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NASA Contractor Report 3892

Contribution of Tonal Components to the Overall Loudness, Annoyance, and Noisiness of Noise

Relation Between Single Tones and Noise Spectral Shape

Rhona P. Hellman

GRANT NSG-1644
MAY 1985

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Prepared for
Langley Research Center
under Grant NSG-1644

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1985

Acknowledgements

A number of people deserve special thanks for their help with this project. They include Allan Schill, Bertram Scharf, and Oliver Welsh who helped to provide the laboratory at Boston University with equipment needed to carry out the experiments. William Hellman provided the technical expertise necessary to design and build the appropriate low- and high-pass filters. I also wish to express my thanks to Noelle Aylward, Barbara Ashkinaze, Linnea Carlson-Morrow, and Gina Maranga who worked diligently as research assistants on this project. Special thanks are also due to the many students at Boston University who faithfully and enthusiastically participated as listeners. Finally, I wish to thank Susan Cannata for her beautiful technical typing of this report.

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Introduction

Numerous experiments have demonstrated that human listeners are able to assess both the separate and combined loudnesses of complex auditory stimuli (see Scharf, 1978). Two questions pertinent to overall judgments of noise-tone complexes need to be answered. First, do tonal components contribute more to overall loudness of noise than predicted by an assumption of energy summation between noise and tone? Second, do tonal components contribute more to overall annoyance and noisiness as distinct from loudness?

The published literature suggests that tonal components increase the perceived annoyance and noisiness more than the loudness of broadband noise. However, the magnitude of the effect varies widely from study to study (e.g., Copeland, Davidson, Hargest, and Robinson, 1960; Hargest and Pinker, 1967; Kryter and Pearsons, 1965; Little, 1961; Little and Mabry, 1969; Ollerhead, 1971, 1973; Pearsons and Bennett, 1971; Pearsons, Bishop and Horonjeff, 1969; Wells, 1967). Estimates of the contribution of pure tones to overall perceived loudness versus annoyance and noisiness range from none (Goulet and Northwood, 1973), to nearly 15 dB (Kryter and Pearsons, 1965).

Based on an analysis of more than 500 spectra with and without added tones, Scharf and Hellman (1979, 1980) suggest that several factors may contribute to the lack of clear-cut results found in the literature. First, some studies (e.g., Goulet and Northwood, 1973; Niese, 1965) examined stimuli with tones below 80 dB SPL where tonal components may be subjectively less important than at SPLs greater than 80 dB. Second, even those studies such as Ollerhead's (1971, 1973) which required evaluative judgments of sounds close to 90 dB SPL and above stressed noisiness as opposed to annoyance. Third, many studies (e.g., Pearsons et al, 1969; Pearsons and Wells, 1970) used ambiguous adjectives when giving instructions other than loudness so that the distinctions to the listener among the judged attributes may have been blurred.

Rule (1964), and Berglund, Berglund, and Lindvall (1975, 1976) suggest that loudness, annoyance, and noisiness are separate, distinct, attributes of sound. Berglund, et al. (1975, 1976) go one step further by suggesting precise definitions of these attributes to be used as descriptors by the experimenter. When this is done, these authors indicate that, at high overall SPLs, annoyance remains considerably greater than both noisiness and loudness. Yet, no measurements seem to be available of "absolute" magnitude of annoyance (as distinct from noisiness) caused by sounds with added tones.

This investigation was undertaken in order to enlarge the available data base, with emphasis on tonal components equal to or greater than 80 dB SPL. The contribution of pure tones to the "absolute" magnitude of judged loudness, annoyance, and noisiness of noise was measured and assessed under controlled laboratory conditions. Loudness, annoyance, and noisiness were distinguished according to the pragmatic definitions suggested by Berglund et al. (1975, 1976). These authors relate annoyance to an individual's reaction to noise within the context of a given situation, noisiness to the quality of the sound, and loudness directly to sound intensity. The results described in this report are subdivided into three sections. Section I focuses on overall judgments determined by tones centered within the noise spectrum. Section II focuses on overall judgments determined by tones located within the high- and low-frequency skirts of the noise spectra. The relation of the obtained findings to proposed tone-correction procedures is addressed in Section III.

The following parameters were examined and evaluated: (1) the overall SPL of the noise-tone complex, (2) tone SPL, (3) noise SPL, (4) tone-to-noise ratio, (5) the frequency of the added tone, (6) noise spectral shape, and (7) subjective attribute judged. Each of these parameters, as well as the relationship among the three judged attributes is considered in the body of the report. Appendices A, B, and C include more detailed analyses. In addition, an attempt was made to quantify the observed effects and to compare them to the results of other investigators.

I. Effect of Tones Centered in Noise on Perceived Magnitude

1. Description of Experiments

A. Stimuli, Apparatus, and Subjects

Single tones were added to three different broadband spectra: flat, low-pass, and high-pass. Tones at 250, 1000, 2000, and 3000 Hz were produced by a Hewlett-Packard (200 CD) audio oscillator. The output of the oscillator was precisely calibrated with a Hewlett-Packard electronic counter (5314A). A General Radio random noise generator (1382) produced the noise signal. To obtain the broadband-flat noise, the output of the noise generator was passed through a continuously variable Krohn-Hite filter (3550) with frequency limits at 100 and 7000 Hz. The low-pass and high-pass filters were designed and built specifically for this investigation by W. Hellman. The low-pass filter attenuated the noise by 3 dB at 600 Hz, and the cutoff frequency of the high-pass filter was at 1060 Hz. Both the cutoff frequency and the steepness of the skirts were adjusted to closely approximate spectra that characterize a wide variety of aircraft and machine noises. Beyond the half-power points, the low- and high-pass filters attenuated the noise by 5 dB/octave; whereas the Krohn-Hite filter attenuated the noise by 20 dB/octave. The noise was then amplified by a General Radio (1206B) unit amplifier. A detailed third-octave-band spectral analysis of the noises was obtained with a 1/3-octave-band filter (Brüel and Kjaer 1612)[1]. (The 1/3-octave-band pressure levels for each of the noise spectra are indicated in Appendix A.)

The outputs of the externally generated signal sources were fed into a dual channel audiometer (Grason-Stadler 162) that was capable of mixing two different inputs. The audiometer was modified to allow separate attenuation control in 1-dB steps of the noise and tone. Each noise, tone, or noise-tone complex was presented for about 1 s, and the interstimulus interval was about 1 s. The presentation of stimuli was manually pulsed by the experimenter. When overall judgments of noise-tone complexes were required, the noise was turned on and off together with the tone.

For the measurements of overall perceived magnitude (loudness, annoyance, and noisiness) the noise and tone stimuli extended over a range of about 70-100 dB SPL. Within these ranges, tone-to-noise ratios varied in 5-dB steps from +5 to +35 dB. Root-mean-square voltages were monitored and measured daily with a Brüel and Kjaer (2409) voltmeter. The stimuli used to generate the complete set of single tone results are shown in Table I. The values of SPLs for both noise and tone that were used to produce the specified tone-to-noise ratios at each of the six tone-noise spectral combinations studied in this section are shown in Tables 1 to 5 and Table 10 in Appendix A.

Listening was binaural through a calibrated pair of TDH-49 earphones mounted in MX-41/AR cushions. The earphones produced an essentially flat response (± 1.5 dB) between 100 and 5000 Hz. From ten to eleven normal-hearing listeners participated in each experimental session. The listeners were seated in a double-walled sound-proof booth and tested individually. The limit of normal hearing permitted for this study was a binaural threshold sensitivity of 14 dB SPL at 1000, 2000, and 3000 Hz, and 32 dB SPL at 250 Hz. Moreover, the interaural difference in threshold sensitivity did not exceed 8 dB and this difference was only measured for two listeners at one frequency, 250 Hz.

B. Procedures

Judgments of perceived magnitude were obtained by absolute magnitude estimation (AME) supplemented by a balanced procedure of loudness matching between either the low-pass or high-pass noise and a 1000-Hz tone. The experimental setup was the same for magnitude estimation and loudness matching. The matches between noise and tone were obtained by the method of adjustment using a continuously variable 100-dB range attenuator custom designed and built by Grason-Stadler Co.

The same ten or eleven listeners judged in separate sessions, the absolute loudness of both noise and a 1000-Hz tone heard alone. In addition,

TABLE I

EXPERIMENTAL STIMULI

	Spectral Shape of Noise		
	Broadband Flat	Low Pass	High Pass
Frequency of added tones:	250, 1000, 2000, and 3000 Hz	250, 1000, 2000, and 3000 Hz	250 and 3000 Hz
SPLs (dB) of noise:	70-100	70-100	70-100
SPLs (dB) of tones:			
250 Hz	68-98	71-101	71-101
1000 Hz	71-101	72-102	
2000 Hz	68-98	71-101	
3000 Hz	71-101	72-102	72-102
Range of tone-to-noise ratios (dB) produced relative to the relevant 1/3-octave band pressure level:	+5 - +30	+5 - +35	+5 - +35

they judged the absolute overall loudness, annoyance, and noisiness of at least one tone-noise spectral combination shown in Table I. Loudness judgments always preceded annoyance and noisiness judgments. The frequency of the added tone, the attribute judged, and the spectral shape of the noise remained constant throughout each listening session. Sessions were spaced about one week apart. The duration of each session was about thirty minutes. Within a session, the experimental variables consisted of the SPLs of the added tone, the SPLs of a specific noise spectrum, and the tone-to-noise ratios relative to the appropriate one-third-octave-band pressure levels. The group loudness judgments of noise and tone alone were used to obtain a baseline or reference function for the overall response.

Although magnitude estimation was developed by S.S. Stevens (1955, 1956) for the measurement of loudness, it has also been used successfully for judgments of sound annoyance and noisiness (e.g., Berglund et al., 1975, 1976, 1981; Bishop, 1966; Galanter, 1978; Kryter, 1974; Scharf and Horton, 1978). The version of magnitude estimation adopted for this study evolved from the extensive research on numerical scaling procedures by S.S. Stevens and his co-workers (e.g., 1956, 1958, 1975). More specifically, Hellman and Zwislocki (1961, 1963, 1964, 1968) found that, when measuring loudness growth, listeners appear to use absolute rather than relative scales so that the numerical estimates used by groups of observers actually reflect the perceived magnitudes of the stimuli. Since those early experiments, confirmation of peoples' ability to pair numerical judgments to perceived magnitudes on an absolute scale has been revealed by several additional investigations (e.g., Barlow and Verrillo, 1976; Hellman, 1976; Rowley and Studebaker, 1969; J.C. Stevens and Marks, 1980; Verrillo, Fraioli, and Smith, 1969; Zwislocki, 1983; Zwislocki and Goodman, 1980). In other words, the outcome of magnitude estimation can determine both the slope and absolute position of sensory magnitude functions on log-log coordinates.

According to the method of absolute magnitude estimation (AME), no explicit or implicit reference standard is assigned. An internal standard common to all groups of listeners is implied. The listeners are simply asked to assign numbers to the loudness of the stimuli so that the subjective magnitude of the two continua, loudness and number, appear equal. The final averaging is achieved without normalization of the obtained numbers (for further details see Hellman and Zwislocki, 1963, 1968; Hellman, 1976, 1981). Most of the data obtained for this study were determined by AME. Prior to the onset of the initial session, line length was used to illustrate the concept of an open-ended number scale.

During a magnitude-estimation session in which overall judgments were made, each of ten listeners judged the perceived magnitude (loudness, annoyance, and noisiness) of 28 to 33 different stimuli three times in random order that differed from listener to listener, and within a session, for each of three separate runs. The stimulus order also differed for each listener, and from listener to listener, for each of the assessed attributes. No standard was designated, and the latter two judgments produced by each individual listener were used for the determination of group geometric means.

The written instructions for magnitude estimation were based on those described previously (Hellman, 1976). The following basic instructions were used throughout this study:

a. Loudness Instructions

"You are going to hear a series of noises of different intensities in random order. Your task is to tell me how loud they sound by assigning numbers to them. You may use any positive numbers that appear appropriate to you — whole numbers, decimals, or fractions. Do not worry about running out of numbers, there will always be a smaller number than the smallest you use and a larger one than the largest you use. Further, do not worry about consistency. Simply try to match an appropriate number to each noise regardless of what you may have called some previous stimulus.

"You may listen to the same noise as often as you wish before deciding on your numerical estimate of its loudness. However, it is best to be as spontaneous and quick in your response as possible. After you have reached a decision, report your judgment to the experimenter through the intercom. Before proceeding to the next noise, wait for a signal from the experimenter. Do you have any questions?"

b. Annoyance Instructions

"Until today you have been asked to judge the loudness of both noises and tones. In addition to loudness, sounds are known to have other psychological attributes. One such attribute is annoyance. Whereas loudness refers directly to the intensity of the sound, annoyance is dependent on context. People tend to identify annoyance when describing their own general reaction to noise. For example, annoyance may arise from our own perception 'after a hard day's work'.

The task today is to judge the annoyance of tones and noise in the same way that you judged loudness by the method of magnitude estimation.

Please reread the instructions for magnitude estimation carefully remembering that you will be assessing annoyance and not loudness."

c. Noisiness Instructions

"Your task is to judge the noisiness of noise-tone combinations. In addition to loudness and annoyance, sounds also have the psychological attribute of noisiness. Noisiness refers to the quality of the sound. For example, noisiness may arise from sound distortion that decreases the clarity of a sound but may not necessarily alter its loudness.

You will be asked to judge the noisiness of tones and noise in the same way that you judged loudness by the method of magnitude estimation.

Please reread the instructions for magnitude estimation carefully remembering that you will be assessing noisiness and not loudness."

The definitions by Berglund, et al. (1975, 1976) served as a basis for the annoyance and noisiness instructions used in this study. Appendix A contains the specific instructions used for loudness matching.

2. Results and Discussion

A. Effect of Overall Sound Pressure Level

Figure 1 shows the loudness results obtained separately for broadband-flat noise (upper solid function), and for a 1000-Hz tone (lower solid function). Each unfilled circle indicates the geometric mean (GM) of 22 judgments by eleven listeners measured at 1000 Hz. Two series of geometric means, obtained on different days, by the same group of eleven listeners are indicated for noise by the filled circles and crosses. Both series are in reasonably good agreement, but the curve is drawn to more closely approximate the initial judgments (filled circles). Note, that without normalization of raw data, the numerical estimates of loudness at 1000 Hz are in close agreement with those reported in earlier studies that used an absolute magnitude-estimation procedure (e.g., Hellman and Zwislocki, 1963; Hellman, 1976; Rowley and Studebaker, 1969; Zwislocki and Goodman, 1980). The mechanics of AME are further demonstrated by the relative positions of the noise and tone loudness functions. The data show that, at the same SPL, the numbers assigned to the loudness of broadband-flat noise are larger than the ones assigned to the loudness of the tone, meaning that the noise is louder than the tone.

Over the stimulus range investigated, both the shape and position of the loudness function for noise are consistent with results found in a wide cross-section of the literature (e.g., Hellman, 1976; Robinson, 1953; Scharf, 1978; Scharf and Fishken, 1970; Stevens, 1955, 1961, 1972; Zwicker, 1958). At high SPLs, where both functions are linear on log-log coordinates, the slight reduction in slope (exponent) from 0.60 re sound pressure, the accepted international standard (ISO R 131-1959), to 0.57, can be ascribed to the

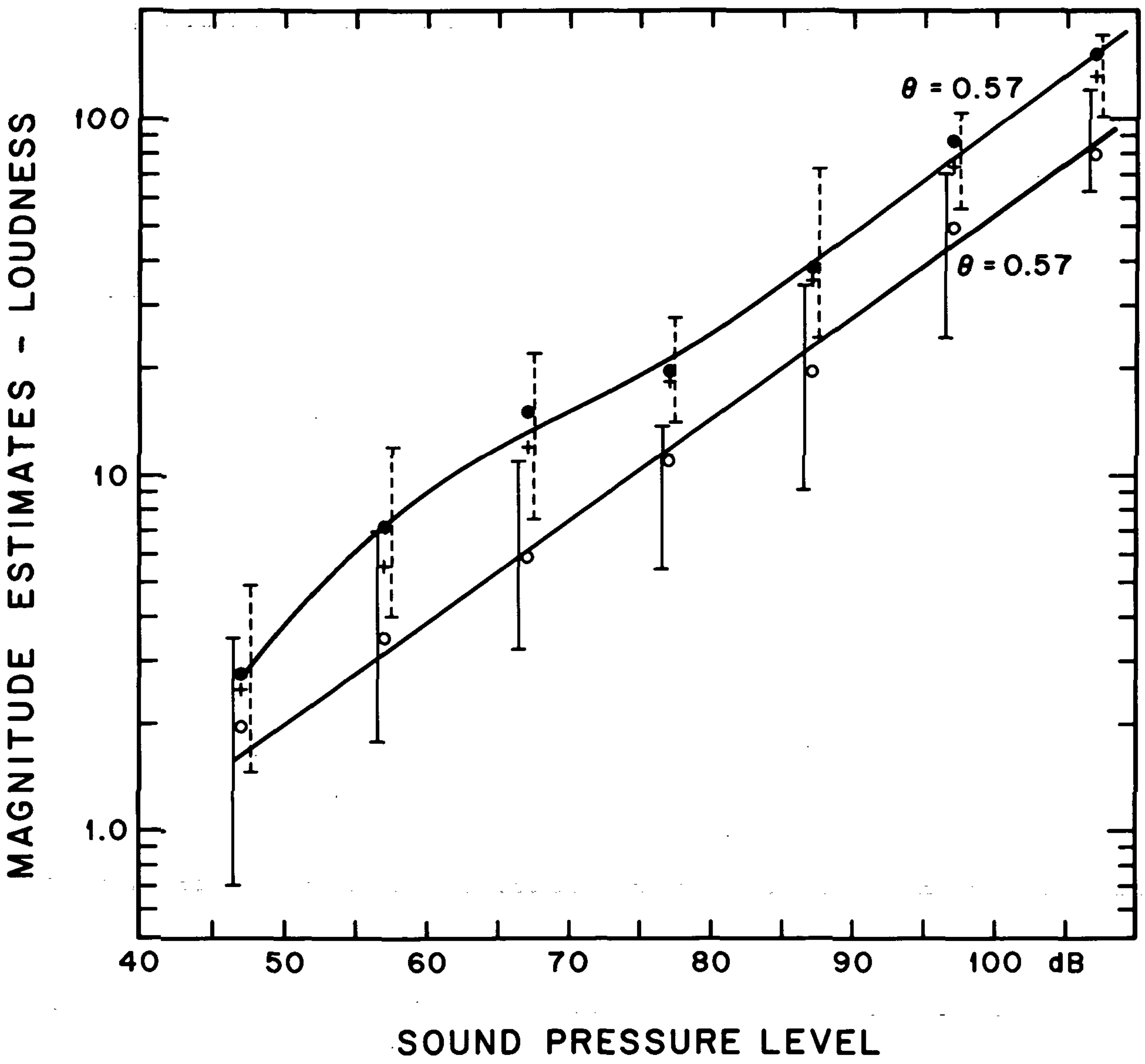

Figure 1. Loudness-estimation function produced by broadband-flat noise (upper solid line) compared to the one produced by a 1000-Hz tone (lower solid line). Filled circles and crosses indicate group geometric means of 22 judgments obtained for noise one week apart by the same group of eleven listeners. Unfilled circles indicate group geometric means of 22 judgments at 1000 Hz by the eleven listeners who also judged the noise. Solid and intermittent vertical bars show the interquartile ranges obtained for tone and noise respectively.

absence of measures of magnitude production (Stevens and Greenbaum, 1966). Such small slope differences however, do not alter the basic outcome of this study. The loudness results shown in Fig. 1 were used to provide a baseline for the judgments of overall perceived magnitude obtained when tones were added to broadband-flat noise. (See Appendix A for loudness values determined for the noise and for the 1000-Hz tone.)

Figure 2 shows loudness, annoyance, and noisiness judgments produced when 1000-Hz tone is combined with the broadband-flat noise. The data are plotted as a function of the overall SPL of the noise-tone complex. Thirty-three different tone-noise combinations are shown for each judged attribute. A single point is based on the GMs of 20 judgments by the group of ten listeners. The lines are simply drawn to connect the points.

The striking feature of Fig. 2 is the sharp increments and decrements displayed by the data. Very similar results, produced by a 250-Hz tone added to low-pass noise, are shown in Fig. 3 for twenty-eight different tone-noise combinations. This pattern of results was found for all tone frequencies studied as well as for individual listeners. (See Appendix A, for group GMs obtained for the entire data set.) Due to the complexity of the listening task, a combined judgment increased the standard error (SE) of the group data from an average value of .13 log units obtained when the tone and noise were judged separately, to about .20. However, the standard error is generally about the same for the three judged attributes. (Tables 1 to 5, 10 to 15, and 20 in Appendix C show group GMs, standard deviations, and ± twice the standard error of the means determined for each of the three judged attributes as a function of both the SPL of the noise and the SPL of the tone.)

Although judged perceived magnitude (loudness, annoyance, and noisiness) does increase with overall SPL, the increase is clearly a nonmonotonic function of the overall SPL of the noise-tone complex. Further, the pattern of results is similar for the three judged attributes, suggesting a common underlying basis,

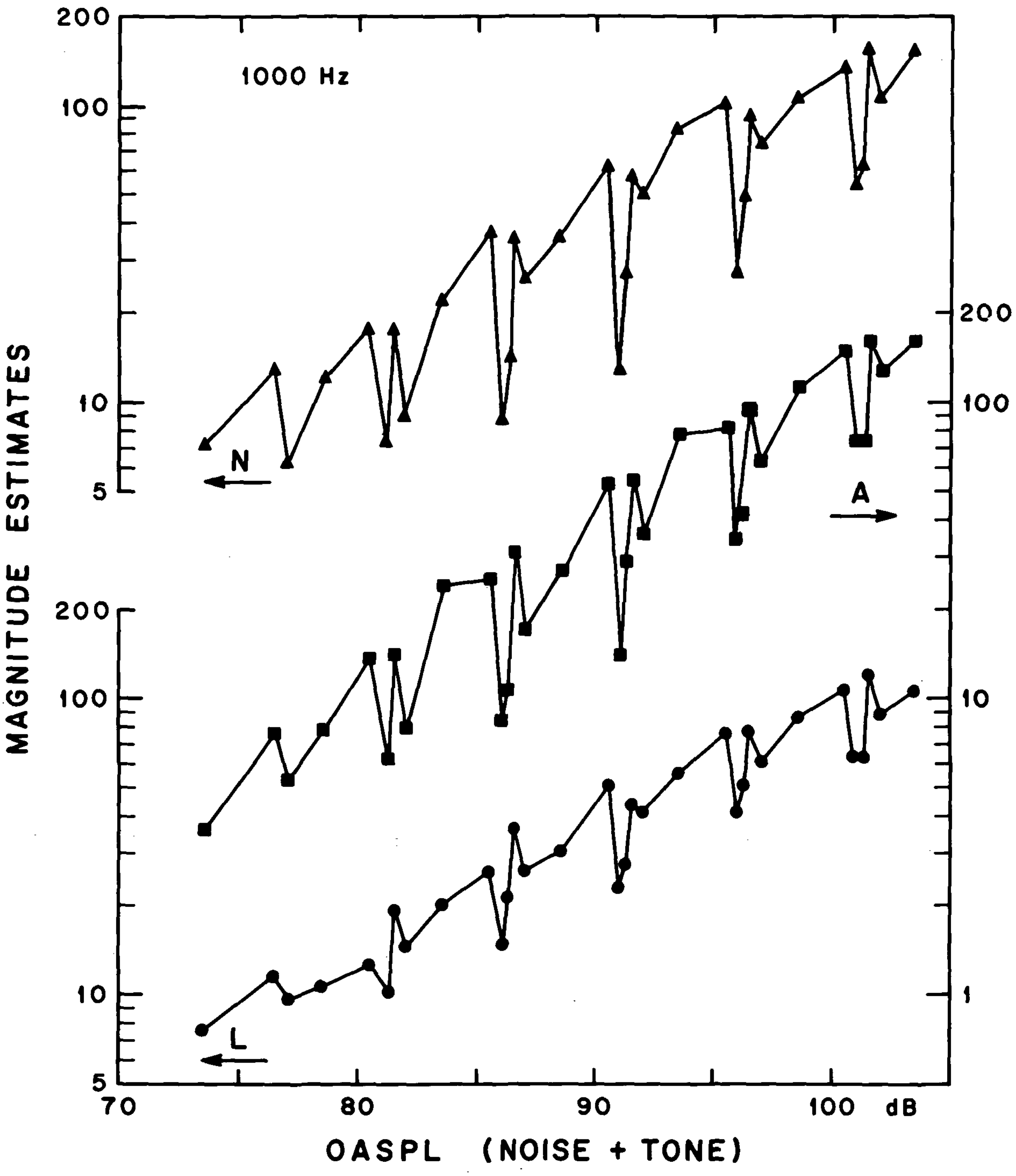

Figure 2. Magnitude estimates of loudness, annoyance, and noisiness determined by a 1000-Hz tone added to broadband-flat noise as a function of the overall SPL of the noise-tone complex. Each point indicates the geometric mean of 20 judgments by the group of ten listeners. Circles represent loudness judgments, squares represent annoyance judgments, and triangles represent noisiness judgments. Arrows refer to the numerical scale that corresponds to each attribute.

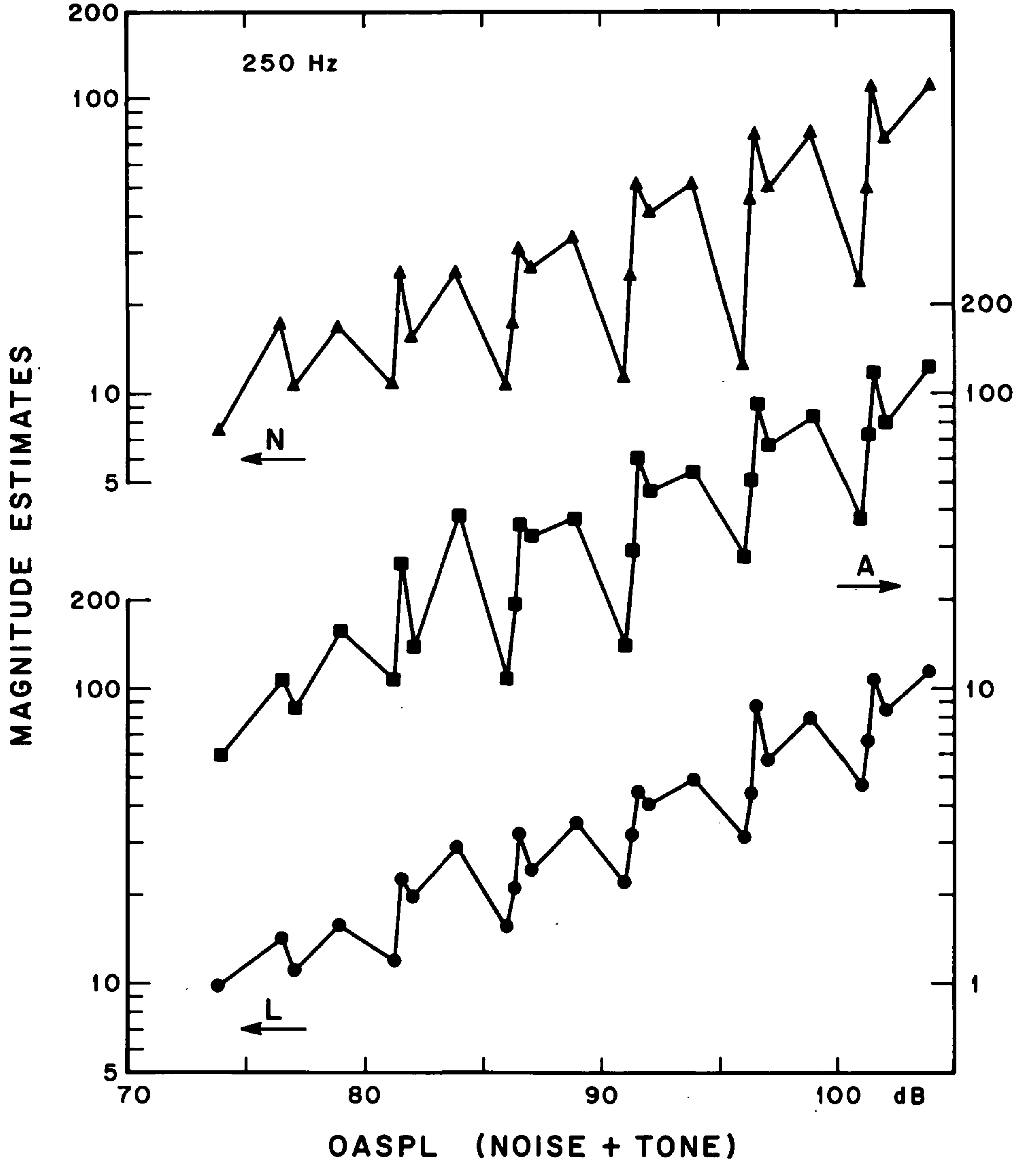

Figure 3. Similar to Figure 2, except that magnitude estimates determined by a 250-Hz tone added to low-pass noise are shown.

but is not similar for the extent of the excursions. The extent of the excursions depends on the judged attribute. It also seems to depend on the spectral characteristic of the noise. Noisiness usually produces the largest maximum-to-minimum response ratio.

B. Effect of Tone-To-Noise Ratio

Detailed analysis of the data like those in Figs. 2 and 3 reveals for all test frequencies and noise spectra that the observed increments correspond to those tone-noise combinations that produce relatively small tone-to-noise ratios (≤ +15 dB) whereas the observed decrements correspond to those combinations that produce relatively large tone-to-noise ratios (≥ +20 dB). Hence, the data were subdivided into two groups according to tone-to-noise ratio. Group I included overall judgments of perceived magnitude produced by tone-to-noise ratios of +5, +10, and +15 dB, and Group II included overall judgments produced by tone-to-noise ratios of +20 dB and greater.

Figure 4 re-evaluates the 1000-Hz data from Fig. 2 on the basis of this dichotomy. Each point shows group geometric means obtained for those tone-noise combinations that produced either small (unfilled symbols), or large (filled symbols) tone-to-noise ratios. The means are plotted as a function of the SPL of the tone. For comparison, the separate loudness functions measured for the noise and tone are also shown. Circles represent loudness judgments, squares represent noisiness judgments, and the triangles represent annoyance judgments. The upper solid line shows the broadband-flat noise loudness function determined from Fig. 1 by combining the results of the two series of noise measurements. The lower solid line shows the 1000-Hz loudness function obtained directly from Fig. 1. (For further details, see Table C-21).

