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EQUAL-LOUDNESS CONTOURS AT HIGH FREQUENCIES

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ABSTRACT
Interfrequency loudness matches were obtained for 12 pairs of frequencies from 1 to 16 kHz over a range of sensation levels (SL) from 4-to-100 dB. At 10 kHz and below, a linear matching function with a slope of 1.0 provides a good account of the data. In contrast, loudness-matching functions at higher frequencies are curvilinear in shape. Moreover, the regional slope values are both level and frequency dependent. The implications of the results for assessing the overall shape and spacing of the equal-loudness contours are described.

1 - INTRODUCTION
Equal-loudness relations at high frequencies are necessary for improved noise evaluation strategies and measuring instruments, for accurate sound quality assessment of communication and audio systems, and for better understanding of signal processing by the auditory system. Yet, despite the importance of high-frequency loudness-level data, few such data exist, especially in the frequency region above 3 kHz (e.g., [1], [2], [3]). To complicate the experimental situation, two established equal-loudness contours [4], [5] are in conflict at high frequencies. Figure 1 provides a comparison.
Above about 8 kHz and a loudness level of 60 phons, the solid curves tend to be more closely spaced than the dashed curves. These results suggest that in a log-log plot loudness at high frequencies based on the equal-loudness measures of Fletcher and Munson [4] increases more rapidly with sound intensity than loudness based on the equal-loudness measures of Robinson and Dadson [5]. This conflict is especially noteworthy because the experimental results of Robinson and Dadson are part of an international standard [6]. In light of the uncertainty of the equal-loudness relations at high frequencies and the dearth of high-frequency loudness data, additional laboratory measurements were collected.

2 - DESCRIPTION OF EXPERIMENTS

2.1 - Stimuli, listening conditions, and subjects
The stimuli were tone bursts generated by a programmable waveform generator (TDT WG2) whose output was attenuated (two TDT PA4s in series), and then amplified (Marantz PM-54 DS). Listening was via a Sennheiser (HDA 200) earphone in a sound-insulated room. Eight paid listeners with thresholds at the test frequencies within 10 dB of the values reported in a previous study [7] took part in the experiments.

2.2 - Method
Interfrequency loudness matches were obtained by the classical method of adjustment. Three frequencies served as the standard tone and eight frequencies served as the comparison tone. Table 1 shows the 12

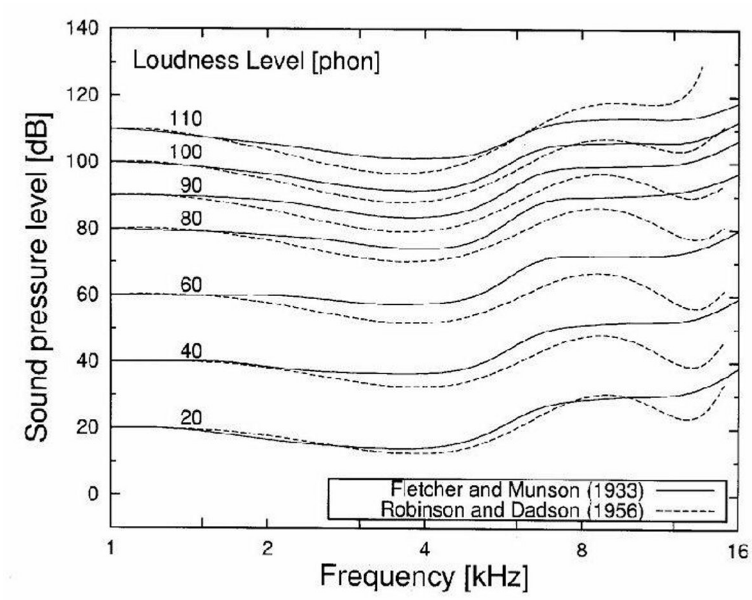

Figure 1: Equal-loudness relations measured in two classic studies.

pairs of test frequencies used for the measurements. The loudness matches spanned a stimulus range from 4 dB SL up to 100 dB SL. Sensation levels were based on individual thresholds measured, in each session, prior to the loudness matches for a randomly chosen pair of standard and comparison tones. Thresholds were obtained by an adaptive 2IFC procedure with feedback. The signal level was varied according to a five-down/one-up decision rule that provides an estimate of the 87 % correct point on the psychometric function. For reasons given elsewhere [2], 3 dB was subtracted from each mean threshold value to approximate the signal level necessary to yield 72 % correct responses.

