BELL LABORATORIES RECORD

LOUDNESS AND PITCH

HARVEY FLETCHER

JANUARY 1935 Vol. XIII No. 5

Loudness and Pitch

By HARVEY FLETCHER
Director of Physical Research

MUSICIANS employ three terms to describe different aspects of the sensation they experience when listening to musical tones. These are pitch, loudness, and timbre, although the term quality, or tone color, is sometimes substituted for timbre. Most textbooks on physics have taught that these psychological characteristics are related in a simple way to three corresponding physical quantities: frequency, intensity, and overtone structure. The relationship between pitch and frequency, and between loudness and intensity, has been thought to be one of direct correspondence: the pitch of each note corresponding to a definite frequency, and the loudness of each note to a definite intensity. The relationship between harmonic structure and timbre has had no such simple formulation, but at least the timbre has been thought to depend on overtone structure alone. Studies in these laboratories, however, have shown that no such simple relationships exist, that each of the psychological quantities—although depending chiefly on the corresponding physical quantity—actually depends on all three. That there has not been a strict one-to-one correspondence between loudness and intensity has been known for some time, but only recently has accurate quantitative data been obtained. Between pitch and frequency, on the other hand, it is still generally thought that there is a strict one-to-one correspondence.

Frequency is the number of vibrations per second made by the sound source, such as a tuning fork or a violin string. Most musical tones, however, are composed of a series of frequencies which are multiples of the lowest or fundamental. For such tones the frequency of the fundamental is considered as the frequency of the tone, while the number and magnitude of the harmonics produce the overtone structure that results in the perception of a definite timbre. The intensity of the tone is the power content of the air vibrations at the position where the listener hears the tone.

Among musicians loudness is roughly gauged in seven steps running from *ppp* to *fff*. Such a scale is entirely inadequate for scientific studies, both because the steps are too large and because there is no definitely established reference loudness. To provide a more suitable measuring scale, it has been the practice for some time in these laboratories to measure loudness in terms of the power intensity of a pure tone at a frequency of 1000 cycles per second. Because of the wide range of intensities to which the ear responds, it has been convenient to use a logarithmic scale of values. The use of such a scale is further justified because the minimum change in intensity that the ear can detect seems to follow more nearly a logarithmic than an arithmetic law. Moreover, since it is convenient to establish the zero of the scale near the lowest loudness that can be detected, zero loudness is taken as that caused by the smallest audible intensity at a frequency of 1000 cycles, which is 10^{-16} watts per square centimeter in a free air wave.

At 1000 cycles the loudness level of a tone is defined as the logarithm of the ratio of the intensity of the tone to the basic intensity of 10^{-16} watts per square centimeter. Thus if L is the loudness level of a 1000-cycle tone and I its intensity in watts per square centimeter, $L = \log I - \log(10^{-16})$ or more briefly $L = [\log I + 16]$. For an intensity of 10^{-14} watts per square centimeter at 1000 cycles, therefore, the loudness level would be $+2$, and for one of 10^{-4} watts it would be $+12$, which is about the greatest intensity that the ear can tolerate without pain. Since the loudness level is defined as the logarithm of the ratio of two powers, the unit is the bel, and thus the loudness scale runs from 0 to 12 bels, or from 0 to 120 decibels.

Intensity level is measured in exactly the same manner, and at 1000 cycles, intensity level and loudness level are, by definition, the same. At any other frequency, the loudness level is defined as equal to the intensity level of a 1000-cycle tone that would be judged equally loud by the average listener. Some of the relationships between loudness and intensity levels for pure tones, which have been determined during the recent studies, are shown in Figure 1.

