DETERMINATION OF EQUAL-LOUDNESS RELATIONS AT HIGH FREQUENCIES

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Abstract

To add to the database and to help clarify the overall shape and spacing of the equal-loudness relations at high frequencies, inter-frequency loudness matches were obtained for high-frequency pure tones. Between 1 and 10 kHz, a linear matching function with a slope of 1.0 gave a good account of the results. Above 10 kHz, the loudness-matching functions were curvilinear in shape. The data suggest that, from 1 to 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. The implications of these results are assessed.

Despite the fundamental importance of high-frequency loudness measures, loudness data in the frequency region above 3 kHz are sparse. (Hellman, 1976; Hellman et al., 1997; Takeshima et al. 1997). Moreover, two classic equal-loudness contours, one measured by Fletcher and Munson (1933), and the other measured by Robinson and Dadson (1956) are in conflict in the high-frequency region. This conflict is especially noteworthy because the experimental results of Robinson and Dadson are part of an international standard in ISO 226. Additional equal-loudness data are needed at high frequencies to resolve this experimental uncertainty.

Knowledge of the growth of loudness for high-frequency tones can also provide a key test of excitation-pattern models of loudness growth and summation (e.g., Zwicker & Scharf, 1965; Zwicker & Fastl, 1990). In light of the potentially significant practical and theoretical implications of high-frequency loudness data, a study of equal-loudness relations in the 1-to-16 kHz frequency region was deemed necessary.

Experimental Procedure

The stimuli were 0.5s tone bursts in the frequency range from 1-to-16 kHz. The tones were generated by a programmable waveform generator (TDT WG2) whose output was attenuated (two TDT PA4 in series), and then amplified (Marantz PM-54 DS). Listening was in a sound-insulated booth through the right earphone of a Sennheiser (HDA 200) headset. Eight paid listeners, all with thresholds at the test frequency within 10 dB of the values determined in the Research Institute of Electrical Communication (RIEC) at Tohoku University for the Sennheiser earphone, took part in the experiments up to 8 kHz; seven of the eight listeners took part in the experiments above 8 kHz.

Individual thresholds were measured in each session for a randomly chosen pair of standard and comparison tones. Thresholds were obtained by an adaptive 2IFC procedure with feedback that provides an estimate of the 87% correct point on the psychometric function. For reasons given elsewhere (Miskiewicz et al., 1993), 3 dB was subtracted from each mean threshold value to approximate the signal level necessary to yield 72% correct responses.

Following the threshold determinations, equal-loudness relations were obtained by matching. Such comparative judgments were considered by Fechner (1860) to reflect basic sensory experience. The loudness matches were made for 12 pairs of frequencies from 1 to 16 kHz over a stimulus range from 4-to-100 dB SL. To test for transitivity in the data, three frequencies set at 1, 3.15, and 5 kHz served as the standard tone. Moreover, to determine the viability of the experimental procedure, two control conditions were run. In one condition, 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 condition, loudness matches were obtained between a 1- and 3.15-kHz tone presented in alternation for 0.5 s to the right ear. For all conditions, the listeners adjusted 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.

Results and Discussion

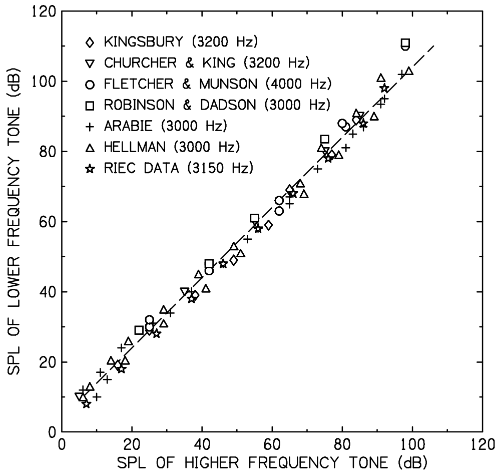

Figure 1. Equal-loudness relation between 1- and 3.15- kHz tones.

Figure 1 compares the group results obtained for the second control condition (stars) to those of other investigations at similar frequencies (Hellman, 1976). Each point from the control condition is based on the midpoint of two data sets, 16 judgments obtained by adjusting the loudness of the 1-kHz tone and 16 judgments obtained by adjusting the loudness of the 3.15-kHz tone. The overall picture is clear. Up to about 100 dB SPL, a linear matching function (dashed line) drawn through the loci of equal SLs represents a reasonable consensus of the various experimental results. Moreover, despite methodological differences and also, differences in listening conditions (i.e., earphones vs free field), the control 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.

