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LOUDNESS SCALING OF NOISE BANDS

by

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CHAPTER I

INTRODUCTION AND REVIEW OF THE LITERATURE

INTRODUCTION

Since the 1930's a great deal of experimentation concerning the form of the loudness function has provided conflicting data and opposing interpretations. In these studies almost all of the available psychophysical scaling techniques have been utilized, each with its own proponents and antagonists. The formulation of the Analysis of Proximities (Shepard, 1962a, 1962b), the implementation of the MONANOVA program (Kruskal, 1968), and the development of the Least Squares Loudness Estimation procedure (Levitt and Richards, 1972) have provided the appropriate tools for analysis of loudness ratio judgments. Richards (1971) utilized the first two of these methods in studying the effects of stimulus range and inter-stimulus spacing on the loudness function of a 1000 Hz tone. His experiment also analyzed the loudness ratio estimates of stimuli of 250 Hz, 4000 Hz and white noise.

Based essentially upon these findings and upon additional unpublished data (Kramer, 1971), which replicated and substantiated Richards' key findings, this study continues along the same lines of inquiry in order to ascertain the form of the loudness function under changes of other parameters--namely the frequency and the bandwidth of noise stimuli.

In addition, these experiments were carried out in order to further examine the assumption that even if a simple power function represents the loudness function of a 1000 Hz tone, can the loudness of a noise be accurately assessed by the loudness balancing of its constituent band components to this 1000 Hz tone loudness function. Accepting Richards' analysis of the loudness functions of the 1000 Hz tone, additional findings other than a power function representation for simple stimuli of differing frequencies and bandwidths would imply the necessity for further evaluation of the conventional methods for computing the loudness of noises (USAS, 1968).

REVIEW OF THE LITERATURE

Nominal, ordinal, interval and ratio are the names given to the four types of scales used in psychophysics. Each has specific advantages over the preceding ones, as well as having its own boundaries for its application (Guilford, 1954; Stevens, 1951, 1958; Torgerson, 1958). Each scale can be represented by one or more salient illustrations. The simplest scale, the nominal, considers only the gross classification of the characteristics under consideration. Thresholds, both differential and absolute, exemplify the nominal scale.

Next in order of scale complexity is the ordinal scale. By its name, the ordinal scale implies order which is ranked against some other attribute. In this scale there is no implication of interval size between two items, and there is no true zero point. Paired comparisons and rank ordering are two examples of the ordinal scales used in psychophysical procedures (Stevens, 1951).

Interval scales represent an advance over the ordinal scale in that there is a quantification of the interval distance between two attributes. Again, like the ordinal scale, there is no true zero point. Bisection exemplifies the use of an interval scale in psychophysics (Stevens, 1955; Stevens and Volkman, 1940).

The most advanced of these scales is the ratio scale. In addition to including the interval scale within its structure, the ratio scale is the only one of the four to utilize the true zero point (Guilford, 1954; Stevens, 1955, 1958, 1960).

Ratio judgments are of great importance in the study of loudness, because they provide information about the ratios between sensations. These scales make it possible to mathematically indicate that the subject perceives one sensation as twice as great, or one-half as great, as another. Stevens' (1955, 1956, 1957a, 1958, 1959, 1960) experimental data and derived loudness functions implicitly show attributes of ratio scales. On this basis it appears that ratio scaling methods are utilizable in the scaling of loudness-intensity relations. Ratio judgments have shown themselves to be a highly efficient method of loudness scaling especially when utilizing a matrix format (Richards, 1971). Employment of this construct provides for a finite number of judgments to be made by each subject, and also lends itself to group data collection techniques. Richards (1971) found that this method produced scales that demonstrated a high degree of self-consistency over the several separate ranges through which they were tested. In addition he has shown that his results were highly replicable, thus providing a direct means of checking the reliability of the ratio scales.

Five methods which make use of ratio scaling procedures have been described in the psychoacoustic literature: Magnitude Estimation, Magnitude Production, Ratio Production, (Fractionation and Multiple Stimuli), Ratio Estimation and Numerical Magnitude Balance (Stevens, 1960).

The Method of Magnitude Estimation requires that the subject compare an experimental stimulus with a standard signal. In one variation of this procedure, the experimenter assigns a numerical value to the standard, and then the subject estimates the loudness of the experimental stimuli relative to the value assigned to the standard. In an alternative version, no numerical value is assigned to the standard, and the subject is required to suggest a ratio which he feels represents the relationship between the loudnesses. These methods have been used extensively in the development of loudness scales (Hellman & Zwislocki, 1961, 1963; Jones & Woskow, 1966; J.C. Stevens, 1958; Stevens & Tulving, 1957).

The subject plays a more active role in the Method of Magnitude Production. Here, the subject is directed to adjust an intensity control so that the experimental signal is perceived to fulfill a proportional relationship dictated by the experimenter (Stevens, 1958). It has been reported that at moderate sensation levels (40-90 dB S.L.), magnitude production techniques and magnitude estimation techniques yield similar results (Hellman & Zwislocki, 1963).

The Method of Adjustment and the Method of Constant Stimuli are two psychophysical methods often associated with ratio production techniques. The Method of Adjustment asks that the subject "adjust" a comparison signal so that its perceived loudness ratio relationship to the standard stimuli is the same as that indicated by the experimenter. In the case of the Method of Constant Stimuli, as applied to loudness, the subject need only indicate whether the ratio between the two signals presented by the experimenter is greater or lesser than the ratio the experimenter has suggested. There appears to be controversy surrounding the preference for the use of one of these techniques over the other in the Method of Ratio Production. Stevens (1955) and Warren (1970) indicate deficiencies which appear inherent in each of these methods, and which will be discussed later. In spite of such sources of error it should be noted that these methods have been widely used in establishing values for the 1:2 and 2:1 loudness ratios (Churcher, King & Davies, 1934; Garner, 1952, 1954; Geiger & Firestone, 1933; Ham, 1956; Ham, Briggs & Cathey, 1962; Pollack, 1951; Richards, 1968, 1971; Robinson, 1953, 1957; Rschevkin & Rabinovich, 1936; Stevens, Rogers & Herrstein, 1955).

McRobert, Bryan and Tempest (1965) published a paper concerning itself with the use of the technique of ratio estimation. This procedure, which was first described by Stevens (1958), directs the subject to "estimate" the loudness ratio between two stimuli. Findings derived from the McRoberts et al (1965) data pointed to overestimation of the loudness ratios by earlier experimenters, a finding that was later supported by Richards (1971).

The Method of Numerical Magnitude Balance is the latest to be developed (Hellman & Zwislocki, 1961, 1963, 1968; Rowley & Studebaker, 1969). It combines the Methods of Magnitude Estimation and Magnitude Production. The procedure requires that the subject first make magnitude estimates of stimuli at several different intensities, being given no framework in which to operate he is free to assign any number he feels is proportional to their loudnesses. At a later session the group medians obtained from the magnitude estimates are incorporated as the experimenter assigned ratio to which the subject must adjust a comparison signal, as in the Method of Magnitude Production. The geometric means of the data generated by the two procedures are then combined to provide loudness scaling data.

BIASING EFFECTS

In order to comprehend the succeeding presentation two loudness measurement units presently used must be understood, namely the "phon" and the "sone". The loudness level (in phons) of any acoustic signal is taken to be the sound pressure level in dB of a standard signal (a 1000 Hz tone) which has been judged to be equally loud. A 1000 Hz tone at 40 dB SPL is assigned a loudness level of 40 phons (Littler, 1965).

Although the loudness level (LL) notation gives us the ability to assign loudness values, it does not provide a strategy for quantitative comparison of these values. To this end the "sone" scale was devised to provide a measure which would be proportional to the magnitude of the loudness sensation. The value of the sone unit has been set equal to the loudness of a 1 KHz tone at 40 dB SPL. A signal judged to be twice as loud would have a value of 2 sones, one-half as loud 0.5 sones, etc.

In ratio scaling, order effect is that phenomenon which exists when, " . . . a pair of sounds heard consecutively, the second sound appears relatively louder than it would if the sounds were presented in the other order." (Robinson, 1957, p. 219) He further indicates that although this biasing increases proportionately with an increase in signal intensity, even at loudness levels of 100 phons, this bias did not exceed 2 dB. These systematic errors, which have been observed in equal loudness judgments, can be compensated for either by presenting the stimuli in random order or by changing the order of the stimuli pair in a second presentation.

Another example of the order effect was described in relation to utilization of the Method of Adjustment (Stevens, 1956a). He observed that when a subject was asked to adjust the first stimulus to an intense second stimuli he tended to underestimate its value relative to the value he would assign if he adjusted the second to match the first. He further observed that the relative value of the two judgments are reversed at very low levels. It appears that randomization of order would provide the correction necessary in this case.

The Centering Effect is the second most common biasing phenomenon encountered in loudness scaling, and is found when fractionation and multiplication are used in the Method of Ratio Production. The effect has been attributed to a resistance on the part of the subject to assign values which are remote from the standard signal (Robinson, 1957). It has also been interpreted to be a subjective preference to retain values in a moderate intensity range (Robinson, 1957; Stevens, 1955).

A specific example of this effect is called "the fractional/multiple anomaly", and is described as a directional dependency causing average changes in intensity to be less for fractional judgments than for corresponding multiple judgments (Ham, Biggs & Cathey, 1962; Robinson, 1957; Semenoff, 1957; Stevens, 1955). In a 1957 paper, Stevens (1957a) reported that he found this directional dependency at low levels of the standard only, and that at higher levels the dB change for the fractional judgments were greater than for the multiple judgments.

Several suggestions have been offered regarding methods which could be utilized to correct these biases. Stevens (1955) feels that reversing the roles of the standard and the variable in succeeding trials would eliminate this bias. He also suggested that if the value for the error could be established, a numerical correction could be applied to this calculation.

Robinson (1957) established that the pivotal point in this fractional-multiple relationship existed at 85 dB SL for the 1000 Hz tone. A correction for both the fractional and multiple biases could be applied around this 85 phon delineation and would be proportional to their distances from it. Robinson presented these corrections in a graphic form (page 22, fig. 2), and applied them to the theretofore irreconcilable data of twelve previous experimenters (Churcher, King & Davies, 1934; Garner, 1952, 1954; Geiger & Firestone, 1933; Ham & Parkinson, 1932; Laird, Taylor & Wille, 1932; Pollack, 1951, 1952, undated communication with Robinson; Poulton & Stevens, 1955; Quietzsch, 1955; Robinson, unpublished data; Rschevkin & Rabinovitch, 1936; Stevens, 1956a, Stevens, Rogers & Herrnstein, 1955).

Robinson (1957) stated that the fractional/multiple anomaly was a centering effect which acted independently of order. He suggested that like all centering effects, it operated selectively and the degree of its effect depended only upon absolute values, as differentiated from order effects, which tended to inflate all incremental and reduce all decremental judgments.

The range values of the comparison stimulus appears to differentially effect loudness ratio judgments. Using the Method of Magnitude Estimation, Stevens (1956a) found that subjects responded differentially when the range of values of the variable was extended from 70 to 90 dB. In the experiment utilizing the 90 dB range, Stevens found that at high intensities there was an overestimation of values (re: the 10 dB rule) and the converse was true for lower levels. In opposition, Engen & Levy (1958) did not find these artifacts from an alteration of the range when their method of "Constant Sum" was utilized.

Another approach to this problem was employed by Tabory & Thurlow (1959) in which they sought differential data relative to open and closed response sets. Two groups of subjects were presented with the upper and lower limit stimuli of two ranges of intensity, and were told that the lower was called "50" and the louder "60". One group was then told that the stimuli in the experiment might fall either inside or outside of this range (open set), while the other group was told that all values would fall within the two limits given (closed set). Incorporating ranges for a 1000 Hz tone of 30 - 90 dB SL and 70 - 90 dB SL, they found that in both cases, lower magnitude estimates were derived for open set responses relative to the closed set responses.

Richards (1971) suggested that it was the range of stimuli values which he presented for ratio estimation, that was primarily responsible for different loudness function shapes in his studies concerning the 1000 Hz tone at moderate levels. The relevant parameters in these experiments which were all presented in 7 x 7 matrices (identified as Matrices A, B, and C) were stimuli ranges of 60, 30 and 15 dB, respectively, with inter-stimulus ranges of 10, 5, and 2 1/2 dB, respectively. He suggested that the spacing might also have provided biases in the judgments but did not provide for the separation of these two factors in the experimental design of his study. This failure to differentiate between the possible effects of stimulus range and inter-stimulus spacing may indeed be an important consideration inasmuch as he concluded that his findings differed from the 0.54 loudness function specifically because in the past there had been a scarcity of studies investigating loudness over narrow and wide inter-stimulus ranges. Unfortunately, his design locked stimulus range and inter-stimulus spacing together by way of the limiting nature of the 7 x 7 matrix.

Relevant studies reflecting the effects of stimulus spacing include those by Beck & Shaw (1965), J.C. Stevens (1958) and Stevens (1956a) which reported that these effects were small in experiments utilizing the Method of Magnitude Estimation. Similar findings for the Method of Ratio Estimation were reported by Engen & Levy (1958).

In contrast, Garner (1954) conducted an experiment which illustrated the consequences of change in the spacing of the variable stimuli when the Method of Constant Stimuli was employed in half-loudness judgments. Three non-overlapping ranges for the variable were used (55-56, 65-75 and 75-85 dB SPL) against a standard of 90 dB SPL. Results in each experiment appeared at approximately the middle of each variable range.

A final phenomenon of importance to this paper concerns the effect of the placement of the standard stimulus when using Methods of Fractionation and Multiplication. Depending upon which of these two methods was used, Robinson (1957) reported that differential results were obtained at different intensities. For the 1000 Hz tone, dB changes were greatest near 55 dB SL, and least near 90 dB SL. Stevens (1957a) found quite similar results, although for doubling only, and not for halving.

THE SHAPE OF THE LOUDNESS FUNCTION

The literature concerning the application of the power function to the growth of loudness with intensity of the 1000 Hz tone is well known (Stevens, 1955). It has become widely accepted that for levels from 30 dB SL through 100 dB SL, the 1000 Hz tone grows with loudness as a power function of its intensity. The exponent of this power function has been calculated to have a value of 0.54 for sound pressure, or 0.27 for power (Hellman & Zwislocki, 1963; Lochner & Berger, 1962; Rowley & Studebaker, 1969). This relates a perceived doubling of the loudness to a 10 dB increase in the intensity (Robinson, 1957; Stevens, 1955, 1956a, 1957a, 1957b, 1957c; Stevens & Poulton, 1956; J. C. Stevens, 1958). Figure 1 shows the loudness function for the 1000 Hz tone (after Hellman & Zwislocki, 1963).

It was Stevens (1955) who first reconciled the seemingly divergent published loudness data of previous experimenters (Churcher, King & Davies, 1934; Garner, 1952, 1954; Geiger & Firestone, 1933; Ham & Parkinson, 1932; Laird, Taylor & Wille, 1932; Pollack, 1951; Richardson & Ross, 1930; Robinson, 1953; Rschevkin & Rabinovitch, 1936) as well

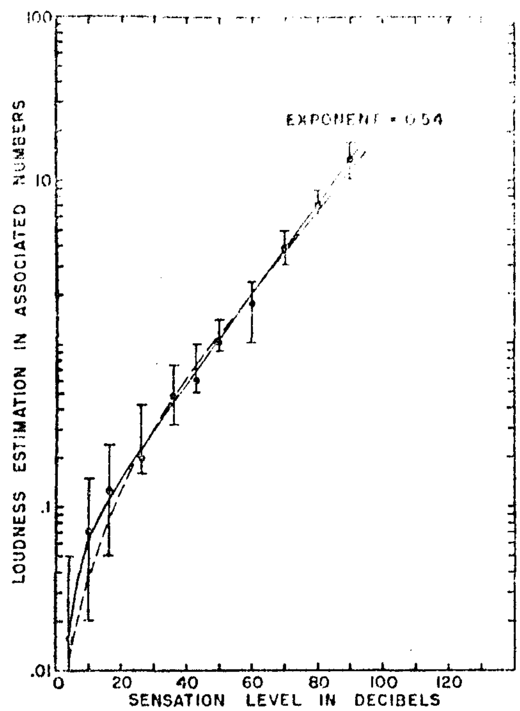

Figure 1. -- Loudness function of 1000 Hz tone. [After Hellman & Zwislocki, 1963]

as unpublished data of the psychoacoustic researchers at the Harvard Psychoacoustic Laboratory. It should be noted that the data selected for his study included only those studies which were based upon judgments of dB differences necessary to halve or double the loudness of the standard stimulus. In addition, not all of the experiments reported dealt with a tone of precisely 1000 Hz; some were as high as 2500 Hz and others, as low as 350 Hz. These factors notwithstanding, Stevens found that although individual values ranged from 2.1 to 24.0 dB, the median value for the 178 data points was exactly 10 dB. He suggested that it was the median value, rather than the arithmetic mean, that best represented the "typical observer". He further suggested that the median was a superior statistic to the mean in those data sets where the distribution was skewed.

Many of the experimenters writing subsequent to Stevens' 1955 paper have verified the power function for the 1000 Hz tone (Ham, Biggs & Cathey, 1962; Lochner & Berger, 1962; Rowley & Studebaker, 1969; J.C. Stevens & Guirao, 1964; Stevens, 1957a, 1959). Not in agreement were McRobert, Bryan & Tempest (1965) who reported that their data for the 1000 Hz tone was by far not in agreement with the sone scale (Stevens' 1955 construct), suggesting that observer estimates are based upon relative loudness rather than absolue loudness, thus implying that loudness does not have an absolute psychological magnitude. Warren (1970) stated that the use of the sone scale (or a sone potentiometer) in experiments, in itself, " . . . reflects the influence of known experimental biases and hence does not represent a fundamental relation between stimulus and sensation." (p. 1397).

Stevens (1970) writing on the subject, "Neural Events and the Psychophysical Law", stated that 0.66 now appeared to be the exponent of the power function which best described the growth of loudness in the human neural auditory system.

Most recently, Richards (1971), utilizing a ratio estimation method, demonstrated that the 0.54 (or the 0.66) power function exponent did not universally fit data he had generated for the 1000 Hz tones. The parameter of inter-stimulus spacing appeared to provide differential results; in two cases the exponent was either above or below the 0.54 exponent, and in the third case, a power function could not be approximated at all.

IMPLICATIONS OF THE LITERATURE AND GOAL OF THIS STUDY

Since the most practical use of loudness scaling concerns its relationship to the perception of noise, many experiments have been conducted utilizing the sone scale as an underlying assumption. That is, relating sones to phons for the 1000 Hz tone (i.e., 1 sone ≑ 40 phons, 2 sones ≑ 50 phons, 4 sones ≑ 60 phons, etc.), the next step is to balance a band of noise (usually with 1000 Hz at or near its geometric mean) to this 100 Hz tone, thus assigning to the noise phon and sone values (Stevens, 1956b). With the band of noise now acting as the standard, equal loudness balances are then performed with octave bands of noise. Having established sone values for the various band sound pressure levels it then became possible to plot these loudnesses as a function of the frequency as in Figure 2 (from Stevens, 1957b), or as nomograms relating band sound pressure level to loudness in sones as in Figure 3 (from Stevens, 1956b). The method by which these bands are added to provide a total loudness for a noise of continuous spectrum is not of concern in this paper. The more important consideration is that it has been effectively assumed that all octave bands of noise grow in loudness as the 1000 Hz tone.

Since noise is often measured in one-third octave bands, formuli were derived for the calculation of total loudness based upon these smaller units. Again, it was assumed that the loudness of these third octave bands grew like that of the full octave bands, which were again assumed to behave as the 1000 Hz tone (Stevens, 1956b).

Both in 1956 (b) and 1957 (b) Stevens noted that there was no experimental data to confirm the assumptions he made regarding the growth of loudness in the one-third octave bands.

Richards' (1971) utilization of the Analysis of Proximities (Shepard, 1962a, 1962b) opened a new approach

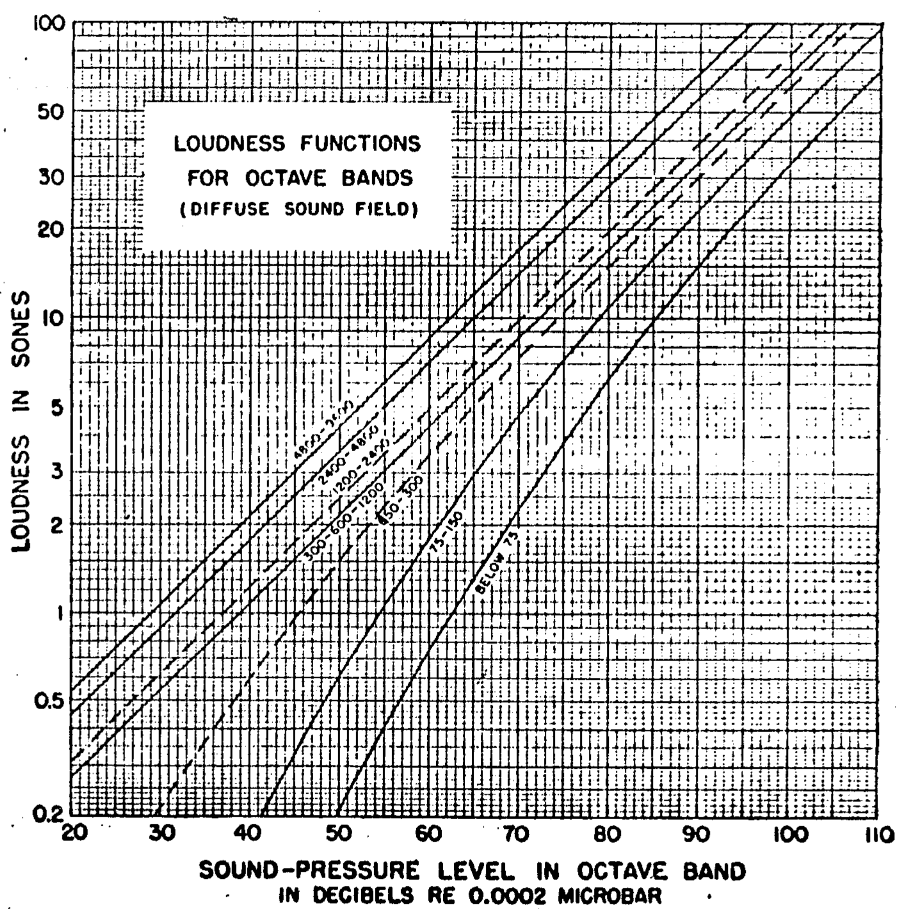

Figure 2. -- Chart for determining the loudness in an octave band as a function of the SPL in the band. [Stevens, 1957b]

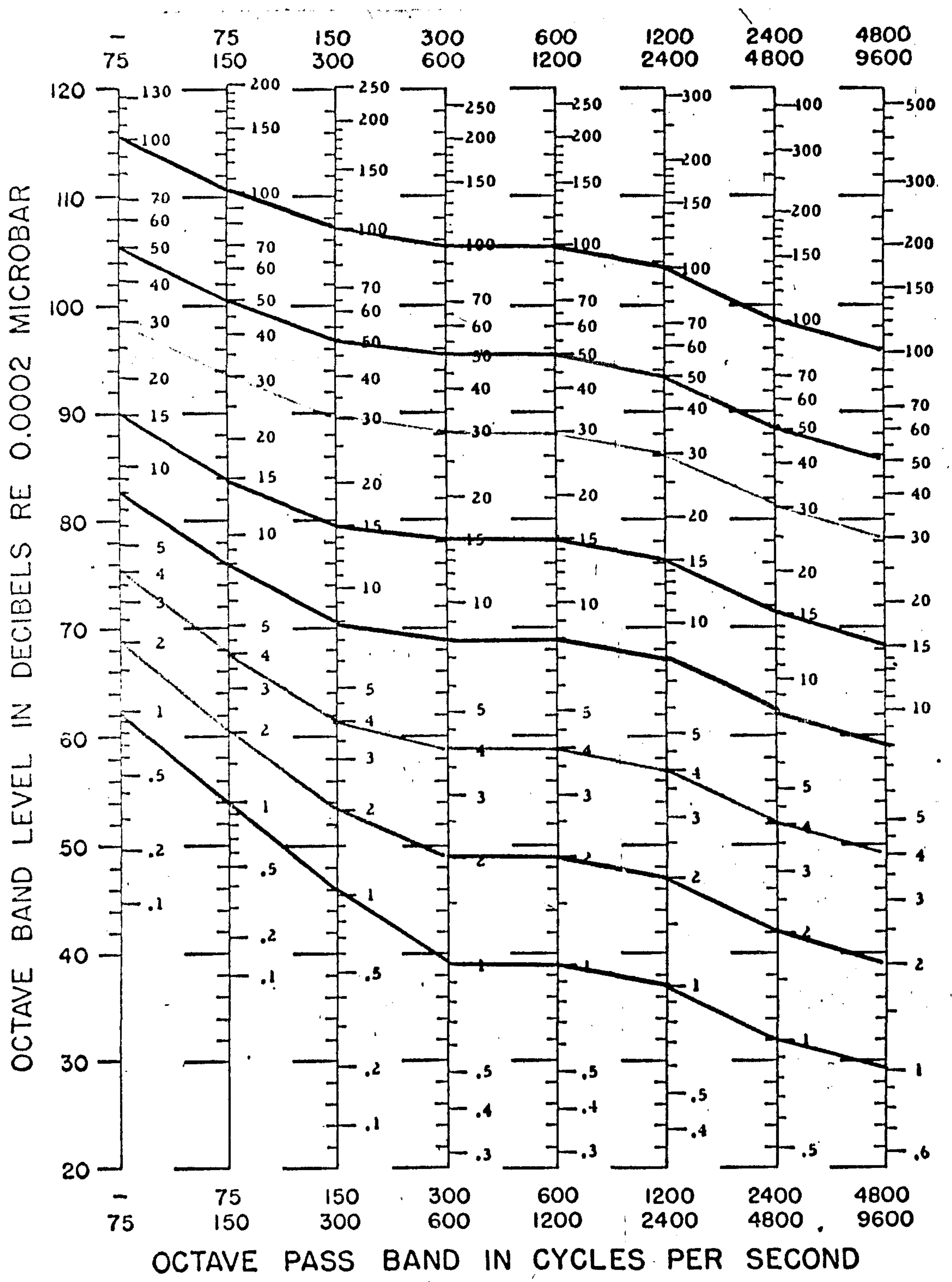

Figure 3. -- Nomograms relating SPL in octave bands to loudness in sones. [Stevens, 1956b]

to the scaling of loudness growth with intensity. His research findings concerning the loudness function of the 1000 Hz tone are quite different from those reported by experimenters who had used more conventional methods. The Analysis of Proximities provides a monotonic transformation of the perceived distances between a pair of stimuli, so as to provide a spatial configuration of minimum dimensionality in representing the stimuli. The relationships between all the pairings of stimuli in the matrix are presented in a Euclidian space with the distances between the plotted points monotonically related to the perceived loudness differences between them. The configurations obtained by Richards were unlike those that would be expected if a simple power function best described the data.

Levitt and Richards (1972) have reviewed Richards' (1971) findings related to inconsistencies between predictions of loudness ratio based upon a power law and actual loudness ratio judgments which had been obtained while utilizing the Analysis of Proximities. A computer program performing the necessary computations has been developed by Kruskal (1968). In analyzing Richards' data they reason that if, in fact, the loudness of a 1000 Hz tone grows as a power function of its intensity, and if the method of loudness ratio judgments does, in fact, yield valid measures of perceived loudness ratios then the relationship between loudness ratio vs. ratio of stimulus intensities should be a straight line. This result was not obtained in

Richards' data. They further reasoned that it might be appropriate to conceive of a model where the loudness ratio judgment could be considered to be made up of at least two elements, one accounting for the sensory effect generated by the stimulus, and the other factor accounting for response bias. That is, if,

$$L_i = E_i \times r_i \qquad \text{(Equation 1)}$$

where L_i is the judged loudness of stimuli i

E_i is the sensory effect generated by the stimulus

r_i is the factor accounting for response bias

then in the case of loudness ratio judgments, Equation 1 reduces to,

$$L_i/L_j = (E_i/E_j) \times r_{ij} + \varepsilon_{ij} \qquad \text{(Equation 2)}$$

where L_i/L_j is the judged loudness ratio

E_i/E_j is the ratio of sensory effects

r_{ij} is the factor accounting for judgmental bias

ε_{ij} is the factor accounting for experimental error

In establishing a simple model to account for loudness ratio data, utilizing a two-way analysis of variance, fixed effects model, each observation (X_{ij}) can be assumed to be made up of four additive components, i.e.,

$$X_{ij} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ij} \qquad \text{(Equation 3)}$$

where μ is an effect common to all observations

α_i is an effect common to the first factor

β_j is an effect common to the second factor

$\alpha\beta_{ij}$ is an effect accounting for the interactions between the two factors

ε_{ij} is the error associated with each measurement

In their discussion it is assumed, as a first approximation, that the value of the interaction term can be assumed to be zero ($\alpha\beta_{ij} = 0$), and how M, A_i and B_j could be used as equivalents for μ, α_i, β_j, respectively, in order to eliminate computational ambiguities. Although the use of these equivalents does not provide a means for establishing the <u>absolute</u> values of the true stimulus effects, α_i and β_j from the data, it does provide a mathematically workable framework for dealing with the <u>relative</u> values of these factors.

Again taking into consideration a two-way analysis of variance, fixed effects model, it is shown that when applied to a matrix of loudness ratio judgments, each loudness ratio judgment can be assumed to have the same form as Equation 3. The log of the loudness ratio judgment in each cell would therefore be,

$$\log(L_i/L_j) = \log E_i - \log E_j + R_{ij} + \varepsilon_{ij} \qquad \text{(Equation 4)}$$

A sample matrix of log loudness ratio judgments for a matrix of size I x I is shown in Figure 4. It can be observed that the average down column i of this matrix is equal to,

$$\log E_i - \overline{\log E} + R_{i.} + \varepsilon_{i.}, \text{ where } \overline{\log E} = \frac{1}{I}\sum_{i}^{I} \log E_i$$

and that similarly, the average across row j is equal to,

$$-\log E_j + \overline{\log E} + R_{.j} + \varepsilon_{.j}, \text{ where } \overline{-\log E} = \frac{1}{I}\sum_{j}^{I} \log E_j$$

Still using the fixed effects analysis of variance, the least squares estimate of A_i would be calculated by subtracting from the column mean, the grand mean. Since the grand mean has the value of $R_{..} + \varepsilon_{..}$, the least squares estimate of A_i would be reduced to,

$$\log E_i - \overline{\log E} + (R_{i.} - R_{..}) + (\varepsilon_{i.} - \varepsilon_{..})$$

By the same mode of computation (row mean - grand mean) the estimate of B_j reduces to,

$$-\log E_j + \overline{\log E} + (R_{.j} - R_{..}) + (\varepsilon_{.j} - \varepsilon_{..})$$

FIRST STIMULUS	SECOND STIMULUS				
	S_1	S_2		S_i	Row Average
S_1	$\log E_1 - \log E_1 +$ $R_{11} + \varepsilon_{11}$	$\log E_2 - \log E_1 +$ $R_{21} + \varepsilon_{21}$	. . . .	$\log E_i - \log E_1 +$ $R_{i1} + \varepsilon_{i1}$	$\overline{\log E} - \log E_1 +$ $R_{.1} + \varepsilon_{.1}$
S_2	$\log E_1 - \log E_2 +$ $R_{12} + \varepsilon_{12}$	$\log E_2 - \log E_2 +$ $R_{22} + \varepsilon_{22}$	. . . .	$\log E_i - \log E_2 +$ $R_{i2} + \varepsilon_{i2}$	$\overline{\log E} - \log E_2 +$ $R_{.2} + \varepsilon_{.2}$
	⋮	⋮	. . . .	⋮	⋮
S_j	$\log E_1 - \log E_j +$ $R_{1j} + \varepsilon_{1j}$	$\log E_2 - \log E_j +$ $R_{2j} + \varepsilon_{2j}$	. . . .	$\log E_i - \log E_j +$ $R_{ij} + \varepsilon_{ij}$	$\overline{\log E} - \log E_j +$ $R_{.j} + \varepsilon_{.j}$
Column Average	$\log E_1 - \overline{\log E} +$ $R_{1.} + \varepsilon_{1.}$	$\log E_2 - \overline{\log E} +$ $R_{2.} + \varepsilon_{2.}$	. . . .	$\log E - \overline{\log E} +$ $R_{i.} + \varepsilon_{i.}$	$R_{..} + \varepsilon_{..}$ (Grand Mean)

Fig. 4. -- Log loudness ratio judgments for a matrix of size I x I [Levitt & Richards, 1972]

It becomes apparent that if there are no response biases ($R_{ij} = 0$) the sensory effects could be determined directly from either row or column means. When this condition occurs the mean of column i would be expected to show a value approximately equal and opposite in sign to that of row i.

While the Levitt and Richards paper goes into further discussion of the theory and application of the Least Squares Loudness Estimation model, those aspects of the model considered relevant to this study have been presented.

In this present study, by attempting to ascertain the growth of loudness with intensity of several auditory stimuli, two major questions have been posed. First, what are the effects of changes in bandwidth and frequency on the growth of loudness, and second (following from the first) does the growth of loudness with stimulus intensity follow a power function? The Least Squares Loudness Estimation model is used in its most basic form to ascertain relative stimulus values in each of the submatrices presented.

Under examination are the loudness functions of 1000 Hz puretones, one-third octave bands of noise with center frequencies at 250 Hz, 1000 Hz and 4000 Hz, and an octave wide band of noise with a center frequency of 1000 Hz. Each of these 6 x 6 matrices was nested in larger 12 x 12 matrices so that combinational judgments could be made between two different types of stimuli (see Chapter II, Table 2 and Figure 5). In all matrices the interstimulus spacing was 5 dB, and the intensity range from 50 through 75 dB SPL.

CHAPTER II

METHOD

SUBJECTS

The group consisted of seven normal hearing student volunteers from various Department of Speech classes at Hofstra University during Summer Session I, 1971. All seven subjects participated in each of the six (6) experiments. None of the subjects had previously participated in any psychoacoustic experiments. The subjects, two males and five females, ranged in age from 19 to 24, with a mean age of just over 20 years.

PROCEDURE

Each subject's eligibility to participate in these experiments was established by puretone threshold testing at the frequencies of interest (i.e., 250 Hz, 1000 Hz and 4000 Hz). The method of threshold determination used was that described by Newby (1964) as based upon reports of Carhart & Jerger (1959) and Hughson & Westlake (1944). A Grason-Stadler Model 1701 Clinical & Research Audiometer equipped with TDH-39 earphones in MX 41-AR cushions, as calibrated within ± 1 dB of the A.N.S.I. S 3.6-1969 Audiometric Standards was used in these measurements.

The audiometric calibration was ascertained with a Bruel & Kjaer Type 2304 Precision Impulse Sound Level Meter with its compatible Type 1613 Octave Filter Set, Type 4132 1" Precision Condenser Microphone, and Type 4152 Artificial Ear, both before and after all threshold measurements were established.

The thresholds for each subject, as well as the means and standard deviations for each frequency are shown in Table 1.

ADMINISTRATION OF EXPERIMENTS

All six experiments were presented to the right ear only. In view of the findings regarding the audibility of short rise and decay time switching artifacts (Wright, 1960: Harris, 1947) these parameters were set at 25 msec (Grason-Stadler Model 829E Electronic Switches).

Experiment I included signals of various bandwidths, but all with a center frequency of 1000 Hz. These included a 1000 Hz puretone, a one-third octave band of noise with a center frequency of 1000 Hz, and a band of noise a full octave wide with a center frequency of 1000 Hz. In Experiment II all stimuli were one-third octave bands of noise, but with center frequencies at 250 Hz, 1000 Hz and 4000 Hz, respectively. The stimuli in Experiments I and II were presented at levels of 50 to 75 dB SPL in 5 dB gradients,

SUBJECT	250 Hz	1000 Hz	4000 Hz
1	7.5	-5.0	5.0
2	15.0	7.5	0.0
5	15.0	-2.5	-15.0
6	7.5	5.0	10.0
7	0.0	-5.0	-15.0
8	10.0	5.0	-15.0
10	5.0	2.5	2.5
mean threshold	8.6	1.1	-3.9
standard deviation [between subjects]	5.4	5.2	10.8

TABLE 1. -- Puretone thresholds of experiment participants (in dB re: ANSI S3.6-1969)

(see Table 2 and Figure 5).