Judgments of perceived magnitude produced by large tone-to-noise ratios show some reduction in magnitude for tones below 90 dB SPL. Above 90 dB SPL, they approximate the 1000-Hz loudness function. On the other hand, judgments produced by small tone-to-noise ratios show a clear-cut increase in perceived magnitude for tones above 80 dB SPL. The calculated loudness increment

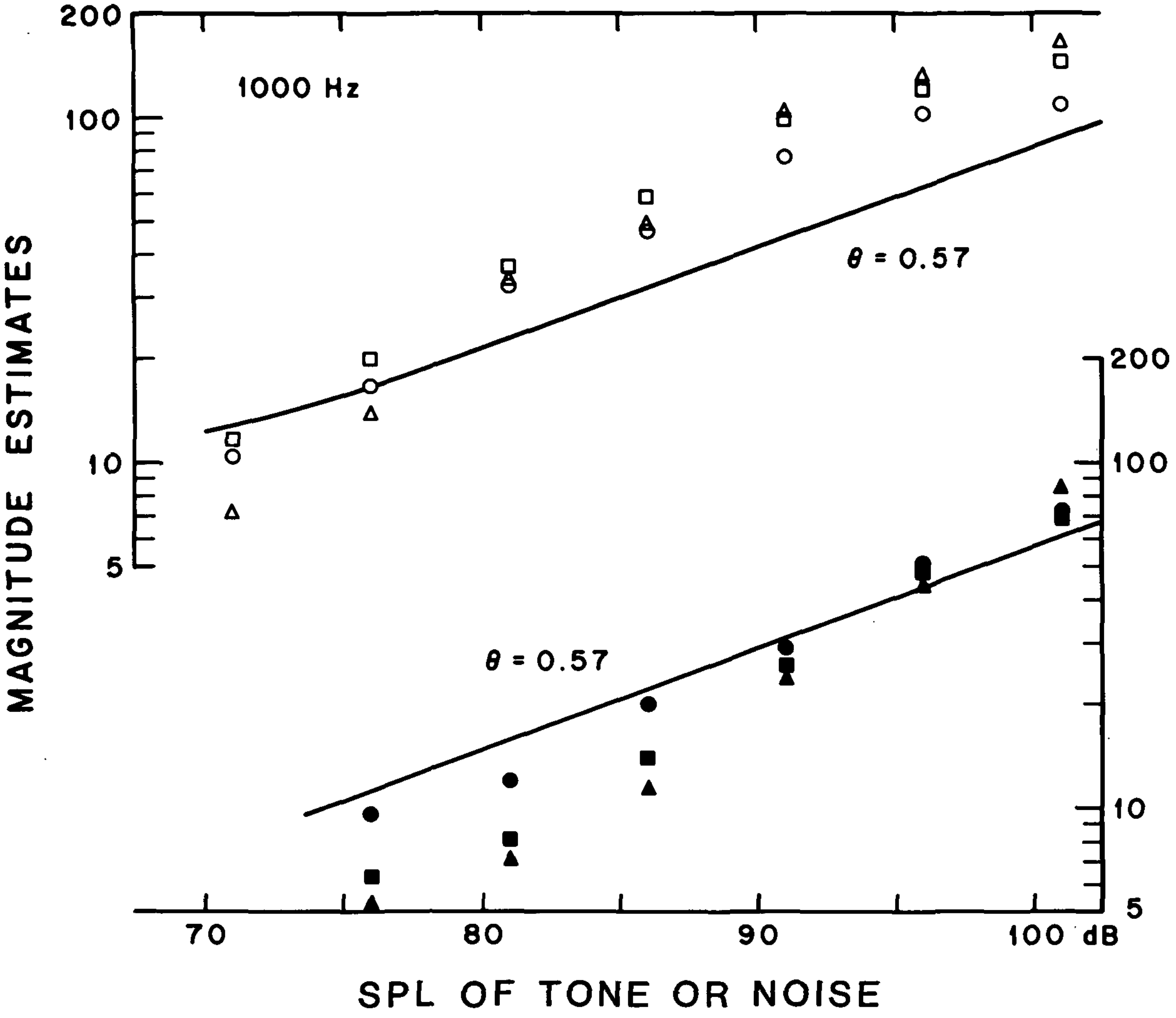

Figure 4. Effect of small (+5, +10, +15 dB) and large (+20, +25, +30 dB) tone-to-noise ratios on loudness, annoyance, and noisiness judgments produced by a 1000-Hz tone added to broadband-flat noise as a function of the SPL of the tone or noise. Unfilled and filled symbols indicate results produced by small and large tone-to-noise ratios, respectively. Circles represent loudness judgments, squares represent noisiness judgments, and triangles represent annoyance judgments. The upper solid line shows the noise loudness function, and the lower solid line shows the 1000-Hz loudness function, both obtained from Figure 1.

obtained for tones at 90 dB SPL and above, is more than that predicted by an assumption of energy summation between noise and tone; below 90 dB SPL, it is less.

Another example is seen in Fig. 5. These data are based on the results in Fig. 3 produced by a 250-Hz tone added to low-pass noise. The upper solid line shows the low-pass loudness function measured in this experiment by loudness matching and magnitude estimation, and the lower solid line is predicted from 250-Hz loudness-estimation measurements by Hellman and Zwislocki (1968). It is of interest to note that, at the same overall SPL, the low-pass loudness function is about 4-6 dB less loud than the one produced by the broadband-flat noise. (Compare noise values in Tables C-21 and C-22.)

Consistent with Fig. 4, Fig. 5 shows that regardless of attribute judged, small tone-to-noise ratios increase the overall perceived magnitude more than large tone-to-noise ratios. Judgments determined by large tone-to-noise ratios closely approximate the 250-Hz loudness function measured in the absence of noise. When tones are added at 75 dB SPL and above, those judgments determined by small tone-to-noise ratios increase the perceived magnitude of the noise more than predicted by an assumption of energy summation between noise and tone. The amount of loudness summation produced by small tone-to-noise ratios is 2 to 3 dB greater than that obtained when either 250-Hz or 1000-Hz tones are added to the broadband-flat noise. Very similar results are obtained with tones added at 2000 and 3000 Hz, and for high-pass noise. However, as indicated in Table II, when 2000- and 3000-Hz tones are added to the noise spectra, little or no loudness summation beyond a simple energy summation is observed at any overall SPL of the noise-tone complex. In fact, the overall loudness is usually substantially less than that predicted by an energy summation hypothesis.

The 3000-Hz data are especially interesting because separately, the tone and broadband-flat noise are about equally loud at the same overall SPLs

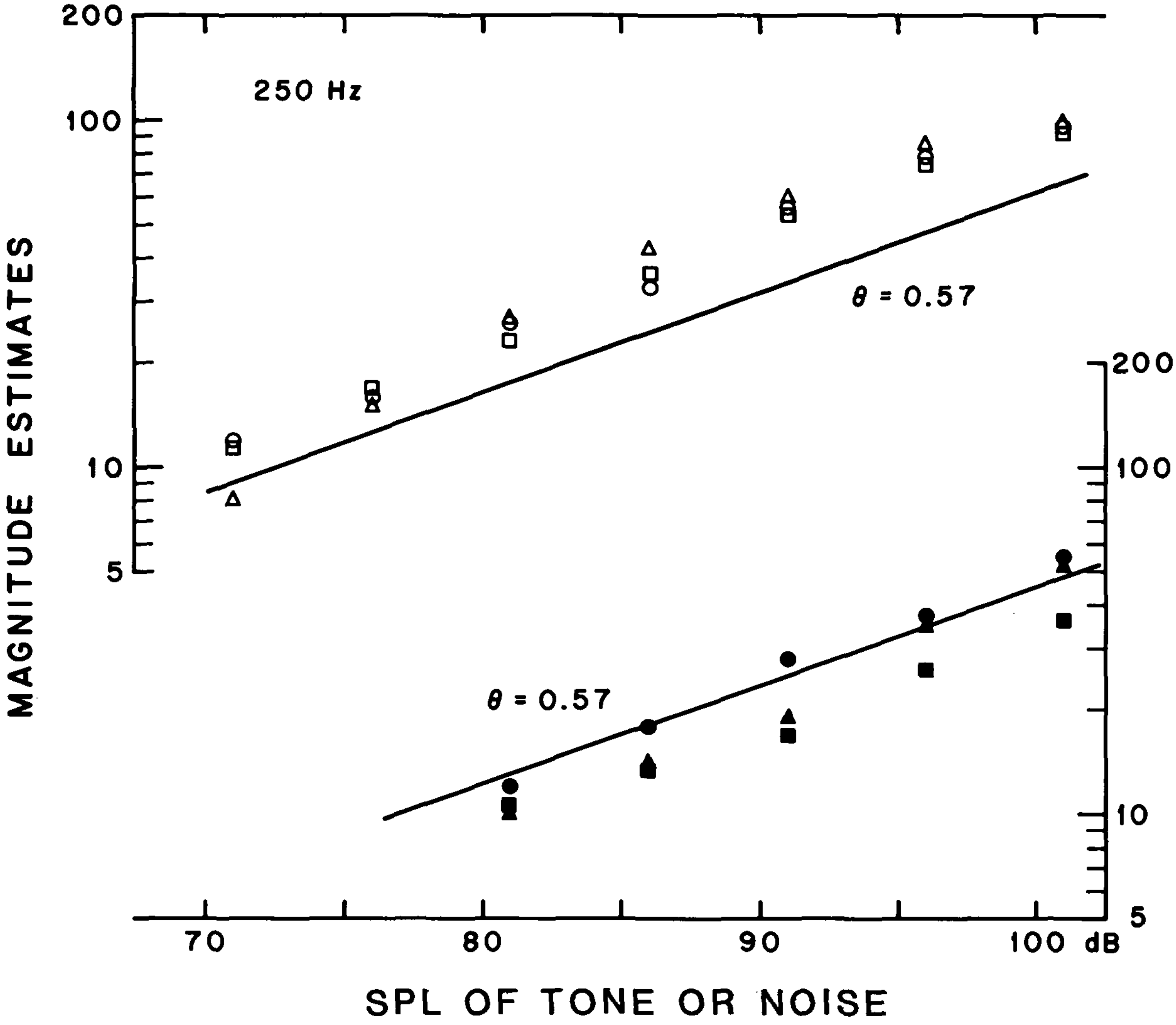

Figure 5. Effect of small (+5, +10, +15 dB) and large (+20, +25, +30 dB) tone-to-noise ratios on loudness, annoyance, and noisiness judgments produced by a 250-Hz tone added to low-pass noise as a function of the SPL of the tone or noise. Symbols are analogous to those described in Figure 4. The upper solid line shows the low-pass loudness function measured in this experiment by loudness matching and magnitude estimation, and the lower solid line is predicted from 250-Hz loudness-estimation measurements by Hellman and Zwislocki (1968).

Table II

*Loudness summation in decibels produced by single tones added to broadband-flat, low-pass, and high-pass spectra

	Broadband-flat				Low-pass	High-pass
Freq (Hz)	250	1000	2000	3000	250	3000
OASPL (dB)						
75	0	0	0	0	.5	--
80	0	0	0	0	2.0	0
85	0	0	0	0	2.0	0
90	1	2.0	0	0	4.0	0
95	1	2.0	0	0	4.0	0
100	2	1.5	1	1	4.0	0

*Loudness summation is defined as a loudness increment greater than that predicted by an assumption of energy summation between noise and tone.

(see Fig. 6a and Table C-23). By comparison, the loudness of a 3000-Hz tone heard alone is greater than that of the high-pass noise (see Fig. 6b and Table C-24), i.e., the numerical estimates assigned to the loudness of the tone are larger than those assigned to the loudness of the noise. These findings indicate that, at the same overall SPLs, a high-pass noise is 9-11 dB less loud than either a broadband-flat noise or a 3000-Hz tone. (Compare loudness values for noise and tone in Tables C-23 and C-24.) Loudness-level curves determined for broadband-flat, low-pass, and high-pass noises by loudness matching combined with magnitude estimation are shown in Appendix B, Fig. 1.

Figure 6a shows results produced by judgments of overall perceived magnitude obtained when a 3000-Hz tone is added to broadband-flat noise. The upper and lower solid lines show the loudness function measured in this study for broadband-flat noise, and the crosses represent previously obtained (Hellman, 1976) loudness-estimation data at 3000 Hz. Not only is very little loudness summation observed for small tone-to-noise ratios, but except for tones above 90 dB SPL, the perceived magnitude of both the tone and the noise are reduced when heard in combination. Further, more substantial, reductions are obtained for large tone-to-noise ratios.[2]

The interaction between tone and noise is very different when the 3000-Hz tone is added to the high-pass noise. These results are indicated in Fig. 6b. The upper solid line shows the loudness-estimation function previously measured at 3000 Hz (Hellman, 1976), and the lower solid line indicates the high-pass loudness function measured in this experiment by loudness matching and magnitude estimation. In contrast to results obtained in broadband-flat noise, no substantial decrease in loudness is found for either small or large tone-to-noise ratios. Moreover, calculated across overall SPLs, loudness is the predominant sensation produced by large tone-to-noise ratios ($P < .05$ by correlated t test), whereas small tone-to-noise ratios also

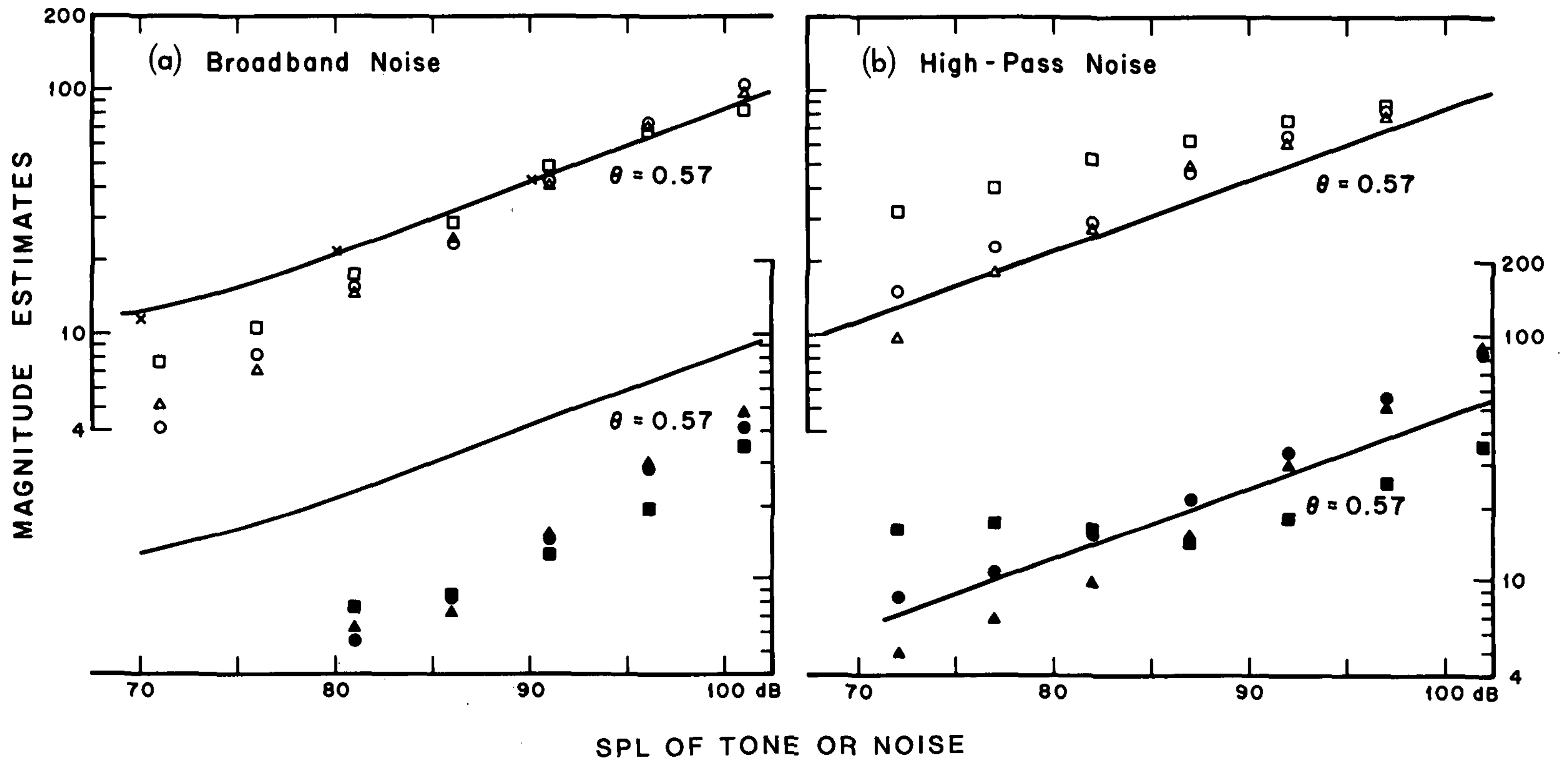

Figure 6. (a) Effect of small (+5, +10, +15 dB) and large (+20, +25, +30 dB) tone-to-noise ratios on loudness, annoyance, and noisiness judgments *produced by a 3000-Hz* tone added to broadband-flat noise as a function of the SPL of the tone or noise. Filled and unfilled symbols are analogous to those described in Figure 4. The upper and lower solid lines show the loudness function measured in this study for broadband-flat noise, and the crosses represent previously obtained (Hellman, 1976) loudness-estimation data at 3000 Hz. (b) Similar to (a), except that loudness, annoyance, and noisiness judgments were produced by a 3000-Hz tone added to high-pass noise. The upper *solid line shows the loudness-estimation function* previously measured at 3000 Hz (Hellman, 1976), and the lower solid line shows the high-pass loudness function measured in this experiment by loudness matching and magnitude-estimation.

increase judged annoyance and noisiness. Finally, it is noted that noisiness produced by large tone-to-noise ratios appears to be nearly independent, over a 30-dB range, of the SPL of the tone. This result is also observed when a 3000-Hz tone is added to low-pass noise. (See Appendix B, Fig. 2 from Hellman and Ashkinaze, 1981.) It suggests that, when a relatively intense high-frequency tone is added to a shaped noise spectrum, regardless of the SPLs of the noises combined with the tone, noisiness magnitude varies little, if at all, with the SPL of the tone.

Taken together, Figs. 2-6 show that, for tones centered in noise, the basic principles of masking and loudness apply. Given two sounds at about the same overall SPL, the one with the more intense noise and less intense tone is judged louder, more annoying, and noisier than the one with the less intense noise and more intense tone. This result obtains whether or not the two sounds separately are equally or unequally loud.

Figure 7 shows previously obtained (Hellman, 1970) loudness-balance data produced by a 1000-Hz tone partially masked by a broadband-flat noise at overall SPLs of 70, 80, and 90 dB. Group mean SPLs obtained for loudness equality between the tone in quiet and the tone in noise are plotted. The large tone-to-noise ratios dealt with in this study correspond to the upper portion of these masked loudness-level functions. In this region, the noise reduces the loudness of the tone at 90 dB SPL and above, less than the tone reduces the loudness of the noise (Hellman, 1972). For tones added at low- and mid-frequencies, the effect of mutual masking is to increase the loudness of the tone so that the tone, which separately is less loud than the noise, becomes the dominant component of the complex, reducing its overall loudness.

When a 3000-Hz tone is added to broadband-flat noise, it is possible that even more masking between tone and noise occurs, further reducing the loudness of both stimuli. Preliminary results obtained by masking broadband-

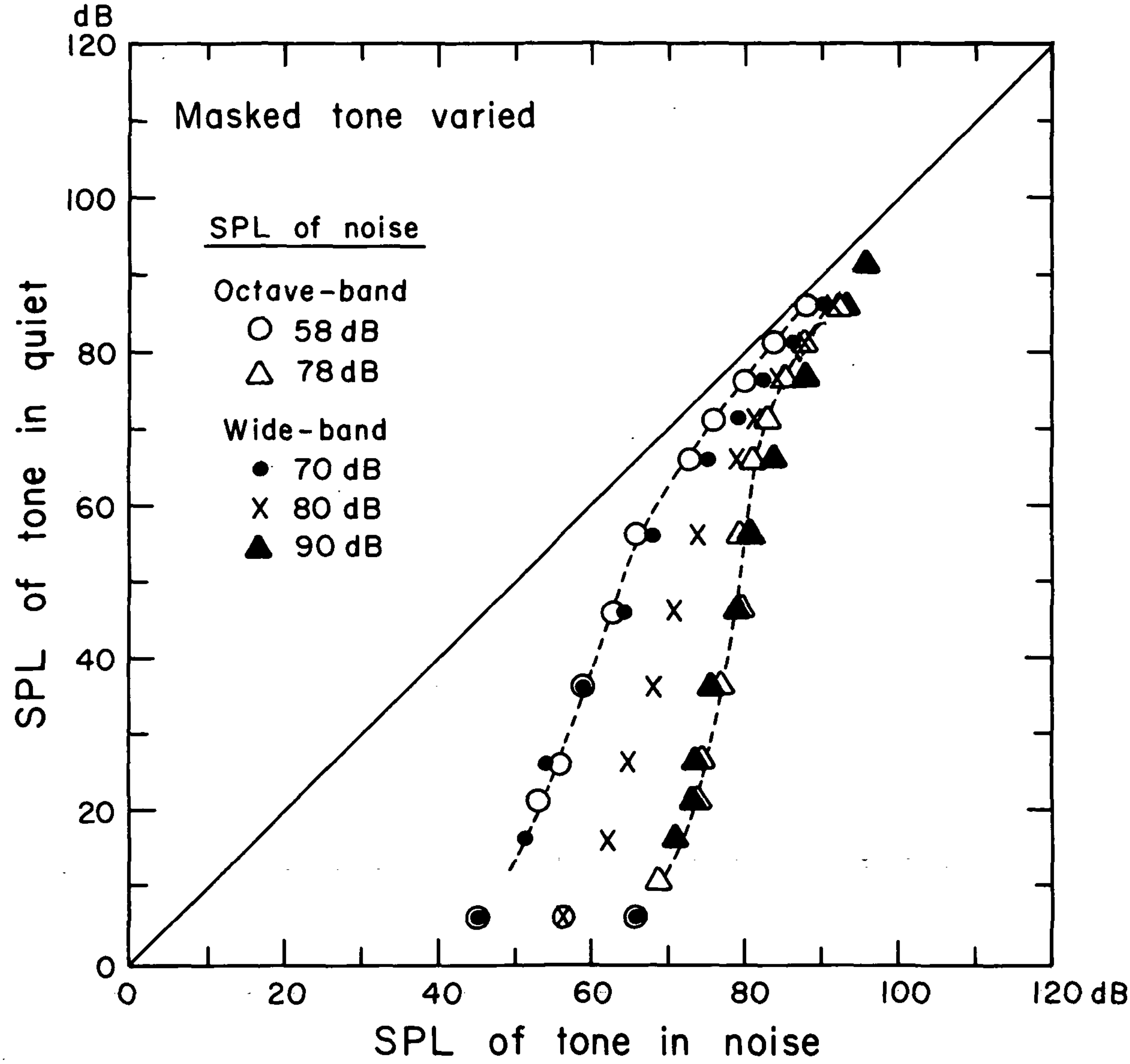

Figure 7. Masked loudness-level functions previously measured for a 1000-Hz tone (Hellman, 1970).

flat noise with a 3000-Hz tone tentatively suggest that the amount of partial masking produced by the tone on the noise is greater than that found at 1000 Hz (Aylward, 1980). On the other hand, despite the reversal of loudnesses produced by a 3000-Hz tone and a high-pass noise, small tone-to-noise ratios still increase the overall perceived magnitude more than large tone-to-noise ratios.[3] Perhaps, due to the decrease in loudness of the noise, a 3000-Hz tone partially masks high-pass noise more than it masks broadband-flat noise. Thus, for large tone-to-noise ratios obtained with tones greater than 90 dB SPL, the overall loudness of the complex exceeds the loudness of the noise by an increment of 2-6 dB. Additional, more comprehensive data are clearly needed to fully explain these results.

Whatever the complete explanation, regardless of tone frequency and noise spectrum, data analysis using both the Wilcoxon and correlated t tests show that loudness is generally the predominant sensation produced by large tone-to-noise ratios. In addition, since overall perceived magnitude is consistently greater for small than for large tone-to-noise ratios, even when the overall SPLs are about the same, the remainder of Section I deals exclusively with the former results. A graphical and statistical evaluation was performed based on measurements like those shown in Figs. 2-6.

C. Relationship Among Judged Attributes

Figure 8 shows the relationship between noisiness and loudness found for tones at 250, 1000, 2000, and 3000 Hz added to broadband-flat noise. Except for a 3000-Hz tone, represented by the filled circles, noisiness increases as loudness increases but at a faster rate. The indicated slope of 1.24, excluding the 3000-Hz points, was determined by a least-squares fit to the data.

The relationship in Fig. 8 between noisiness and loudness measured for tones added at 250, 1000, and 2000 Hz to broadband-flat noise is consistent

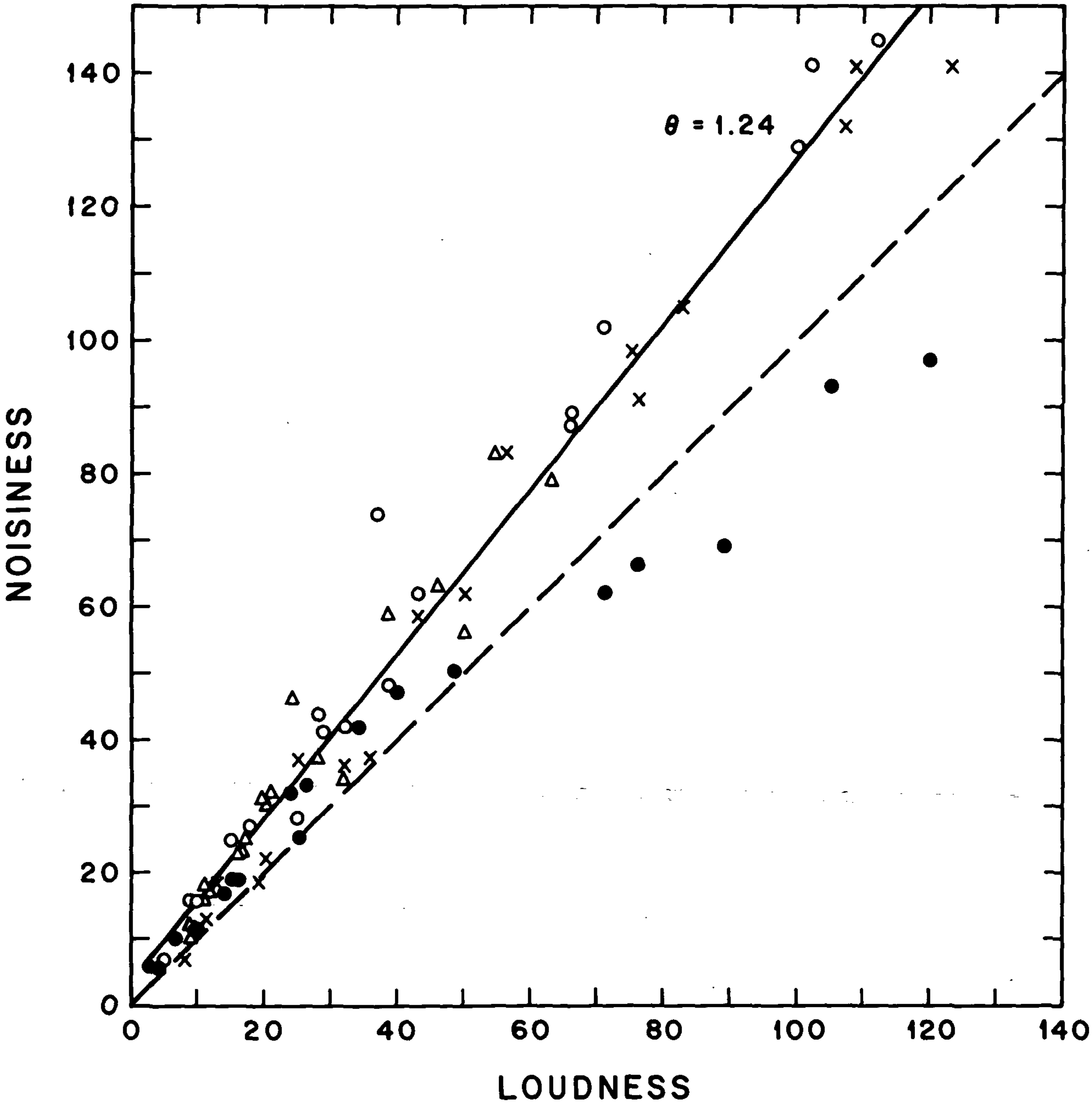

Figure 8. Relationship between noisiness and loudness found for tones at 250 (unfilled circles), 1000 (crosses), 2000 (triangles), and 3000 (filled circles) Hz added to broadband-flat noise. The indicated slope of 1.24, excluding the 3000-Hz points, was determined by a least-squares fit to the data.

with the one reported by Berglund, Berglund, and Lindvall (1975, 1976) for broadband community noises without tonal components. It was not found however, for all added frequencies (e.g., 3000 Hz), or for all three spectral shapes. No statistically significant difference ($p > .05$), as determined by a correlated t test, was obtained between noisiness and loudness produced by a 250-Hz tone added to the low-pass spectrum.

Data such as those shown in Fig. 8 can be used to compute the ratios of noisiness-to-loudness (N/L) as a function of the overall SPL of the noise-tone complex. These ratios can then be converted into decibels using the measured loudness function obtained for each noise spectrum. Figure 9 provides two examples.

Panel *a* shows the noisiness-to-loudness ratio calculated for tones added at 250, 1000, and 2000 Hz, and Panel *b* shows the noisiness-to-loudness ratio determined for a 3000-Hz tone. Least-squares regression lines were fitted to the data. In the upper segment, the 3000-Hz tone was added to high-pass noise (unfilled circles), and in the lower segment, it was added to broadband-flat noise (filled circles). In contrast to tones added at 250, 1000, and 2000 Hz that produce a constant noisiness-to-loudness ratio of 1.4 ($r_{xy} = -.08$, $p > .05$), product-moment correlation coefficients show that the noisiness-to-loudness ratio produced by a 3000-Hz tone added to the two different noise spectra decreases significantly as overall SPL increases ($r_{xy} = -.77$ for high-pass noise, and $-.79$ for broadband-flat noise, $p < .05$).

The ratio of 1.4 (re an exponent of 0.57) translates to a decibel increment of 5 dB whereas the decibel increment determined by a 3000-Hz tone strongly depends on the overall SPL of the noise-tone complex. Indeed, when a 3000-Hz tone is added to noise, at overall SPLs greater than 100 dB loudness may actually exceed noisiness. The decibel increment measured for noisiness should be added to the estimated values of loudness summation shown

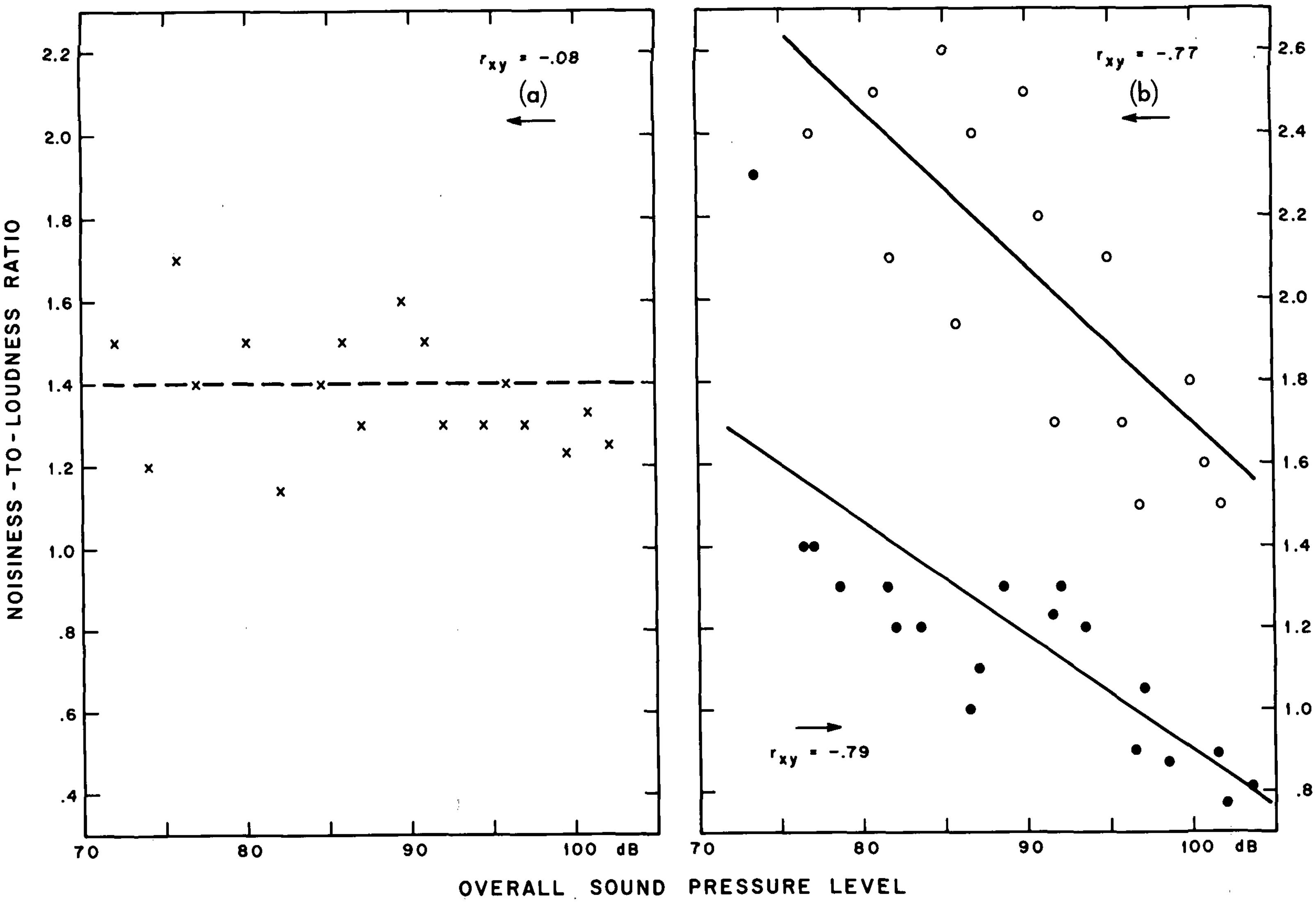

Figure 9. Noisiness-to-loudness ratio (N/L) as a function of the overall SPL of the noise-tone complex. (a) Calculated N/L ratio was obtained by combining data used to Figure 8 produced by tones added at 250, 1000, and 2000 Hz to broadband-flat noise. (b) Analogous to (a), except that results produced by a tone added at 3000 Hz are shown. In the upper segment, the 3000-Hz tone was added to high-pass noise (unfilled circles), and in the lower segment it was added to broadband-flat noise (filled circles). Least-squares regression lines were fitted to the data.

in Table II to determine the total effect of the added tone to perceived noisiness.

