Letters to the Editor

Effect of Sound Velocity on Reverberation Time

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ACCORDING to the geometrical concept of room acoustics, the reverberation time is inversely proportional to the sound velocity, i.e.,

$$T=4V\ln 10^6/c\alpha S, \tag{1}$$

where V is the room volume, c is the velocity of sound, α is the average absorption coefficient, and S is the surface area. In a recent investigation, it was desired to increase the reverberation time of a small hard-walled enclosure at high frequencies by using a low-velocity gas (e.g., SF_6), but contrary to expectations, no increase in reverberation time was observed. The explanation is that α is not a constant for a given nonporous surface, but depends on the characteristic impedance of the medium. This may be seen by expressing α in terms of the acoustic conductance ratio κ[1], where, for uniform distribution of sound, we have $\alpha=8\kappa$, and $\kappa=\rho c\cos\phi/|Z|$, with $|Z|$ the magnitude of the wall impedance and ϕ the phase angle. Substituting these relations into Eq. (1) and remembering that $\rho c^2=\gamma P_0$, we obtain

$$T=|Z|V\ln 10^6/2S\gamma P_0\cos\phi, \tag{2}$$

which shows that T is dependent explicitly on γ rather than the sound velocity.

P. M. Morse and R. H. Bolt, Revs. Mod. Phys. 16, 82 (1944).

Lower Limits of Auditory Periodicity Analysis

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Tests utilizing an iterated, uninterrupted section of random noise disclose that periodicity (iteration) is easily detectable to about 1 cps and detectable with especial difficulty below 0.5 cps. Frequencies bounding regions of perception of pitch, motorboating, and whooshing are specified as 19, 4, and 1 cps, respectively.

FREQUENCY analysis in the ear is evidently both mechanical and neural. Mechanical analysis, which roughly separates the spectral components of a signal along the basilar membrane, is limited to frequencies above 25–50 cps.[1] Neural analysis follows mechanical analysis and operates on acoustic-nerve firing frequency; its mode of operation is unknown. We may speculate that neural analysis is incapable of additional spectral decomposition and is limited, for purposes of frequency determination, to detecting membrane waveform features such as periodicity.[2]

What is the lower limit of neural frequency analysis? According to Guttman and Pruzansky,[3] 19 cps is the lowest periodicity imparting pitch. Pitch perception and periodicity perception are not synonymous, however, and we must still locate the critical frequencies limiting periodicity perception.

To test the question we listened to a signal several seconds long composed by iterating an identical section of wide-band random noise. The duration of the section was T sec, and the critical frequencies in question are given as T^{-1} cps. Producing the signal on a high-speed digital computer insured precise and transientless juxtapositions of the noise sections. (It seems necessary in this type of investigation to avoid stimuli with obvious waveform time markers such as pulses. Our tests used two types of noise, gaussian and a sequence of equiprobable 0's and 1's.)

The results have led us to recognize four regions of low-frequency periodicity perception and to suggest their limiting frequencies. Above 19 cps, periodicity is heard as pitch. The remaining three regions are pitchless. Periodicity is heard as motorboating in the range 4–19 cps, and as whooshing in the range 1–4 cps. Below 1 cps, a listener hears the iterations only if he scrutinizes the stimulus with effort. It is difficult to set a lower limit to this mode of perception since a listener may extend his range by practice. He finds a frequency of 0.5 cps to be trying.[4]

It appears to us that the basis of pitchless periodicity preception must lie in the detection of short-term power-spectrum recurrence. Probably any part of the spectrum may contribute toward the perception since high- or low-pass filtering of the signal does not change the critical frequencies.

In interpreting these results, we may group the four regions according to two different criteria. One criterion is effort.[5] Perceived effortlessly, pitch, motorboating, and whooshing under this criterion form a class whose lower limit is about 1 cps. The second criterion categorizes by what might be called homogeneity of quality. When pitch or motorboating is heard, the stimulus is smooth or homogeneous within periods. The lower limit of this class is about 4 cps. In the two lower frequency regions, the rate is slow enough for intraperiod roughness to be heard. Irrespective of criterion, the lowest detectable periodicity for the kind of stimulus used in this experiment is at least as low as 0.5 cps.

Frequency analysis requires memory. If we assume that each group is served by a common memory system, we conclude that the minimal extents of neural memory systems underlying homogeneity of quality and effortlessness are 0.25 and 1 sec, respectively. The extent of "conscious" memory becomes at least 2 sec. Naturally, the extent of memory for a section containing familiar or easily learned cues is practically unlimited.

[1] G. von Békésy, *Experiments in Hearing* (McGraw-Hill Book Company Inc., New York, 1960), p. 448.

[2] The terms "frequency" and "periodicity" are somewhat interchangeable. We use the latter when it seems necessary to emphasize that the stimulus may not contain fundamental-frequency energy.

[3] N. Guttman and S. Pruzansky, "Lower Limits of Pitch and Musical Pitch," J. Speech and Hearing Res. 5, 207–214 (1962).

[4] G. von Békésy (reference 1, p. 258) reports that exceedingly high-level sinusoids at frequencies as low as 1 cps produce auditory sensations. According to G. A. Brecher ["Die untere Hör- und Tongrenze," Pflüg. Arch. ges. Physiol. 234, 380–393 (1934)], and E. G. Wever and C. W. Bray ["The Perception of Low Tones and the Resonance-Volley Theory," J. Physiol. 3, 101–114 (1937)], at frequencies below approximately 18 cps, the sensations are noisy and lack tone. We interpret these observations to mean that low-frequency sinusoids through physiological distortion produce a recurring periodic noise which is effortlessly heard. If 1 cps appears to be the lower limit of "sinusoid" perception, it is because periodicity perception requiring conscious effort can be difficult.

[5] For a discussion of the criterion of spontaneous perception, see B. Julesz, "Visual Pattern Discrimination," IRE PGIT, IT-8, 84–92 (1962).