The 12 x 12 matrices were so constructed that they contained four discrete 6 x 6 submatrices. The three 12 x 12 matrices in each, Experiment I and Experiment II, provided for one replication of each of the 6 x 6 matrices in that experiment, and further provided for 6 x 6 matrices which were made up of cells containing paired combinations of those stimuli which had been studied individually.

These double matrices were so constructed so that the data from one experiment could be linked to previously generated data. For example, 1000 Hz puretone data in Experiments I-A and I-C can be compared with Richards' (1971) data. 1000 Hz Narrow Band Noise in Experiments II-A and II-B could be compared with data generated in Experiments I-A and I-B.

The stimulus sequence for each trial commenced with the first stimulus of 1500 msec duration, followed by a 500 msec pause, which was then followed by the second member of the stimulus pair, also of 1500 msec duration. A five second pause was inserted between each pair of stimuli so that the subjects were afforded the opportunity to record their responses on the response forms provided. After every tenth pair a pause of 13.5 seconds was provided so that the subjects were able to ascertain if their answers were in synchrony with the stimulus presentations.

Each subject listened to one 12 x 12 matrix each day. There were two groups of listeners with the instrumentation

EXPERIMENT	STIMULI	
	X	Y
I-A	1 KHz Tone	1 KHz NBN
I-B	1 KHz NBN	1 KHz OBN
I-C	1 KHz Tone	1 KHz OBN
II-A	250 Hz NBN	1 KHz NBN
II-B	1 KHz NBN	4 KHz NBN
II-C	250 Hz NBN	4 KHz NBN

TABLE 2. -- Matrix Configurations - Experiments I & II

		STIMULUS X (DB SPL)						STIMULUS Y					
		50	55	60	65	70	75	50	55	60	65	70	75
STIMULUS X (DB SPL)	50												
	55												
	60												
	65												
	70												
	75												
STIMULUS Y	50												
	55												
	60												
	65												
	70												
	75												

Fig. 5. -- Matrix formats - Experiments I & II

calibrated before each session. The six matrices were presented to the listeners in a random order, although both groups heard the matrices in the same order.

The presentation of each matrix began with ten practice pairs, followed by the experiment proper of 144 pairs and then concluded with six additional practice pairs for a total of 160 ratio judgments per session. The subjects were unaware of which stimuli were practice and which were recorded responses.

APPARATUS

A block diagram of the apparatus used in the preparation of the stimuli tapes is seen in Figure 6. The source of the puretone signal used in Experiments I-A and I-C was a Hewlett-Packard 202C Low Frequency Oscillator. The lack of distortion in the puretone signal was checked periodically with a Tektronix 564 Oscilloscope, with the frequency monitored on a Hewlett-Packard Type 522B Electronic Counter and found to be within the limits of ± 3 Hz of the nominal frequency of 1000 Hz. The Bruel & Kjaer Precision Impulse Sound Level Meter Model 2204 was also used periodically to check the signal amplitude. Daven "T" Series Attenuators followed the oscillator to provide control of its output.

A Grason-Stadler Type 901 B Noise Generator was the source of the white noise which was filtered into bands of

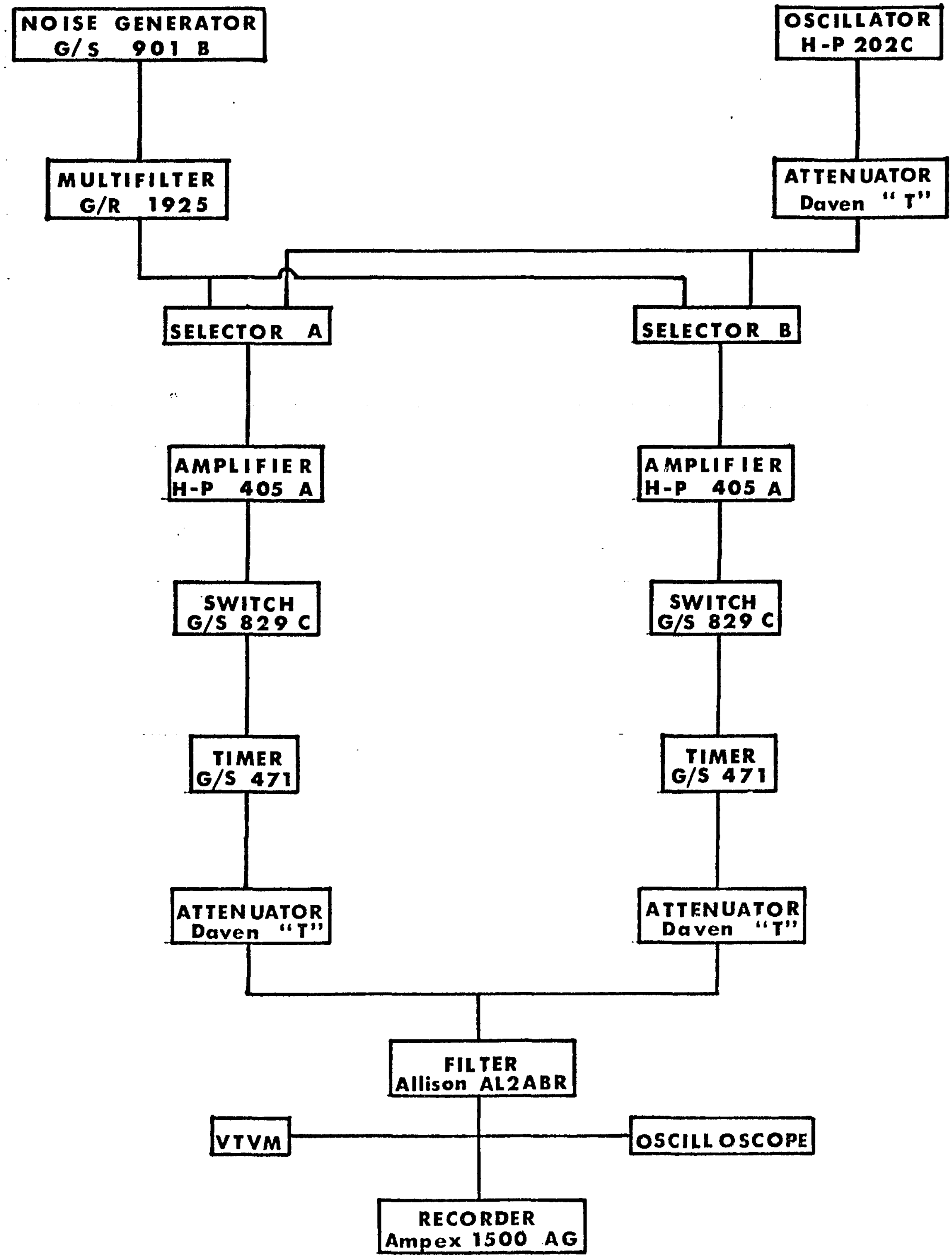

Fig. 6. -- Apparatus used in preparation of stimulus tapes

noise by a General Radio Type 1925 Multifilter. Third octave bands of noise were drawn from the individual band outputs of the Multifilter and were matched through 10 Kilo-Ohm resistors, mixed, and then were made available at two selector switches (one for each, Stimulus A and Stimulus B). The tone originating from the Hewlett-Packard Oscillator was also available for selection at the switch.

The chosen signals from each of the selectors were separately amplified by a pair of Hewlett-Packard Type 450-A Amplifiers and directed to the inputs of separate Grason-Stadler Type 829C Electronic Switch and Type 471 Interval Timer combinations. These instruments were set in a reciprocal relationship so that controlled outputs of the interval timers triggered one another. The triggering of each timer in turn activated its paired switch. The end result was the timing sequence of each sequence as described earlier.

The output of each of the switch-timer combinations is then attenuated as necessary by a pair of matched Daven "T" Series Precision Attenuators. At this point they are mixed and passed through an Allison AL-2ABR filter, monitored by an oscilloscope and vacuum tube voltmeter, and finally introduced to the Ampex 1500 AG Tape Recorder.

In order to check the spectral composition of each of the stimuli, each was recorded at a constant level on the Ampex 1500 AG Tape Recorder then replayed through an analyzer system made up of a Bruel & Kjaer Type 2603 Microphone Amplifier, Bruel & Kjaer 1612 Band Pass Filter Set, and Bruel & Kjaer Type 2305 Graphic Level Recorder as shown in Figure 7.

Analysis made in this manner on frequency calibrated paper indicated that the stimuli were essentially as described, that is, the band energy is symmetrical around the specified frequencies. A check on timing sequences was made using the same instrumentation, with this parameter being found to be as specified within ± 5 msec.

In a final check of the stimulus levels and timing, the Ampex 1500 AG was replaced with a Sony 360 Stereo Center/Tape Recorder which was used during the data collection phases of the study. This analysis of the 960 stimulus pairs in the six matrices indicated that the intensity and time parameters of all test stimuli corresponded to the specifications of the experiment; the intensity within ± 1 dB, and the timing within ± 5 msec.

During the recording of each matrix, a 1000 Hz calibration tone was set equal to the highest sound pressure level to be administered in that test. This level was chosen to be the highest voltage which could be presented to the tape recorder without signal distortion measured at both input and output of the recorder. All other stimuli values were achieved by attenuating in 5 dB steps from the original values to produce all six levels required in Experiments I and II. This ensured that the optimal dynamic range of the recording tape could be utilized.

A block diagram of the playback instrumentation is

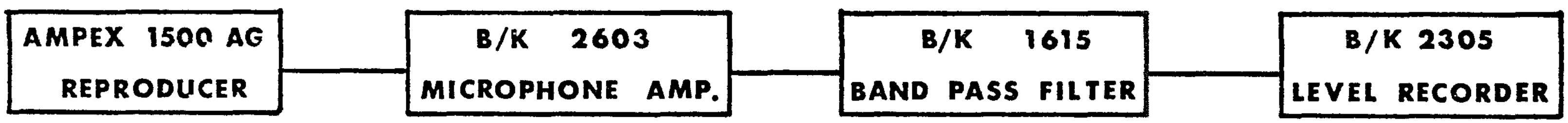

Fig. 7. -- Instrumentation used in spectral analysis of stimuli

shown in Figure 8. It can be seen that five subjects could be tested at each session. The TDH-49 earphones, which were wired in parallel and mounted in MX 41-AR cushions, were used in all sessions. Each subject was assigned a phone which he used for all sessions.

Calibration for each session was achieved by placing the earphone designated as #1 onto the artificial ear and adjusting the attenuator until the calibration tone on the tape produced a deflection of 75 dB SPL; this being the highest signal level used.

To ascertain the frequency responses of each of the TDH-49 phones used in the experiment, curves were obtained using the instrumentation shown in Figure 9.

The sound pressure levels generated by a 100 mV tone at the frequencies of interest are seen in Table 3. (It should be noted that phones #1 and #2, and #3 and #4 were purchased as matched pairs.)

All the data were collected in the audiometric testing suite at the Speech & Hearing Center at Hofstra University. Table 4 shows the ambient noise levels in the control room (where subjects were seated during the experiment) using the Bruel & Kjaer Precision Impulse Sound Level Meter and Octave Filter Set.

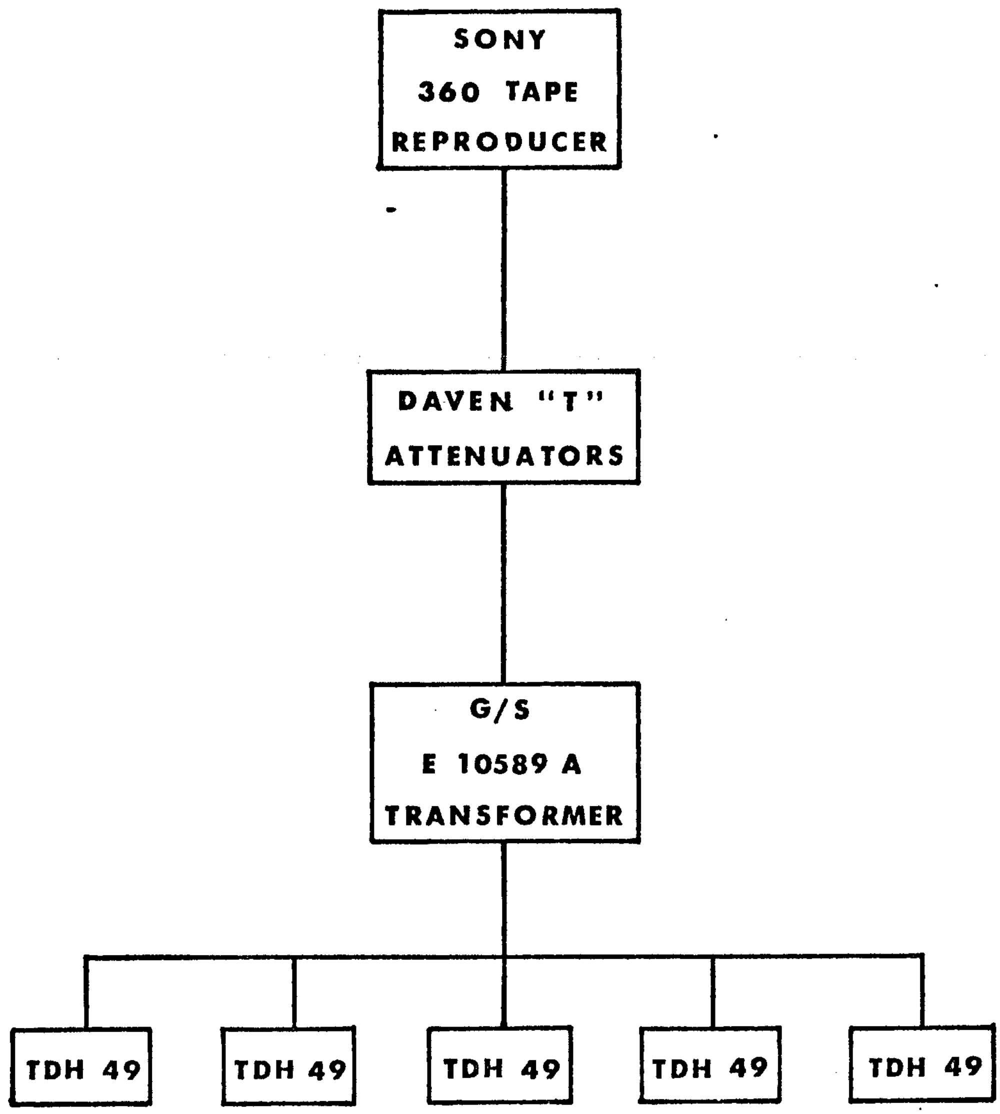

Fig. 8. -- Playback instrumentation used in running experiment

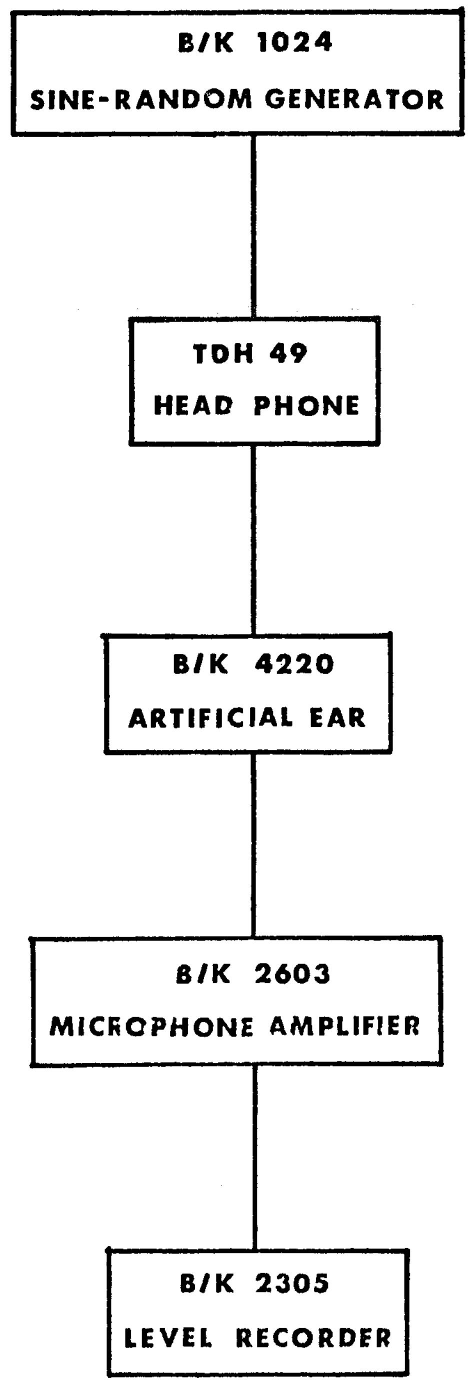

Fig. 9. -- Instrumentation used for frequency response curves of the TDH-49 phones

PHONE	250 Hz	1000 Hz	4000 Hz
1	0.0	0.0	-2.0
2	0.0	0.0	-1.5
3	-1.5	-1.5	-3.5
4	0.0	0.5	-2.0
5	0.5	0.0	-1.5

TABLE 3. -- Frequency responses of five (5) TDH-49 phones used in the experiments [in dB re: 250 Hz, Phone 1]

Center Frequency	dB SPL
250 Hz	36
1 KHz	14
4 KHz	15

TABLE 4. -- Ambient noise levels in test rooms

CHAPTER III

RESULTS

INTRODUCTION

This study is divided into two experiments (identified as I and II) which investigated the effects upon loudness ratio judgments of changes of bandwidth and center-frequency, respectively. Each of these two experiments was performed in the format of three 12 x 12 matrices, which were again divided into four 6 x 6 submatrices each. In order to simplify identification of these submatrices in this chapter, each of the submatrices has been assigned a three symbol code. The first unit, a roman numeral, indicates the experiment number. The second unit, a letter, indicates the matrix. The last, an arabic number, indicates the submatrix (See Figure 10).

It is helpful to be able to easily identify the cells in each of the submatrices. As indicated in the last chapter, all cells in similar locations in each submatrix will have the same physical intensities for each of the stimuli. In terms of order, the row stimuli (A) was always presented first, followed by the common value (B). Again, all judgments were the perceived loudness of the second stimuli

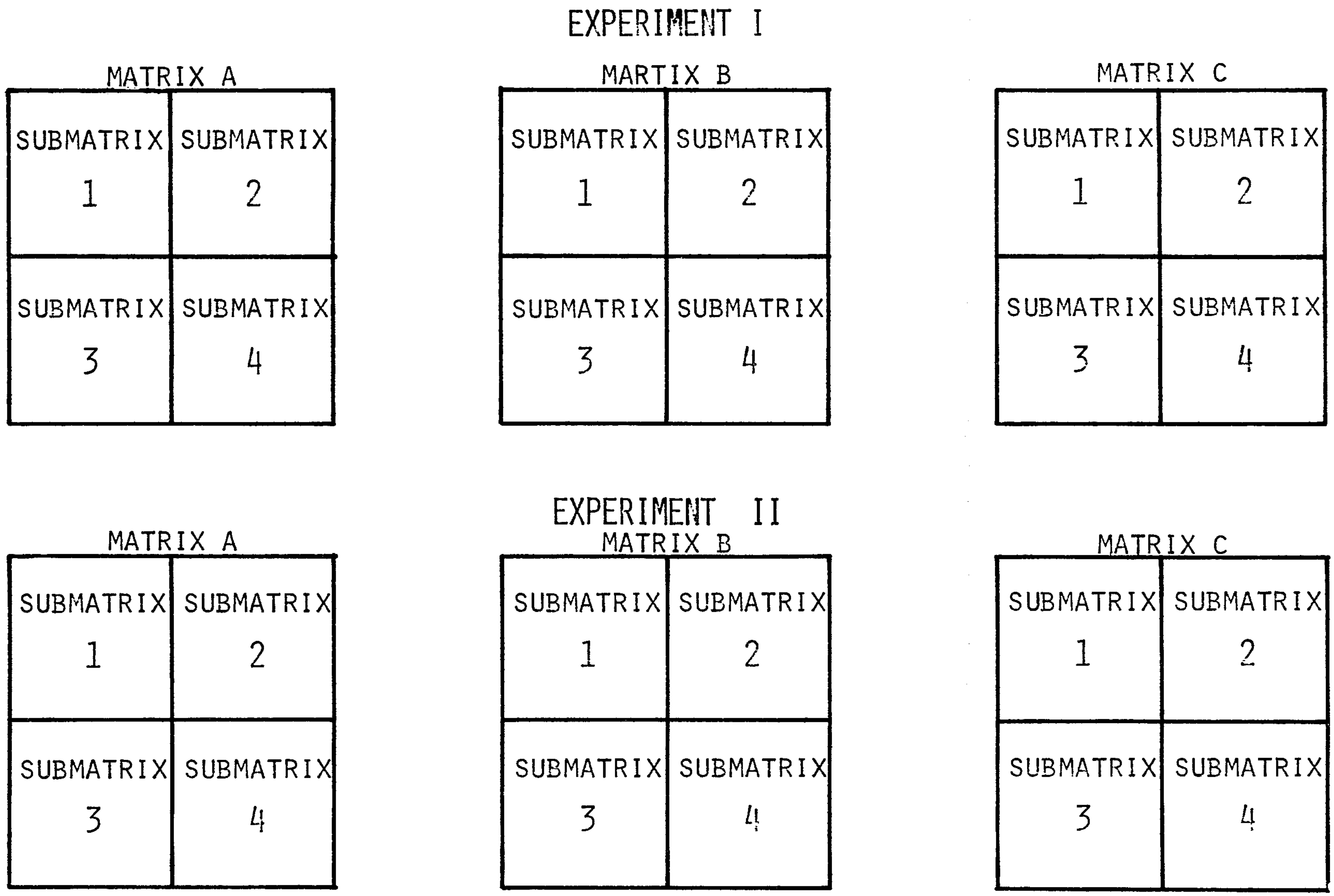

Fig. 10. -- Method of Identification of Submatrices

referred to the first (B re A).

Each cell will be designated a number which ranges from 1-15 in the top half of the submatrix, and 1L-15L in the lower half; cells with the same identifying numeral in the upper and lower submatrix have similar stimulus pairs but reversed in stimulus order. In addition, cells in which the stimuli have the same physical intensities (e.g., 50/50, 55/55, 60/60, 65/65, 70/70 and 75/75 dB SPL) have been identified as D1-D6. Figure 11 shows how each cell in these 6 x 6 submatrices is classified.

The terms tone (T), narrow band noise (NBN) and octave band noise (OBN) shall be used henceforth to identify the tone signal (1 KHz), the one-third octave bands of noise, and the full (1/1) octave band of noise with center frequency at 1 KHz, respectively.

All data presented in the first part of the chapter are in their original linear ratio forms. Although the values printed in the tables which follow are carried to the third decimal place, it should be noted that third place precision is not implied, but the data are found in this form because they were to be used for further computation. These mean values were obtained by adding each subject's judgment for a particular cell and dividing the sum by the number of subjects (7).

The results of these experiments can most adequately be described by dividing the twenty-four submatrices into four groups as follows:

		STIMULUS 'B'					
		50	55	60	65	70	75
STIMULUS 'A'	50	D1	1	2	3	4	5
	55	1L	D2	6	7	8	9
	60	2L	6L	D3	10	11	12
	65	3L	7L	10L	D4	13	14
	70	4L	8L	11L	13L	D5	15
	75	5L	9L	12L	14L	15L	D6

Fig. 11. -- Format for the Specification of Each Cell in a 6 x 6 Submatrix.

Group I investigates the effects of bandwidth on ratio judgments of loudness in cases where the only parametric difference between the two elements of the stimuli pair is the intensity. All stimuli in this group have a center-frequency of 1 KHz. The six submatrices, and their bandwidths:

Pure Tone	Narrow Band Noise†	Octave Band Noise
I-A-1	I-A-4	I-B-4
I-C-1	I-B-1	I-C-4

Group II studies the effect of the change in frequency on loudness judgments of pairs of narrow band noises. In this group, again the only parametric difference between the two elements of the stimuli pair may be that of intensity. There are six submatrices in this group, and the center-frequency of each narrow band noise is given:

250 Hz	1 KHz†	4 KHz
II-A-1	II-A-4	II-B-4
II-C-1	II-B-1	II-C-4

Group III deals with those submatrices in Experiment I in which subjects were to judge a signal of a particular bandwidth against a preceding signal of a different bandwidth. Designated "combinational submatrices", there are six possible orderings of these signals, and each ordering was presented in one submatrix. The submatrices included

---

†1 KHz NBN were judged against themselves in both Groups I and II.

in this group:

[Indicated pair ordering reversed in second row.]

Tone/NBN	NBN/OBN	Tone/OBN
I-A-2	I-B-2	I-C-2
I-A-3	I-B-3	I-C-3

Group IV is similar to Group II in that it concerns combinational submatrices; in this case, those of Experiment II. Examined in Group IV are:

250 Hz/1 KHz	1 KHz/4 KHz	250 Hz/4 KHz
II-A-2	II-B-2	II-C-2
II-A-3	II-B-3	II-C-3

RESULTS

In all cases the subjects made loudness ratio judgments by evaluating the second stimulus of the pair relative to the first (B re A). The decision not to replicate the experiments utilizing the opposite response mode (i.e., A re B) was based upon Richards' (1971) finding that, " . . . the influence of judgmental response mode does not have considerable effects until the level of the louder stimulus in a pair reaches approximately 80 dB SPL." (p. 68)

GROUP I (VARIABLE BANDWIDTH)

The first set of tables (Tables 5-10) display the mean

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.964	1.000	1.000	1.300	1.542	2.714
	55	0.978	1.000	1.000	1.266	1.671	2.750
	60	0.835	1.000	0.964	1.035	1.607	2.057
	65	0.647	0.843	0.821	1.000	1.053	1.992
	70	0.559	0.564	0.700	0.951	1.000	2.060
	75	0.470	0.466	0.435	0.716	0.875	1.014

MATRIX I-A-1
1 KHZ TONE / 1 KHZ TONE

TABLE 5

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.000	1.000	1.185	1.428	2.357	3.357
	55	0.885	1.000	1.014	1.471	1.392	4.000
	60	0.659	0.939	1.000	1.000	1.457	2.985
	65	0.542	0.619	1.000	1.000	1.000	2.757
	70	0.533	0.511	0.597	0.754	1.000	1.435
	75	0.314	0.421	0.407	0.739	0.683	0.964

MATRIX I-C-1
1 KHZ TONE / 1 KHZ TONE

TABLE 6

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.000	1.000	1.071	1.500	2.071	2.714
	55	0.898	1.000	1.071	1.414	2.092	3.000
	60	0.740	0.928	1.000	1.028	1.835	2.621
	65	0.551	0.521	0.814	1.000	1.021	2.178
	70	0.342	0.514	0.721	0.783	1.000	2.128
	75	0.380	0.404	0.535	0.642	0.836	0.964

MATRIX I-A-4
1 KHZ N.B.N. / 1 KHZ N.B.N.

TABLE 7

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.928	1.000	1.100	1.685	3.714	4.714
	55	0.928	1.000	1.000	1.600	2.571	3.071
	60	0.490	0.845	0.928	1.000	2.250	3.428
	65	0.511	0.683	0.807	1.000	1.285	2.571
	70	0.411	0.523	0.552	0.957	1.000	1.766
	75	0.303	0.349	0.509	0.561	0.804	1.000

MATRIX I-B-1
1 KHZ N.B.N. / 1 KHZ N.B.N.

TABLE 8

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.000	0.985	1.657	1.511	2.857	5.357
	55	0.928	1.000	1.219	1.571	2.500	4.285
	60	0.742	0.964	1.000	1.600	2.285	3.285
	65	0.511	0.757	0.985	1.000	1.728	2.571
	70	0.457	0.440	0.814	0.907	1.000	1.771
	75	0.383	0.413	0.461	0.569	0.861	1.071

MATRIX I-B-4
1 KHZ W.B.N. / 1 KHZ W.B.N.

TABLE 9

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.892	1.142	1.128	1.642	2.842	4.714
	55	0.761	0.985	1.270	1.207	2.342	4.107
	60	0.697	0.914	1.014	1.164	1.992	3.928
	65	0.559	0.578	0.950	1.142	1.171	2.750
	70	0.466	0.552	0.632	0.878	1.139	1.857
	75	0.357	0.404	0.523	0.505	0.667	1.285

MATRIX I-C-4
1 KHZ W.B.N. / 1 KHZ W.B.N.

TABLE 10

ratio judgments obtained from seven subjects for each of the indicated submatrices. One immediately observes that in all six of these submatrices, the points along the diagonal (D1-D6) have values at, or very close to unity (1.00). The mean values for the six cells which fall upon the diagonal in each submatrix are: 0.99, 0.99, 0.99, 0.98, 1.01 and 1.08, for submatrices I-A-1, I-C-1, I-A-4, I-B-1, I-B-4 and I-C-4, respectively. Since along the diagonal, both stimuli in the pair have the same physical intensity, it would be expected that they would be judged equal in loudness. Above the diagonal all cells with the exception of one (0.98), were assigned values of 1.00 or greater, which is consistent with the physical parameters of the stimuli pairs, because in these cells the second stimuli always had a greater intensity than the first. Below the diagonal (with the exception of two cells [assigned the value of 1.00]), all values are less than unity. Again, fractional values are expected here because the second stimuli of the pair had a lower intensity than the first in the lower part of the matrix.

Two very important trends are seen in this set of submatrices. Firstly, the judged loudness ratios appear to grow monotonically with difference in stimulus intensity. That is, with an increase in intensity difference between the elements of the stimulus pair there is also an increase in the loudness judgments. As the second element of the pair increases in intensity, there are increased values to the right of the diagonal. Departing from the diagonal to the left, decreasing second stimulus values (re: the first) are seen producing fractional values. These same trends are seen when moving in the columns above and below the diagonals, respectively. There are relatively few departures from this pattern of loudness growth, and for the most part, these deviations are relatively small in relation to the value of the surrounding cells.

A second trend pertains to the values of the cells below the diagonal relative to the values obtained from the corresponding cells above. One would expect that these values would show a reciprocal relationship to one another inasmuch as the only difference between them is the order in which the two stimuli were presented. This does not appear to be the case with these submatrices. Although there is a continuity of the monotonic scale as the diagonal is crossed, an exact reciprocal relationship is not observed between the corresponding cells on either side. In fact, if the reciprocals of the values in the lower half of the submatrix are added, it is found that their sum is less than that of the cells above. In addition, when the differences between the sums of the upper halves of the two submatrices with the same parameters are averaged with the differences of the other two submatrix pairings, it is noted that when this is compared to the same calculation from the reciprocal of the lower halves, the mean of the lower halves is substantially smaller. This would appear to indicate that, on average, the values in the lower halves of these paired submatrices tended to show less variability between judgment values on two similar submatrices.

In order to establish an explanation for this particular behavior, a sign test was applied to the original judgments in all submatrices in Group I. The data were observed to follow certain rules. If the intensity of the second stimuli was greater than that of the first, a loudness ratio judgment of unity or greater was found in all cases. If the second was less than the first, a value of unity or less was observed. In those cases where the stimuli were of the same physical intensity, judgments equal to unity were most often made. Of the 252 judgments made of equivalent stimuli pairs, only 16 were not given values equal to 1.00. The range of these 16 judgments was from 0.50 to 1.50 and were equally distributed into judgments above and below 1.00; the mean value, 0.98.

Although this test shows that judgments were not accidently reversed (A re B rather than B re A), it still fails to provide a suitable explanation for this pattern (incomplete monotonicity) of the data.

A final phenomenon, "an equality confusion", was observed in four of the six submatrices in Group I. This phenomenon exhibits itself as two or more adjacent cells being assigned a loudness ratio of 1.00. One would anticipate that this value would be reserved for judgments along the diagonal (D1-D6) where the intensities of the stimuli are equal. If any other cell is assigned this value, it appears to be on the basis of a lack of discrimination between two differing intensities. One notes that in all four of the submatrices where "equality confusions" exist, that the judgment for cell #1 has been assigned the value of 1.00.

Of particular interest are the values observed in the upper right corner (cell #5) and the lower left corner (cell #5L) in each of these submatrices. These cells represent the largest differences between the stimuli in the pairs 50 dB SPL/75 dB SPL and 75 dB SPL/50 dB SPL, respectively. In order to compare these values, the reciprocal of cell #5L is computed. The values observed in the Group I submatrices are summarized in Table 11.

One notes that in several submatrices in this group, the upper right corner (cell #5) does not contain the largest mean ratio found in the submatrix, nor does the lower left (cell #5L) contain the smallest. The cell containing this value is usually found to be displaced either by a single column or a single row.

The second set of tables (Tables 12-14) in this group exhibit data which have been averaged from each pair of duplicated matrices, i.e., I-A-1 and I-C-1, I-A-4 and I-B-1, I-B-4 and I-C-4 for tone/tone, narrow band noise/narrow band noise and octave band noise/octave band noise, respectively.

In general, all relationships observed in the sub-

STIMULUS	SUB-MATRIX	CELL 5	1/CELL 5L	MEAN	G. MEAN
1 KHz tone/	I-A-1	2.71	2.12	2.42	2.84
1 KHz tone	I-C-1	2.35	3.18	3.27	
1 KHz NBN/	I-A-4	2.71	2.63	2.67	3.39
1 KHz NBN	I-B-1	4.71	3.30	4.00	
1 KHz OBN/	I-B-4	5.35	2.61	3.98	3.87
1 KHz OBN	I-C-4	4.71	2.80	3.75	

TABLE 11. -- Summary of values obtained in Cell 5 and in the Reciprocal of Cell 5L in Group I Submatrices.

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.982	1.000	1.092	1.364	1.950	3.035
	55	0.932	1.000	1.007	1.368	1.532	3.375
	60	0.747	0.969	0.982	1.017	1.532	2.521
	65	0.595	0.731	0.910	1.000	1.026	2.375
	70	0.546	0.538	0.648	0.853	1.000	1.747
	75	0.392	0.443	0.421	0.727	0.779	0.989

MEANS OF 1 KHZ TONE / 1 KHZ TONE DATA
COMBINATION OF SUB-MATRICES I-A-1 & I-C-1

TABLE 12

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.964	1.000	1.085	1.592	2.892	3.714
	55	0.913	1.000	1.035	1.507	2.332	3.035
	60	0.615	0.886	0.964	1.014	2.042	3.025
	65	0.531	0.602	0.810	1.000	1.153	2.375
	70	0.377	0.519	0.636	0.870	1.000	1.947
	75	0.342	0.377	0.522	0.602	0.820	0.982

MEANS OF 1 KHZ N.B.N. / 1 KHZ N.B.N. DATA
COMBINATION OF SUB-MATRICES I-A-4 & I-B-1

TABLE 13

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.946	1.064	1.392	1.577	2.850	5.035
	55	0.845	0.992	1.244	1.389	2.421	4.196
	60	0.720	0.939	1.007	1.382	2.139	3.607
	65	0.535	0.667	0.967	1.071	1.450	2.660
	70	0.461	0.496	0.723	0.892	1.069	1.814
	75	0.370	0.408	0.492	0.537	0.764	1.178

MEANS OF 1 KHZ O.B.N. / 1 KHZ O.B.N. DATA
COMBINATION OF SUB-MATRICES I-B-4 & I-C-4

TABLE 14

matrices are also observed when they are paired and averaged. A normalizing effect is also observed in that the number of departures from the monotonic pattern is reduced in the tone/tone case and eliminated in the other two. All values above the diagonal are now 1.00 or greater, and those below are less than unity.