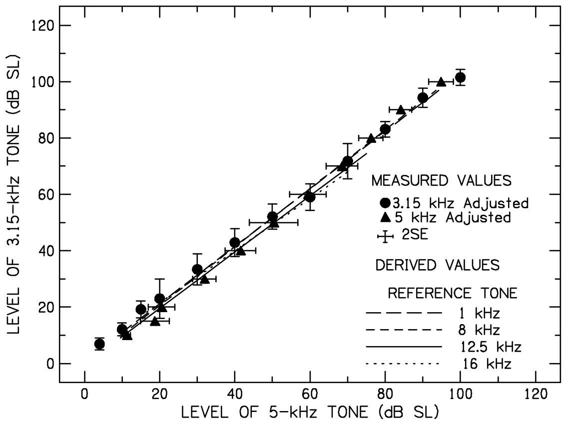

Figure 2. Measured and derived equal-loudness levels.

Figure 2 illustrates the degree of internal consistency observed in the group data. Both the 3.15- and 5-kHz tones were matched in loudness to the four reference tones set at 1, 8, 12.5, and 16 kHz. This paradigm made it possible to derive the matching relation between the 3.15- and 5-kHz tones from each of the four pairs of equal-loudness functions. The results are shown by the solid, dotted, and dashed lines. For comparison, the directly measured loudness-matching data between tones at 3.15- and 5-kHz are plotted together with their respective standard error bars. Clearly, the measured and derived results closely agree indicating that transitivity was preserved for the group.

Inter-frequency loudness matches for a sample of six pairs of test frequencies from which the transitivity data were derived are shown in Fig. 3 as a function of SL. The circles are group means obtained by adjusting the loudness of the lower frequency tone; the triangles are those obtained by adjusting the loudness of the higher frequency tone. Also indicated, by the vertical and horizontal bars, are +/-2SE around the means. The dashed line shows the locus of equal SLs for each tone pair. In contrast to the results at 8 kHz, at 12.5 and 16 kHz the matching functions become increasingly curvilinear in shape with a decreasing slope at high SLs. Moreover, in accord with earlier findings (e.g., Zwicker et al., 1957), the loudness of the tone set at a fixed level tends to be overestimated at moderate levels and to be underestimated at high levels.

From inter-frequency matching relations such as those in Fig. 3, a family of loudness-matching functions can be obtained. The results of this analysis determined for seven standard-comparison tone pairs in increasing order of frequency from 3.15 to 16 kHz are shown in Fig. 4. 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. 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 values are based on 32 judgments/level; at higher frequencies, the midpoint values are based on 28 judgments/level. The lines are the least-squares fits to the average group data. According to Fig. 4, a linear function with a slope of 1.0 provides a good description of the data at 10 kHz and below. In contrast, a 3rd order polynomial fit more accurately describes the data at higher frequencies.

The next step in our analysis was the transformation of the group data in Fig. 4 for 12.5-, 15- and 16-kHz tones into loudness level in phons. Despite different standard frequencies, such a transformation was possible because, as shown in Fig.2, transitivity was preserved for the group. The results are given in Fig. 5.