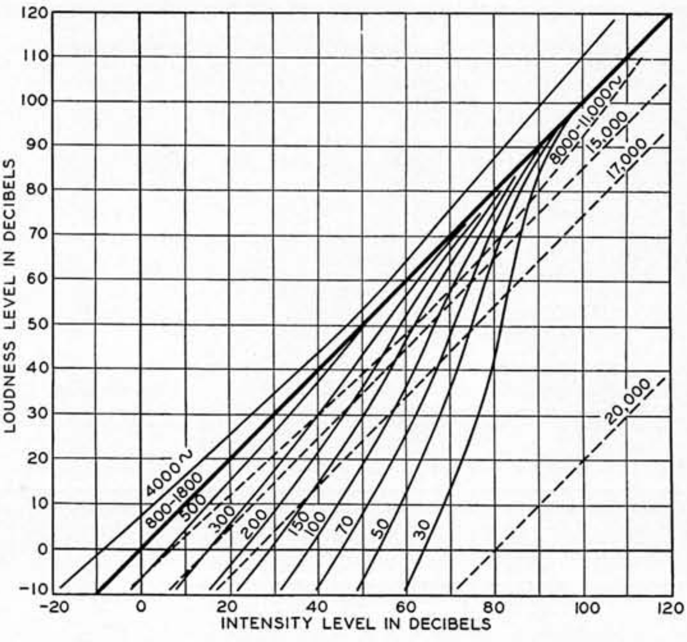


Fig. 1—Relationship between loudness and intensity levels for pure tones of various frequencies

The heavy straight line running up at an angle of 45° to the right represents a tone of 1000 cycles where by definition loudness level and intensity level are the same. This equality also holds very closely for all frequencies between 800 and 1800, and for frequencies from 500 to 6000 cycles there is no very great difference between the loudness level and intensity level. At 30 cycles, however, the intensity must be raised to 64 db before the tone is audible, and above this the loudness increases rapidly—a 36 db increase in intensity causing a 100 db increase in loudness.

To study the relationship between pitch and frequency, scales of pitch and frequency levels were established somewhat analogous to those of loudness and intensity. There is no natural scale of intensity, and thus logarithms to the base ten were employed, with the result that an intensity of level 4 represents 10 times the power of one of level 3. With pitch the situation is different, because there is a natural pitch scale—the octave. Two pure tones of the same loudness will be judged to be an octave apart when one frequency is double that of the other. Thus for these scales it seemed desirable to use logarithms to the base 2. As in defining loudness a constant frequency was selected for the reference tone, so in defining pitch a constant loudness level, that of 40 db has been selected. In selecting a zero level of loudness, the lowest audible intensity of the test tone was chosen, and a similar procedure seemed desirable with pitch. It is also desirable to have the pitch scale based on international pitch, which assigns a frequency of 440 cycles to A above middle C, and since a tempered scale is almost universally used, C is the natural starting point. The zero of the pitch scale was thus taken as C four octaves below middle C, which corresponds to a frequency of 16.35 cycles per second. The pitch level of a tone of loudness level 40 is thus defined as the logarithm to the base 2 of the ratio of the frequency of the tone to 16.35 cycles; or if P stands for the pitch level of a tone of loudness level 40, then $P = \log_2 f - \log_2 16.35$.

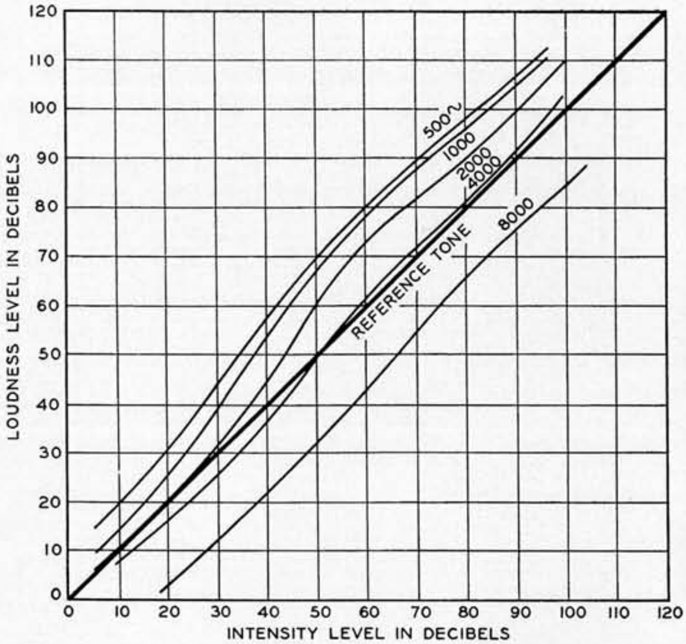


Fig. 3—The loudness of a group of harmonic tones of equal loudness is found to be greater than the sum of the loudnesses of the individual tones