		FREQUENCY (Hz) (COMPARISON TONE)						
FREQUENCY (Hz) (STANDARD TONE)	1.0	3.15	5.0	–	–	–	–	–
	3.15	5.0	8.0	10.0	12.5	14.0	15.0	16.0
	5.0	8.0	12.5	16.0	–	–	–	–

Table 1: Standard and comparison tones.

Following the threshold determinations, equal-loudness judgments were made. The listeners were instructed to adjust the loudness of the comparison tone to equal the loudness of the standard tone by means of bracketing. An unmarked knob that enabled the listeners to vary the level of the comparison tone to levels both above and below the level of the standard tone was used for the adjustments. In one run, the level of the standard tone was fixed and the level of the comparison tone was adjusted. In the second run, the roles of the standard and comparison tones were reversed. For each stimulus pair, two separate matches to each standard tone were obtained. Both the standard and comparison tones were presented in alternation to the right ear for 0.5 s with an interburst interval of 0.5 s. After the judgment was made, the stimuli were turned off for 5 s. Then, a different pair of quasi-randomly chosen test levels were presented. A DEC(XL) PC executed the threshold and loudness-matching procedures and stored the data.

3 - RESULTS AND DISCUSSION

To determine the viability of the experimental procedure, two control conditions were run. In one experiment, a 1-kHz tone in the right ear was adjusted to match in loudness a 1-kHz tone heard in alternation in the left ear. In the second experiment, loudness matches were obtained between a 1- and 3.15-kHz tone presented in alternation to the right ear. Both experiments produced linear matching functions in good agreement with data from previous studies (e.g., [1], [2]).
Figure 2 presents an example of group loudness-level data measured in this study for tones at 1- and 3.15-kHz. Also shown, are the results of other investigators at similar frequencies [1]. Each point from

the current study (stars) is based on the midpoint of two data sets, 16 judgments obtained by adjusting the loudness of the 1-kHz tone and 16 obtained by adjusting the loudness of the 3.15-kHz tone. The overall picture is clear. Up to a sound pressure level near 100 dB, a linear matching function (dashed line) drawn through the loci of equal sensation levels represents a reasonable consensus of the various experimental results. Above 100 dB SPL, the few available data lie below the equal-sensation level line. The reason for this deviation is uncertain [1]. Most important, despite methodological differences and also, differences in listening conditions (i.e., earphones vs free field), the current results are consistent with those determined in a cross-section of other studies. This agreement permitted the matching relation between the 1- and 3.15-kHz tones to provide a baseline function for assessing the matching relations at higher frequencies.

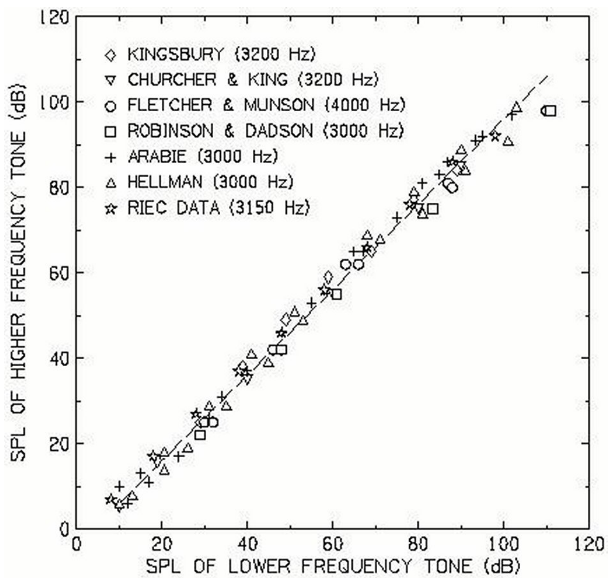

Figure 2: Interfrequency loudness matches compared to the results of other investigators.

Figure 3 shows a family of loudness-matching functions determined for seven standard-comparison-tone pairs in increasing order of frequency from 3.15 to 16 kHz. As in Fig. 2, each point is the midpoint of two data sets for the group, one obtained by adjusting the loudness of the standard tone and the other, obtained by adjusting the loudness of the comparison tone. Moreover, because the results in Fig. 2 tend to fall along the equal-sensation level line, all data are plotted in SL rather than in SPL. For clarity of presentation, the curves are shifted along the abscissa relative to the SL of the 3.15-kHz tone. Up to 8 kHz, the midpoint value is based on 32 judgments/level; at higher frequencies, the midpoint value is based on 28 judgments/level. The lines are the least-squares fits to the average group data. According to Fig. 3, a linear function with a slope of 1.0 provides a good description of the experimental data at 10 kHz and below. In contrast, a 3rd order polynomial fit more accurately describes the data at higher frequencies.