Similar analyses were performed for annoyance and loudness, and for annoyance and noisiness. (See Table B-6 for further details.) Figure 10 shows the results obtained for annoyance and loudness as a function of the overall SPL of the noise-tone complex for four different tone-noise spectral combinations. According to Fig. 10, the annoyance-to-loudness ratio (A/L) clearly depends on the frequency of the added tone.

When a low-frequency, 250-Hz tone is added to broadband-flat noise (Panel _b_), the annoyance-to-loudness ratio remains constant at about 1.3, equivalent to a decibel increment of 4 dB ($r_{xy} = +.12$, $p > .05$). A 250-Hz tone added to low-pass noise (Panel _c_) closely resembles these results, but above 80 dB SPL, the calculated annoyance-to-loudness ratio remains at about 1.1, equivalent to a decibel increment of about 2 dB ($r_{xy} = +.43$, $p > .05$). By comparison, the ratio obtained for tones added at 1000 and 2000 Hz to broadband-flat noise (Panel _a_) increases significantly as a function of overall SPL ($r_{xy} = +.84$, $p < .05$), whereas perceived annoyance and loudness of tones added at 3000 Hz (Panel _d_) are the same ($r_{xy} = +.18$, $p > .05$). Further, as for noisiness, it is important to note that the loudness increment to be added to the decibel increment determined for annoyance depends on the interaction between a specific tone frequency and the shape of the noise spectrum. For example, a 250-Hz tone added to broadband-flat noise produces a maximum loudness increment of 1 to 2 dB. The same tone added to low-pass noise produces a maximum loudness increment of 4 dB (see Table II). The increase in loudness summation probably arises from a reduction in masking of the high-frequency skirt of the tone by the low-pass noise (Hellman, 1970, 1974; Scharf, 1964). Similarly, although overall loudness produced by a 3000-Hz tone combined with noise is less than that predicted by an energy summation hypothesis, the same tone added to either broadband-flat or

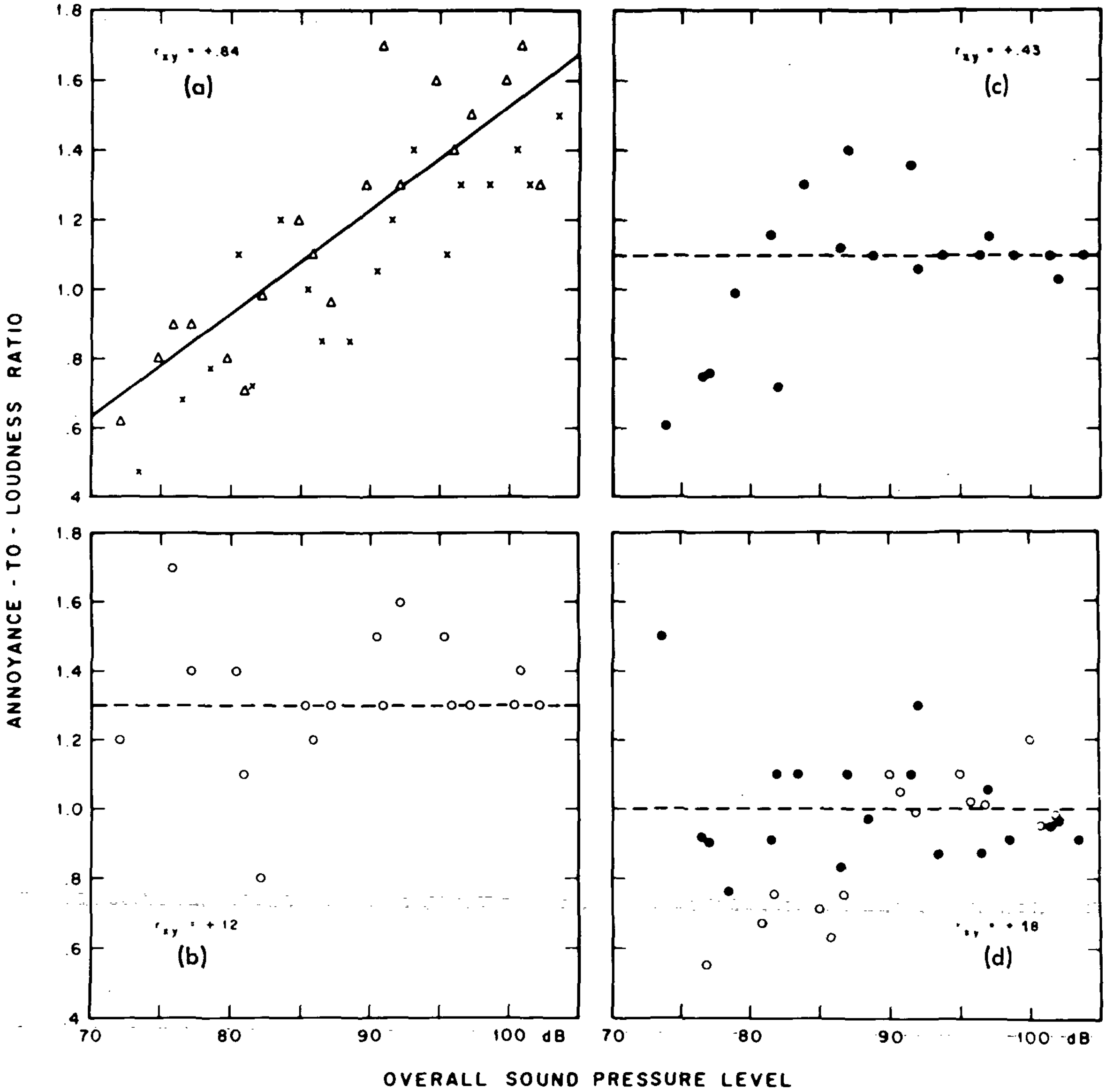

Figure 10. Annoyance-to-loudness ratio (A/L) calculated for four different tone-noise spectral combinations as a function of the overall SPL of the noise-tone complex. (a) Ratio of A/L found when tones at 1000 and 2000 Hz (crosses and triangles, respectively) are added to broadband-flat noise. The positive linear relationship was determined by a least-squares fit to the data. (b) Similar to (a), except that the A/L ratio was produced by a 250-Hz tone added to broadband-flat noise. (c) Similar to (a), except that A/L ratio was produced by a 250-Hz tone added to low-pass noise. (d) Similar to (a), except that the A/L ratio was produced by a 3000-Hz tone added to both broadband-flat and high-pass noises (filled and unfilled circles, respectively).

high-pass noises produces measurably different results (see Figs. 6a and 6b).

Figure 11 shows how the noisiness-to-annoyance ratio varies as a function of the overall SPL of the noise-tone complex. Panel a shows results produced by 250, 1000, 2000, and 3000-Hz tones added to broadband-flat noise, and Panel b shows results produced by a 3000-Hz tone added to the high-pass noise. Despite the scatter of data, and different slopes of the regression lines, the trend is clear. The fairly strong negative correlation coefficients, also found for low-pass noise, mean that sounds containing pure tones are more noisy than annoying at moderate overall SPLs, but more annoying than noisy at high overall SPLs ($r_{xy} = -.75$ for broadband-flat noise, and -.92 for high-pass noise, $p < .05$).[4] (See Table 2 in Appendix B for a detailed correlational analysis of the entire data set.)

3. Summary of Findings

Single tones centered within the noise spectrum were added to three different broadband spectra: flat, low pass, and high pass. Judgments of overall loudness, annoyance, and noisiness (perceived magnitude) were obtained by absolute magnitude estimation (AME) supplemented by loudness matching. The data were evaluated to determine how the overall SPL of the noise-tone complex, and tone-to-noise ratio affect judged perceived magnitude. In addition, the relationship among the three judged attributes was assessed. Results obtained with the different noise spectra show that the growth of perceived magnitude is a nonmonotonic function of the overall SPL of the noise-tone complex. Regardless of attribute judged, even when the overall SPLs are about the same, small tone-to-noise ratios ($\leq$ +15 dB) increase overall perceived magnitude more than large tone-to-noise ratios ($\geq$ +20 dB). Data analysis suggests that the extent of the increments and decrements in perceived magnitude depends on the absolute loudnesses of the component stimuli, the interaction between a specific tone frequency and noise spectrum, and the attribute judged.

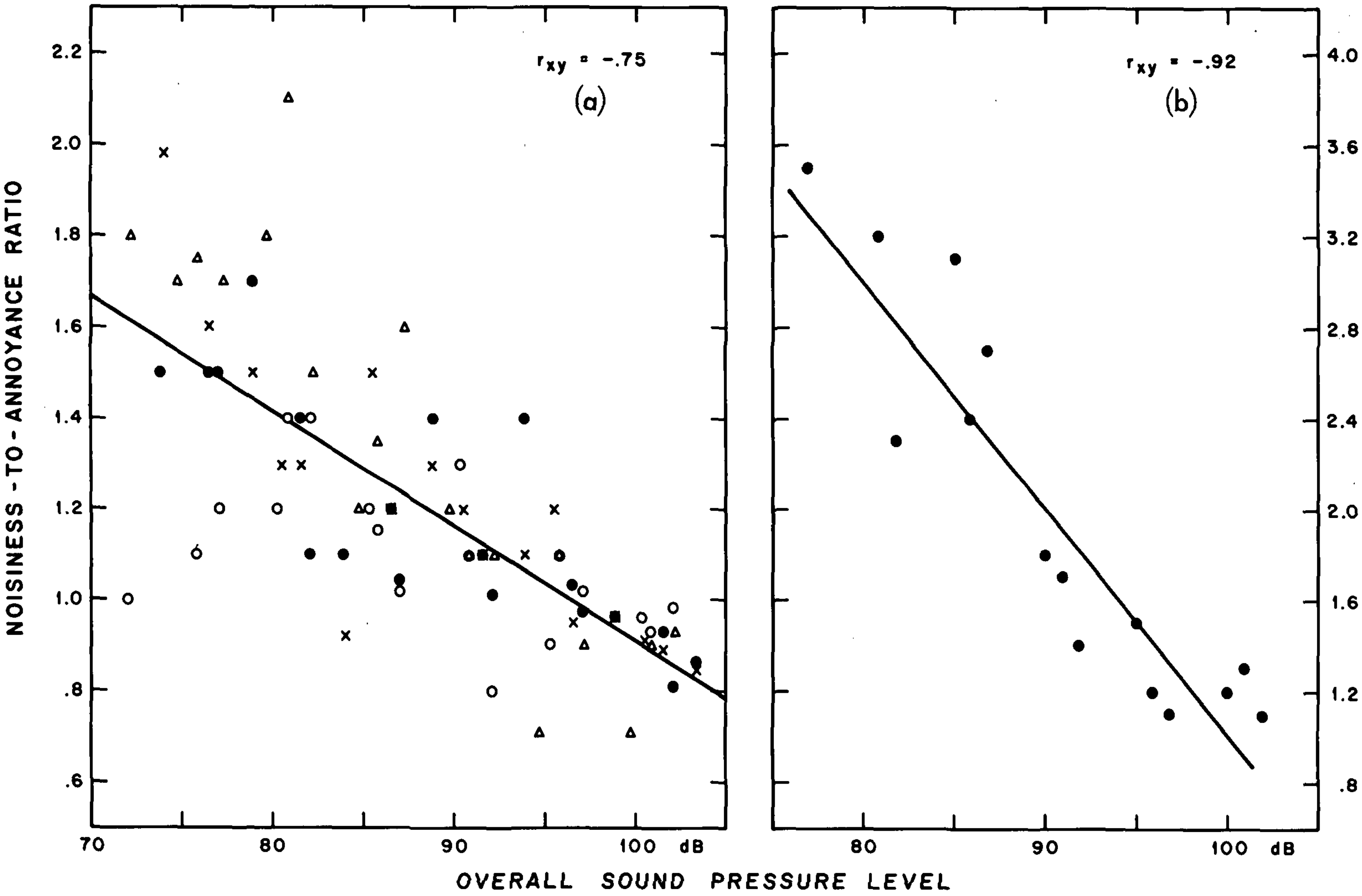

Figure 11. Noisiness-to-annoyance ratio (N/A) as a function of the overall SPL of the noise-tone complex. (a) Ratio of N/A found when tones at 250 (unfilled circles), 1000 (crosses), 2000 (triangles), and 3000 (filled circles) Hz are added to broadband-flat noise. (b) Similar to (a), except that a 3000-Hz tone was added to high-pass noise. Least squares regression lines were fitted to the data.

Whereas loudness is the predominant sensation produced by large tone-to-noise ratios, the relationship among the three perceived attributes determined by small tone-to-noise ratios depends on the overall SPL of the noise-tone complex, the frequency of the added tone, and the spectral shape of the noise. Once the amount of loudness summation is determined, it is then possible to compute the ratios of noisiness-to-loudness (N/L), annoyance-to-loudness (A/L), and noisiness-to-annoyance (N/A) as a function of the overall SPL of the noise-tone complex. These ratios can then be converted into decibels and added, when appropriate, to the measured loudness increment to determine the total contribution of the tone to perceived annoyance and noisiness. In general, when low-, middle-, and high-frequency tones are added to broadband-flat and high-pass noises, noisiness predominates below an overall SPL of 95 dB. Above 95 dB SPL, annoyance is greater than both loudness and noisiness at 250, 1000, and 2000 Hz but equal to loudness at 3000 Hz. When a 250-Hz tone is added to low-pass noise, annoyance predominates. The relation of these findings to those obtained with tones located within the high- and low-frequency skirts of the noise spectra is described in Section II.

II. Effect of Tone Located Within the Noise Skirts on Perceived Magnitude

1. Background

With the exception of data reported by Hargest and Pinker (1967), who found that when a 2000-Hz tone is added to noise overall annoyance decreases for tone-to-noise ratios that exceed +15 dB, the results described in Section I do not agree with those reported by other investigators (e.g., Kryter and Pearsons, 1965; Pearsons, Bishop, and Horonjeff, 1969). Since several calculation procedures (e.g., FAR 36, 1969; Kryter and Pearsons, 1965; Little, 1961) designed to predict perceived magnitude produced by noise spectra with tonal components increase the value of the tone correction, more for high- than for low-frequency tones, with increasing tone-to-noise ratio beyond a ratio of +15 dB, the measured discrepancy, particularly at 3000 Hz, appeared puzzling.

Tone-correction procedures are generally based on measurements of added tones either centered in octave-band noise (Kryter and Pearsons, 1965), or o tones located within the high-frequency skirt of a shaped low-pass noise resembling aircraft noise (e.g., Hargest and Pinker, 1967; Pearsons et al., 1969). Under both conditions, the partial masking produced by a noise on the tone is less than when the tone is centered within a broadband noise (e.g., Gleiss and Zwicker, 1964; Hellman, 1970, 1972, 1974; Scharf, 1964; Stevens and Guirao, 1967). Therefore, it was hypothesized that the source of the discrepancy between the results observed in Section I and the findings of other investigators might be due not only to differences among noise spectra used in each study, but also, to the location of the tone within the spectrum. Consequently, the primary purpose of the experiments described below was to determine the contribution of tonal components to overall perceived magnitude of noise-tone complexes for tones located within the high-and low-frequency skirts of the noise spectra. The results are compared to those obtained with tones centered within the spectrum, and assessed in relation to basic mechanisms governing loudness and masking.

2. Description of Experiments

A. Stimuli, Apparatus, and Subjects

Stimuli, apparatus, and subjects were the same as those described in Section I, except that single tones at 250, 1000, 2000, and 3000 Hz were added to low-pass noise and tones at 250 and 3000 Hz were added to high-pass noise. Figure 12 shows the frequency characteristic of the noises and the location of the tones within the spectra. The values of SPLs for both noise and tones that were used to produce the specified tone-to-noise ratios at each of the six tone-noise spectral combinations studied in this section are shown in Table I and in greater detail in Tables 5 to 10 in Appendix A. Listening was binaural through a calibrated pair of TDH-49 earphones mounted in MX-41/AR cushions. The earphones produced an essentially flat response (± 1.5 dB) between 100 and 5000 Hz; the high-pass noise bandwidth was limited only by the earphone response.

B. Procedures

The experimental procedures were analogous to the ones outlined in Section I. As in Section I, judgments of overall perceived magnitude were obtained mainly by absolute magnitude estimation (AME) according to the instructions given in IB. Following threshold evaluations, ten listeners with normal hearing judged the absolute loudness, annoyance, and noisiness of at least one tone-noise spectral combination shown in Fig. 12. Loudness judgments always preceded annoyance and noisiness judgments.

3. Results and Discussion

A. Relation Between Overall Sound Pressure Level and Tone-To-Noise Ratio

Loudness, annoyance, and noisiness growth behavior (perceived magnitude) typically produced by tones located within the noise spectrum was shown in Figs. 2 and 3. More summation between tone and noise was found for

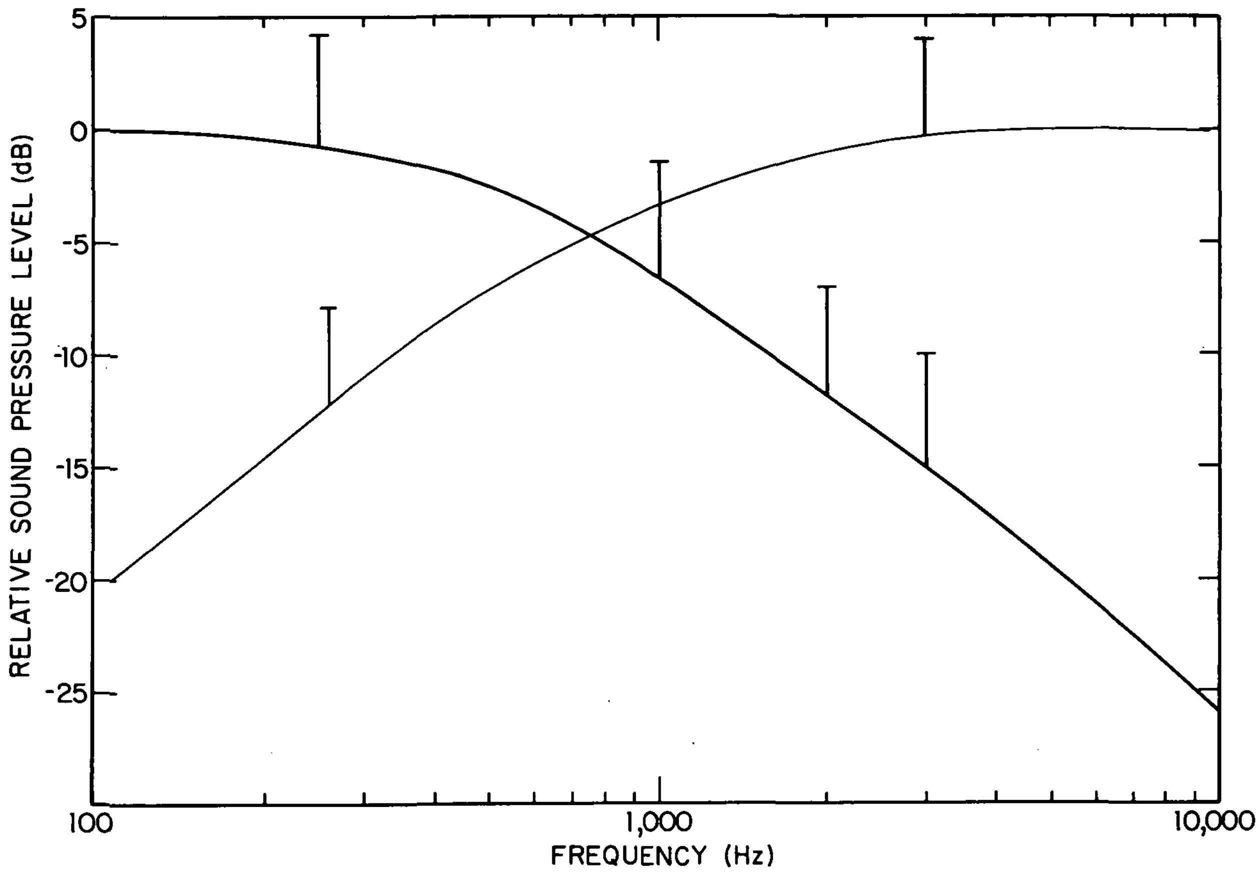

Figure 12. Frequency characteristic of low- and high-pass spectra.

relatively small tone-to-noise ratios (≤ +15 dB), as measured in 1/3-octave bands, than for relatively large tone-to-noise ratios (≥ +20 dB). By comparison, when tones are added to the noise skirt of either high- or low-pass noise, only noisiness exhibits strong nonmonotonic growth behavior. On double logarithmic coordinates, loudness and annoyance produce linear growth functions that are approximated by power functions. These results are seen in Fig. 13 for a 1000-Hz tone and in Fig. 14 for a 3000-Hz tone, both added to low-pass noise. The difference between noisiness on the one hand, and loudness and annoyance on the other, is quite striking. Figures 13 and 14 also show that, although loudness and annoyance are governed by power functions, annoyance yields a power function that is steeper than the one measured for loudness. Group mean loudness estimates at 1000 Hz obey a power function of sound pressure with an exponent (slope) of 0.63; those at 3000 Hz obey a power function with an exponent of 0.92. The corresponding exponents (slopes) for annoyance are 0.95 at 1000 Hz and 1.1 at 3000 Hz. Similar results were also obtained with a 2000-Hz tone added to low-pass noise, and with a 250-Hz tone added to high-pass noise. (See Appendix A, for group GMs obtained for the entire data set.)

Power functions imply that loudness and annoyance primarily depend on the overall SPL of the noise-tone complex. Large tone-to-noise ratios do not produce decrements in perceived magnitude, as they do for noisiness or, for tones located within the noise spectrum. Thus, irrespective of tone-to-noise ratio, an increase in overall SPL generally increases the overall loudness and annoyance of the sound. But what about the loudness and annoyance of two sounds presented at approximately the same overall SPL? Do listeners perceive a difference in magnitude on the basis of tone-to-noise ratio? An answer to this question requires an assessment of loudness and annoyance estimates produced by tone-noise combinations at nearly the same overall SPL, with tone-to-noise ratio as the independent variable.

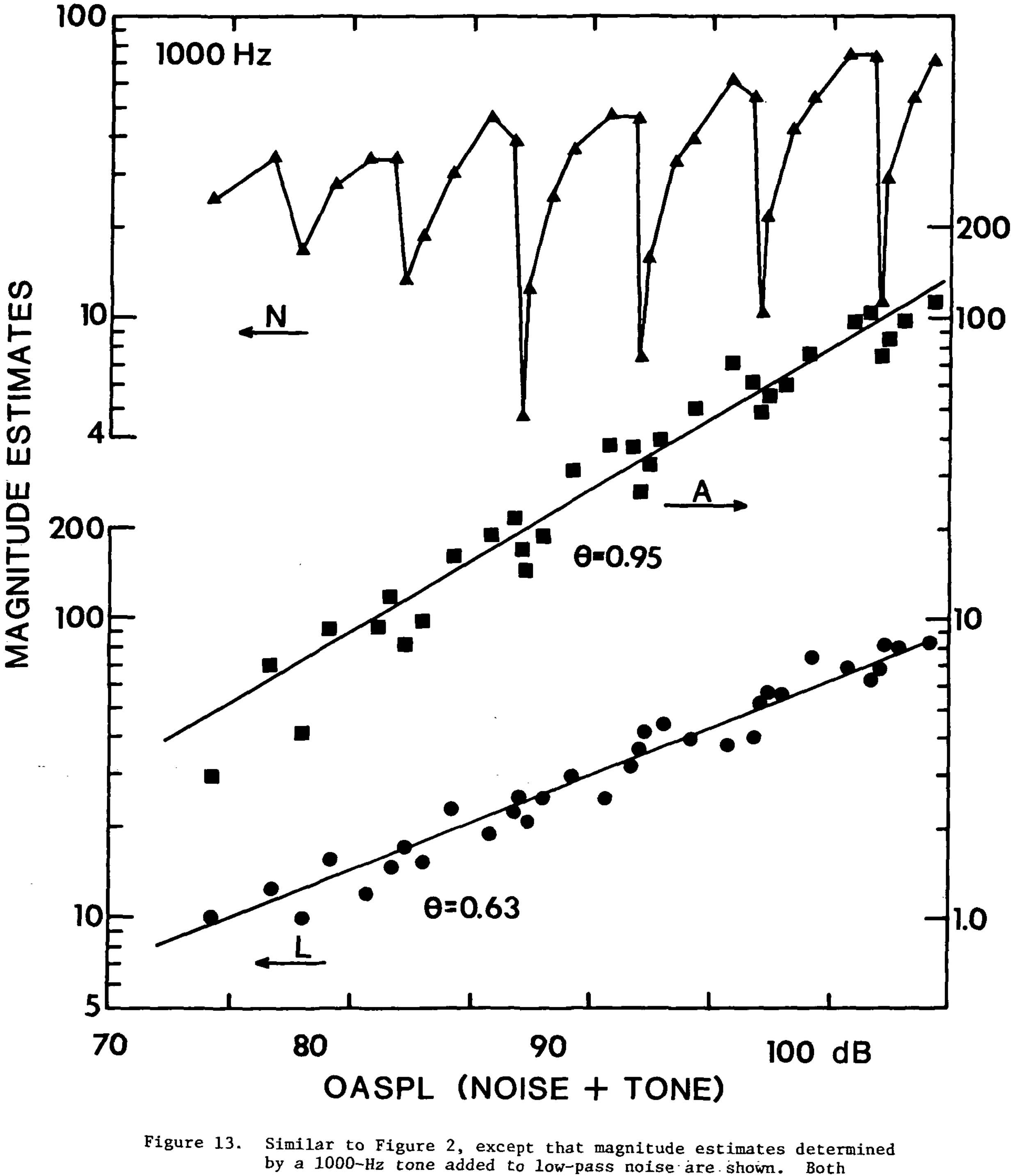

Figure 13. Similar to Figure 2, except that magnitude estimates determined by a 1000-Hz tone added to low-pass noise are shown. Both loudness and annoyance are described by power functions.

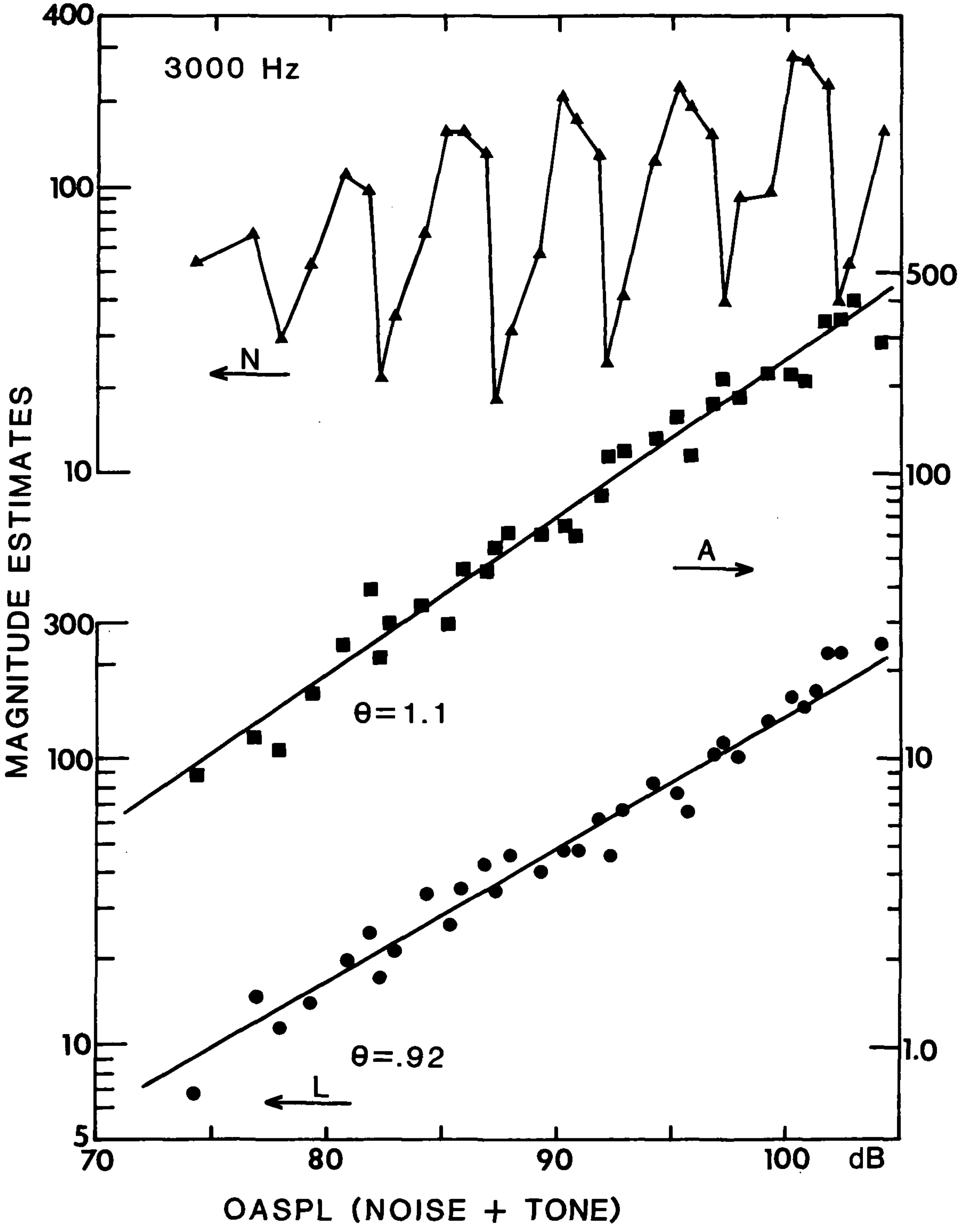

Figure 14. Similar to Figure 2, except that magnitude estimates determined by a 3000-Hz tone added to low-pass noise are shown. Both loudness and annoyance are described by power functions.

Figures 15 to 19 depict the relationship between perceived magnitude and tone-to-noise ratio for tone-noise combinations at a given overall SPL. Circles indicate loudness judgments, triangle indicate annoyance judgments, and squares indicate noisiness judgments. Each point is again based on the GMs of 20 judgments by the group of ten listeners. The parameter is the overall SPL of the noise-tone complex. All points along each curve were obtained at about the same overall SPL.

Figure 15 shows the results for a 250-Hz tone added to low-pass noise. Parallel curves were fitted to the data. They show that, for all three attributes, overall perceived magnitude peaks near a tone-to-noise ratio of +5 dB, and then decreases by one half at a ratio of +25 dB. The decrease continues up to a tone-to-noise ratio of +30 dB, the limit of these measurements.

Figure 16 is analogous to Fig. 15, except that the 250-Hz tone was combined with high-pass noise. Few data at small tone-to-noise ratios are available because the 1/3-octave-band-pressure level of the 250-Hz tone, corrected by the width of the critical band at low frequencies (Kryter, 1970; Searle et al., 1979), is 34 dB below the overall SPL of the noise. Nevertheless, at overall SPLs of 90 dB and above, noisiness decreases as tone-to-noise ratio increases beyond about +15 dB. Loudness and annoyance follow a different pattern and continue to increase up to a tone-to-noise ratio of at least +35 dB. Notice also, that at all overall SPLs, loudness exceeds annoyance. For tone-to-noise ratios of +20 dB and greater, the loudness increase relative to annoyance is independent of the overall SPL of the noise-tone complex ($r_{xy} = +.42$, $P > .05$).