GROUP II (VARIABLE CENTER FREQUENCY--NARROW BAND NOISES)

The next set of tables (Tables 15-20) show the mean ratio judgments obtained from the seven subjects for each of the indicated submatrices. In general, the data patterns observed in the Group I data are again observed with this group. The diagonals are again seen to have values at or very close to unity. The mean values for the six cells (D1-D6) which fall upon the diagonal in each submatrix are: 1.00, 0.96, 0.96, 0.98, 1.00 and 1.04 for submatrices II-A-1, II-C-1, II-A-4, II-B-1, II-B-4 and II-C-4, respectively.

Again, with the exception of one cell, the diagonal in effect divides the values of unity or greater in the upper half of the submatrices from the fractional values of the lower halves. The strong trends towards monotonicity are again seen with approximately the same number of departures from the monotonic loudness growth pattern (reversals) seen in Group I.

As in Group I, the greatest and the smallest loudness

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.000	1.142	1.528	2.087	3.285	5.730
	55	0.671	1.000	1.057	1.678	2.928	4.714
	60	0.547	0.747	1.035	1.142	1.835	3.178
	65	0.260	0.404	0.551	0.982	1.064	2.500
	70	0.119	0.247	0.330	0.621	1.000	1.157
	75	0.238	0.196	0.478	0.609	0.857	1.000

MATRIX II-A-1
250 N.B.N. / 250 HZ N.B.N.

TABLE 15

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.035	1.035	1.089	2.471	3.528	9.428
	55	0.728	0.857	1.000	1.460	2.457	4.285
	60	0.507	0.485	1.000	1.285	1.607	2.464
	65	0.417	0.504	0.660	1.000	1.050	2.500
	70	0.231	0.240	0.340	0.809	0.875	1.171
	75	0.140	0.184	0.347	0.378	0.583	1.000

MATRIX II-C-1
250 N.B.N. / 250 HZ N.B.N.

TABLE 16

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.892	1.000	1.196	2.150	2.271	3.250
	55	0.917	0.985	1.142	1.535	2.464	4.785
	60	0.616	0.975	1.014	1.142	1.642	1.658
	65	0.533	0.654	0.967	0.892	1.107	2.571
	70	0.380	0.559	0.690	0.750	1.000	1.664
	75	0.321	0.371	0.559	0.688	0.741	1.000

MATRIX II-A-4
1 KHZ N.B.N. / 1 KHZ N.B.N.

TABLE 17

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.964	1.000	1.207	1.632	2.547	3.400
	55	0.814	0.928	1.071	1.192	1.435	3.642
	60	0.553	0.946	1.000	1.385	2.057	2.857
	65	0.564	0.490	0.764	1.000	1.100	2.857
	70	0.371	0.526	0.554	0.710	1.014	1.850
	75	0.395	0.459	0.495	0.533	0.761	1.000

MATRIX II-B-1
1 KHZ N.B.N. / 1 KHZ N.B.N.

TABLE 18

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.000	1.000	1.000	1.685	3.542	3.757
	55	0.836	1.000	1.000	1.051	2.892	4.485
	60	0.838	0.985	1.000	1.023	1.835	3.214
	65	0.560	0.685	0.876	1.000	1.207	3.285
	70	0.461	0.518	0.507	0.730	1.000	1.778
	75	0.392	0.382	0.416	0.682	0.630	0.978

MATRIX II-B-4
4 KHZ N.B.N. / 4 KHZ N.B.N.

TABLE 19

DB SPL		DB SPL 50	55	60	65	70	75
	50	1.047	1.319	1.371	1.678	2.457	6.285
	55	0.745	0.982	0.964	1.714	2.471	4.000
	60	0.732	0.833	1.000	1.157	2.757	4.250
	65	0.351	0.601	0.892	0.992	1.178	2.971
	70	0.511	0.541	0.675	0.916	1.000	2.171
	75	0.404	0.604	0.362	0.596	0.823	1.228

MATRIX II-C-4
4 KHZ N.B.N. / 4 KHZ N.B.N.

TABLE 20

ratio judgments are not always found in the upper right (cell #5) and the lower left (cell #5L), respectively. The sign test was also applied to these data with essentially the same results. One error was observed out of each of the 630 greater than unity and less than unity relationships, judgments of 0.75 and 1.10, respectively. When the physical intensity of both stimuli were the same, judgments other than unity ranged from 0.50 to 2.00 (27 of 252 judgments), while the mean value approached unity with a value of 0.995.

Regarding the relationship between the sum of the values of the cells above the diagonal and the sum of the reciprocals of the cells below, again the upper cells have larger values for all the 1 KHz NBN/1 KHz NBN and 4 KHz NBN/4 KHz NBN submatrices. There is an inversion of this relationship in the 250 Hz NBN/250 Hz NBN submatrices--submatrices which will be shown to also deviate from other general trends in submatrix data.

Another measure identified in the description of Group I data pertained to the variability of the sums of the cells above the diagonal and the sums of the reciprocals of the cells below. As in Group I, if the differences between the sums of the upper halves of the submatrices with the same parameters are averaged with the other paired matrices, and compared with a similar calculation of the reciprocals of the lower halves, again, the mean of the lower matrices is substantially smaller; in this case, by a factor of eight.

The "equality confusions" of Group I are rarely seen in Group II. Only one is observed in the 250 Hz NBN/250 Hz NBN in cell #6. Several appear in one of the 4 KHz NBN/4 KHz NBN submatrices (II-B-4) while none occur in the other. It is interesting to note that this phenomenon is observed in cells 1L of both of the 1 KHz NBN/1 KHz NBN submatrices. It is further noted that the 50 dB SPL/50 dB SPL (D1) value in both submatrices are fractional values.

The key mean ratio value judgments, those cells with the greatest difference between the two stimulus physical intensities, are given in Table 21.

A second set of tables (Tables 22-24) exhibit the data which have been averaged from each pair of duplicate submatrices, i.e., II-A-1 and II-C-1, II-A-4 and II-B-1, II-B-4 and II-C-4 for 250 Hz NBN/250 Hz NBN, 1 KHz NBN/1 KHz NBN, and 4 KHz NBN/4 KHz NBN, respectively. Once again the same relationships found in the individual submatrices are tempered by the normalizing effects of data averaging. The departures from the monotonic pattern are substantially reduced. The mean values of the diagonals are brought closer to unity.

A supplemental table which exhibits the average mean loudness ratio judgments for the 1 KHz NBN/1 KHz NBN submatrices in Experiments I and II (I-A-4, I-B-1. II-A-4 and II-B-1) is seen in Table 25. It is not surprising to find that the averaging of these four submatrices further eliminates some of the departures from the monotonic pattern observed in each of the submatrices individually. Each

STIMULUS	SUB-MATRIX	CELL 5	1/CELL 5L	MEAN	G. MEAN
250 Hz NBN/	II-A-1	5.73	4.20	4.96	6.62
250 Hz NBN	II-C-1	9.42	7.14	8.28	
1 KHz NBN/	II-A-4	3.25	3.11	3.18	3.07
1 KHz NBN	II-B-1	3.40	2.53	2.96	
4 KHz NBN/	II-B-4	3.75	2.55	3.15	3.76
4 KHz NBN	II-C-4	6.28	2.47	4.38	

TABLE 21. -- Summary of values obtained in Cell 5 and in the Reciprocal of Cell 5L in Group II Submatrices.

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.928	1.000	1.201	1.891	2.409	3.325
	55	0.866	0.957	1.107	1.364	1.950	4.214
	60	0.585	0.960	1.007	1.264	1.850	2.257
	65	0.548	0.572	0.866	0.946	1.103	2.714
	70	0.376	0.542	0.622	0.730	1.007	1.757
	75	0.358	0.415	0.527	0.610	0.751	1.000

MEANS OF 1 KHZ N.B.N. / 1 KHZ N.B.N. DATA
COMBINATION OF SUB-MATRICES II-A-4 & II-B-1

TABLE 22

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.017	1.089	1.308	2.279	3.407	7.579
	55	0.700	0.928	1.028	1.569	2.692	4.500
	60	0.527	0.616	1.017	1.214	1.721	2.821
	65	0.338	0.454	0.605	0.991	1.057	2.500
	70	0.175	0.244	0.335	0.715	0.937	1.164
	75	0.189	0.190	0.413	0.493	0.720	1.000

MEANS OF 250 HZ N.B.N. / 250 HZ N.B.N. DATA
COMBINATION OF SUB-MATRICES II-A-1 & II-C-1

TABLE 23

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	1.023	1.159	1.185	1.682	3.000	5.021
	55	0.791	0.991	0.982	1.383	2.682	4.242
	60	0.785	0.909	1.000	1.090	2.296	3.732
	65	0.455	0.643	0.884	0.996	1.192	3.128
	70	0.486	0.530	0.591	0.823	1.000	1.975
	75	0.398	0.493	0.389	0.639	0.727	1.103

MEANS OF 4 KHZ N.B.N. / 4 KHZ N.B.N. DATA
COMBINATION OF SUB-MATRICES II-B-4 & II-C-4

TABLE 24

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.946	1.000	1.143	1.741	2.651	3.519
	55	0.889	0.978	1.071	1.435	2.141	3.625
	60	0.600	0.923	0.985	1.139	1.946	2.641
	65	0.540	0.587	0.838	0.973	1.128	2.544
	70	0.376	0.530	0.629	0.800	1.003	1.852
	75	0.350	0.396	0.524	0.606	0.786	0.991

GRAND MEANS OF 1 KHZ N.B.N. / 1 KHZ N.B.N. DATA
COMBINATION OF SUB-MATRICES I-A-4,I-B-1,II-A-4,II-B-4

TABLE 25

cell in this matrix represents the averaging of twenty-eight judgments (four similar submatrices judged by seven subjects). Some of the characteristics of the results which have already been mentioned are still seen in this compilation. The sum of the reciprocals of the cells below the diagonal continue to be less than the sum of the cells above. The mean value of the cells along the diagonal (D1-D6) is slightly less than unity, 0.98. The cell showing the greatest loudness ratio judgment is not cell #5, but rather cell #9. The value of either of these two cells is substantially greater than the value of the reciprocal of cell #5L. Other than these deviations, monotonicity is observed throughout this averaged submatrix.

GROUPS III AND IV (COMBINATIONAL SUBMATRICES)

Although these groups of six submatrices each differ from each other by nature of the parameter under study, review of the tables (Tables 26-37) illustrates that in this particular tabular form the results appear very much alike.

Apparent is the lack of a diagonal demonstrating values approximating unity. It was anticipated that because the two stimuli had parametric differences other than intensity, the diagonal would be shifted to compensate for a constant difference in loudness. An unsuccessful attempt was made to estimate the position that would be occupied by

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.793	0.740	0.928	1.500	1.571	3.000
	55	0.842	0.821	0.721	1.357	2.178	3.714
	60	0.582	0.776	0.771	0.835	1.557	2.957
	65	0.528	0.554	0.654	0.850	1.642	2.742
	70	0.410	0.600	0.654	0.869	0.971	2.071
	75	0.305	0.649	0.600	0.607	0.997	1.850

MATRIX I-A-2
1 KHZ TONE / 1 KHZ N.B.N.

TABLE 26

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.990	0.990	1.233	1.821	2.357	2.692
	55	0.895	0.928	1.152	1.857	2.185	3.107
	60	0.907	0.726	0.961	1.104	1.528	2.821
	65	0.445	0.754	1.127	1.728	1.657	2.464
	70	0.404	0.595	0.766	1.607	1.685	2.028
	75	0.307	0.485	0.678	0.914	1.250	1.778

MATRIX I-A-3
1 KHZ N.B.N. / 1 KHZ TONE

TABLE 27

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.890	1.964	2.114	2.957	3.071	5.428
	55	0.907	1.152	1.785	2.742	3.714	4.857
	60	0.716	0.750	1.195	1.921	3.285	4.000
	65	0.488	0.702	0.926	1.464	2.428	3.857
	70	0.440	0.518	0.664	1.011	2.557	2.607
	75	0.542	0.442	0.514	0.561	1.761	2.642

MATRIX I-B-2
1 KHZ N.B.N. / 1 KHZ W.B.N.

TABLE 28

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.542	0.714	1.071	1.000	2.357	3.714
	55	0.509	0.638	0.678	1.064	1.928	3.428
	60	0.454	0.435	0.671	1.157	2.171	3.000
	65	0.395	0.507	0.578	0.783	1.792	2.928
	70	0.319	0.433	0.395	0.654	0.902	2.285
	75	0.250	0.297	0.364	0.468	1.092	1.297

MATRIX I-B-3
1 KHZ W.B.N. / 1 KHZ N.B.N.

TABLE 29

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.904	1.114	0.928	1.600	3.035	4.000
	55	0.833	1.000	1.050	2.428	4.000	3.571
	60	0.773	0.985	1.154	1.678	1.707	3.857
	65	0.416	0.771	0.950	0.964	2.028	2.821
	70	0.597	0.640	0.828	0.914	1.542	2.928
	75	0.547	0.559	0.661	0.830	0.921	1.185

MATRIX I-C-2
1 KHZ TONE / 1 KHZ W.B.N.

TABLE 30

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.928	1.000	1.035	1.171	1.535	3.085
	55	0.642	0.738	1.250	1.142	1.885	2.828
	60	0.557	0.783	0.857	1.457	1.678	2.564
	65	0.542	0.773	0.845	1.500	1.428	2.750
	70	0.614	0.580	0.726	1.000	1.107	2.500
	75	0.407	0.440	0.552	0.755	1.500	1.357

MATRIX I-C-3
1 KHZ W.B.N. / 1 KHZ TONE

TABLE 31

		DB SPL					
		50	55	60	65	70	75
	50	2.458	2.500	2.785	4.428	5.642	10.428
	55	1.357	2.250	1.996	4.714	3.928	6.000
	60	1.428	2.750	1.360	2.857	3.000	4.714
DB SPL	65	0.697	0.828	0.952	1.300	2.428	7.285
	70	0.507	0.750	1.214	1.128	1.571	3.464
	75	0.399	0.569	0.792	0.804	1.635	2.821

MATRIX II-A-2
250 HZ N.B.N. / 1 KHZ N.B.N.

TABLE 32

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.395	0.366	0.666	0.728	1.714	3.371
	55	0.258	0.390	0.550	1.385	1.785	3.571
	60	0.242	0.298	0.557	0.511	1.357	2.742
	65	0.237	0.304	0.436	0.426	1.464	1.928
	70	0.163	0.272	0.392	0.365	0.666	2.600
	75	0.179	0.193	0.272	0.485	0.785	1.571

MATRIX II-A-3
1 KHZ N.B.N. / 250 HZ N.B.N.

TABLE 33

		DB SPL					
		50	55	60	65	70	75
	50	0.839	1.083	1.671	2.000	3.000	5.071
	55	1.035	1.142	0.773	1.821	3.214	4.142
	60	0.690	1.053	0.909	2.135	2.178	5.214
DB SPL	65	0.773	0.678	0.845	1.142	2.285	4.214
	70	0.592	0.426	0.826	1.300	1.757	3.500
	75	0.457	0.321	0.514	0.922	1.557	2.964

MATRIC II-B-2
1 KHZ N.B.N. / 4 KHZ N.B.N.

TABLE 34

		DB SPL					
		50	55	60	65	70	75
	50	0.535	0.585	1.214	2.328	3.214	4.642
	55	0.773	1.142	0.807	1.850	3.142	4.000
	60	0.397	0.872	0.778	0.880	2.642	4.142
DB SPL	65	0.626	0.457	0.835	1.357	2.285	2.392
	70	0.416	0.602	0.755	1.210	1.392	3.642
	75	0.358	0.330	0.622	1.176	1.304	1.385

MATRIX II-B-3
4 KHZ N.B.N. / 1 KHZ N.B.N.

TABLE 35

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	3.464	2.678	3.071	5.096	6.857	9.428
	55	1.892	3.571	3.071	3.428	5.142	6.285
	60	2.142	1.433	1.578	2.392	4.357	9.857
	65	0.453	1.476	1.211	1.607	3.192	5.857
	70	0.726	1.228	1.003	0.760	1.988	4.500
	75	0.562	0.686	0.511	0.898	1.871	2.592

MATRIX II-C-2
250 HZ N.B.N. / 4 KHZ N.B.N.

TABLE 36

		DB SPL					
		50	55	60	65	70	75
DB SPL	50	0.310	0.349	0.707	0.612	1.735	4.571
	55	0.197	0.428	0.339	0.834	1.907	2.521
	60	0.257	0.265	0.527	0.668	1.250	2.128
	65	0.171	0.235	0.546	0.483	1.714	2.028
	70	0.126	0.215	0.283	0.714	0.986	1.196
	75	0.152	0.173	0.272	0.354	0.907	1.103

MATRIX II-C-3
4 KHZ N.B.N. / 250 HZ N.B.N.

TABLE 37

a judgment approximating unity in each row, and hopefully connecting these points to provide a line parallel to the diagonal.

An interesting observation regards the maximal and minimal loudness ratio judgments. Even though a shift in equal loudness judgments is evident, these judgments tend to remain in the upper right and lower left corners of the submatrices, respectively. Eleven of the twelve submatrices had their largest loudness ratio judgments in either cell #5 or one cell removed in cell #9. Eleven of the twelve submatrices had their smallest loudness ratio judgments in cell #5L or one cell removed in #9L or #4L.

The propensity of the data to maintain an essentially monotonic pattern is again seen in Groups III and IV. The data in these groups appears to be generally ordered within individual rows and columns, with reversals apparently effecting one dimension in most cases.

Further consideration of these combinational submatrices will be reserved for the next section of this chapter where the Least Squares Loudness Estimation method will be utilized to analyze and describe the growth of loudness in these submatrices. The high degree of monotonocity between judged loudness ratio and intensity difference (between stimuli) suggests that the relatively simple Least Squares Loudness Estimation procedure will provide consistent estimates, and that highly sophisticated multi-dimensional scaling procedures will not be necessary to analyze the data matrices.

LEAST SQUARES LOUDNESS

The Least Squares Loudness Estimation procedure of Levitt and Richards (1972) was applied to the mean loudness ratio data in each of the submatrices. As described in Chapter I, this technique provides a method of estimating the growth of loudness as a function of intensity, separating out stimulus and response bias effects so as to minimize the role of the response bias. It should be noted that all loudness ratio data were converted to the form $\log_2$ in order that the present data could be easily compared to much of the earlier research which utilized judgments of doubling and halving of loudnesses. Of specific interest would be the often reported power function which would manifest itself as a straight line on a log-log plot. As a matter of convenience, a line representing Stevens' (1955) "10 dB Rule" has been drawn onto each figure. Simply stated, this rule specifies that for each 10 dB increase in intensity, a doubling (1 log unit on these plots) of perceived loudness would take place.

For Group I and Group II data, the Least Squares Loudness Estimation procedure was applied in its simplest form which assumes that bias is negligible. That is, the value of each cell was, specifically for purposes of this analysis, considered to be made up of three factors: the value of the row factor, the value of the column factor and a biasing factor, R_{ij} (R_{ij} negligible). Figure 12 shows a sample I x I matrix indicating the values in each cell, the row and column means, and the grand mean. Assuming negligible response bias, the relative values of the stimuli were taken directly from the row and column means. (This assumption was later found to be unreliable for asymmetric matrices.) For purposes of simplicity in the comparison of rates of growth, after the utilization of the Least Squares Loudness, the loudness of the 50 dB SPL stimuli were set to zero loudness units, and all other values were adjusted accordingly. The vertical axis is loudness in log loudness units.

GROUP I

Figures 13 and 14 illustrate the data obtained from Submatrices I-A-1 and I-C-1, respectively, both of which are for 1 KHz tone stimuli being judged against other 1 KHz tone stimuli. It will be observed that there are several plots for each submatrix; one for when the stimulus in question was judged first in the pair (Stimulus A - rows), and another for when it was judged second (Stimulus B - columns). These positions in the pairs have been designated on the graphs as 1 and 2, respectively. A third plot shows the mean value of the other two. It can be easily seen that when the 1 KHz tone is heard second in the pair, the function becomes steeper and the maximal value for the plot be-

LOG LOUDNESS RATIO JUDGMENTS

		SECOND STIMULUS (I)				
		S_1	S_2		S_i	Row Average
FIRST STIMULUS (J)	S_1	$\log E_1 - \log E_1 + R_{11}$	$\log E_2 - \log E_1 + R_{21}$	. . .	$\log E_i - \log E_1 + R_{i1}$	$\overline{\log E} - \log E_1 + R_{.1}$
	S_2	$\log E_1 - \log E_2 + R_{12}$	$\log E_2 - \log E_2 + R_{22}$	. . .	$\log E_i - \log E_2 + R_{i2}$	$\overline{\log E} - \log E_2 + R_{.2}$
		⋮	⋮		⋮	⋮
	S_j	$\log E_1 - \log E_j + R_{1j}$	$\log E_2 - \log E_j + R_{1j}$	. . .	$\log E_i - \log E_j + R_{ij}$	$\overline{\log E} - \log E_j + R_{.j}$
Column Average		$\log E_1 - \overline{\log E} + R_{1.}$	$\log E_2 - \overline{\log E} + R_{2.}$	. . .	$\log E_i - \overline{\log E} + R_{i.}$	$\overline{\log E} - \overline{\log E} + R_{..}$ (Grand Mean)

Fig. 12. -- Typical matrix of dimension I x I used in the computation of the Least Squares Loudness Estimation Model.

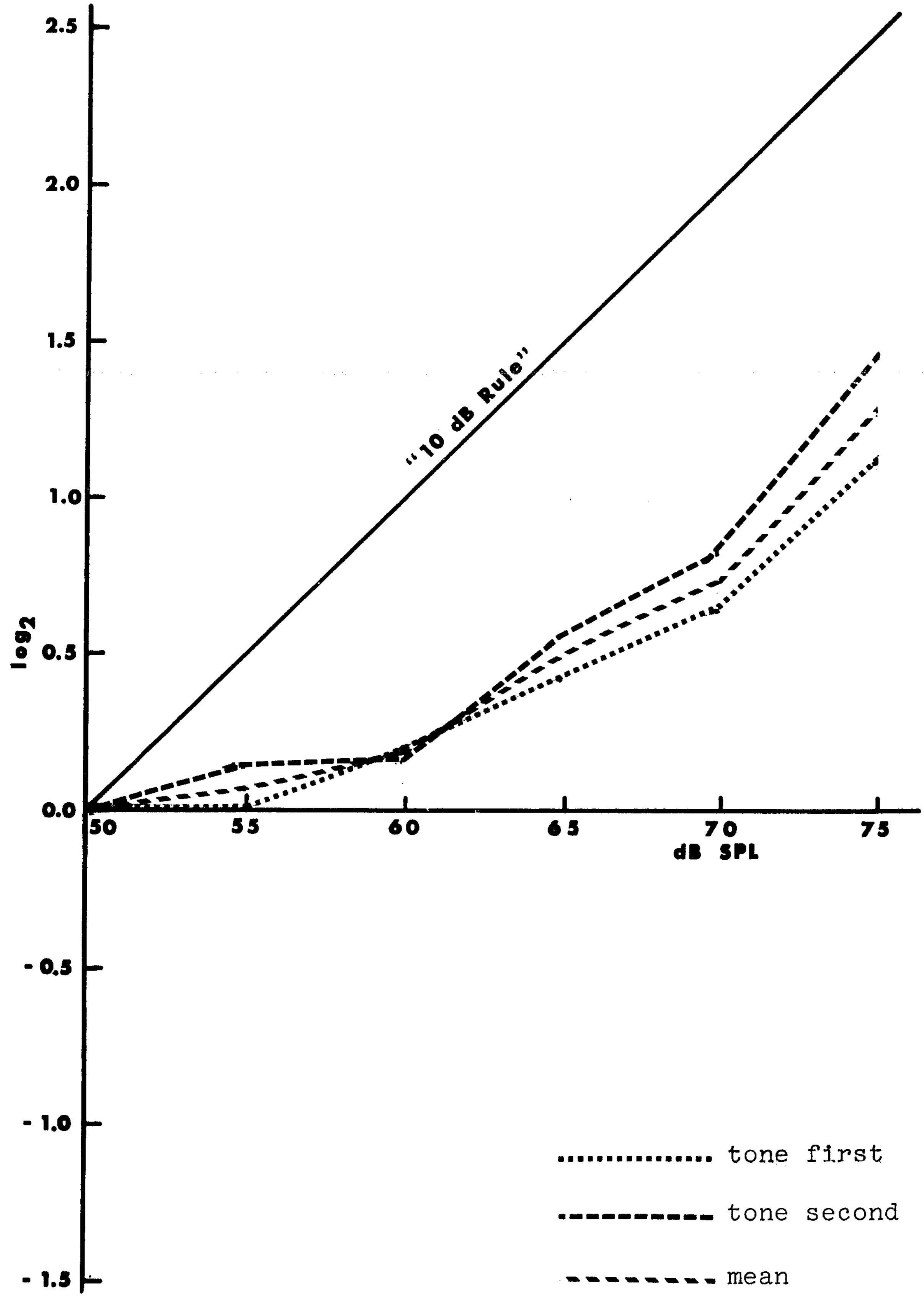

Fig. 13. -- Least Squares Loudness Estimations for Submatrix I-A-1

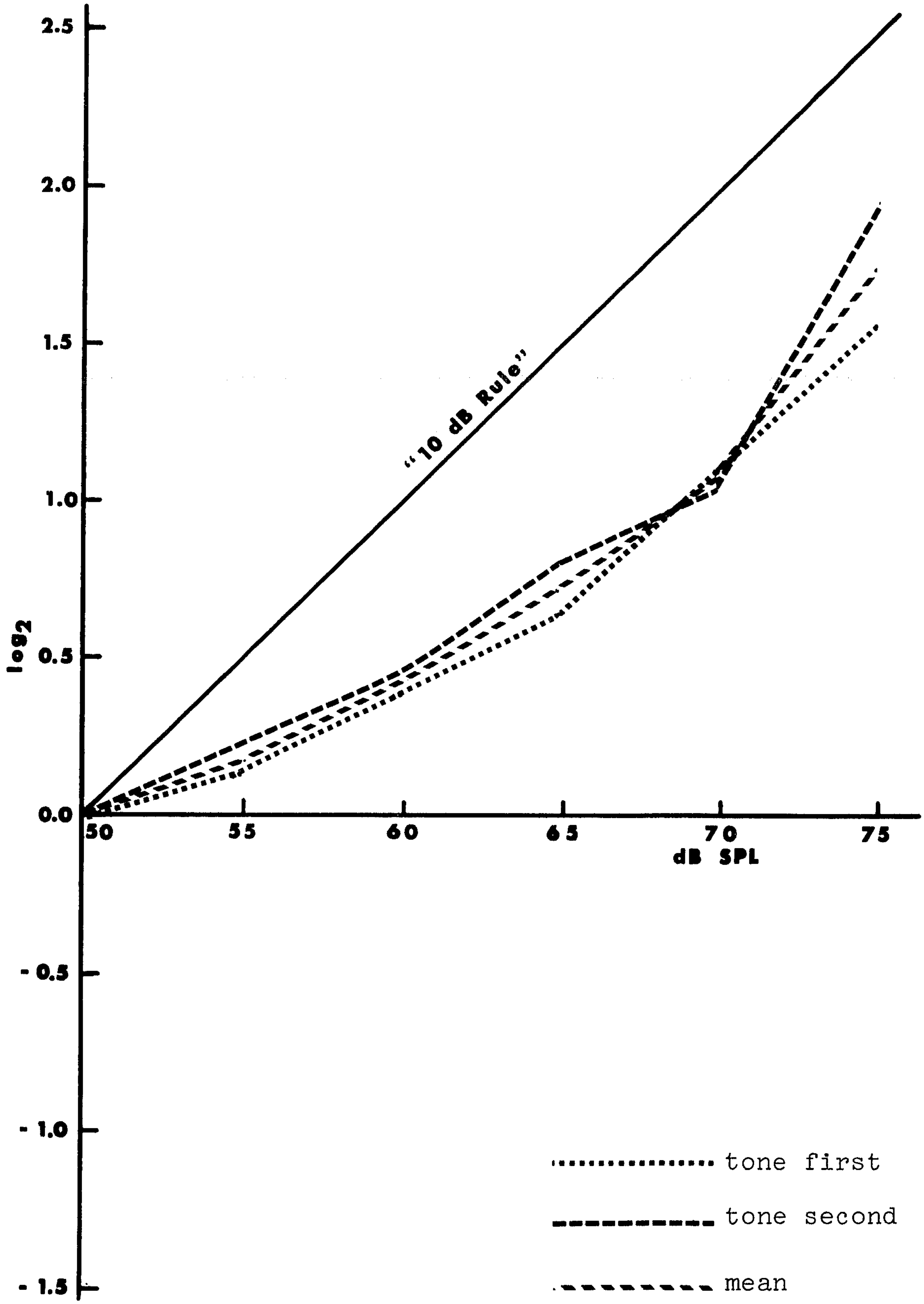

Fig. 14. -- Least Squares Loudness Estimations for Submatrix I-C-1

comes greater. This finding was obtained in all data sets in Groups I and II. For purposes of clarity, Figure 15 shows the means of Submatrices I-A-1 and I-C-1 together with a third plot representing the grand mean of all the puretone data. The two means are similar in form but it will be observed that the greatest loudness ratio of one is substantially greater than the other.

The puretone data is of special interest because of the abundance of data from earlier experiments using this stimuli. The lowest tone stimulus used in these present experiments was 50 dB SPL, and since the present standard for audiometric zero for a 1 KHz tone is 7 dB SPL (ANSI, 1969), and since the mean threshold for the subjects in these experiments was 1 dB re: audiometric zero at 1 KHz, the 50 dB SPL stimulus was reaching the subjects at approximately 40 dB Sensation Level (SL). As indicated in Chapter I, a great deal of the reported research on the loudness function of the 1 KHz tone indicates that it follows a loudness function exponent of approximately 0.60 at levels above 40 dB SL. If this were the case, the ratio judgment for the greatest intensity difference in a stimulus pair (50-75 dB SL [approximately 40-65 dB SL])in this matrix would be 5.65 or in the form $\log_2$, 2.50. From Figure 12 it can be seen that the grand mean value is approximately 1.75 ($\log_2$), a value substantially lower than the one expected. Further discussion of the comparisons of this data to other data will be reserved for Chapter IV.

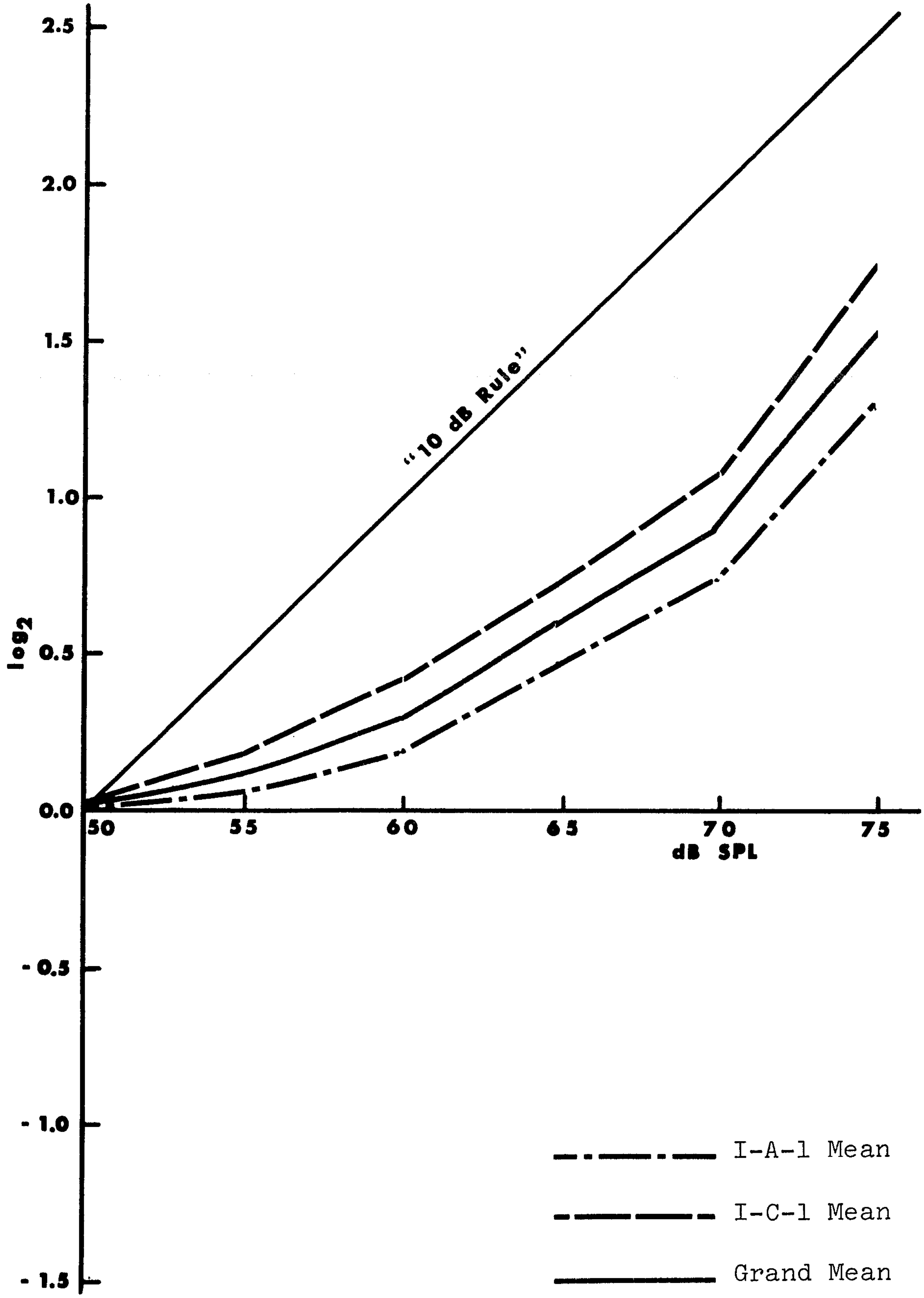

Fig. 15. -- Means of Least Squares Loudness Estimations for submatrices comparing tone vs. tone

Plots for octave band noise (OBN) with a center frequency at 1 KHz judged against similar stimuli are observed in Figures 16 and 17 (Submatrices I-B-4 and I-C-4). Although all of the plots are quite similar in form, it can be seen that in both cases the stimuli that were judged second in the pair gave substantially higher values than those which were judged first. The plots for the means and the grand mean values are shown in Figure 18. Again the values have been adjusted so that the loudness of the 50 dB SPL signal is set to zero loudness units. Compared to the "10 dB Rule", the plot of the OBN at first climbs at a slower rate and then appears to parallel the rule above a level of 65 dB SPL. Although the value of the largest stimulus intensity of the grand mean is somewhat greater than for the 1 KHz tone, at a value of 1.86 ($\log_2$), it is still less than would be expected if the "10 dB Rule" was applicable.

