsignificant. However, the mean difference was approximately 5 dB at the higher masking level and this latter difference was significant ($p < .01$).

Figure 10 shows the interaction of spectrum level and frequency and reflects the dependence of the MLD on the two levels of frequency as well as on the intensity of the masker. The mean difference between the two masker intensities was significant and approached 5 dB ($p < .05$) and 9 dB ($p < .01$) for frequencies of 150 cps and 200 cps respectively. In general, the difference between any two durations was small (about 1-2 dB) and not significant overall. The size of the mean MLD for duration showed the largest values at 60 msec and the smallest at either 100 msec (35 dB) or 20 msec (5 dB).

The relation between the signal intensity and duration is presented in Fig. 11. The thresholds for each condition (NO SO and NO SM) decreased as a function of duration. The near linear decrease in threshold with increases in duration was found for all experimental conditions. The nega-

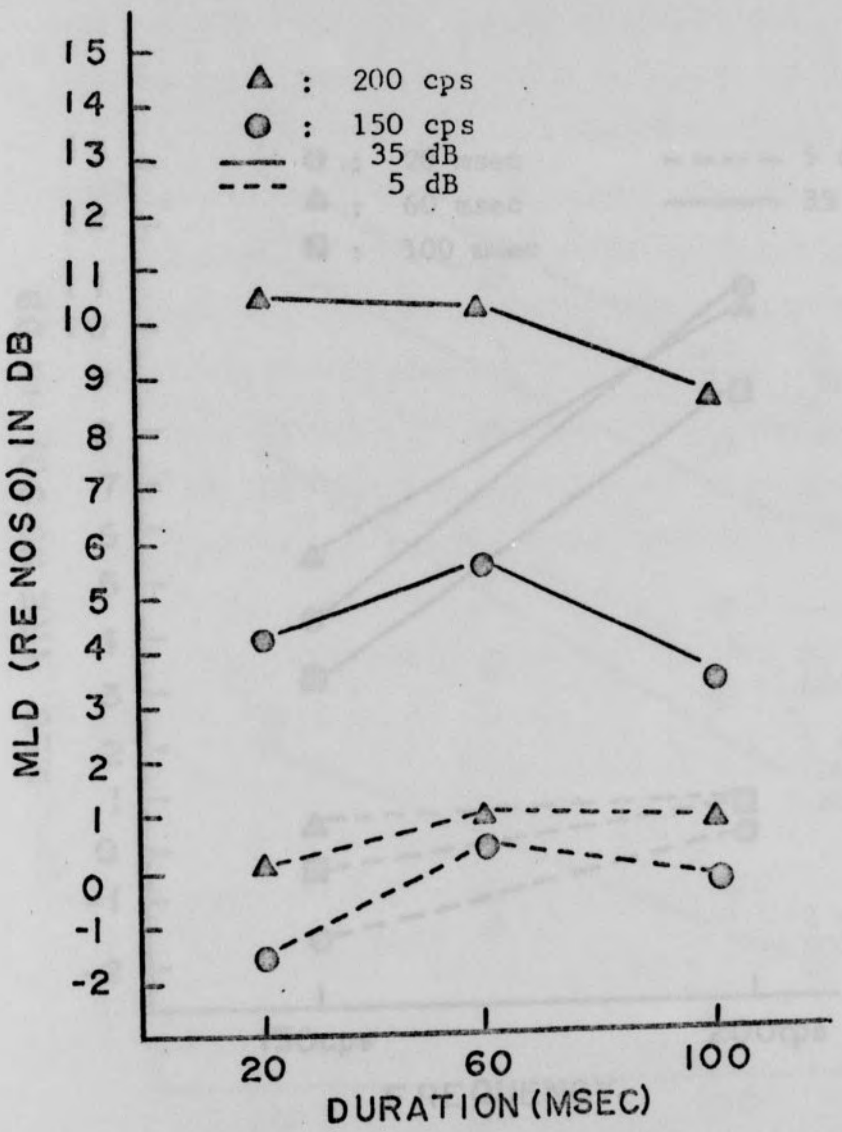

Figure 9. Mean MLDs as a function of duration. Each parameter represents a masker spectrum level and a signal frequency.