Another important characteristic of the curves in Fig. 3 is the relation of the loudness-matching function to the sensation level of the standard and comparison tones judged to be equally loud. For interfrequency matches below 8 kHz not only does a linear matching function with a slope of 1.0 provide a good account of the data, but, despite different test frequencies, two tones at the same SL are also equally loud. This latter result does not hold at higher frequencies. At 8 kHz and above, the higher frequency tone is generally louder at the same SL than the lower frequency standard to which it is matched. Figure 4 gives an example. Each datum point is based on 14 judgments by seven listeners. The dotted curves are the 3rd order fits to the data.

Figure 4 shows that, except at SLs close to threshold, both curves lie above the equal-sensation level line (dashed line). Thus, just as in the 8-to-10-kHz frequency region, a 12.5-kHz tone is louder than a 3.15-kHz tone at the same SL. However, unlike the data at 10 kHz and below in Fig. 3, the curvilinear shapes of the loudness-matching functions in Fig. 4 imply that the increase in loudness of the 12.5-kHz tone relative to the loudness of the 3.15-kHz tone is level dependent. This result indicates that the increase in loudness level of the high-frequency tone must also vary with level. To test this conjecture, the group data in Fig. 3 for 12.5-, 15-, and 16-kHz tones were transformed into loudness levels in phons. Despite

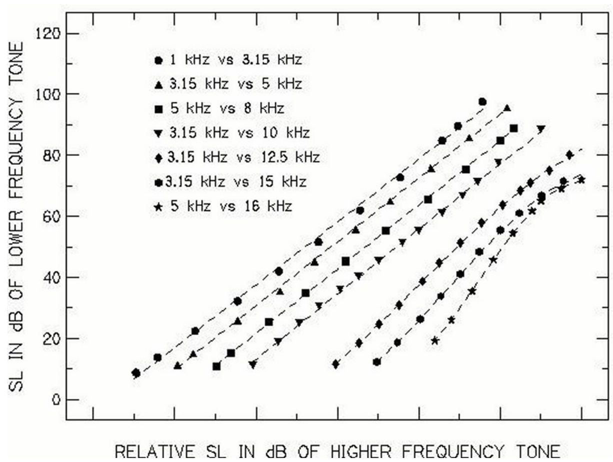

Figure 3: Loudness-matching functions for seven pairs of test frequencies.

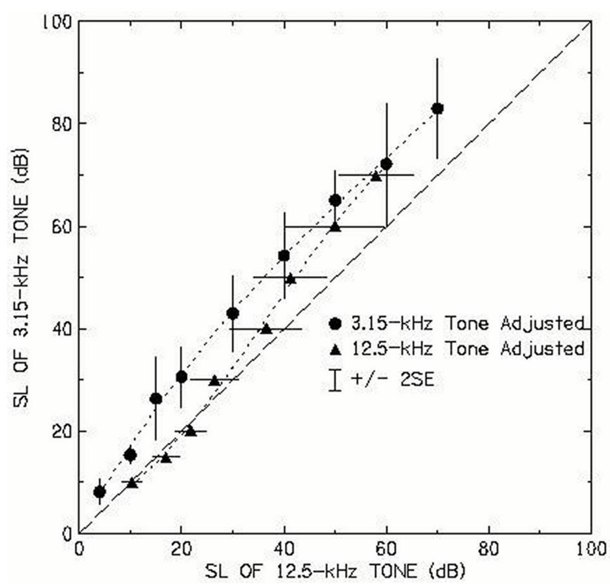

Figure 4: Loudness matches between 3.15- and 12.5-kHz tones.

different standard frequencies, such a transformation was possible because transitivity was preserved for the group [8]. The results are given in Fig. 5.