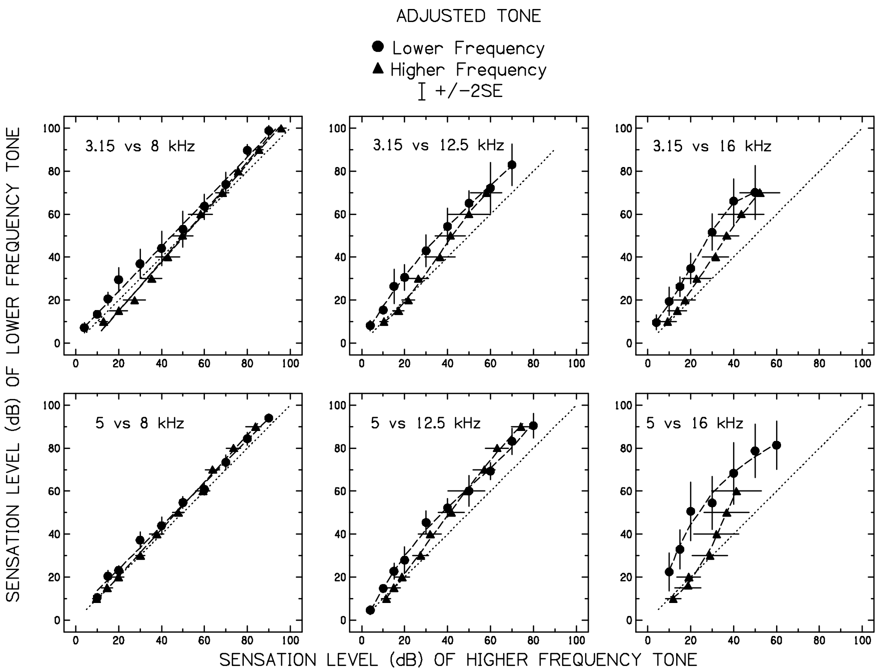

Figure 3. Inter-frequency loudness matches for six pairs of frequencies.

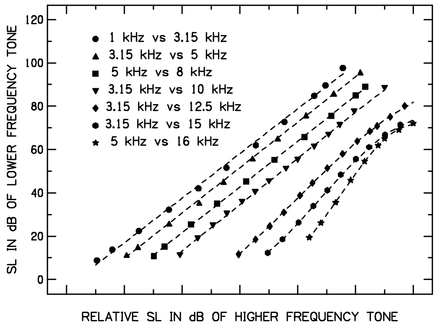

Figure 4. Loudness-matching function for seven pairs of test frequencies.

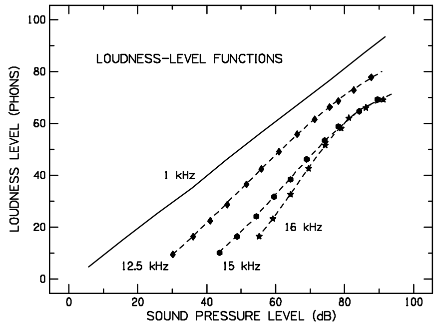

Figure 5. Loudness-level functions at 12.5, 15, and 16 kHz.

Figure 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 at 16 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.

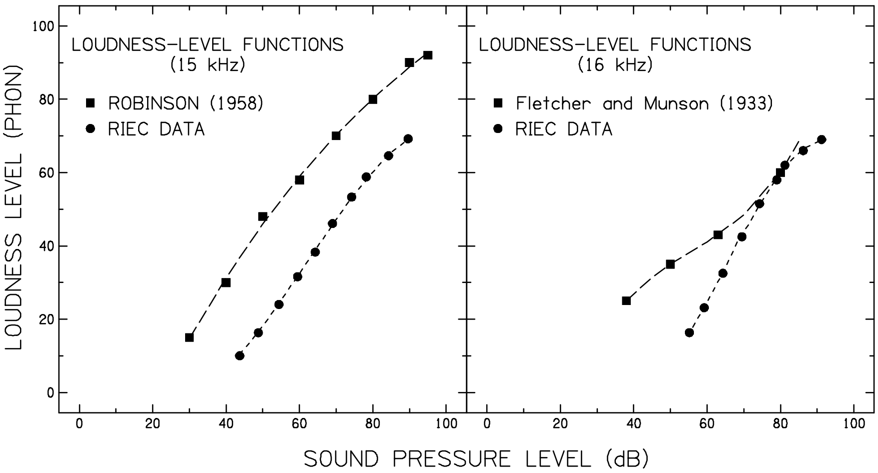

Figure 6. Loudness-level functions of Robinson (1958) and of Fletcher and Munson (1933).

To complete the analysis, the loudness-level functions for 15- and 16-kHz tones in Fig. 5 were compared to those in two established studies (Fletcher & Munson, 1933; Robinson, 1958). Figure 6 gives the results. The curvilinear shape of the function reported by Robinson (1958) closely agrees with the overall shape and slope of the function determined from the RIEC data in Fig. 5 for a 15-kHz tone (left panel). On the other hand, the function reported by Fletcher and Munson (1933) differs distinctly from the function determined from the RIEC data for a 16-kHz tone (right panel) as well as from Robinson's (1958) curve.

Conclusions

Equal-loudness relations determined for high-frequency pure tones 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. These findings suggest that for frequencies from 1 to 10 kHz the loudness functions are parallel, whereas at 12.5 kHz and higher the rate of loudness growth depends on both frequency and level being steeper at low and moderate loudness levels than at high loudness levels. Overall, the results above 1 kHz are consistent with ISO/R 226 (1961). The decrease in slope at high levels is also compatible with loudness models that enable loudness to be predicted on the basis of restricted excitation patterns (e.g., Zwicker & Scharf, 1965; Zwicker & Fastl, 1990).

Acknowledgment

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