The final set of data in Group I is for the 1 KHz narrow band noise (NBN) pairs (Submatrices I-A-4 and I-B-1), shown in Figures 19 and 20. Characteristics observed in the previous two sets are again seen here, i.e., sets of stimuli positioned second in the pair are judged louder than those which are first, the mean value is less than that predicted by the "10 dB Rule" (Figure 21). The configuration of the mean data is almost exactly the same as that of the 1 KHz Octave Band Noise, as observed in Figure 22 where the grand mean values of the three stimuli of Group I (1 KHz tone, 1 KHz NBN and 1 KHz OBN) have been compared. The max-

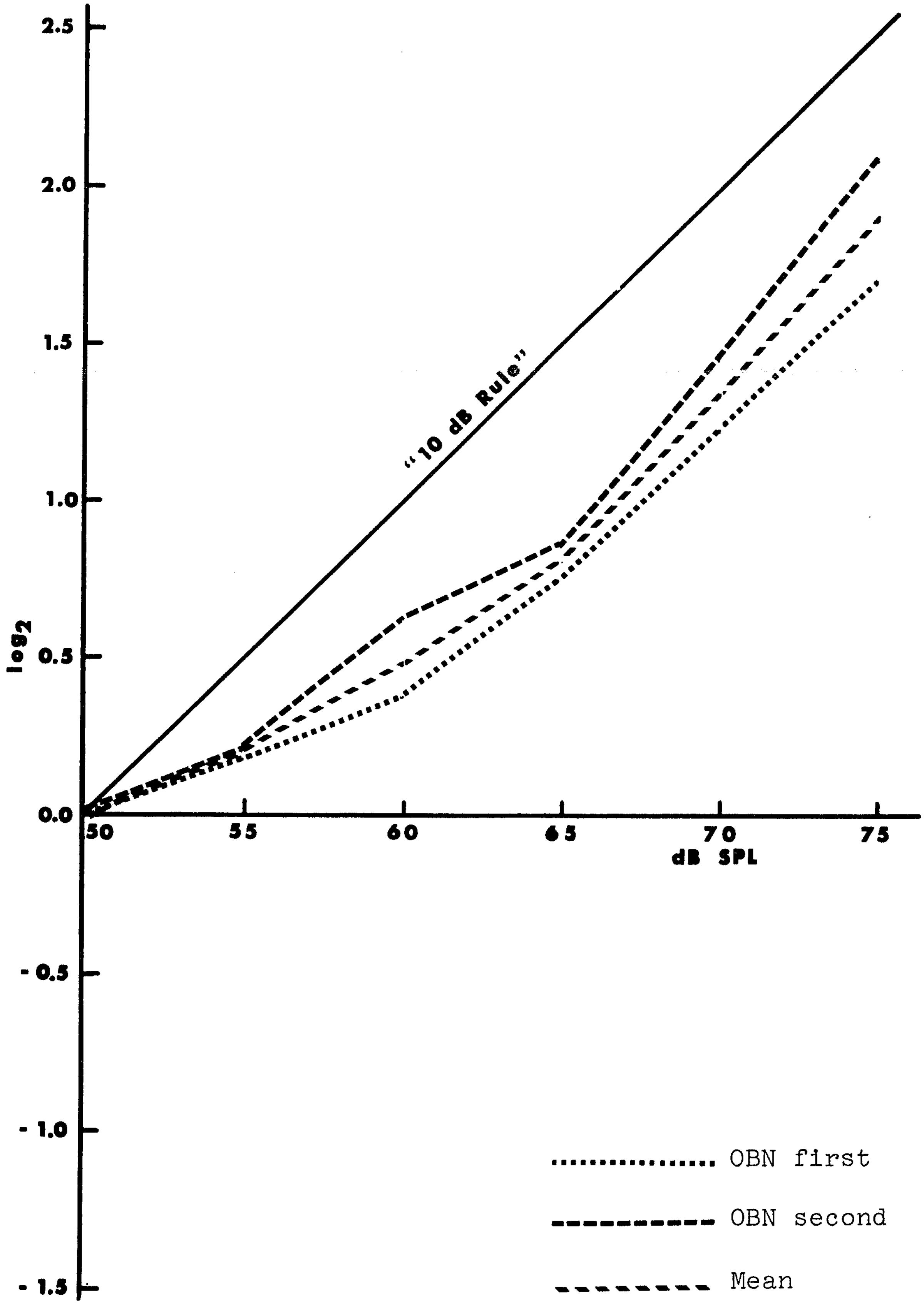

Fig. 16. -- Least Squares Loudness Estimations for Submatrix I-B-4

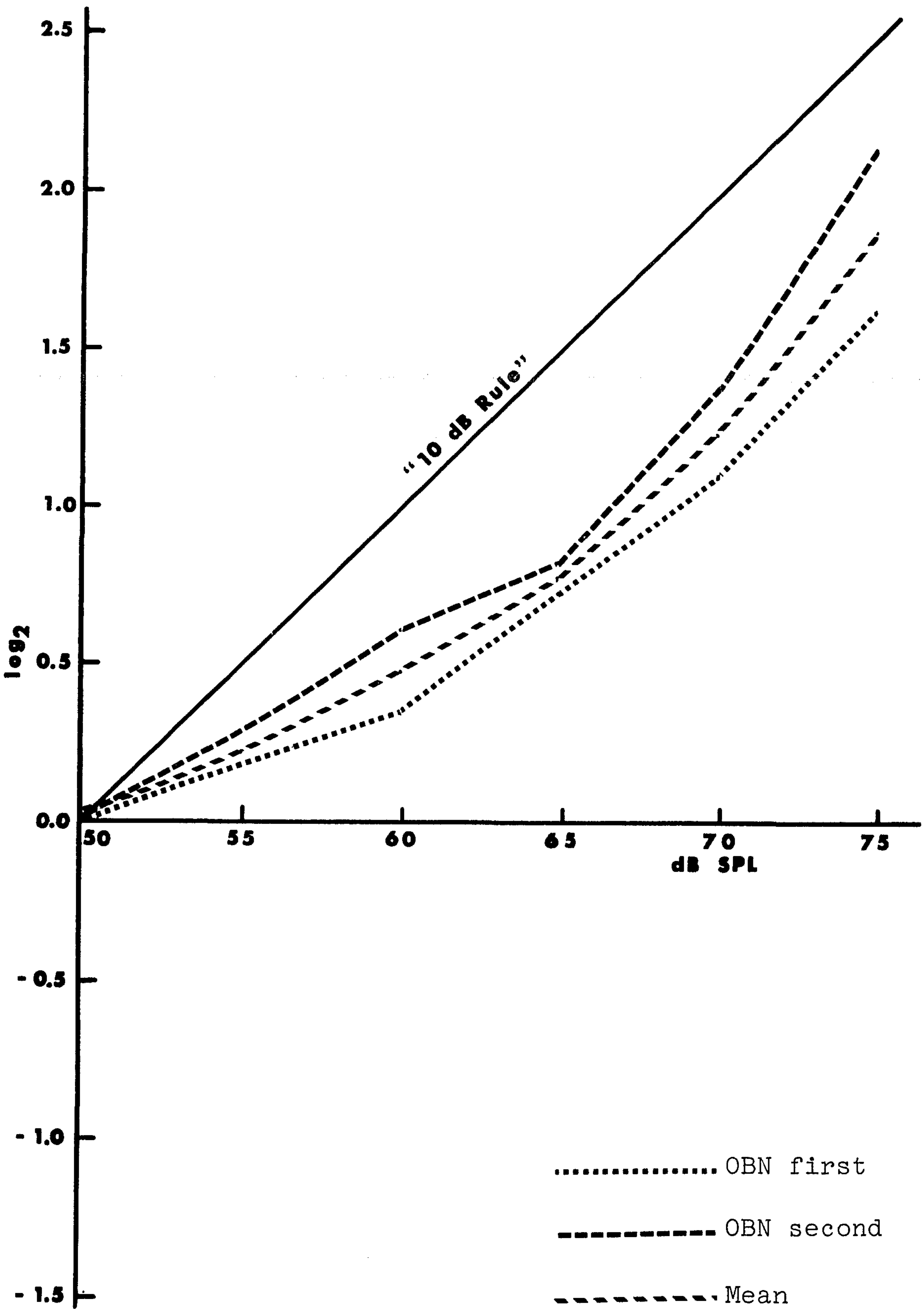

Fig. 17. -- Least Squares Loudness Estimations for Submatrix I-C-4

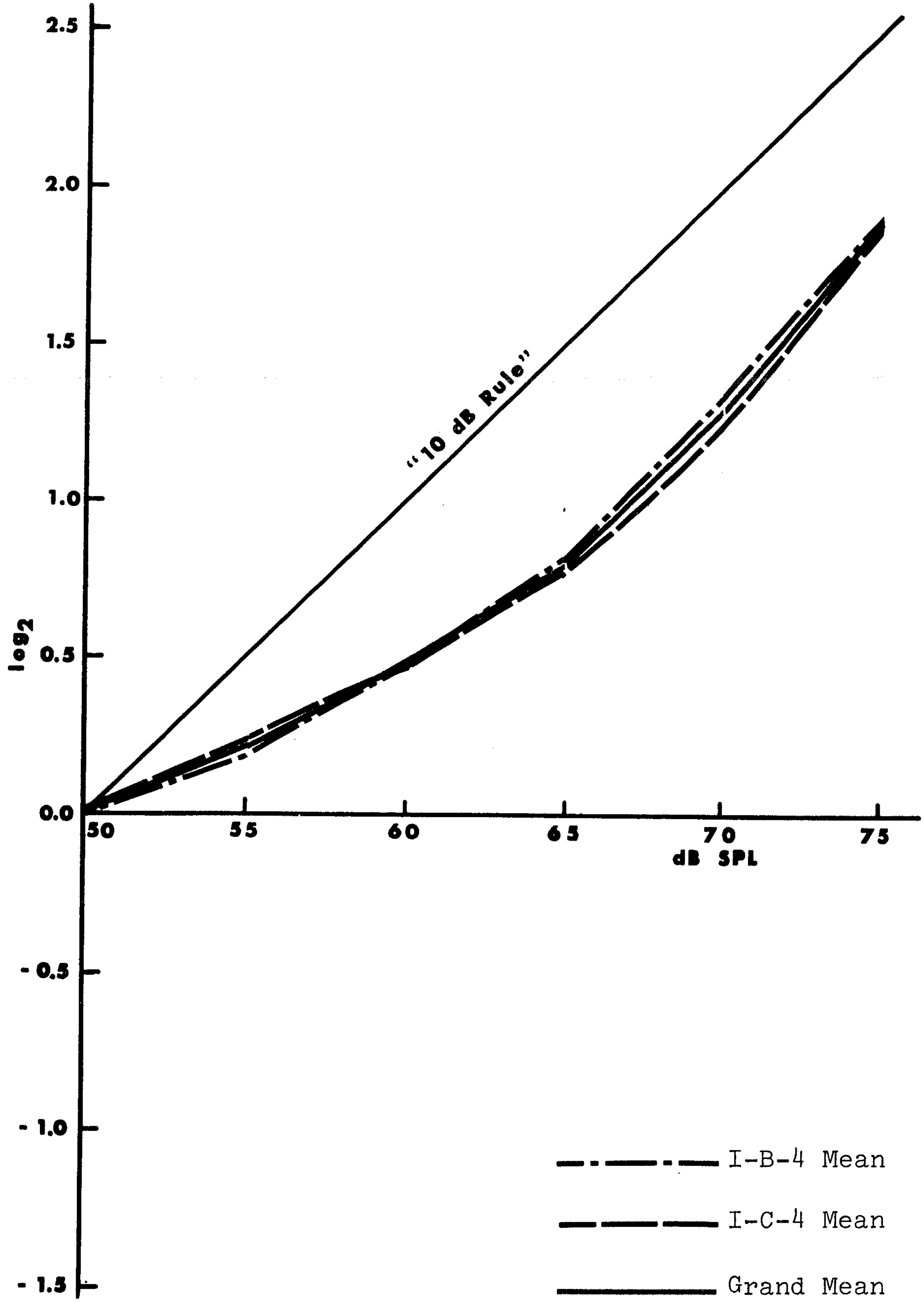

Fig. 18. -- Means of Least Squares Loudness Estimations for submatrices comparing OBN vs OBN

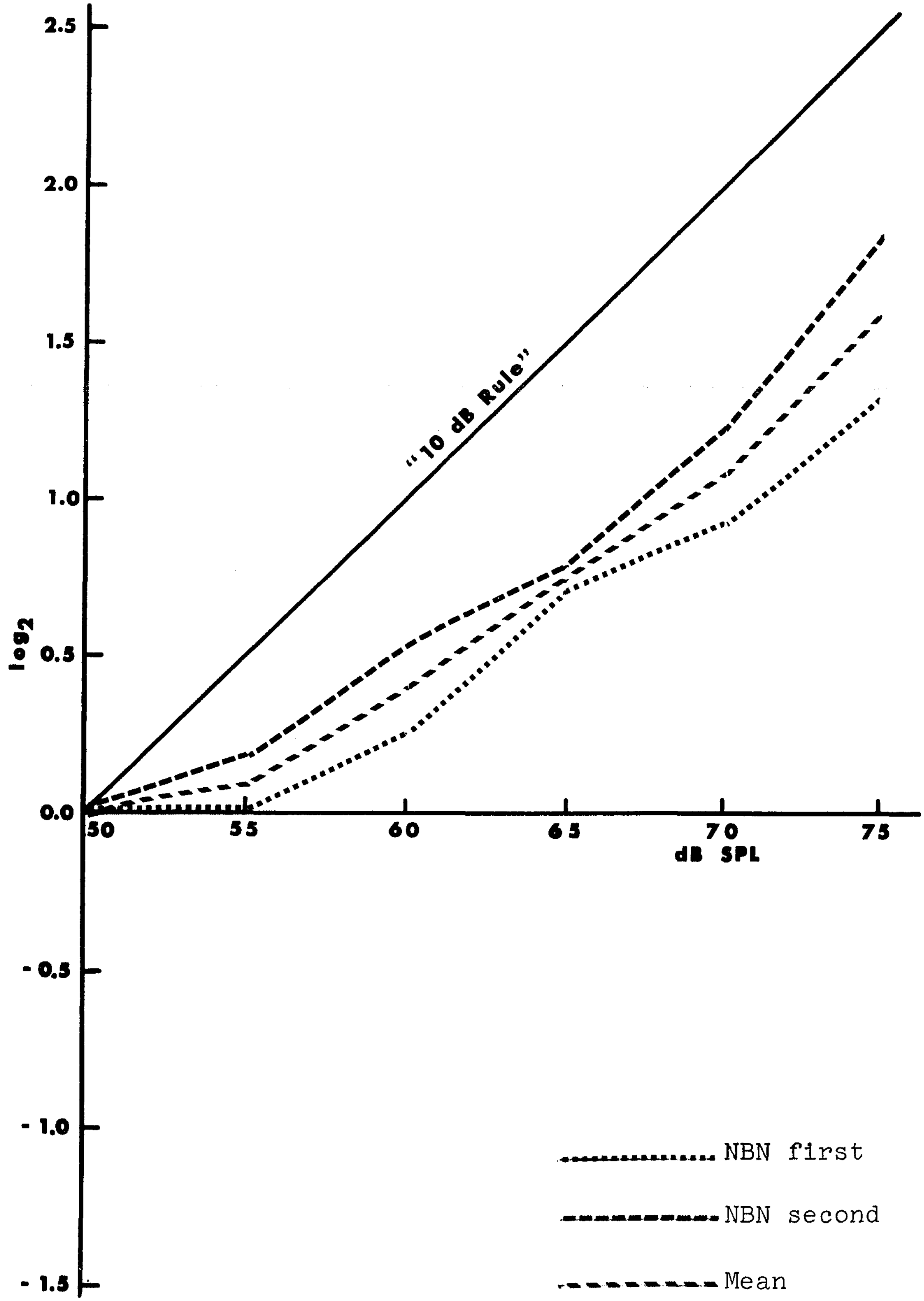

Fig. 19. -- Least Squares Loudness Estimations for Submatrix I-A-4

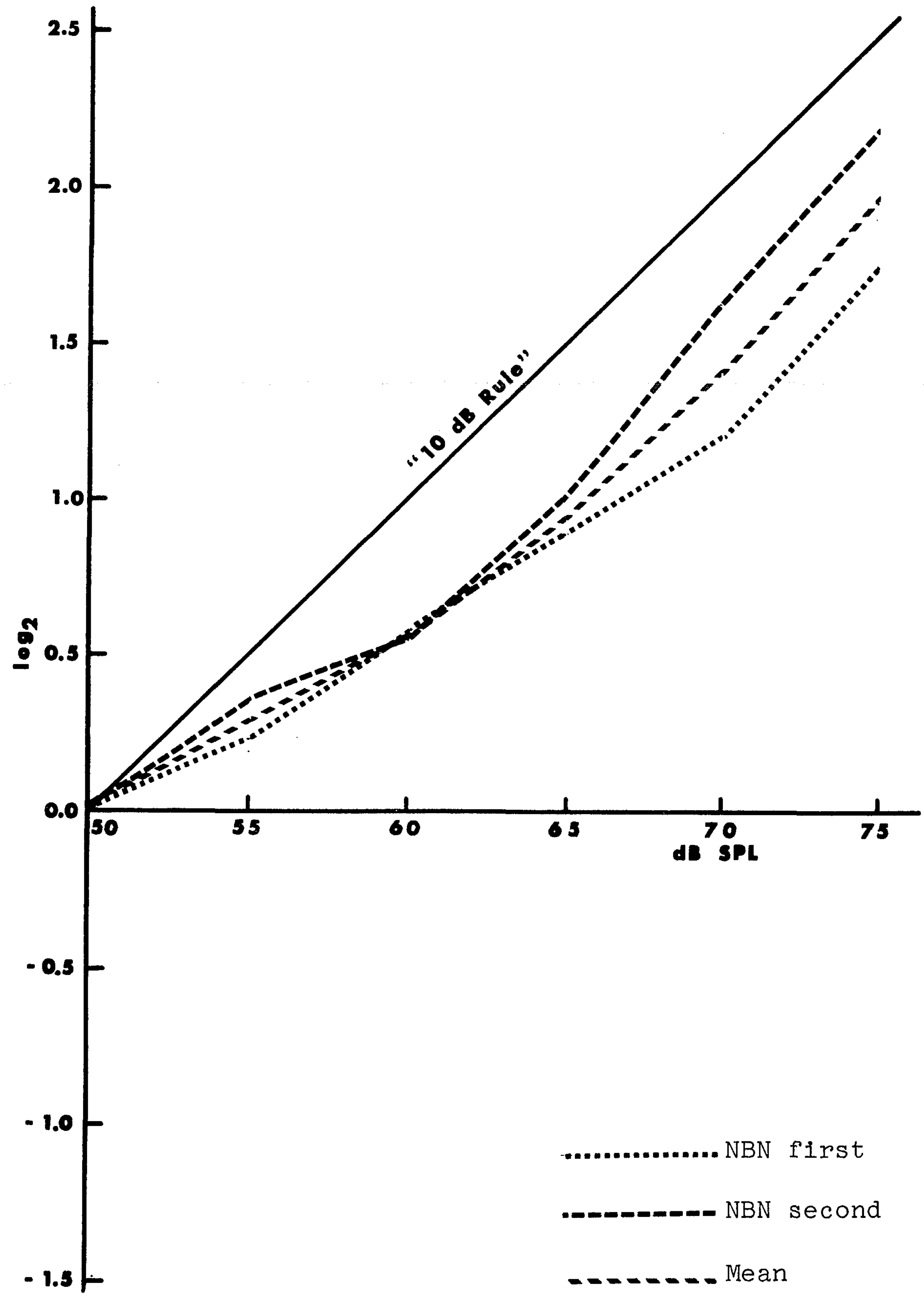

Fig. 20. -- Least Squares Loudness Estimations for Submatrix I-B-1

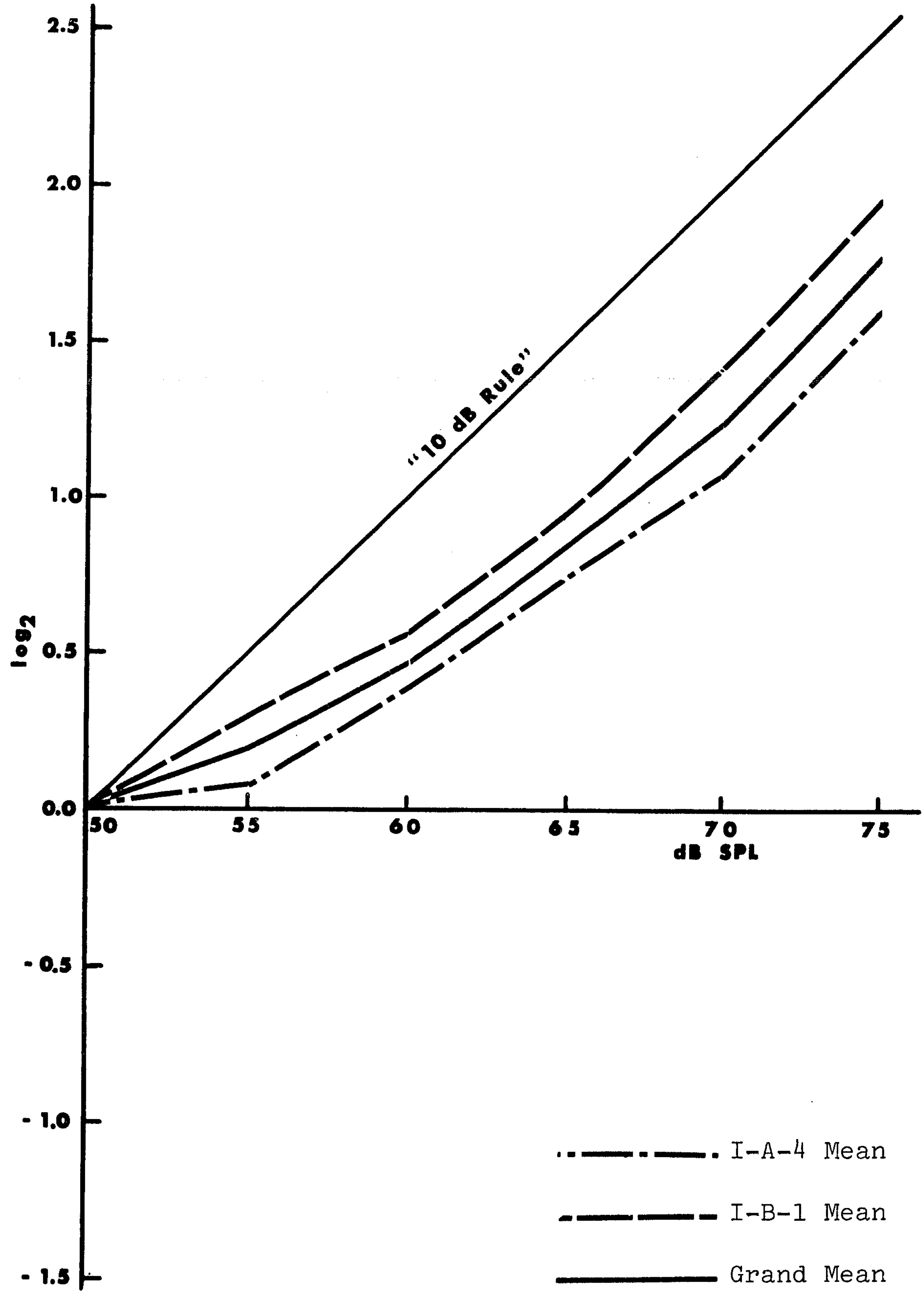

Fig. 21. -- Means of Least Squares Loudness Estimations for submatrices comparing 1 KHz NBN vs. 1 KHz NBN in Group I

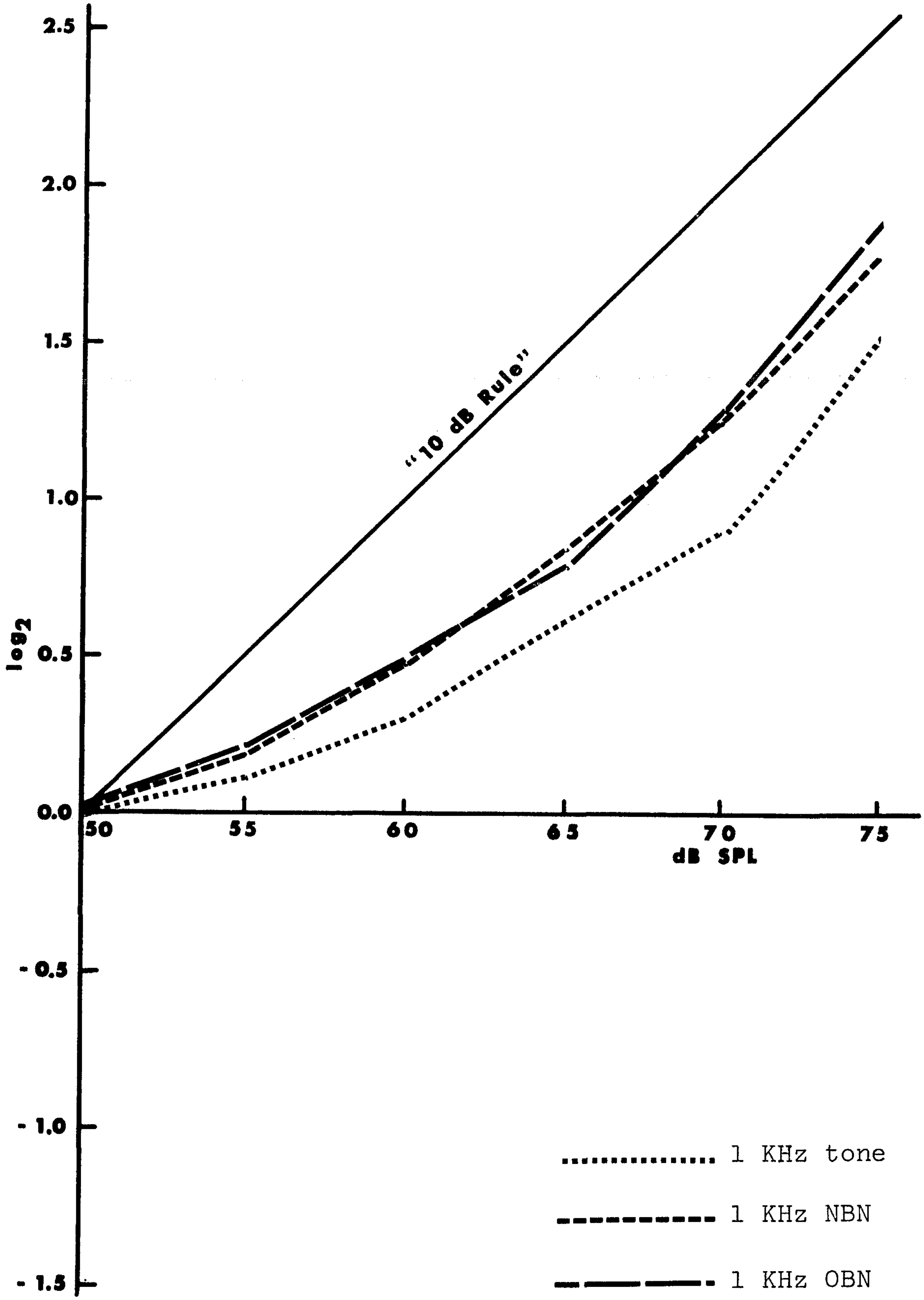

Fig. 22. -- Comparison of Means of Least Squares Loudness Estimations in Group I

imal terminal point of the NBN is slightly higher than the OBN, but not significantly so (1/10 $\log_2$ unit).

GROUP II

As previously stated, Group II data represent a set of submatrices in which the bandwidth of one-third octave bands of noise have been held constant while the center frequencies have been varied. In this group the growth of loudness of the 1 KHz NBN was again observed. Figures 23 and 24 illustrate the data obtained for 1 KHz NBN Submatrices II-A-4 and II-B-1.

The familiar patterns observed in Group I data are seen again. Included are the higher values for the second of a pair stimuli. The means of these data (Figure 25) are quite similar, and when the mean from this group is plotted on the same figure as that of the data from 1 KHz NBN in Group I, it is possible to see that there is almost perfect coincidence (Figure 26).

The data for the 250 Hz NBN (Submatrices II-A-1 and II-C-1) are plotted in Figures 27 and 28. The slopes of the data observed here are much greater than those observed in any of the previous data sets. In this case it can be seen that the data points are distributed close to the line representing the "10 dB Rule". The plotting of the means (Figure 29) reflect this proximity and the grand mean for this data falling almost entirely upon this line. This is

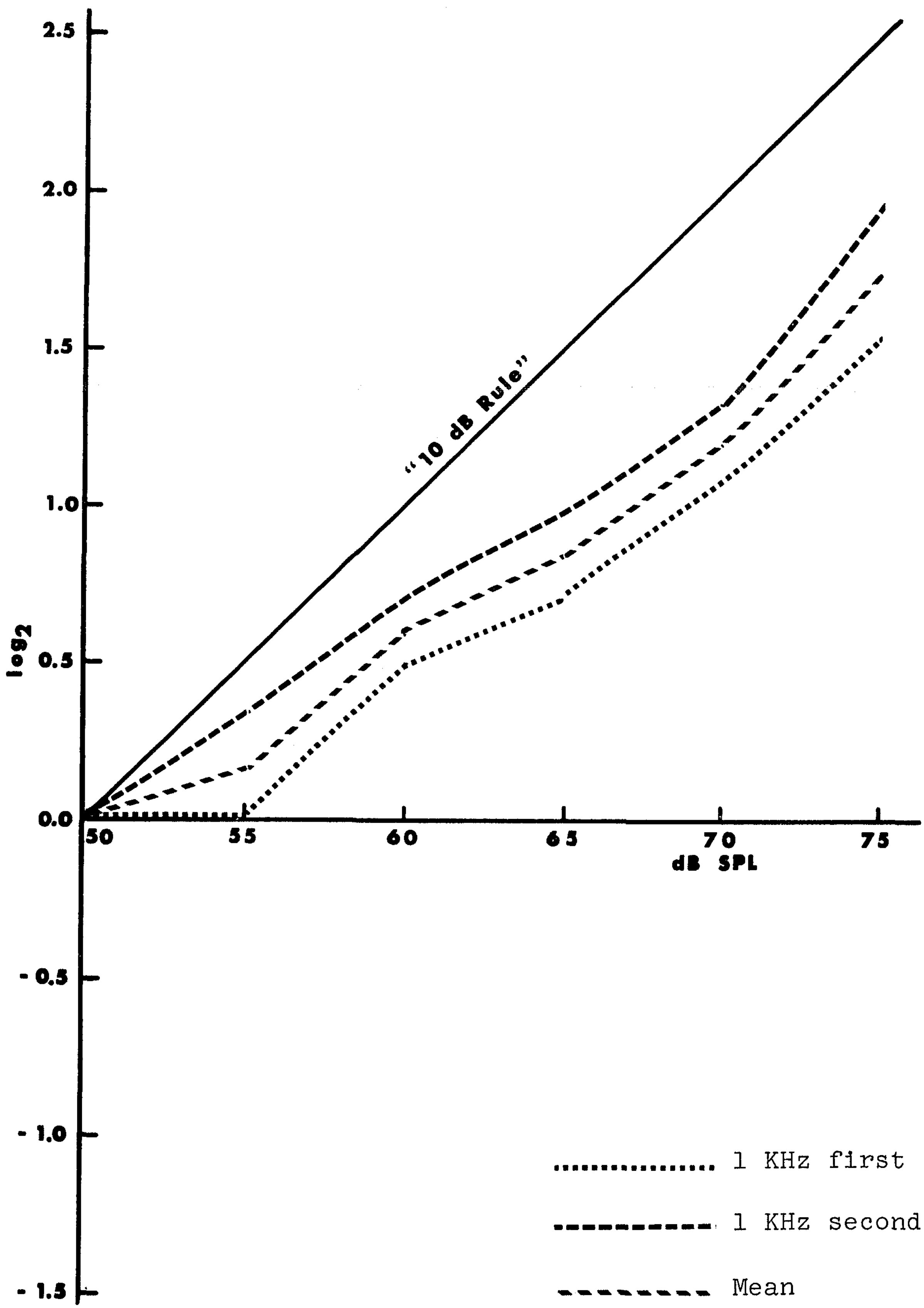

Fig. 23 -- Least Squares Loudness Estimations for Submatrix II-A-4

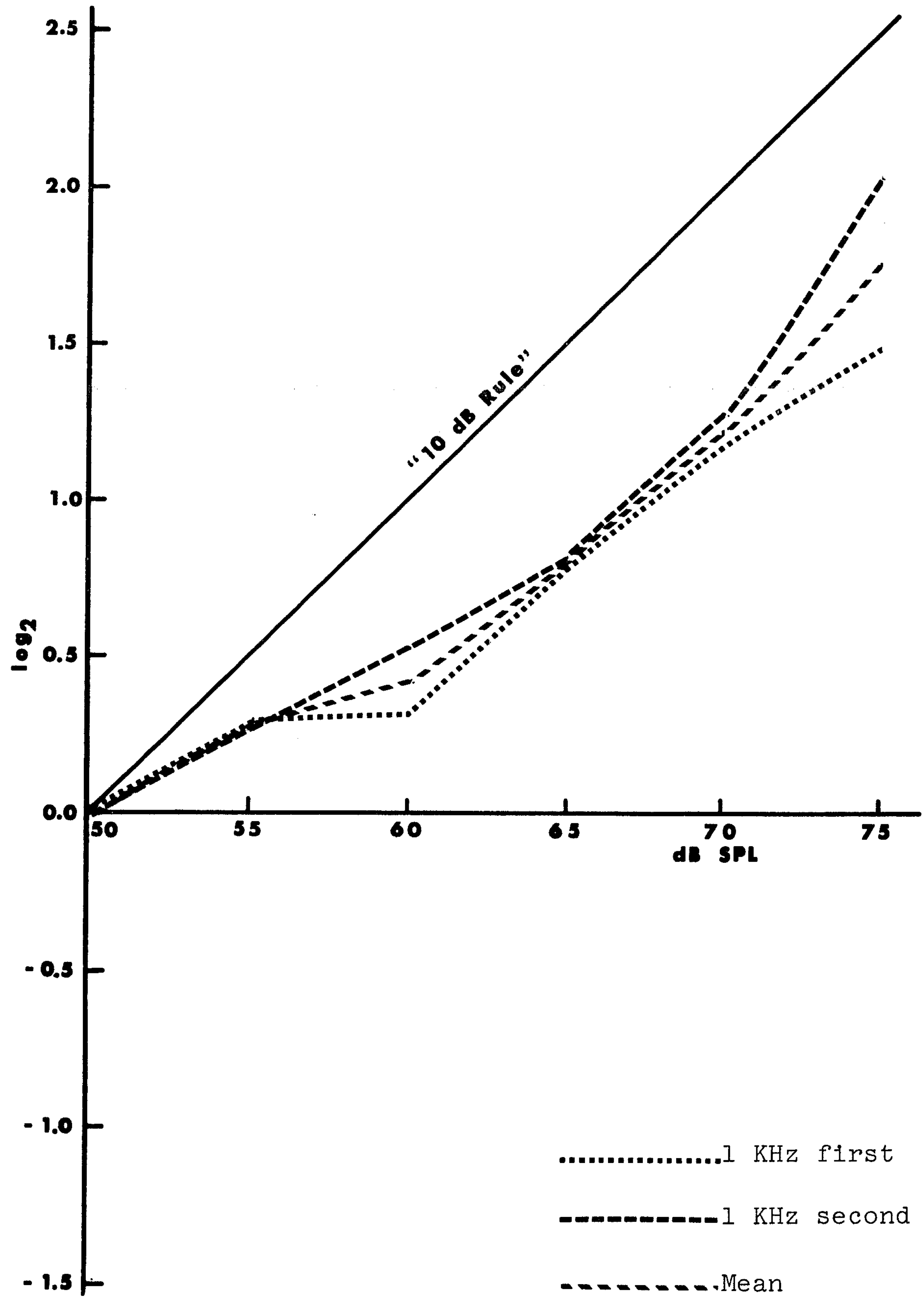

Fig. 24. -- Least Squares Loudness Estimations for Submatrix II-B-1

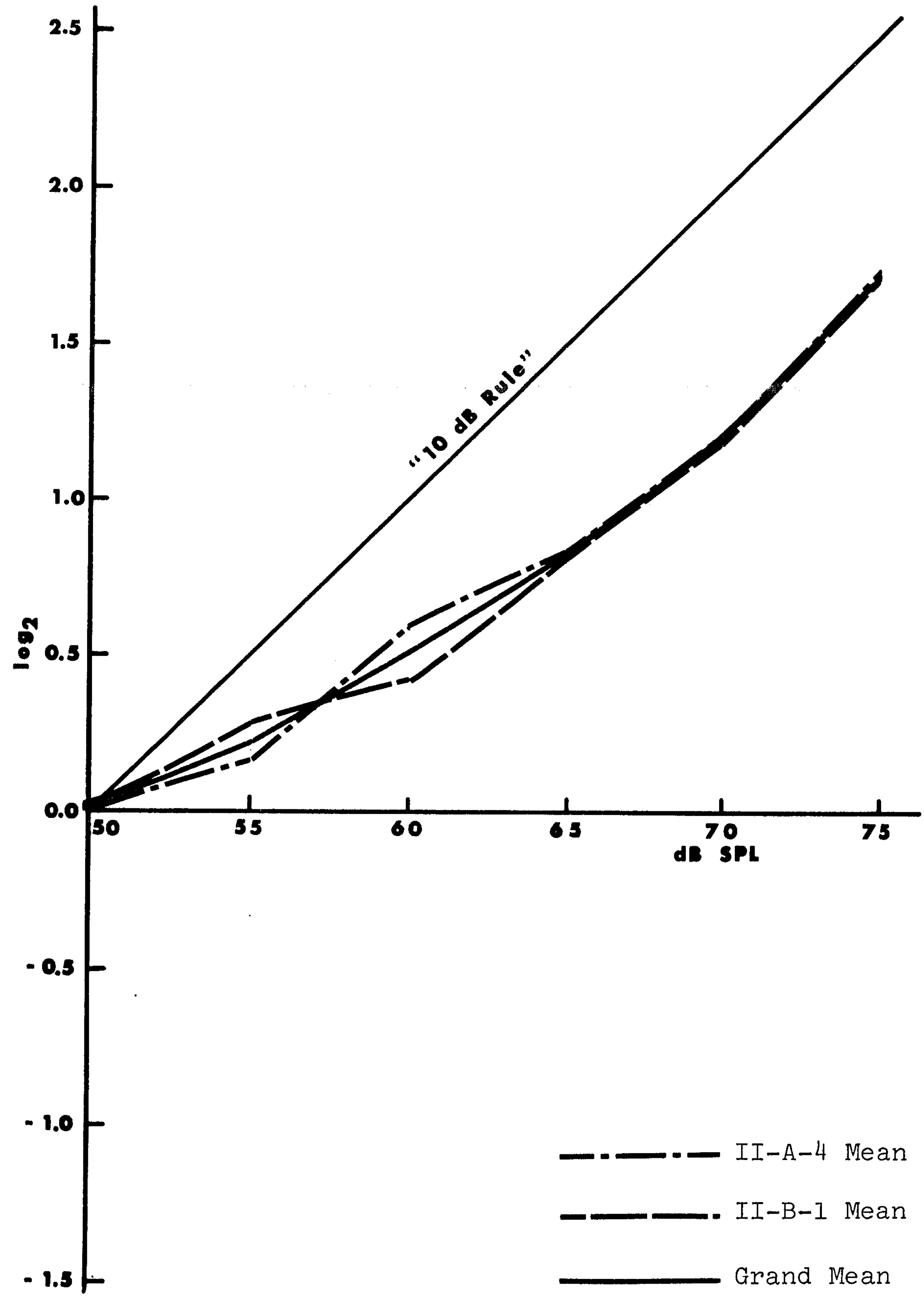

Fig. 25. -- Means of Least Squares Loudness Estimations for submatrices comparing 1 KHz NBN vs 1 KHz NBN in Group II