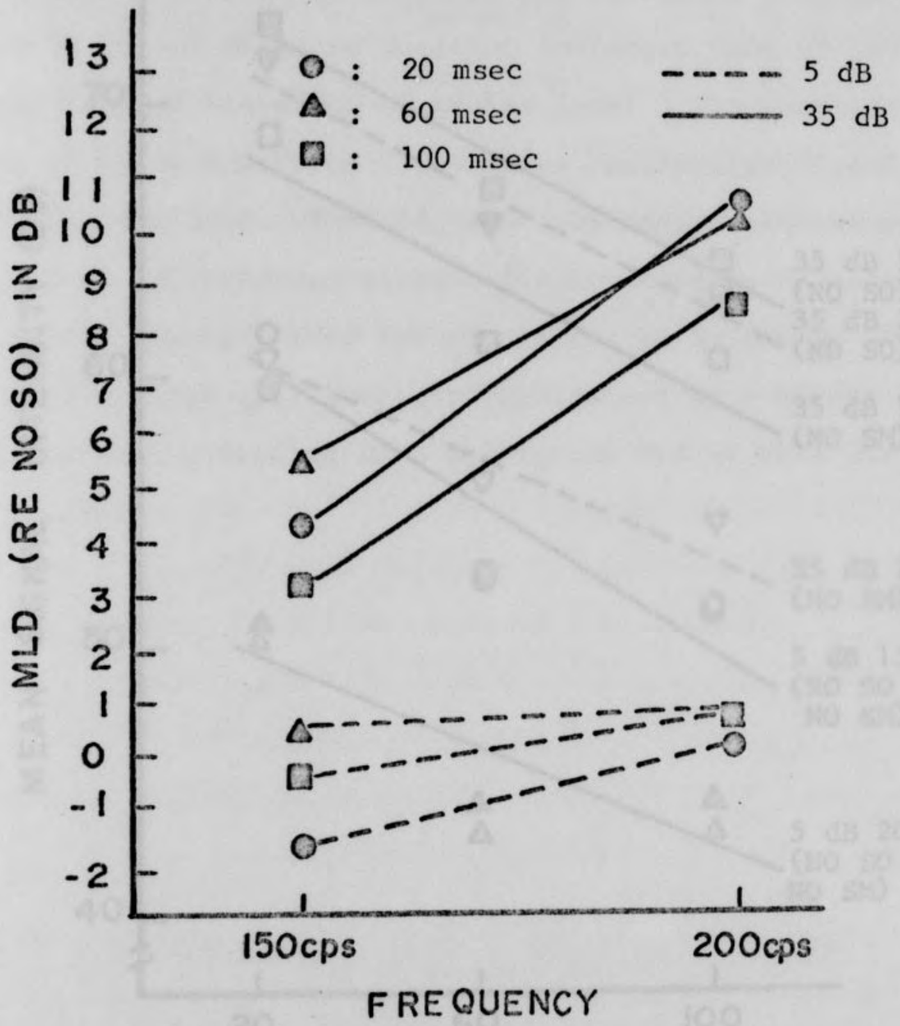

Figure 10. MLD as a function of frequency. Each parameter represents a signal duration and masker intensity.