A divergence between loudness and annoyance on the one hand, and noisiness on the other, becomes even more apparent as the tone frequency is progressively shifted within the low-pass spectrum. Figure 17 shows results

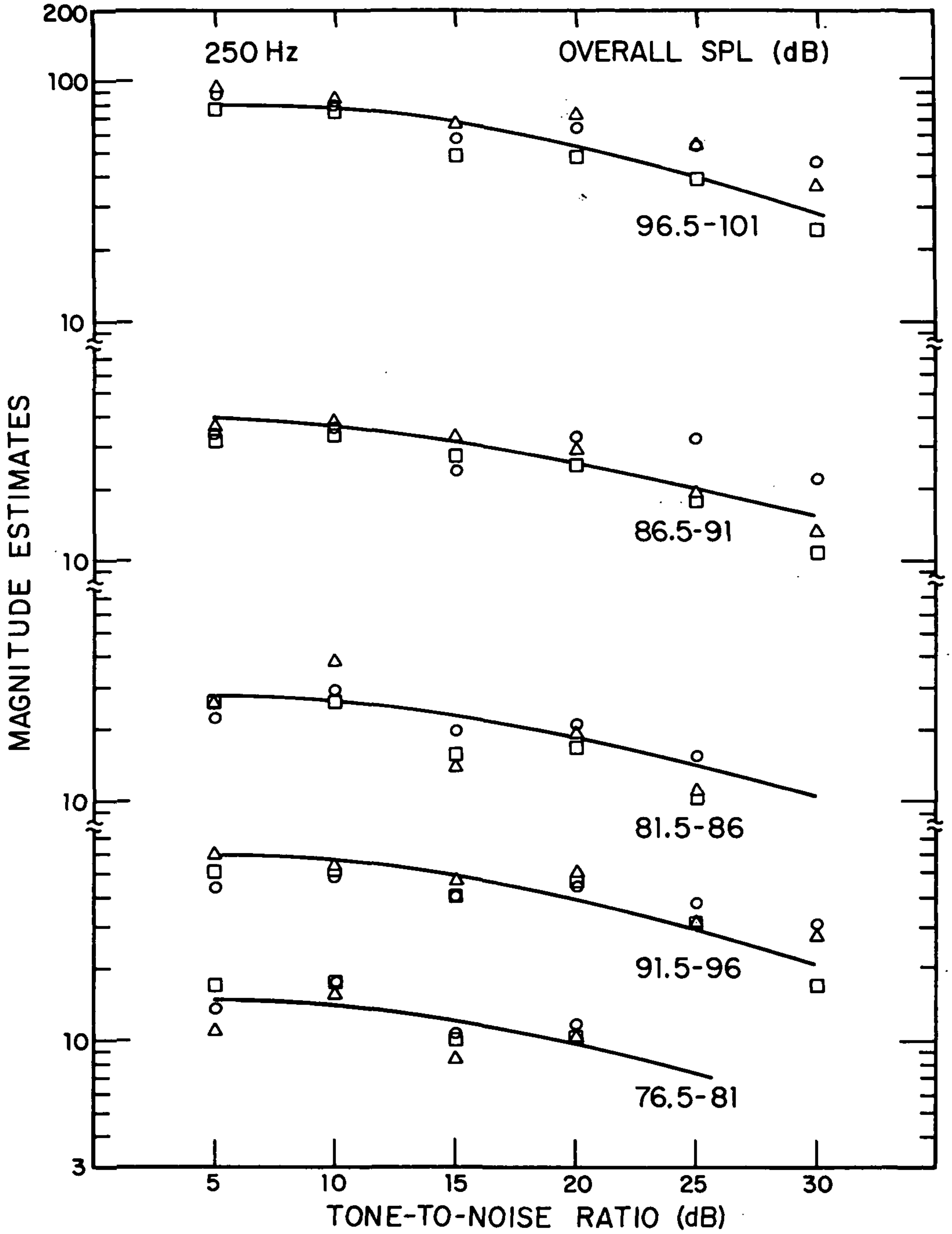

Figure 15. Relationship between perceived magnitude and tone-to-noise ratio for a 250-Hz tone combined with low-pass noise. Each point is based on the geometric mean of 20 judgments by the group of ten listeners. Circles indicate loudness judgments, triangles indicate annoyance judgments, and squares indicate noisiness judgments. The parameter is the overall SPL of the noise-tone complex. All points along each curve were obtained at about the same overall SPL.

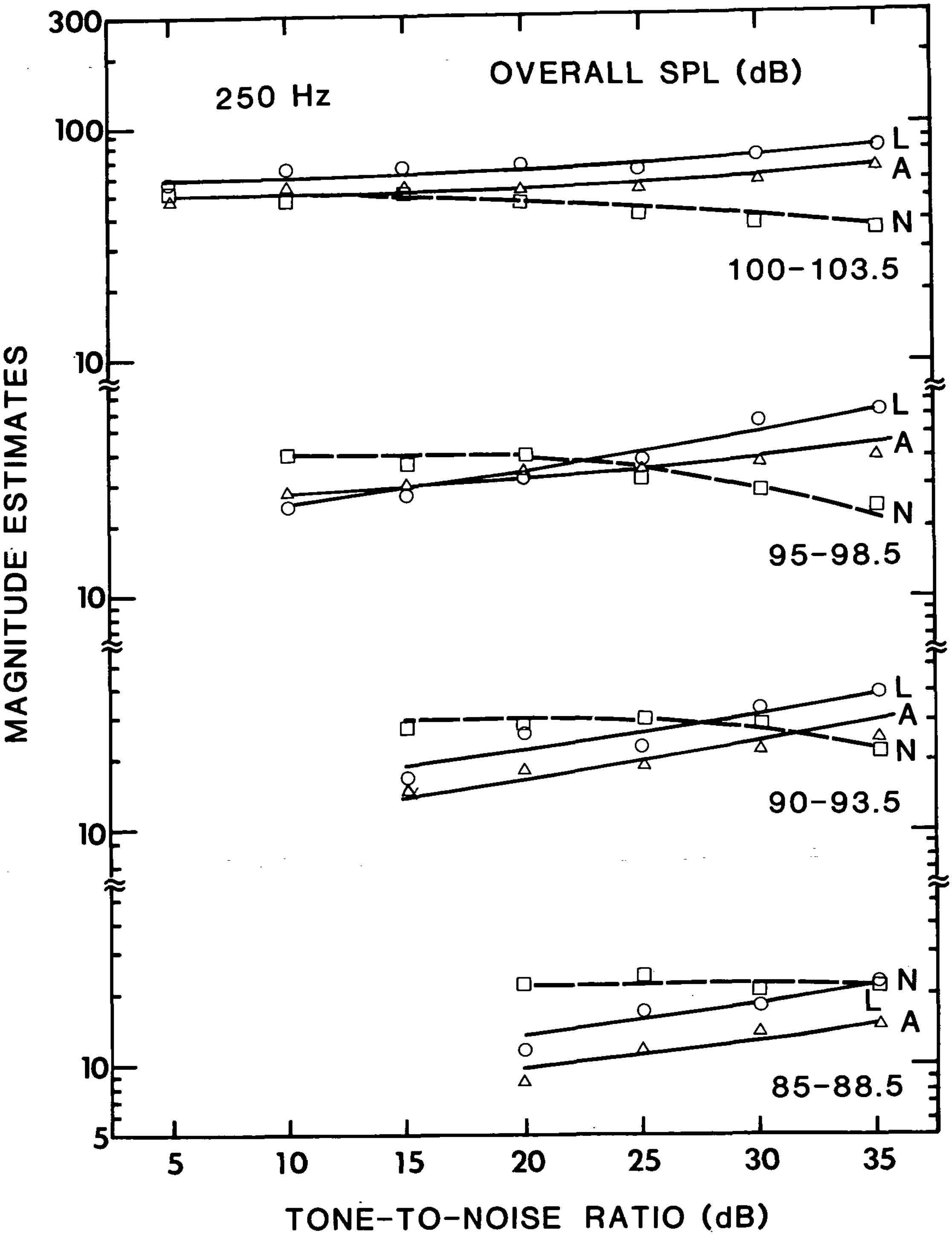

Figure 16. Relationship between perceived magnitude and tone-to-noise ratio for a 250-Hz tone combined with high-pass noise. Plot similar to that in Figure 15.

measured at 1000 Hz. As found at 250 Hz, noisiness peaks near a tone-to-noise ratio of +5 dB, and then decreases as tone-to-noise ratio increases. Unlike noisiness, loudness and annoyance increase up to a tone-to-noise ratio of +15 dB. For ratios that exceed +15 dB, loudness and annoyance decrease slightly reaching an asymptotic value which appears to extend to a tone-to-noise ratio as large as +35 dB.

Results at 2000 Hz, shown in Fig. 18, are very similar to those at 1000 Hz in Fig. 17; both show that loudness and annoyance reach a maximum at a tone-to-noise ratio of +15 dB. However, in contrast to the 1000-Hz results, annoyance is consistently greater than loudness. Whereas at 1000 Hz, annoyance is greater than loudness only above 100 dB SPL, at 2000 Hz annoyance exceeds loudness, particularly for large tone-to-noise ratios (greater than +20 dB), over the whole range of SPLs covered in this study ($r_{xy} = +.23$, $P > .05$).

The most dramatic effect of tone-to-noise ratio is observed at 3000 Hz in Fig. 19. Like the data obtained at lower frequencies, noisiness decreases continuously as tone-to-noise ratio increases, but loudness and annoyance increase as tone-to-noise ratio increases, more at high than at moderate overall SPLs, beyond a ratio of +15 dB. (These effects are also evident in Fig. B-2.) Furthermore, in accord with the 2000-Hz data, averaged across overall SPLs annoyance exceeds loudness by about 1.4, equivalent to a decibel increment (re an exponent of 0.57) of about 5 dB. But the ratio of annoyance-to-loudness tends to increase with overall SPL for tone-to-noise ratios less than +15 dB ($r_{xy} = +.67$, $P < .05$), while it remains independent of overall SPL for ratios greater than +20 dB ($r_{xy} = +.46$, $P > .05$). (See Tables 3 to 5 in Appendix B for a detailed correlational analysis of the entire data set.)

Several important differences are seen between the 3000-Hz data and those obtained with a 250-Hz tone added to high-pass noise (compare Figs.

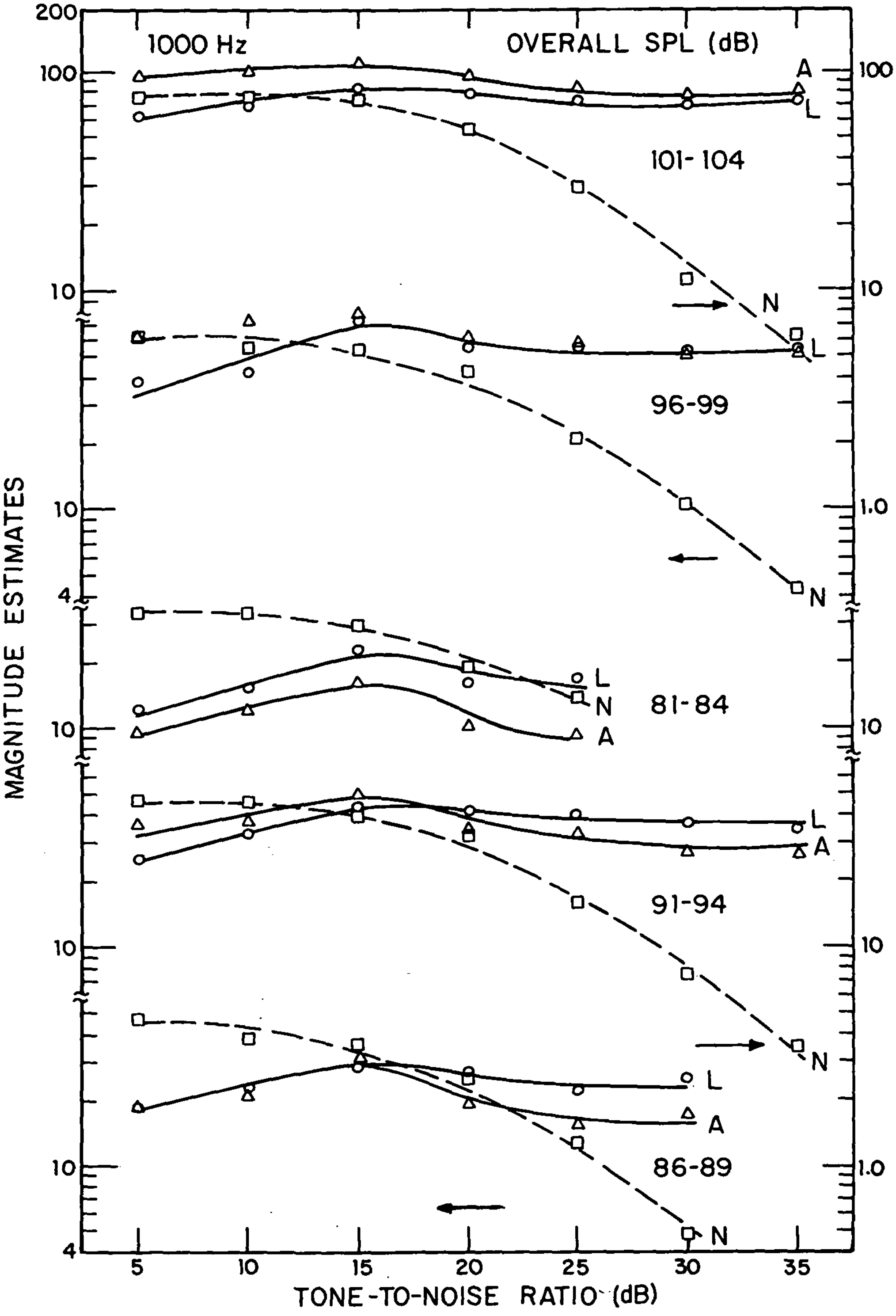

Figure 17. Relationship between perceived magnitude and tone-to-noise ratio for a 1000-Hz tone combined with low-pass noise. Plot similar to that in Figure 15.

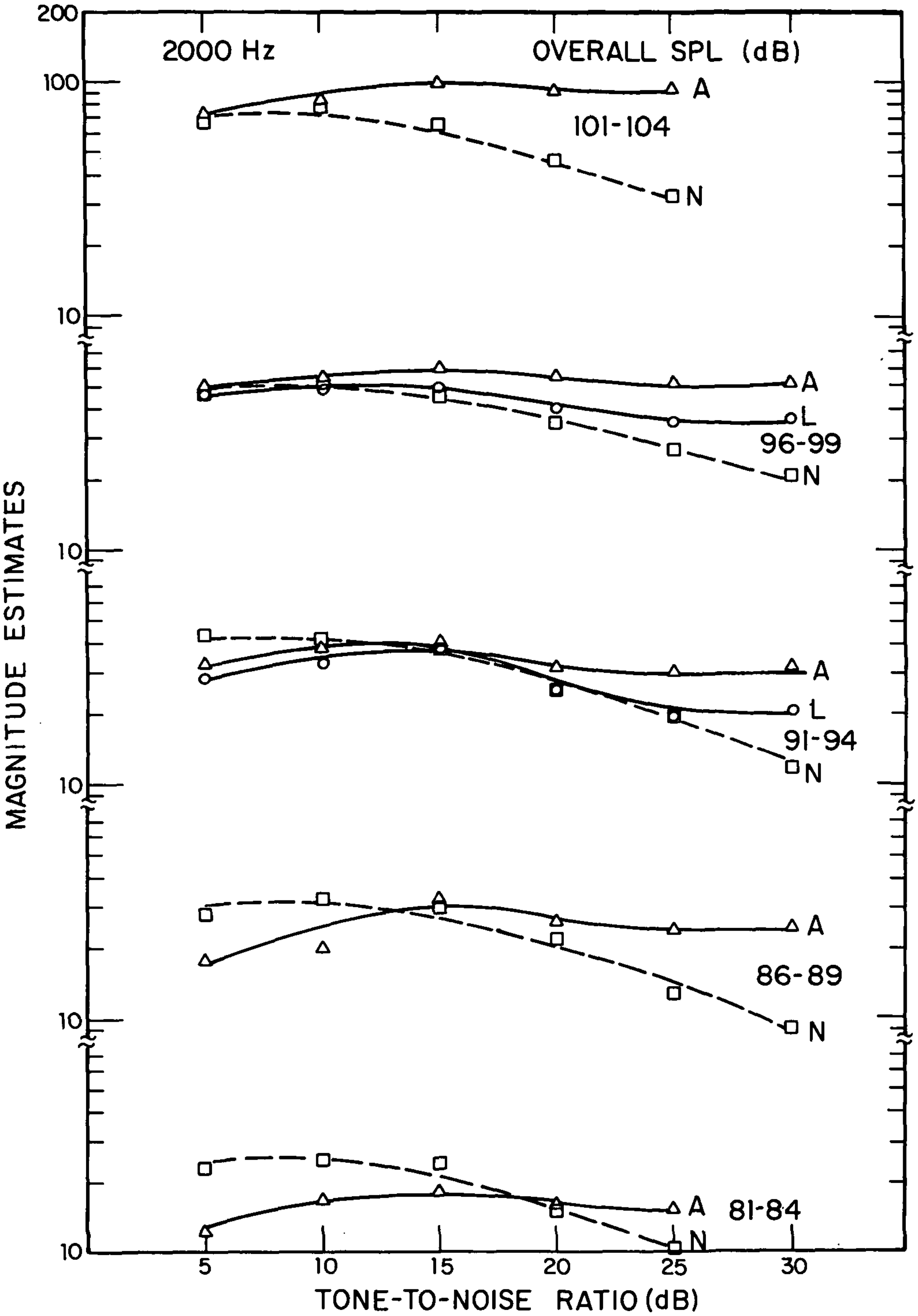

Figure 18. Relationship between perceived magnitude and tone-to-noise ratio for a 2000-Hz tone combined with low-pass noise. Plot similar to that in Figure 15.

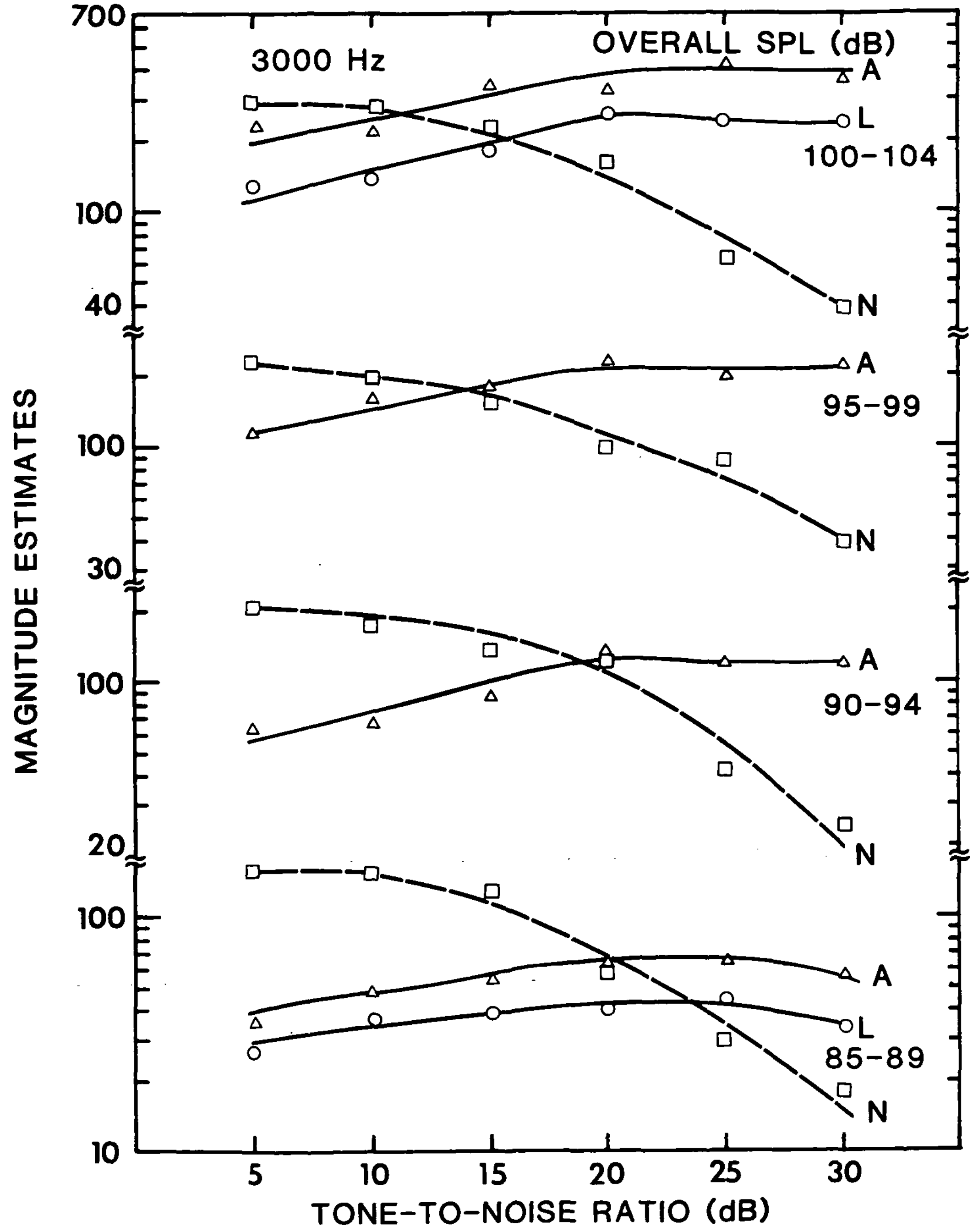

Figure 19. Relationship between perceived magnitude and tone-to-noise ratio for a 3000-Hz tone combined with low-pass noise. Plot similar to that in Figure 15.

16 and 19). First, the change in noisiness as a function of tone-to-noise ratio is less marked with the 250-Hz than with the 3000-Hz tone. Second, in contrast to the results obtained at 3000 Hz, annoyance never exceeds loudness. Third, whereas the addition of a 250-Hz tone to high-pass noise increases loudness and annoyance up to a tone-to-noise ratio of +35 dB, loudness and annoyance at 3000 Hz reach a maximum near a ratio of +20 dB. Beyond a ratio of +20 to +25 dB, loudness and annoyance seem to level off, and may acutally decrease slightly below an overall SPL of 90 dB.

Taken together, Figs. 13 to 19 show that, although power functions may provide an adequate first order approximation of data obtained with tones added to the noise skirt, when the overall energy of the complex is nearly constant loudness and annoyance are also a function of tone-to-noise ratio. The magnitude of the effect is dependent on the particular tone-noise configuration studied. Moreover, annoyance is more closely related to loudness than to noisiness. Matched at the same overall SPLs and the same tone-to-noise ratios, the absolute numerical loudness and annoyance estimates of the 3000-Hz noise-tone complex are significantly larger than those produced by tones added at lower frequencies ($p < .05$ by Wilcoxon test), meaning that the loudness and annoyance of the 3000-Hz complex have actually increased (Hellman and Zwislocki, 1961; Zwislocki and Goodman, 1980). This result provides support for a loudness summation hypothesis. The increase in loudness and annoyance measured at 3000 Hz as a function of tone-to-noise ratio may be primarily due to the wider frequency spacing between the predominantly low-frequency noise and the added tone (Scharf, 1978). The corresponding increase at 250 Hz suggests that at high SPLs as the tone's excitation extends into the frequency region of the high-pass noise, the tone interacts with the noise and becomes the dominant component in the complex, thereby increasing its overall loudness. In addition, the results indicate that a tone correction for perceived annoyance is needed for tones added to low-pass noise, but not for tones added to high-pass noise, as seen in Fig. 16 and in Section I.

B. Growth Rate as a Function of Tone-To-Noise Ratio

To better understand the relation between the spectral shape of the noise and the location of the tone within the spectrum, the data were further analyzed to determine whether loudness and annoyance growth rates are a function of tone-to-noise ratio. Vertical cuts across SPL in Figs. 15 to 19 suggest that the slopes of the loudness- and annoyance-growth functions are dependent on tone-to-noise ratio when tones are added to the noise skirt, but not when they are centered within the spectrum. On the other hand, for those noises studied, the relation between noisiness growth rate and tone-to-noise ratio seems to be independent of the position of the tone in the noise.

These results, coupled with the unusually steep loudness and annoyance functions seen in Figs. 13 and 14, indicated that a more complete analysis of loudness and annoyance was warranted. Even though the measured stimulus range was only 30 dB, the loudness exponent, specifically, was expected to be of the order of 0.60 re sound pressure (Stevens, 1975; Teghtsoonian and Teghtsoonian, 1978). Although the loudness exponent at 1000 Hz is about 0.60, the exponent of 0.92 at 3000 Hz is outside of the range of values typically found (Marks, 1974). Hence, both for individual listeners and the group, loudness and annoyance growth rates as a function of the overall SPL of the complex were computed for a fixed tone-to-noise ratio.

Figure 20 contrasts loudness judgments produced at tone-to-noise ratios of +10 and +30 dB by a 3000-Hz tone combined with both low- and high-pass noises. The filled points were determined with the low-pass noise and the unfilled points were determined with the high-pass noise. Tone-to-noise ratios of +10 and +30 dB were selected for illustrative purposes because

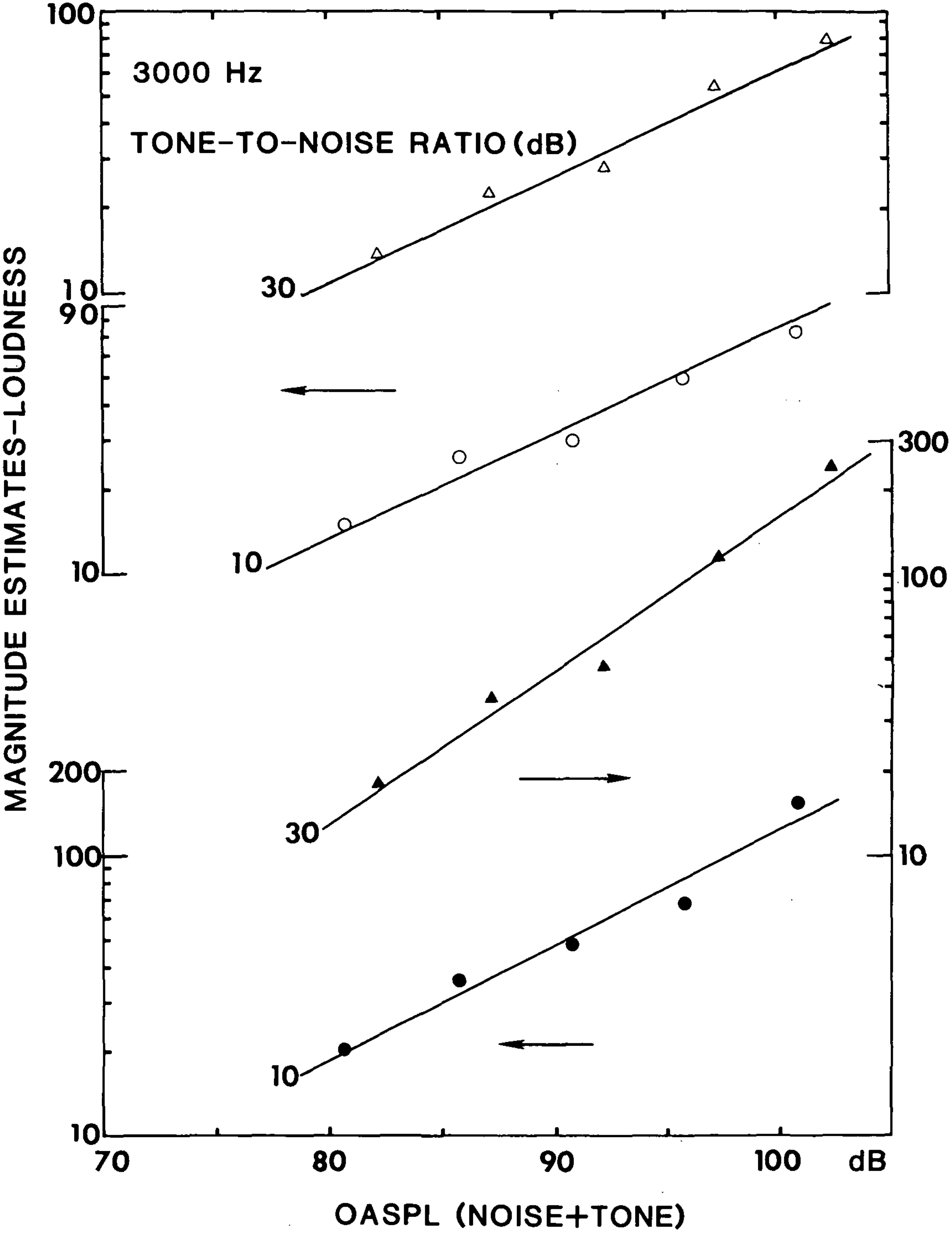

Figure 20. Loudness growth rate at 3000 Hz. Filled and unfilled symbols indicate results obtained with low- and high-pass noise, respectively. Circles represent group means at a tone-to-noise ratio of +10 dB; triangles represent means at a tone-to-noise ratio of +30 dB.

growth behavior could be evaluated over equivalent stimulus ranges. Analysis of the results in Fig. 20 shows that, when a 3000-Hz tone is combined with low-pass noise, loudness increases as a power function of sound pressure with an exponent of 1.1 at a tone-to-noise ratio of +30 dB, and with an exponent of 0.80 at a tone-to-noise ratio of +10 dB. Therefore, the larger ratio of +30 dB yields a steeper function than the ratio of +10 dB. By comparison, the curves determined with the same tone combined with the high-pass noise are equally steep. They approximate power functions of sound pressure with an exponent of 0.75.

Figure 21 is analogous to Fig. 20, except that a 250-Hz tone was combined with the low- and high-pass noises. Again, stimulus ranges were selected to be as nearly comparable as possible. Figure 21 shows that the addition of the low-frequency tone to the same shaped noise spectra alters the growth rate of loudness as a function of tone-to-noise ratio. When the 250-Hz tone is combined with low-pass noise (filled symbols), the curves determined by tone-to-noise ratios of +5 and +20 dB are equally steep. They approximate power functions of sound pressure with an exponent of 0.66. However, the addition of the 250-Hz tone to high-pass noise (unfilled symbols), reveals that loudness increases as a power function of sound pressure with an exponent of 0.86 at a tone-to-noise ratio of +20 dB, and with an exponent of 0.70 at a tone-to-noise ratio of +35 dB. Added to high-pass noise, the low-frequency tone yields a steeper function when the tone-to-noise ratio is at +20 dB than when it is increased to +35 dB.

