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ASSESSMENT OF THE LOUDNESS AND ANNOYANCE OF LOW-FREQUENCY NOISE FROM A PSYCHOACOUSTICAL PERSPECTIVE

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INTRODUCTION

In recent years, sound annoyance produced by low-frequency noise has generated increased attention (e.g. [1] [2] [3]). The major sources of low-frequency noise inside buildings are modern energy efficient heating, refrigeration, and air-conditioning systems. These noises, collectively known as HVAC spectra, are often the cause of increased interior room complaints [4] [5]. Despite the widespread recognition of this problem, little agreement exists about how to assess and quantify the perceived annoyance. To this end, we report the results of an ongoing ASHRAE sponsored psychoacoustical investigation and analysis of the perceived annoyance of HVAC noise. Based on the accumulated evidence that loudness is the primary component of sound annoyance [6] [7] [8] [9], both loudness and annoyance measures were obtained for all test stimuli. This experimental protocol provided baseline loudness data, enabling the annoyance-to-loudness relation to be accurately determined.

DESCRIPTION OF EXPERIMENTS

Stimuli, listening conditions, and subjects. The stimuli were 12 noise spectra similar in overall shape, level, and spectral content to a broad sample of more than 70 HVAC noises recorded in an earlier study [2]. The spectra extended over a range of SPLs from 72.8 to 92 dB. Owing to the low-frequency emphasis of the noises, the range of A-weighted levels was much lower extending from 40.6 to 61.4 dB. Figure 1 provides the 1/3-octave-band levels of four spectra typical of the noise samples. Note that for all spectra the maximum sound energy is located well below 300 Hz. However in some samples, for example, spectra 11 and 12, the decrease in level with frequency is relatively smooth, whereas in others, as in spectra 1 and 9, the noises contain dominant tonal peaks located below 100 Hz.

Listening was through two loudspeakers in a sound-isolated test room [10]. The stimuli were presented one at a time for 10 s with an interburst interval of 7 s. A total of 16 listeners with normal hearing took part in the experiments. The listeners sat in one of three seats at a desk. At each seat location, the acoustic stimulus was nominally the same, enabling up to three listeners to be tested at the same time.

Method. Judgments of loudness and annoyance were obtained by the method of absolute magnitude estimation (AME). This method has been used successfully in previous studies to differentiate and assess the overall loudness and annoyance of noise-tone complexes (e.g. [7] [8]). According to the method of AME, no reference standard is designated. An internal standard common to all groups of listeners is implied. Listeners are simply asked to assign a positive number, including decimals and fractions, to the loudness (or annoyance) of the stimuli so that the subjective magnitude of the two continua, loudness and number, appear equal. The rationale for using this version of magnitude estimation is described elsewhere [11].

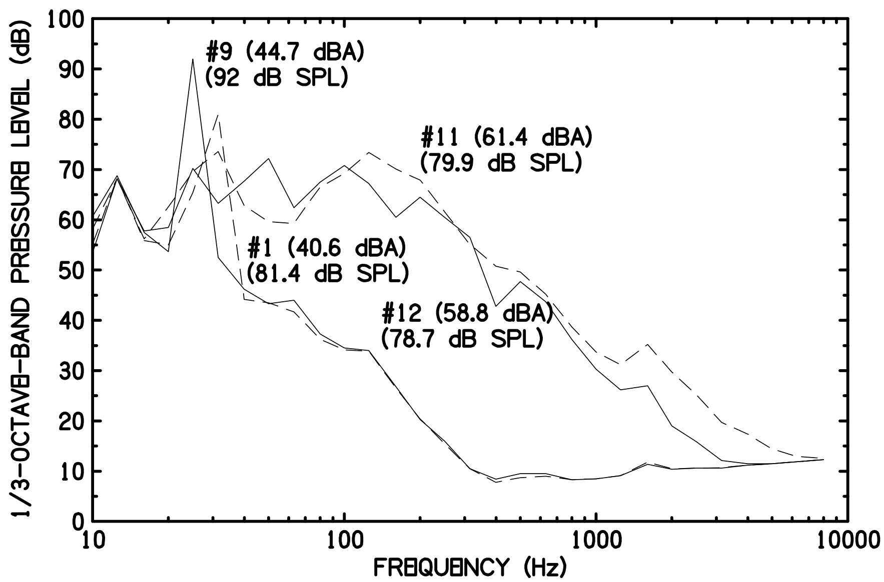

Figure 1: Illustrative spectrum shapes

During a given session, each listener judged the loudness (or annoyance) of the 12 sample noises three times in a quasi-random order that differed for each of the three runs [10]. All the judgments were made after each of the noise stimuli were turned off. The judgments were individually recorded and then stored in a computer.

