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MEASUREMENT OF THE 2F1-F2 CUBIC DIFFERENCE TONE WITH THE BINAURAL MASKING LEVEL DIFFERENCE

by

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"Not, however, until relatively recently did the basic premise begin to permeate our corporate thinking that life is very nonlinear."

Dallos (1973)

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VITA

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He has submitted the following papers for publication: Distortion of perceived onset in human vision: A duration dependent temporal illusion, to Perception and Psychophysics, 1979; Temporal interference of pitch perception: The effects of interference tone intensity, to Perception and Psychophysics, 1978; Two-tone unmasking in the forward masking procedure: Suppression or temporal cueing?, to Journal of the Acoustical Society of America, 1979; and Measurement of the 2f1-f2 cubic difference tone with the binaural masking level difference, to the Journal of the Acoustical Society of America, 1979.

TABLE OF CONTENTS

Chapter

LIST OF TABLES

LIST OF FIGURES

Figure Page

CONTENTS OF APPENDICES

CHAPTER I

INTRODUCTION

Two tones sounding simultaneously may give rise to the sensation of one or more additional tones. The additional tones are called combination tones. Musicians and composers have been aware of the existence of combination tones for many years. The earliest communications on a third clearly audible tone date back to the German organist Sorge (1744) and the Italian violinist and composer Tartini (1754). Tartini made good use of the phenomenon by establishing the audibility of the additional tone as a criterion for tuning his instrument. However, composers have been in general most intimately aware of combination tones for the unwanted dissonance they may produce in their musical compositions. The auditory scientist's interest in combination tones has waivered on and off since Helmoholtz's (1856) initial model of the ear as a linear frequency analyzer. To the auditory scientist, combination tones represent the clearest manifestation of the inherent nonlinearity of the ear.

As for any nonlinear system the response can often be complex and unpredictable. A nonlinear system might behave in a particular fashion for a certain combination of input parameters, yet another combination could result in an apparently unrelated or opposing behavior. For this reason, auditory scientists (e.g. Wightman, 1973), while acknowledging the ear's nonlinearity, have traditionally preferred to avoid the complexities implied by pursuing, as far as limits would allow, the study of the ear as a linear device amenable to linear systems analysis (see Appendix A). However, advances in computer technology and the development of computer techniques for solving complex nonlinear differential equations (Boyce and DiPrima, 1969) have in part been responsible for a recent revival of interest in the ear's nonlinearity, particularly in regard to combination tones and their physiological origin. Theoretical thinking is now more often guided by models (e.g., Yost, 1979) that describe the ear as a device possessing a nonlinear transfer characteristic (1).

Consider how combination tones are generated by one such transfer characteristic, that of an overloading nonlinearity as given by the classic power series expansion:

---

(1) A nonlinear transfer charachteristic describes the input-output relationship of a device that violates one or both of the conditions defining a linear system (see Appendix A).

$$F(x) = W_1x + W_2x^2 + \ldots + W_2x^n ,$$

where, x is the input waveform and W1 through Wn are weighting coefficients (2). If x is a superposition of two simple tones with frequencies f1 and f2 (f2 >f1):

$$x = a_1 \cos 2\pi f_1 t + a_2 \cos 2\pi f_2 t.$$

Or, for economy of notation,

$$x = a_1 f_1 + a_2 f_2.$$

The quadratic term, x^2, equals:

$$(a_1 f_1 + a_2 f_2)^2 = 1/2a_1^2 + 1/2a_2^2 + 1/2a_1^2(2f_1) + 1/2a_2^2(2f_2) + a_1a_2(f_2 + f_1) + a_1a_2(f_2 - f_1).$$

Thus, this term introduces combination tones with frequencies f2+f1 and f2-f1 with amplitudes proportional to a_1a_2. The cubic term, x^3, is equal to:

---

(2) The polynomial expansion is typically used to describe the response of physical systems driven beyond their dynamic range and is therefore often refered to as an overloading nonlinearity. It can be used to describe any monotonic input-output relationship to any degree of accuracy simply by choosing appropriate values of the weighting coefficients for a sufficient number of terms.

$$(a_1f_1 + a_2f_2)^3 = (3/4a_1^3 + 3/2a_1a_2^2)f_1 +$$
$$(3/4a_2^3 + 3/2a_1^2a_2)f_2 + 1/4a_1^3(3f_1) + 1/4a_2^3(3f_2) +$$
$$3/4a_1^2a_2(2f_1 + f_2) + 3/4a_1a_2^2(2f_2 + f_1) +$$
$$3/4a_1a_2(2f_1 - f_2) + 3/4a_1a_2(2f_2 - f_1).$$

This term introduces combination tones with frequencies 2f1+f2 and 2f1-f2 both with amplitudes proportional to $a_1^2a_2$, and combination tones with frequencies 2f2+f1 and 2f2-f1 both with amplitudes proportional to $a_1a_2^2$. Still higher order combination tones; 3f1-2f2, 3f2-2f1, etc., are generated by the higher order terms in the nonlinear transfer characteristic.

Of all combination tones, the 2f1-f2 cubic difference tone (CDT), so called because it is generated by the cubic term in the polynomial expansion, has held the most interest for auditory scientists. Unlike other combination tones, high stimulus levels are not needed for the 2f1-f2 CDT to be heard. It is audible at stimulus levels as low as 20 dB SL (Smoorenburg, 1972). The 2f1-f2 CDT figured substantially in early auditory theory and has since been shown to have functional significance for a number of auditory phenomena (Greenwood, 1972; Hall, 1972; Houtsma and Goldstein, 1972).

A cancellation procedure has been the standard method for measuring the 2f1-f2 CDT psychophysically. The cancellation procedure requires that a physical cancellation tone of frequency 2f1-f2 be present simultaneously in the same ear as the two primary tones that produce the CDT. However, recent studies suggest that the primary tones may interact with the cancellation tones when simultaneously in the same ear to distort measurements of the CDT (Smoorenburg, 1974; Smoorenburg et al., 1976; Greenwood et al., 1976; Houtgast, 1977; Goldstein et al., 1978). The resolution of this issue is essential for understanding discrepancies that exist between CDT psychophysics and physiology and as such bears on the question as to the physiological origin of the CDT.

The present investigation describes a new psychophysical procedure for studying combination tones that circumvents this potential interaction. The procedure makes use of a well established auditory phenomenon known as the binaural masking level difference (BMLD). The BMLD simply refers to an improvement in signal detectability that results from the use of two ears over one. In the procedure, the functional equivalent of the cancellation tone, a probe tone, is presented to the ear opposite the primaries and measurements are derived from a BMLD resulting from the interaction of this tone with the CDT. Confounding interaction between the probe tone and the primaries is avoided by having the probe and the primaries present in different cochleas.

With this procedure it is hoped that current discrepancies that exist between psychophysical cancellation data and physiological data on the CDT might be resolved, thereby helping to elucidate the physiological mechanism underlying CDT generation. The reasons for developing this new procedure and selectively applying it to the study of CDTs are discussed in more detail in following chapters.

CHAPTER II

LITERATURE REVIEW

A. Early History

Of all the distortion products produced by the ear in response to two tone stimulation, the 2f1-f2 CDT has undoubtedly played the most important role in the historical development of hearing theory. In 1843, Ohm formulated his famous definition of tone, which says that a tone with frequency m is heard only when the complex sound contains $a\sin(2\pi mt + p)$ as a component. Yet, many years before Ohm's Acoustic Law, Tartini (1714) first noted the pitch sensation of the CDT for which there existed no sinusoidal component of corresponding frequency in the physical stimulus complex. Von Helmholtz (1856, 1863) maintained Ohm's Law, but added the concept of a nonlinearity resulting from a mechanical overloading of middle ear structures at high stimulus levels to account for the perception of the CDT. The CDT was thus assumed to be analyzed after the middle ear at the "place" an acoustic tone of frequency 2f1-f2 is analyzed.

"Temporal" theorists of the time emphasized the persistent observation that the CDT is apparent at very low stimulus levels (Hallstrom, 1832) and is heard by people without tympanic membrane and ossicles (Bingham, 1897; Schaefer, 1899). The limited frequency resolution of the ear (Plomp, 1964) provided a basis by which temporal theorists explained the CDT through the interaction of unresolved frequency components in much the same manner that produces the sensation of beats.

Nevertheless, the nearly universal acceptance of Helmholtz's hearing theory brought with it general acceptance of the distortion hypothesis for the generation of the CDT. The origin of the CDT remained a dormant issue for several decades thereafter until subjective reports were replaced by psychophysical methodologies for obtaining quantitative measurements of the CDT.

B. Psychophysical Methodology and Results

1. Method of Best Beats

Two tones of approximately equal amplitude differing in frequency by a few cycles will produce the sensation of beats; a periodic waxing and waning of the loudness of the sound. The strength of the beats is greatest if the amplitudes of the two tones are equal. This simple observation provides the basis by which the method of best beats has been used to obtain level estimates of the CDT. A tone tuned two to three cycles off the frequency of the CDT is adjusted in amplitude so as to produce the strongest sensation of beats. The amplitude of the tone at this point is then taken as an estimate of the amplitude of the CDT.

The method of best beats is no longer used to measure CDT amplitude because of a critical problem of interpretation. The problem is that the perception of beats may simply result from the fluctuation of the temporal envelope of the entire stimulus waveform and thus have little to do with the CDT. For this reason the method of best beats is excluded form further consideration here. A more complete development of the criticism against the use of the method of best beats is given by Timmer and Firestone (1937).

2. The Cancellation Method

By far the most frequently employed procedure for measuring the CDT is the cancellation method. An attractive feature of this technique is that it enables estimates of both the phase and the amplitude of the CDT. In the cancellation procedure, a tone of frequency 2f1-f2 is adjusted in both level and phase so as to cancel the perception of the CDT. The level and antiphase of the tone that just cancels the perception of the CDT is then taken as an estimate of the level and phase of the CDT, respectively (Zwicker, 1955).

Cancellation studies indicate that both the level and the phase of the CDT are strongly dependent on the frequency separation of the primary tones; level decreasing by as much as 100 dB/octave (Goldstein, 1967). Since the basilar membrane is at least the first if not the only frequency selective element in the ear, this frequency dependence strongly implies that the CDT is generated at or subsequent to the basilar membrane in the cochlea, not in the middle ear structures as Helmholtz originally held. Moreover, for primaries of equal level, cancellation estimates of CDT level increase directly with stimulus level (i.e., 1dB/dB) not with the cube of stimulus amplitude (i.e., 3dB/dB) as the overloading type of nonlinearity originally advanced by Helmholtz predicts (Goldstein, 1967; Smoorenburg, 1972). Cancellation estimates of CDT phase also show a strong dependence on the level of the primaries; decresing anywhere from 3 to 18 degrees/dB (Goldstein, 1976; Smoorenburg, 1972).

The cancellation procedure requires that a probe tone (the cancellation tone) be present in the same ear as and simultaneous with the primaries. This situation allows potential interactions between the probe and the primaries to confound CDT cancellation measurements. For instance, it is now known from studies of two-tone suppression (Shannon, 1976) that under certain conditions higher amplitude tones (e.g. the primaries) may suppress the effective amplitude of lower amplitude tones (e.g., the probe). Also, recent evidence suggests that higher amplitude tones may distort the effective phase of lower amplitude tones (Houtgast, 1977). The recent demonstration of these types of interactions has thrown caution to the interpretation of cancellation measurements of the CDT and has caused investigators to search for alternative methods for performing CDT measurements. One approach has been to circumvent interaction between probe and primaries by temporally separating the probe from the primaries. This approach is discussed in the following section.

3. Nonsimultaneous Methods

Smoorenburg (1972, 1974) has presented data from two procedures yielding CDT level estimates with probe temporally separated from the primaries. In the so-called gap masking procedure, detection threshold for the probe is measured with the primaries as maskers occuring both immediately before and after the probe. The level of the CDT is then estimated by the level of a referent masker of the probe frequency that produces an amount of masking equivalent to that produced by the primaries. The gap masking procedure is somewhat inefficient in that it requires many followup observations with the referent masker to obtain meaningful estimates of CDT level.

A more direct estimate is obtained with the second nonsimultaneous method used by Smoorenburg (1974); the pulsation threshold technique. In this procedure, the probe is alternated with the primaries and the level of the probe is adjusted by the subject so as to produce a just detectable pulsating sensation (the pulsation threshold). The level of the probe at pulsation threshold is then taken as a direct estimate of CDT level. Pulsation threshold estimates of CDT level as a function of primary level are compared to cancellation estimates for a single subject in the upper panel of Figure 1. Note that above 25 dB level of the primaries, cancellation level estimates are consistently above corresponding pulation threshold estimates, greater by as much as 20 dB. The difference in level estimates produced by the two procedures has been attributed to suppression of the cancellation tone by the primaries in the cancellation procedure (Smoorenburg, 1972). Presumably, cancellation tone levels must overestimate CDT level to override the suppressive effects of the primaries. Such suppressive effects are presumed absent in the pulsation threshold procedure because the probe is temporally separated from the primaries.

C. Essential Nonlinearities

Both Goldstein (1967) and Smoorenburg (1972) have described the dependence of CDT level on primary level with essential nonlinearities. An essential nonlinearity is one in which the relative amount of distortion remains nearly constant with input level. In this section the essential nonlinearities advanced by Goldstein and Smoorenburg are discussed.

1. Goldstein's Normalized Power Series Expansion

Recall from the introduction that the magnitude of the 2f1-f2 component generated by the cubic term in the classic power series expansion increases as the cube of stimulus amplitude (i.e., proportional to $a_1^2 a_2$). This translates to a 3 dB/dB growth in the 2f1-f2 component with stimulus level, clearly incompatible with the 1 dB/dB growth indicated by the cancellation data.

To better account for the growth of the CDT with stimulus level (Goldstein, 1967) proposed what he refers to as a normalized version of the power series expansion. If the classic power series expansion is written as

$$f(x) = x[W_0 + \sum_{n=1}^{\infty} W_n x^n],$$

the nonlinear system described by Goldstein is given by

$$f(x) = x[W_0 + \sum_{n=1}^{\infty} W_n (x/a_p)^n],$$

where, each term in the expansion is normalized by the peak amplitude (a_p) of the input signal x. For an input comprised of two sinusoids with amplitudes a_1 and a_2, a_p assumes a value of $a_1 + a_2$. Goldstein's normalized model therefore predicts the amplitude of the 2f1-f2 component to be proportional to $a_1 a_2 / (a_1 + a_2)^2$. The resulting growth of the 2f1-f2 component with input level is such that the relative amount of distortion remains constant as is reflected in a 1dB/dB growth of this component for equal level primaries.

Although Goldstein's normalized power series nonlinearity provides a better description of the behavior of the CDT than does the classic power series, an objection to this model has been raised. The objection acrues from the fact that because Goldstein's nonlinearity incorporates a normalizing factor equal to the peak amplitude of the input, some time must be required to accomplish this normalization. Such nonlinearities requiring time are said to have a memory. Smoorenburg (1974), however, has presented data which have been taken in support of a memoryless nonlinearity. The data are from a forward masking paradigm in which the duration of the primaries as short as 24 msec had no measurable effect on CDT generation. Still, existing data does not completely rule out a nonlinear system with a memory since it is entirely possible that the time needed for normalization is simply less than 24 msec. Indeed, modelling results of Crane (1972) suggest a time constant on the order of 5 msec.

2. Smoorenburg's vth Law Device.

Smoorenburg (1972) suggested as an alternative model of CDT behavior a different type of essential nonlinearity. The nonlinearity proposed by Smoorenburg is referred to as a vth law device and is expressed as follows:

$$f(x) = x^{v},\ x>0$$

and

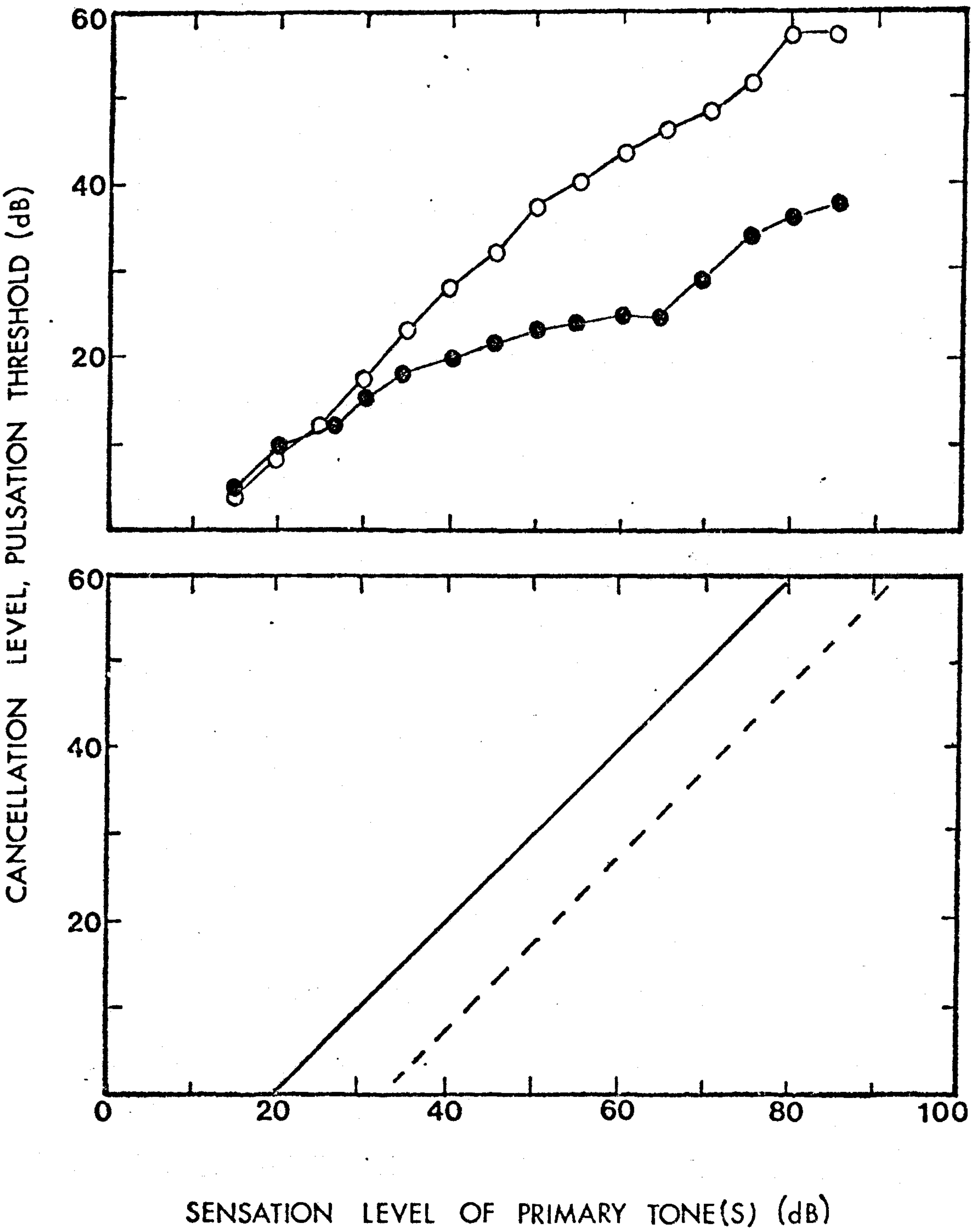
$$f(x) = -|x|^{v},\ x<0$$

where v<1. The vth law device is an essential nonlinearity by virtue of its not containing a linear term. The absence of a linear term forces the relative amount of distortion to be nearly constant with input level.