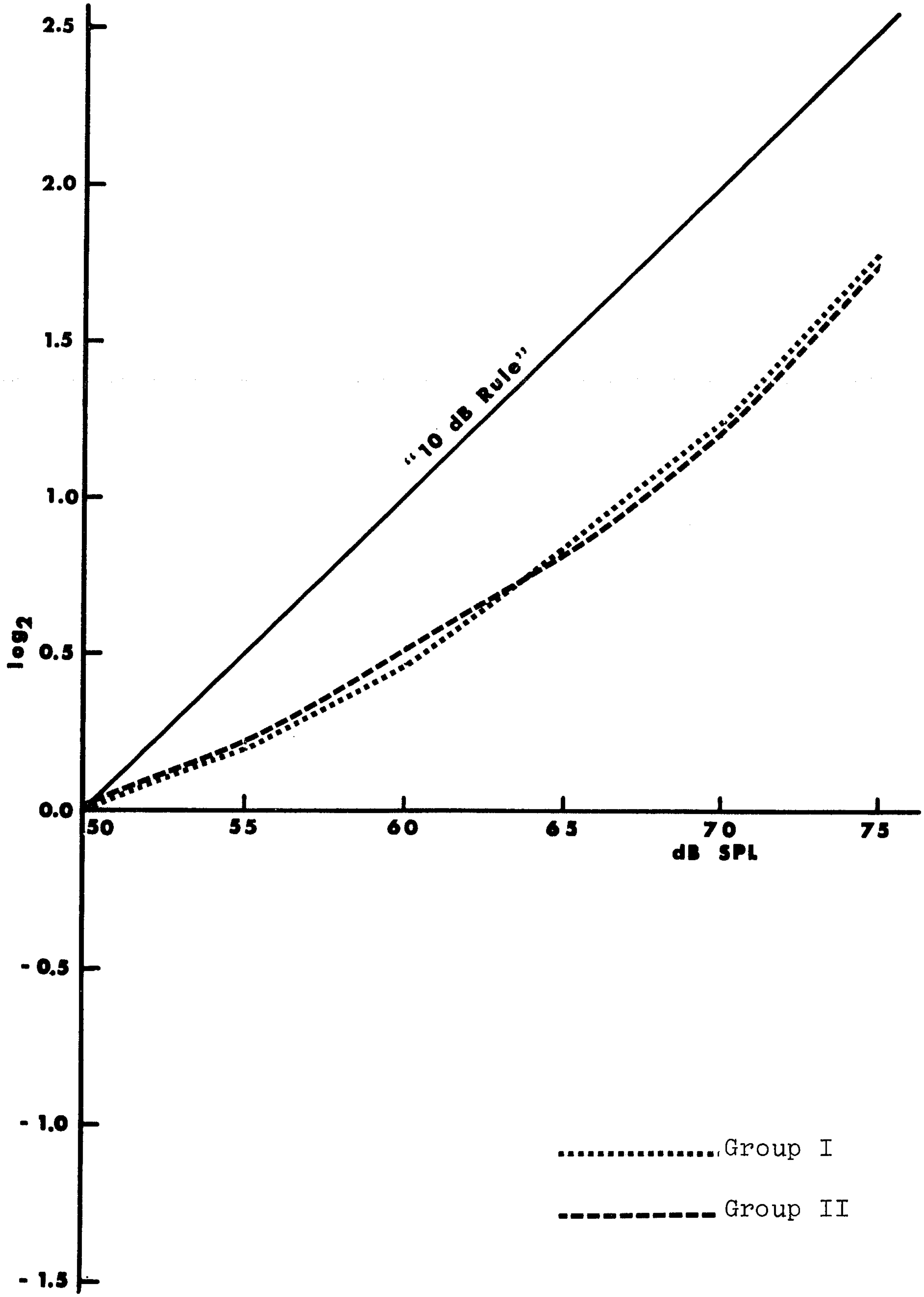

Fig. 26. -- Comparison of 1 KHz NBN Means in Group I and Group II.

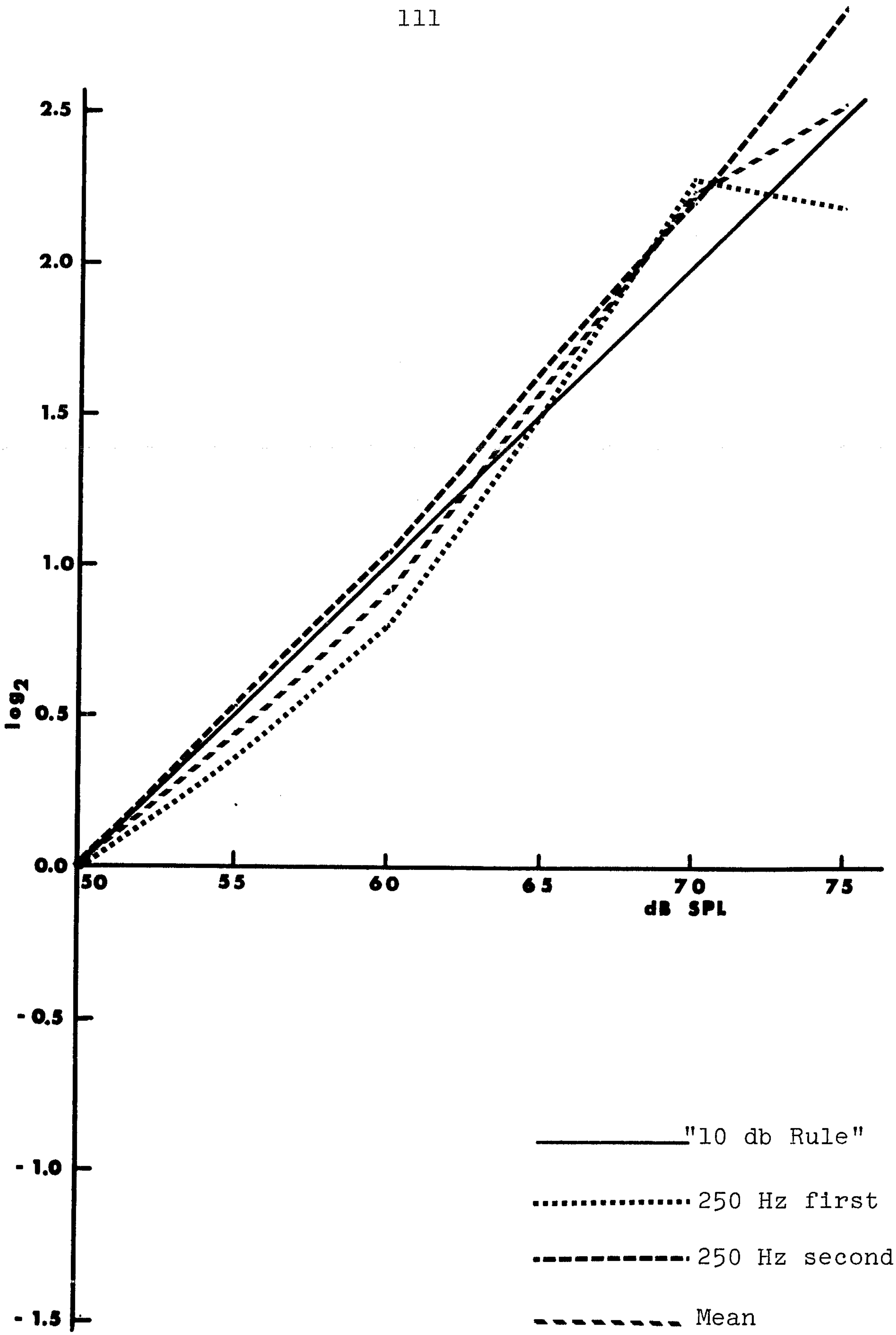

Fig. 27. -- Least Squares Loudness Estimations for Submatrix II-A-1

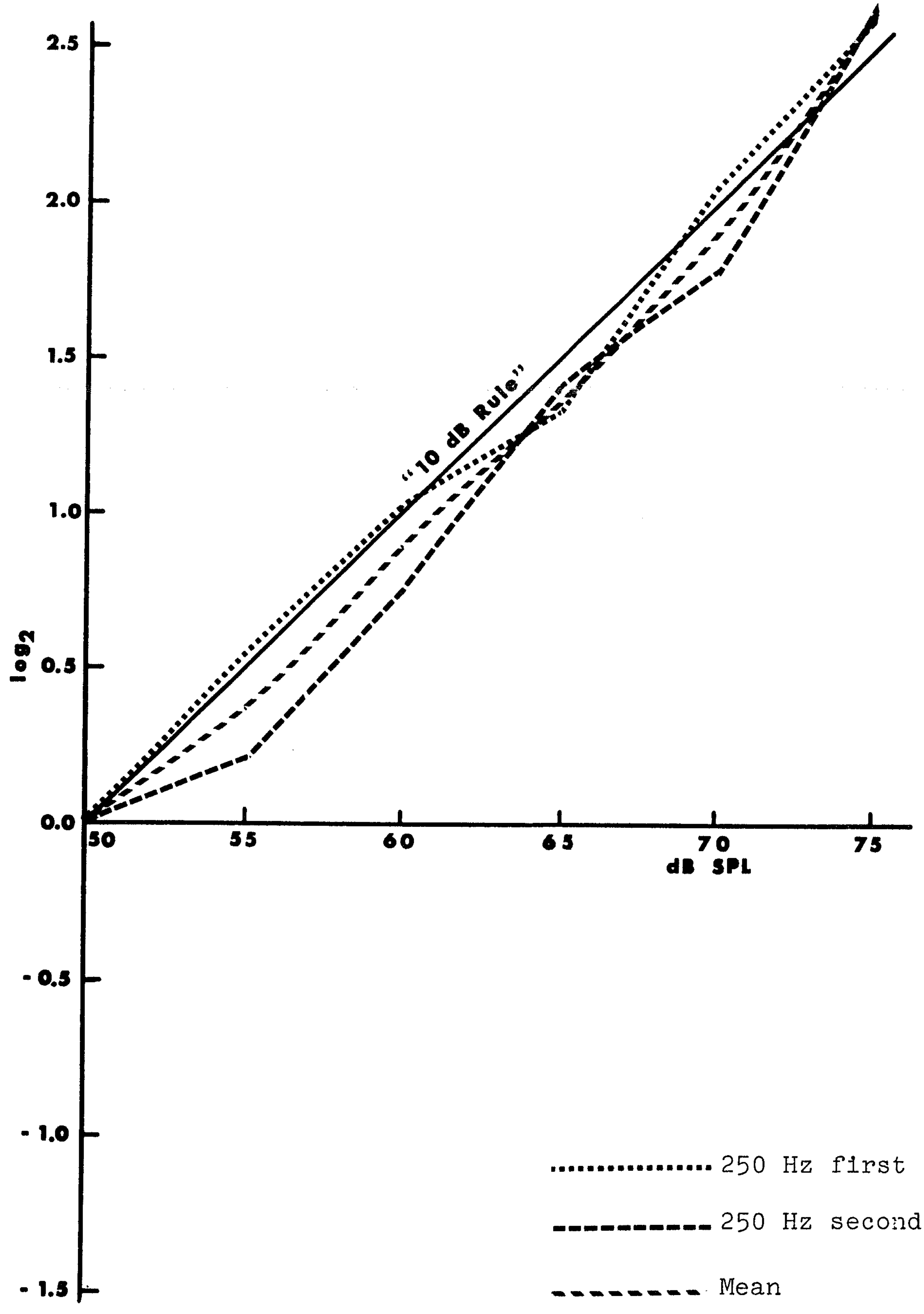

Fig. 28. -- Least Squares Loudness Estimations for Submatrix II-C-1

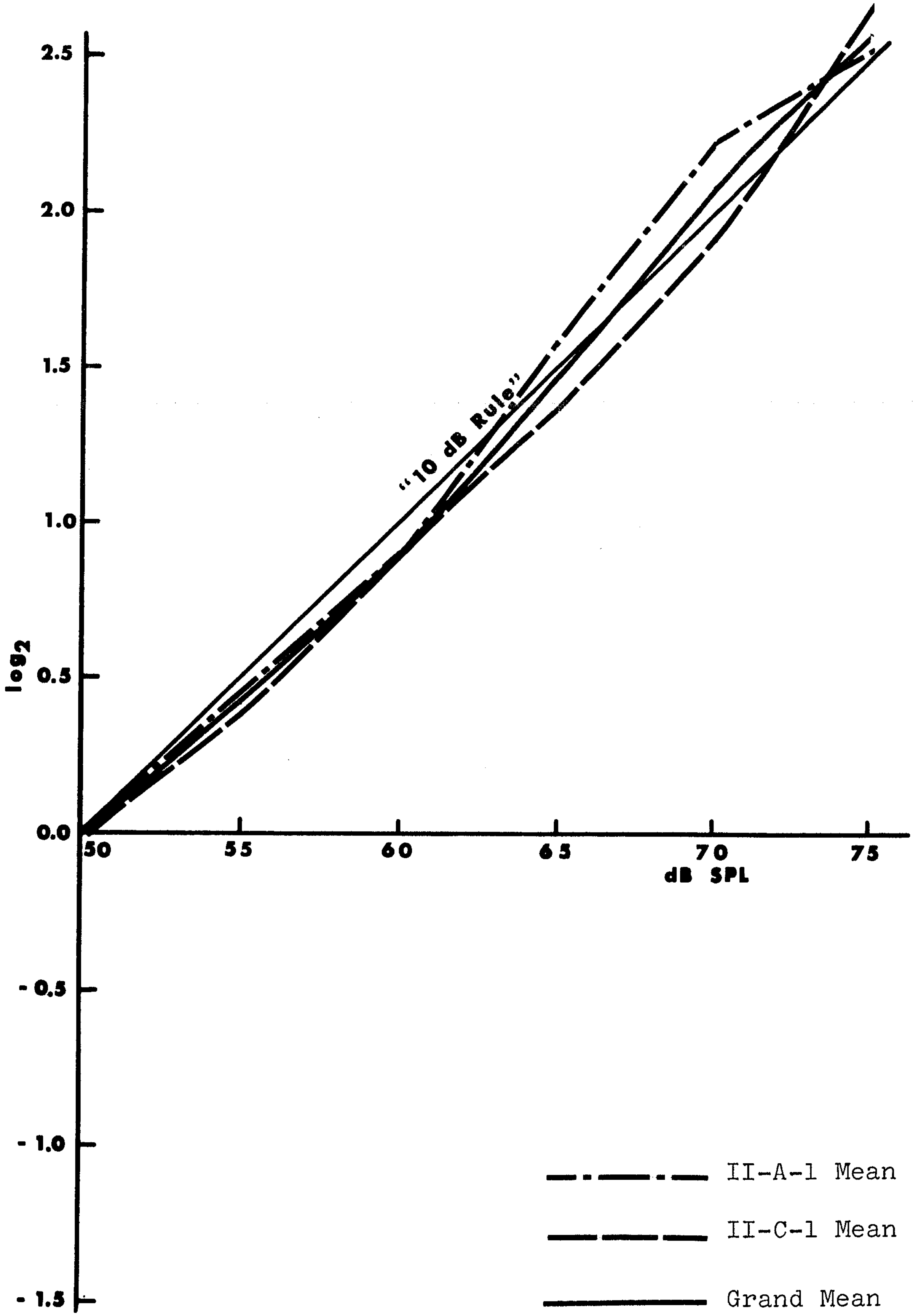

Fig. 29. -- Means of Least Squares Loudness Estimations for submatrices comparing 250 Hz NBN vs. 250 Hz NBN

the only set of data encountered in this study which shows such an apparently close approximation to this rule.

The 4 KHz NBN data (Submatrices II-B-4 and II-C-4) are plotted in Figures 30 and 31. In all four plots a mild plateau is seen between the 55 and 60 dB SPL points and then they all appear to approximate the growth of loudness of the "10 dB Rule". The differences between the second elements in the pair of stimuli and the first in the pair appear again. The mean values for these data are seen in Figure 32, along with the grand means. The knee in the data notwithstanding, it can be seen that the configuration of of the 4 KHz NBN falls upon the grand mean of the 1 KHz NBN data. This relationship can be visualized in Figure 33 where the grand means for the three stimuli in Group II have been plotted on the same axis.

GROUP III

The comparison of stimuli of different bandwidths in Group III submatrices makes it necessary to modify the Least Squares Loudness Estimation procedure as it was applied to Group I and II data. In order to compare the growth of loudness of the stimuli of two different bandwidths, the Least Squares Loudness Estimation technique was utilized by taking the mean row values from submatrices designated number "2", and the column means from the submatrices designated number "3" for the first stimuli values, and the re-

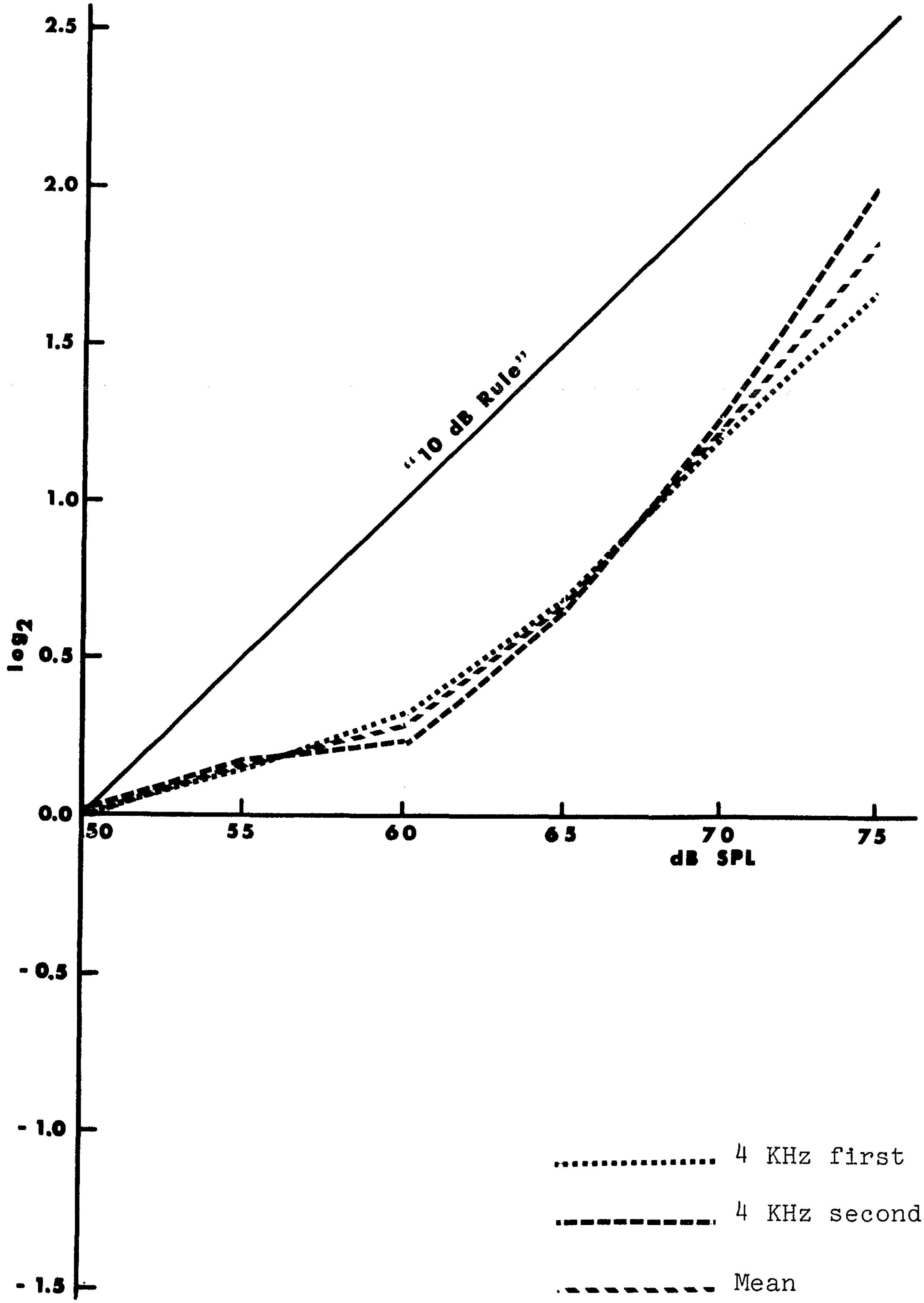

Fig. 30. -- Least Squares Loudness Estimations for Submatrix II-B-4

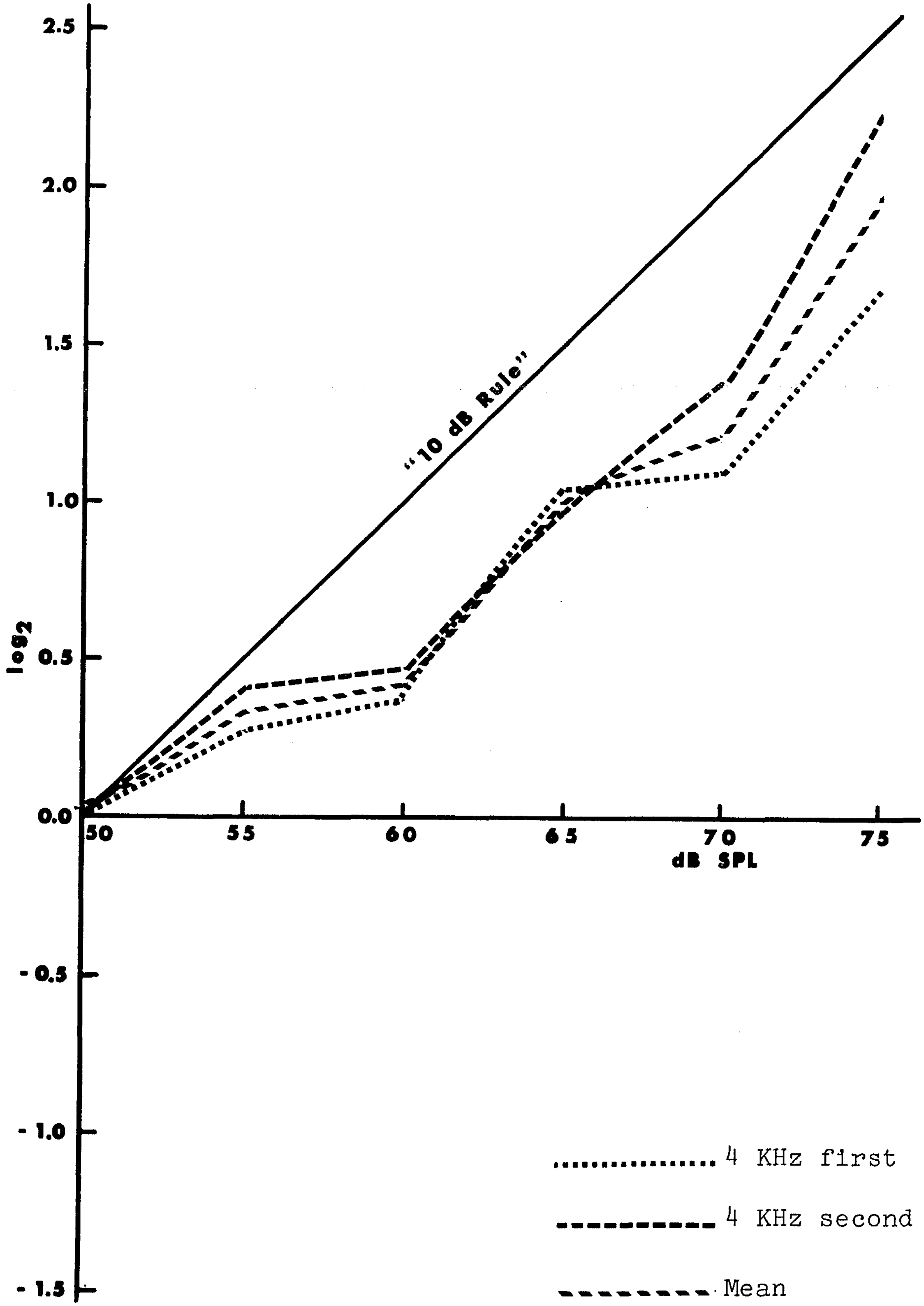

Fig. 31. -- Least Squares Loudness Estimations for Submatrix II-C-4

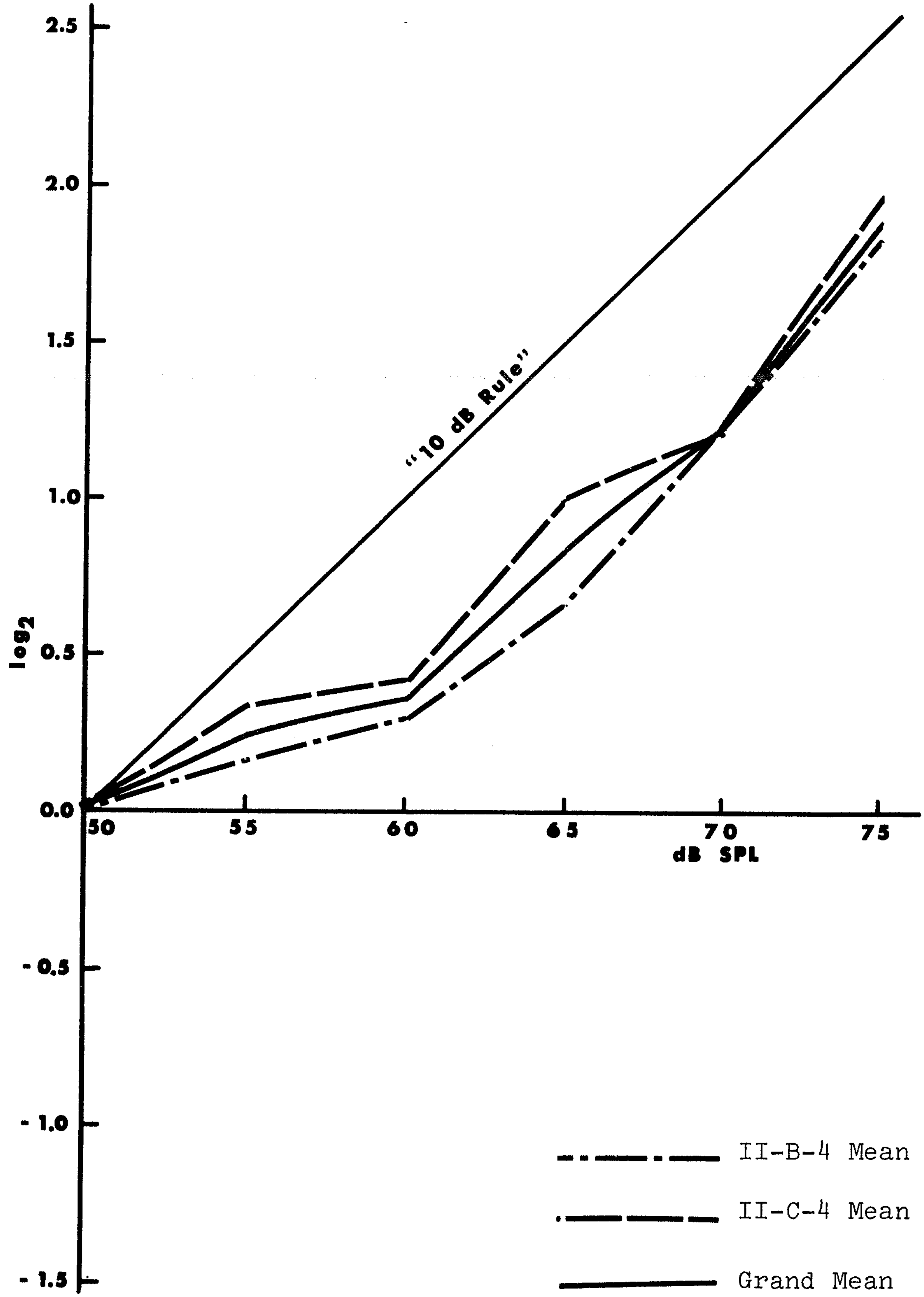

Fig. 32. -- Means for Least Squares Loudness Estimations for submatrices comparing 4 KHz NBN vs. 4 KHz NBN

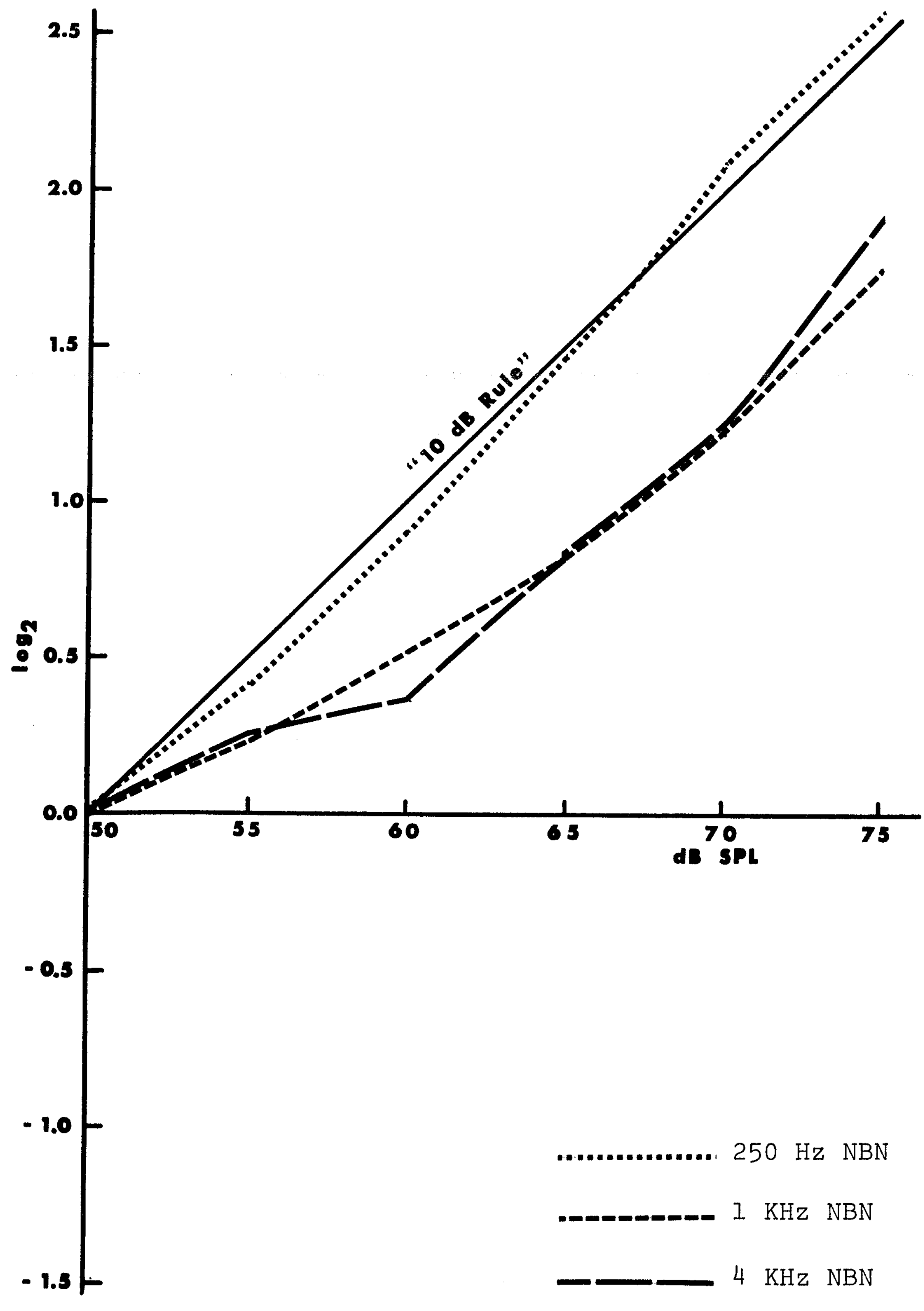

Fig. 33. -- Comparison of Means of Least Squares Loudness Estimations in Group II

verse for the second. Values for each stimulus were computed, and the 50 dB SPL stimuli of the reference signal set to zero by applying an averaging procedure to row and column means and computing intermediate values using the submatrix grand means. Samples of the submatrices and calculations used to obtain these values are illustrated in Figures 34a-d. All entries in these figures are to be assumed to be in a logarithmic ($\log_2$) form.

The analysis of data in this group begins with the consideration of submatrices I-A-2 and I-A-3 (Figure 35). Under investigation here are the growth of loudness of a 1 KHz tone and a 1 KHz NBN when they are paired with each other, rather than with other stimuli like themselves as in Group I. As previously described, the 50 dB SPL tone was assigned the value of $\log_2 = 0$. By so doing, the growth of loudness for the tone stimuli is plotted with its origin at zero, while the growth of the NBN has as its origin some point which describes its loudness relative to the loudness of the 50 dB SPL tone.