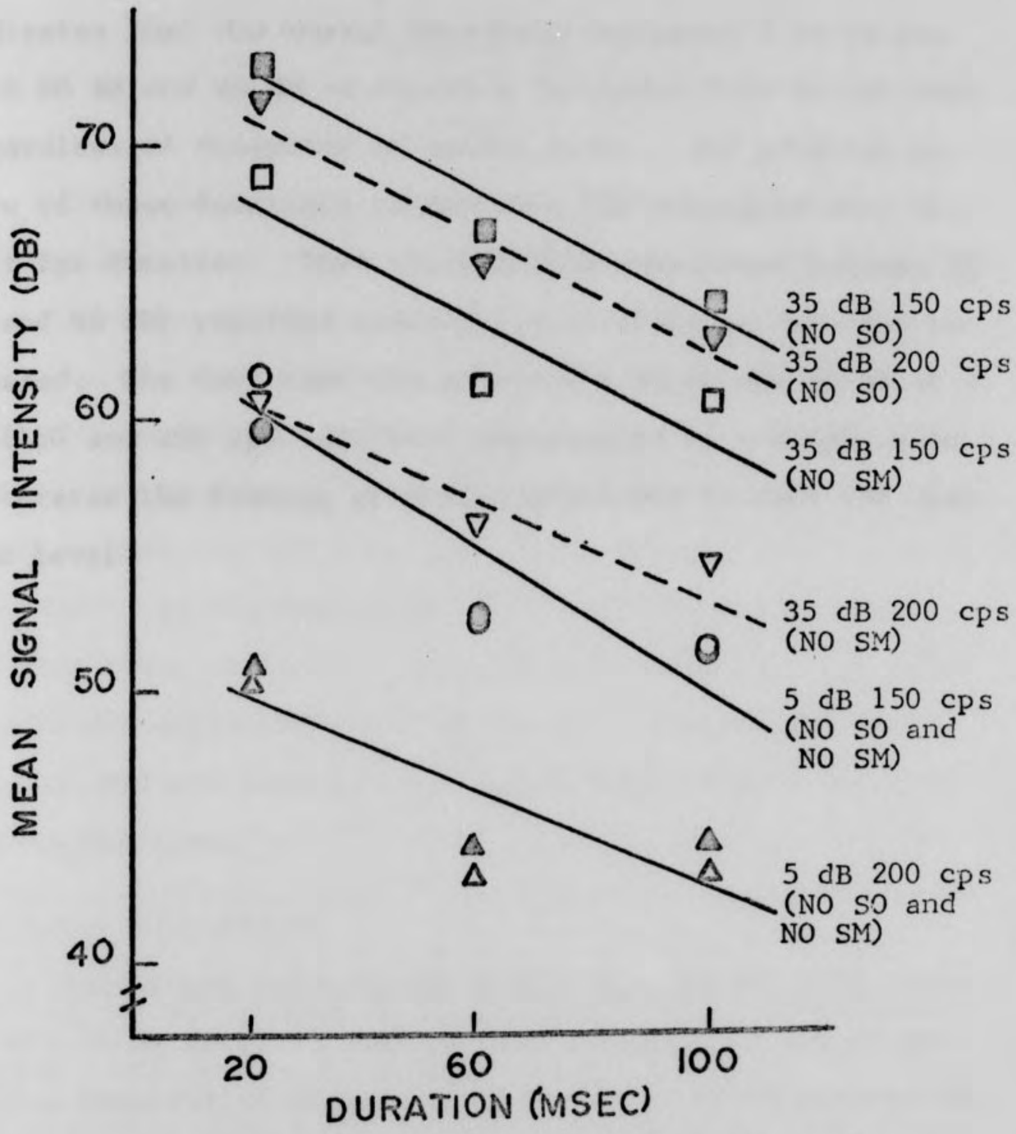

Figure 11. Mean signal intensities for threshold values of NO SO and NO SM as a function of duration. The lines represent a visual "best fit." The points for NO SO and NO SM at 5 dB spectrum level are considered to fall along a single line (negligible MLD).

tive slope of the functions for NO SO and NO SM in Fig. 11 indicates that the masked threshold decreased 6-10 dB for both NO SO and NO SM as duration increased from 20-100 msec regardless of frequency or masker level. The parallel nature of these functions illustrates the nonsignificant result for duration. That is, MLD (the comparison between NO SO and NO SM) remained essentially constant as duration increased. The fact that the points for NO SO and NO SM at 5 dB (150 and 200 cps) are best represented by a single line reiterates the finding of a negligible MLD at this low spectrum level.