Some advantages of the vth law device are its instantaneous (memoryless) response and its ability to account for many properties of the nonlinear phenomena of two-tone suppression (Duifuis, 1976; Smoorenburg, 1974). The latter feature derives from the compressive nature of the device (i.e., high amplitude components suppress the amplitude of lower amplitude components). The lower panel of Figure 1 illustrates this property and its ability to account for the difference between cancellation and pulsation threshold estimates of CDT level. The panel shows the dependence of the 2f1-f2 distortion product level on primary level predicted by the vth law device for v = 0.6. This particular value of v has been suggested for use when describing data on the growth of the CDT with primary level (Smoorenburg, 1972). The solid line gives the predicted growth of the CDT with compression of the probe included. The dashed line gives predicted growth without compression.

FIGURE 1

Theoretical and obtained growth of the CDT
with primary level for cancellation
and pulsation threshold procedures.


CANCELLATION LEVEL, PULSATION THRESHOLD (dB)
60
40
20
60
40
20
0
20
40
60
80
100
SENSATION LEVEL OF PRIMARY TONE(S) (dB)

B. Current Issues.

Current research effort evolving from initial cancellation studies has been divided between psychophysics and physiology bearing upon two important issues. The first issue is the basic stimulus-like properties of the CDT. The second issue concerns the physiological origin of the CDT. Both these issues are considered in detail in this section.

1. Stimulus-like Properties

Psychophysical studies reveal that the CDT behaves as if a tonal component at 2f1-f2 were actually present in the physical stimulus complex. The first indications of the stimulus-like properties of the CDT were provided by the cancellation studies of Zwicker (1955) and Goldstein (1967), namely, its pitch quality, loudness equivalence, beating, and cancellation with an external tone. Subsequent investigations have made clear still other stimulus-like properties of the CDT as well as the functional significance these properties have for a number of auditory phenomena.

Greenwood (1971, 1972) demonstrated that the CDT acts as an effective masking stimulus, and that combinations of narrowband noise stimuli or narrowband noise and line spectra generate combination bands which also act as effective masking stimuli. He has convincingly argued that the pronounced notch observed just above masker frequency in the classic masking patterns of Egan and Hake (1950) can be attributed to the detection of combination tones or bands generated just below the masker frequency. The argument is based on his demonstration that a narrow band masker in the frequency region of the notch has little or no effect on the notch, whereas a narrowband masker in the region where combination tones or bands are expected can eliminate the notch entirely. Smoorenburg (1972) provided additional masking data to show that the CDT acts as an effective temporal masking stimulus.

Hall (1972a) accounted for a monaural phase effect for two primary tones in the frequency ratio f1:f2 = 2:3 by physical vector summation of 2f1-f2 and f2-f1 distortion products. At this frequency ratio the 2f1-f2 and f2-f1 distortion products are of the same frequency. Thus, depending on the phase angle between the two primary tones these distortion products, like physical tones, either cancel or reinforce so that changes in the phase angle between the two primary tones are accompanied by changes in the perceived quality of the sound. Buunen et al. (1974) similarly accounted for a monaural phase effect for three tone harmonic complexes by vector summation of the CDT with the lowest frequency component in the complex.

A more striking demonstration of the equivalence of CDTs and physical tones is provided by Hafter et al.

(1973) who found that a CDT in one ear and an external tone of the same frequency in the opposite ear produces a lateralized image that varies with the relative phase of the tone. The image can be centered by appropriate adjustments in both the level and relative phase of the tone (Sachs and Zurek, 1977). Moreover, Zurek and Leshowitz (1976) have shown that interaural phase discrimination of the CDT and a tone of the same frequency to the other ear is quantitatively similar to that of physical tones.

Finally, the binaural pitch experiments of Houtsma and Goldstein (1972) indicate that CDTs are treated as effective tonal components in the pitch extraction process for complex stimuli, and as such, resolve questions raised by Ritsma's (1967) data regarding the so-called second effect of the pitch shift. This effect refers to a somewhat larger shift in the pitch of inharmonic tone complexes shifted in frequency than is predicted by the frequency shift of the central component of the complex. The effect puzzled auditory scientists until Houtsma and Goldstein (1972) and others (Smoorenburg, 1970) demonstrated that CDTs, processed as effective tonal components in the complex, shift the effective central component to a lower rank number where a given shift in frequency produces a larger corresponding shift in pitch.

2. Physiological Origin

The second issue regarding the CDT concerns the physiological basis for its perception. Stimulus-like properties of the CDT revealed by psychophysics suggest that the CDT is generated by a nonlinearity in the mechanical motion of the basilar membrane. However, intracochlear recordings have not evidenced a 2f1-f2 component that behaves in a manner compatible with that of the psychophysical cancellation data. The amplitude of the 2f1-f2 component of the cochlear microphonic (CM) is no less than 35-60 dB below equal level primaries and is little affected by the frequency separation of the primaries (Dallos, 1970). Moreover, at moderate stimulus levels (below 80 dB SPL) the 2f1-f2 component of CM is not generated at the 2f1-f2 place along the basilar membrane, as might be expected for a tone of frequency 2f1-f2 to cancel the CDT (Dallos, 1970). Measurements of basilar membrane motion using capacitive probe technique (Wilson and Johnston, 1975) and Mossbauer effect (Rhode, 1977) also fail to show a significant 2f1-f2 component, even though specifically investigated. Thus, a simple mechanical correlate of the psychophysical CDT may not exist on the cochlear partition.

Alternatively, phase locking and selective tuning to a 2f1-f2 referent has been found in both the activity of single nerve fibers in the eighth nerve (Goldstein and

Kiang, 1968) and in anteroventral cochlear nucleus (AVCN) (Smoorenburg, et al., 1976) of the cat. In almost every respect the behavior of the neural response agrees well with CDT psychophysics. True to the stimulus-like properties of the CDT, the discharge rate and phase locking response of fibers with a range of characteristic frequencies (CFs) can be cancelled with a 2f1-f2 tone of appropriate phase and amplitude. Moreover, cancellation amplitudes of the neural response and comparable psychophysical cancellation data show a near equivalent dependence on frequency separation and level of the primaries. The phase of the neural response in period histograms does not, however, show the same sharp dependence on level of the primaries as in CDT psychophysics (Goldstein and Kiang, 1968; and Goldstein, 1970).

The question raised by this one discrepancy is whether the cancellation procedure or a psychophysical difference between humans and cats is responsible. An answer to this question is of major importance for determining the manner is which CDT's and real tones propagate in the cochlea and are subsequently transduced (Goldstein, et al., 1978). CDT phase has been assumed to reflect the travel time of the CDT from place of generation to the detection site (Buunen and Rhode, 1978). Thus, in the absence of evidence from intracochlear recordings for a traveling wave along the basilar membrane corresponding to the CDT, CDT phase dependence on primary level has implications for the manner in which CDTs and physical tones may propogate to their site of analysis. Recent psychophysical and physiological studies suggest, however, that an explanation of the phase dependence on primary level may be found in a potential intrusion inherent in cancellation estimates.

Smoorenburg, et al, (1976) measuring the response of single cells in the AVCN of cat found no significant change in phase with stimulus level in agreement with Goldstein and Kiang (1968). Like Goldstein and Kiang (1968) the phase of the CDT was determined directly from PST histograms, no cancellation estimates of phase were reported in these studies. Greenwood, et al., (1976) also measured from AVCN of cat but found a clear phase dependence on stimulus level. However, Greenwood, et al.'s (1976) measurements were taken from phase adjustments of a cancellation tone at 2f1-f2 which minimized the neural response rate in fibers with CF at 2f1-f2. The implication of these two studies taken together is that while the phase of a cancellation tone is affected by stimulus level the phase of the CDT itself is not. Consistent with this notion is Smoorenburg's et al., (1976) observation in the same study that the phase of the neural response to the f1 primary is influenced by the level of the f2 primary.

Psychophysical data consistent with this notion comes from a recent study by Houtgast (1977). Subjects judged whether the lateralized image of a 500-Hz tone was to the right or left of midline as the interaural phase difference of the tone was rotated through 360 degrees. The observation of primary interest was that when a second tone of greater amplitude and higher frequency (much like the f1 primary in relation to the cancellation tone) was presented to one ear, the interaural phase difference of the lateralized tone yielding 50% right judgements shifted by as much as 90 degrees. Again, this result suggests that cancellation tone phase may be distorted by the f1 primary in the cancellation procedure, and that an apparent CDT phase dependence on primary level may be due to this distortion.

The only direct support for this notion, however, comes from a study by Goldstein, et al. (1978). In the study, the interaction between primaries (f2, f3) and cancellation tone was avoided by spatial separation of the cancellation tone from the primaries. CDT phase was inferred from psychophysical cancellation measurements of a secondary CDT (SCDT) generated by the interaction of the first CDT with a third primary of lower frequency (f1). If the phase of the first CDT (2f2-f3) varies with the level of the primaries, f2 and f3, that generate it, the phase of the SCDT (2f1-fCDT) should vary directly, since according to the phase referent chosen, the phase of the SCDT (ϕSCDT) changes with $2\phi1-\phi$CDT. The phase of the SCDT was found to be independent of the level of the f2 and f3 primaries, indicating psychophysical independence of CDT phase and primary level.

Clearly the development and application of other nonintrusive psychophysical measures of CDT phase are required before it may be concluded that both psychophysically and physiologically CDT phase is independent of stimulus level. The present study is largely motivated to provide such measurements. However, before considering the logic of the present approach a brief discussion of the BMLD phenomenon is in order.

CHAPTER III

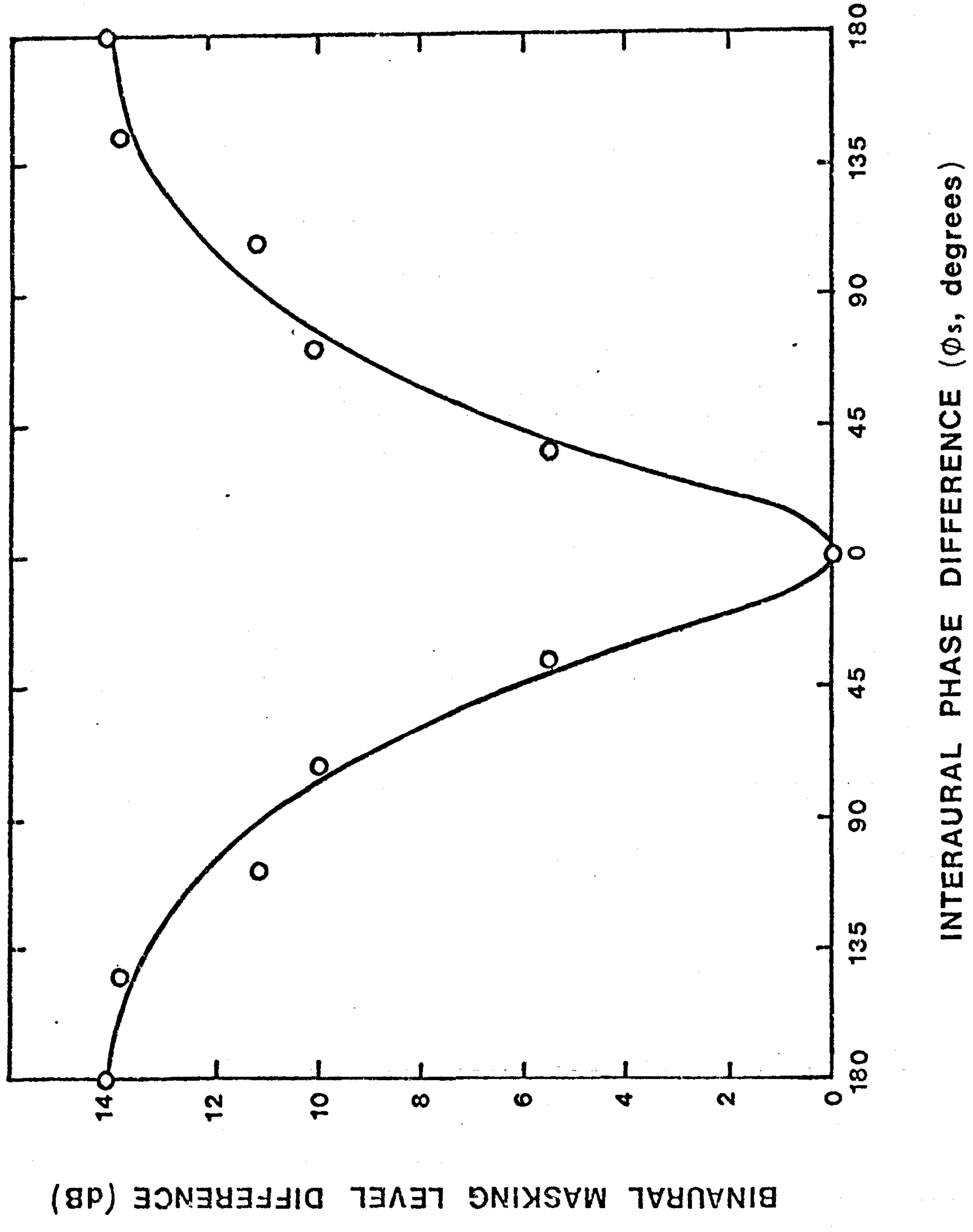
THE BINAURAL MASKING LEVEL DIFFERENCE

The binaural masking level difference (BMLD) refers specifically to an improvement in signal detectability that results from the binaural auditory system's use of interaural differences that exist for the signal or the noise. The largest BMLD, obtained by inversion of the signal between the two ears (SπNo), typically amounts to a 12 to 16 dB improvement in signal detectability relative to diotic signal and noise (SoNo) (Durlach and Colburn, 1977). In addition to being one of the largest magnitude effects observed among psychoacoustical phenomena the BMLD is a well documented phenomenon and is clearly evidenced by all normal hearing subjects under a variety of stimulus conditions (Hirsh, 1948; Rilling and Jeffress, 1965; Colburn and Durlach, 1965; Green and Yost, 1975).

Figure 2 presents data (open circles) from the classic study of Jeffress, Blodgett and Deatherage (1952) demonstrating the BMLD for a 500-Hz sinusoidal signal in diotic broadband noise as the interaural phase difference of the signal is varied through 180 degrees. The BMLD is expressed on the ordinate as the improvement in signal detectability in decibels relative to threshold for the diotic signal in the noise. Note that the BMLD is a

FIGURE 2

The binaural masking level difference
for a 500-Hz tone in broadband noise
as a function of the interaural
phase difference of the tone
(after Jeffress, Blodgett,
and Deatherage, 1952)


BINAURAL MASKING LEVEL DIFFERENCE (dB)
0
2
4
6
8
10
12
14
180
135
90
45
0
45
90
135
180
INTERAURAL PHASE DIFFERENCE (φs, degrees)

maximum of 14 dB at 180 degrees interaural phase difference and converges rapidly to a minimum at 0 degrees interaural phase difference.

A quantitative description of the BMLD as a function of the interaural phase difference of the signal is given by Durlach (1963). The expression is as follows:

$$\mathrm{BMLD} = 10\log[(k-\cos\phi s)/(k-1)],$$

where k is the only free parameter estimated from the data, and ϕs is the interaural phase difference of the signal. The solid curve drawn in Figure 2 is a theoretical prediction based on the expression above, where k was chosen to minimize the sum of the squared deviations between the data and the predictions (least squares criterion). The fit to the data is excellent -- the standard error of estimate averaging less than 0.6 dB. The availability of a precise quantitative description of the BMLD for these conditions will be of use in the next section where the BMLD is applied to the study of the CDT.

CHAPTER IV

APPLICATION OF THE BINAURAL MASKING LEVEL DIFFERENCE TO THE STUDY OF THE CUBIC DIFFERENCE TONE

Herein follows an attempt to study the behavior of the 2f1-f2 CDT by way of the BMLD phenomenon. The motivating reasons for taking this new approach are based on the issues discussed above. They are:

1) to determine whether, as the stimulus-like property of the CDT implies, a BMLD can be obtained for a CDT,
2) to provide convergent psychophysical evidence regarding the physiological origin of the CDT,
3) to provide nonintrusive measurements of the CDT in hopes of resolving the discrepancy that exists between CDT psychophysics and physiology regarding phase dependence on stimulus level.

The study is conducted in two stages. The first stage addresses objectives 1) and 2), while the second stage addresses objective 3). Specific details of the approach and the logic underlying the application of the approach for an understanding of the issues is presented in the following sections.

A. Stimulus-like properties of 2f1-f2 CDT.

The first issue relates to the stimulus-like properties of the 2f1-f2 CDT. If the CDT truely behaves in all respects like a stimulus tone, the detectability of a signal tone in one ear at frequency 2f1-f2 should be enhanced by addition of a CDT generated out of phase with the signal tone in the other ear. Added evidence would then have been obtained for the stimulus-like properties of the CDT. The strong correlation that exists between BMLD and lateralization data (Durlach and Colburn, 1977) in conjunction with the already established ability of listener's to lateralize CDTs with tones to the opposite ear attests to a high probability of success with this approach.