Essentially the same results as those shown in Figs. 20 and 21 for loudness were found for annoyance. (See Figs. B-3 and B-4, and Table B-1.) Table B-1 shows in greater detail the power function exponents obtained as a function of tone-to-noise ratio for all the low-pass and high-pass tone-noise spectral combinations studied. Individual loudness and annoyance functions are consistent with those for the group, so that the results are

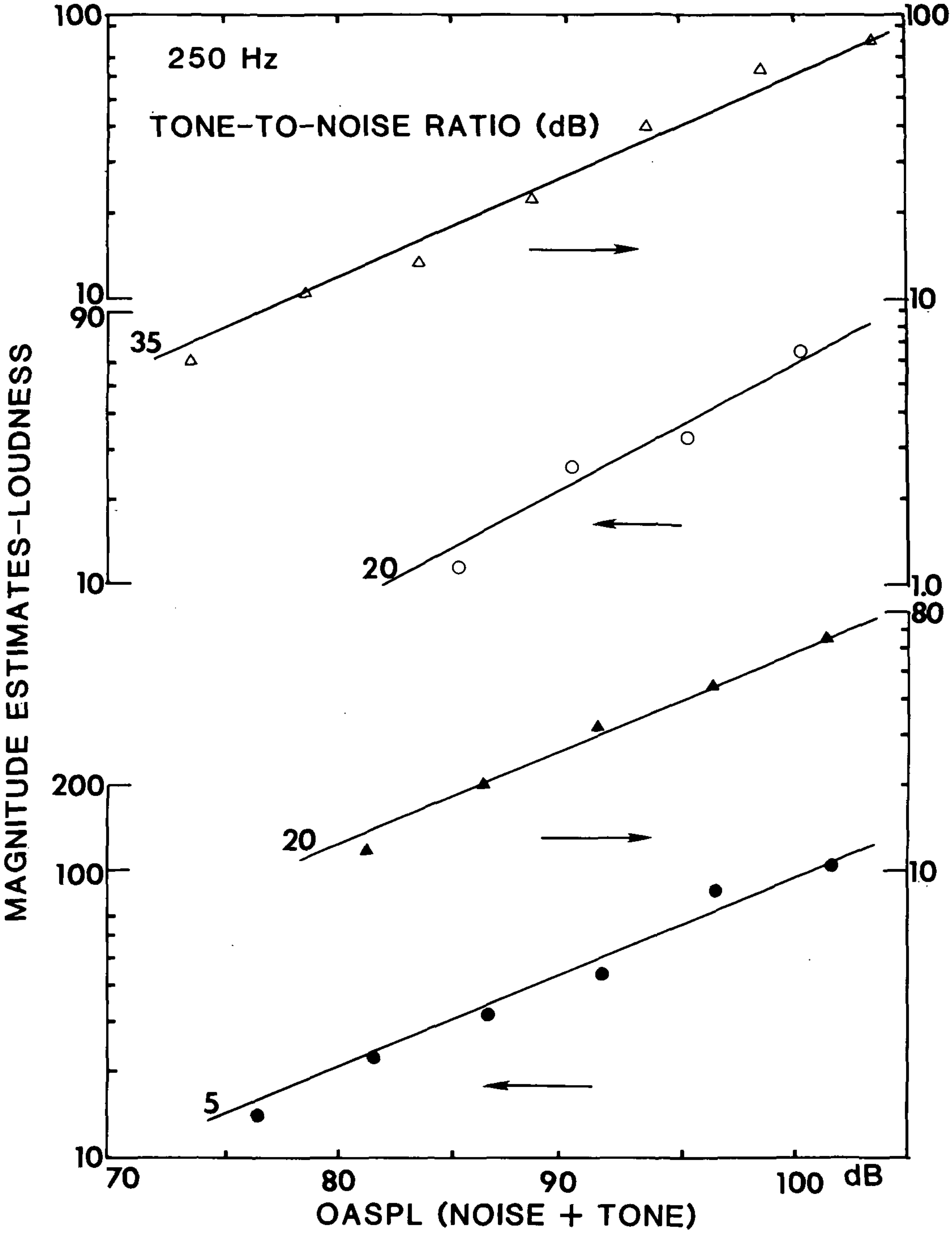

Figure 21. Loudness growth rate at 250 Hz. Filled and unfilled symbols indicate results obtained with low- and high-pass noise, respectively. With low-pass noise, group means at tone-to-noise ratios of +5 and +20 dB (filled circles and triangles) are shown. With high-pass noise, group means at tone-to-noise ratios of +20 and +35 dB (unfilled circles and triangles) are shown.

probably not due to averaging. They suggest that the growth rate of loudness and annoyance is a function of the position of the tone within the spectrum.

Figure 22 summarizes loudness results observed across frequency. Power-function exponents obtained with pure tones added to low-pass noise are indicated by the unfilled points; exponents obtained with tones added to high-pass noise are indicated by the filled points. Three results are noted. First, when the tone is centered within the spectrum the loudness exponent is invariant across tone-to-noise ratio. Second, as the tone's frequency is progressively shifted from 250 to 2000 Hz within the low-pass spectrum, the power-function exponents gradually increase as tone-to-noise ratio increases. The value of the exponents range from 0.6, the established slope of the loudness function (ISO/R 131-1959), to about 0.8. Third, the addition of a pure tone further along the tail of the noise skirt markedly alters the loudness slope. A least-squares fit to the data shows that a linear function describes the relationship between the measured exponents and tone-to-noise ratio. The addition of a 3000-Hz tone to low-pass noise systematically increases the exponents as tone-to-noise ratio increases ($r_{xy} = +.99$), whereas the addition of a 250-Hz tone to high-pass noise decreases the exponents ($r_{xy} = +.98$). It also seems of interest to mention that the slopes of the regression functions are nearly equal, but opposite in sign.

Figure 23 shows, in accord with Figs. 13 and 14, that the power-function exponents measured for annoyance tend to be larger than those measured for loudness. Otherwise, the relationship found between the obtained exponents and tone-to-noise ratio is the same.

The invariance of loudness exponents across tone-to-noise ratio for tones embedded within the noise is consistent with results determined from an earlier study of overall loudness of noise-tone complexes (Fishken, 1971).

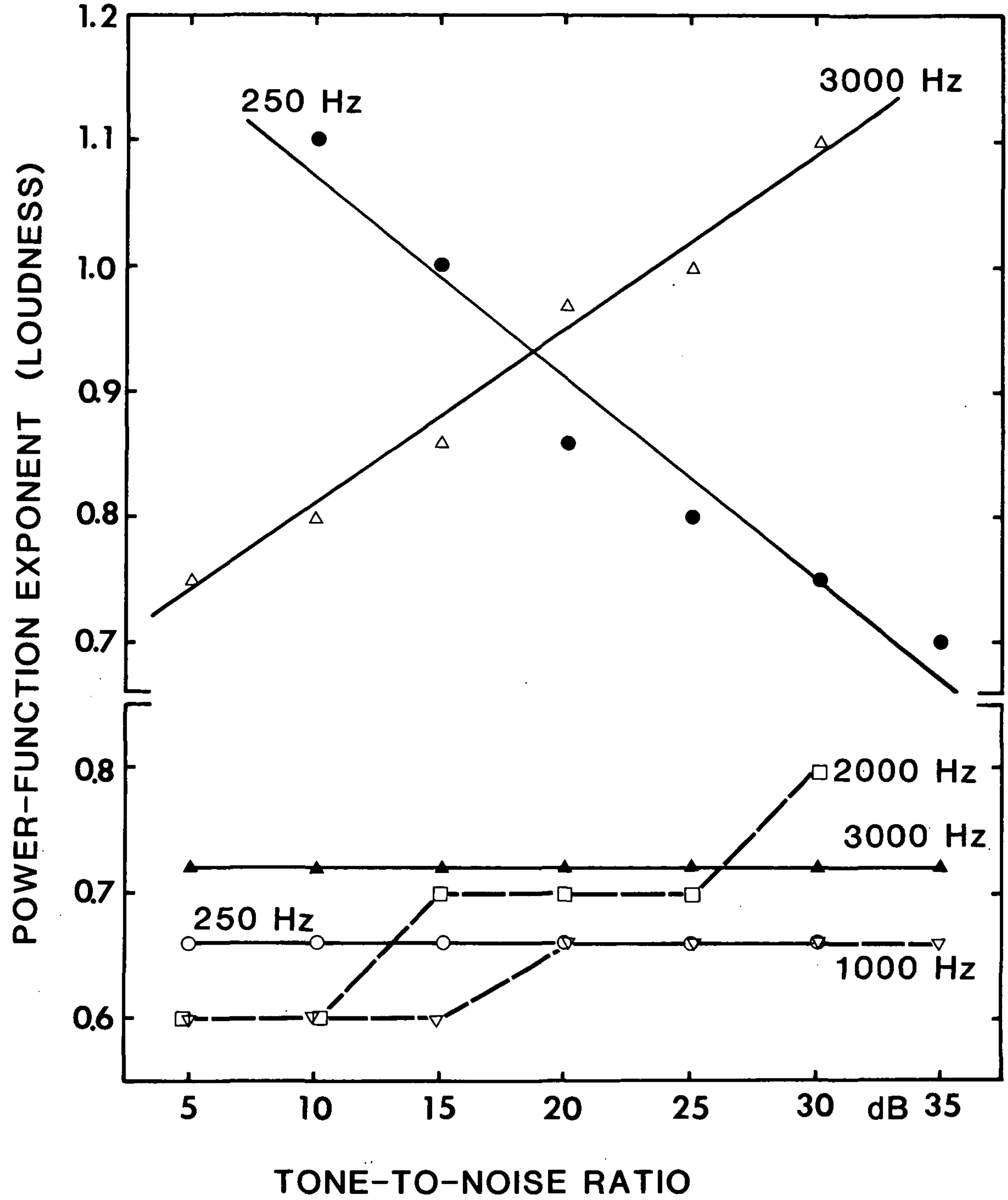

Figure 22. Loudness exponents across frequency as a function of tone-to-noise ratio. Filled symbols indicate exponents determined by pure tones combined with high-pass noise. Unfilled symbols indicate exponents determined by pure tones combined with low-pass noise. The linearly increasing and decreasing functions were determined by a least-squares fit to the data.

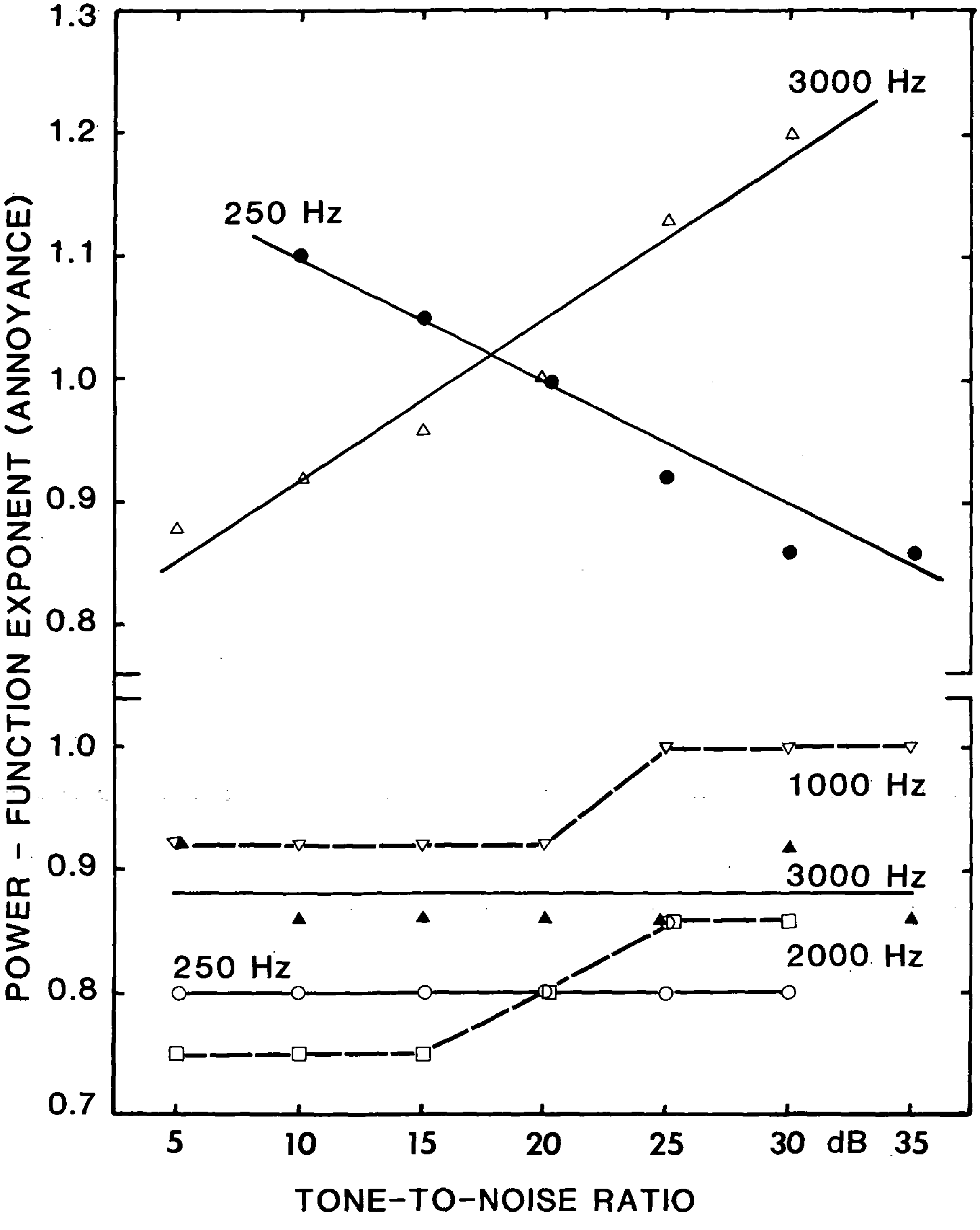

Figure 23. Annoyance exponents across frequency as a function of tone-to-noise ratio. Plot similar to that in Figure 22.

In agreement with previous findings (Hellman, 1974), the data also hint that, when a 250-Hz tone is combined with an equally intense high-pass noise, the loudness exponent is determined mainly by the tone. However, no study seems to show how the loudness growth rate of the complex varies as a function of tone-to-noise ratio when the tone's position is shifted within the noise spectrum. Although power-function exponents cannot be precisely estimated on the basis of a single psychophysical procedure (S.S. Stevens, 1959, 1975), the data trend is compatible with the asymmetry and nonlinear growth behavior of excitation patterns known to be produced by auditory stimuli at high sound intensities (e.g., Egan and Hake, 1950; Ehmer, 1959; Greenwood, 1971, 1972; Kiang and Moxon, 1974; Zwicker, 1970; Zwicker and Scharf, 1965; Zwislocki, 1978).

At the very high SPLs used in this study, the excitation evoked in the ear by an auditory stimulus spreads much more toward high than toward low frequencies (e.g., Egan and Hake, 1950; Zwicker, 1970). As the stimulus level is increased, the asymmetrical spread of excitation becomes more extensive so that at 100 dB SPL, virtually the entire high frequency region of the basilar membrane is activated. Moreover, neither the high- nor the low-frequency excitation patterns increase in direct proportion to increases in stimulus level. Rather, the excitation growth rate is greater than 1.0 at frequencies above the center frequency of the activating stimulus, whereas it is less than 1.0 at lower frequencies (Egan and Hake, 1950; Scharf, 1971; Zwicker, 1958; Zwislocki, 1978). The simultaneous addition of an intense pure tone to the skirt of low- or high-pass noise increases the complexity of these effects.

How do the excitation patterns evoked by the tone and noise combine to produce an overall perceived magnitude? When a high frequency tone is added to low-pass noise, each stimulus produces an excitation pattern that is broadly skewed toward high frequencies. Since the frequency separation between the tone and the predominantly low-frequency noise is sufficiently wide, both stimuli should contribute to the overall loudness of the complex, more for large than for small tone-to-noise ratios. Just the opposite probably occurs when a low-frequency tone is added to high-pass noise. Then, we are dealing with the effects of partially separate excitation patterns only at small tone-to-noise ratios. As tone-to-noise ratio increases, more of the excitation elicited by the noise is overlapped by the tone's excitation pattern, substantially reducing the contribution of the noise to the overall loudness and thus, the loudness growth rate of the complex (Hellman, 1974; Scharf, 1964; Zwicker and Scharf, 1965).

To further complicate matters, combination components are known to be generated at high SPLs by the simultaneous presentation of noise and tone (Greenwood, 1971, 1972). We do not yet understand what effects these components may have on the overall loudness and annoyance of the complex. It is possible that the presence of combination components as well as the nonlinear excitation growth behavior, both alter the loudness and annoyance growth rates in the direction observed experimentally.

4. Summary of Findings

The relation between overall loudness, annoyance, and noisiness (perceived magnitude) of noise-tone complexes and the location of the tone within the spectrum was investigated by absolute magnitude estimation (AME). Overall perceived magnitude produced by single tones combined with low- and high-pass noises is described and assessed. The results disclose that, in contrast to noisiness, loudness and annoyance growth is dependent on the relationship between the frequency of the added tone and the spectral shape of the noise. Tone centered in noise produce nonmonotonic loudness and annoyance growth functions; those added to the noise skirt produce power functions. The measured exponents are invariant across tone-to-noise ratio when the tones are located within the noise spectrum, but not when they are added to the skirt. A high-frequency tone combined with low-pass noise increases the loudness and annoyance growth rates as tone-to-noise ratio increases. Conversely, a low-frequency tone combined with high-pass noise decreases the loudness and annoyance growth rates with increases in tone-to-noise ratio. In addition, when the overall SPL of the noise-tone complex is approximately constant, the position of the tone within the spectrum determines the functional relationship between loudness (or annoyance) and tone-to-noise ratio. These findings, as well as those described in Section I, indicate that although loudness, annoyance, and noisiness often produce distinctly different results, annoyance is more closely related to loudness than to noisiness.

The close correspondence between loudness and annoyance suggests in agreement with other studies (Berglund et al., 1976, 1981; Powell, 1979c; Scharf, 1974), that loudness is the primary component of annoyance. Moreover, the outcome of this investigation provides some clarification of the discrepancy between the results of Pearsons et al. (1969) and those of Hargest and Pinker (1967). In agreement with Hargest and Pinker (1967), tones added along the noise skirt in the vicinity of 2000 Hz produce an increase in judged annoyance up to a tone-to-noise ratio of +15 dB, but the decrease obtained for larger tone-to-noise ratios is not continuous as their data suggest. Rather, perceived loudness and annoyance peak at a tone-to-noise ratio of +15 dB, and then decrease slightly reaching an asymptotic value that is maintained for ratios larger than +20 dB. Only when the frequency separation between the added tone and the predominantly low-frequency noise is sufficiently wide, do annoyance and loudness judgments continue to increase beyond a ratio of +15 dB. In the present study, this occurs when the added tone is at 3000 Hz. Then, consistent with the results of Pearsons et al. (1969), the increase in perceived magnitude extends to a tone-to-noise ratio of about +25 dB. The greater effect found at 3000 Hz is attributed mainly to an increase in loudness summation between noise and tone. The relation of these findings, together with those observed in Section I, to proposed tone-correction procedures is discussed below in Section III.

III. Relation to Proposed Tone Corrections

Calculation procedures that deal specifically with the effect of pure tones on overall annoyance of noise all consider the relationship between perceived annoyance and tone-to-noise ratio (FAR 36, 1969; Kryter and Pearsons, 1965; Little, 1961). The amount by which the tone exceeds the noise is usually calculated relative to the 1/3-octave-band pressure level in the noise band that contains the identified tone. Except for the tentative procedure, the various procedures also include a correction for tone frequency by adding the largest correction for tones that lie in the frequency range between 500 and 5000 Hz (for further details see Scharf and Hellman, 1979). However, Stevens's procedure uniquely considers the SPL in the 1/3-octave band, adding a larger correction at low- than at high-noise levels. Thus, irrespective of frequency, a tone that protrudes 20 dB above a 1/3-octave-band noise at 30 dB SPL requires a correction of 9 dB, whereas 20 dB above a noise band at 90 dB SPL the tone correction amounts to 2 dB. By comparison, for mid-frequency tones at a tone-to-noise ratio of +20 dB the FAR 36 (1969) procedure recommends a maximum correction of 6.67 dB. The largest tone correction, in close agreement with Little's (1961) value, is recommended by Kryter and Pearsons (1965) who show that this maximum occurs at a tone-to-noise ratio of +25 dB. Furthermore, the added correction increases continuously with frequency reaching a peak of almost 15 dB at 4000 Hz.

None of the proposed tone-correction procedures appear to include all of the variables relevant to perceived annoyance of noise-tone complexes. The results of this investigation show that the magnitude of the tone correction depends on the frequency of the added tone, tone-to-noise ratio, the overall SPL of the noise-tone complex, the spectral shape of the noise, as well as the location of the tone within the spectrum. Hence, each of the proposed tone-correction procedures has limited usefulness.

Table III shows the maximum tone correction estimated for annoyance of the ten noise-tone configurations studied.[5] The total annoyance correction estimated for the tone consists of the sum of the maximum annoyance and loudness increments, both in decibels. The loudness increment was obtained from Table II and from Figs. 15 to 19. Conversion to decibels was based on the assumption that, on the average, measured in this study, perceived loudness of noise or tone grows as the 0.57 power of sound pressure (see Figs. 1, 4, 5, and 6, and Tables A-11 to A-14). The average exponent value is very close to 0.60 which is the international standard (ISO R 131-1959). Once the amount of loudness summation was determined, it was then possible to compute the ratios of noisiness-to-loudness (N/L), annoyance-to-loudness (A/L), noisiness-to-annoyance (N/A), and annoyance-to-noisiness (A/N), as a function of the overall SPL of the noise-tone complex and to convert these ratios, like the loudness ratios, into decibels. The results of these computations are shown in detail in Tables B-6 to B-9 for small (≤ +15 dB) and large (≥ +20 dB) tone-to-noise ratios. A range of values means that the decibel change is dependent on the overall SPL of the noise-tone complex, as seen in Figs. 9 to 11 and in Tables B-2 to B-5. Thus, a positive change indicates that an annoyance correction is needed, more at high- than at low-levels, whereas a negative change indicates that loudness exceeds annoyance.

To determine the estimated corrections show in Table III, the maximum annoyance increments were computed from the ratios of A/L in Tables B-6 to B-9 and added, when appropriate, to the measured loudness increments. For example, measured above 95 dB overall SPL, the maximum correction estimated for annoyance of a tone added to broadband-flat noise is 6 dB at 250 Hz, 9 dB at 1000 Hz, and 8 dB at 2000 Hz. No annoyance correction is needed when tones are added at

Table III

Maximum Estimated Tone Correction In Decibels for Annoyance

	Frequency (Hz)			
	250	1000	2000	3000
Noise Spectra	A + L = Sum (dB)	A + L = Sum (dB)	A + L = Sum (dB)	A + L = Sum (dB)
Broadband-flat				
T/N ≤ +15 dB	4 + 2 = 6	7 + 2 = 9	7 + 1 = 8	none
T/N ≥ +20 dB	none	none	none	none
Low-pass				
T/N ≤ +15 dB	2 + 4 = 6	6 + 4 = 10	3 + 3 = 6	6 + 5 = 11
T/N ≥ +20 dB	none	4 + 3 = 7	5 + 0 = 5	6 + 8 = 14
High-pass				
T/N ≤ +15 dB	none	-	-	none
T/N ≥ +20 dB	none	-	-	none

3000 Hz, or, at tone-to-noise ratios equal to or greater than +20 dB. Except at 3000 Hz, the estimated values lie within the same ballpark as those reported by Kryter and Pearsons (1965) when tones at a tone-to-noise ratio of +15 dB are combined with octave bands of noise. By comparison, the addition of a 3000-Hz tone to low-pass noise requires a tone correction for annoyance, and the magnitude of the correction increases with increasing tone-to-noise ratio beyond a ratio of +15 dB. Consistent with Kryter and Pearsons's recommendation, the maximum estimated correction reaches a value as large as 14 dB.

The degree to which the relation between annoyance and tone-to-noise ratio is a function of the location of the tone within the spectrum helps to clarify the puzzling discrepancy between the results described in Section I and those reported by other investigators (e.g., Kryter and Pearsons, 1965; Pearsons et al., 1969). Some light is also shed on the discrepancy observed between the results of Hargest and Pinker (1967) and those of Pearsons et al. (1969). Moreover, since Scharf and Hellman (1979, 1980) did not separately examine the interactive effects produced by tone frequency, spectral shape, and tone-to-noise ratio as they relate to the overall SPL of the noise-tone complex, their failure to demonstrate a clear-cut need for a tone correction is partly explained.

As seen in Table III, whereas no tone correction for annoyance is required at large tone-to-noise ratios ($\geq$ +20 dB) when tones are centered within the noise spectrum, a tone correction is required at large tone-to-noise ratios when tones are located within the high-frequency skirt of low-pass noise. However, only when a 3000-Hz tone is added to low-pass noise does annoyance increase continuously as tone-to-noise ratio increases. Then, in agreement with Pearsons et al. (1969), the increase extends up to a ratio of at least +20 dB (+25 dB above 100 dB SPL). Thus, the need for a tone correction is seen at large tone-to-noise ratios when a 3000-Hz tone is combined with low-pass noise, but not when the same tone is combined with either broadband-flat or high-pass spectra. Unlike results at 3000 Hz, at lower frequencies maximum annoyance is reached at relatively small tone-to-noise ratios ($\leq$ +15 dB). (For reasons given in Section

II, the addition of a 250-Hz tone to high-pass noise increases loudness more than annoyance, negating the need for an annoyance correction.) Therefore, as Hargest and Pinker (1967) suggest, it is possible that, when single tones in the 1000- to 2000-Hz range are added to low-pass noise, the magnitude of the tone correction may actually decrease somewhat for ratios that exceed +15 dB. Although the tone correction for annoyance tends to be frequency dependent in the direction predicted by several calculation procedures (e.g., FAR 36, 1969; Kryter and Pearsons, 1965; Little, 1961), the proposed procedures, do not predict a decrease in the magnitude of the tone correction at large tone-to-noise ratios.

A similar computational procedure was used to determine the maximum tone correction estimated for noisiness. Tone-correction procedures do not usually distinguish between sound annoyance and noisiness. Nonetheless, the results of this investigation show that noisiness typically predominates at low overall SPLs (see for example, Fig. 11 and Tables B-6 to B-9). Furthermore, as shown in Figs. 15 to 19, noisiness reaches a maximum near a tone-to-noise ratio of +5 dB, and then decreases as tone-to-noise ratio increases. Measured at an overall SPL of about 73 dB, the maximum correction estimated for noisiness of tones added to broadband-flat noise is 7 dB at 250, 1000, 2000, and 3000 Hz. The estimated noisiness correction can amount to 20 dB or greater, as found when tones at 1000 and 3000 Hz are added to low-pass noise or, when tones at 250 and 3000 Hz are added to high-pass noise, but the correction decreases significantly as overall SPL increases. The noisiness decrease with level is consistent with previous findings (Berglund et al., 1976).

The noisiness corrections obtained for the three noise spectra are considerably greater than the 2-dB increment calculated by Scharf and Hellman (1979, 1980), using Ollerhead's (1971, 1973) data. But Ollerhead's sounds consisted exclusively of aircraft noises that were almost all above 90 dB overall SPL, with many close to 100 dB. In fact, both perceived level (PL) and perceived noise level (PNL) calculated by Scharf and Hellman averaged about 100 dB for Ollerhead's four sources of aircraft sounds. According to the present results, at these high overall SPLs the noisiness increment is substantially smaller than that produced by complexes at 85 dB overall SPL and below. Hence, the 2-dB increment reported by Scharf and Hellman is in agreement with the results of this investigation.

IV. Conclusions and Significance

A large scale laboratory investigation of loudness, annoyance, and noisiness produced by single-tone-noise complexes was undertaken to establish a broader data base for quantification and prediction of perceived annoyance. Judgments were obtained by absolute magnitude estimation (AME) supplemented by loudness matching. Three distinctly different spectral patterns of noise with and without added tones were studied: broadband-flat, low-pass, and high-pass. Based on the results, the following conclusions are suggested:

(1) Consistent with the outcome of experiments by Berglund et al. (1975, 1976), loudness, annoyance, and noisiness often produce distinctly different results. Nonetheless, annoyance is more closely related to loudness than to noisiness. Noisiness is associated more with sound quality or clarity and, in contrast to both loudness and annoyance, typically predominates at moderate overall SPLs decreasing significantly as overall SPL increases.

(2) Unlike noisiness, loudness and annoyance growth functions depend on the relationship between the frequency of the added tone and the spectral shape of the noise. Tones centered in noise produce nonmonotonic loudness and annoyance growth functions; those added to the noise skirt produce power functions. The power-function exponents measured for annoyance are larger than those measured for loudness. Otherwise, loudness and annoyance exhibit similar growth behavior.

(3) Compared to noisiness, loudness and annoyance growth rates are also a function of tone-to-noise ratio. The measured loudness and annoyance exponents are invariant across tone-to-noise ratio when the tones are located within the noise spectrum, but not when they are added to the skirt. On the other hand, for those noises studied, the relation between noisiness growth rate and tone-to-noise ratio is independent of the position of the tone in the noise. Individual loudness and annoyance growth functions are consistent with those for the group, so that the results are probably not due to averaging.

(4) When the overall SPL of the noise-tone complex is approximately constant, noisiness generally peaks near a tone-to-noise ratio of +5 dB, and then decreases continuously as tone-to-noise ratio increases. By comparison, the position of the tone within the spectrum determines the functional relationship between loudness (or annoyance) and tone-to-noise ratio.

(5) Once the amount of loudness summation is determined, the ratios of noisiness-to-loudness (N/L), annoyance-to-loudness (A/L), noisiness-to-annoyance (N/A), and annoyance-to-noisiness (A/N) as a function of the overall SPL of the noise-tone complex can be more precisely estimated for specific noise-tone spectral combinations. These ratios can then be converted into decibels and added, when appropriate, to the measured loudness increment to determine the total contribution of the tone to perceived annoyance and noisiness.

(6) In general, noise-tone complexes produce maximum annoyance at overall SPLs greater than 95 dB, while maximum noisiness is reached at overall SPLs less than 75 dB.

(7) The amount by which annoyance exceeds loudness depends on the frequency of the added tone, the overall SPL of the noise-tone complex, tone-to-noise ratio, the spectral shape of the noise, as well as on the tone's location within the spectrum. Irrespective of frequency, single tones combined with low-pass noise produce the largest annoyance increment, more at 3000 than at 250 Hz.

(8) Whereas no tone correction for annoyance is required at large tone-to-noise ratios (≥ +20 dB) when the tones are centered within the noise spectrum or, when a low frequency 250-Hz tone is added to high-pass noise, annoyance exceeds loudness at large tone-to-noise ratios when the tones are located within the high-frequency skirt of low-pass noise.

(9) The complex interactions uncovered help to account for the widely disparate published estimates of the effect of tonal components on perceived annoyance.

The close correspondence between loudness and annoyance suggests, in agreement with other studies (Berglund et al., 1981; Powell, 1979c; Scharf, 1974), that loudness is the underlying basis of perceived annoyance. Therefore, to better understand perceived annoyance of sound mixtures it is necessary to relate the results to basic auditory mechanisms governing loudness and masking. When assessing the contribution of pure tones centered within the noise spectrum to the overall annoyance of noise, the absolute loudness of the component stimuli as well as the mutual masking measured between the components need to be considered (e.g., Hellman, 1972; Powell, 1979a, 1979b; Schroeder, Atal, and Hall, 1979). The results obtained with shaped noise spectra are compatible with the asymmetry and nonlinear growth behavior of excitation patterns known to be produced by auditory stimuli at high sound intensities (e.g., Egan and Hake, 1950; Ehmer, 1959; Kiang and Moxon, 1974; Zwicker, 1970; Zwicker and Scharf, 1965; Zwislocki, 1978). Data interpretation must also consider the potential effects of combination components generated at high SPLs by the simultaneous presentation of noise and tone (Greenwood, 1971, 1972). It is possible that both the presence of combination components and the nonlinear excitation growth behavior alter the loudness and annoyance growth rates in the direction observed experimentally.

Nevertheless, despite the similarities observed between loudness and annoyance, annoyance of noise-tone complexes is not usually equivalent to loudness. Non-auditory factors summarized by Scharf (1974) probably also play a role. The obtained results cannot be satisfactorily accounted for by either an assumption of energy summation, or loudness summation. Neither can they be simply explained by a "loudest component" rule suggested by Berglund et al. (1981) as a practical guide for estimating the overall perceived magnitude of wideband noises with similar spectral characteristics. The results are in qualitative agreement with a summation and inhibition model of annoyance proposed by Powell (1979c), but that model does not deal explicitly with the effect of tonal components. Although a tone correction for annoyance is warranted for certain noise-tone configurations, none of the proposed calculation procedures concerned specifically with the effect of pure tones (FAR 36, 1969; Kryter and Pearsons, 1965; Little, 1961) consider all the variables relevant to perceived annoyance of tonal components. How best to modify the proposed procedures to include the many factors that contribute to perceived annoyance of noise-tone complexes needs to be determined.

Notes

1. The 1/3-octave-band pressure level was increased at 250 Hz, in accordance with the increased level in the critical band (Kryter, 1970; Searle et al., 1979).
2. These results were closely replicated by another group of ten listeners, as seen in Tables C-25 and C-26.
3. The high-pass noise energy extended to 50,000 Hz and was not band limited at high frequencies. Hence, the 1/3-octave-band pressure level of the 3000-Hz tone is 18 dB below the overall SPL of the noise. Since the noise judged separately is substantially less loud than the tone, this means that for large tone-to-noise ratios, the loudness decrease due to the reduced SPL of the noise is more than the loudness increase due to the greater SPL of the tone. Consequently, the overall loudness of the complex decreases even though the overall SPL may have been increased. Conversely, for small tone-to-noise ratios the loudness increase due to the greater SPL of the noise is substantially larger than the decrease due to a reduction in SPL of the tone, increasing the overall loudness of the complex.
4. The omission of three unusually variable points (SE = .30 log units) below 80 dB SPL produced by the added 250-Hz tone (unfilled circles) increases the calculated value of r_{xy} for broadband-flat noise from -.75 to -.82.
5. Since the tone-correction values were mainly based on the results of a single psychophysical procedure, they should be viewed as a first order best estimate, subject to some refinement.