CHAPTER IV
DISCUSSION

The results of the present experiment indicated that the magnitude of the MLD at low frequencies was strongly dependent on the spectrum level of the masker. This is, perhaps, the most important variable upon which the MLD depends. It was also clear that the MLD resulting from a high (35 dB) spectrum level was different from the MLD at a low (5 dB) masker and the difference was strongly related to frequency. At the high spectrum level, the MLD at 200 cps exceeded those at 150 cps by about 5 dB; whereas, the difference was approximately 1 dB for the low spectrum level. Duration did not seem to be a significant variable for predicting MLD size.

Individual Variability

Individual differences in the size of the MLDs found in this study (Fig. 8) reflect the influence of one or possibly a combination of several S variables (task motivation, attention, or ear threshold differences between the right and left ears). An additional and perhaps more important source of variability may be attributed to the physical relation of the headphones on the ears (Dolan, 1968). Slight changes in the position of the headphones from trial to trial, session to session, as well as involuntary movements by the S, result in nuisance factors which act to degrade performance in all signal detecting tasks, but most at low frequencies.

The data showed considerable variability at the high spectrum level and less at the low spectrum level. The more pronounced variability displayed for the high spectrum level is likely related to individual differences as well as experimental conditions. The larger variability at 35 dB may be more apparent than real. The improvement in signal detection is at most 4-5 dB for low noise levels. Since the MLD depends importantly on masker spectrum level in such a way that low spectrum levels yield small MLDs (Dolan, 1968; McFadden, 1968), this may elucidate the seeming shift in variability with spectrum level. In other words, the smaller variability at 5 dB spectrum level may represent a restriction on the operation of individual differences dependent on that experimental condition. Similarly, as the advantage of NO SM over NO SO is increased by adding more intense noise (e.g., 35 dB), the opportunity for individual differences, and hence variability, to appear in the data increases.

Brief mention may be made of the negative MLDs found at 5 dB spectrum level. The negative MLD has been shown to depend on a gated masker; onset of signal and masker are simultaneous (McFadden, 1966; Wightman, 1969). This explanation is not satisfactory since this study did not use a gated masker. A possible explanation concerns the low level of the masker. Research in which the masker was removed has shown that binaural signals (SO) are 3-5 dB more detectable than "best ear" monaural (SM) ones (Diercks and Jeffress, 1962; Hirsh, 1948a; Pollack, 1948; Shaw, Newman, and Hirsh, 1947). In this study by adding 5 dB spectrum level noise to both ears, the binaural advantage was lost; the two ears were on the average equivalent (MLD was about zero). This is in agreement with findings of no MLD between NO SO and NO SM as the noise in both ears was increased from "off" to about 10 dB spectrum level (Blodgett, Jeffress, and Whitworth, 1962; Diercks and Jeffress, 1962; Hirsh, 1948b). Perhaps the slight advantage for NO SO (negative MLD) arose because the noise (5 dB spectrum level) was sufficient to degrade the 3-5 dB advantage of the "good ear" enough to provide a slight binaural advantage.

<u>Spectrum Level, Frequency, and the Internal Noise Hypothesis</u>

The internal noise hypothesis that has been extended to explain the dependency of MLD on noise spectrum level is based on the considerable amount of masking noise produced in the ear canal by such physiological actions as breathing, heart beat, muscle tonus, etc. (McFadden, 1968; Wilbanks and Whitmore, 1968). Stevens and Davis (1938) have also suggested that the effect of physiological noise, which is associated with the tight fit of the headphones on the ears, may act to mask tones.