As in studies [7] and [8] cited above, the latter two judgments produced by each individual listener were geometrically averaged. The individual geometric averages were then used for the determination of group geometric means. Final averaging was achieved without normalization of the obtained numbers. This procedure permitted both the absolute and relative perceived magnitudes to be determined and analyzed.

RESULTS AND DISCUSSION

Figure 2 shows the group geometric means obtained by 11 listeners for loudness and annoyance. The hatched bars on the left side of each pair are for loudness; those on the right side are for annoyance. The vertical lines are twice the SE around the mean data. In general, loudness and annoyance are closely coupled. That is, an increase in loudness tends also to be accompanied by an increase in annoyance. For example, a comparison between the loudness and annoyance data for spectra 1 and 6 indicates that an increase in loudness also results in an increase in annoyance.

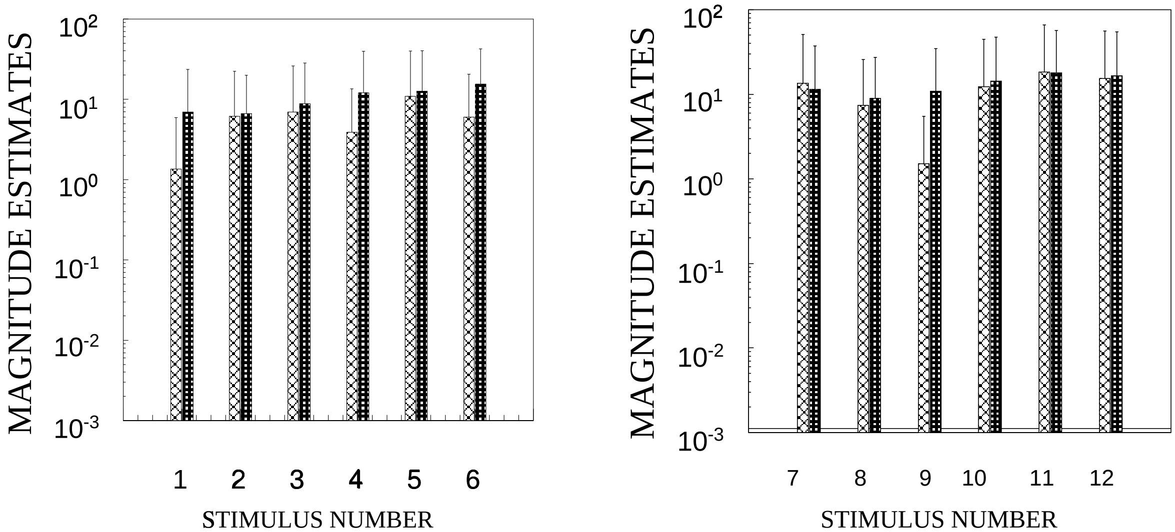

Figure 2: Group mean loudness and annoyance judgments for 12 spectra

The close relation between loudness and annoyance implies that to a large extent annoyance, like loudness, reflects the way in which sounds are processed by the auditory system. If true, then a psychoacoustically-based model of loudness, like the one proposed by Zwicker in ISO 532B [12], ought to predict the measured loudness magnitudes. Also, it ought to provide baseline loudness values for determining the annoyance-to-loudness relation. A test of these assumptions is provided in Fig. 3.

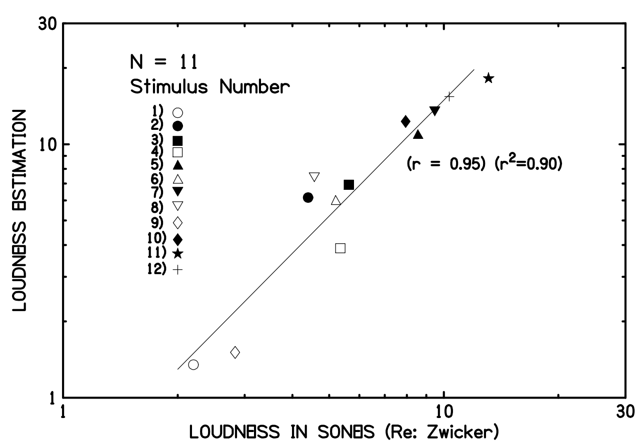

Figure 3: Relation between measured and predicted loudness values

Figure 3 shows that the correlation between the group loudness-estimation data and the loudness predictions in Sones according to Zwicker's model [12] is quite good (rxy= 0.95; r2= 0.90). Moreover, without normalization of the raw data, the actual numerical values the listeners assigned to the loudness of the different spectra and the predicted Sone values lie within the same range. By comparison, Fig. 4 shows that the correlation between the loudness-estimation data and the A-weighting, which is more typically used to assess the loudness of noise (e.g. [1] [9] [13]), is poorer (rxy = 0.86; r2= 0.74). The analysis of the annoyance-to-loudness ratios (A/L) makes the limitations of the A-weighting even more evident.