Experiment I

Purpose: Preliminary test to determine if a BMLD exists for a signal tone in one ear with a CDT of the same frequency generated in the other ear.

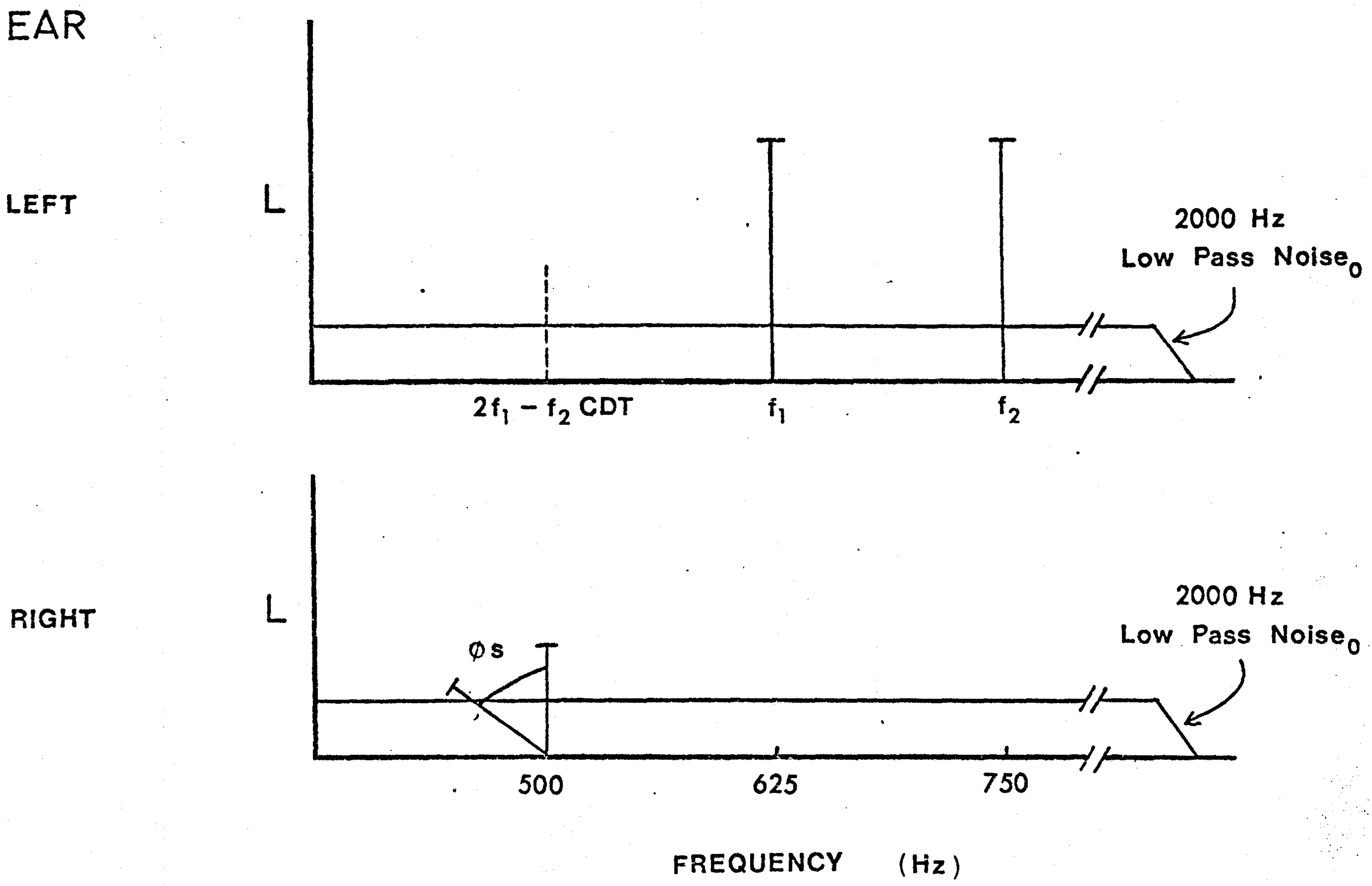
Subjects: Four subjects with normal hearing, age 20-27 years volunteered their services for the experiment.

They were each paid $3.10 /hour for their participation.

Stimuli and Apparatus: Figure 3 illustrates the stimulus configuration. Primary and signal tones were computer (PDP 8/e) generated at a 10k sampling rate. Primary tones (625-Hz, 750-Hz) were led to one ear through one D/A converter, the signal tone (500-Hz) was led to the other ear through a separate D/A converter. The output of each D/A converter was led through the two stages of separate Khron Hite (334R) filters each with a 2kHz low pass cutoff. The relative phase of signal and primary tones was computer controlled. Primaries

FIGURE 3

Diagram for the stimulus configuration
of Experiment I


EAR
LEFT
L
2000 Hz
Low Pass Noise$_0$
$2f_1 - f_2$ CDT
f_1
f_2
RIGHT
L
ϕs
2000 Hz
Low Pass Noise$_0$
500
625
750
FREQUENCY (Hz)

were programmed at cosine (0 degrees) starting phase while signal phase relative to the primaries varied at 0, 45, 90, 135, 180, 225, 270 and 315 degrees (3). The levels of the signal (30-dB SPL) and primary (65-dB SPL) tones were calibrated by external attenuators. The level of the signal is chosen to approximate the level of the CDT generated by 65-dB primaries for f2/f1 = 1.2 (see Smoorenburg, 1974). Error in this estimate is not expected to strongly affect a potential BMLD as Egan (1965) has obtained BMLD's as large as 5-dB for interaural intensity differences as large as 10-dB. All tones were shaped by external switches with a 10 msec rise and decay time and had a total duration of 400 msec. A continuous low pass noise generated by passing the output of a General Radio (445C) noise generator through the two stages of a Spencer-Kennedy (302) filter with 2000-Hz cutoff comprised the masking stimulus. The level of the low pass masking noise was controlled by a programmable attenuator. All stimuli were presented over TDH-49 impedance matched

(3) All permutations of these three phase angles need not be studied as de Boer (1961) has shown phase induced perceptual effects of a harmonic complex to be independent of a linear plus constant phase transformation. This means that the above complex with phase angles ϕ_s, ϕ_1 and ϕ_2 is perceptually equivalent to the complex with phase angles θ, 0, and 0, respectively, where:

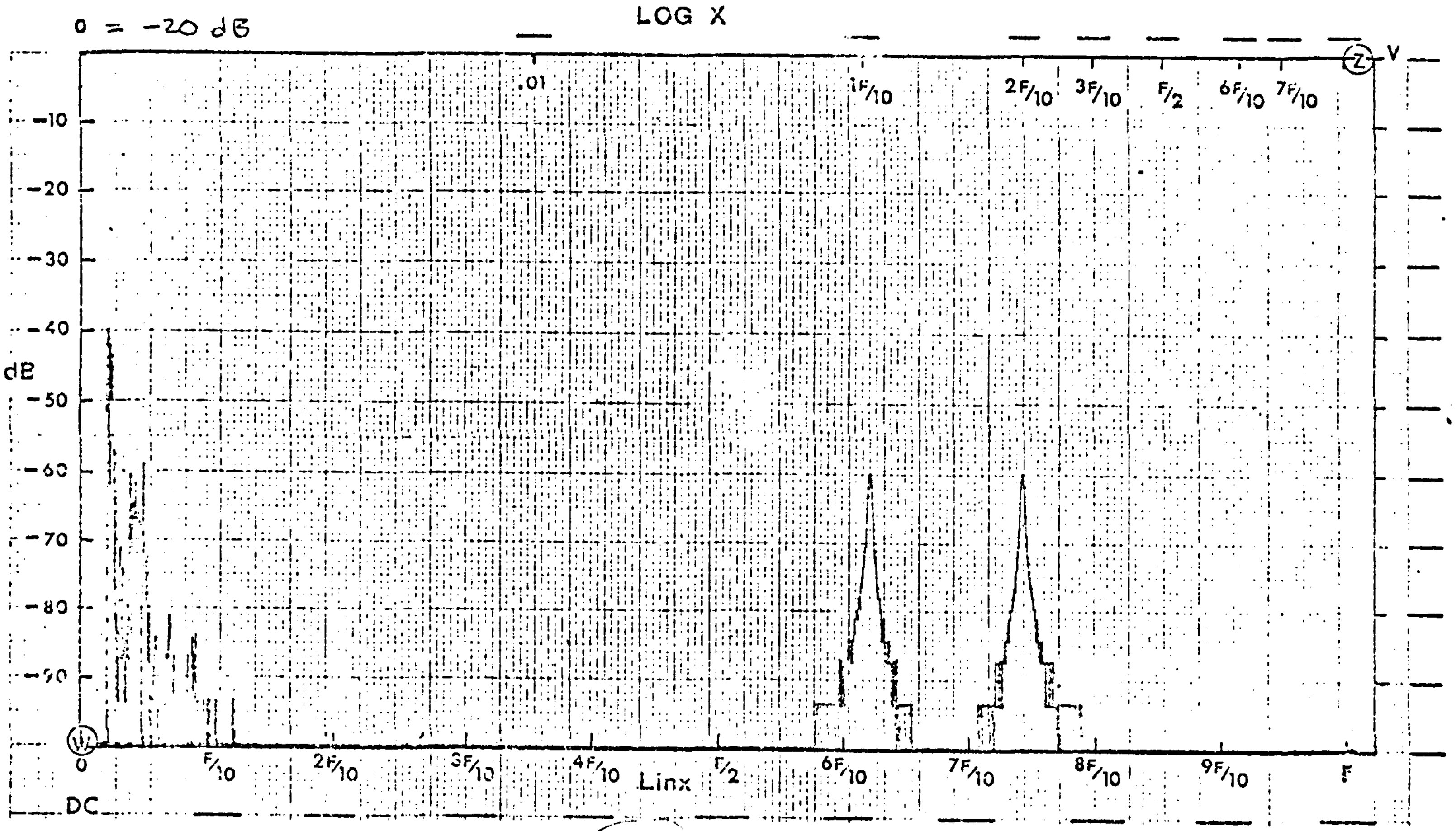
$$\theta = \phi_s - (\phi_1 + \phi_2)/2.$$

Thus, the effects of all three phase angles are conveniently described by only one effective phase angle, θ, which varies directly with ϕ_s.

headphones. Figure 4 shows no distortion measured at the output of the headphones for the highest level of the primaries used (i.e. 85-dB SPL).

FIGURE 4

Spectral content of the output of the headphones for 85-dB SPL primaries.



F = Analysis range = 1K

V = Sensitivity = 10

Average: [✓ No]

Yes, number ____

Clock: [✓ internal]

external, rate ____

Transient capture: No [✓ Yes]

Weighting: Flat [✓ Hann]

Alais: [✓ In] Out

No. points: 1024 [✓ 2048]

Redundancy: Max

R = 1

Procedure: Signal thresholds for each relative signal phase were obtained in a two interval same-different adaptive procedure (4). The two observation intervals were marked by lights and separated by 600 ms. The first observation interval was a standard and always contained the primaries without the signal. In the second observation interval the primaries were always present but the signal occured randomly across trials. Subjects were instructed to indicate whether or not the second observation interval appeared to contain the signal. For two consecutive correct responses, noise level was increased by 2-dB. For one incorrect response noise level was decreased by 2-dB. Feedback was given after a 1.5 second response interval. The trial sequence continued until 100 trials were completed and/or twenty reversals

(4) In an initial experiment thresholds were obtained using a two-interval forced choice (2IFC) adaptive procedure. This procedure yeilded an unacceptable amount of variability (see Appendix A). Subjects often reported being confused in the 2IFC task by having clearly detected the "signal" in the nonsignal interval. Confusions of this type could be expected when signal phase approaches that of the CDT and so approximates the SoNo condition for physical tones. For this case, the CDT may be clearly audible when the signal is absent, whereas the presence of the signal may cause both the CDT and the signal to become inaudible. This is because without the signal, the CDT to one ear is analogous to the dichotic condition of signal to one ear (SmNo) which can amount to an 8-dB improvement in detectability over the SoNo condition. Thus, when the signal is present the subject may only detect the CDT in the interval in which the signal is absent, and so confuse the CDT for the signal. The same-different procedure was used to remedy this situation by providing the subject with a standard interval known not to contain the signal which could be used as a referent to judge whether the signal, not just the CDT, was heard in the nonstandard interval.

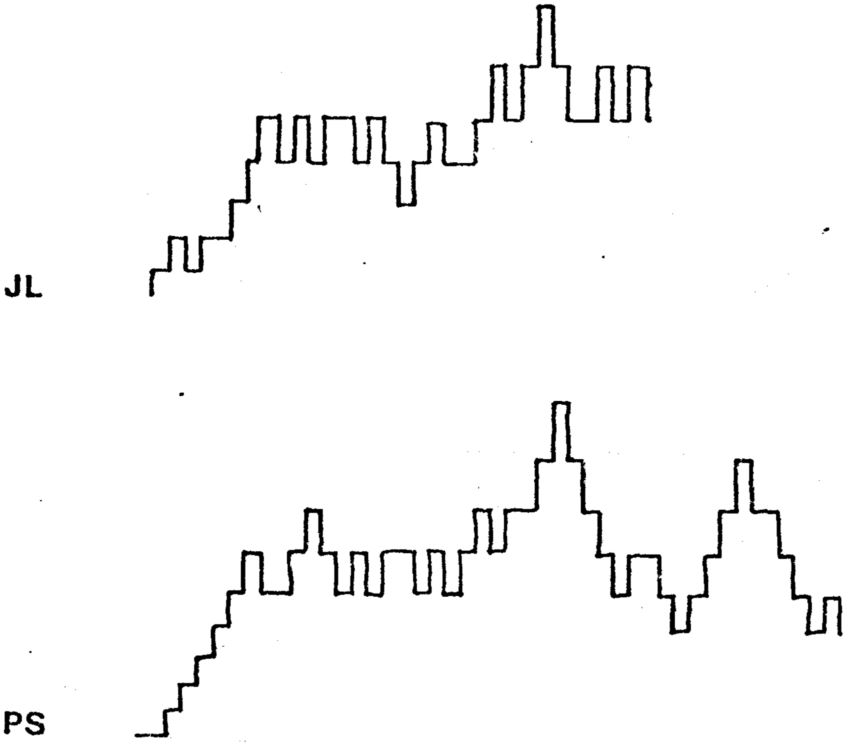
were obtained. A reversal is defined as a change in the direction of noise attenuation. If twenty reversals were not obtained after 100 trials, the trial block was discarded. Otherwise, the first four reversals were ignored and the average of the stimulus values for the remaining reversals established a threshold (5). Figure 5 gives representative examples of the increments and decrements in noise attenuation over a trial sequence. The average of two threshold estimates within 3-dB SPL of each other determined a data point. If more than two thresholds estimates were within 3-dB of each other, the last two were averaged as a data point. Typically, no more than two estimates were required per data point.

Subjects performed an hour each day for four consecutive days of each week until criterion for all data points had been met. Within the hour, subjects were given three breaks at about 15 min. intervals of each other. The first and third breaks were brief, the second break was longer.

(5) This procedure for threshold estimation was adopted after Levitt (1971) for its reltive effeciency, robustness, and low estimation bias.

FIGURE 5

Representative examples of the course
of noise attenuation over
a trial sequence
(two subjects).


JL
PS

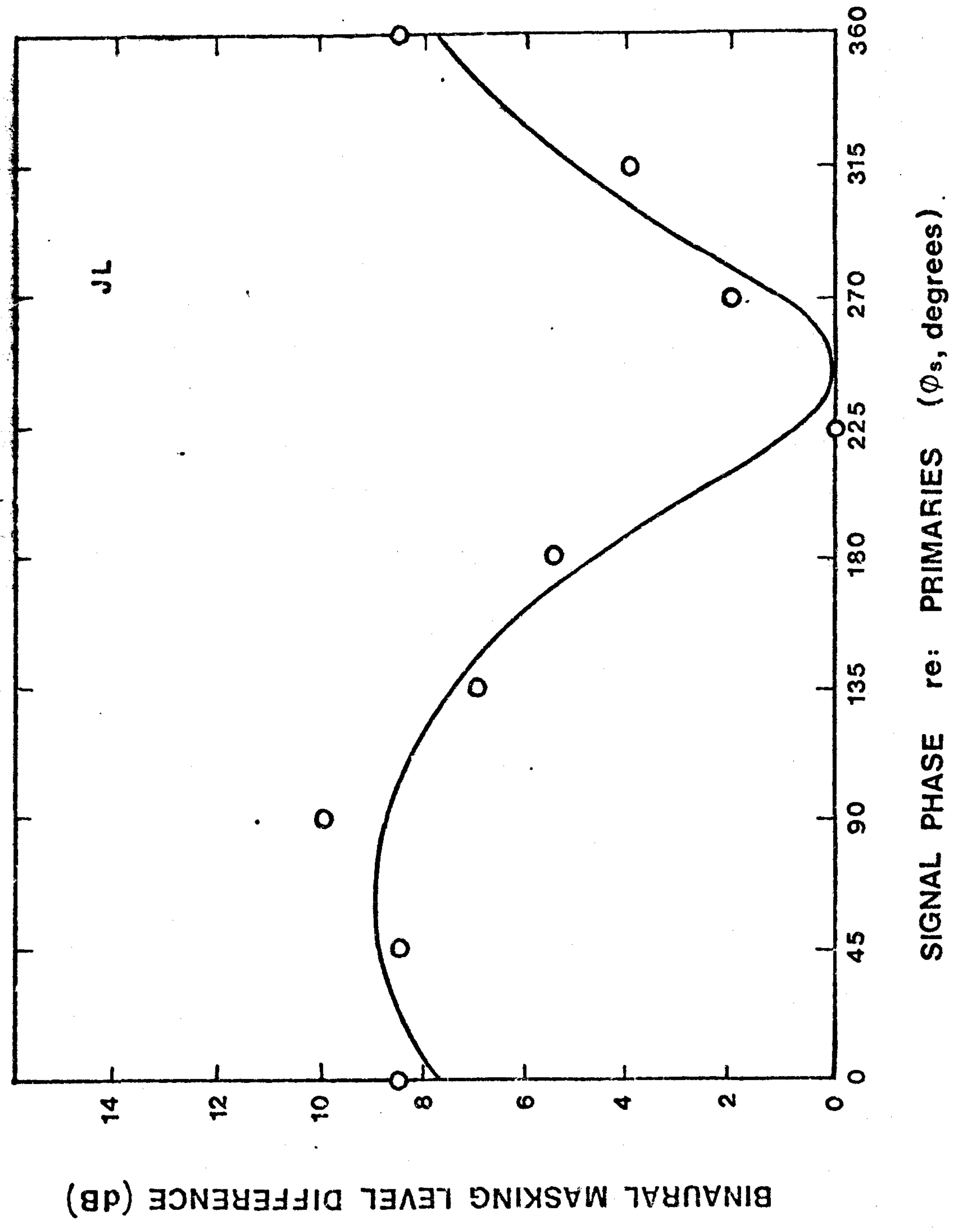
Results: In order to measure the data of Experiment I against the theoretical description of the BMLD for physical tones given by Durlach (1963), the threshold signal-to-noise ratios were transformed to BMLDs by the following rule:

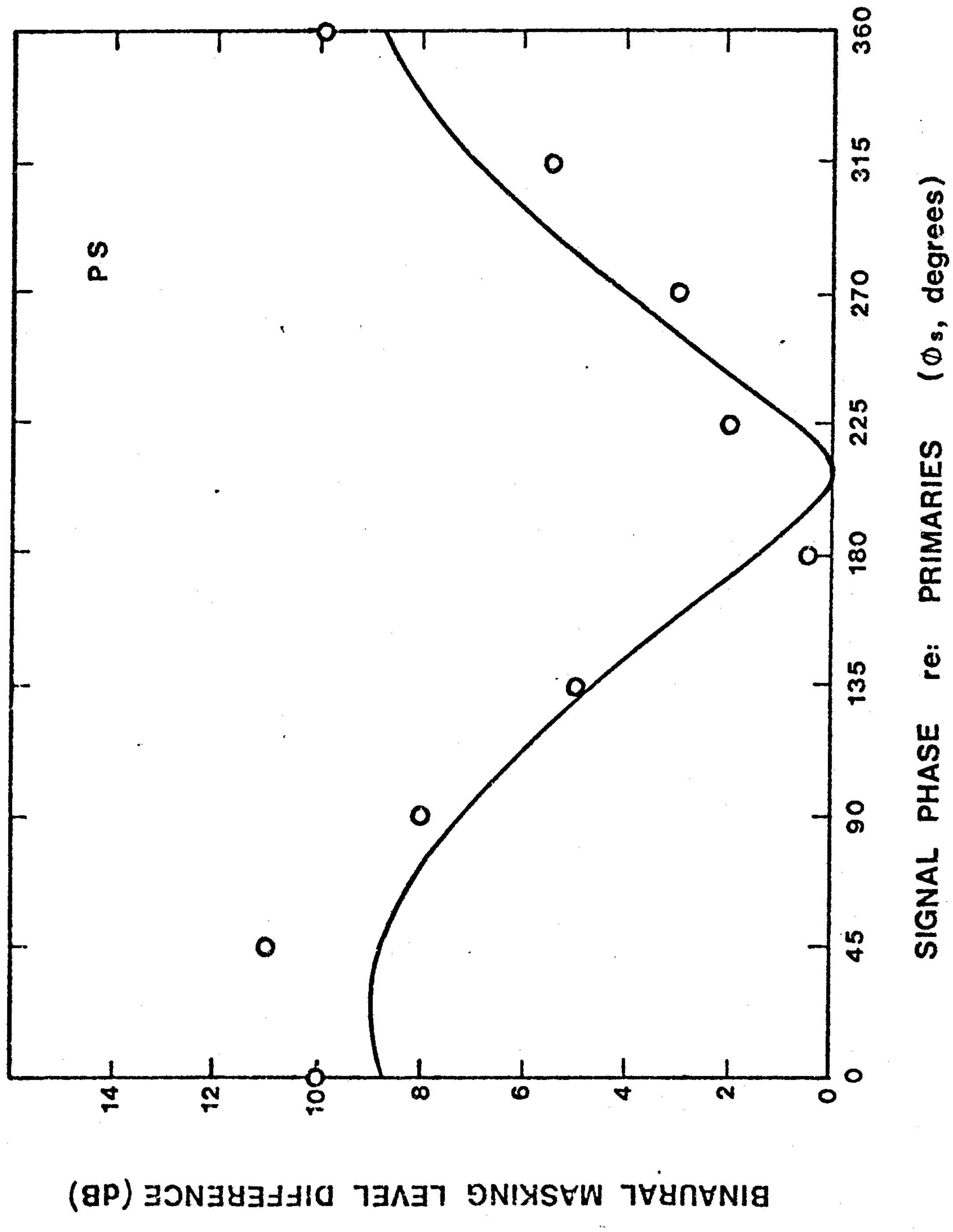
$$\mathrm{BMLD}_d(\phi s) = C - 10\log(E/No \text{ @ Thresh.})$$

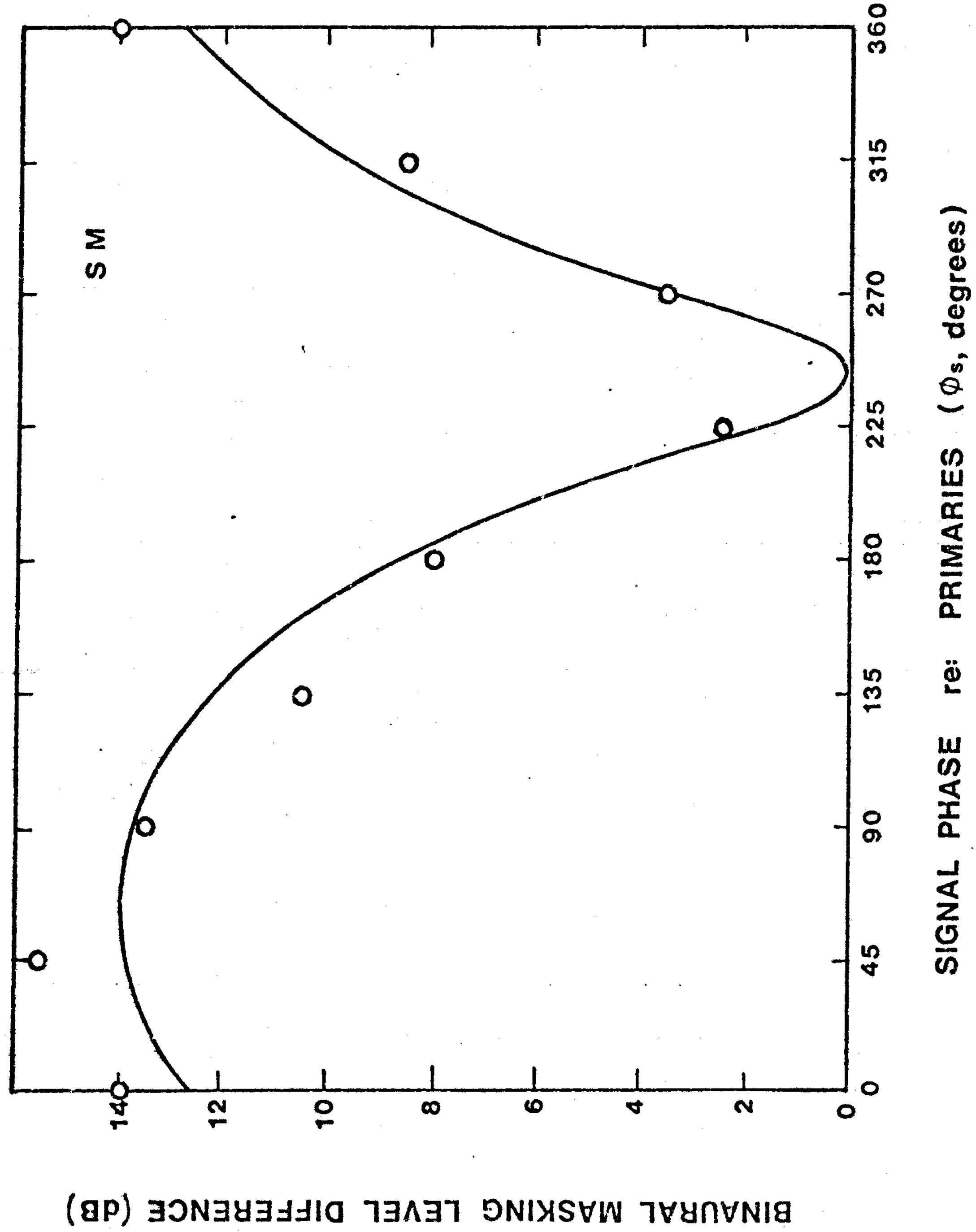
where C is a constant representing the signal to noise ratio for 0 interaural phase difference between the signal and the CDT. The relative phase of the CDT is unknown, therefore, C is a free parameter estimated from the data. The data for the four subjects are expressed as BMLD_d values by the open circles in Figures 6 through 9, where the BMLD is given as a function of signal phase (ϕs) relative to the primaries.

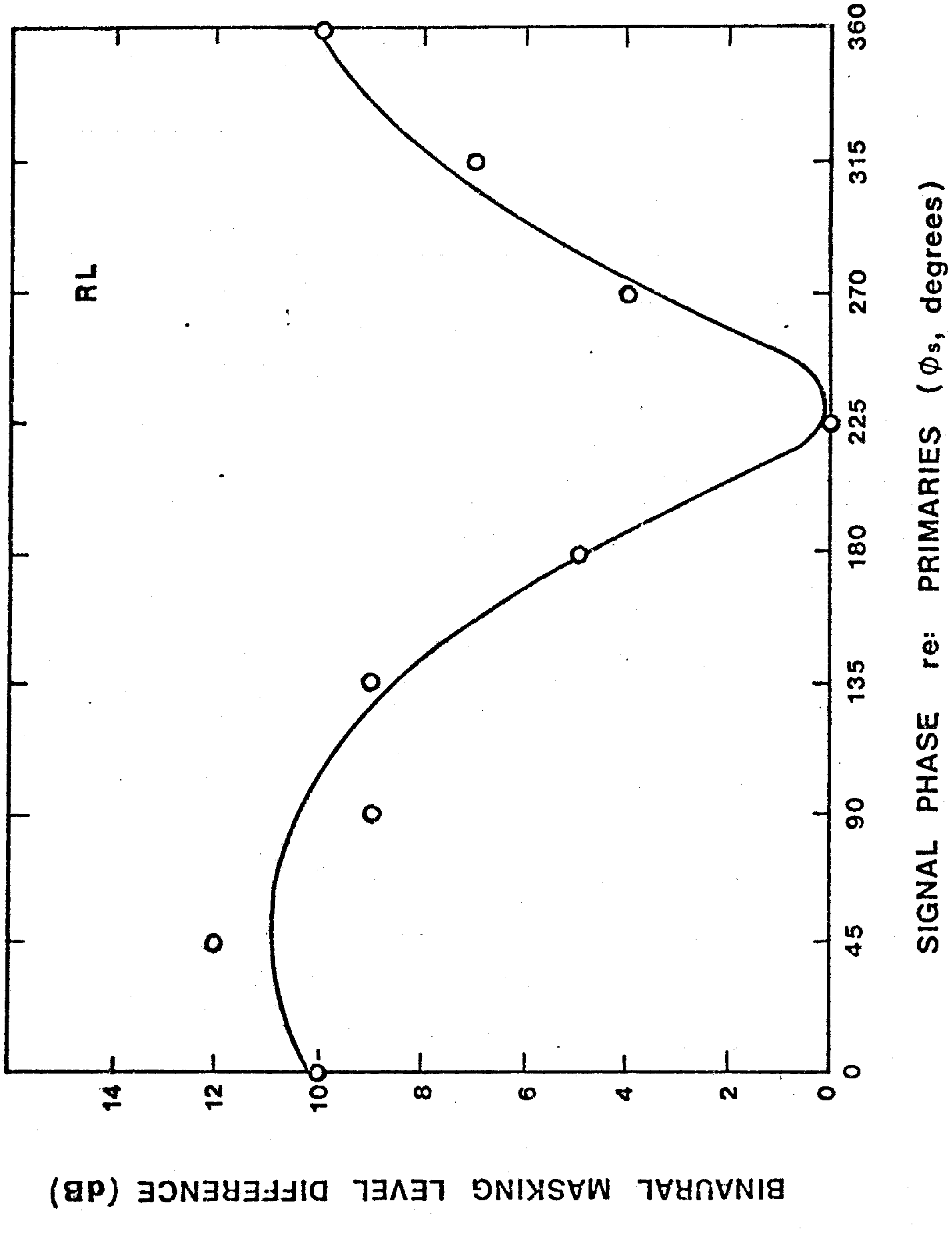
FIGURES 6 THROUGH 9

The binaural masking level difference as a function of signal phase (ϕs) relative to the primaries for four subjects. Circles are data, the curve is theoretical.


JL
BINAURAL MASKING LEVEL DIFFERENCE (dB)
0
2
4
6
8
10
12
14
SIGNAL PHASE re: PRIMARIES (ϕ_s, degrees)
0
45
90
135
180
225
270
315
360


PS
BINAURAL MASKING LEVEL DIFFERENCE (dB)
0
2
4
6
8
10
12
14
SIGNAL PHASE re: PRIMARIES (ϕ_s, degrees)
0
45
90
135
180
225
270
315
360


S M
BINAURAL MASKING LEVEL DIFFERENCE (dB)
0
2
4
6
8
10
12
14
SIGNAL PHASE re: PRIMARIES (ϕ_s, degrees)
0
45
90
135
180
225
270
315
360


RL
BINAURAL MASKING LEVEL DIFFERENCE (dB)
0
2
4
6
8
10
12
14
SIGNAL PHASE re: PRIMARIES (ϕ_s, degrees)
0
45
90
135
180
225
270
315
360

The curve drawn through these points satisfies a linear extension of the mathematical description of the BMLD given by Durlach (1963). The extended expression is as follows:

$$BMLD_t(\emptyset s) = 10\log[(k-\cos(\emptyset s-B))/(k-1)].$$

Here, B is an additional free parameter included to allow the zero minimum, of the function to be shifted to some value B >= 0. The best fitting curve to the data was obtained for each subject by selecting the values of C, k, and B so as to minimize the sum of the squared deviations between $BMLD_d$ and $BMLD_t$. That is, if

$$SS = (BMLD_t - BMLD_d)^2,$$

C, k and B were chosen so that

$$SS/\delta C = SS/\delta k = SS/\delta B = 0.$$

The Fortran program for performing this operation is presented in Appendix C. For each subject the fit is good -- the standard error of estimate averaging about 1dB. As shown, the curve fitting procedure yields maximum estimates of 9 to 14-dB $BMLD_t$s depending on the subjects. These estimates are in general agreement with BMLDs of 8 to 10-dB obtained with adaptive procedures (Colburn and Durlach, 1965).

Discussion

The outcome of Experiment I indicates that BMLDs of at least 9-dBs can be obtained through the interaction of a 500-Hz acoustic tone and a CDT of the same frequency presented to the opposite ear. Interaction between the 500 -Hz tone and the lower primary (f1) is ruled out as an explanation of this outcome since a control experiment identical in all respects to the present experiment but with the upper (f2) primary removed yielded no apparent evidence of a BMLD. These data are presented as threshold signal to noise ratios in Table I for subjects PS and JL. Scharf et al (1978) have shown that lateralization with interaural onset time differences for tones differing in frequency between the ears is as good as tones of identical frequency as long as the frequency difference does not exceed the critical band. In Experiment I, the frequency separation between the signal and the lower frequency primary (f1) is just greater than the critical band estimated by Scharf et al. (1978) at 500 -Hz (125-Hz re: 110-Hz). thus, even under the assumption that a common mechanism underlies the lateralization and BMLD phenomena, these tones would not be expected to interact to produce a BMLD.

TABLE I

Threshold signal to noise ratios as a
function of signal phase (Øs)
relative to the primaries
with the f2 primary removed.

	SIGNAL PHASE re: PRIMARIES (Øs, degrees)							
S	0	45	90	135	180	225	270	315
JL	12.5	12.5	11.5	11.5	12.0	13.0	13.5	9.5
PS	12.5	13.0	15.0	9.5	14.5	10.5	14.5	10.5

Neither does some aspect of the periodic relation between the signal and the two tone waveform in the other ear appear a viable explanation for the BMLD observed, as no evidence of a BMLD was obtained with a signal harmonically related to the primaries but 125-Hz lower than the CDT frequency. These data are presented in Table II, again for subjects PS and JL. The failure to evidence a BMLD for either of these controls points to interaction between the signal and the CDT as the only realistic explanation of the BMLD observed in Experiment I.

Given the above, it is possible to consider how first order approximations of the phase of the CDT can be extracted from these data. By definition, the BMLD is at a minimum (is zero) for the condition in which no interaural differences exist for the signal or the noise -- this is the SoNo condition. Note that the BMLD in Durlach's (1963) formulation rapidly converges to the zero minimum as the interaural phase difference of the signal (Øs) approaches zero. By analogy to the case for physical tones, the BMLD for the CDT should converge to a minimum at the relative phase value of the signal equal to that of the CDT. This phase value is given by the term B in the extended version of Durlach's (1963) formulation. thus, B provides a direct estimate of CDT phase. The B values compare well for the four subjects ranging from 208 to 245 degrees relative to the primaries.

TABLE II

Threshold signal to noise ratios as a function of signal phase (Øs) relative to the primaries, signal frequency is 375-Hz.

	SIGNAL PHASE re: PRIMARIES (Øs, degrees)							
S	0	45	90	135	180	225	270	315
JL	8.0	9.0	12.0	11.0	12.0	11.0	11.0	8.0
PS	11.5	13.5	13.0	14.0	12.0	11.0	12.0	10.5

Hall (1972b) presents cancellation data for CDTs generated by low frequency primaries for a single subject. CDT measurements for which stimulus conditions were most comparable to the present experiment were obtained for f1=583-Hz, f2/f1=1.2, with primary tones at 68-dB SPL. under these conditions, the cancellation estimate of CDT phase is about 270 degrees relative to the primaries. Given differences in stimulus conditions and the large degree of variance encountered for cancellation estimates of CDT phase (plus or minus 70 degrees in the Hall (1972) study) the BMLD phase estimates can be taken as being in general agreement with the cancellation estimates.