It may be argued, therefore, that the MLD at 150 cps should be larger than at 200 cps. In other words, as the level of the external masker decreases to a low level, there is (in contrast or relative to the external noise) an increased effect of the internal noise. That is, the internal noise may, conceptually, replace the external noise as a masker. In this respect it is of interest to note that it has been shown that a portion of the internal noise occurs in the auditory meatus and is 19-22 dB more intense at 125 cps than at 250 cps (Shaw and Piercy, 1962; Watson, Franks, and Hood, 1967). Thus it is possible to conclude that a 150 cps signal should have a larger MLD than at 200 cps (or 250 cps) because a more intense noise is related to a larger MLD. (This assumes that the effects of an internal and external masker are equivalent.)

The present study does not substantiate the internal noise hypothesis (nor did Dolan, 1968). MLDs were larger at 200 cps than 150 cps for 35 dB spectrum level by approximately 5.5 dB, a reverse of the prediction. More significantly, however, the MLD at 200 cps was also slightly greater (0.5 dB) than at 150 cps for the low spectrum level where presumably the higher level of internal noise would have provided a frequency advantage for 150 cps. These results suggest two things. First, the effects of internal and external maskers on MLD probably can not be considered similar. Second, whatever the advantage provided for NO SM over NO SO by higher spectrum levels, it disappears at low spectrum levels such that if internal noise is implicated, its role does not appear to be frequency specific. In other words, the size of the MLD was nearly equivalent at the low spectrum level, regardless of frequency.

A more plausible interpretation, which explains the reduction in binaural assistance (smaller MLDs) with decreases in frequency below 250 cps, is based on the neural input to the central nervous system. It is possible that the reduction in MLD with decreased frequency results from less synchronized neural activity at the cochlea for a 150 (or 200) cps signal than for 250 cps. Perhaps increasing the intensity of the masker increases the synchrony of the neural volley subsequent to the cochlea (Wilbanks and Whitmore, 1968). This would improve the assistance which noise to both ears provides to a monaural (or Sπ) signal, increasing the MLD. This physiological speculation has received support from Teas (1966), who showed that the speed of propagation of the traveling wave was the major determiner of neural synchrony for low frequencies. The fact that the MLDs obtained in the present study showed a clear dependence on noise level, then, may suggest that physiologically the speed of the traveling wave is the major determiner of binaural unmasking for these low frequency signals.

MLD as a Function of Duration

Blodgett, Jeffress, and Taylor (1958) did not show large changes in MLD with duration using a 400 cps signal. Rather, the 2-5 dB decrease in MLD they found as duration increased involved the overall range of durations studied (5-500 msec). The amount of change (1-2 dB) they found in MLD over 20-100 msec was not very dissimilar from that found in this experiment despite the frequency difference. The trend of the present study (Fig. 9) was slightly reversed at 5 dB spectrum level (MLD increased, 0.5-1.3 dB, with increased duration).

The failure to find a significant result for duration is most easily accounted for by considering Fig. 11. The negatively sloping (parallel) functions for NO SO and NO SM (masked thresholds) are similar to results reported by Garner and Miller (1947). Despite the fact that these thresholds decreased with increased signal duration, the advantage for NO SM over NO SO was basically unaffected (i.e., MLD was almost constant). Binaural unmasking, as defined, is not importantly related to the signal duration.

Comparison with Past Research

Comparisons with previous data are difficult due to the diverse intensities, frequencies, signal durations, and experimental listening conditions reported in the literature. However, a comparison with other data is possible since a rank order is generally maintained in terms of the conditions (Hirsh, 1948b; Jeffress, Blodgett, Sandel, and Wood, 1956). For example, the advantage for NO Sπ over NO SM ranges between 4-7 dB depending on intensity and frequency.