Whereas Fig. 2 shows that, in general, loudness and annoyance tend to vary together in tandem, loudness and annoyance do not always have the same magnitude. An examination of the A/L ratios reveals the extent to which annoyance may differ from loudness for each of the 12 spectra. Mean values (filled circles) of the A/L ratios and the associated standard error bars are plotted in Fig. 5 for the group of 11 listeners. For eight spectra the ratios of A/L are about 1.0 indicating that for these stimuli annoyance can be well accounted for by our knowledge of loudness. However for four spectra, 1, 4, 6, and 9, the A/L ratios are all significantly greater than 1.0, ranging from about 2.0 to more than 7.0. Moreover, as shown by the unfilled circles and squares, the larger ratios are repeatable over time. In all instances, the spectra that evoke A/L ratios exceeding 1.0 are characterized by low-frequency tones. Further data analysis indicates that loudness levels calculated for each spectra, in accord with Zwicker's model [12], provide a better account of the A/L relation than the A-weighted levels. These results are presented in Figs. 6 and 7.

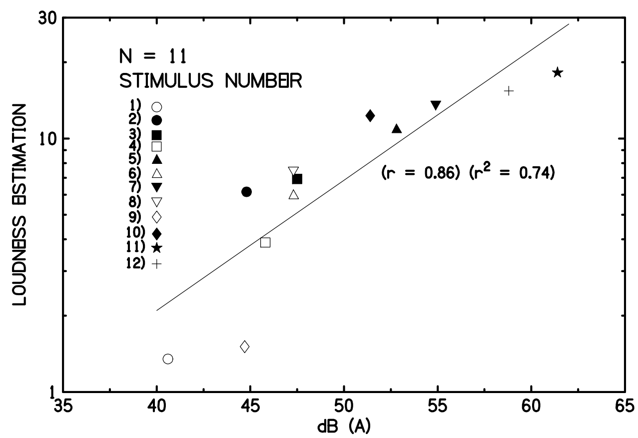

Figure 4: Relation between measured loudness and dB(A) values

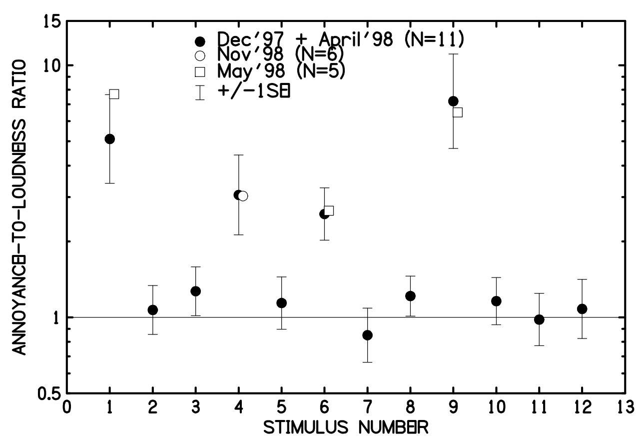

Figure 5: Annoyance-to-loudness ratio obtained for each of 12 spectra

Figure 6 is a plot of the A/L ratio as a function of the dB(A) values. The results in Fig. 6 hint that, for the four stimuli containing strong tonal components, the A/L ratio is inversely related to level. However, the correlation between the A/L ratio and dB(A) is too low to be meaningful. Spectra 4 and 9 (squares and diamonds) produce nearly the same A-weighted levels [45 vs 46 dB(A)], but they evoke very different A/L ratios [3.1 vs 7.2]. In contrast, as shown in Fig. 7, the same analysis based on ISO 532B [12] more closely predicts the inverse relation between A/L and sound level. Here, the squares and diamonds are clearly differentiated; spectrum 9, which elicits an A/L ratio of 7.2, is 9 phons lower than spectrum 4. Moreover, consistent with a summary report [1], Figs. 6 and 7 show that the A-weighted levels markedly underestimate the loudness levels for all stimuli. Because loudness is derivable from loudness level, this result also means that the dB(A) values underestimate the measured loudness data in Fig. 3.