References

Aylward, N. (1980). "The loudness of white noise in the presence of intense pure tones," Masters thesis. Boston University.

Barlow, R. and Verrillo, R.T. (1976). "Brightness sensation in a ganzfeld," Vision Res. 16, 1291-1297.

Berglund, B., Berglund, U., and Lindvall, T. (1975). "Scaling loudness, noisiness, and annoyance of aircraft noise," J. Acoust. Soc. Am. 57, 930-934.

Berglund, B., Berglund, U., and Lindvall, T. (1976). "Scaling loudness, noisiness, and annoyance of community noises," J. Acoust. Soc. Am. 60, 1119-1125.

Berglund, B., Berglund, U., Goldstein, M., and Lindvall, T. (1981). "Loudness (or annoyance) summation of combined community noises," J. Acoust. Soc. Am. 70, 1628-1634.

Bishop, D. (1966). "Judgments of the relative and absolute acceptability of aircraft noise," J. Acoust. Soc. Am. 40, 108-122.

Copeland, W.C.T., Davidson, I.M., Hargest, T.J., and Robinson, D.W. (1960). "A controlled experiment on the subjective effects of jet engine noise," J. Roy. Aeron, Soc. 64, 33-36.

Egan, J. and Hake, H. (1950). "On the masking pattern of a simple auditory stimulus," J. Acoust. Soc. Am. 22, 622-630.

Ehmer, R. (1959). "Masking by tones vs. noise bands," J. Acoust. Soc. Am. 31, 1253-1256.

FAR 36, Federal Aviation Administration (1969). "Aircraft certification procedure," Federal Aviation Regulation Part 36.

Fishken, D. (1971). "Loudness summation between tones and noise," Doctoral dissertation, Northeastern University.

Galanter, E. (1978). "The annoyance of sound and of other life events," J. Acoust. Soc. Am. 63 S17 (A).

Gleiss, N. and Zwicker, E. (1964). "Loudness function in the presence of a masking noise," J. Acoust. Soc. Am. 36, 393-394.

Greenwood, D. (1971). "Aural combination tones and auditory masking," J. Acoust. Soc. Am. 50, 502-543.

Greenwood, D. (1972). "Masking by narrow bands of noise in proximity to more intense pure tones of higher frequency: Application to measurement of combination band levels and some comparisons with masking by combination noise," J. Acoust. Soc. Am. 52, 1137-1143.

Goulet, P. and Northwood, T.C. (1973). "Subjective rating of broad-band noises containing pure tones," J. Acoust. Soc. Am. 53, 365 (A).

Hargest, T.J. and Pinker, R.A. (1967). "The influence of added narrow band noises and tones on the subjective response to shaped white noise," J. Roy. Aeron. Soc. 71, 428-430.

Hellman, R.P. (1970). "Effect of noise bandwidth on the loudness of a 1000-Hz tone." J. Acoust. Soc. Am. 48, 500-504.

Hellman, R.P. (1972). "Asymmetry of masking between noise and tone," Percept. Psychophys. 11, 241-246.

Hellman, R.P. (1974). "Effect of spread of excitation on the loudness function at 250 Hz," in Sensation and Measurement - papers in honor of S.S. Stevens, edited by H.R. Moskowitz, B. Scharf, and J.C. Stevens (Reidel, Dordrecht).

Hellman, R.P. (1976). "Growth of loudness at 1000 and 3000 Hz," J. Acoust. Soc. Am. 60, 672-679.

Hellman, R.P. (1981). "Stability of individual loudness functions obtained by magnitude estimation and production." Percept. Psychophys. 29, 63-70.

Hellman, R.P. and Ashkinaze, B. (1981). "Effect of tone location within the noise spectrum on overall loudness, annoyance, and noisiness," J. Acoust. Soc. Am. 70, S68 (A).

Hellman, R.P. and Zwislocki, J. (1961). "Some factors affecting the estimation of loudness," J. Acoust. Soc. Am. 33, 687-694.

Hellman, R.P. and Zwislocki, J. (1963). "Monaural loudness function at 1000 cps and interaural summation," J. Acoust. Soc. Am. 35, 856-865.

Hellman, R.P. and Zwislocki, J. (1964). "Loudness function of a 1000 cps tone in the presence of a masking noise," J. Acoust. Soc. Am. 36, 1618-1627.

Hellman, R.P. and Zwislocki, J. (1968). "Loudness determination at low sound frequencies," J. Acoust. Soc. Am. 43, 60-64.

International Organization for Standardization (1959). "Expression of the physical and subjective magnitudes of sounds," ISO/R 131-1959 (E).

Kiang, N.Y.-S., and Moxon, E.C. (1974). "Tails of tuning curves of auditory-nerve fibers," J. Acoust. Soc. Am. 55, 620-630.

Kryter, K.D. (1970). "The effects of noise on man," (Academic, New York).

Kryter, K.D. (1974). "Predictions of paired-comparison and magnitude-estimation judgments of noisiness," in Sensation and Measurement - papers in honor of S.S. Stevens, edited by H.R. Moskowitz, B. Scharf, and J.C. Stevens (Reidel, Dordrecht).

Kryter, K.D. and Pearsons, K.S. (1965). "Judged noisiness of a band of random noise containing an audible pure tone," J. Acoust. Soc. Am., 38, 106-112.

Little, J.W. (1961). "Human response to jet engine noise," Noise Control 7, 11-13.

Little, J.W. and Mabry, J.E. (1969). "Empirical comparisons of calculation procedures for estimating annoyance of jet aircraft flyovers," J. Sound Vib. 10, 59-68.

Marks, L.E. (1974). "On scales of sensation: Prolegomena to any future psychophysics that will be able to come forth as science," Percept. Psychophys. 16, 358-376.

Niese, H. (1965). "Beitrag zur relation zwischen lautstärke und lästigkeit von geräuschen," Acustica 15, 236-243.

Ollerhead, J.B. (1971). "An evaluation of methods for scaling aircraft noise perception," NASA CR-1883.

Ollerhead, J.B. (1973). "Scaling aircraft noise perception," J. Sound Vib. 26, 361-388.

Pearsons, K.S. and Bennett, R.L. (1971). "Effects of temporal and spectral combinations on the judged noisiness of aircraft sounds," J. Acoust. Soc. Am. 49, 1076-1082.

Pearsons, K.S., Bishop, D.E., and Horonjeff, R.D. (1969). "Judged noisiness of modulated and multiple tones in broad-band noise," J. Acoust. Soc. Am. 45, 742-750.

Pearsons, K.S. and Wells, R.J. (1970). "Judged noisiness of sounds containing multiple pure tones," J. Acoust. Soc. Am. 47, 89 (A).

Powell, C.A. (1979a). "Effects of road-traffic background noise on judgments of individual airplane noises," NASA Technical Paper 1433.

Powell, C.A. (1979b). "Laboratory study of annoyance to combined airplane and road-traffic noise," NASA Technical Paper 1478.

Powell, C.A. (1979c). "A summation and inhibition model of annoyance response to multiple community noise sources," NASA Technical Paper 1479.

Robinson, D.W. (1953). "The relation between the sone and phon scales of loudness," Acustica 3, 344-358.

Rowley, R., and Studebaker, G. (1969). "Monaural loudness-intensity relationships for a 1000-Hz tone," J. Acoust. Soc. Am. 45, 1186-1192.

Rule, S. (1964). "Effect of instructional set on responses to complex sounds," J. Exp. Psychol. 67, 215-220.

Scharf, B. (1964). "Partial masking," Acustica 14, 17-23.

Scharf, B. (1971). "Fundamentals of auditory masking," Audiology 10, 30-40.

Scharf, B. (1974). "Loudness and noisiness - same or different?" Inter-noise 74, Washington D.C.

Scharf, B. (1978). "Loudness," in Handbook of Perception, Vol. IV, edited by E.C. Carterette and M.P. Friedman (Academic, New York).

Scharf, B. and Fishken, D. (1970). "Binaural summation of loudness: Reconsidered," J. Exp. Psychol. 86, 374-379.

Scharf, B. and Hellman, R. (1979). "Comparison of various methods for predicting the loudness and acceptability of noise. Part II: Effects of spectral pattern and tonal components," EPA 550/9-79-102.

Scharf, B. and Hellman, R. (1980). "How to best predict human response to noise on the basis of acoustic variables," in Proceedings of the Third International Congress on Noise as a Public Health Problem, ASHA report No. 10.

Scharf, B. and Horton, T.J. (1978). "Scaling loudness and annoyance as a function of duration," J. Acoust. Soc. Am. 63, S16 (A).

Schroeder, M.R., Atal, B.S., and Hall, J.L. (1979). "Optimizing digital speech coders by exploiting masking properties of the human ear," J. Acoust. Soc. Am. 66, 1647-1652.

Searle, C.L., Jacobson, J.Z., and Rayment, S.G. (1979). "Stop consonant discrimination based on human audition," J. Acoust. Soc. Am.65, 799-809.

Stevens, J.C. and Marks, L.E. (1980). "Cross-modality matching functions generated by magnitude estimation," Percept. Psychophys. 27, 379-389.

Stevens, S.S. (1955). "The measurement of loudness," J. Acoust. Soc. Am. 27, 815-829.

Stevens, S.S. (1956). "The direct estimation of sensory magnitudes-loudness," Am. J. Psychol. 69, 1-25.

Stevens, S.S. (1958). "Problems and methods of psychophysics," Psychol. Bull. 55, 177-196.

Stevens, S.S. (1959). "On the validity of the loudness scale," J. Acoust. Soc. Am. 31, 995-1003.

Stevens, S.S. (1961). "Procedure for calculating loudness: Mark VI," J. Acoust. Soc. Am. 33, 1577-1585.

Stevens, S.S. (1972). "Perceived level of noise by Mark VII and decibels (E)," J. Acoust. Soc. Am. 51, 575-601.

Stevens, S.S. (1975). "Psychophysics," edited by G. Stevens, (Wiley, New York).

Stevens, S.S. and Greenbaum, H. (1966). "Regression effect in psychophysical judgment," Percept. Psychophys. 1, 439-446.

Stevens, S.S. and Guirao, M. (1967). "Loudness functions under inhibition," Percept. Psychophys. 2, 459-465.

Teghtsoonian, R. and Teghtsoonian, M. (1978). "Range and regression effects in magnitude scaling," Percept. Psychophys. 24, 305-314.

Verrillo, R.T., Fraioli, A.J., and Smith, R.L. (1969). "Sensation magnitude of vibrotactile stimuli," Percept. Psychophys. 2, 59-64.

Wells, R.J. (1967). "Recent research relative to perceived noise level," J. Acoust. Soc. Am. 42, 1151 (A).

Zwicker, E. (1958). "Über psychologische und methodische grundlagen der lautheit," Acustica 8, 237-258.

Zwicker, E. (1970). "Masking and psychological excitation as consequences of the ear's frequency analysis," in Frequency Analysis and Periodicity Detection in Hearing, edited by R. Plomp and G.F. Smoorenburg (Leiden, The Netherlands).

Zwicker, E. and Scharf, B. (1965). "A model of loudness summation," Psych. Rev. 72, 3-26.

Zwislocki, J.J. (1978). "Masking: Experimental and theoretical aspects of simultaneous, forward, backward, and central masking," in Handbook of Perception, Vol. IV, edited by E.C. Carterette and M.P. Friedman (Academic, New York).

Zwislocki, J.J. (1983). "Group and individual relations between sensation magnitudes and their numerical estimates," Percept. Psychophys. 33, 460-468.

Zwislocki, J.J. and Goodman, D.A. (1980). "Absolute scaling of sensory magnitudes: A validation," Percept. Psychophys. 28, 28-38.

Appendix A

Loudness Matching -- Tone Standard

You will hear two sounds, a noise and a 1000-Hz pure tone, in alternation. You will be asked to match the loudness of the tone to the loudness of the noise. Your task is to adjust the loudness of the noise until it appears subjectively equal to the loudness of the tone. The loudness of the tone will be your standard and will remain fixed. The best way to approach loudness equality is by bracketing, i.e., turn the noise up until it appears definitely louder than the tone, then turn it down until it appears definitely softer than the tone. Between these two settings attempt to "zero" in on the point of subjective equality.

After you have reached a decision, keep your final setting intact and report your judgment through the intercom.

Loudness Matching -- Noise Standard

You will hear two sounds, a noise and a 1000-Hz pure tone, in alternation. You will be asked to match the loudness of noise to the loudness of a 1000-Hz pure tone. Your task is to adjust the loudness of the tone until it appears subjectively equal to the loudness of the noise. The loudness of the noise will be your standard and will remain fixed. The best way to approach loudness equality is by bracketing, i.e., turn the tone up until it appears definitely softer than the noise. Between these two settings attempt to "zero" in on the point of subjective equality.

After you have reached a decision, keep your final setting intact and report your judgment through the intercom.

Table A-1

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Broadband Noise

Sound Pressure Level of 250-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels					
	+5	+10	+15	+20	+25	+30
100	88	93	98			
95	83	88	93	98		
90	78	83	88	93	98	
85	73	78	83	88	93	98
80	68	73	78	83	88	93
75		68	73	78	83	88
70			68	73	78	83

Table A-2

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Broadband Noise

Sound Pressure Level of 1000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels					
	+5	+10	+15	+20	+25	+30
100	91	96	101			
95	86	91	96	101		
90	81	86	91	96	101	
85	76	81	86	91	96	101
80	71	76	81	86	91	96
75		71	76	81	86	91
70			71	76	81	86

Table A-3

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Broadband Noise

Sound Pressure Level of 2000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels +5	+10	+15	+20	+25	+30
100	93	98				
95	88	93	98			
90	83	88	93	98		
85	78	83	88	93	98	
80	73	78	83	88	93	98
75	68	73	78	83	88	93
70		68	73	78	83	88

Table A-4

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Broadband Noise

Sound Pressure Level of 3000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels					
	+5	+10	+15	+20	+25	+30
100	96	101				
95	91	96	101			
90	86	91	96	101		
85	81	86	91	96	101	
80	76	81	86	91	96	101
75	71	76	81	86	91	96
70		71	76	81	86	91

Table A-5

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Low-Pass Noise

Sound Pressure Level of 250-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels					
	+5	+10	+15	+20	+25	+30
100	96	101				
95	91	96	101			
90	86	91	96	101		
85	81	86	91	96	101	
80	76	81	86	91	96	101
75	71	76	81	86	91	96
70		71	76	81	86	91

Table A-6

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Low-Pass Noise

Sound Pressure Level of 1000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels						
	+5	+10	+15	+20	+25	+30	+35
100	92	97	102				
95	87	92	97	102			
90	82	87	92	97	102		
85	77	82	87	92	97	102	
80	72	77	82	87	92	97	
75		72	77	82	87	92	
70			72	77	82	87	

Table A-7

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Low-Pass Noise

Sound Pressure Level of 2000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels					
	+5	+10	+15	+20	+25	+30
100	91	96	101			
95	86	91	96	101		
90	81	86	91	96	101	
85	76	81	86	91	96	
80	71	76	81	86	91	96
75		71	76	81	86	91
70			71	76	81	86

Table A-8

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in Low-Pass Noise

Sound Pressure Level of 3000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels					
	+5	+10	+15	+20	+25	+30
100	87	92	97	102		
95	82	87	92	97	102	
90	77	82	87	92	97	102
85	72	77	82	87	92	97
80		72	77	82	87	92
75			72	77	82	87
70				72	77	82

Table A-9

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in High-Pass Noise

Sound Pressure Level of 250-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels						
	+5	+10	+15	+20	+25	+30	+35
100	71	76	81	86	91	96	101
95		71	76	81	86	91	96
90			71	76	81	86	91
85				71	76	81	86
80					71	76	81
75						71	76
70							71

Table A-10

Values of Sound Pressure Levels for Noise and Tone Needed to Produce Specified Tone-to-Noise Ratios in High-Pass Noise

Sound Pressure Level of 3000-Hz Tone (dB)

Overall Sound Pressure Level of Noise (dB)	Tone-to-Noise Ratios in Decibels						
	+5	+10	+15	+20	+25	+30	+35
100	87	92	97	102			
95	82	87	92	97	102		
90	77	82	87	92	97	102	
85	72	77	82	87	92	97	102
80		72	77	82	87	92	97
75			72	77	82	87	92
70				72	77	82	87

TABLE A-11

Loudness - Pure Tones
(Without Added Noise)

Tone SPLs (dB)	Frequency (Hz)		
	*250	1000	**3000
70	6.2	7.6	11.5
75	8.7	10.5	16.0
80	12.0	14.5	22.0
85	17.0	20.5	31.0
90	23.0	29.0	43.0
95	32.5	40.0	60.0
100	45.0	56.2	84.0
θ re Sound Pressure	0.57	0.57	0.57

No direct estimates of loudness available at 2000 Hz

* Based on predictions from Hellman and Zwislocki (1968)

** Based on direct estimates from Hellman (1976)

TABLE A-12

Loudness - Broadband-Flat Noise (Without Added Tone)

Noise SPLs (dB)	Frequency of added tone (Hz)			
	250	1000	*2000	3000
70	12.5	12.5	14.0	12.5
75	16.0	16.0	18.5	16.0
80	21.5	21.5	24.5	21.5
85	30.0	30.0	33.0	30.0
90	42.0	42.0	44.0	42.0
95	59.0	59.0	58.0	59.0
100	83.0	83.0	78.0	83.0
θ re Sound Pressure	0.57	0.57	0.50	0.57

* A different group of observers participated in this series of judgments of noise alone.

TABLE A-13

Loudness - Low-Pass Noise *
(Without Added Tone)

Noise SPLs (dB)	Frequency of added tone (Hz)			
	250	1000	2000	3000
70	8.6	10.5	13.0	17.0
75	12.0	14.2	17.0	23.5
80	16.5	19.5	21.5	32.0
85	23.0	27.0	27.5	44.0
90	32.0	37.0	35.0	60.5
95	44.0	50.0	45.0	84.0
100	62.0	68.0	58.0	115.0
θ re Sound Pressure	0.57	0.55	0.43	0.55

* Four different groups of observers (10 Os/group) were involved.

TABLE A-14

Loudness - High-Pass Noise
(Without Added Tone)

Noise SPLs (dB)	Frequency of added tone (Hz)	
	250	3000
70	8.4	6.4
75	11.1	8.9
80	15.0	12.2
85	20.0	17.0
90	27.0	24.0
95	36.0	33.0
100	48.0	46.0
θ re Sound Pressure	0.50	0.57

TABLE A-15

Broadband-Flat Noise
(100-7000 Hz wide)

1/3-Octave-band Analysis

Measured at 110 dB OASPL

Freq (Hz)	SPL (dB) in 1/3-octave-band
50	—
63	67.0
80	75.0
100	80.0
125	85.0
160	86.5
200	87.5
250	*89.5
315	90.0
400	91.0
500	92.0
630	92.5
800	94.0
1000	95.5
1250	96.0
1600	97.0
2000	98.0
2500	99.0
3150	100.5
4000	101.5
5000	102.0
6300	102.5
8000	99.0
10,000	96.0
12,500	87.0
16,000	81.0
20,000	75.0

* 3.4 dB added to this value in accordance with critical-band measurements at low frequencies (Kryter, 1970; Searle et al., 1979).

TABLE A-16

Broadband-Flat Noise (100-7000 Hz)

250-Hz Tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB) (+)	L	A	N
72.2	70	68	15	5.3	6.3	6.3
74.7	70	73	20	6.5	6.8	7.6
75.8	75	68	10	8.7	14.8	15.9
77.2	75	73	15	10.2	13.8	15.9
78.6	70	78	25	7.8	9.3	7.6
79.7	75	78	20	14.5	13.8	15.5
80.3	80	68	5	15.0	21.4	25.2
80.8	80	73	10	17.8	19.5	26.9
82.2	80	78	15	24.6	19.7	28.2
83.2	70	83	30	9.6	12.7	9.3
83.6	75	83	25	20.9	16.6	19.1
84.7	80	83	20	19.1	29.5	26.3
85.3	85	73	5	28.2	38.0	43.7
85.8	85	78	10	28.8	35.5	40.8
87.2	85	83	15	32.4	40.7	41.7
88.2	75	88	30	20.4	20.0	16.6
88.6	80	88	25	24.0	30.9	22.9
89.7	85	88	20	24.0	31.6	32.4
90.3	90	78	5	37.2	57.5	74.1
90.8	90	83	10	42.7	57.5	61.7
92.2	90	88	15	38.9	60.3	47.9
93.2	80	93	30	30.9	35.5	28.2
93.6	85	93	25	38.0	53.7	52.5
94.7	90	93	20	46.8	61.7	61.7
95.3	95	83	5	66.1	97.7	87.1
95.8	95	88	10	70.8	89.1	102.0
97.2	95	93	15	66.1	87.1	89.1
98.2	85	98	30	38.5	49.0	28.2
98.6	90	98	25	61.0	74.1	66.1
99.7	95	98	20	72.4	100.0	91.2
100.3	100	88	5	112.2	151.4	145.0
100.8	100	93	10	100.0	138.0	129.0
102.2	100	98	15	112.2	144.5	141.0

TABLE A-17

Broadband-Flat Noise (100-7000 Hz)

1000-Hz tone				Geometric Means (10 Os, 20 judgment/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
73.5	70	71	15	7.6	3.6	7.1
76.5	75	71	10	11.5	7.7	12.6
77.0	70	76	20	9.6	5.3	6.3
78.5	75	76	15	10.3	7.8	12.0
80.5	80	71	5	12.6	13.5	17.8
81.4	70	81	25	10.0	6.2	7.3
81.5	80	76	10	19.3	13.8	17.8
82.0	75	81	20	14.1	8.1	8.9
83.5	80	81	15	20.0	24.0	21.9
85.5	85	76	5	25.7	25.1	37.2
86.0	70	86	30	14.8	8.3	6.9
86.4	75	86	25	20.9	10.5	13.8
86.5	85	81	10	36.3	30.9	36.9
87.0	80	86	20	25.7	17.0	26.6
88.5	85	86	15	31.6	26.9	35.5
90.5	90	81	5	50.2	52.5	61.7
91.0	75	91	30	23.0	13.5	12.9
91.4	80	91	25	26.9	28.8	26.9
91.5	90	86	10	42.7	52.5	57.5
92.0	85	91	20	40.8	35.5	49.0
93.5	90	91	15	56.3	75.9	83.2
95.5	95	86	5	75.1	81.3	97.7
96.0	80	96	30	40.7	34.7	28.2
96.4	85	96	25	50.1	42.7	47.9
96.5	95	91	10	75.9	96.4	91.2
97.0	90	96	20	63.1	61.7	77.6
98.5	95	96	15	83.2	109.6	104.7
100.5	100	91	5	107.0	144.5	131.8
101.0	85	101	30	63.1	72.4	51.3
101.4	90	101	25	63.1	74.2	63.1
101.5	100	96	10	123.0	158.5	141.3
102.0	95	101	20	87.1	117.5	103.5
103.5	100	101	15	109.0	166.0	141.3

TABLE A-18

Broadband-Flat Noise (100-7000 Hz)

2000-Hz tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB) (+)	L	A	N
72.2	70	68	10	8.7	5.4	9.5
74.7	70	73	15	9.1	7.2	12.3
75.8	75	68	5	11.5	10.2	17.8
77.2	75	73	10	12.0	10.2	17.4
78.6	70	78	20	10.7	11.0	8.7
79.7	75	78	15	11.5	9.1	16.2
80.8	80	73	5	15.8	11.2	23.4
82.2	80	78	10	17.4	17.0	25.1
83.2	70	83	25	11.7	10.7	8.1
83.6	75	83	20	12.9	14.5	15.8
84.7	80	83	15	16.2	20.0	23.4
85.8	85	78	5	19.5	21.9	29.5
87.2	85	83	10	20.9	20.0	32.4
88.0	70	88	30	15.1	18.6	7.9
88.2	75	88	25	14.5	19.5	11.0
88.6	80	88	20	18.2	25.1	23.4
89.7	85	88	15	19.5	25.1	30.9
90.8	90	83	5	24.0	41.7	45.7
92.2	90	88	10	27.5	35.5	37.2
93.0	75	93	30	18.2	29.5	8.7
93.2	80	93	25	23.4	26.3	13.2
93.6	85	93	20	26.3	37.2	22.4
94.7	90	93	15	31.6	50.1	33.9
95.8	95	88	5	38.9	56.2	58.9
97.2	95	93	10	45.7	70.8	63.1
98.0	80	98	30	28.8	51.3	10.2
98.2	85	98	25	33.1	52.5	17.4
98.6	90	98	20	38.0	58.9	33.9
99.7	95	98	15	50.1	79.4	56.2
100.8	100	93	5	55.0	93.3	83.2
102.2	100	98	10	63.1	85.1	79.4

TABLE A-19

Broadband-Flat Noise (100-7000 Hz)

3000-Hz Tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB) (+)	L	A	N
73.5	70	71	10	2.5	3.8	5.8
76.5	75	71	5	7.4	6.8	10.2
77.0	70	76	15	4.2	3.8	5.8
78.5	75	76	10	9.8	7.4	12.4
81.4	70	81	20	5.6	6.3	7.6
81.5	80	76	5	13.7	12.5	17.3
82.0	75	81	15	10.0	10.7	11.8
83.5	80	81	10	15.0	16.2	18.5
86.0	70	86	25	5.9	5.9	6.0
86.4	75	86	20	12.3	8.9	12.4
86.5	85	81	5	24.6	20.4	24.6
87.0	80	86	15	16.2	17.8	18.6
88.5	85	86	10	23.4	22.9	31.5
*91.0	70	91	30	12.6	12.0	7.8
91.4	80	91	20	19.1	20.0	21.4
91.5	90	86	5	34.1	36.3	41.7
92.0	85	91	15	25.9	32.4	32.7
93.5	90	91	10	39.8	34.7	47.1
**96.0	75	96	30	23.2	22.9	12.9
96.4	85	96	20	35.5	43.7	30.2
96.5	95	91	5	70.8	61.7	63.8
97.0	90	96	15	49.0	51.3	49.7
98.5	95	96	10	75.9	69.2	66.1
***101.0	80	101	30	42.7	46.8	25.1
101.4	90	101	20	66.1	69.2	53.7
101.5	100	96	5	105.9	100.0	93.1
102.0	95	101	15	89.1	85.1	68.7
103.5	100	101	10	120.2	109.6	97.1
* 91.0	75	91	25	12.8	14.1	12.0
** 96.	80	96	25	28.2	27.5	19.5
*** 101	85	101	25	51.3	58.9	31.6

Asterisks show results obtained at the same overall SPLs, but at different tone-to-noise ratios.

TABLE A-20

Low-Pass Noise
(3-dB cutoff point at 600 Hz)

1/3 Octave-band analysis

Measured at 108 dB OASPL

Freq. (Hz)	SPL (dB in 1/3 octave-band
50	88.0
63	90.0
80	92.0
100	92.0
125	93.0
160	95.0
200	95.5
250	*95.5
315	96.5
400	96.5
500	96.5
630	96.5
800	96.0
1000	95.0
1250	94.5
1600	94.0
2000	93.5
2500	92.0
3150	90.0
4000	89.5
5000	89.0
6300	88.5
8000	88.0
10,000	87.5
12,500	87.0
16,000	87.0
20,000	86.5

*3.4 dB added to this value in accordance with critical-band measurements at low frequencies (Kryter, 1970; Searle et al., 1979).

TABLE A-21

Low-Pass Noise (3-dB cutoff point at 600 Hz)

250-Hz tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
73.5	70	71	10	9.8	6.0	7.6
76.5	75	71	5	14.1	10.7	17.4
77.0	70	76	15	11.0	8.5	10.5
78.5	75	76	10	15.8	15.7	17.0
81.4	70	81	20	12.0	10.5	10.7
81.5	80	76	5	22.4	26.0	25.7
82.0	75	81	15	19.5	14.0	15.5
83.5	80	81	10	28.8	38.0	25.9
86.0	70	86	25	15.3	10.7	10.5
86.4	75	86	20	20.9	19.1	17.4
86.5	85	81	5	31.6	35.5	31.0
87.0	80	86	15	24.0	33.3	26.9
88.5	85	86	10	34.7	37.2	33.5
*91.0	70	91	30	21.9	12.9	11.2
91.4	80	91	20	31.6	28.6	25.1
91.5	90	86	5	43.7	59.6	51.1
92.0	85	91	15	39.8	46.0	40.3
93.5	90	91	10	49.0	52.5	50.8
**96.0	75	96	30	30.9	27.5	12.5
96.4	85	96	20	43.7	50.1	45.2
96.5	95	91	5	87.1	91.2	75.9
97.0	90	96	15	57.5	66.1	49.0
98.5	95	96	10	79.4	83.2	76.9
***101.0	80	101	30	46.8	37.0	24.0
101.4	90	101	20	64.6	72.4	48.6
101.5	100	96	5	107.2	117.5	111.2
102.0	95	101	15	83.2	77.6	72.4
103.5	100	101	10	112.2	121.6	113.5
* 91	75	91	25	31.6	18.8	17.6
** 96	80	96	25	38.0	30.9	31.3
*** 101	85	101	25	55.0	54.7	38.6

Asterisks show results obtained at the same overall SPLs, but at different tone-to-noise ratios.

TABLE A-22

Low-Pass Noise (3-dB cutoff point at 600 Hz)

1000-Hz Tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
74.2	70	72	15	10.0	3.0	25.1
76.7	75	72	10	12.6	7.1	33.9
77.8	70	77	20	10.0	4.1	17.0
79.2	75	77	15	15.5	9.3	27.5
80.6	80	72	5	12.3	9.6	33.9
81.7	80	77	10	14.8	11.8	33.9
82.3	70	82	25	17.0	9.1	13.8
82.8	75	82	20	15.9	10.0	19.1
84.2	80	82	15	22.9	16.2	30.2
85.6	85	77	5	19.1	19.1	46.8
86.7	85	82	10	22.4	21.4	38.9
87.0	70	87	30	25.0	17.0	4.7
87.3	75	87	25	22.0	14.8	12.9
87.8	80	87	20	25.7	19.1	25.1
89.2	85	87	15	28.8	30.9	37.2
90.6	90	82	5	25.1	37.2	47.9
91.7	90	87	10	33.1	37.2	46.8
*92.0	75	92	30	35.5	26.9	7.4
92.3	80	92	25	40.7	32.4	15.9
92.8	85	92	20	43.7	38.9	33.1
94.2	90	92	15	39.8	50.1	39.8
95.6	95	87	5	38.0	72.4	61.7
96.7	95	92	10	40.7	61.7	55.0
**97.0	80	97	30	52.0	50.1	10.5
97.3	85	97	25	54.0	55.0	21.4
97.8	90	97	20	56.2	60.3	42.7
99.2	95	97	15	74.1	77.6	53.7
100.6	100	92	5	69.2	98.6	75.9
101.7	100	97	10	61.7	104.7	75.9
***102.0	85	102	30	69.2	77.0	11.0
102.3	90	102	25	71.3	83.0	29.5
102.8	95	102	20	79.4	97.7	53.7
104.2	100	102	15	83.2	114.8	72.4
* 92	70	92	35	35.0	26.0	3.5
** 97	75	97	35	54.0	50.0	4.3
**102	80	102	35	72.0	81.0	6.2

Asterisks show results obtained at the same overall SPLs, but at different tone-to-noise ratios.