For this experiment, the direction of the results is in agreement with Dolan (1968), who found larger MLDs at 300 cps than at 150 cps when the spectrum level of noise was less than 50 dB. McFadden (1968) has reported data, regarding absolute noise and MLD, that showed an MLD of 8 dB at 5 dB spectrum level for an Sπ signal (400 cps). Jeffress, Blodgett, and Taylor (1958) have also shown that the MLDs for Sπ signals are typically 6-7 dB larger than SM (at 500 cps). The interpolation is somewhat tenuous since the Jeffress et al. study used a spectrum level of 60 dB and a different frequency than McFadden. Nevertheless, since MLDs are generally larger for NO Sπ than NO SM, it may not be unreasonable to expect this advantage to be present (although possibly varying some with frequency and intensity). The exact difference in dB between NO Sπ and NO SM is possibly not as important as the ordinal position. An indication that this may be the case is that Dolan (1968) found an MLD of 6 dB (150 cps) and 15 dB (200 cps) for Sπ at 35 dB spectrum level. The MLD was 15 dB at spectrum levels beyond 50 dB.

In the case of duration, comparisons are similarly complicated and include: different signal conditions (Green, 1966a; Jeffress, Blodgett, Sandel, and Wood, 1956; Wightman, 1969) and/or different durations (Blodgett, Jeffress, and Taylor, 1958). Some crude comparison may be possible. For instance, for NO SM (at 500 cps) Blodgett, Jeffress, and Taylor (1958) found MLDs of 10, 10, and 9 dB for 20, 50, and 100 msec, respectively, for a spectrum level of 60 dB. This corresponds closely to the mean MLDs (at 200 cps and 35 dB) of 10.5, 10.2, and 8.5 for 20, 60, and 100 msec in the present study. Since there is an interaction between frequency and spectrum level differences, this agreement may not be rigidly interpreted. The mean MLD (3.2 dB) for the 100 msec 150 cps signal at 35 dB spectrum level was in reasonable agreement with Dolan's (1968) MLD of 7 dB at the same frequency for a 150 msec Sπ signal. The approximation is close if one considers that Blodgett, Jeffress, and Taylor (1958) found a difference between NO SM and NO Sπ of some 4-5 dB at 100 msec.

Theoretical Considerations

The EC model of Durlach (1960a) and the TD model of Webster-Jeffress (1951) may elucidate why detection was better in the NO SM condition than for NO SO. The EC model is primarily concerned with quantitative predictions while the TD model is more conceptual. From Fig. 1 it can be seen that the EC model predicts the MLD will asymptote at about 15 dB for NO Sπ below 250 cps.

Although the MLD at 200 cps (35 dB) may be considered in agreement with the EC prediction (if the advantage of an Sπ signal over SM is assumed to be 4-6 dB as it is at 500 cps), the MLD at 150 cps is discrepant. The data show that MLD decreases from 200 cps to 150 cps which is in conflict with the prediction. The dependence of both frequencies on spectrum level suggests either: 1) that the MLD at 200 cps was not degraded as much by internal noise as it was at 150 cps, or 2) MLD decreases with frequency (for the range studied). The latter interpretation seems more likely.

The TD model theorizes that improved detection under NO SM results because of an assumed interaural phase shift between the narrow bands of masking noise ("critical bands") at the ears. The interaural phase shift of the critical bands of noise is assumed to occur when the signal is added at one ear. The direction of the interaural phase shift is random and consequently favors one ear for some additions of the signal and the opposite ear for other additions. The magnitude of the interaural phase shift is determined by both the level of the signal relative to the level of noise (S/N ratio) and the phase difference between the signal and noise at the time of addition. Accordingly, the advantage of NO SM over NO SO (at 35 dB) would be accounted for by the ability of the hearing apparatus to detect the sudden changes in the timing of events at the ears (caused by adding a signal to the right ear against a background of noise in both).

This fails to explain the negligible MLDs found at 5 dB spectrum level. In other words, why was the detectability advantage of NO SM over NO SO lost at this low spectrum level? One interpretation is, of course, the one already discussed based on neural excitation. In addition, Jeffress (1965) has suggested that the preservation of the timing information in the stimulus (resulting from adding a signal to noise) is not perfect and this vagueness or "noise" may have the same effect on MLD as a reduction in interaural noise correlation. In other words, an interaural phase shift occurs regardless of the noise intensity. However, at a low noise intensity the interaural shift in the noise critical band is probably not preserved (retained) long enough for it to have an effect on the MLD. Further study may clarify this consideration.