The loudness of the tone is seen to increase minimally between 50 and 55 dB SPL, then climb at a rate approximately equal to the "10 dB Rule" to 65 dB SPL, from where it continues to 75 dB SPL on a lesser slope. The narrow band noise which is judged less loud than the tone at 50 dB SPL is seen to grow slowly in loudness from 50 to 65 dB SPL and then grow more rapidly (perhaps with a power exponent of 0.60) to 75 dB SPL. In comparing the two stimuli, they

SUBMATRICES NUMBERED 2

		STIMULUS B (Y)						
		50	55	60	65	70	75	Row Mean
STIMULUS A (X)	50	$-X_{50}+Y_{50}$	$-X_{50}+Y_{55}$	$-X_{50}+Y_{60}$	$-X_{50}+Y_{65}$	$-X_{50}+Y_{70}$	$-X_{50}+Y_{75}$	$-X_{50}+\bar{Y}$
	55	$-X_{55}+Y_{50}$	$-X_{55}+Y_{55}$	$-X_{55}+Y_{60}$	$-X_{55}+Y_{65}$	$-X_{55}+Y_{70}$	$-X_{55}+Y_{75}$	$-X_{55}+\bar{Y}$
	60	$-X_{60}+Y_{50}$	$-X_{60}+Y_{55}$	$-X_{60}+Y_{60}$	$-X_{60}+Y_{65}$	$-X_{60}+Y_{70}$	$-X_{60}+Y_{75}$	$-X_{60}+\bar{Y}$
	65	$-X_{65}+Y_{50}$	$-X_{65}+Y_{55}$	$-X_{65}+Y_{60}$	$-X_{65}+Y_{65}$	$-X_{65}+Y_{70}$	$-X_{65}+Y_{75}$	$-X_{65}+\bar{Y}$
	70	$-X_{70}+Y_{50}$	$-X_{70}+Y_{55}$	$-X_{70}+Y_{60}$	$-X_{70}+Y_{65}$	$-X_{70}+Y_{70}$	$-X_{70}+Y_{75}$	$-X_{70}+\bar{Y}$
	75	$-X_{75}+Y_{50}$	$-X_{75}+Y_{55}$	$-X_{75}+Y_{60}$	$-X_{75}+Y_{65}$	$-X_{75}+Y_{70}$	$-X_{75}+Y_{75}$	$-X_{75}+\bar{Y}$
Column Mean		$-\bar{X}+Y_{50}$	$-\bar{X}+Y_{55}$	$-\bar{X}+Y_{60}$	$-\bar{X}+Y_{65}$	$-\bar{X}+Y_{70}$	$-\bar{X}+Y_{75}$	$-\bar{X}+\bar{Y}$ Grand Mean

Fig. 34a. -- Scheme of cell values, means and grand mean for Submatrices Numbered 2

SUBMATRICES NUMBERED 3

		STIMULUS B (X)						
		50	55	60	65	70	75	Row Mean
STIMULUS A (Y)	50	$-Y_{50}+X_{50}$	$-Y_{50}+X_{55}$	$-Y_{50}+X_{60}$	$-Y_{50}+X_{65}$	$-Y_{50}+X_{70}$	$-Y_{50}+X_{75}$	$-Y_{50}+\bar{X}$
	55	$-Y_{55}+X_{50}$	$-Y_{55}+X_{55}$	$-Y_{55}+X_{60}$	$-Y_{55}+X_{65}$	$-Y_{55}+X_{70}$	$-Y_{55}+X_{75}$	$-Y_{55}+\bar{X}$
	60	$-Y_{60}+X_{50}$	$-Y_{60}+X_{55}$	$-Y_{60}+X_{60}$	$-Y_{60}+X_{65}$	$-Y_{60}+X_{70}$	$-Y_{60}+X_{75}$	$-Y_{60}+\bar{X}$
	65	$-Y_{65}+X_{50}$	$-Y_{65}+X_{55}$	$-Y_{65}+X_{60}$	$-Y_{65}+X_{65}$	$-Y_{65}+X_{70}$	$-Y_{65}+X_{75}$	$-Y_{65}+\bar{X}$
	70	$-Y_{70}+X_{50}$	$-Y_{70}+X_{55}$	$-Y_{70}+X_{60}$	$-Y_{70}+X_{65}$	$-Y_{70}+X_{70}$	$-Y_{70}+X_{75}$	$-Y_{70}+\bar{X}$
	75	$-Y_{75}+X_{50}$	$-Y_{75}+X_{55}$	$-Y_{75}+X_{60}$	$-Y_{75}+X_{65}$	$-Y_{75}+X_{70}$	$-Y_{75}+X_{75}$	$-Y_{75}+\bar{X}$
Column Mean		$-\bar{Y}+X_{50}$	$-\bar{Y}+X_{55}$	$-\bar{Y}+X_{60}$	$-\bar{Y}+X_{65}$	$-\bar{Y}+X_{70}$	$-\bar{Y}+X_{75}$	$-\bar{Y}+\bar{X}$ Grand Mean

Fig. 34b. -- Scheme of cell values, means and grand mean for Submatrices Numbered 3

METHOD OF COMPUTATION OF MIXED MATRICES USING LEAST SQUARES LOUDNESS ESTIMATION

1. COMPUTATION OF X_{50} THROUGH X_{75}

a. From submatrix numbered '2', take Row Means

$$(-X_i + \overline{Y}) = a_i$$

b. From submatrix numbered '3', take Column Means

$$(-\overline{Y} + X_i) = b_i$$

c. Combine Values (Row Mean - Column Mean)

$$1/2\ (a-b)_i = (-X_i + \overline{Y}) - (-\overline{Y} + X_i) = -X_i + \overline{Y}$$

d. X_{50} is arbitrarily assumed to have a loudness of zero units,

$$\text{if } X_{50} = 0,\ \overline{Y} = 1/2\ (a-b)_{50}$$

e. Since a value has now been assigned to $\overline{Y}$, the values for X_{50} through X_{75} can be computed by substituting for Y in the formula, $-X_i + \overline{Y} = 1/2\ (a-b)_i$

2. COMPUTATION OF Y_{50} THROUGH Y_{75}

a. From submatrix numbered '2', take Column Means

$$(-\overline{X} + Y_j) = a_j$$

b. From submatrix numbered '3', take Row Means

$$(-Y_j + \overline{X}) = b_j$$

Fig. 34c.-- L.S.L. - Method of Computation of Mixed Matrices

(. . . METHOD OF COMPUTATION - CONTINUED)

c. Combine Values (Column Mean - Row Mean)

$$1/2\ (a-b)_j = (-Y_j + \overline{X}) - (-\overline{X} + Y_j) = -Y_j + \overline{X}$$

d. Utilizing the value for $\overline{Y}$ from " 1 " above, and the grand mean of the submatrix designated 2, the value of $\overline{X}$ can be computed,

$$\text{Grand Mean} = -\ \overline{X} + \overline{Y}$$

$$\overline{X} = \overline{Y} - \text{Grand Mean}$$

e. $Y_j = 1/2\ (a-b)_j + \overline{X}$

Fig. 34d. -- L.S.L. - Method of Computation of Mixed Matrices (continued)

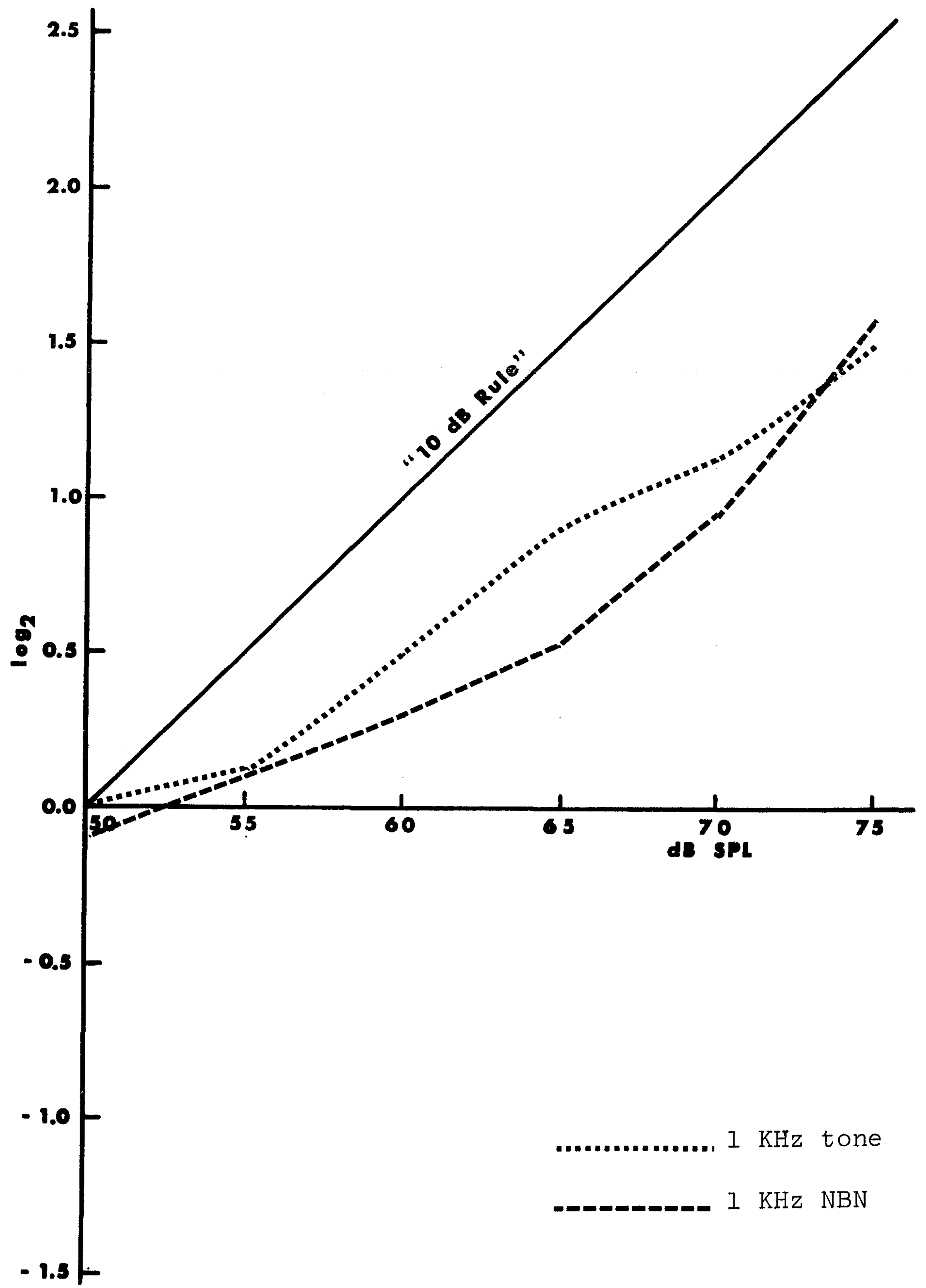

Fig. 35. -- Least Squares Loudness Estimations of tone and NBN combinations in Matrix I-A

appear to be judged almost equivalent to each other at 50 dB SPL, exactly equivalent at 55 dB SPL and then diverge to a maximum at 65 dB SPL, followed by a convergence to equality again at 75 dB SPL.

The second combination of stimuli pairs to be compared in this group is that of the tone and the wide band noise, submatrices I-C-2 and I-C-3 (Figure 36). The tone stimulus is again used as the reference and its 50 dB SPL stimuli is set to zero. The tone shows little increase in loudness to the 55 dB SPL, very much as it did in the previous matrix. After this point the loudness grows a little more rapidly. By comparing the growth of loudness for the tones in matrices I-A and I-C, Figure 37 demonstrates their close similarity in form. Also shown in this figure is the plot for the grand mean of tone data from Group I. The configuration of the tone data in Matrix I-C is reasonably similar to the tone/tone data, while the data from I-A shows greater deviation especially in the middle intensities.

The last combination in this group compares the growth of loudness of the narrow band noise and the octave band noise which were found in Submatrices I-B-2 and I-B-3, and which are illustrated in Figures 38-39. There are several ways in which the growth of loudness of the two stimuli under examination could be plotted. By one method, previously determined values for $\overline{OBN}$ and $\overline{NBN}$ from Matrices I-A and I-C could be utilized in the calculations of NBN_i and OBN_j, respectively, as shown in Figure 38. Calculation of the

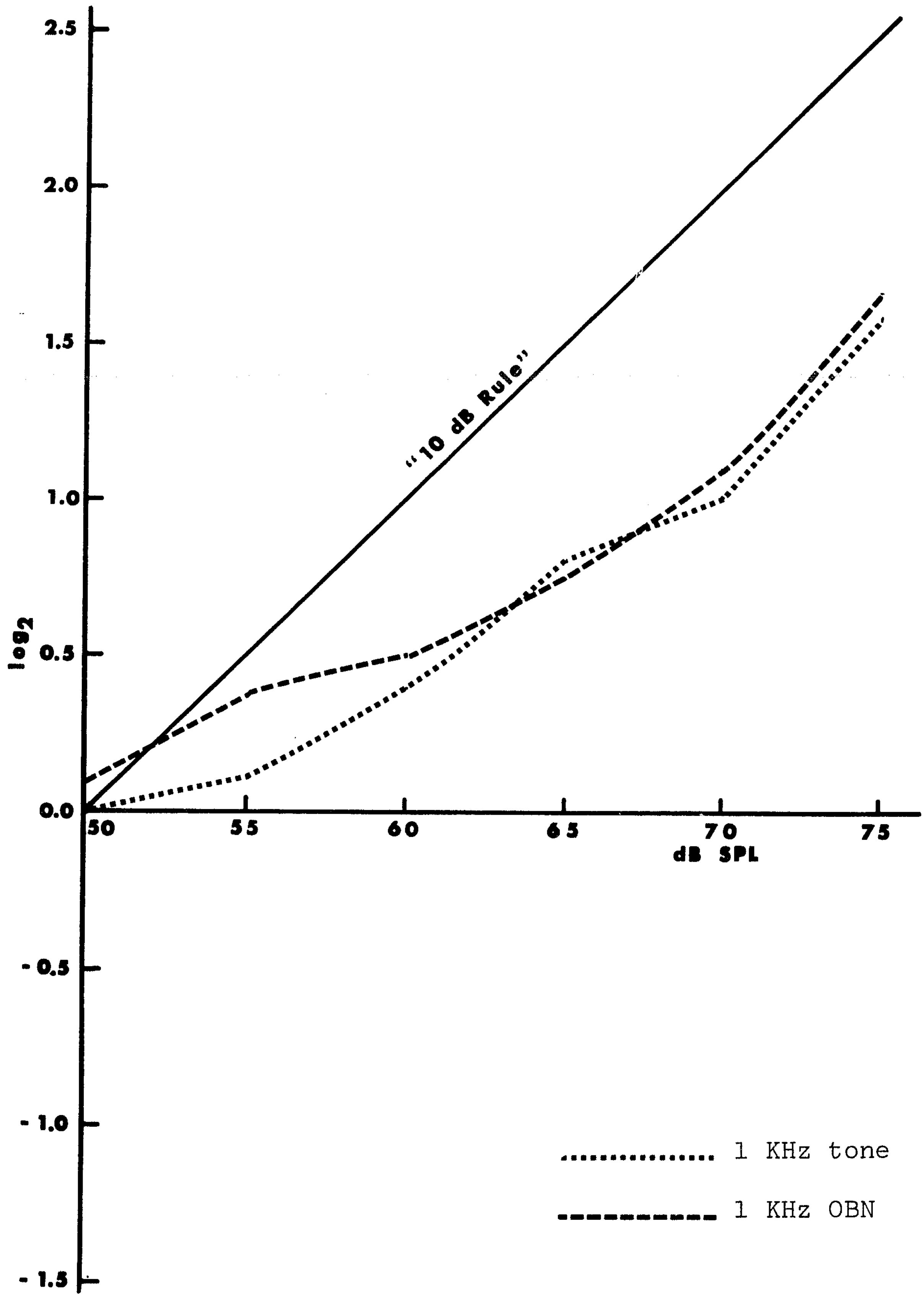

Fig. 36. -- Least Squares Loudness Estimations of tone and OBN combinations in Matrix I-C

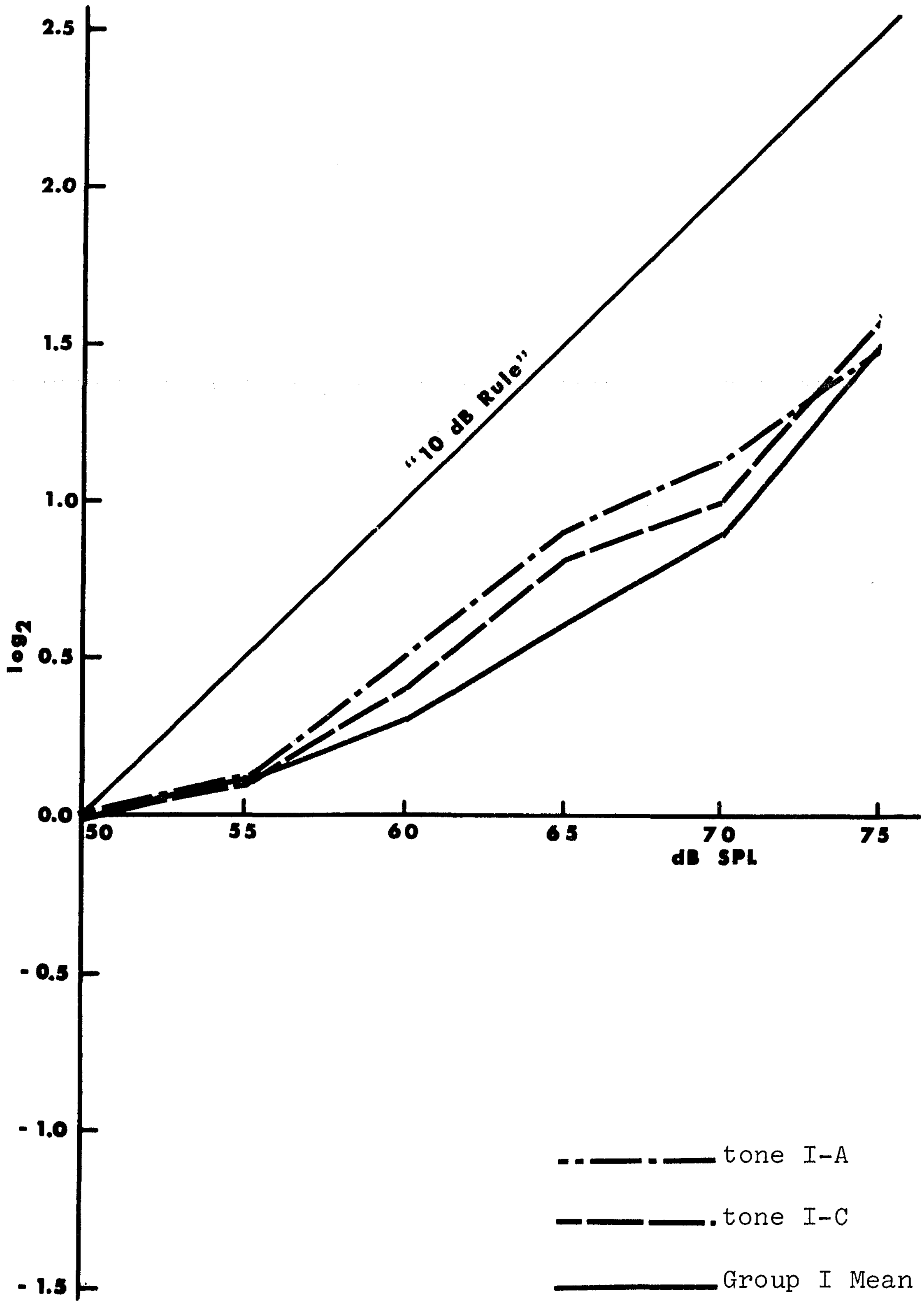

Fig. 37. -- Comparison of Least Squares Loudness Estimations for 1 KHz tones obtained in Group III

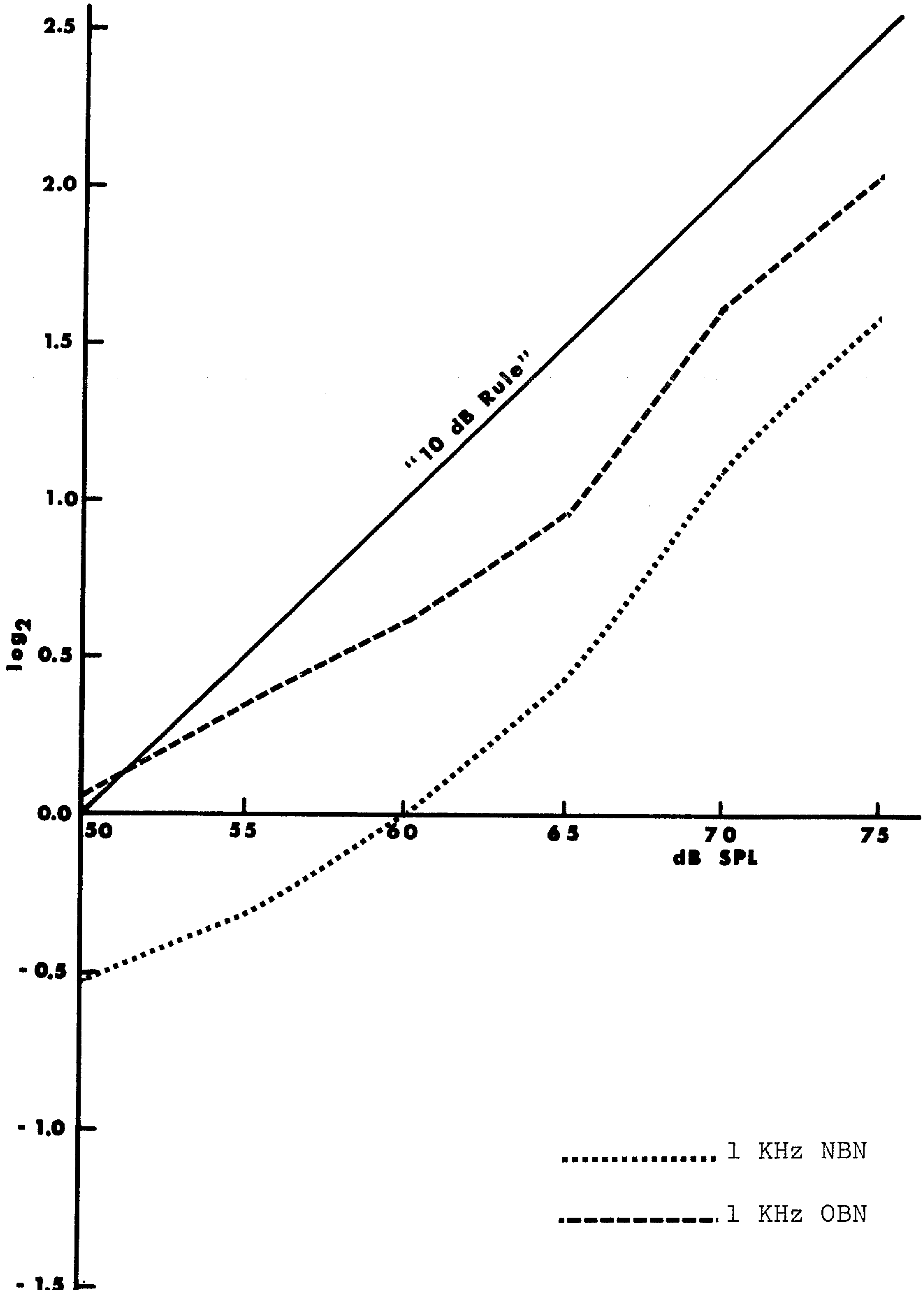

Fig. 38. -- Least Squares Loudness Estimations for 1 KHz NBN and OBN in Matrix I-B: Method I. Using previously obtained values for $\overline{NBN}$ and $\overline{OBN}$

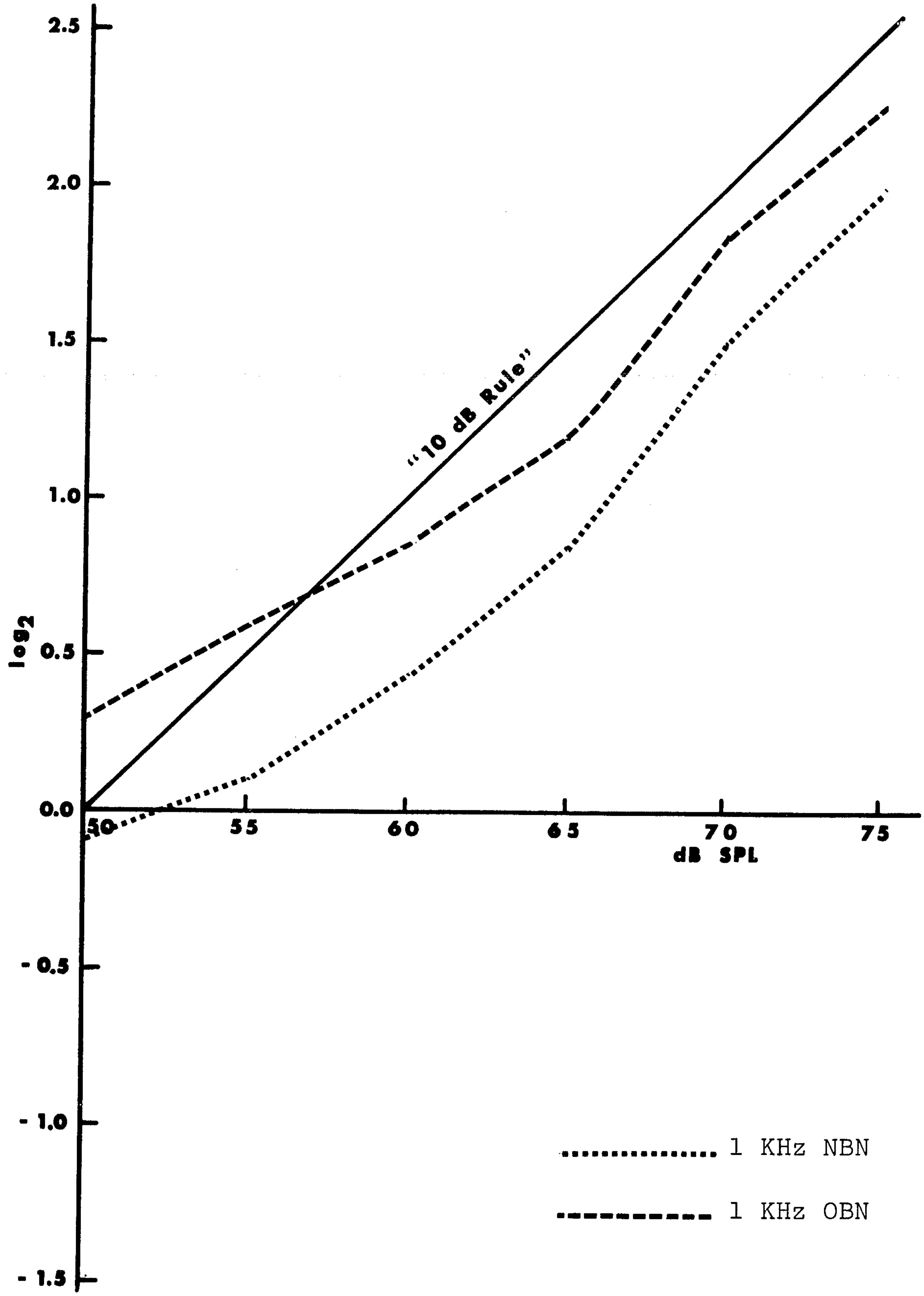

Fig. 39. -- Least Squares Loudness Estimations for 1 KHz NBN and OBN in Matrix I-B: Method II. Using a previously determined value for NBN_{50}

grand mean from these values yields a value not in agreement with the actual grand mean ($-\overline{NBN}+\overline{OBN} = -0.56 + 0.75 \neq 0.19$). An alternative method (shown in Figure 39) uses the value for NBN_{50} (-0.10) obtained in I-A as the origin for the NBN_i plots, and then OBN_j is plotted relative to it. Under this condition, the shapes of the loudness functions remain unchanged, but are now closer to one another. The calculation of the grand mean now shows agreement with the actual grand mean ($-\overline{NBN}+\overline{OBN} = 0.79 + 1.17 = 0.38$).

Figures 40 and 41 compare the configurations for the NBN and the OBN data obtained in this group with other data obtained for the NBN/NBN and OBN/OBN conditions, respectively. It should be noted that in these figures all of the origins (X_{50}) have been set to zero to facilitate comparisons.

In comparing the NBN from Matrix I-B to the NBN/NBN data, very close approximation of the plots is seen to 65 dB SPL, where the stimuli diverge and then parallel each other from 70 to 75 dB SPL. NBN data from I-A presents a different relationship; where there is coincidence to 55 dB SPL then spreading divergence below the NBN/NBN data to 65 dB SPL followed by essentially parallel plots to 75 dB SPL.

Comparison of the OBN data from I-B with the OBN/OBN data shows very similar patterns of loudness growth when both origins are set equal to zero. I-C data patterns are not as closely related as that from I-B, especially at the higher end of the intensities studied, where greater diver-

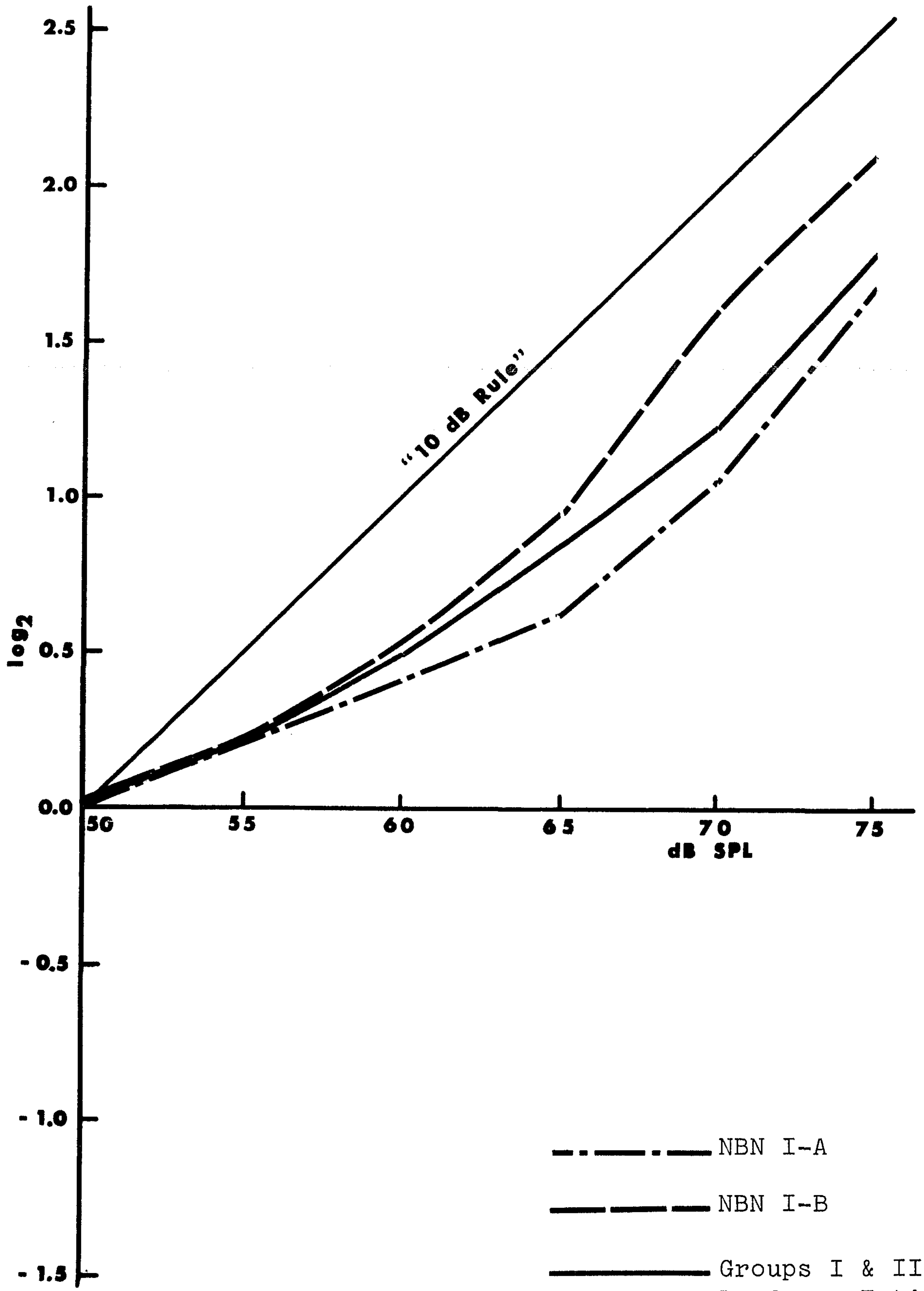

Fig. 40. -- Comparison of Least Squares Loudness Estimations for 1 KHz NBN obtained in Group III with 1 KHz NBN Grand Mean from Groups I & II

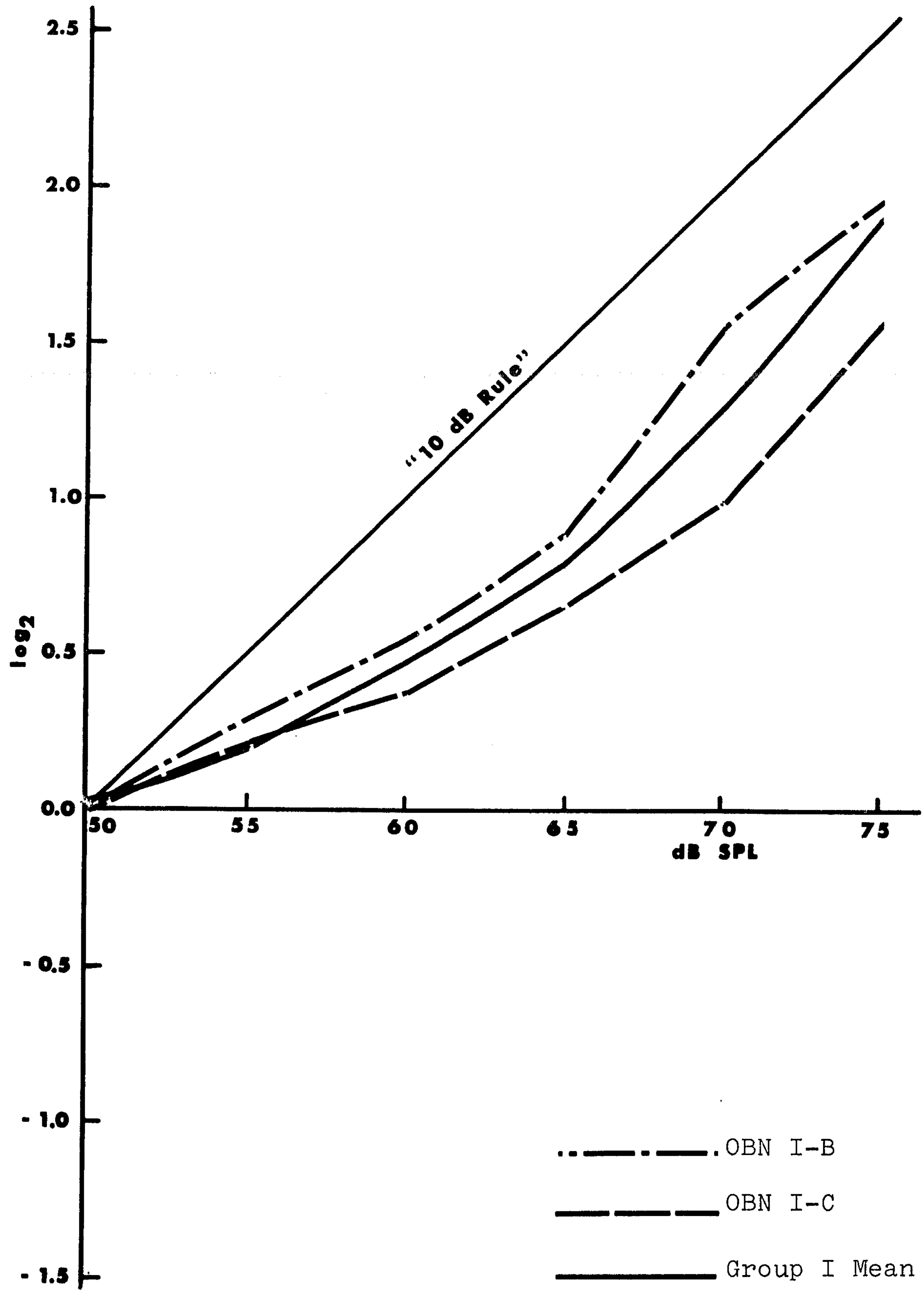

Fig. 41. -- Comparison of Least Squares Loudness Estimation for 1 KHz OBN obtained in Group III

gence is seen.