Frequency level, F, is defined in a similar manner; $F = \log_2 f - \log_2 16.35$. As loudness level at a frequency of one thousand cycles is defined as equal to the intensity level, so pitch level at forty db loudness level is defined as equal to the frequency level. At any other loudness level, pitch level is defined as the frequency level of a tone of 40 db, loudness level, that is judged equal to it in pitch. Since for both the frequency and pitch scales, logarithms to the base 2 are employed, the

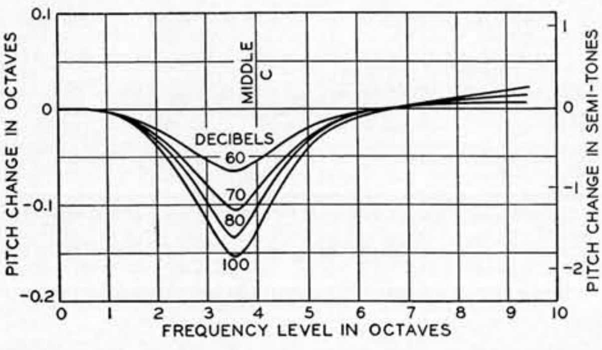


Fig. 2—Relationship between pitch change and frequency level for pure tones of various loudness

unit is the octave rather than the bel, and the audible scale covers a range of about ten octaves.

Until recently accurate studies of pitch at high loudness levels have been handicapped by the lack of suitable apparatus for producing very pure tones of high intensity. Such studies are now possible, however, by use of the apparatus developed for stereophonic, or auditory perspective, reproduction.* Some of the results obtained are shown in Figure 2. Here the abscissas are frequency level and the ordinates, the difference between the pitch and frequency levels. Curves are drawn for tones of various loudness; the curve for 40 db loudness would by definition lie along the line of zero pitch change.

The pitch changes indicated here are rather startling to those of us who have been accustomed to think of a definite frequency always corresponding to the same pitch. If for example middle C is sounded at a loudness level of 40, the frequency, on the international pitch scale we are using, would be 262 cycles. If this frequency were held constant but the loudness increased from 40 to 80 db, the pitch level would drop 0.1, more than a half tone, or to a pitch that at 40 db loudness level would require a frequency of 238.7 cycles. The greatest changes occur at a frequency level of about 3.5 or what roughly corresponds to a pitch of F sharp below middle C. At this frequency an increase in loudness of 50 db lowers the pitch almost a full tone. For very low notes and for those at a frequency level between 6 and 7 (corresponding to frequencies from 1050 to 2100) the changes in pitch with increasing loudness become negligible. For very high notes, however, for frequency levels above 8 (frequencies above 4200) the pitch level increases slightly with increase in loudness.

The results discussed above pertain to pure tones, but studies were also made of complex tones of various types. The relationships between intensity level and loudness level for complex tones having ten equally intense harmonic components are given in Figures 3 and 4. The curve labelled 1000, of Figure 3, for example, represents the results for a tone having a fundamental frequency of 1000 c.p.s. and overtones having frequencies of 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10,000 c.p.s., all having the same intensity. The intensity level of the combined components is given by the abscissas and the resulting loudness level by the ordinates. By adding the nine overtones to the 1000-cycle pure tone the intensity