CHAPTER V
SUMMARY

The present study dealt with the role of several variables (signal duration, frequency, and noise intensity) on masking-level difference (MLD). MLD was defined as the difference between threshold (75-80% correct responses) values for two listening conditions. Both listening conditions consisted of binaural noise (NO) with either a monaural signal (SM) or a binaural signal (SO). The MLD (measured in dB) represented the difference obtained in a comparison between the threshold values for NO SO and NO SM.

The experimental parameters of interest were: 1) signal frequency: 150 and 200 cps; 2) noise spectrum level: 5 and 35 dB; and 3) signal duration: 20, 60, and 100 msec. Each of the three Ss received a different random schedule of all possible combinations of these parameters (for NO SO and NO SM). Data were collected using a two-alternative forced choice procedure (2ATFC) in a repeated measures design. The dependent variable was MLD.

Significant relations were found for frequency, intensity, and the frequency-intensity interaction. Duration was not significant. The results indicated that the magnitude of the MLD at low frequencies was strongly dependent on the spectrum level of the masker. This is probably the most important variable upon which the MLD depends. It was also clear that the MLD resulting from a high (35 dB) spectrum level was different from the MLD at a low (5 dB) masker and the difference was strongly related to frequency. At the high spectrum level, the MLD at 200 cps exceeded those at 150 cps by about 5 dB; whereas, the difference was approximately 1 dB for the low spectrum level. Duration was not shown to be an important variable for predicting MLD size at the frequencies and masker levels studied.

The results were discussed in terms of: 1) the internal noise hypothesis; 2) masked thresholds for duration; and 3) two theories of binaural hearing. Two general conclusions were offered. First, MLD probably decreases as the signal frequency is lowered below 200 cps (although this is strongly dependent on the masker spectrum level). Second, the internal noise hypothesis was shown to be inadequate as a plausible interpretation of the present results.

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APPENDIX

TABLE 2

SUMMARY OF OVERALL ANALYSIS OF VARIANCE

SOURCE OF VARIATION	SS	DF	MS	F
Frequency	98.34	1	98.34	61.85**
Frequency x Ss	3.18	2	1.59	.09
Spectrum Level	437.50	1	437.50	18.54**
Spectrum Level x Ss	47.19	2	23.60	1.41
Signal Duration	9.05	2	4.53	2.34
Duration x Ss	7.74	4	1.94	.12
Subjects	33.51	2	16.76	
Frequency x Spectrum Level	41.18	1	41.18	37.78**
Frequency x Spectrum Level x S	2.17	2	1.09	
Frequency x Duration	3.39	2	1.70	1.06
Frequency x Duration x Ss	6.41	4	1.60	
Spectrum Level x Duration	9.73	2	4.87	4.43
Spectrum Level x Duration x Ss	4.40	4	1.10	
Frequency x Spectrum Level x Duration	.05	2	.03	.02
Frequency x Spectrum Level x Duration x Ss	4.90	4	1.23	
Total	708.74	35		

** Significant at $p < .05$

TABLE 3

SUMMARY OF SIMPLE EFFECTS ANALYSIS OF VARIANCE ON FREQUENCY -- INTENSITY INTERACTION

SOURCE OF VARIATION	SS	DF	MS	F
Frequency	98.34	1	98.34	90.22**
Frequency at 5 dB Spectrum Level	6.13	1	6.13	5.62
Frequency at 35 dB Spectrum Level	133.38	1	133.38	122.37*
Spectrum Level	437.50	1	437.50	401.38*
Spectrum Level at 150 cps	105.12	1	105.12	96.44**
Spectrum Level at 200 cps	373.55	1	373.55	342.71*
Frequency x Spectrum Level	41.18	1	41.18	37.78**
Frequency x Spectrum Level x Ss	2.17	2	1.09	
Total	579.19	5		

* Significant at $p < .01$

** Significant at $p < .05$