TABLE A-23

Low-Pass Noise (3-dB cutoff point at 600 Hz)

2000-Hz tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
73.5	70	71	15	6.5	7.4	10.5
76.5	75	71	10	10.0	8.5	15.1
77.0	70	76	20	8.1	8.5	12.6
78.5	75	76	15	12.3	13.5	16.2
80.5	80	71	5	16.6	12.0	19.5
81.4	70	81	25	8.5	15.5	10.2
81.5	80	76	10	16.2	17.0	25.1
82.0	75	81	20	12.9	16.0	15.5
83.5	80	81	15	13.5	17.8	24.0
85.5	85	76	5	24.0	19.5	25.7
86.0	70	86	30	13.2	25.1	9.1
86.4	75	86	25	15.5	24.0	13.2
86.5	85	81	10	22.4	18.2	33.1
87.0	80	86	20	20.0	25.7	21.9
88.5	85	86	15	25.1	32.4	30.2
90.5	90	81	5	28.8	31.6	43.7
91.0	75	91	30	21.4	32.4	12.0
91.4	80	91	25	20.4	30.2	20.9
91.5	90	86	10	33.1	38.9	41.7
92.0	85	91	20	25.7	30.9	26.3
93.5	90	91	15	38.9	38.0	38.9
95.5	95	86	5	46.8	47.9	46.8
96.0	80	96	30	36.3	52.5	20.9
96.4	85	96	25	35.0	51.3	26.9
96.5	95	91	10	47.9	52.5	46.8
97.0	90	96	20	39.8	56.2	34.7
98.5	95	96	15	50.1	60.3	51.3
100.5	100	91	5	67.6	70.8	67.6
101.4	90	101	25	57.5	93.3	33.1
101.5	100	96	10	66.1	81.3	64.6
102.0	95	101	20	70.8	91.2	46.8
103.5	100	101	15	75.9	97.7	77.6

TABLE A-24

Low-Pass Noise (3-dB cutoff point at 600 Hz)

3000-Hz tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
74.2	70	72	20	6.8	9.1	53.7
76.7	75	72	15	14.8	12.3	69.2
77.8	70	77	25	11.8	11.0	29.5
79.2	75	77	20	14.5	17.4	53.7
80.6	80	72	10	20.4	25.7	114.8
81.7	80	77	15	25.7	40.7	100.0
82.3	70	82	30	18.2	22.9	20.4
82.8	75	82	25	21.9	30.2	35.5
84.2	80	82	20	34.7	34.7	67.6
85.2	85	72	5	26.9	30.2	158.5
85.6	85	77	10	36.3	47.9	158.5
86.7	85	82	15	43.7	47.9	131.8
87.3	75	87	30	45.0	60.0	18.2
87.8	80	87	25	46.8	63.1	30.2
89.2	85	87	20	40.7	63.1	58.9
90.2	90	77	5	49.0	66.1	208.9
90.6	90	82	10	49.0	63.1	173.8
91.7	90	87	15	63.1	87.1	134.9
92.3	80	92	30	45.7	120.0	24.0
92.8	85	92	25	69.2	120.2	41.7
94.2	90	92	20	83.2	134.9	123.0
95.2	95	82	5	77.6	158.5	229.1
95.6	95	87	10	67.6	117.5	195.0
96.7	95	92	15	104.7	177.8	154.9
97.3	85	97	30	114.8	218.8	38.9
97.8	90	97	25	107.2	200.0	91.2
99.2	95	97	20	138.0	229.1	97.7
100.2	100	87	5	166.0	223.9	295.1
100.6	100	92	10	158.5	213.8	288.4
101.7	100	97	15	177.8	346.7	223.9
102.3	90	102	30	239.9	355.0	38.9
102.8	95	102	25	239.9	407.0	62.5
104.2	100	102	20	251.2	310.0	162.2

TABLE A-25

High-Pass Noise
(3-dB cutoff point at 1060 Hz)

1/3 Octave-band analysis

Measured at 118 dB OASPL

Freq (Hz)	SPL (dB) in 1/3-octave-band
100	68.0
125	74.0
160	76.0
200	78.5
250	*80.5
315	83.0
400	86.0
500	88.0
630	90.0
800	92.0
1000	94.0
1250	96.0
1600	97.5
2000	98.5
2500	99.0
3150	100.0
4000	102.0
5000	103.5
6300	105.0
8000	105.5
10,000	107.0
12,500	108.0
16,000	109.0
20,000	110.0

* 3.4 dB added to this value in accordance with critical-band measurements at low frequencies (Kryter, 1970; Searle et al., 1979).

TABLE A-26

High-Pass Noise (3-dB cutoff point at 1060 Hz)

250-Hz tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
73.5	70	71	35	4.5	2.9	8.7
76.5	75	71	30	6.0	3.9	14.8
78.5	75	76	35	10.5	4.6	11.0
80.5	80	71	25	9.3	5.9	19.1
81.5	80	76	30	11.0	8.9	12.6
83.5	80	81	35	13.5	8.9	13.8
85.2	85	71	20	11.5	8.5	21.9
85.5	85	76	25	16.6	11.8	23.4
86.5	85	81	30	17.8	14.1	20.9
88.5	85	86	35	22.4	14.8	21.9
90.0	90	71	15	16.6	15.5	27.5
90.2	90	76	20	26.3	18.2	29.5
90.5	90	81	25	22.4	19.1	30.9
91.5	90	86	30	32.4	21.9	28.8
93.5	90	91	35	39.8	25.1	21.9
* 95.0	95	76	15	26.9	29.0	37.0
95.2	95	81	20	32.4	33.9	40.0
95.5	95	86	25	38.0	35.0	33.0
96.5	95	91	30	56.2	38.0	29.0
98.5	95	96	35	63.1	40.0	25.0
**100.0	100	81	15	64.6	53.7	52.5
100.2	100	86	20	66.1	52.5	46.0
100.5	100	91	25	67.6	53.7	44.0
101.5	100	96	30	75.9	60.3	38.9
103.5	100	101	35	81.3	67.6	36.3
* 95	95	71	10	23.4	28.2	41.0
** 100	100	71	5	56.2	47.9	51.3
** 100	100	76	10	64.6	53.7	49.0

Asterisks show results obtained at the same overall SPLs, but at different tone-to- noise ratios.

TABLE A-27

High-Pass Noise (3-dB cutoff point at 1060 Hz)

3000-Hz tone				Geometric Means (10 Os, 20 judgments/pt)		
OASPL (dB)	SPL Noise (dB)	SPL Tone (dB)	T/N Ratio (dB)(+)	L	A	N
74.2	70	72	20	8.3	4.9	16.0
76.7	75	72	15	12.3	6.8	24.0
77.8	70	77	25	10.1	6.3	13.5
79.2	75	77	20	11.5	7.4	21.3
80.6	80	72	10	14.8	9.9	31.3
81.7	80	77	15	16.4	12.3	28.1
82.3	70	82	30	13.6	6.1	8.7
82.8	75	82	25	14.8	10.5	17.9
84.2	80	82	20	17.2	14.1	23.6
85.2	85	72	5	19.1	13.5	42.9
85.6	85	77	10	26.1	16.5	40.3
86.7	85	82	15	20.8	15.6	41.6
87.0	70	87	35	18.0	10.5	5.7
87.3	75	87	30	22.2	14.1	12.4
87.8	80	87	25	20.5	15.7	20.4
89.2	85	87	20	26.4	20.3	29.7
90.2	90	77	5	27.5	30.6	57.5
90.6	90	82	10	29.3	31.0	53.0
91.7	90	87	15	32.7	32.4	43.9
92.0	75	92	35	26.6	25.1	7.7
92.3	80	92	30	27.5	21.5	11.7
92.8	85	92	25	37.1	30.6	26.3
94.2	90	92	20	43.3	45.8	45.2
95.2	95	82	5	39.0	43.0	64.7
95.6	95	87	10	50.1	51.0	65.6
96.7	95	92	15	56.0	56.7	62.2
97.0	80	97	35	40.0	38.0	10.7
97.3	85	97	30	53.7	46.1	17.0
97.8	90	97	25	57.5	53.0	29.9
99.2	95	97	20	70.8	72.9	52.5
100.2	100	87	5	57.5	69.1	83.2
100.6	100	92	10	72.9	69.2	89.7
101.7	100	97	15	81.3	79.4	88.9
102.0	85	102	35	80.9	71.1	14.8
102.3	90	102	30	79.4	83.2	23.3
102.8	95	102	25	82.4	91.6	47.9
104.2	100	102	20	87.1	104.1	83.2

Appendix B

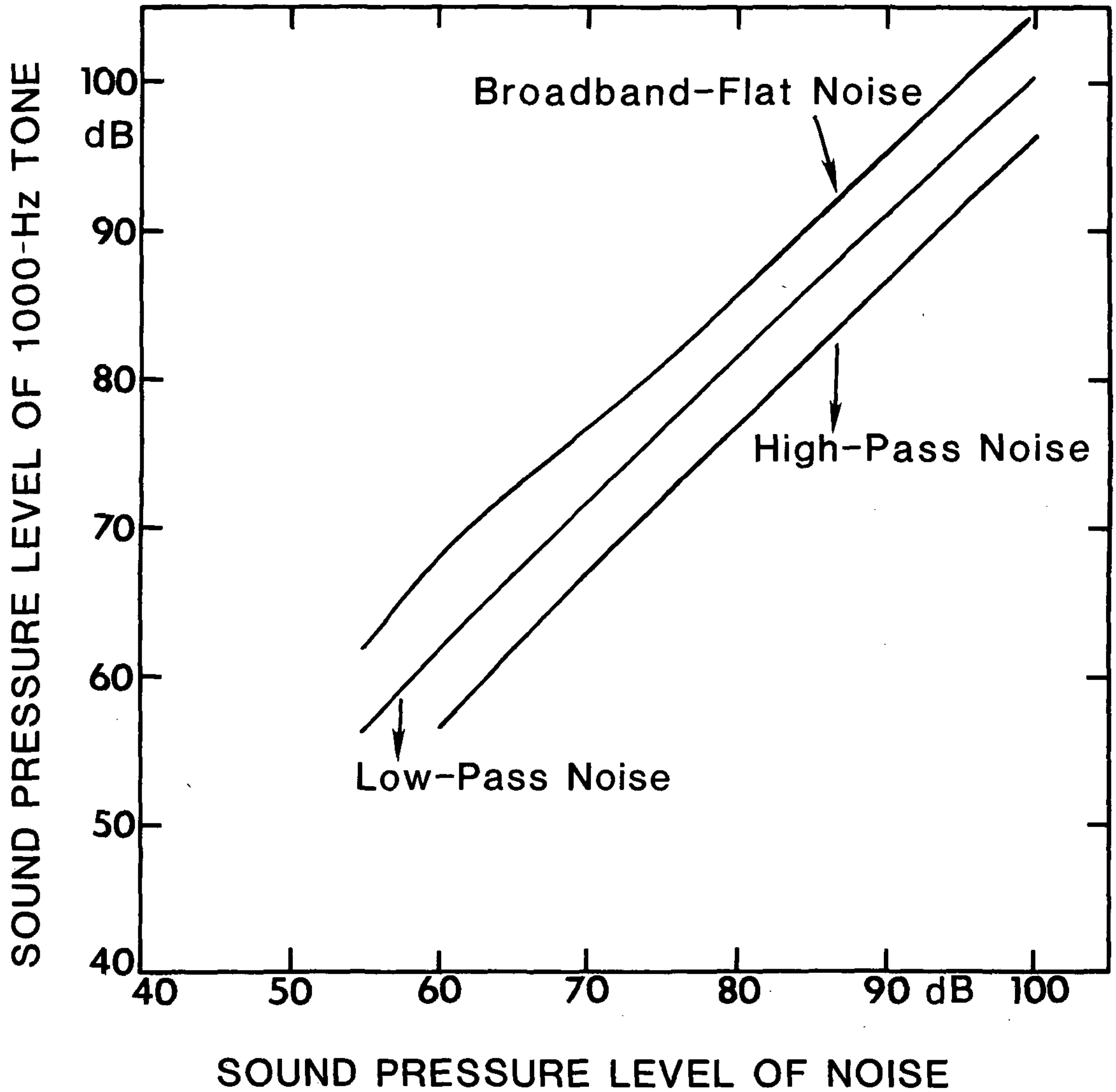

Figure B-1. Loudness-level curves determined by loudness matching and magnitude estimation for broadband-flat (upper curve), low-pass (middle curve), and high-pass (lower curve) noises.

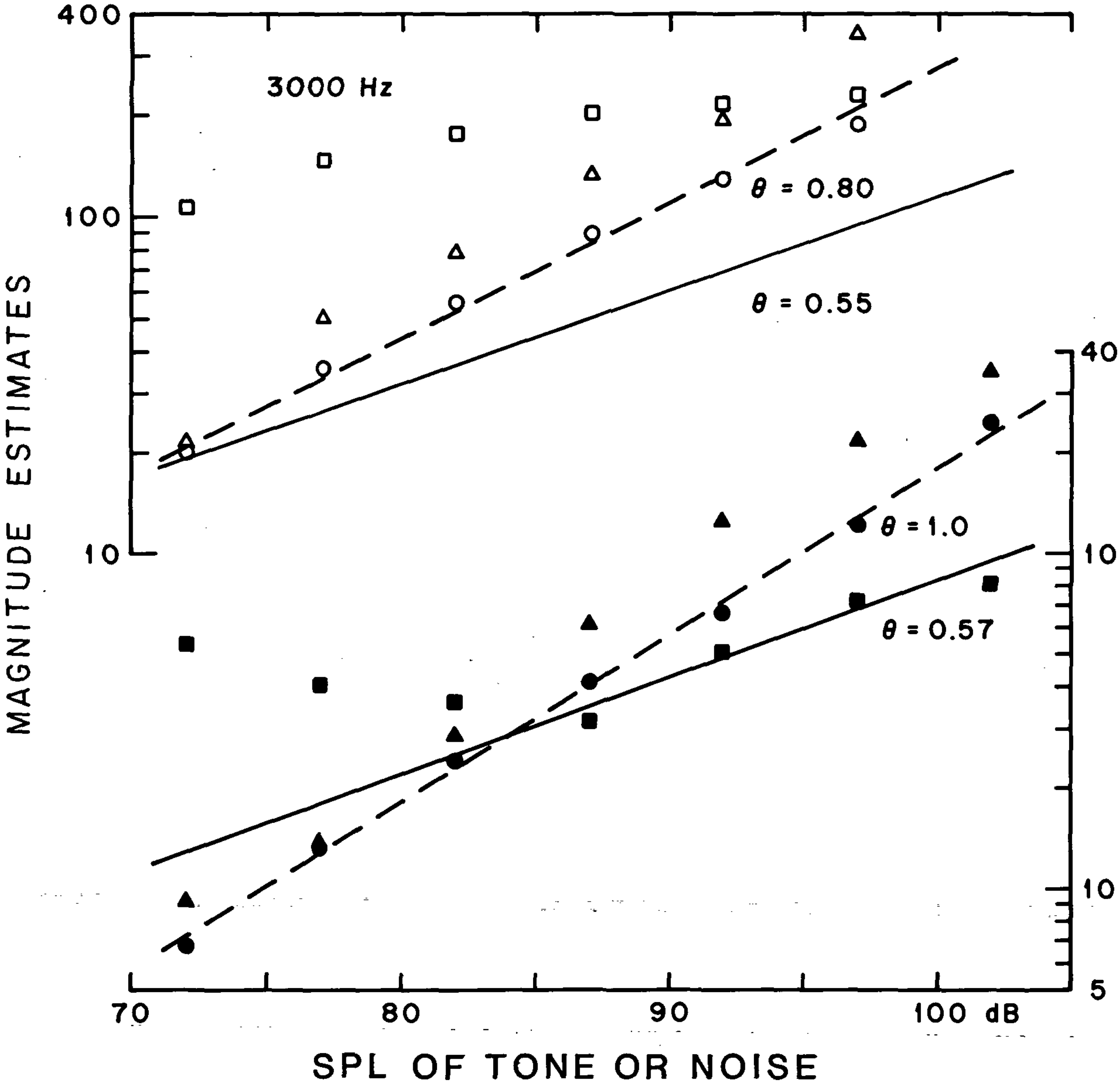

Figure B-2. Effect of small (+5, +10, +15 dB) and large (+20, +25, +30 dB) tone-to-noise ratios on loudness, annoyance, and noisiness judgments produced by a 3000-Hz tone added to low-pass noise as a function of the SPL of the tone or noise. Symbols are analogous to those described in Fig. 4. The upper solid line shows the low-pass loudness function measured in this experiment by loudness matching and magnitude estimation, and the lower solid line shows the loudness-estimation function previously measured at 3000 Hz (Hellman, 1976). The upper and lower intermittent lines approximate the loudness data produced by small and large tone-to-noise ratios, respectively. The slope (θ) of each line is indicated next to the line.

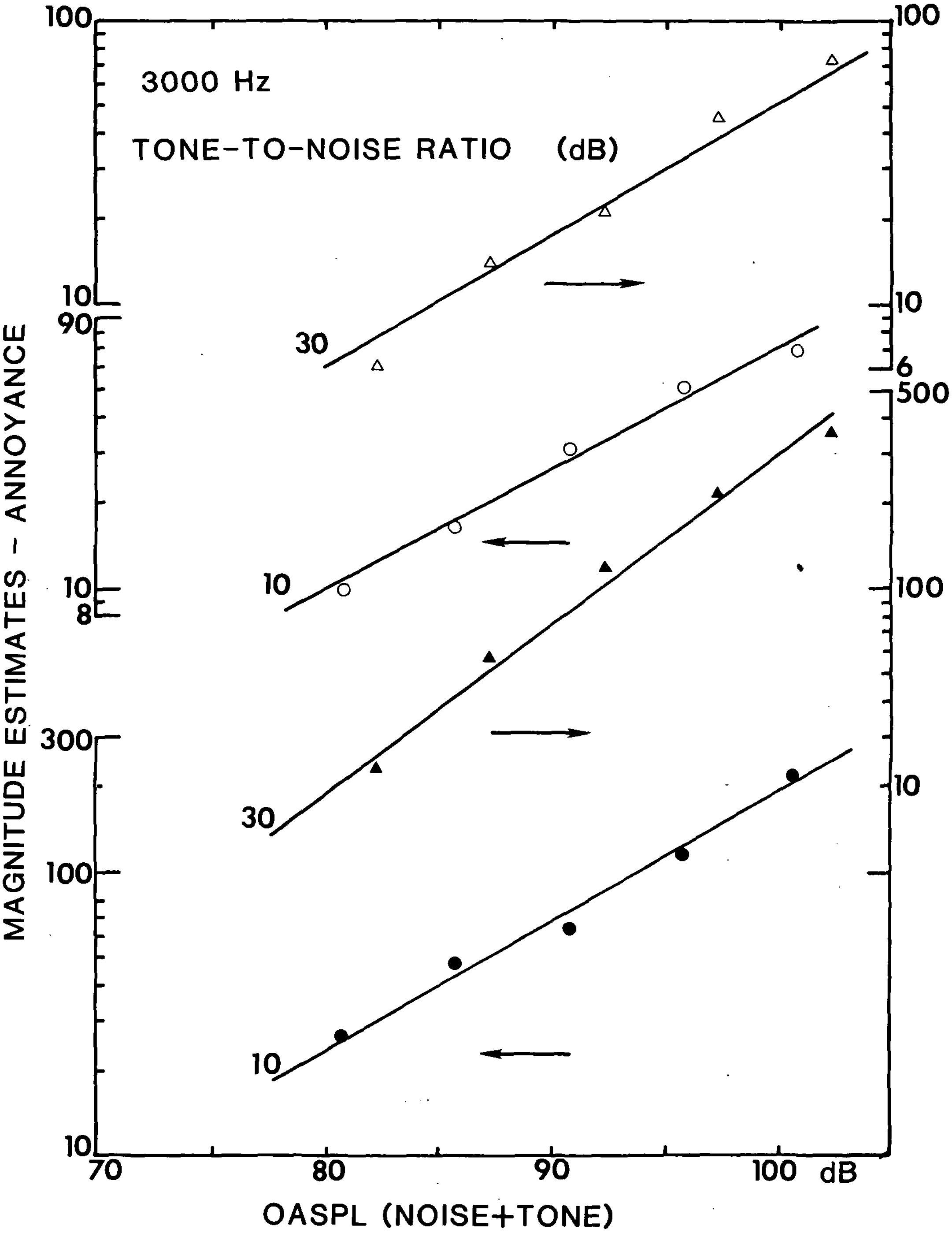

Figure B-3. Annoyance growth rate at 3000 Hz. Filled and unfilled symbols indicate results obtained with low- and high-pass noise, respectively. Circles represent group means at a tone-to-noise ratio of +10 dB; triangles represent means at a tone-to-noise ratio of +30 dB. All results are approximated by power functions of sound pressure.

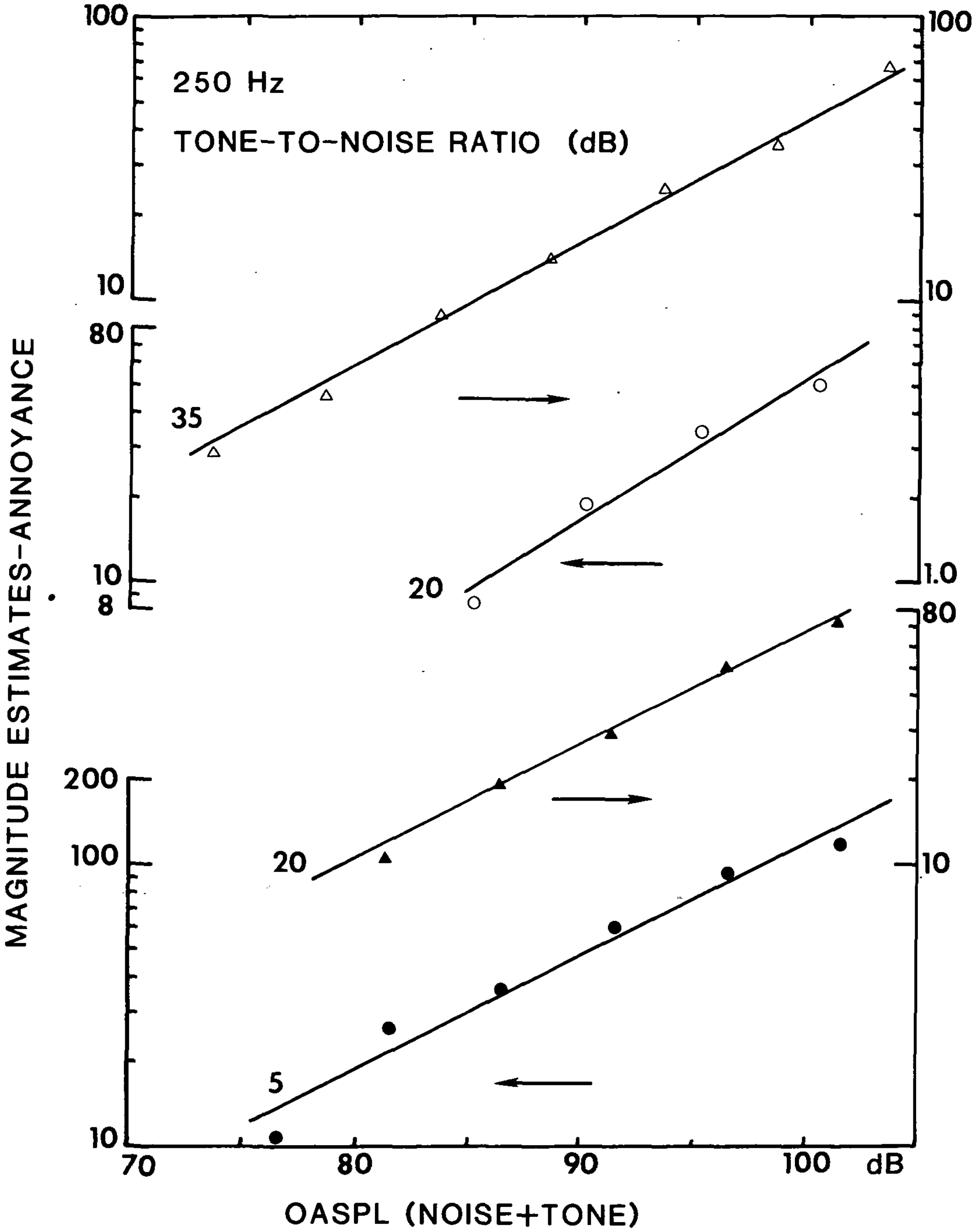

Figure B-4. Annoyance growth rate at 250 Hz. Filled and unfilled symbols indicate results obtained with low- and high-pass noise, respectively. With low-pass noise, group means at tone-to-noise ratios of +5 and +20 dB (filled circles and triangles) are shown. With high-pass noise, group means at tone-to-noise ratios of +20 and +35 dB (unfilled circles and triangles) are shown. All results are approximated by power functions of sound pressure.

TABLE B-1

Measured Power-Function Exponents (Θ) Obtained for Loudness (L)
and Annoyance (A) as a Function of Tone-To-Noise Ratio (dB)

T/N Ratio (dB)(+)	Frequency (Hz) of Tone Added to Noise Spectra											
	Low-Pass Noise								High-Pass Noise			
	250		1000		2000		3000		250		3000	
	L	A	L	A	L	A	L	A	L	A	L	A
5	.66	.80	.60	.92	.60	.75	.75	.88	—	—	.66	.92
10	.66	.80	.60	.92	.60	.75	.80	.92	1.10	1.10	.75	.86
15	.66	.80	.60	.92	.70	.75	.86	.96	1.00	1.05	.66	.86
20	.66	.80	.66	.92	.70	.80	.97	1.00	.86	1.00	.75	.86
25	.66	.80	.66	1.00	.70	.86	1.00	1.13	.80	.92	.75	.86
30	.66	.80	.66	1.00	.80	.86	1.10	1.20	.75	.86	.75	.92
35	—	—	.66	1.00	—	—	—	—	.70	.86	.75	.86
X_Θ	.66	.80	.63	.95	.68	.80	.91	1.02	.87	.97	.72	.88

TABLE B-2

CORRELATIONAL ANALYSIS OF ANNOYANCE-TO-LOUDNESS RATIO (A/L), NOISINESS-TO-ANNOYANCE RATIO (N/A), AND NOISINESS-TO-LOUDNESS RATIO (N/L) AS A FUNCTION OF OASPL IN DECIBELS OF THE NOISE-TONE COMPLEX (Tone-To-Noise Ratios of +5, +10, +15 dB)

FREQUENCY (Hz)	SPECTRUM SHAPE	r_{xy}	COEFFICIENT OF DETERMINATION (%)	t	p
A/L					
1000, 2000	flat	+.84	70.56	9.23	$<.01$
250	flat	+.12	1.44	0.48	$>.05$
250	low-pass	+.43	18.49	1.96	$>.05$
3000	flat & high pass	+.18	3.24	1.03	$>.05$
N/L					
250, 1000, 2000	flat	-.08	0.64	-0.33	$>.05$
3000	flat	-.79	62.41	-5.30	$<.01$
3000	high-pass	-.77	59.29	-4.34	$<.01$
250	low-pass	-.10	1.00	-0.41	$>.05$
N/A					
250, 1000, 2000, 3000	flat	-.75	56.25	-9.59	$<.01$
250	low-pass	-.60	36.00	-3.09	$<.01$
3000	high-pass	-.92	84.64	-8.56	$<.01$

TABLE B-3

Correlational Analysis Across Perceived Attributes as a Function of Overall SPL in Decibels of the Low-Pass Tone-Noise Complex (Tone-to-Noise Ratios of +5, +10, +15 dB)

Frequency (Hz)	r_{xy}	N	Coefficient of Determination (%)	t	p
A/L					
250	+.43	19	18.5	1.96	> .05
1000	+.85	18	72.3	6.50	< .01
2000	+.40	18	16.0	1.80	> .05
3000	+.67	15	44.9	3.30	< .01
N/A					
250	-.60	19	36.0	-3.09	< .01
1000	-.83	18	68.9	-6.00	< .01
2000	-.78	18	60.8	-5.00	<.01
3000	-.87	15	75.7	-6.40	<.01
N/L					
250	-.10	19	1.0	-0.41	>.05
1000	-.83	18	68.9	-6.00	<.01
2000	-.74	18	54.8	-4.40	<.01
3000	-.84	15	70.6	-5.60	<.01

TABLE B-4

Correlational Analysis Across Perceived Attributes as a Function of Overall SPL in Decibels of the Low-Pass Tone-Noise Complex (Tone-to-Noise Ratios of +20, +25, +30 dB).

Frequency (Hz)	r_{xy}	N	Coefficient of Determination (%)	t	p
A/L					
250	+.41	12	16.8	1.42	>.05
1000	+.98	15	96.0	17.70	<.01
2000	+.23	14	5.3	0.82	>.05
3000	+.46	18	21.2	2.07	>.05
A/N					
250	+.53	12	28.1	1.98	>.05
1000	+.61	15	37.2	2.80	<.05
2000	+.61	14	37.2	2.70	<.05
3000	+.77	17	59.3	4.70	<.01
N/L					
250	-.22	12	4.8	-0.71	>.05
1000	-.65	15	42.3	-3.10	<.01
2000	-.78	14	60.8	-4.40	<.01
3000	-.71	18	50.4	-4.10	<.01

TABLE B-5

CORRELATIONAL ANALYSIS ACROSS PERCEIVED ATTRIBUTES AS A FUNCTION OF OVERALL SPL IN DECIBELS OF THE HIGH-PASS TONE-NOISE COMPLEX.[1]

FREQUENCY (Hz)	r_{xy}	N	Coefficient of Determination (%)	t	p
A/L					
250	+.42	22	17.6	2.07	>.05
3000	+.18	15	3.2	1.03	>.05
A/N					
250	+.91	22	82.8	9.90	<.01
3000	+.92	15	84.6	8.56	<.01
N/L					
250	-.81	22	65.6	-6.20	<.01
3000	-.77	15	59.3	-4.34	<.01

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[1] Results at 250 Hz were calculated for tone-to-noise ratios of +20, +25, +30, +35 dB. Those at 3000 Hz were calculated for tone-to-noise ratios of +5, +10, +15 dB.