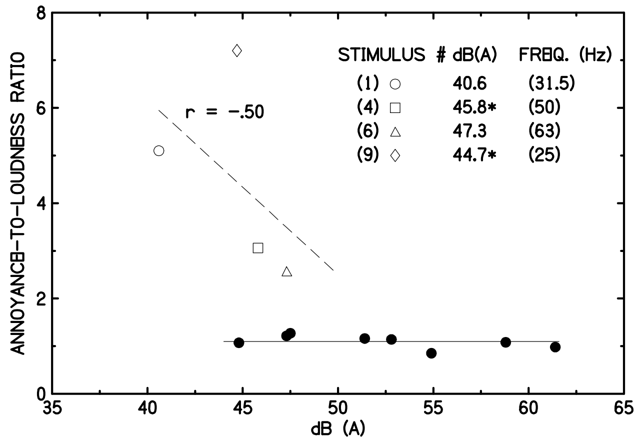

Figure 6: Relation between annoyance-to-loudness ratio and dB(A)

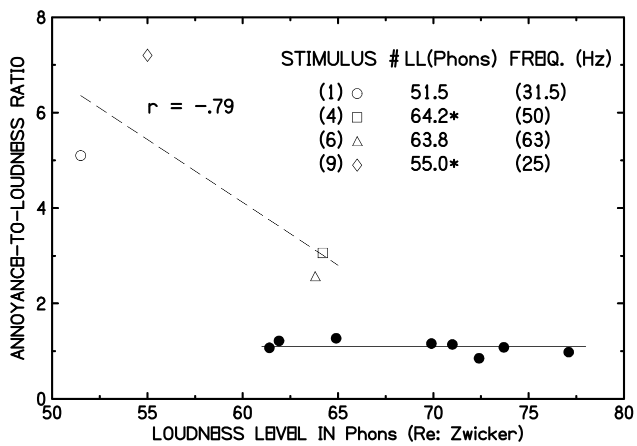

Figure 7: Relation between annoyance-to-loudness ratio and loudness level

The finding that annoyance exceeds loudness, more at low than at moderate loudness levels, implies that loudness is not the sole controlling perceptual attribute for the increased annoyance. For low-frequency noises containing dominant tonal peaks another perceptual attribute must also play a role. Independent evidence to support this notion comes from a recent study of the perceived roughness of low-frequency pure tones [14]. Measured by AME at a constant loudness level of 35 phons, perceived roughness of low-frequency tones varies inversely with frequency reaching a maximum at a frequency of 25 Hz, the same frequency that evokes the maximum A/L ratio in Figs. 6 and 7. Figure 8 compares these two diverse sets of data. The high correlation between roughness and the A/L ratio (re: a value of 1.0 at 25 Hz) strongly suggests, in accord with earlier findings [8], that an increase in roughness induces an increase in annoyance relative to loudness. As a result, even though the loudness may decrease the A/L ratio increases.

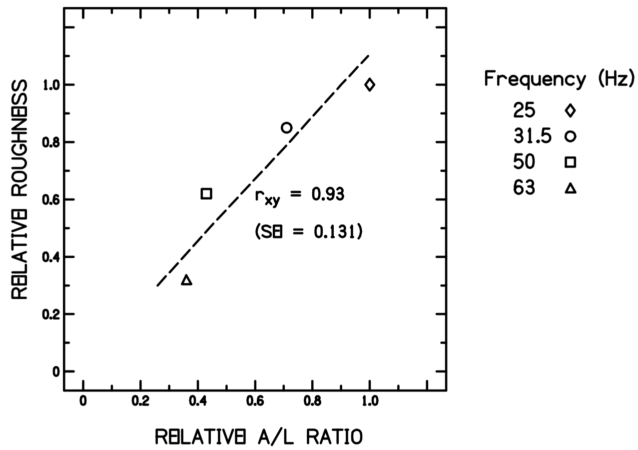

Figure 8: Relation between relative roughness and relative A/L ratio

CONCLUSIONS

Taken together, loudness and annoyance measures of low-frequency HVAC noise provide a psychoacoustical framework for understanding the observed effects. A comparison between measured and calculated loudness values shows that Zwicker's model in ISO 532B more accurately describes perceived loudness than the A-weighting. Not only does ISO 532B better predict the overall loudness of the various spectra, it also more closely predicts the A/L relation. Stimuli with nearly the same low A-weighted levels can evoke very different A/L ratios. This is not true however for ISO 532B. In addition to loudness, perceived roughness contributes to the increased annoyance produced by low-frequency noises characterized by spectral peaks below 100 Hz.

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