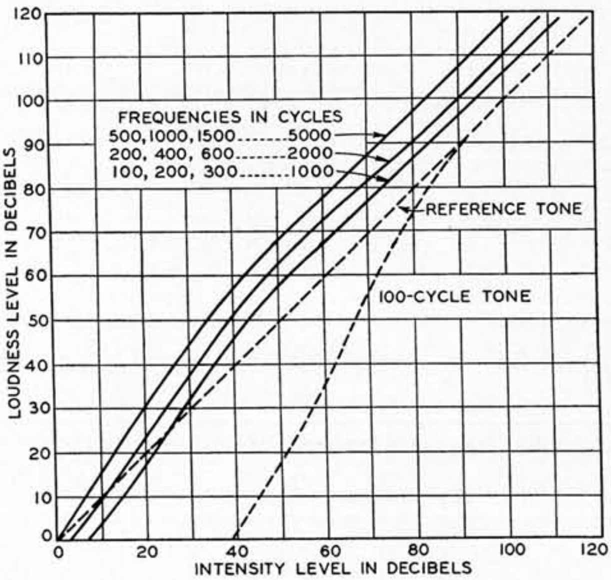
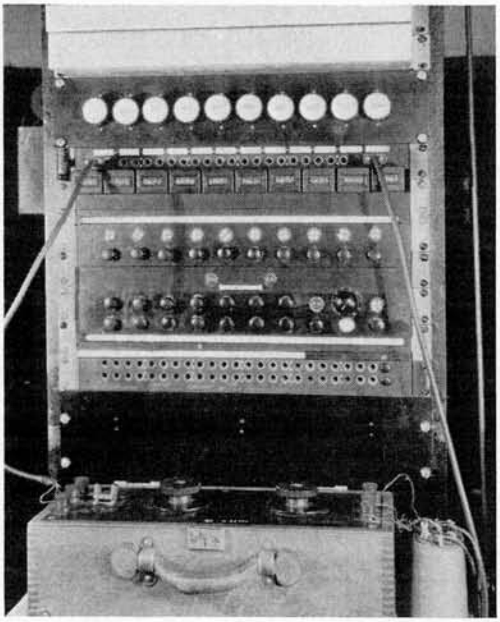


Fig. 4—Relationships between loudness and intensities of groups of ten harmonic tones

*Record, May, 1933, p. 254.



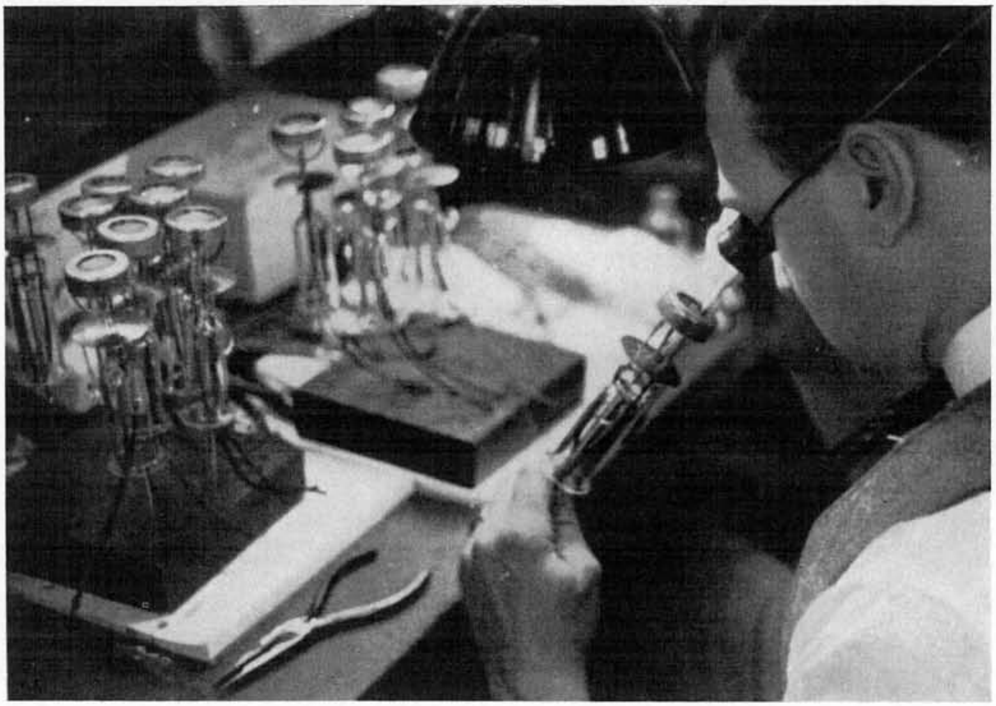
The apparatus at the right automatically presents a sound to be measured and a thousand-cycle comparison tone; the observer, Miss F. Torpadie, records her judgment as to which of the two sounds is the louder