Table B-6

Relationship Between Judged Attributes Produced by Single Tones Added to Broadband-flat Noise (T/N ≤ +15dB)

Frequency (Hz)	N/L		A/L		N/A	
	Ratio	Decibel Change	Ratio	Decibel Change	Ratio	Decibel Change
250	1.4	+5.0	1.3	+4.0	1.6 to 0.8	+7.0 to -4.0
1000	1.4	+5.0	1.0 to 1.6	0 to +7.0	1.6 to 0.8	+7.0 to -4.0
2000	1.4	+5.0	1.0 to 1.6	0 to +7.0	1.6 to 0.8	+7.0 to -4.0
3000	1.6 to 0.8	+7.0 to -4.0	1.0	0	1.6 to 0.8	+7.0 to -4.0

Legend:

N/L = Noisiness/Loudness
A/L = Annoyance/loudness
N/A = Noisiness/Annoyance

Table B-7

Relationship Between Judged Attributes Produced by Single Tones Added to Low-pass Noise (T/N ≤ +15 dB)

Frequency (Hz)	N/L		A/L		N/A	
	Ratio	Decibel Change	Ratio	Decibel Change	Ratio	Decibel Change
250	1.0	0	1.14	+2.0	1.2 to 0.76	+3.0 to -4.0
1000	2.5 to 0.75	+14.0 to -4.5	0.5 to 1.5	-10.5 to +6.0	5.0 to 0.9	+24.0 to -2.0
2000	1.7 to 1.10	+8.0 to +1.0	1.2	+3.0	1.6 to 0.8	+7.0 to -4.0
3000	6.4 to 1.30	+23.0 to +4.0	1.0 to 1.5	0 to +6.0	5.6 to 0.8	+26.0 to -4.0

Legend:

N/L = Noisiness/Loudness
A/L = Annoyance/Loudness
N/A = Noisiness/Annoyance

Table B-8

Relationship Between Judged Attributes Produced by Single Tones Added to Low-pass Noise (T/N ≥ +20 dB)

Frequency (Hz)	N/L		A/L		A/N	
	Ratio	Decibel Change	Ratio	Decibel Change	Ratio	Decibel Change
250	0.71	-5.0	0.86	-3.0	1.3	+4.0
1000	1.2 to 0.1	+3.0 to -34.5	0.3 to 1.3	-18.0 to +4.0	0.5 to 4.0	-10.5 to +21.0
2000	1.5 to 0.6	+6.0 to -8.0	1.4	+5.0	0.5 to 2.2	-10.5 to +12.0
3000	4.7 to 0.9	+23.0 to -2.0	1.5	+6.0	0.95 to 6.5	-1.0 to +28.0

Legend:

N/L = Noisiness/Loudness
A/L = Annoyance/Loudness
A/N = Annoyance/Noisiness

Table B-9

Relationship Between Judged Attributes Produced by Single Tones Added to High-pass Noise

Frequency	N/L		A/L		A/N	
	Ratio	Decibel Change	Ratio	Decibel Change	Ratio	Decibel Change
250						
T/N ≤ +15 dB	-	-	-	-	-	-
T/N ≥ +20 dB	2.4 to 0.7	+13.0 to -5.5	0.72	-5.0	0.3 to 1.5	-18.0 to +6.0
3000						
T/N ≤ +15 dB	2.3 to 1.1	+12.5 to +1.0	1.0	0	0.3 to 1.7	-18.0 to +8.0
T/N ≥ +20 dB	1.6 to 0.3	+7.0 to -18.0	0.50 to 1.0	-10.5 to 0	0.1 to 2.9	-34.5 to +16.0

Legend:

N/L = Noisiness/Loudness
A/L = Annoyance/Loudness
A/N = Annoyance/Noisiness

Appendix C

Table C-1

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 250-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	7.1	14.1	21.4	30.9	44.7	69.2	107.2
Annoyance	8.5	15.9	25.7	40.7	61.7	93.3	144.5
Noisiness	7.6	16.6	26.9	39.0	61.7	92.5	138.0
Standard Deviations (Assigned Numbers)							
Loudness	4.6	3.5	3.2	2.8	2.7	2.9	3.1
Annoyance	5.9	4.6	4.9	6.0	5.9	6.8	6.2
Noisiness	5.0	3.5	4.0	4.2	5.4	5.9	6.3
*±2X Standard Error							
Loudness	2.7-18.6	6.2-32.4	10.2-44.7	16.2-58.9	23.4-85.1	34.7-138.0	53.7-213.8
Annoyance	2.8-25.7	6.0-41.7	9.3-70.8	12.9-128.8	20.4-186.2	28.2-309.0	45.7-457.1
Nosiness	2.8-20.9	7.6-36.3	11.3-64.6	15.9-100.0	21.9-182.0	30.9-282.0	43.7-437.0

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-2

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat noise with an added 1000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	10.0	15.1	22.9	39.8	53.7	79.4	113.0
Annoyance	5.5	9.3	20.4	35.5	63.1	100.0	158.5
Noisiness	6.9	12.0	22.7	42.7	68.5	100.0	139.5
Standard Deviations (Assigned Numbers)							
Loudness	3.0	2.8	2.3	2.0	1.9	2.6	3.6
Annoyance	4.9	4.6	5.1	3.5	4.1	4.7	5.4
Noisiness	6.8	6.6	4.7	5.2	5.4	6.3	5.6
*±2X **Standard Error**							
Loudness	5.0-20.0	7.9-28.8	13.2-39.8	25.1-63.1	35.5-81.3	43.7-144.5	50.0-257.0
Annoyance	2.0-15.1	3.5-24.6	7.4-56.2	16.2-77.6	26.3-151.4	38.0-263.0	55.0-457.1
Noisiness	2.1-23.0	3.6-40.0	8.7-60.3	14.8-123.0	24.0-200.0	31.7-317.0	46.8-427.0

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-3

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 2000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	11.0	13.2	20.0	25.0	32.0	46.0	67.0
Annoyance	9.6	14.1	25.1	31.6	50.0	67.6	89.1
Noisiness	9.3	14.1	18.6	25.7	37.2	58.9	81.3
Standard Deviations (Assigned Numbers)							
Loudness	3.2	3.2	2.9	2.8	3.0	3.0	3.3
Annoyance	4.6	4.0	3.4	3.8	3.8	4.2	4.1
Noisiness	5.8	5.0	4.5	4.5	5.3	4.9	5.5
*±2X Standard Error							
Loudness	5.2-22.9	6.3-27.5	10.0-39.8	12.3-44.7	15.1-60.3	22.9-91.2	32.4-141.3
Annoyance	3.6-25.1	5.9-33.9	10.2-49.0	12.9-67.6	19.5-102.3	26.9-169.8	37.2-213.8
Noisiness	3.1-28.2	5.1-38.9	7.1-49.0	10.2-64.6	12.9-107.2	21.4-162.2	28.2-234.4

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-4

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 3000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	5.4	11.8	20.4	30.7	45.7	77.6	112.2
Annoyance	5.8	10.8	21.4	33.0	46.2	70.8	106.0
Noisiness	6.5	12.0	20.0	30.2	47.9	66.1	95.2
Standard Deviations (Assigned Numbers)							
Loudness	4.9	3.7	2.9	2.7	3.0	3.0	3.0
Annoyance	5.4	3.5	3.2	2.6	3.1	3.0	3.1
Noisiness	6.0	4.5	3.1	2.8	2.5	2.4	2.7
*±2X Standard Error							
Loudness	2.0-14.8	5.1-26.9	10.2-40.8	17.0-56.2	22.9-91.2	49.0-155.0	56.2-224.0
Annoyance	2.0-16.6	4.9-23.5	10.2-44.7	18.2-60.3	22.4-97.8	35.5-141.0	53.7-214.0
Noisiness	2.0-20.4	4.6-31.6	9.6-41.7	15.9-57.5	27.5-83.2	38.0-114.8	50.0-182.0

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-5

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 250-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	13.5	21.4	30.9	39.8	52.5	83.2	110.0
Annoyance	9.4	16.9	31.9	44.2	61.7	83.8	119.1
Noisiness	9.9	15.8	26.3	37.2	50.1	74.1	112.2
Standard Deviations (Assigned Numbers)							
Loudness	3.3	3.0	3.6	3.6	4.3	4.5	4.5
Annoyance	3.6	3.1	3.5	4.8	4.9	5.0	6.0
Noisiness	3.9	4.2	3.7	4.1	3.8	3.8	4.7
*±2X Standard Error							
Loudness	6.5-28.2	10.7-42.7	13.5-70.8	17.4-91.2	20.9-131.8	31.6-218.8	41.7-288.4
Annoyance	4.1-21.6	8.1-35.3	13.9-73.1	16.0-121.6	22.4-169.8	30.4-203.7	37.7-376.7
Noisiness	4.1-23.8	6.6-38.0	11.5-60.3	15.5-89.1	21.9-114.8	32.7-169.8	42.7-295.1

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-6

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 1000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	17.0	22.4	29.5	35.5	43.7	55.0	70.8
Annoyance	8.1	14.5	23.4	35.5	51.3	75.9	107.2
Noisiness	10.0	13.8	19.1	28.8	40.7	56.2	74.1
Standard Deviations (Assigned Numbers)							
Loudness	4.1	3.9	3.8	3.4	3.4	3.4	3.0
Annoyance	4.0	3.5	3.4	3.5	3.5	3.9	4.2
Noisiness	2.6	2.1	2.1	2.1	2.3	2.5	2.8
* **±2X Standard Error**							
Loudness	7.1-40.7	9.3-53.7	12.9-67.6	16.2-77.6	20.0-95.5	25.1-120.2	35.5-141.3
Annoyance	3.4-19.5	6.6-31.6	10.7-51.3	16.2-77.6	23.4-112.2	31.6-182.0	42.7-269.2
Noisiness	5.5-18.2	8.7-21.9	11.5-31.6	18.2-45.7	23.4-70.8	32.4-97.7	38.9-141.3

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-7

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 2000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	8.7	13.8	19.5	25.7	38.9	53.7	69.2
Annoyance	11.7	17.0	22.9	28.2	47.9	60.3	83.2
Noisiness	10.5	14.5	21.9	28.2	39.0	47.9	69.2
Standard Deviations (Assigned Numbers)							
Loudness	5.3	4.4	4.0	3.8	3.5	3.9	3.9
Annoyance	8.3	6.9	5.9	6.6	6.8	6.9	6.0
Noisiness	5.2	5.6	4.8	4.9	4.9	4.1	4.3
*±2X Standard Error							
Loudness	3.0-25.1	5.5-34.7	8.1-46.8	11.2-58.9	17.8-85.1	22.4-128.8	28.8-166.0
Annoyance	3.1-44.7	4.9-58.9	7.6-69.2	8.5-93.3	14.5-158.5	17.4-208.9	26.3-281.8
Noisiness	3.6-30.2	4.8-43.7	7.9-60.3	10.2-77.6	13.8-104.7	20.0-114.8	27.5-173.8

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-8

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 3000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	11.5	20.4	33.1	49.0	83.2	112.2	186.2
Annoyance	13.2	24.6	49.0	69.2	123.0	199.5	263.0
Noisiness	31.6	39.8	56.2	83.2	114.8	128.8	234.4
Standard Deviations (assigned Numbers)							
Loudness	5.6	5.5	5.4	6.9	7.4	7.6	10.2
Annoyance	6.9	5.8	5.9	6.2	5.9	6.2	5.9
Noisiness	5.3	5.0	5.6	6.6	6.9	6.5	7.4
* ±2X Standard Error							
Loudness	3.8-34.7	7.1-58.9	11.5-95.5	14.8-162.2	22.9-302.0	30.9-407.4	42.7-812.8
Annoyance	3.8-45.7	8.1-74.1	15.9-144.5	21.9-218.9	40.7-371.5	63.1-631.0	87.1-794.3
Noisiness	11.0-91.2	14.5-109.7	18.6-170.0	25.1-275.4	33.1-398.1	40.7-407.4	64.6-851.1

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-9

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of High-Pass Noise with an added 250-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	4.5	7.9	11.2	16.6	26.3	37.2	67.6
Annoyance	2.9	4.2	7.8	12.0	20.0	32.4	55.0
Noisiness	8.7	12.9	14.8	21.9	27.5	33.9	44.7
Standard Deviations (Assigned Numbers)							
Loudness	5.0	5.0	4.7	5.3	4.1	3.9	3.4
Annoyance	3.9	2.8	3.8	4.3	4.7	4.0	4.1
Noisiness	7.1	5.3	4.1	4.1	3.2	2.7	3.4
*±2X Standard Error							
Loudness	1.6-12.3	2.9-21.9	4.3-29.5	5.8-47.9	11.2-64.6	15.9-91.2	30.9-148.0
Annoyance	1.2-6.9	2.2-7.9	3.4-17.8	4.8-30.2	7.6-52.5	13.5-77.6	22.9-131.8
Noisiness	2.5-30.2	4.5-37.2	6.2-35.5	9.1-52.5	13.2-57.5	17.8-64.6	20.4-97.7

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-10

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of High-Pass Noise with an added 3000-Hz Tone as a Function of Noise SPL (dB) N = 10

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	12.0	16.5	21.3	33.1	41.5	57.8	74.1
Annoyance	6.7	11.3	16.7	25.5	42.7	60.8	79.4
Noisiness	10.1	15.4	19.4	28.2	40.2	58.2	86.1
Standard Deviations (Assigned Numbers)							
Loudness	4.6	4.5	4.8	5.3	5.4	6.3	6.0
Annoyance	3.2	3.0	3.5	4.0	5.1	5.8	5.9
Noisiness	3.2	4.1	4.4	5.5	5.8	6.0	8.1
* ±2X Standard Error							
Loudness	4.6-31.6	6.3-43.6	7.7-58.7	11.5-95.5	14.4-119.7	18.3-182.8	23.4-234.4
Annoyance	3.2-13.9	5.7-22.5	7.6-36.6	11.2-58.6	14.8-123.0	20.1-183.7	26.3-239.9
Noisiness	4.8-21.1	6.4-37.0	7.7-48.8	9.8-81.3	13.3-121.3	18.4-184.1	22.6-327.3

*The columns correspond to the Sound Pressure Levels of Noise indicated above the calculated means.

Table C-11

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 250-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	68	73	78	83	88	93	98
Geometric Means							
Loudness	8.8	13.5	19.5	26.3	39.4	51.3	66.1
Annoyance	12.6	16.2	21.9	33.9	50.1	67.6	85.1
Noisiness	13.8	19.5	25.1	31.6	45.7	63.1	70.0
Standard Deviations	(Assigned Numbers)						
Loudness	4.0	3.6	3.1	2.8	3.0	3.0	3.1
Annoyance	6.0	4.9	5.0	5.4	5.0	6.2	6.8
Noisiness	7.1	4.6	4.7	3.3	4.0	4.9	5.1
* ±2X Standard Error							
Loudness	3.7-21.1	5.9-30.9	9.8-38.9	13.8-50.1	19.7-78.5	25.7-102.3	33.1-131.8
Annoyance	4.0-40.0	5.9-44.7	7.9-60.3	11.8-97.7	18.2-138.0	21.4-213.8	25.7-281.8
Noisiness	4.0-47.9	7.4-51.3	9.6-66.1	15.1-66.1	19.1-110.0	22.9-174.0	25.4-193.0

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-12

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 1000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	71	76	81	86	91	96	101
Geometric Means							
Loudness	10.3	14.8	21.9	30.2	47.9	64.6	79.5
Annoyance	7.2	11.0	18.2	23.5	50.0	72.1	100.0
Noisiness	11.5	15.1	21.4	28.2	51.3	69.2	83.2
Standard Deviations (Assigned Numbers)							
Loudness	2.8	3.1	2.5	2.2	2.2	2.6	2.6
Annoyance	5.0	4.9	4.5	3.8	4.1	4.6	4.7
Noisiness	8.5	5.5	5.0	5.0	5.2	5.8	5.9
*±2X Standard Error							
Loudness	5.4-19.5	7.4-29.6	12.6-38.1	18.2-50.2	28.9-79.5	35.5-118.0	43.7-145.0
Annoyance	2.6-20.0	4.0-30.0	7.3-46.0	10.3-54.0	21.0-120.0	27.4-190.0	38.0-260.0
Noisiness	3.0-43.7	5.0-45.7	7.8-58.9	10.2-77.6	17.8-147.9	22.9-208.9	27.5-251.2

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-13

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 2000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	68	73	78	83	88	93	98
Geometric Means							
Loudness	10.0	12.0	14.5	16.6	21.0	30.2	38.9
Annoyance	7.4	9.3	15.8	20.0	27.5	50.1	64.6
Noisiness	13.2	17.0	18.2	20.4	22.9	27.5	30.9
Standard Deviations (Assigned Numbers)							
Loudness	3.0	3.0	3.0	2.8	3.0	3.0	3.2
Annoyance	4.0	3.6	3.3	3.5	4.1	4.5	4.5
Noisiness	4.9	4.8	5.8	5.5	4.7	4.5	4.8
* ±2X Standard Error							
Loudness	5.0-20.0	6.0-24.0	7.2-28.8	8.7-31.6	10.5-41.7	15.1-60.3	18.6-81.3
Annoyance	3.1-17.8	4.1-21.4	6.6-31.6	8.7-41.7	11.5-66.1	17.4-120.2	24.5-169.8
Noisiness	4.8-36.3	6.2-46.8	6.0-55.0	7.1-58.9	8.7-60.3	11.0-69.2	11.2-85.1

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-14

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Broadband-flat Noise with an added 3000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	71	76	81	86	91	96	101
Geometric Means							
Loudness	4.4	8.3	12.1	15.5	24.6	45.7	69.2
Annoyance	5.1	7.1	12.3	15.1	25.2	46.8	70.8
Noisiness	7.7	10.8	14.2	17.8	24.0	36.3	49.0
Standard Deviations (Assigned Numbers)							
Loudness	5.9	3.7	3.5	3.2	3.0	2.9	2.8
Annoyance	4.6	5.1	3.6	3.5	3.0	2.8	2.9
Noisiness	6.3	6.3	4.7	3.8	2.9	2.7	2.8
*±2X Standard Error							
Loudness	1.5-13.2	3.6-19.1	5.5-26.4	7.4-32.4	12.4-49.0	22.9-91.2	36.3-132.0
Annoyance	2.0-13.5	2.6-19.5	5.3-27.9	6.9-33.1	12.6-50.2	24.6-89.1	35.5-141.0
Noisiness	2.4-24.3	3.4-33.9	5.4-37.2	7.8-40.7	12.0-47.9	19.1-69.2	25.7-93.3

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-15

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 250-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	71	76	81	86	91	96	101
Geometric Means							
Loudness	11.7	15.9	21.6	25.7	38.9	53.7	67.6
Annoyance	8.1	15.1	20.9	27.5	33.9	55.0	67.6
Noisiness	11.5	16.6	19.1	24.3	30.2	44.0	51.8
Standard Deviations (Assigned Numbers)							
Loudness	2.8	3.1	3.0	3.7	3.9	3.7	4.4
Annoyance	5.0	3.2	3.2	3.3	3.5	4.2	5.1
Noisiness	4.4	4.6	3.7	3.7	3.7	4.4	3.8
*±2X Standard Error							
Loudness	6.2-22.4	7.6-33.1	10.8-43.2	11.2-58.9	16.2-93.3	23.4-123.0	26.9-169.8
Annoyance	2.9-22.9	7.2-31.6	10.0-43.7	12.6-60.3	15.5-74.1	21.9-138.0	24.6-186.2
Noisiness	4.6-28.8	6.3-43.7	8.3-43.7	10.6-55.7	13.2-69.2	17.5-110.4	22.6-118.6

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-16

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 1000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	72	77	82	87	92	97	102
Geometric Means							
Loudness	11.5	14.5	20.4	28.2	41.7	58.9	79.4
Annoyance	5.9	9.6	15.9	26.9	41.7	60.3	87.1
Noisiness	30.2	29.5	27.5	23.4	21.9	23.4	24.0
Standard Deviations (Assigned Numbers)							
Loudness	4.8	4.1	3.4	3.7	3.2	3.5	3.7
Annoyance	3.8	4.1	3.5	3.3	3.6	3.6	3.6
Noisiness	2.7	2.5	2.4	2.2	2.1	2.0	2.2
* ±2X **Standard Error**							
Loudness	4.4-30.2	6.0-34.7	9.3-44.7	12.3-64.6	20.0-87.1	26.9-129.0	34.7-182.0
Annoyance	2.6-13.5	4.0-22.9	7.2-34.7	12.3-58.9	19.1-91.2	27.5-131.8	38.0-199.5
Noisiness	15.9-57.5	16.2-53.7	15.9-47.9	14.1-38.9	13.8-34.7	14.8-37.2	14.5-39.8

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-17

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an Added 2000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	71	76	81	86	91	96	101
Geometric Means							
Loudness	10.2	14.1	15.8	23.4	33.9	43.7	67.6
Annoyance	9.1	14.1	18.6	30.2	39.8	58.9	93.3
Noisiness	14.5	19.1	22.4	23.4	30.2	36.3	50.1
Standard Deviations (Assigned Numbers)							
Loudness	4.5	3.7	4.1	3.9	4.1	4.0	4.2
Annoyance	6.0	6.0	5.6	7.4	7.6	6.9	6.9
Noisiness	6.5	4.4	4.8	5.0	4.9	5.1	4.4
*±2X Standard Error							
Loudness	3.9-26.9	6.2-32.4	6.6-38.0	9.8-56.2	14.1-81.3	18.2-104.7	28.2-162.2
Annoyance	2.9-28.8	4.5-44.7	6.2-56.2	8.3-109.6	11.0-144.5	17.8-195.0	26.9-323.6
Noisiness	4.4-47.9	7.6-47.9	8.5-58.9	8.5-64.6	11.0-83.2	12.6-104.7	20.0-126.0

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-18

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of Low-Pass Noise with an added 3000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	72	77	82	87	92	97	102
Geometric Means							
Loudness	15.5	23.4	36.3	60.3	87.1	131.8	239.9
Annoyance	17.4	30.2	46.8	89.1	147.9	239.9	346.7
Noisiness	91.2	87.1	79.4	77.6	89.1	93.3	69.2
Standard Deviations (Assigned Numbers)							
Loudness	6.5	5.6	7.2	6.0	7.2	7.8	9.1
Annoyance	5.4	5.5	4.8	6.6	6.9	6.9	7.6
Noisiness	5.9	6.2	6.6	5.8	6.6	5.9	8.5
* **±2X Standard Error**							
Loudness	4.7-51.3	7.8-70.8	10.5-125.9	19.1-190.5	25.1-302.0	36.3-478.6	60.3-955.0
Annoyance	6.0-50.1	10.0-91.2	17.8-123.0	26.9-295.1	44.7-489.8	69.2-831.8	95.5-1258.9
Noisiness	28.8-288.4	27.5-275.4	24.0-263.0	25.7-234.4	26.9-295.1	30.9-281.8	18.2-263.0

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-19

Comparison of Geometric Means, Standard Deviations, and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of High-Pass Noise with an added 250-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	71	76	81	86	91	96	101
Geometric Means							
Loudness	13.2	21.0	25.7	37.2	53.7	69.2	81.3
Annoyance	10.0	15.5	21.4	26.9	36.3	46.8	67.6
Noisiness	22.9	23.4	28.2	29.5	31.6	33.1	36.3
Standard Deviations (Assigned Numbers)							
Loudness	4.7	4.3	4.3	3.9	3.3	3.5	3.5
Annoyance	3.7	4.1	3.6	4.3	4.0	4.0	3.8
Noisiness	4.8	3.7	3.6	2.9	2.3	2.1	2.6
* ±2X Standard Error							
Loudness	5.0-34.7	8.3-52.5	10.2-64.6	15.5-89.1	25.7-112.2	31.6-151.4	37.4-177.8
Annoyance	4.4-22.9	6.5-37.2	9.3-49.0	10.7-67.6	15.1-87.1	19.5-112.2	28.2-162.2
Noisiness	8.3-63.1	10.2-53.7	12.3-64.6	14.8-58.9	18.2-55.0	20.9-52.5	20.0-66.1

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

Table C-20

Comparison of Geometric Means, Standard Deviations and ± Twice the Standard Error of the Means obtained for Loudness, Annoyance, and Noisiness of High-Pass Noise with an added 3000-Hz Tone as a Function of Tone SPL (dB) N = 10

	Sound Pressure Level of Tone (dB)						
	72	77	82	87	92	97	102
Geometric Means							
Loudness	13.0	16.9	20.9	29.7	41.1	58.7	82.4
Annoyance	8.2	12.4	16.3	24.5	38.0	55.6	86.5
Noisiness	26.7	28.5	28.4	27.0	29.0	30.3	35.5
Standard Deviations (Assigned Numbers)							
Loudness	4.7	4.8	5.0	5.5	5.3	5.4	5.8
Annoyance	3.3	3.6	3.6	3.9	4.9	4.7	5.5
Noisiness	4.9	5.4	4.8	4.9	5.4	5.4	6.0
* ±2X Standard Error							
Loudness	4.9-34.2	6.1-46.6	7.6-57.5	10.3-85.7	14.3-118.6	20.4-169.4	27.3-248.9
Annoyance	3.9-17.1	5.4-28.1	7.1-37.4	10.2-58.9	13.8-104.7	21.1-146.2	30.0-249.5
Noisiness	9.7-73.6	9.9-82.2	10.8-74.8	9.8-74.3	10.1-83.8	10.5-87.5	11.2-112.2

*The columns correspond to the Sound Pressure Levels of Tone indicated above the calculated means.

TABLE C-21

Values in Figure 4 of Judged Perceived Magnitude (1000-Hz Tone + Broadband-flat Noise)

Magnitude Estimates (GMs of 10 θs)

T/N (≤ +15 dB)					T/N (≥ +20 dB)				
SPLs (dB)$_{\bar{X}}$					SPLs (dB)$_{\bar{X}}$				
Tone	Noise	Loudness	Annoyance	Noisiness	Tone	Noise	Loudness	Annoyance	Noisiness
71	75.0	10.3	7.2	11.7	71	-	-	-	-
76	80.0	17.0	14.0	19.9	76	70.0	9.6	5.2	6.3
81	85.0	33.1	33.9	36.8	81	72.5	11.9	7.1	8.0
86	90.0	46.7	48.6	58.9	86	75.0	20.0	11.4	13.6
91	95.0	76.9	102.3	100.0	91	80.0	29.3	24.0	25.7
96	97.5	101.2	131.8	121.6	96	85.0	50.5	45.1	47.1
101	100.0	109.0	166.0	141.3	101	90.0	70.8	85.1	69.6

Loudness of Noise and 1000-Hz Tone Judged Separately

SPLs (dB)		SPLSs (dB)	
Noise	Magnitude Estimates	1000-Hz Tone	Magnitude Estimates
70	12.5	70	7.6
75	16.0	75	10.5
80	21.5	80	14.5
85	30.0	85	20.5
90	42.0	90	29.0
95	59.0	95	40.0
00	83.0	100	56.2
θ re Sound Pressure	0.57	θ re Sound Pressure	0.57

TABLE C-22

Values in Figure 5 of Judged Perceived Magnitude
(250-Hz Tone + Low-pass Noise)

Magnitude Estimates (GMs of 10 θs)

T/N (≤ + 15 dB)					T/N (≥ + 20 dB)				
SPLs (dB)$_{\bar{X}}$					SPLs (dB)$_{\bar{X}}$				
Tone	Noise	Loudness	Annoyance	Noisiness	Tone	Noise	Loudness	Annoyance	Noisiness
71	72.5	11.8	8.0	11.5	71	-	-	-	-
76	75.0	15.8	15.1	16.6	76	-	-	-	-
81	80.0	26.1	26.6	23.1	81	70.0	12.0	10.5	10.6
86	85.0	33.1	42.0	35.8	86	72.5	18.0	14.3	13.5
91	90.0	55.3	60.3	53.7	91	75.0	28.0	19.1	17.0
96	95.0	78.9	86.5	74.6	96	80.0	37.2	34.9	26.1
101	97.5	96.4	97.9	90.6	101	85.0	55.0	52.7	35.5

Loudness of Low-Pass Noise and 250-Hz Tone
Judged Separately

SPLs (dB)		SPLs (dB)	
Noise	Magnitude Estimates	250-Hz Tone	Magnitude Estimates
70	8.6	70	6.2
75	12.0	75	8.7
80	16.5	80	12.0
85	23.0	85	17.0
90	32.0	90	23.0
95	44.0	95	32.5
100	62.0	100	45.0
θ re Sound Pressure	0.57	θ re Sound Pressure	0.57

TABLE C-23

Values in Figure 6a of Judged Perceived Magnitude (3000-Hz Tone + Broadband-flat Noise)

Magnitude Estimates (GMs of 10 θs)

T/N (≤ + 15 dB)					T/N (≥ + 20 dB)				
SPLs (dB)		$\bar{X}$			SPLs (dB)		$\bar{X}$		
Tone	Noise	Loudness	Annoyance	Noisiness	Tone	Noise	Loudness	Annoyance	Noisiness
71	72.5	4.3	5.1	7.7	71	-	-	-	-
76	75.0	8.3	7.1	10.7	76	-	-	-	-
81	80.0	15.5	15.2	17.5	81	70.0	5.6	6.3	7.6
86	85.0	23.4	24.5	29.0	86	72.5	8.5	7.2	8.6
91	90.0	41.7	41.1	46.1	91	75.0	14.6	15.0	12.6
96	95.0	73.1	70.8	67.5	96	80.0	28.5	30.2	19.7
101	97.5	103.5	96.6	81.7	101	85.0	52.5	57.5	34.9

Loudness of Noise and 3000-Hz Tone Judged Separately

SPLs (dB)		SPLs (dB)	
Noise	Magnitude Estimates	3000-Hz Tone	Magnitude Estimates
70	12.5	70	11.5
75	16.0	75	16.0
80	21.5	80	22.0
85	30.0	85	31.0
90	42.0	90	43.0
95	59.0	95	60.0
100	83.0	100	84.0
θ re Sound Pressure	0.57	θ re Sound Pressure	0.57

TABLE C-24

Values in Figure 6b of Judged Perceived Magnitude (3000-Hz Tone + High-pass Noise)

Magnitude Estimates (GMs of 10 Os)

T/N (≤ + 15 dB)					*T/N (≥ + 20 dB)				
SPLs (dB)$_{\bar{X}}$					SPLs (dB)				
Tone	Noise	Loudness	Annoyance	Noisiness	Tone	Noise	Loudness	Annoyance	Noisiness
72	80.0	15.0	9.7	31.8	72	70.0	8.3	4.9	16.0
77	85.0	22.9	18.2	40.3	77	72.5	10.8	6.8	17.0
82	90.0	28.8	27.5	52.5	82	75.0	15.1	9.7	15.8
87	95.0	45.7	48.5	62.1	87	77.5	21.4	14.7	14.5
92	97.5	64.6	62.7	74.7	92	82.5	33.1	29.5	18.1
97	100.0	81.3	79.4	88.9	97	87.5	55.0	50.9	25.0
102	-	-	-	-	102	92.5	82.2	86.7	35.0

*Includes T/N ratio of +35 dB

Loudness of Noise and 3000-Hz Tone Judged Separately

SPLs (dB)		SPLs (dB)	
Noise	Magnitude Estimates	3000-Hz Tone	Magnitude Estimates
70	6.4	70	11.5
75	8.9	75	16.0
80	12.2	80	22.0
85	17.0	85	31.0
90	24.0	90	43.0
95	33.0	95	60.0
100	46.0	100	84.0
θ re Sound Pressure	0.57	θ re Sound Pressure	0.57

Table C-25

Comparison Between Group I (Row 1) and Group II (Row 2)
Geometric Means Obtained for Loudness, Annoyance, and
Noisiness of Broadband-flat Noise with an Added 3000-Hz
Tone as a Function of Noise SPL (dB).
N is 10 in each Test Group.

	Sound Pressure Level of Noise (dB)						
	70	75	80	85	90	95	100
Geometric Means							
Loudness	5.4	11.8	20.4	30.7	45.7	77.6	112.2
	9.2	12.3	19.9	34.8	46.8	79.8	112.2
Annoyance	5.8	10.8	21.4	33.0	46.2	70.8	106.0
	7.2	11.5	20.0	36.7	47.6	68.4	123.0
Noisiness	6.5	12.0	20.0	30.2	47.9	66.1	95.2
	8.0	14.0	20.4	28.8	44.7	67.6	89.1

Table C-26

Comparison Between Group I (Row 1) and Group II (Row 2)
Geometric Means Obtained for Loudness, Annoyance, and
Noisiness of Broadband-flat Noise with an Added 3000-Hz
Tone as a Function of Tone SPL (dB).
N is 10 in each Test Group.

	Sound Pressure Level of Tone (dB)						
	71	76	81	86	91	96	101
Geometric Means							
Loudness	4.4	8.3	12.1	15.5	24.6	45.7	69.2
	3.9	9.1	10.2	15.1	20.9	50.1	71.3
Annoyance	5.1	7.1	12.3	15.1	25.2	46.8	70.8
	5.7	7.6	10.0	17.8	26.4	50.3	75.0
Noisiness	7.7	10.8	14.2	17.8	24.0	36.3	49.0
	9.5	10.0	12.3	15.7	23.4	39.5	48.0

1. Report No.
NASA CR-3892

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
CONTRIBUTION OF TONAL COMPONENTS TO THE OVERALL LOUDNESS, ANNOYANCE, AND NOISINESS OF NOISE - Relation Between Single Tones and Noise Spectral Shape

5. Report Date
May 1985

6. Performing Organization Code

7. Author(s)
Rhona P. Hellman

8. Performing Organization Report No.

9. Performing Organization Name and Address
Dept. of Communication Disorders
Boston University
Boston, Massachusetts 02215

10. Work Unit No.

11. Contract or Grant No.
NSG-1644

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code
505-33-53-03

15. Supplementary Notes
Langley Technical Monitor: Kelli F. Willshire
Final Report (1979—1984)

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16. Abstract
A large scale laboratory investigation of loudness, annoyance, and noisiness produced by single-tone-noise complexes was undertaken to establish a broader data base for quanitification and prediction of perceived annoyance of sounds containing tonal components. Loudness, annoyance, and noisiness were distinguished as separate, distinct, attributes of sound. Three different spectral patterns of broadband noise with and without added tones were studied: broadband-flat, low-pass, and high-pass. Judgments were obtained by absolute magnitude estimation supplemented by loudness matching. The data were examined and evaluated to determine the potential effects of (1) the overall sound pressure level (SPL) of the noise-tone complex, (2) tone SPL, (3 noise SPL, (4) tone-to-noise ratio, (5) the frequency of the added tone, (6) noise spectral shape, and (7) subjective attribute judged on "absolute" magnitude of annoyance. Results showed that, in contrast to noisiness, loudness and annoyance growth behavior depends on the relationship between the frequency of the added tone an the spectral shape of the noise. The close correspondence between loudness and annoyance suggests that, to better understand perceived annoyance of sound mixtures, i is necessary to relate the results to basic auditory mechanisms governing loudness and masking. To a large extent, complex interactions generated by the simultaneous presentation of noise and tone can account for the experimental effects. However, since tonal components often measurably increase annoyance more than loudness, nonacoustic factors probably also play a role. The complex interactions uncovered hel to account for the widely disparate published estimates of the effect of tonal components on perceived annoyance.

17. Key Words (Suggested by Author(s))
Annoyance
Loudness
Noisiness
Tones
Noise
Masking

18. Distribution Statement
Unclassified—Unlimited
Subject Category 71

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
150

22. Price
A07

For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Washington, D.C.
20546

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