In estimating CDT phase from the BMLD data, the relative signal phase for which the best fitting theoretical curve converged to a minimum is assumed to be representative of the SoNo condition for physical tones. This assumption can be evaluated by comparing theoretically projected threshold signal to noise ratios at this point to those obtained with an SoNo control in which the diotic signal is a 30-dB SPL, physical tone at 500-Hz. Threshold signal to noise ratios for the minima of the theoretical curves obtained in Experiment I and for the SoNo control (control 1) are presented for the four subjects in Table III. Also included as an additional point for comparison are threshold signal to noise ratios for the maxima of the theoretical curves and for the SπNo condition for the 500

Hz physical tone. The SoNo and SπNo thresholds are normal for those obtained under these conditions but are substantially below the theoretical thresholds assumed to be representative of the SoNo and SπNo conditions for signal and CDT. Where subject PS was unavailable for threshold determination two dashes have been inserted.

TABLE III

Theoretical and obtained SoNo and SπNo thresholds (see text for explanation).

	SM	RL	PS	JL
Theoretical				
SoNo	22.0	17.5	19.5	25.5
S No	8.0	6.5	10.5	16.5
BMLD	14.0	11.0	9.0	9.0
Control 1				
SoNo	16.5	11.5	12.5	15.0
S No	0.0	-3.0	--	0.0
BMLD	16.5	14.5	--	15.0
Control 2				
SoNo	17.0	14.0	13.5	14.0
S No	7.5	-2.0	--	4.0
BMLD	9.5	16.0	--	10.0

Two possible reasons exist for the higher thresholds in the Experiment I task. The first is the presence of central masking by the primaries. Central masking refers to the masking of a signal presented to the ear opposite the masker (see Zwislocki, et al., 1968). The second is the difficulty that may have been incorporated into the task by the necessity to always include the primaries in both observation intervals, so as not to provide a positive cue for detection. For physical tones, this procedure is analogous to always having the "signal" (in Experiment I, the CDT) occur in one ear in both observation intervals.

Both these possibilities were tested simultaneously by presenting the lower frequency primary (f1) and a 30-dB, 500-Hz tone (the "signal") to one ear in both observation intervals. The 500-Hz tone that is always presented to one ear thus simulates the CDT in the Experiment I task. Threshold signal to noise ratios for the SoNo and S No conditions of this control are listed in Table III as control 2. Although control 2 does reduce the size of the BMLD from control 1 for some subjects, the SoNo thresholds for control 2 do not differ essentially from those of control 1 for any of the subjects. This result does not support the notion that for the reasons given above, the Experiment I task is overall more difficult than the traditional BMLD task for physical tones. Presently, no simple explanation for the generally higher thresholds obtained in Experiment I is forthcoming except to consider the effect of interaural intensive differences introduced by error in the signal level chosen to approximate CDT level. Such differences could only be expected to account for the lower thresholds in dichotic (SπNo) controls. Nonetheless, this aspect of the data is considered not so crucial as to overshadow the basic outcome of Experiment I: that a BMLD can be obtained for a CDT.

A BMLD for a CDT is in keeping with other stimulus-like properties of the CDT and provides convergent psychophysical evidence establishing the origin of the CDT at a peripheral stage of the auditory system, prior to convergence of input from the two ears. As discussed in the literature review, phase locking and selective tuning to a 2f1-f2 referent in the activity of single eighth nerve fibers of the cat place the site of CDT generation as far peripheral as the cochlea (Goldstein and Kiang, 1968). Equally important, the outcome of Experiment I provides the impetus to pursue other issues regarding the CDT with the BMLD procedure.

Conclusions

1) A BMLD can be obtained for a CDT and a physical tone of the same frequency to the other ear.
2) This result establishes the origin of the CDT prior to convergence of input from the two ears.

B. CDT Phase Dependence on Stimulus Level

Perhaps the most significant of the issues regarding the CDT is the question as to whether psychophysical and physiological cancellation estimates of CDT phase are contaminated by interaction between cancellation tone and primaries. As indicated in the literature review, an answer to this question is important for an understanding of the apparent discrepancy that exists between CDT psychophysics and physiology regarding phase dependence on stimulus level. Interaction of the primaries with the probe tone can be avoided by either temporally or spatially separating the probe from the primaries.

Smoorenburg (1972) took the first approach in a gap masking procedure in which the CDT functioned as a temporal masking stimulus. First, the masked threshold of a signal tone at 2f1-f2 was determined with the CDT as masker. The level of the CDT was then estimated by the level of a referent masking tone at 2f1-f2 that just masked this signal. Estimates of CDT level obtained in this manner are about 20-dB below comparable cancellation estimates. However, when the lower primary tone (f1) is included in the referent masker, gap masking and cancellation estimations of CDT level agree well, indicating that the 2f1-f2 tone in the referent masker is suppressed by the lower primary. The implication of these data, is that the cancellation procedure overestimates CDT level because the lower frequency primary suppresses the effective level of the cancellation tone. Pulsation threshold data of Smoorenburg (1974), as discussed in section II.B. are also consistent with this view. Neither the pulsation threshold procedure nor the gap masking procedure, however, has been successfully applied to determining the effect, if any, of the lower primary on the effective phase of the cancellation tone..

One procedure for spatially separating the probe tone from the primaries has been explored by Goldstein, et al. (1978) as discussed in section II.B.. A more complete spatial separation is achieved by presenting the probe tone to the ear opposite the CDT as in the present BMLD experiment. Because the probe is presented simultaneously with the CDT, the BMLD has the potential added avantage of providing phase measurements of the CDT. Given the outcome of Experiment I, the BMLD is next applied to obtain nonintrusive psychophysical measurements of CDT phase as a function of the level of the primaries in Experiment II.

Experiment II.

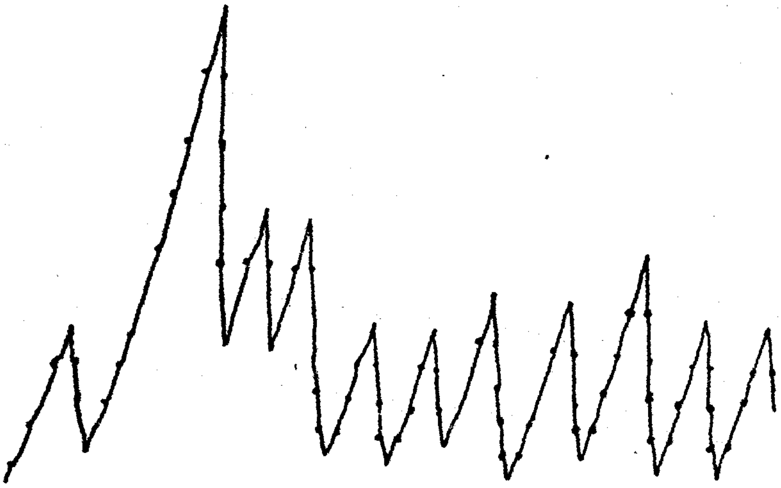
Purpose: The purpose of Experiment II is three fold. the experiment provided a preliminary test of a new psychophysical procedure for faster and more efficient data collection that allows measurement of CDT level as well as phase. It attempted a replication of the results of Experiment I with this procedure for different subjects, and, most importantly, it provided data on the extent to which CDT phase as estimated with the BMLD is dependent on primary level.

Stimuli and Apparatus: Same as Experiment I except primary level was varied from 60 to 85-dB in 5-dB steps. Also, for each primary level, a range of signal levels was investigated. Signal levels varied at 3-dB steps about a value 35-dB down from the primaries.

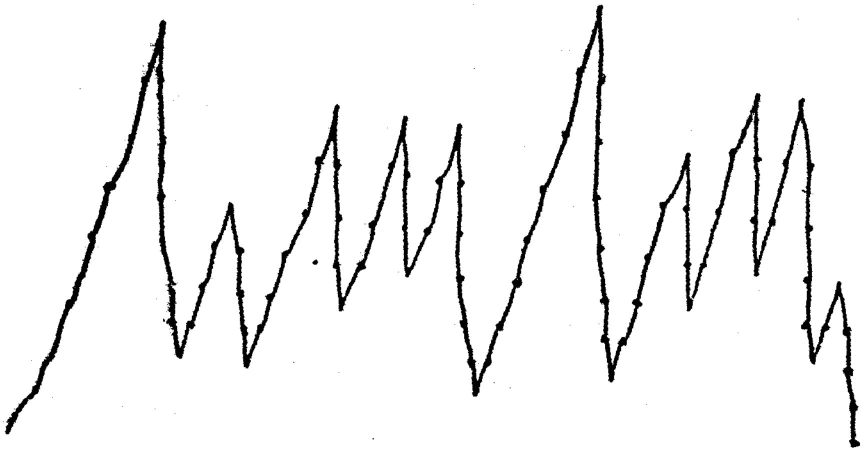
Procedure: Signal thresholds were obtained by a method of adjustment. Alternating signal and non-signal observation intervals were separated by 500 ms. and marked by separate lights. The subject pressed a button causing noise level to increase at a rate of 2-dB per signal-nonsignal alternation for as long as the button was held down. When the subject no longer detected the signal, he/she released the button causing noise level to begin to decrease at the same rate. When the subject once again detected the signal he/she pressed the button causing noise level to increase again. This process continued until twenty reversals in the direction of the noise level had been obtained. The first four reversals were discarded and the average of the remaining reversals established a threshold. Figure 10 shows two representative examples of the course of noise attenuation for threshold determination over a sequence of trials.

FIGURE 10

Representative examples of the course of noise attenuation over a trial sequence for method of adjustment (two subjects).



RL.



JP

Signal thresholds for each combination of primary level, signal level and signal phase were obtained to find the signal level for which the BMLD is largest for each primary level. Systematic collection of the data made it unnecessary to obtain thresholds for more than four signal levels at each primary level.

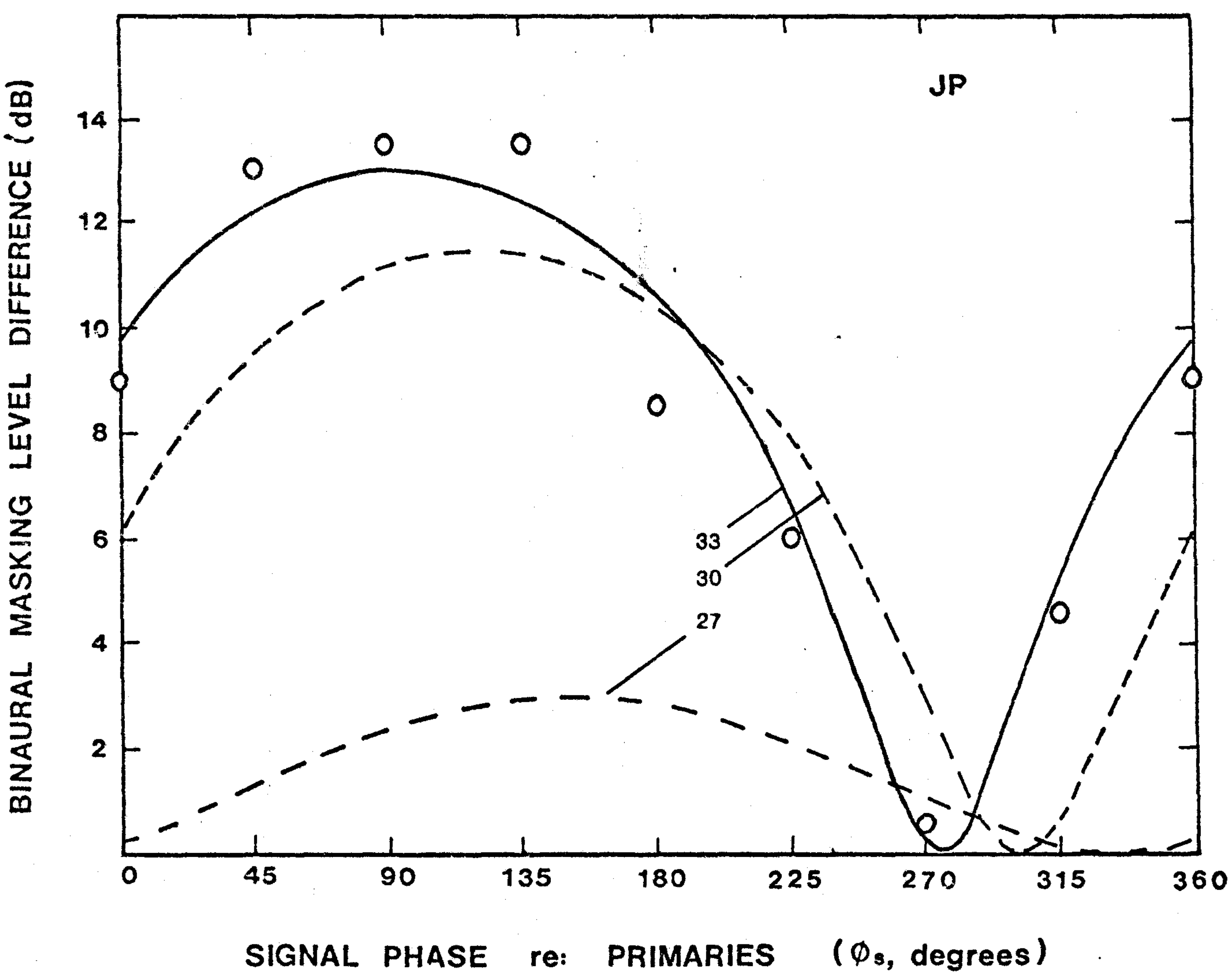
Some words of explanation are in order regarding this new procedure. In Experiment I, only one signal level was investigated. This level was chosen to estimate CDT level from the pulsation threshold data of Smoorenburg (1974). Estimation of CDT level in this manner is not extended to the present experiment for two reasons. First, we wished to develop a convergent technique for measuring CDT level that depends on the BMLD phenomena. Our estimates of CDT level could then be evaluated against those obtained by other procedures. Second, error in estimates taken from pulsation threshold data could conceivably cause error in measures of CDT phase. Time-intensity trading contours for the BMLD have been plotted by Colburn and Durlach (1965). The trading ratios are a complex function of interaural phase and intensity differences and magnitude of the BMLD. For reasonaly sized BMLDs the potential time-intensity trading ratios are large enough that significant error in the level of the signal chosen to approximate CDT level could cause significant error in CDT phase measurements through a time-intensity trade-off. Differences in this error for the different primary level conditions would therefore make inviable any implication of the results for the question of CDT phase dependence on primary level.

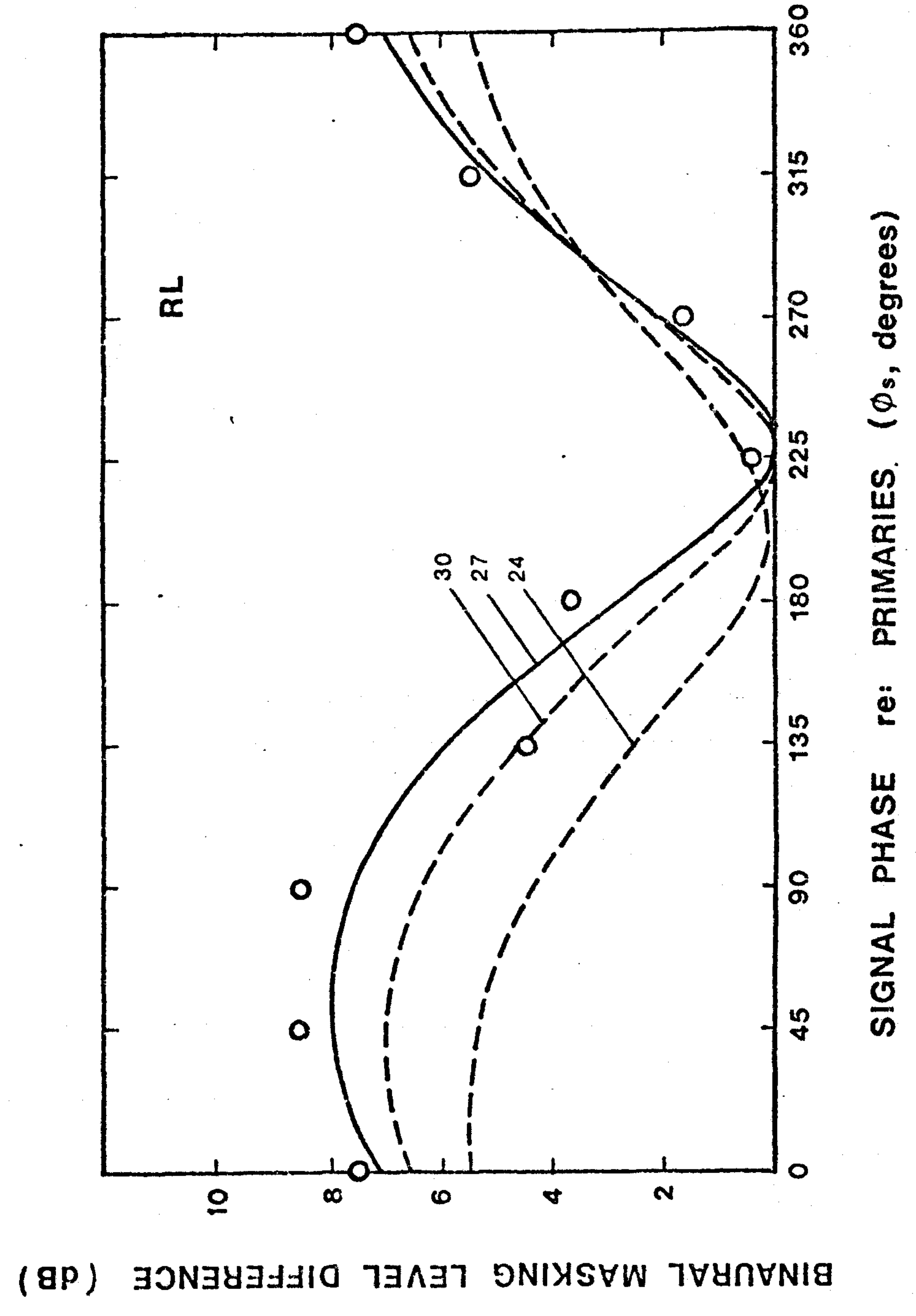
So that BMLD estimates of CDT level and phase could be more directly compared to cancellation estimates, cancellation estimates were also obtained for subjects of Experiment II. The cancellation estimates were obtained under stimulus conditions identical to those under which BMLD estimates were obtained with the exception that the signal to the right ear was replaced by a 500-Hz cancellation tone to the left ear and the masking noise was removed. Subjects were given control of both the level and relative phase of the cancellation tone and were instructed to adjust the level and phase so as to cancel the CDT percept in the nonstandard observation interval.