level is raised 10 db, but the loudness level, it will be noticed, is increased nearly 30 db. In other words, increasing the overtone content of such a musical tone increases its loudness level much faster than one would expect from the increase produced upon its intensity level. It is interesting to note from Figure 4 the very large increase in the loudness level of the 100-cycle pure tone when an overtone structure is added to it. At an intensity level of 60 db, for example, the loudness level of the pure tone is slightly over 35 db. With the addition of nine overtones, however, the intensity level is increased ten db but the loudness level becomes 77 db—an increase of over 40 db. These results show why it is easy to increase the loudness of a musical tone by increasing its overtone content, a practice which is common in producing musical tones.

Another fact that becomes evident from these curves is that the loudness is greater the greater the separation between the harmonic frequencies. This is plainly evident in Figure 4, but in Figure 3 the higher harmonics become less important when all are of equal intensity because of the decrease in loudness at the higher frequencies as shown by the dotted curves of Figure 1.

Many interesting phenomena in connection with the pitch of complex tones were also discovered. It was found, for example, that while the pitch level of a pure tone of 200 cycles—a frequency level of 3.6—was lowered .15 octaves as the loudness level was raised from 40 to 100 db (as shown in Figure 2), the pitch level of a complex tone composed of tones of frequencies of 200, 400, 600, 800 and 1000, dropped only .03 octave. At 100 db loudness level, therefore, the pure tone was at a pitch level of 3.46 octaves and the complex tone at a level of 3.58 octaves—3/4 of a tone higher, and when the two were sounded successively this difference was plainly noticeable. With this difference in pitch it would be expected that if the two were sounded together they would be discordant, but such was not found to be the fact. The effect is to strengthen the fundamental, and to lower the pitch of the resultant tone to a level of 3.54 octaves. Whether or not two tones will be harmonious when sounded together depends therefore on the frequency rather than on the pitch of the components.

Although no quantitative measurements have been made upon the timbre of a musical tone, we know that it depends not only upon the overtone structure but also upon the intensity. If a violin tone, for example, is reproduced at a very much higher intensity than that at which it is usually heard, it will be very evident that the timbre is changed. A scale for representing timbre is now being worked out and it will be interesting to see if some quantitative measurements similar to those reported under loudness and pitch can be made to describe the quality aspects of the tone. It is sufficient to say here that there is no doubt but that the results will show that timbre is dependent not only upon the overtone structure but also upon the intensity and the pitch of the tone. It is thus a safe conclusion that each of the three psychological characteristics of a tone is dependent on all three of the physical characteristics, although the influence of one is predominant in each case.



Inspecting the cathode of a mercury rectifier tube before sealing-in

Harvey Fletcher received his undergraduate degree from Brigham Young University in 1907 and the Ph.D. degree from the University of Chicago in 1911. During his years of graduate study he was Instructor in Physics first at Brigham Young and then at Chicago, and on receiving the graduate degree became Professor of Physics at Brigham Young. In 1916 he came to these Laboratories, undertaking the investigations of speech and hearing which have made him one of the foremost authorities in this field. For many years he was, as Acoustical Research Director, in charge of groups occupied in studying the many aspects of sound, including the development of methods for aiding those who hear with difficulty. At the present time, as Physical Research Director, his supervision covers research work in acoustics, electronics, magnetism, and vibrating systems.

Harvey Fletcher