GROUP IV

The method of application of the Least Squares Loudness used in Group III was again used in Group IV where the study of the effects of center frequency was carried on. Since there was no tone stimuli in Group IV, it was decided that the 1 KHz NBN would be utilized as the standard primarily because of its theoretical similarities to the tone and ease in comparison to other data.

Figure 42 shows the plots of the 250 Hz NBN and the 1 KHz NBN derived from the data from Matrix II-A. The divergence of the values between the two stimuli (1.3 $\log_2$ units at 50 dB SPL) is clearly seen in the lower intensities with a gradual convergence (0.3 $\log_2$ units at 75 dB SPL) in the higher ones. The 250 Hz NBN appears to be essentially parallel to the "10 dB Rule" to 65 dB SPL and then increases its rate of loudness growth to the 70 dB SPL level, returning to a parallel position to 75 dB SPL.

The 1 KHz NBN is next compared to the 4 KHz NBN in Figure 43. The results, obtained from Matrix II-B, illustrate two stimuli which show reasonable proximity to one another through most of their range. The 4 KHz signal shows a rate of loudness growth similar to that of the "10 dB Rule" from 55 through 65 dB SPL.

Figure 44 summarizes the growth of loudness for the

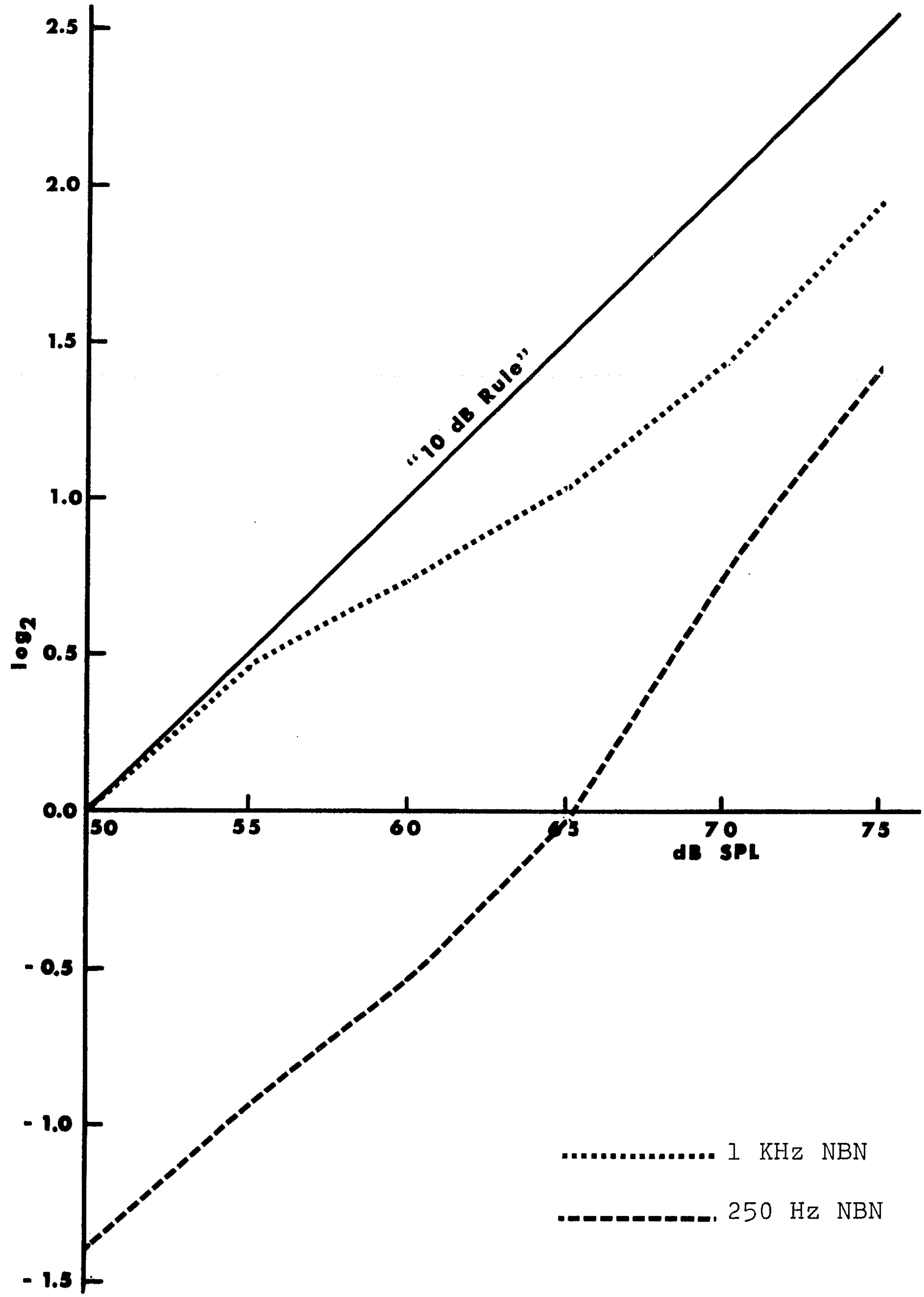

Fig. 42. -- Least Squares Loudness Estimations of 250 Hz NBN vs 1 KHz NBN combinations in Matrix II-A

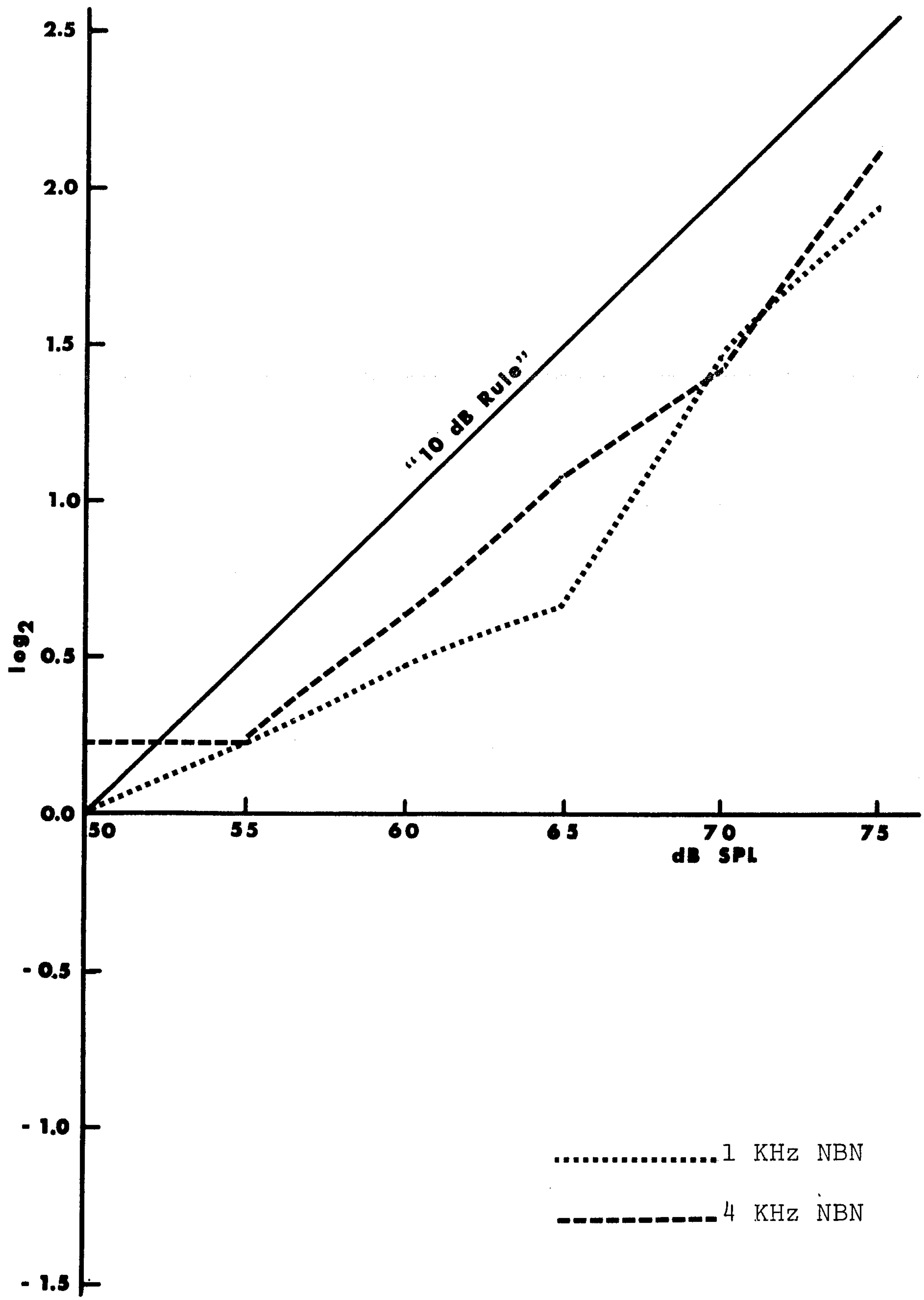

Fig. 43. -- Least Squares Loudness Estimations of 1 KHz NBN vs. 4 KHz NBN combinations in Matrix II-B

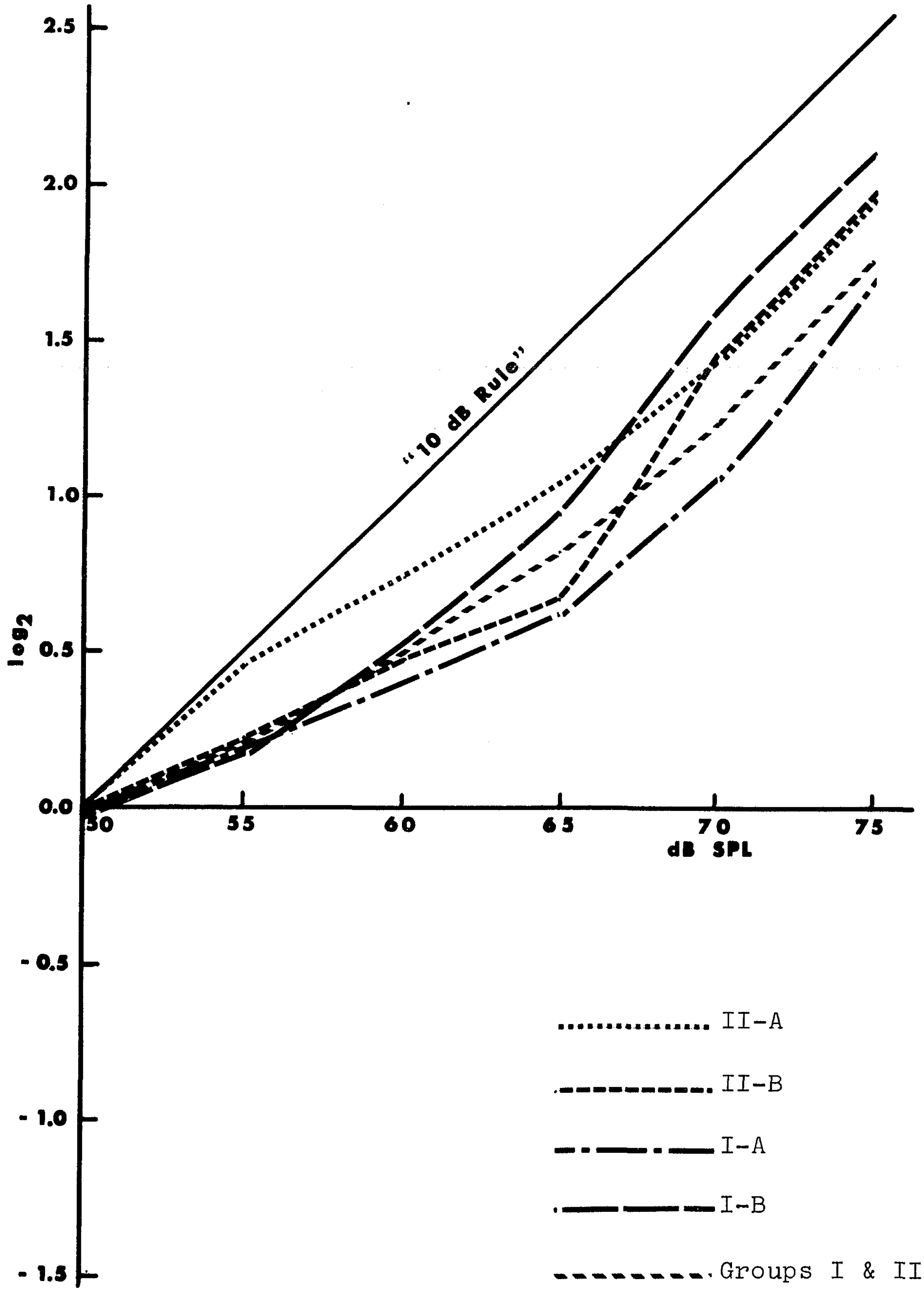

Fig. 44. -- Comparison of Least Squares Loudness Estimations for 1 KHz NBN

1 KHz NBN from several sources in this study. Aside from the two plots in Group IV, it demonstrates the two sets of values obtained in Group III and the grand mean of Groups I and II. The data from all of these taken at the same time appears to be related to a crude approximation only. Aside from the end point showing very close agreement, there seems to be wide disagreement between plots.

The last pair to be compared is from Matrix II-C, the 250 Hz NBN and the 4 KHz NBN whose data are shown in Figure 45. As in Matrix I-B, of the previous group, several approaches could be applied to the analysis of this data. It was decided to assign the value to $\overline{\text{4 KHz}}$ which was established in II-B, with all other calculations continuing from there. The relationship of the 4 KHz NBN to the 250 Hz NBN is not substantially unlike that obtained between the 1 KHz NBN and the 250 Hz NBN in II-A. There is wide divergence in the lower intensities (1.5 $\log_2$ units at 50 dB SPL) narrowing at the upper limits (0.5 $\log_2$ units at 70 and 75 dB SPL). The 250 Hz NBN is again seen to generally parallel the growth of loudness of the "10 dB Rule", as it did in II-A.

Figures 46 and 47 compare the growth of loudness for the 250 Hz NBN and the 4 KHz NBN obtained in this group with that obtained in earlier parts of this study. Figure 46 illustrates these configurations for 250 Hz NBN data. Very close approximation is observed between all configurations shown including the "10 dB Rule".

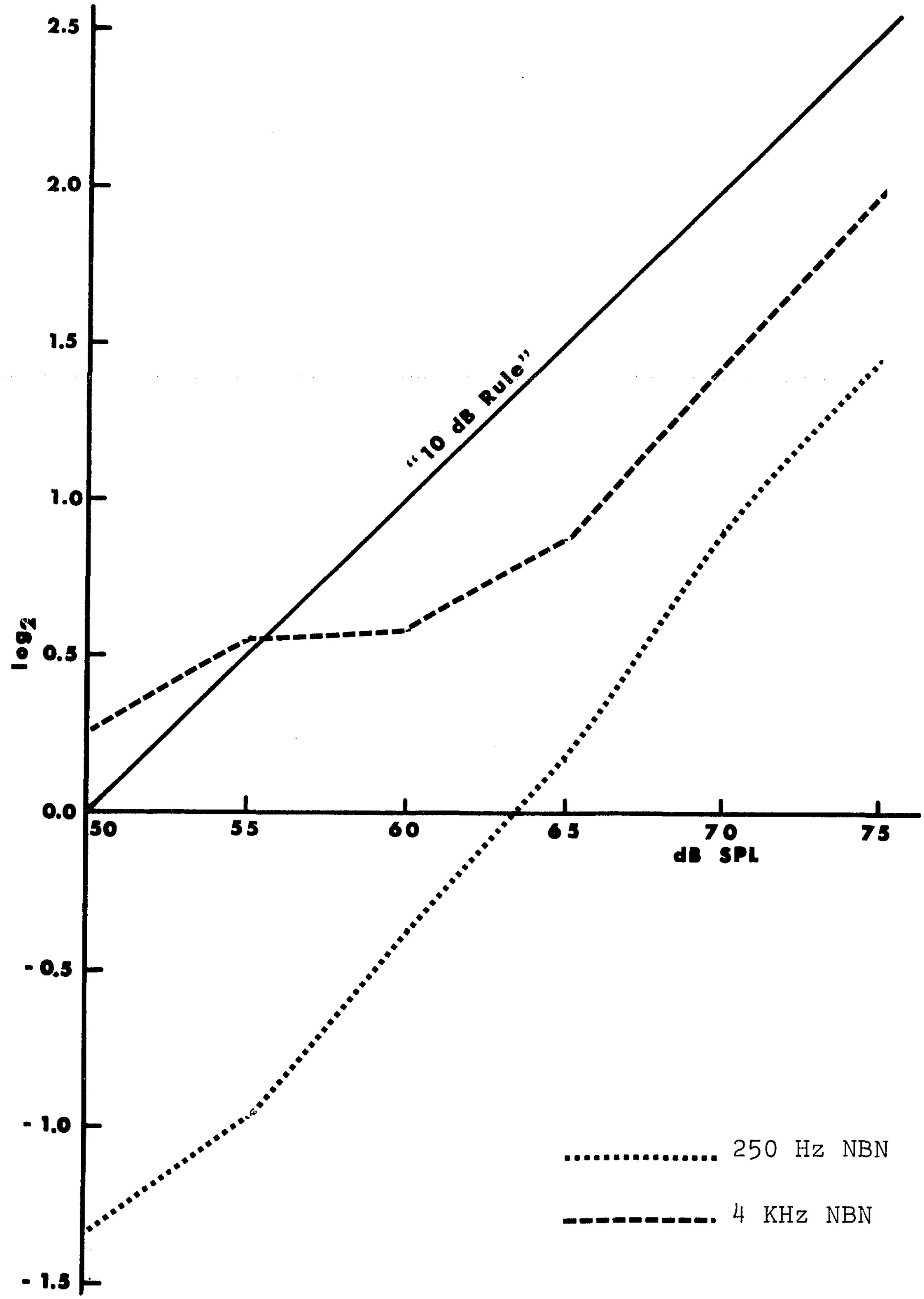

Fig. 45. -- Least Squares Loudness Estimations of 250 Hz NBN vs. 4 KHz NBN combinations in Matrix II-C

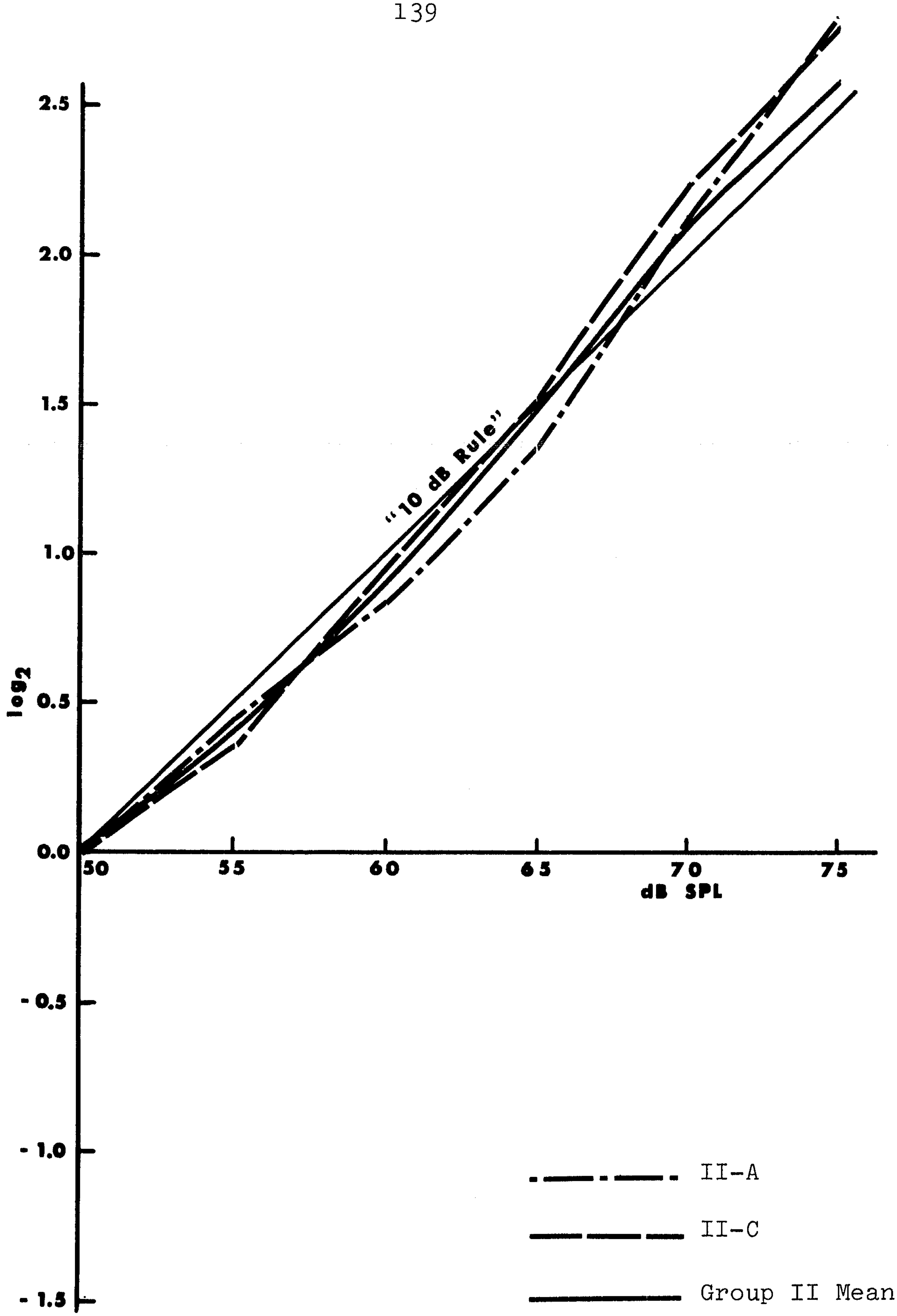

Fig. 46. -- Comparison of Least Squares Loudness Estimations for 250 Hz NBN obtained in Group IV

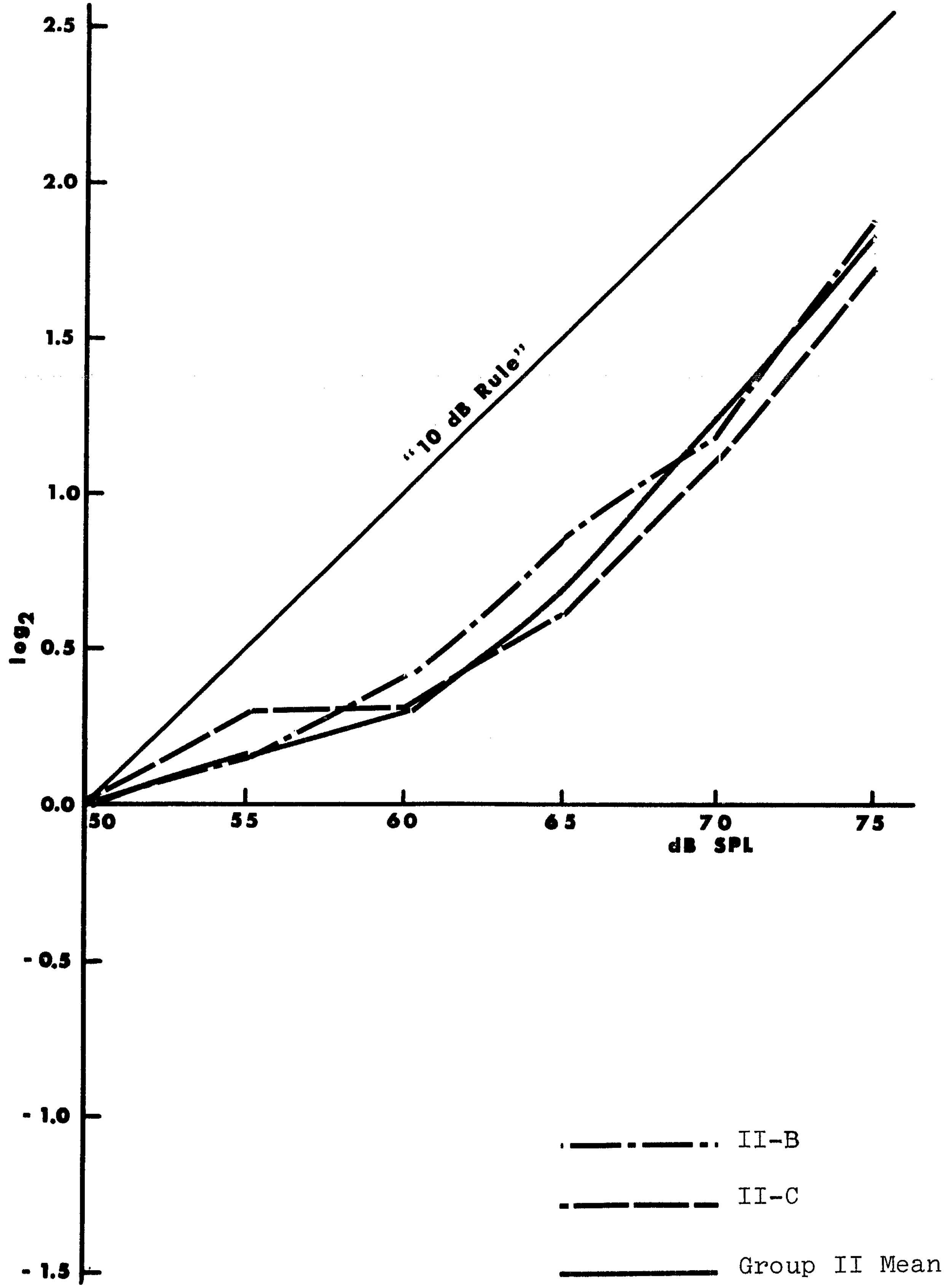

Fig. 47. -- Comparison of Least Squares Loudness Estimations for 4 KHz NBN obtained in Group IV

Finally, Figure 47 demonstrates the growth of loudness from several submatrices for the 4 KHz NBN. Data from II-C shows a close similarity to the 4 KHz NBN/4 KHz NBN data of Group II, as does the data of II-B at levels above 60 dB SPL. Each of the structures of the 4 KHz NBNs seems to have different ranges which grow parallel to the "10 dB Rule". The 75 dB values tend to approximate equality.

GOODNESS OF FIT

A Chi Square test built into the Least Squares Loudness Estimation computer program (Levitt and Richards, 1972) was utilized to measure the goodness of fit which is provided for the data. This measurement is obtained by dividing the square of the residual (observed-fitted) by the mean of the variances of the judgments in each cell. The submatrices can be broken into two groups, one containing symmetrical submatrices (Groups I and II), and the other, asymmetrical submatrices (Groups III and IV). Table 38 displays the results of the Chi Square Tests for each submatrix, the evaluation of which will be covered in Chapter IV.

SUBMATRIX	STIMULI	SYMMETRIC	ASYMMETRIC
I-A-1	Tone/Tone	28.4	
I-A-2	Tone/NBN		66.8
I-A-3	NBN/Tone		49.3
I-A-4	NBN/NBN	50.2	
I-B-1	NBN/NBN	55.0	
I-B-2	NBN/OBN		133.7
I-B-3	OBN/NBN		115.9
I-B-4	OBN/OBN	53.8	
I-C-1	Tone/Tone	43.1	
I-C-2	Tone/OBN		109.3
I-C-3	OBN/Tone		64.7
I-C-4	OBN/OBN	22.2	
II-A-1	250/250	86.9	
II-A-2	250/1000		282.3
II-A-3	1000/250		256.4
II-A-4	1000/1000	45.7	
II-B-1	1000/1000	55.1	
II-B-2	1000/4000		82.7
II-B-3	4000/1000		111.3
II-B-4	4000/4000	52.3	
II-C-1	250/250	80.9	
II-C-2	250/4000		203.8
II-C-3	4000/250		274.4
II-C-4	4000/4000	37.4	

TABLE 38. -- Chi Square values for Least Square Loudness Estimations - Submatrices I-A-1 / II-C-4

CHAPTER IV

DISCUSSION

The primary purpose of this present investigation is to ascertain what effects changes in bandwidth and center frequency have upon the growth of loudness, utilizing the basic procedure developed by Levitt and Richards (1972). Of special interest is the relationship between the observed patterns of loudness growth in the present data and other reported configurations, especially those of Stevens (1955, 1961) and Richards (1971).

THEORETICAL EXPECTATIONS

The first factor to be considered is the configurations of loudness ratio judgments, which might be expected on the basis of published data. The power law with an exponent of 0.6 (i.e., the 10 dB Rule) described by Stevens (1955, 1956b, 1961) is possibly the most important in view of its incorporation into a widely used loudness standard (USAS, 1968). Based primarily on Stevens' 1955 paper, the 10 dB Rule, which originally was applied only to the 1 KHz tone, would lead us to expect a doubling in loudness ratio judgments for each 10 dB difference between stimuli. Since the range of intensities in this present study is from 50 through 75 dB SPL, the maximum interstimulus difference would be expected to have a loudness ratio judgment of 5.66 or 2.5 in the form $\log_2$. Scrutiny of Stevens' (1956b) Figures 18 and 21 [Stevens' Figure 21 is reproduced as Figure 48 in this paper.] indicates no reason to believe that the growth of loudness in both the narrow band (third-octave) and the octave band of noise (both frequency centered at 1 KHz) would be any different than that for the 1 KHz tone.

The growth of loudness of the 250 Hz NBN and the 4 KHz NBN and their relationship to the 1 KHz NBN (and to one another) is a somewhat more complex problem. Stevens (1956b, 1957) raises the question of the acceptability of the extrapolation of octave band configurations to permit analysis by third-octave bands. He mentions that, one, " . . . no direct experimental test has been made to validate such an extrapolation", and two, " . . . equal loudness contours have not been determined for third-octave bands." (1956b, p.826). Review of subsequent literature has failed to reveal reports of experimental data on direct calculation of loudness values for third-octave bands of noise.

According to his "Chart for determining the loudness in a third-octave band as a function of the SPL in the band" (Figure 48) the bands containing the 250 Hz NBN and the 1 KHz NBN are essentially equal to one another in loud-

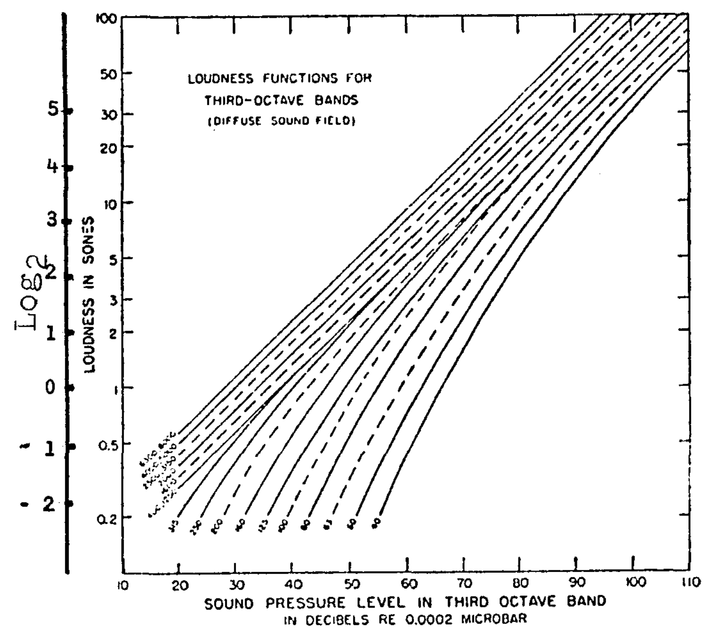

Fig. 48. -- Chart for determining the loudness in a third-octave band as a function of the SPL in the band [Stevens, 1956b]

ness at levels above 50 dB SPL, while the 4 KHz NBN, which shows the same rate of growth, is plotted as being approximately twice as loud as the other two at each intensity level (See Table 39). It is interesting to note that these relative values differ from the values shown for octave band noises with the same center frequencies. According to these nomograms [Stevens, 1956b, Figure 18--Nomograms relating SPL in octave bands to loudness in sones.], which are found in this paper as Figure 3, the octave band 150 - 300 Hz would have loudness values of 1.5 sones, 11.0 sones and 16.0 sones for intensities of 50, 75 and 80 dB SPL, respectively. This would indicate a growth of loudness in excess of a power function exponent of 0.60. The values for the octave band 600 - 1200 Hz were roughly 2.2, 12.0 and 17 sones again for 50, 75 and 80 dB SPL, a very close approximation to the 10 dB Rule. The 50 dB SPL 4 KHz octave band noise (2400 - 4800 Hz) had a value of 3.5 sones, with 20 sones at 75 dB and 28 sones at 80 dB SPL (See Figure 48). This also corresponds to a power function exponent of 0.60.

Abstracting from Stevens' results, we would then expect to find the three stimuli (tone, NBN and OBN) with 1 KHz center frequencies to have essentially the same rate of loudness growth, all conforming to the 10 dB Rule, but with a consistent small difference between the tone and the noise. Since the noise has a slightly higher sone value, it might be expected that the noises would have higher loudness ratio judgments when paired with 1 KHz tones of the

BAND LEVEL (dB SPL)	250 Hz		1 KHz		4 KHz	
	1/3†	1/1††	1/3†	1/1††	1/3†	1/1††
50	2.2	1.5	2.2	2.2	4.5	3.5
55	3.3	2.3	3.3	3.2	6.0	5.0
60	4.5	3.5	4.5	4.4	8.5	7.0
65	7.0	5.0	7.0	6.2	12.0	10.0
70	9.0	7.7	9.0	9.6	16.5	14.0
75	14.0	11.0	14.0	12.0	24.0	20.0
80	18.0	16.0	18.0	17.5	32.0	28.0

† See Figure 48

†† See Figure 3

TABLE 39. -- Loudness of bands of noise (in sones) approximated from Figures 48 & 3

same intensity. The anticipated relationships of the third-octave bands, when related to Figure 48 predict the 250 Hz NBN to be slightly less loud than the 1 KHz NBN at 50 dB SPL, and then equal to it at levels above 55 dB SPL. Similarly, the 1 KHz NBN is represented as being approximately one-half the loudness of the 4 KHz NBN through the range of interest (50 - 75 dB SPL). If Figure 3 of this present study were to be utilized (although developed for octave-band noises) similar relationships would be expected with the exception of the 250 Hz NBN growing in loudness at a rate in excess of the other two stimuli and the 10 dB Rule.

In comparing the present results with those of Stevens it must be remembered that his values for noise bands are based upon equal loudness contours using various tones and noise references, which were then extrapolated utilizing the 10 dB Rule for all other values. The exception to this procedure were the bands of 150 - 300 Hz and below, in which there is projected a more rapid loudness growth at low and moderate intensities. The growth of loudness for each stimuli in the present experiments was measured individually and is not extrapolated.

Richards' (1971) results are also directly relevant to this experiment. In his Matrix B, ratio loudness judgments were made for 1 KHz tones in a 7 x 7 matrix. The interstimulus spacing was 5 dB and the range was 40 through 70 dB SL, which is quite similar to the symmetrical 1 KHz tone submatrices in the present study. Richards reported that, of all his 1 KHz tone data, Matrix B gave results that were closest to those predicted by Stevens' 10 dB Rule.