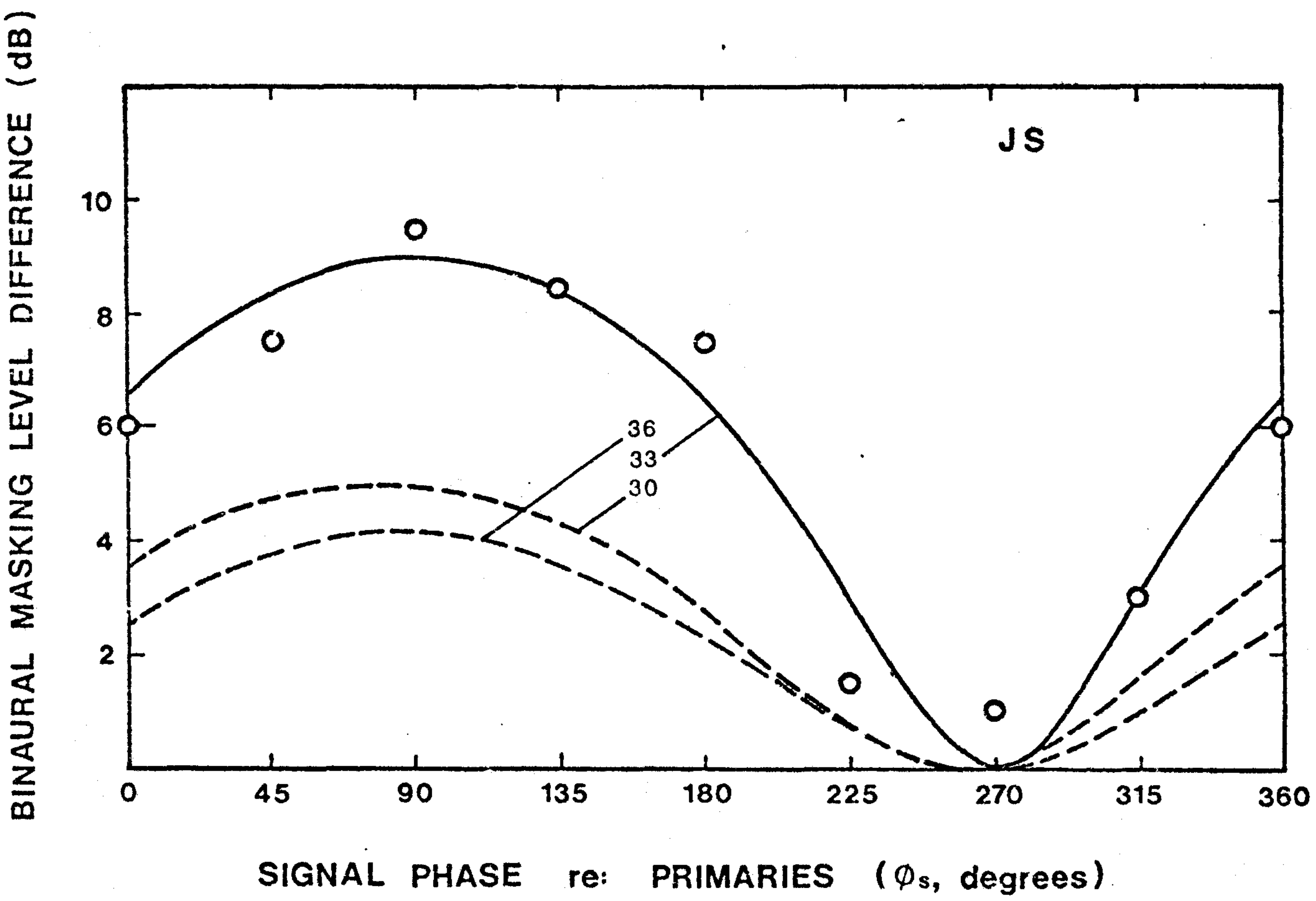
Results and Discussion: Theoretical curves like those of Experiment I were fit to the BMLD data of Experiment II; one curve for each combination of signal and primary level. Examples of these curves are shown in Figures 11 through 13 for 65-dB primaries, with signal level as the parameter. A solid curve and data points are plotted for the signal level yielding the largest BMLD for this level of the primaries. The dashed curves are for signal levels yielding smaller BMLDs. The data points for the dashed curves have been omitted for clarity of presentation. Theoretical curves for 65-dB primaries are chosen as examples so as to allow direct comparison to Figures 6 through 9 of Experiment I. However, these curves are generally representative of those obtained for each level of the primaries. The relevant parameters of the curve yielding the largest BMLD for each level of the primaries are summarized in Appendix D, and the raw BMLD data (threshold signal-to-noise ratios) are presented in Appendix E.

FIGURES 11 THROUGH 13

The binaural masking level difference as a function of the level (Ls) and phase (Øs) of the signal relative to the primaries (three subjects).


JP
BINAURAL MASKING LEVEL DIFFERENCE (dB)
14
12
10
8
6
4
2
33
30
27
0
45
90
135
180
225
270
315
360
SIGNAL PHASE re: PRIMARIES (φs, degrees)


RL
30
27
24
0
45
90
135
180
225
270
315
360
2
4
6
8
10
SIGNAL PHASE re: PRIMARIES (ϕs, degrees)
BINAURAL MASKING LEVEL DIFFERENCE (dB)


JS
BINAURAL MASKING LEVEL DIFFERENCE (dB)
10
8
6
4
2
0
45
90
135
180
225
270
315
360
36
33
30
SIGNAL PHASE re: PRIMARIES (φ_s, degrees)

Comparison of Figures 6 through 9 with Figures 11 through 13 makes clear the negligable effects procedural changes in Experiment II had upon the BMLD for the CDT. The theoretical fit to the data of Experiment II did not suffer with procedural changes. As for Experiment I, the standard error of estimate averages about 1-dB. Also, the phase value at which the BMLD converges to a minimum appears not to have been affected. Although the size of the BMLD diminishes for RL who was the only subject participating in both Experiments, the phase value at which the BMLD converges to a minimum changes by no more than a few degrees. No systematic indication of a time-intensity trade was observed in the BMLD data, therefore, a statistical analysis for such was not performed.

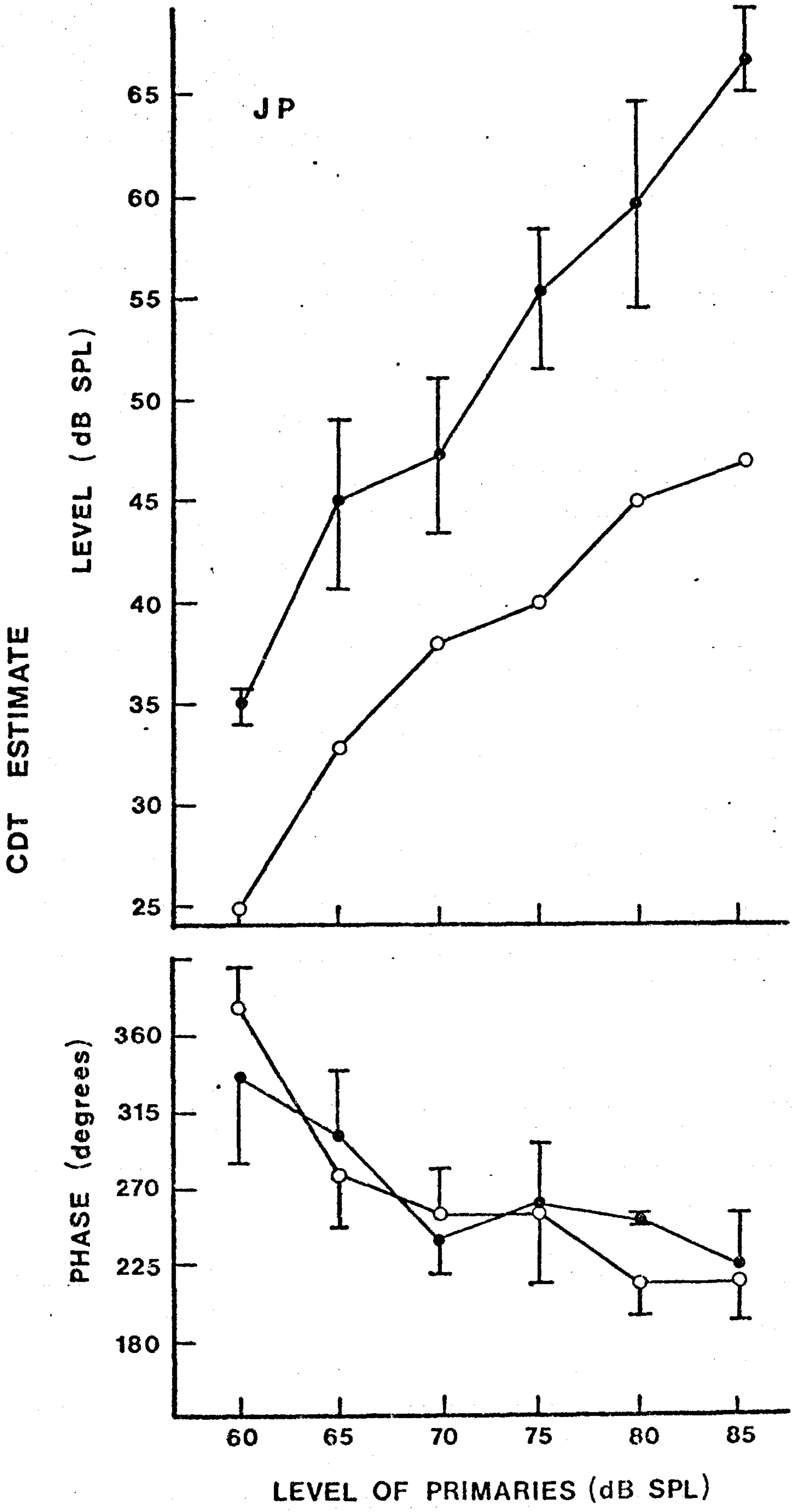
For each level of the primaries CDT phase and level estimates were derived from the curve showing the largest $BMLD_t$. Specifically, CDT phase was estimated (as in Experiment I) by the phase value at which this curve converged to a minimum, and CDT level was estimated by the signal level that produced the curve. Derivation of level estimates in this manner is based on the observation noted in Chapter III, that variation in the interaural phase difference of a physical tone yields the largest BMLD when the level of the tone is equal at the two ears. Again, the implicit assumption of the BMLD level estimation procedure is that the CDT behaves as a physical tone.

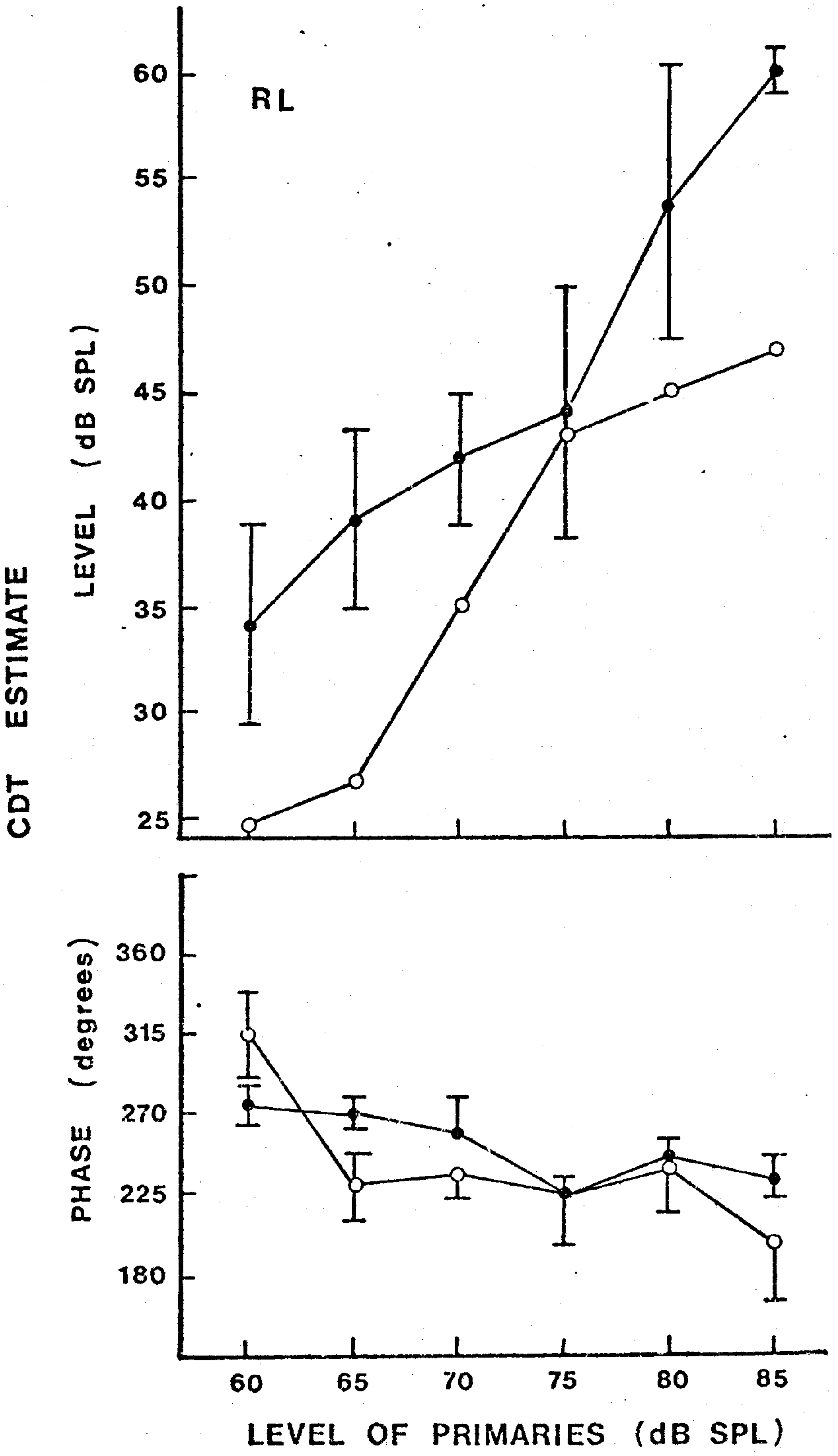
BMLD phase and level estimates are plotted in Figures 14 through 16 along with cancellation estimates for the three subjects. Cancellation estimates represent the average of 3 to 4 adjustments. Error bars indicating one standard error on either side of the data point have been plotted where appropriate. Comparison of the variability of BMLD and cancellation level estimates is not possible as only one value went into the determination of each BMLD level estimate. The variability associated with phase estimates on the other hand, differs little for the two procedures. The standard error of estimate for BMLD phase estimates averages 29 degrees; the standard error of the mean for cancellation phase estimates averages 22 degrees.

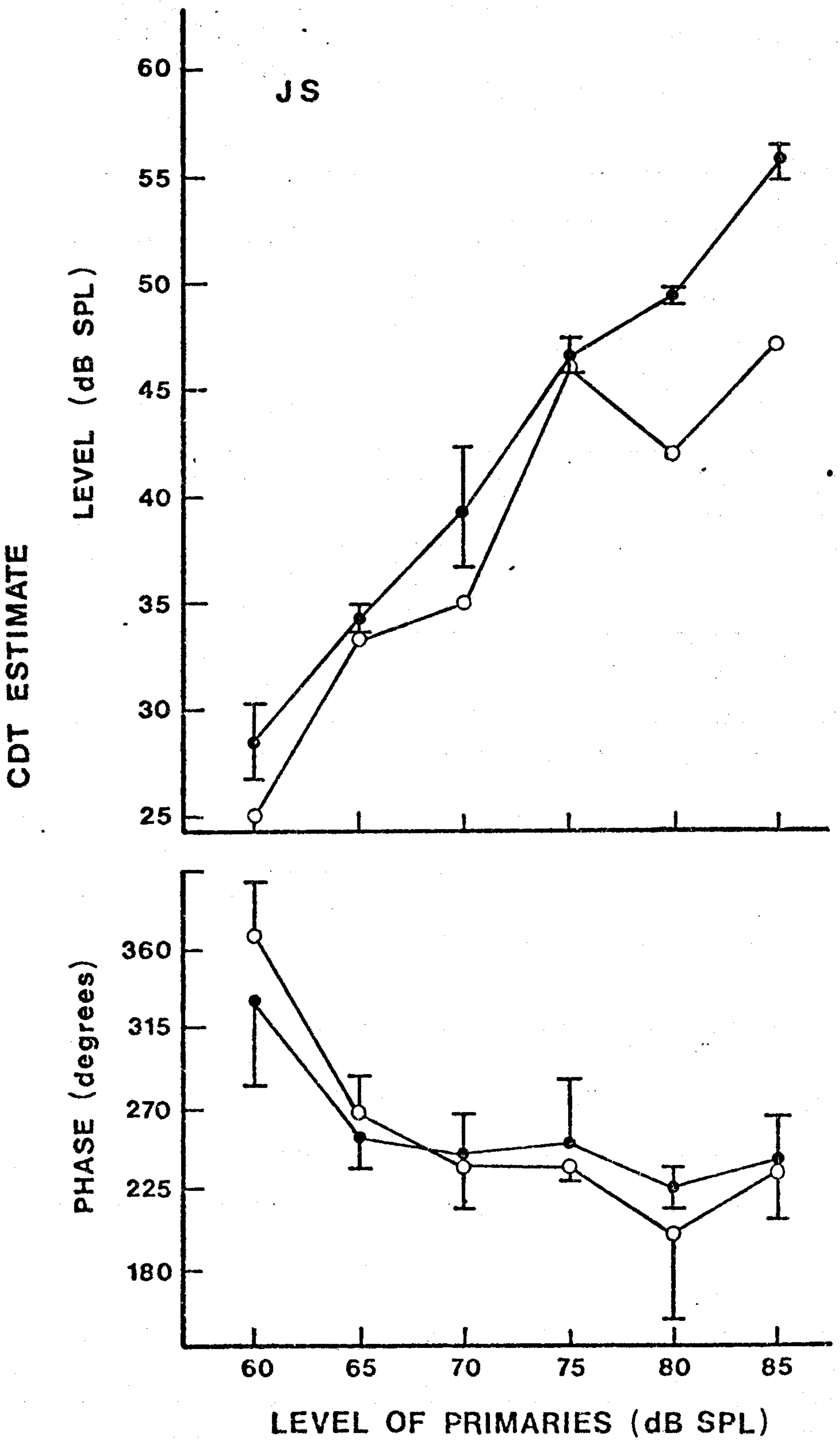
The BMLD level estimates agree with the present and with previous cancellation estimates (Smoorenburg, 1972) in showing about a 10 dB growth in the CDT for every 10-dB increase in primary level. However, cancellation level estimates are consistently above corresponding BMLD estimates, greater by an average of about 4-dB for subject JS to as much as 14-dB for subject JP. The difference in level estimates between the two procedures might be attributed to suppression of the effective level of the cancellation tone by the lower (f1) primary which only can occur in the cancellation procedure. Again, cancellation tone level must overestimate CDT level to override this