In accord with our assumption, Fig. 5 shows that, relative to the linear loudness-level function for a standard 1-kHz tone, the overall shapes and slopes of the loudness-level functions at high frequencies are level dependent. Moreover, the slopes also depend on frequency. Up to a loudness level of 60 phons, the loudness-level functions at 12.5 kHz and higher become progressively steeper with frequency; above 60 phons, the functions become progressively flatter. At 60 phons and below, slopes calculated along the approximately linear segments of the loudness-level functions are 1.31 at 12.5 kHz, 1.44 at 15 kHz, and 1.79 at16 kHz. In contrast, above 60 phons linear fits to the functions yield slopes of 0.98 at 12.5 kHz, 0.86 at 15 kHz, and 0.74 at 16 kHz.

To complete the analysis, the loudness-level functions for 15- and 16-kHz tones in Fig. 5 were compared to those measured in two established studies [4], [9]. Figure 6 gives the results. The curvilinear shape of the function reported by Robinson [9] closely agrees with the overall shape and slope of our function for a 15-kHz tone (left panel). The main difference between the two curves is in their absolute position. This difference may well be caused by the 14-dB threshold difference between the two studies. On the other hand, the function reported by Fletcher and Munson [4] differs distinctly from our function for a 16-kHz tone (right panel).

At 60 phons and below, the slope derived from Robinson's data is 1.47; above 60 phons it decreases to 0.91. These slope values are in good agreement with the corresponding slopes of 1.44 and 0.86 derived

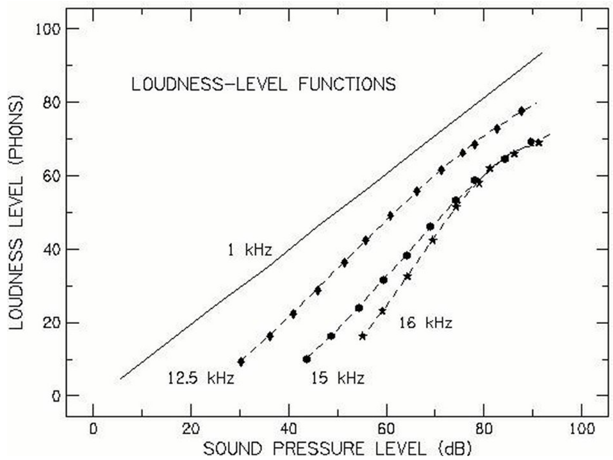

Figure 5: Loudness-level functions at 12.5, 15, and 16 kHz.

for a 15-kHz tone in Fig. 5. Just the opposite appears to hold for the data of Fletcher and Munson [4]. Below 60 phons, instead of the steepening observed both in our results and in Robinson's function, Fletcher and Munson's data yield a relatively flat function with a matching slope of 0.81. Conversely, their projected function becomes steeper at higher phon levels. Overall, the results at 12.5 kHz and above are compatible with the equal-loudness relations published in Appendix B in ISO/R226 [6].

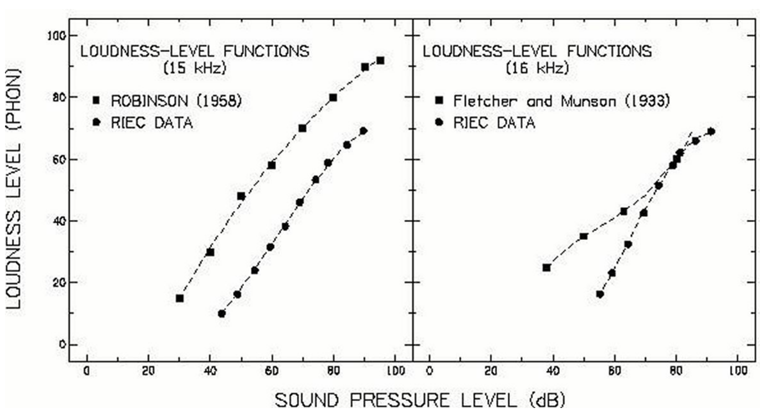

Figure 6: Loudness-level function of Robinson [9] and of Fletcher and Munson [4].

4 - CONCLUSIONS

To add to the database and to clarify the overall shape of the equal-loudness contours from 1 to 16 kHz, a laboratory study of equal-loudness relations was undertaken. Consistent with ISO/R 226 [6], the data imply that, for frequencies between 1 and 10 kHz, the spacing between the equal-loudness contours is independent of loudness level. In contrast, above 10 kHz the equal-loudness contours are more closely spaced below 60 phons than at higher loudness levels. Moreover, the higher the frequency the more strongly does the spacing vary with loudness level.

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