McRobert _et al_ (1965) found that Stevens' "sone scale" was not an adequate description of the growth of loudness of the 1 KHz tone. In an experiment designed to minimize bias and context effects, they found that a formula for relative loudness of two stimuli in a pair,

$$\log_{10} S = 0.21 + 0.021\ P$$

where S is the mean loudness estimate

P is the difference (in dB) in intensity levels between two stimuli

was more consistent with his data. The function of this equation is compared with Stevens' 10 dB Rule in Figure 49.

GOODNESS OF FIT

The comparison of experimental results and the discussion of the growth of loudness of various stimuli as demonstrated by the Least Squares Loudness Estimation technique cannot be undertaken without first mentioning the results of the test for the goodness of fit (Chi Square) performed on each submatrix. As noted at the end of the previous chapter (Table 38), the submatrices can be assigned to two categories--symmetrical and asymmetrical. The symmetrical category contains those submatrices in Groups I and II in which stimuli are judged against similar stimuli, differing

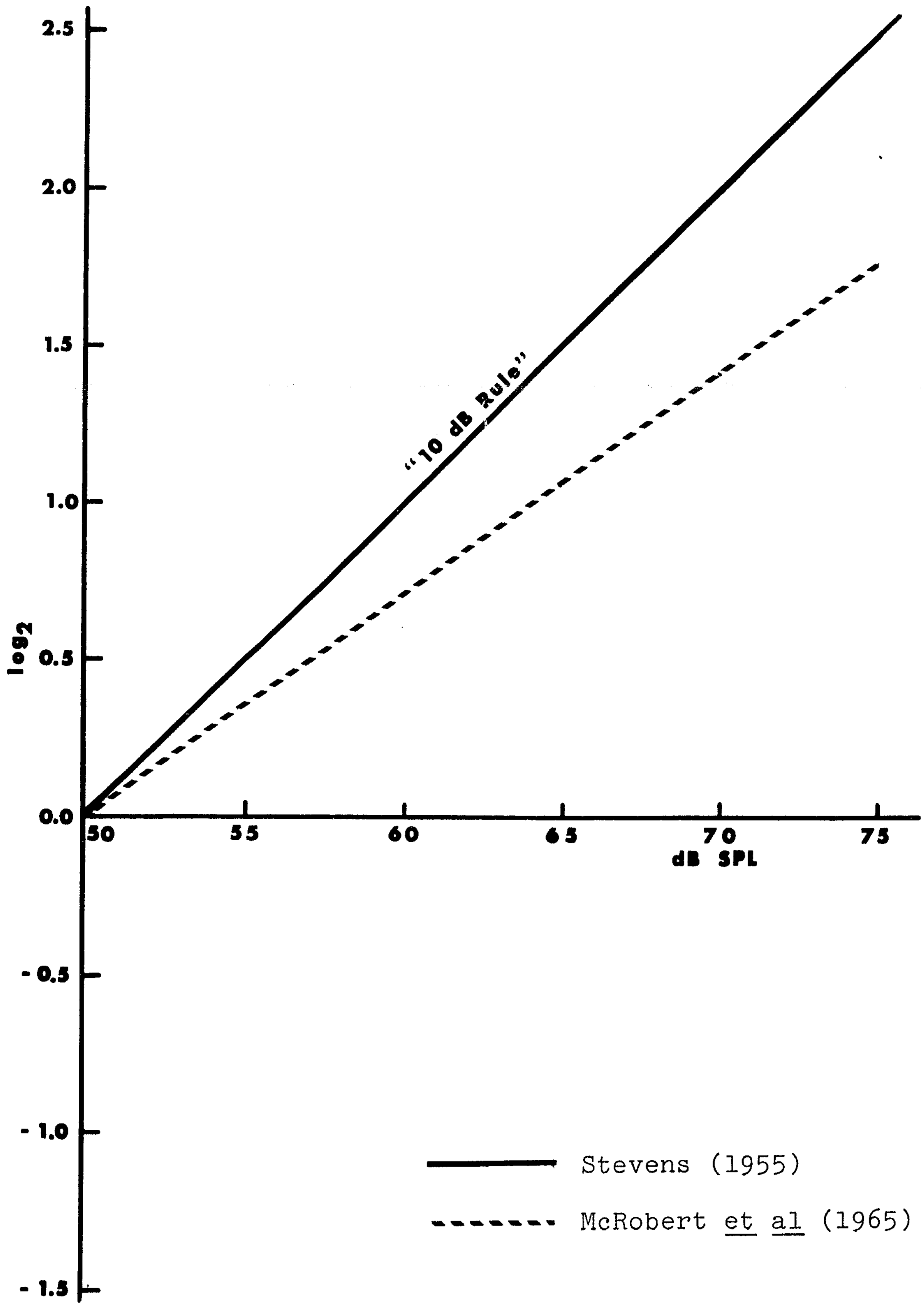

Fig. 49. -- Comparison of loudness functions described by Stevens (1955) and McRobert _et al_ (1965)

only in intensity. while the asymmetrical category included Groups III and IV in which stimuli were judged against stimuli that had different bandwidths or center frequencies.

With the possible exception of the 250 Hz NBN data, the values of the Chi Squares for the symmetrical submatrices are substantially lower (on average, by a factor of four) than those for the asymmetrical submatrices. Although the symmetrical submatrices have Chi Square values in excess of 35 (the 0.01 significance level for 18 df) these values are quite similar to those obtained by Levitt before biasing effects were taken into account. Taking response biasing effects into account in this study would similarly lower the Chi Square values to an acceptable level. In contrast, the deviation from the simple model with the asymmetrical matrices was so great (i.e., the Chi Square values were in excess of four times the cut-off level) that a simple modification of this type, which would yield acceptable fit was not obtained. Response bias functions were not of direct interest and therefore, not derived in this study. The least squares loudness estimates are independent of the response bias function and the loudness functions obtained would be the same when response bias functions are considered.

As pointed out in an earlier chapter, these experiments had been designed in such a manner as to permit progressive comparisons of the results. Figure 50 illustrates how the 1 KHz tone data from Experiment I is directly compared with data from Richards' Matrix B. Within Experiment

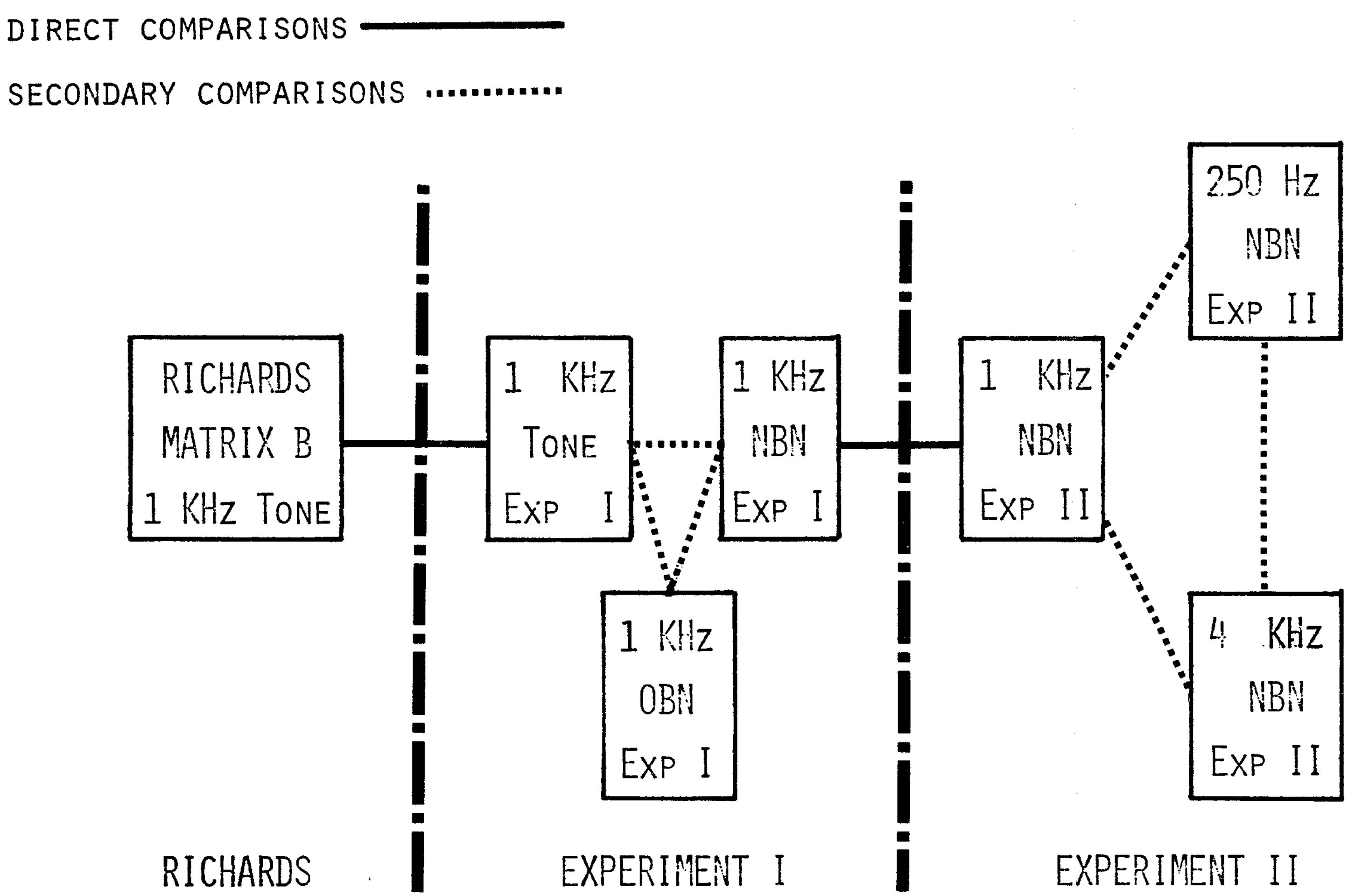

Fig. 50. -- Block diagram of experimental design

I, the effects of bandwidth can be explored by evaluation of the results on the tone, NBN, and OBN data. This is followed by direct comparison of the 1 KHz NBN data from Experiment I and Experiment II, and then consideration of center frequency effects in Experiment II by evaluation of the 250 Hz, 1 KHz and 4 KHz NBN data. Not shown in Figure 50 are Groups III and IV which evaluate the growth of loudness in asymmetric matrices.

COMPARISON WITH RICHARDS' MATRIX B

Discussing the results of his experiments, Richards (1971) noted that the loudness function derived from Matrix B were most like those that would be predicted by Stevens (1955) 10 dB Rule. Richards reported that, "the overall range of the stimulus range is quite influential in determining how loudness-ratios grow, and that the more constricted the range, the more rapid the loudness growth ratio." He concluded, "In general, it appears that when the stimulus range reaches approximately 30 dB, the results obtained using the present technique compare quite closely with those implied by the conventional unidimensional scale implied by the 10 dB Rule."

Several minor adjustments are necessary in order to compare the present 1 KHz tone data with Richards' Matrix B. It has been shown in Chapter 3 that dB SPL levels for the tones in the Richards study have approximately the same dB SPL levels in this study. The deletion of the 70 dB SPL judgment from Richards' matrix gives us a comparable 6 x 6 matrix.

Figure 51 illustrates the relationship between Richards' matrix B and the 1 KHz tone in the present study (Submatrices I-A-1 and I-C-1). In addition, the growth of loudness functions implied by Stevens' sones (1955) and McRobert et al (1965) are shown. It can easily be seen that Richards' data is in closer proximity to the function described by McRobert et al than that of Stevens, although at levels above 60 dB SPL (50 dB SL) Richards' loudness data grows essentially at the same rate as Stevens'.

The growth of loudness in both 1 KHz tone symmetrical submatrices in this experiment (I-A-1 and I-C-1) are seen to grow at a rate substantially slower than that predicted by Stevens 10 dB Rule. At levels from 60 to 70 db SPL there appears to be growth essentially parallel to that predicted by McRobert et al, followed by a more rapid growth to 75 dB. In summary, the tone data in this experiment is seen to grow at substantially slower rates than those predicted by the earlier reports of McRobert et al (1965), Richards (1971) and Stevens (1955). There was one area of loudness growth (between 60 and 70 dB SPL) where the growth of loudness as predicted by the McRobert et al formulation was observed. Only in the segments from 70 to 75 dB SPL are values in line with the 10 dB Rule observed.

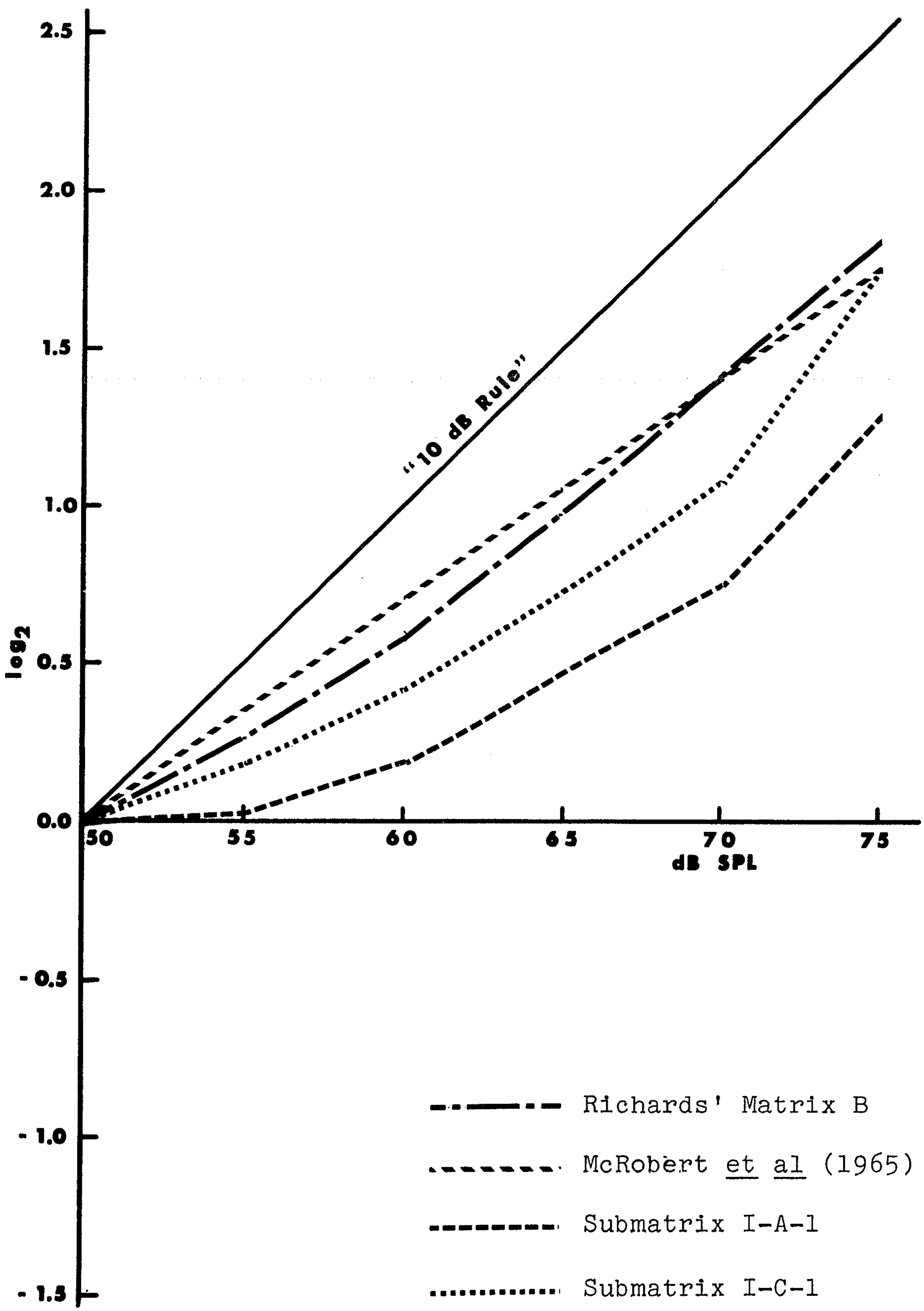

Fig. 51. -- Comparison of 1 KHz Tone data with Richards' Matrix B and function described by McRobert *et al*

COMPARISON OF SYMMETRICAL SUBMATRIX DATA WITHIN EXPERIMENT I

The Results Chapter described in detail the relationships between data sets on the basis of their loudness growth configurations as provided by the Least Squares Loudness Estimation model. The sets of data for the 1 KHz tone were seen to vary both within submatrices and between submatrices. By "within submatrices", it is meant the difference in estimated loudness functions between the first and second items in the pair. The estimated loudness for the second item in the pair was generally greater than for the first. The difference between the loudness functions, resulting from order, for the 1 KHz tone is shown in Figures 13 and 14. This difference is much smaller than the difference in estimated loudness functions between submatrices. The differences in loudness functions between experimenters are greater than these differences between submatrices, but not by a wide margin. The loudness function for the 1 KHz octave band noise data was observed to show greater consistency within and between submatrices than for the tone. As in the case of the tone data, the mean octave band noise data would appear to be in closer proximity to the McRobert _et al_ predictions for most of its range, while paralleling the growth of loudness as in Stevens' formulation at levels of 65 dB SPL and above.

Similarly, the loudness functions for the 1 KHz NBN again show the intra and inter-submatrix variability seen for tones. In both 1 KHz NBN submatrices a point of equal loudness judgment is seen between stimuli judged first in a pair and those judged second (Figures 19 and 20). The mean loudness function (averaged over the order effect) for the 1 KHz NBN data is coincidental with that of the 1 KHz OBN noise (Figure 22). Figure 52 compares the means of the Least Squares Loudness Estimations from Group I with the 10 dB Rule and the McRobert et al formulation. There is a clear distinction between the growth of loudness of the tones and the two noises; the tone growing in loudness at a much slower rate, and the noises growing at the same rate as each other but at a rate still slower than would be predicted by the 10 dB Rule. The McRobert et al prediction seems to fit the data more closely. As in the tone data, the only segment of the range which is observed to grow at a rate predicted by the 10 dB Rule is that segment from 70 - 75 dB SPL.

COMPARISONS OF 1 KHZ NBN DATA--
EXPERIMENTS I & II

The mean values of the 1 KHz NBN from the Least Squares Loudness Estimations in Experiments I and II were compared in Figure 26 showing they are very similar. Obviously the growth of loudness in both of these submatrices and their relationship to data of other experimenters is the same as that described for the 1 KHz NBN data in the previous section.

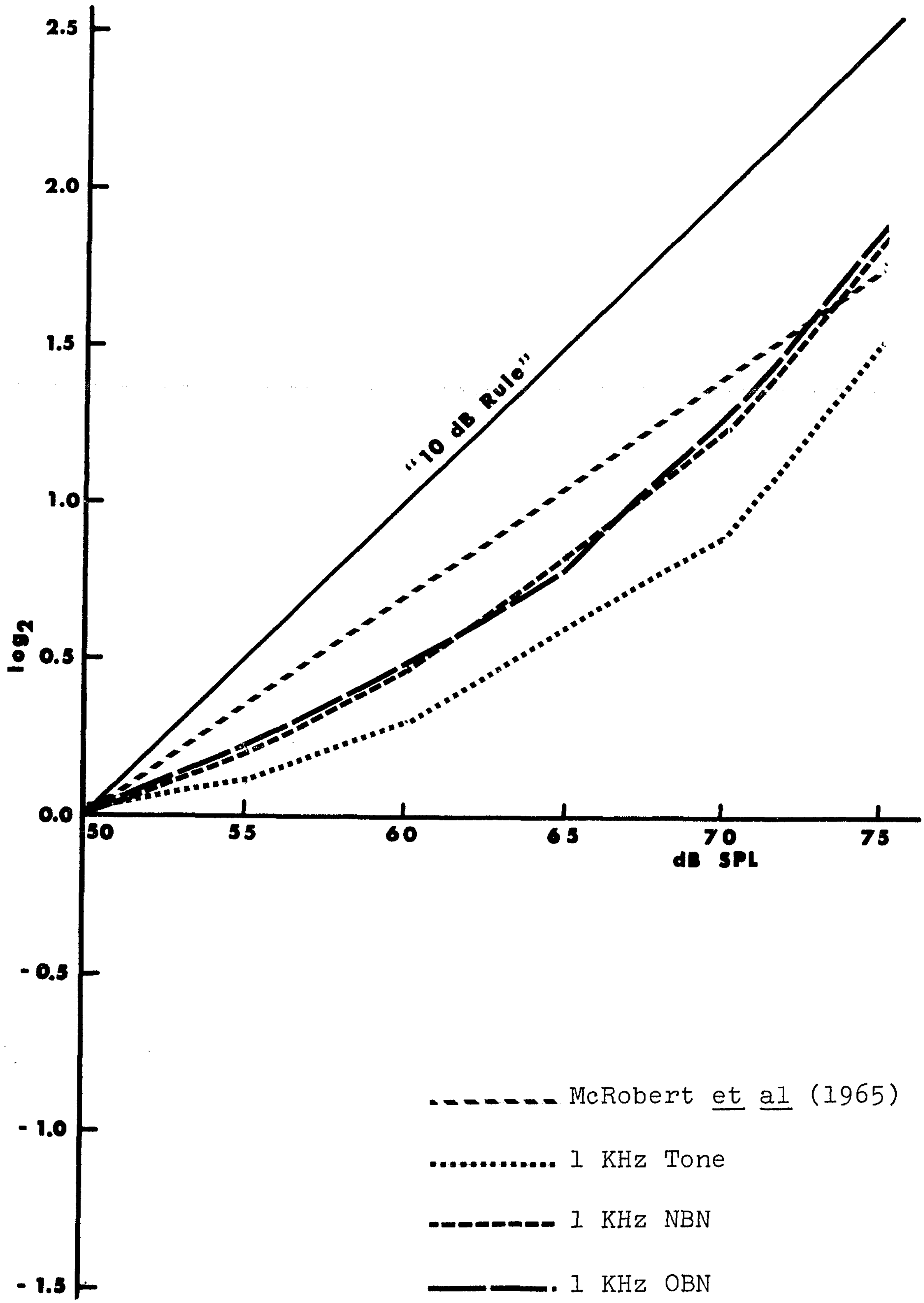

Fig. 52. -- Comparison of symmetrical submatrices in Group I with loudness function described by McRobert et al

COMPARISON OF SYMMETRICAL SUBMATRIX DATA WITHIN EXPERIMENT II

The Least Squares Loudness Estimations for the 250 Hz NBN shown in Figures 27 - 29 comprise the only set of data in these experiments which closely approximate the values predicted by Stevens' 10 dB Rule. The grand mean for all 250 Hz NBN data in this experiment is seen to coincide completely with the sone line(Figure 29). There would appear to be a good case for agreement with Stevens' construct if it were not for the very poor Chi Square ratios demonstrated by these two submatrices, 86.9 and 80.9. Values of such magnitude must be considered to be representative of poor fit and divide these submatrices from the other symmetrical submatrices.

Both 4 KHz submatrices display relatively close agreement of data for the differing judgmental order, but demonstrate different mean judgments (Figures 30 - 32). The grand mean of the data is seen to show essentially the same configuration as the 1 KHz NBN (Figure 53). After a relatively slow growth of loudness from 50 to 60 dB SPL, the 4 KHz NBN is seen to parallel the 10 dB Rule to 70 DB SPL and then show an ever sharper rise in loudness growth. As expected, because of its similarity to the 1 KHz data, the 4 KHz NBN is shown to be in closer proximity to the function described by McRobert _et al_ than Stevens.

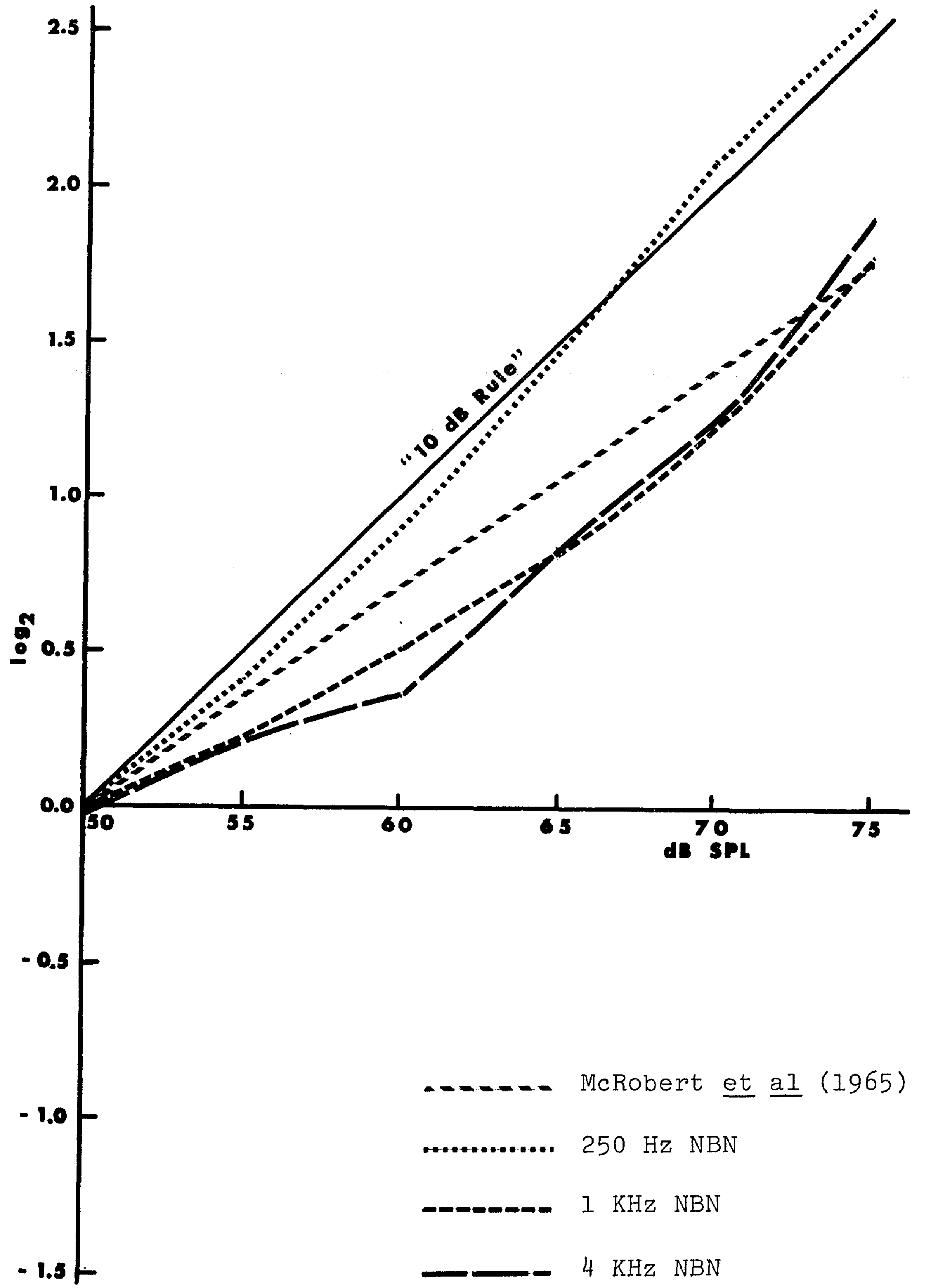

Fig. 53. -- Comparison of symmetrical submatrices in Group II with loudness function described by McRobert *et al*

COMPARISON OF ASYMMETRIC MATRICES
IN EXPERIMENTS I & II

The first factor to be considered in the discussion of the "mixed matrices" concerns the poor goodness of fit (see Table 38). Perusal of asymmetrical submatrices (Figures 34 - 57) discloses the extent of the biasing of loudness ratio judgments which is substantially greater than for the symmetrical matrices. The inability to find a simple pattern for these biases and provide a monotonic fit appears to be a serious factor not taken into consideration in the Least Squares Loudness Estimation model. Although the configurations derived do not, from a statistical point of view, provide an adequate description of the data, it is surprising to see the large amount of consistency which is demonstrated in these configurations. Any observations made on such data must be interpreted with this lack of goodness of fit in mind.

When compared to the mean configuration from Experiment I, the tone data which has been judged against NBN and OBN stimuli appear to show a more rapid rate of loudness growth than the symmetrical submatrix data. The general form of the two tone data configurations are quite identical and only a short distance apart (Figure 37). Although not shown, they show a rate of growth just below that predicted by McRobert et al.

The 1 KHz NBN data in Group III is more divergent, with its configuration showing much more rapid loudness growth when judged against an octave band noise than when judged against a noise (Figure 40). The grand mean value of the 1 KHz NBN, derived from Experiment I and II is observed to pass between these other two configurations. Similar patterns are observed for the 1 KHz OBN mixed submatrices, where in combination with another noise there is a relatively rapid growth in loudness, and a substantially slower rate of growth when paired with a tonal stimuli (Figure 41). When taken together, the stimuli (NBN or OBN) vs. tone and vs. other noise, demonstrate the same relative patterns. This would appear to be consistent with predictions of higher loudness judgments for bands of noise (Stevens, 1956b; Robinson and Whittle, 1964) and relative "underestimation" or loudness of tones when compared directly to noise (Stevens, 1956b), see Table 39.

The form of the loudness growth configuration of the 250 Hz NBN is almost an exact duplication of its mean configuration in Group II. As expected, at equivalent SPL levels, the 250 Hz NBN is judged significantly less loud than either the 1 KHz NBN or the 4 KHz NBN. This is consistent with equal loudness contours for both tones and bands of noise (Stevens, 1956b; Robinson and Whittle, 1964). A similar relationship is seen in the 1 KHz NBN judged against the 4 KHz NBN, where at equal SPL levels the 4 KHz NBN is judged louder.

The growth of loudness of the 1 KHz NBN when compared to the 250 Hz NBN and the 4 KHz NBN tends to be highly variable. When compared to the 250 Hz NBN, it rises sharply at a rate almost equal to the 0.54 power function exponent, moderates to 65 dB and then rises more rapidly again (Figure 42). When judged against a 4 KHz NBN, after no change in loudness at 55 dB, it rises at a moderate rate to 65 dB and then continues at a rate greater than that predicted by the sone scale to 70 dB where it moderates again.

The configurations of the 4 KHz NBN data, when compared to the 250 Hz NBN and the 1 KHz NBN are essentially the same, and are not unlike the symmetrical data from Group II.

SUMMARY AND CONCLUSIONS

The purpose of this present investigation has been to ascertain the effects of changes in bandwidth and center frequency upon the growth of loudness, using the basic procedure developed by Levitt and Richards (1972) in the Least Squares Loudness Estimation model. For purposes of simplicity, response bias effects were omitted, these being relatively small compared to the magnitude of the ratio loudness judgments, and do not effect the estimation of the loudness function. Comparisons have been made throughout this presentation relating the present data to the Stevens' (1955, 1956b, 1957, 1961) sone scale and 10 dB Rule because of its inclusion in a widely accepted loudness computation standard (USAS, 1968). Comparison was also made with the results of Richards' (1971) work and a relative loudness growth formula suggested by McRobert *et al* (1965).

The Chi Square analysis utilized in the Least Squares Loudness Estimation procedure indicated that, while the loudness growth configurations dervied from the method provided only a borderline goodness of fit of the symmetrical data, Levitt and Richards (1972a) obtained similar Chi Square values for their data before response biasing effects were taken into account. In contrast, the test for goodness of fit in the asymmetrical submatrices were very poor and could not be improved substantially by a simple monotonic transform for response bias. All conclusions drawn from these asymmetric submatrices must be exceedingly guarded. It appears that the Least Squares Loudness Estimation model, as it is now constituted, fails to provide an adequate description for the data in the asymmetrical submatrices. In addition, the data in the asymmetrical submatrices showed substantial biases and presents serious problems for any method of analysis.

In general, the data generated by this experiment did not yield configurations similar to those espected by predictions based upon a power law with exponent n = 0.6. There is agreement with Richards' (1971) finding that there are areas of the range covered which appear to grow in loudness at a rate predicted by a 0.54 power exponent. Typically, the present experiments produced configurations which initially grew very slowly in loudness, increasing in the moderate intensity range (sometimes paralleling the growth predicted by the sone scale) and finally exceeding this slope between 70 and 75 dB SPL.

With the exception of the areas of the configurations which appear to grow in loudness as predicted by Stevens, the present experiment does not reaffirm the adequacy of the 10 dB Rule in describing the growth of loudness in any of the submatrices with the exception of those containing the 250 Hz NBN. In most submatrices it appears that the McRobert et al predictions would provide a more adequate representation of the data.

In theory and practice the use of loudness ratio judgments and the Least Squares Loudness Estimations techniques appears to provide an economical, simple model for the evaluation of the growth of loudness in experiments utilizing simple discrete matrix designs. The problems facing the Least Squares Loudness Estimation model reflect inherent asymmetries in the data and are now problems to be faced by any loudness model.

DIRECTIONS FOR FURTHER RESEARCH

The high Chi Square values for the asymmetric submatrices were rather disappoingtin, in that they prevent the experimenter from making positive statements about the relationships between different stimulus types judged against each other. These findings tend to point to the need for a reanalysis of the underlying theory of the Least Squares Loudness Estimation model, as it pertains to the large biasing effects of ordering in asymmetric matrices.

Although compound matrices are very economical in data collection, the asymmetric matrices need to be investigated directly in simpler, discrete units. In addition, parameters of matrix size and inter-stimulus spacing must also be evaluated.

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AUTOBIOGRAPHICAL STATEMENT

I earned my B.A. in Speech Pathologoy and M.A. in Audiology at Temple University in 1965 and 1967, respectively, studying Audiology and Physiological Acoustics with Professors Alfred Finck and Philip E. Rosenberg. During my stay at Temple, I was awarded a Graduate Clinical Traineeship in Audiology at the Veterans Administration Out Patient Clinic where I worked under the supervision of Dr. Mort Altshuler.

At the Graduate Division I have had the opportunity to study Clinical Audiology under Professors Moe Bergman, Maurice Miller and Hayes Newby, and Hearing Science with Professors J. Donald Harris, Harry Levitt and Jergen Tonndorf. While at the Graduate Center I have been on advisory groups to the President (formerly the Provost), the Chancellor, and a member of the Steering Committee of the Doctoral Students Council. My early studies at the Graduate Division were under grants to work on the Parkchester Project [Hearing and Aging] with Professor Bergman, and to assemble the Communication Sciences Laboratory in its new quarters.

My particular areas of academic interest are Clinical and Research Audiology and Psychoacoustics. More specifically, I am interested in each of these areas as they pertain to the effects of noise on man, and the conservation of hearing in noise.

I have been the Chief of Service of the Department of Audiology/Speech Pathology at the Sunset Park Family Health Center/Lutheran Medical Center for the past three years. In 1971 I formed Noise & Hearing Consultants of America, Incorporated with Dr. Alan Richards, another C.U.N.Y. graduate, as a commercial venture to provide the expert advice needed on the conservation of hearing in noise in industry. In February, 1972, I was appointed Assistant Professor and Director of the Hearing and Speech Science Laboratory at Hofstra University and Adjunct Assistant Professor at the Hunter College Institute of Health Sciences of C.U.N.Y.. Recently, I have been named a Special Consultant to the Medical Division of the New York City Fire Department to direct a special project on noise.

At present I am the Chairman of the Audiology Study Group of New York (1972-1973) and the Acting Chairman of the Ad Hoc Committee on Industrial Audiology. To date, I have delivered several papers on the subject of noise legislation to the New York State Speech and Hearing Associaton.

I presently hold memberships in the International Audiologic Society, American Speech & Hearing Association (Certified in Audiology), New York State Speech & Hearing Association, National Association of Hearing and Speech Agencies, Acoustical Society of America, Scientists Committee for Public Information, Directors of Hospital Based Programs in Speech Pathology and Audiology and Affiliates, and the Long Island Speech and Hearing Association.