FIGURES 14 THROUGH 16

Cubic difference tone phase and level estimates
as a function of the level of the primaries
obtained with the BMLD (open circles) and
cancellation (filled circles) procedure
for three subjects


JP
CDT ESTIMATE
LEVEL (dB SPL)
65
60
55
50
45
40
35
30
25
PHASE (degrees)
360
315
270
225
180
60
65
70
75
80
85
LEVEL OF PRIMARIES (dB SPL)


RL
CDT ESTIMATE
LEVEL (dB SPL)
60
55
50
45
40
35
30
25
PHASE (degrees)
360
315
270
225
180
60
65
70
75
80
85
LEVEL OF PRIMARIES (dB SPL)


JS
CDT ESTIMATE
LEVEL (dB SPL)
60
55
50
45
40
35
30
25
PHASE (degrees)
360
315
270
225
180
60
65
70
75
80
85
LEVEL OF PRIMARIES (dB SPL)

suppression. Evidence for this account is given by the nonsimultaneous masking data of Smoorenburg (1974) as discussed in the literature review. The BMLD level estimates agree well in absolute value with estimates obtained from these data (see Figure 1 of this paper), and similarly indicate a slightly smaller growth of the CDT with primary level compared to cancellation estimates. Also, consistent with this interpretation is the observation that the large variation between subjects in the difference between BMLD and cancellation level estimates is due almost entirely to variation of the absolute value of the cancellation level estimates. Shannon (1976) has shown that the extent of the suppressive effect of one tone upon another also varies as much from one subject to the next.

Of greater interest, however, is the generally good agreement between BMLD and cancellation phase estimates of the CDT. The phase functions for the two procedures agree both in terms of their absolute values and their slopes. Subjects show some variability in the slopes of the cancellation phase functions, ranging from an average phase reduction of about 3 degrees/dB for RL to 5 degrees/dB for JP. Such variability is not uncommon for cancellation phase data. The slopes of the BMLD phase functions follow these differences across subjects. Phase functions given by BMLD estimates do tend to show slightly shallower slopes than those given by the cancellation estimates. On the assumption that the BMLD procedure yields an undistorted phase function, an opposite trend is indicated by the nonlinear model of basilar membrane motion by Hall (1974) (see Figure 7 of that paper). Presently, no explanation of this finding is forthcoming. Nonetheless, a clear CDT phase dependence on primary level obtained with the BMLD procedure argues against the notion that the same dependence evidenced with the cancellation procedure is caused by interaction between primaries and cancellation tone in the same ear.

This outcome is reinforced by unpublished data of Sachs and Zurek (1977). These investigators used a binaural lateralization procedure for measuring CDT phase in which the phase of a probe tone was adjusted to center the image of a CDT of the same frequency in the opposite ear. As with the BMLD procedure, interaction between probe and primaries was averted by presenting probe and primaries to opposite ears. On the assumption the the CDT behaves as a physical tone, the relative phase of the probe for a centered image provided a measure of CDT phase (see Sayers, 1964). Sachs and Zurek showed lateralization and cancellation estimates of CDT phase to be parallel functions of primary level, decreasing at about 3 to 10 degrees/dB for stimulus conditions comparable to those presented here.

Attempts to account for the discrepancy that exists between CDT psychophysics and physiology regarding CDT phase dependence on primary level have attributed the psychophysically observed dependence to possible confounding interactions between cancellation tone and primaries (Goldstein, et al., 1978). The data of Experiment II do not support this account. A CDT phase dependence is obtained when such confounding interactions are circumvented by presenting probe and primaries to different cochleas. Consequently, these data provide no resolution to the issue as to why a similar phase dependence is not also evident in the neural response to the CDT. They do, however, point to a need to consider alternative explanations of the discrepancy. One possible explanation is suggested here.

This account cautions against deciding that an effect does not exist on the basis of the failure of limited attempts to evidence the effect. To see why, a closer examination of the neural data that has supported the contention that the neural CDT phase response does not change with stimulus level is in order. The data come from two studies; the one by Goldstein and Kiang (1968) and the other by Smoorenburg et al., (1976). In the study by Goldstein and Kiang (1968), PST histograms synchronized to 2f1-f2 are presented as a function of primary level for only one nerve fiber. The PST histograms show no change in phase with primary level for this fiber. Smoorenburg et al. (1976) present phase functions of primary level for a number of fibers (see Figures 16 and 19 of that paper). For most of these fibers the phase functions are essentially flat. However, for at least two fibers, the phase functions show a clear phase reduction of about 5 degrees/dB, consistent with psychophysical cancellation data (Goldstein, et al., 1978). Although few in number, fibers showing CDT phase dependence on stimulus level indicate that if one looks hard enough for these fibers, they can be found.

This statement is supported by very recent recordings from auditory nerve fibers of cat in response to the CDT, reported by Buunen and Rhode (1978). These investigators present data for a significant number of fibers which show 4 to 5 degrees shifts in CDT with primary level, although no systematic trend in the direction of the phase shifts is apparent (see Figures 8 and 9 of that paper). In view of these data and the analysis given above, the conclusion based on the Goldstein and Kiang (1968), and Smoorenburg et al (1976) studies that a neural CDT phase dependence on stimulus level does not exist may have been premature. Perhaps, the subject "listens" only with those fibers that show a CDT phase dependence on stimulus level when performing the psychophysical cancellation task.

Conclusions

1) BMLDs produced by the CDT are robust. They are evidenced by all six subjects tested and are little affected by changes in the psychophysical task.

2) BMLDs produced by CDTs can be used to derive phase and level estimates of the CDT.

3) Although an average of 4 to 14-dB below cancellation estimates, BMLD level estimates of the CDT, like cancellation estimates, show a 10-dB growth in the CDT with every 10-dB increase in primary level. The difference in the absolute values of the level estimates for the two procedures may be due to suppression of the cancellation tone in the cancellation procedure.

4) BMLD phase estimates of the CDT agree with cnacellation estimates in both their absolute values and in the slopes of the functions relating CDT phase to primary level, the later showing phase reductions of 3 to 5 degrees/dB. The cancellation procedure, therefore, appears to yield undistorted estimates of CDT phase.

CHAPTER V

SUMMARY

The last two decades of psychoacoustical research have yielded a proliferation of studies on the properties of the 2f1-f2 CDT. The research effort has been motivated by the theoretical and functional significance the CDT has for a number of auditory phenomena, as well as an interest generated by the enigmatic character that separates the CDT from other distortion products of the ear. Yet, the realization of this research effort owes its existence to the cancellation procedure which has provided a methodology for studying the CDT quantitatively.

Two major issues have evolved from cancellation studies. The first issue concerns the stimulus-like properties of the CDT; the observation that the CDT behaves as if a component at 2f1-f2 were physically present in the stimulus complex. The second issue involves the question as to the physiological basis of the CDT. In regard to this second issue, current psychophysical and physiological studies have been conducted in an attempt to understand the discrepancy that exists between these studies regarding the dependence of CDT phase on stimulus level. A conclusion of this research is that cancellation data may provide misleading information about the CDT. The data are consistent with the notion that the effective phase of the cancellation tone itself, not the CDT, changes with primary level. If this notion were correct, the discrepancy between psychophysical and physiological data could be explained by a confounding interaction between cancellation and primary tones in the cancellation procedure.

The present investigation addresses both of these issues. It describes a convergent psychophysical technique for making phase and level measurements of the CDT that avoids the potential interaction between cancellation and primary tones inherent in the cancellation procedure. This interaction is circumvented by an extreme form of spatial separation. The probe tone at frequency equals 2f1-f2 is presented to the ear opposite the ear containing the primaries. The masked threshold of the probe tone (the signal) is then measured for different relative phases and levels of the probe. The success of the approach depends of the assumption that at some level of the probe, the probe and CDT in the other ear will interact to produce a BMLD. The level of the probe for which the BMLD is largest is taken as an estimate of CDT level, and the relative phase of the probe at this level for which the BMLD conveges to a minimum is taken as an estimate of CDT phase.

Experiment I tested the assumption that a probe at 2f1-f2 will interact with a CDT in the other ear to produce a BMLD. The experiment directly addresses the issue concerning the stimulus-like properties of the CDT. The data indicate a BMLD for probe and CDT as would be expected if the CDT truely behaves as a physical tone. Control experiments discounted the possibility that the BMLD could have resulted from binaural interaction of the probe with the lower frequency primary or from interaction between probe and modulation envelope of the two tone waveform in the other ear. Experiment I also addresses the question as to the physiological origin of the CDT. The positive indication of a BMLD for the CDT establishes the origin prior to convergence of input from the two ears.

In Experiment II, the BMLD procedure was applied to perform measurements on the CDT for different levels of the primaries. The experiment is an attempt to understand the reason for the discrepancy that exists between psychophysical and physiological studies regarding CDT phase dependence on primary level. It is, therefore, indirectly addressed to the issue of the physiological basis for the CDT. Data for Experiment II show a near equivalent shift in CDT phase with primary level for both BMLD and cancellation procedures suggesting that the shift observed in psychophysical cancellation studies is not the result of interaction between the cancellation and primary tones. The data also replicate the basic outcome of Experiment I with different subjects and a different psychophysical procedure for faster and more efficient data collection, thus establishing the practical applicability of the approach to measurement of auditory nonlinearities under a variety of stimulus conditions.

CHAPTER VI

FUTURE APPLICATIONS

Having established the feasability of using the BMLD to study the 2f1-f2 CDT in Experiments I and II, possible future applications of the BMLD to the study of still other issues regarding this combination tone as well as additional nonlinear auditory phenomena are discussed in the following sections.

A. 2f1-f2 CDT Nonmonotonicity

Several cancellation studies (Helle, 1969, 1970; Smoorenburg, 1972; Weber and Mellert, 1975) have revealed stimulus conditions for which the 2f1-f2 CDT behaves irregularly. As either the frequency separation or the level of the primary tones changes, the level of the CDT decreases, reaches a minimum, and then increases again. In the neighborhood of the amplitude dip, there is also an abrupt change in the phase of the CDT. This nonmonotinicity remains a curiosity. However, in a detailed study of the nonmonotonicity, Hall (1975) has demonstrated a close relationship of the amplitude dip to the existence of cancellation tone phase dependence on primary level. By association, this relationship implicates interaction between the cancellation tone and primaries as a possible explanation for the nonmonotonicity. On this account, it is interesting to note that a similar nonmonotonicity has yet to be observed in the physiological data on the CDT. Application of the BMLD procedure in an attempt to reveal irregular CDT behavior might serve to clarify the reason for this nonmonotonicity.

B. CDT Measurements in Hearing Impaired Listeners

A major concern of the present study is the issue regarding the site of CDT generation. The resolution of this issue is essential for a desription of the physiological mechanism underlying the CDT nonlinearity and for an understanding of peripheral transduction of the auditory stimulus. The most promising psychophysical approach to this issue has been to infer the site of generation from measurements of cubic distortion in listeners with well defined hearing losses.

Smoorenburg (1972) first took this approach with a subject who had a threshold elevation in one ear in a narrow frequency region of his audiogram. The threshold elevation was diagnosed as resulting from a defect in tonotopic processing, presumably of hair cell origin. The subject clearly perceived the CDT in the normal ear, but could not hear the same CDT in the defective ear when only the primaries were located in the region of the loss. This observation is taken to indicate that the defect precedes the nonlinearity responsible for CDT generation where it prevents the primary components' response from reaching the nonlinearity so as to produce the CDT. If, alternatively, the nonlinearity preceded the defect, the primary components should, have interacted in the nonlinearity to produce a CDT that would have then bypassed the defect. Leshowitz and Lindstrom (1977) present similar data from a hearing impaired listener that further suggest the nonlinearity exists in the cochlea just basal to the characteristic place of the primaries.

While these studies provide valuable information regarding the site of the nonlinearity, their methodological limitations prohibit quantitative measurements of the effects a particular defect may have on CDT phase and amplitude. These types of measurements would greatly facilitate a description of the physiological mechanism of the CDT nonlinearity. For cancellation studies to provide these measurements, assumptions would have to be made regarding the influence the defect may have on processing of the cancellation tone. On the other hand, any potential influence of the defect on processing of a probe tone could be bypassed by presenting the probe to the opposite ear (the normal ear) as is done in the BMLD procedure for measuring the CDT. Thus, measurement of cubic distortion in hearing impaired listeners with the BMLD procedure promises to be of value in helping to reveal the physiological basis for the nonlinearity underlying CDT generation.

It is also expected that the BMLD procedure will provide an efficient means for diagnosing and understanding auditory distortion in impaired ears. Previous work has led to the speculation that auditory distortion in ears with cochlear damage is especially pronounced, yet, a consistent picture of distortion in these ears has not yet emerged (e.g. Nelson and Bilger, 1974). In view of the problems encountered in psychoacoustical measurements in clinical populations, same-different methodology (i.e. Experiment I) would be of great use in efforts to produce a detailed analysis of auditory distortion in impaired ears.

C. The 2f2-f1 CDT

In contrast to the 2f1-f2 CDT, the 2f2-f1 CDT has been virtually ignored. The reason for this neglect has to do with the elusive nature of the 2f2-f1 CDT rather than any consensus of theoretical insignificance. The 2f2-f1 CDT is of a frequency just above the frequencies of the primaries so that it may be rendered inaudible by the upward spread of masking produced by the primaries

(Smoorenburg, 1972 and Plomp, 1967). The upward spread of masking is always more effective than the lower spread of masking (Egan and Hake, 1950). Yet, this account is by no means certain. Goldstein (1967) has shown that in the presence of equal level primaries, a tone at 2f2-f1 is clearly detectable at a level well below that predicted for the 2f2-f1 CDT assuming symetrical distortion above and below the primaries. He concludes that the 2f2-f1 CDT is rendered inaudible by an asymetrical peripheral weighting function of frequency that places least weight on frequencies above the primaries. Likewise, the basilar membrane model for distortion products by Hall (1974) places little weight on frequencies above the primaries. The model does not support vibration above the characteristic frequency at the place where the distortion products are assumed to originate (i.e. where f1 and f2 overlap). Nevertheless, the model produces a 2f2-f1 component that is as large or larger than the 2f1-f2 component making it necessary to invoke masking of the 2f2-f1 CDT by the primaries to reconcile the model with the data.

Data on the 2f2-f1 CDT would promote attempts to model distortion produced by the peripheral ear. Because techniques for collecting these data are presently unavailable, it is not known whether the 2f2-f1 CDT is generated by an essential nonlinearity as is believed responsible for the 2f1-f2 CDT, is rather described by a quadratic nonlinearity as Hall's (1974) model holds, or indeed, whether it exists at all. Estimation of the relative magnitude of 2f2-f1 distortion is also important for determining the extent to which reiterative generation of distortion products supports distortion at frequencies above the primaries (Russek and MacLeod, 1976).

A further reason for pursuing the BMLD as a means of measuring distortion products is the potential for developing a technique that will uncover the properties of the elusive 2f2-f1 CDT. As discussed above, the inability to hear the 2f2-f1 CDT has been attributed on the one hand to the upward spread of masking by the primaries and on the other to an asymetrical peripheral weighting function of frequency. If the former interpretation is at least partly correct, the possibility exists for releasing the 2f2-f1 CDT from this masking with a BMLD for this distortion product and a tone of the same frequency to the opposite ear.

Failure to evidence a BMLD for the 2f2-f1 CDT and the signal to the other ear will support the notion that minimal weighting by the peripheral ear on frequencies above those of the primaries causes the 2f2-f1 CDT to be inaudible. Otherwise, evidence of a BMLD will indicate that masking by the primaries is at least partly responsible. Given the later outcome, the measured level of the 2f2-f1 CDT will be of interest for determining the nature of the nonlinearity responsible for generation of this CDT.

Goldstein (1967) has assumed that both the 2f1-f2 and 2f2-f1 CDTs are generated by an overloading type of nonlinearity in which each term in the expression is normalized by the peak amplitude of the stimulus (see section C.I.). The normalized nonlinearity is a symetrical nonlinearity; equivalent distortion exists at frequencies equal distances above and below the primaries. Thus, if the above assumption is correct, the measured level of the 2f2-f1 CDT should be approximately equal to that measured for the 2f1-f2 CDT in Experiment II.

In the basilar membrane model of cubic distortion by Hall (1974), 2f2-f1 distortion at any point along the membrane is given by the square of the f2 component at that point times the f1 component at that point. Thus, the model produces greater distortion at the 2f2-f1 place than at the 2f1-f2 place along the membrane. If Hall's model is correct, the measured level of the 2f2-f1 CDT should therefore, be greater than that of the 2f1-f2 CDT in Experiment II.

A final possible outcome is that the level of the 2f2-f1 CDT will be below that of the 2f1-f2 CDT. This result would imply that more than masking by the primaries is responsible for previous failures to evidence the 2f2-f1

CDT. Differences in weighting above and below the frequencies of the primaries may therefore be a contributing factor. This outcome would make impossible interpretation of the results with respect to the nature of the nonlinearity underlying generation of the 2f2-fl CDT. An additional experiment investigating the growth of the 2f2-fl CDT with primary level would be required to explore this issue.

D. The f2-fl Difference Tone

In the introduction brief mention was made of the f2-fl combination tone, commonly refered to as the difference tone (DT). Cancellation studies reveal the DT to behave markedly in contrast to the CDT. Unlike the CDT, the DT is heard only at relatively high stimulus levels (greater than 50 dB SPL). Its growth with stimulus level is described by the classic power series expansion (quadratic term), increasing with the cube of stimulus amplitude, and its amplitude is little affected by the frequency separation of the primaries (Goldstein, 1972) (6). Because the basilar membrane is known to be the first frequency selective element of the ear, the independence of the DT on the frequency separation of the primaries led to

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(6) However, see Hume, 1979, and Hall, 1972a.

initial speculation that the DT is generated prior to the basilar membrane, possibly in the overlaoding of middle ear structures. However, Hall (1972) has shown that at low (less than 500 Hz) frequencies the DT behaves more like that of the CDT. A direction future research may take would be to investigate quadratic distortion at low and high frequencies with the BMLD procedure.

E. High Frequency Stimuli

Although the BMLD is primarily a low frequency phenomenon (Hilling and Jeffress, 1965), McFadden, et al. (1975) have shown substantially sized BMLDs for high frequency narrowband noise stimuli. It should, therefore, prove possible to study the behavior of high frequency 2f1-f2 and f2-f1 combination bands.

F. Two Tone Suppression

Smoorenburg (1974) has noted that the vth law device he proposes to describe CDT behavior produces suppressive effects: high amplitude components suppress the amplitude of lower amplitude components (see section C.2.). A qualitative manifestation of this property of the nonlinearity is evidenced in psychophysical and physiological studies of two-tone "suppression" (Houtgast, 1972; Shannon, 1976; Sachs and Kiang, 1968; Javel, et al., 1978). In physiological studies, the suppression is observed as a reduction in the neural discharge rate to a tone (f1) upon addition of a second tone (f2). For psychophysical studies the suppression is evidenced as a reduction in the masking effectiveness of a forward masker (masker precedes signal) that may accompany the addition of an f2 component to the masker. Simultaneous masking procedures (coincident signal and masker) have not revealed such suppressive effects, presumably because the f2 component suppresses both the signal and the masker to the same extent leaving the signal to noise ratio constant (Houtgast, 1972). Suppression of the signal is, therefore, circumvented in the forward masking procedure by temporally separating the signal from the masker.

Nonetheless, the forward masking procedure for measuring suppression is somewhat inefficient in the respect that it requires many observations in a masker simulation procedure to accurately estimate the magnitude of suppression (Houtgast, 1972). In addition, it provides no estimate of potential phase distortion of the f1 component by the f2 component; though such distortion has been demonstrated in recent physiological (Smoorenburg, et al., 1976) and psychophysical (Houtgast, 1977) studies. Quantitative measurement of this phase distortion is important for a meaningful description of the physiological mechanism underlying two-tone suppression. The BMLD procedure may provide an efficient means of performing these measurements.

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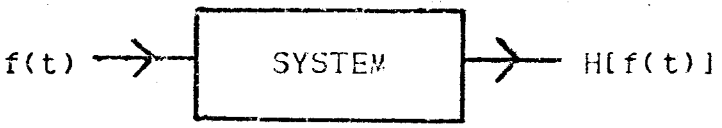
APPENDIX A

APPENDIX A

Linear Systems Analysis

Linear systems analysis refers to a broad category of analytic techniques that can be applied specifically to the determination of the input output response characteristics of linear systems. As illustrated below, for any system there is an input signal and an output signal or response function, where H describes



the operation that is performed by the system on the input f(t). The system is said to be linear if H satisfies two conditions:

$$H[f_1(t) + f_2(t) + \ldots + f_n(t)] =$$
$$H[f_1(t)] + H[f_2(t)] + \ldots + H[f_n(t)]$$

and

$$H[af(t)] = aH[f(t)].$$

The first condition, superposition, requires that the output to a number of independent inputs be expressible as the sum of the outputs that would have been obtained if each input were presented alone. The second condition, homogeneity, requires that the outputs to inputs of different magnitudes only differ by a constant of proportionality. Any system that violates either one of these conditions is said to be nonlinear.

One of the most powerful linear system analytic techniques, the one applied most extensively to the study of the ear, is Fourier Analysis. According to the theorem of Fourier. any periodic function f(t) no matter how complex can be expressed as the sum of harmonically related sinusoids of frequency $w_n = nw_0$. Specifically,

$$f(t) = a_0 + \Sigma(a_n \cos nw_0 t + b_n \sin nnw_0 t)$$

where, a_0, a_n and b_n are coefficients obtained by the equations:

$$a_0 = 2\pi^{-1}\int_0^{2\pi} f(t)dt$$

$$a_n = 2\pi^{-1}\int_0^{2\pi} f(t)\cos nw_n tdt$$

$$b_n = 2\pi^{-1}\int_0^{2\pi} f(t)\sin nnw_n tdt$$

The power of this appraoch lies in its selection of the sinusoid as a basis function. Any derivative of a sinusoid is a sinusoid of the same frequency. Thus, the response of a linear system to a sinusoidal input is easy to calculate and measure--the response is just an amplitude-scaled and phase-shifted replica of the input. Likewise, the response of a liner system to any periodic input can be completely described by superimposing the responses to the individual sinusoids that comprise the input.

APPENDIX B

APPENDIX B

Threshold signal-to-noise ratios (dB SPL)
as a function of signal phase (Øs)
relative to the primaries
for the 2IFC task.

SIGNAL PHASE re: PRIMARIES (Øs, degrees)

S	0	45	90	135	180	225	270	315
JL	3.0	4.5	8.5	10.0	12.5	15.0	13.0	17.0
PS	3.0	10.0	3.5	13.5	11.5	16.5	9.5	13.5
SM	6.0	6.5	5.5	10.5	9.0	26.0	19.5	13.0

APPENDIX C

```
C     MLDFIT estimates the values of K, B and C in
C     the expressions,
C
C         BMLDt = 10LOG((K-COS(PHASs-B))/(K-1),
C
C     and,
C
C               BMLDd = C-10LOG(E/No)@Thresh.
C
C     so as to minimize
C
C                     SUM(BMLDt-BMLDd)**2.
C
C     It then plots the input data and the best
C     fitting curve (Author: Robert A. Lutfi).
C
C     Accept input; BMLDd, PHASs (las).
C
C
      DIMENSION DMLD(20),TDMLD(20),DPHAS(20),TDPHAS(20)
      SSDEVM=99999999.
      TYPE 5
5     FORMAT(' N='$)
      ACCEPT 6,N
6     FORMAT(I3)
      TYPE 10
10    FORMAT(' INPUT DATA')
      ACCEPT *,(DMLD(I),DPHAS(I),I=1,N)
      TYPE 14
14    FORMAT(' LOWER LIMIT MLD EST. INT.='$)
      ACCEPT 6,IAMLDL
      TYPE 15
15    FORMAT(' LOWER LIMIT PHASE EST. INT.='$)
      ACCEPT 6,IPHASL
      IMLDL=IAMLDL*2
      IMLDU=IMLDL+10
      IPHASU=IPHASL+20
C
C     Search for values of K, B and C that minimizes
C
C                     SUM(BMLDt-BMLDd)**2
C
      DO 40 IL=1,11
      RIDC=IL*.5-.5
      DO 16 I=1,N
      TDMLD(I)=DMLD(I)+RIDC
16    CONTINUE
      DO 40 IMLD=IMLDL,IMLDU
      RIMLD=IMLD*.5
      RK=(10.**(RIMLD/10.)+1.)/(10.**(RIMLD/10.)-1.)
      DO 40 IPHAS=IPHASL,IPHASU
      SSDEVA=0.
      DO 20 I=1,N
      TDPHAS(I)=(DPHAS(I)-IPHAS)*.01745329
```

```
FORTRAN IV      V02.04     Sat 05-May-79 09:53:00                PAGE 002

0031            BMLD=10.*ALOG10((RK-COS(TDPHAS(I)))/(RK-1.))
0032            SSDEVA=(BMLD-TDMLD(I))**2+SSDEVA
0033     20     CONTINUE
0034            IF(SSDEVA.GT.SSDEVM)GO TO 40
0036            SSDEVM=SSDEVA
0037            PIPHAS=IPHAS
0038            PIMLD=RIMLD
0039            PDC=RIDC
0040            PK=RK
0041     40     CONTINUE
         C
         C      Calculate Sx.y and Sy.x.
         C
0042            SSDEVP=0.
0043            DO 50 I=1,N
0044            PDMLD=DMLD(I)+PDC
0045            ARG1=PK-(10.**((PDMLD)/10.))*(PK-1.)
0046            ARG2=1.-ARG1**2
0047            BPHAS=ATAN2(SQRT(ABS(ARG2)),ARG1)*57.29578+PIPHAS
0048            IF(PIMLD.LT.PDMLD)BPHAS=PIPHAS+180.
0050            TDPHAS(I)=DPHAS(I)
0051            IF(DPHAS(I).LT.PIPHAS)TDPHAS(I)=ABS(2.*PIPHAS-DPHAS(I))
0053            IF(DPHAS(I).GT.PIPHAS+180)TDPHAS(I)=ABS(360.+2.*PIPHAS-DPHAS(I))
0055            SSDEVP=(BPHAS-TDPHAS(I))**2+SSDEVP
0056            TYPE *,BPHAS,TDPHAS(I)
0057     50     CONTINUE
0058            SSEP=SQRT(SSDEVP/(N-2.))
0059            SSEM=SQRT(SSDEVM/(N-2.))
         C
         C      Plot data and best fitting curve.
         C
0060     80     TYPE 85
0061     85     FORMAT(' HIT AUTO PLOT, RETURN')
0062            ACCEPT 6
0063            DO 90 K=1,40
0064            GPHAS=K*9.-9.
0065            RGPHAS=(PIPHAS+GPHAS)*.01745329
0066            GMLD=10.*ALOG10((PK-COS(RGPHAS))/(PK-1.))
0067            TYPE *,GPHAS,GMLD
0068     90     CONTINUE
0069            TIPHAS=ABS(PIPHAS-360.)
0070            TYPE *,SSEM,SSEP,TIPHAS,PK,PDC
0071            ACCEPT 6
0072            DO 100 I=1,N
0073            GDPHAS=ABS(DPHAS(I)-360.)
0074            GDMLD=DMLD(I)+PDC
0075            TYPE *, GDPHAS,GDMLD
0076    100     CONTINUE
0077            LPNT=360.
0078            GDMLD=DMLD(1)+PDC
0079            TYPE *, LPNT,GDMLD
0080            GO TO 80
0081            END
```

APPENDIX D

APPENDIX D

Parameters of least squares fit for the curve yielding the largest BMLD at each level of the primaries.

S		LEVEL OF THE PRIMARIES (dB SPL)					
		60	65	70	75	80	85
JS/	B (degs.)	368	269	239	238	200	234
	$s_{x\cdot y}$ (degs.)	32	18	27	12	49	29
	C (dB SPL)	16.5	16.0	10.5	14.0	7.5	15.0
	$s_{y\cdot x}$ (dB SPL)	1.1	1.0	1.1	0.4	1.5	1.3
	K	2.61	1.29	1.78	1.67	1.92	1.13
	BMLD (dB SPL)	3.5	9.0	5.5	6.0	5.0	12.0
JP/	B	375	265	250	248	213	218
	$s_{x\cdot y}$	25	34	27	41	23	56
	C	20.0	22.5	20.5	21.5	22.5	25.0
	$s_{y\cdot x}$	1.0	2.8	1.1	3.2	1.1	1.9
	K	1.58	1.13	1.38	1.12	1.50	1.50
	BMLD	6.5	12.0	8.0	12.5	7.0	7.0
RL/	B	315	232	238	227	240	198
	$s_{x\cdot y}$	24	20	15	27	27	35
	C	14.5	17.5	14.0	18.0	13.5	15.5
	$s_{y\cdot x}$	0.7	0.8	1.2	1.2	0.8	2.5
	K	1.92	1.38	1.38	1.20	1.50	1.25
	BMLD	5.0	8.0	8.0	10.5	7.0	9.5

APPENDIX E

APPENDIX E

Threshold signal to noise ratios for Experiment II.

S: JP

L1L2	Ls re:	SIGNAL PHASE (Øs) re: PRIMARIES							
	L1L2	0	45	90	135	180	225	270	315
60	-29	10.0	8.5	8.5	8.0	9.0	9.0	10.5	12.5
	-32	9.0	6.0	5.5	6.5	9.0	10.0	10.0	12.0
	-35	18.5	20.0	16.0	14.0	13.5	14.5	14.0	18.5
65	-32	13.5	9.5	9.0	9.0	14.0	16.5	22.0	18.0
	-35	14.5	10.0	4.0	2.0	11.0	12.0	15.0	16.5
	-38	16.0	14.0	12.5	13.0	12.5	13.5	15.0	14.0
70	-29	15.5	13.5	15.5	16.5	14.0	19.5	21.0	16.5
	-32	13.0	11.5	13.5	14.5	14.5	19.0	20.0	17.0
	-35	10.5	9.5	13.0	12.5	12.0	15.0	14.5	10.5
75	-32	18.0	17.5	17.5	18.5	19.5	21.5	19.5	20.0
	-35	9.0	9.0	4.0	9.0	14.5	18.0	15.5	15.5
	-38	21.5	17.5	15.0	15.5	19.0	20.5	22.0	17.5
80	-32	16.5	17.0	19.0	19.5	21.0	21.0	18.5	20.0
	-35	16.5	14.0	16.0	18.5	22.5	21.5	20.0	18.5
	-38	16.0	16.0	17.5	17.5	15.5	18.0	15.5	15.0
85	-32	18.0	16.5	16.5	19.5	20.0	21.5	20.5	21.5
	-35	16.5	17.0	16.5	17.0	18.5	20.5	21.5	20.0
	-38	17.5	18.0	17.5	16.5	22.5	22.0	22.0	15.0
	-41	14.0	11.0	12.0	12.5	15.5	15.5	15.0	13.5

S: RL

L1L2	Ls re: L1L2	SIGNAL PHASE (Øs) re: PRIMARIES							
		0	45	90	135	180	225	270	315
60	-32	14.0	3.0	14.0	11.5	13.5	14.5	14.0	16.0
	-35	12.0	11.0	10.0	8.0	9.0	11.0	13.0	15.0
	-38	14.5	13.5	13.0	11.5	11.0	12.5	13.0	14.0
65	-32	11.0	9.0	9.0	9.0	13.0	16.0	15.0	13.0
	-35	9.0	8.0	14.0	15.0	16.0	17.0	17.5	15.0
	-38	8.0	7.0	7.0	11.0	12.0	15.0	14.0	10.0
	-41	9.0	9.0	11.0	12.0	15.0	14.0	12.0	12.0
70	-32	11.0	8.0	9.0	--	--	13.5	14.0	11.5
	-35	9.0	4.0	7.0	8.0	12.0	13.5	13.5	9.5
	-38	5.0	5.0	7.5	--	--	11.0	11.5	7.0
75	-29	12.5	12.0	11.0	14.5	16.0	20.5	18.5	15.0
	-32	7.5	7.5	10.0	12.5	16.5	18.5	15.0	10.0
	-35	6.0	3.5	6.0	7.0	7.5	14.0	12.0	10.0
80	-32	--	--	--	--	--	--	--	--
	-35	7.5	7.5	6.0	7.0	10.5	14.0	11.5	10.0
	-38	5.0	3.0	6.0	7.5	11.5	6.5	10.0	7.0
85	-32	8.0	7.0	8.0	10.0	13.0	14.0	13.0	11.0
	-35	12.0	9.0	11.0	16.0	16.0	18.0	17.0	14.0
	-38	1.0	3.0	8.0	5.5	13.5	9.5	9.5	7.0
	-41	4.5	2.5	7.5	7.0	11.5	12.5	10.0	4.0

S: JS

L1L2	Ls re:	SIGNAL PHASE (Øs) re: PRIMARIES							
	L1L2	0	45	90	135	180	225	270	315
	-32	17.5	15.5	--	--	15.5	14.5	17.0	16.5
60	-35	18.0	14.5	15.0	13.5	12.5	14.0	13.5	14.5
	-38	--	--	--	--	--	--	--	--
	-29	11.5	10.0	10.0	11.0	11.5	13.5	14.0	13.5
65	-32	10.0	8.5	6.5	7.5	8.5	14.5	15.0	13.0
	-35	6.5	6.0	5.5	8.0	10.0	9.5	11.5	11.5
	-29	9.0	12.0	10.0	--	9.5	8.5	9.0	--
70	-32	12.0	11.5	8.0	8.0	11.0	12.0	14.0	13.5
	-35	6.5	--	4.5	7.5	7.0	11.0	10.0	6.5
	-38	3.0	6.0	6.0	5.0	4.0	6.0	2.5	--
	-29	8.5	7.5	8.0	8.5	11.5	13.5	13.5	10.0
75	-32	9.0	7.0	6.0	8.0	7.0	13.5	8.5	6.5
	-35	3.0	4.0	1.5	1.5	2.5	7.0	6.5	4.5
	-35	9.0	--	4.5	3.0	8.5	12.0	8.5	7.0
80	-38	4.0	0.0	3.5	5.0	5.0	8.5	3.5	1.5
	-41	2.5	0.5	1.5	--	3.0	2.5	3.0	--
	-35	11.0	12.0	12.0	13.5	14.0	15.0	14.0	11.0
85	-38	3.0	1.5	2.0	7.0	9.5	14.0	11.5	7.5
	-41	5.0	3.5	5.0	5.5	5.5	9.5	10.5	7.0

APPROVAL SHEET

The dissertation submitted by Robert A. Lutfi has been read and approved by the following committee:

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The final copies have been examined by the director of the dissertation and the signature which appears below verifies the fact that any necessary changes have been incorporated and that the dissertation is now given final approval by the Committee with reference to content and form.

The dissertation is therefore accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Sept 1, 1979
Date

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