Vorl

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Hearing. Its ps. & phys.

1954 N.Y.

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much is clear. But then, as the rate is increased, although the maximum continues to move back and forth, the movement no longer appears as a change of pitch. After the rate reaches 7 per second, no matter how extensive the excursion of the maximum on the membrane (no matter how wide the range of modulation), its gliding character is lost. Hence, 7 per second appears as the limiting value for the preception of this phenomenon. In terms of the two limiting positions of the maximum of the disturbance, it would appear that if they succeed each other less often than $\overset{2}{7}$ times per second they can be perceived as occurring successively in time. At faster rates they appear in perception as occurring simultaneously. (This rule holds for wide ranges of modulation, where the end positions of the disturbance are far apart.) In other words, if the disturbance alternates between two positions within 0.14/2 sec, it does not appear successive. The figure of 0.14 sec reminds us that Békésy reported that the persistence of an auditory sensation lasts about this length of time (p. 222). Hence, it is not unreasonable to suppose that the two stimulations, due to the disturbance when it is at the two ends of its excursion, are perceived as simultaneous when they have not had time to die out to some definite value (not necessarily zero) before stimulation recurs. Just what this value is has not, as yet, been determined.

$\frac{7}{\frac{1}{2}\,\text{Weg}} = 14$

This unproved, but suggestive, relation between the critical rate of modulation and auditory persistence would mean that, whereas most experiments on persistence have turned out to be experiments on amplitude-modulation, certain experiments on frequency-modulation yield information relative to the decay of auditory sensations.

Vorl/ Stevens & Davis, Hearing
1954 N.Y.

Now, it is clear from Fig. 97 that the experience of a gliding pitch may vanish at rates below 7 per second, but that then the range is definitely smaller and the disturbance on the basilar membrane does not move so far. This fact is apparent if we plot the spectra of the modulations giving singleness of pitch for the 500-cycle tone. These diagrams, presented in Fig. 98, reveal how much narrower is the spectrum which gives unitary pitch at a rate of 4.5 cycles than that which does not appear unitary until the rate of 7 cycles is reached. Another important difference between these spectra is the predominance of the central component at the lower rate. When this component is large, and when the spectrum is narrow, the maximum of the disturbance moves back and forth; but, when the maximum is at one end of its excursion, the part of the membrane located at the position corresponding to the other end of the excursion is still being stimulated almost to the maximal extent. In other words, when the range of modulation is narrow, the difference between maximal and minimal stimulation at any one place on the basilar membrane is not so large as when the range is wide, and the maximum is, therefore, not so prominent. Under these conditions a relatively slow rate will obscure the movements of the maximum, and the pitch will not appear to glide up and down.

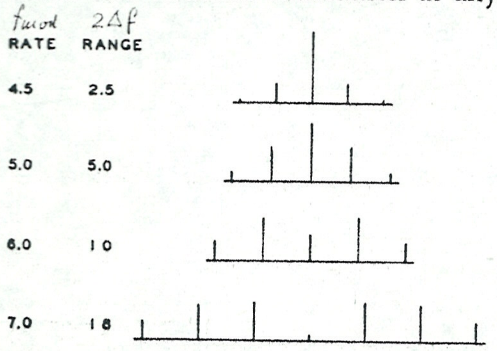

FIG. 98. The spectra for a 500-cycle tone whose frequency is modulated at the rates and ranges indicated. These rates and ranges are the critical ones which produce singleness of pitch.

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THE PITCH OF FREQUENCY-MODULATED TONES

Tiffin and Seashore summarized the earlier work on the vibrato with a statement to the effect that the vibrato, due to frequency-modulation, is heard as one salient pitch corresponding very nearly to the mean frequency of the modulation, and that, when the range of the vibrato is wide, the pitch is less accurately determined. A consideration of the spectra of satisfactory musical vibratos would lead us to believe that the pitch

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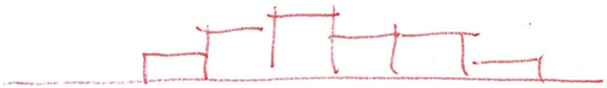

Vorl. Stevens & Davis, Hearing - 1954 N.Y.

of all vibratos is less certain than that of a single pure tone. Furthermore, it is quite possible that a very useful aspect of the vibrato, from the musician's point of view, is precisely this uncertainty of pitch, for it covers up slight errors in tuning. If a singer with a good vibrato sings slightly off key, the audience will be unaware of it.

Since a modulated tone has a spectrum composed of several steady tones, we are led to ask whether any of the components in a vibrato can be heard separately. In order to investigate this problem, three tones were modulated at the rate of 8 per second (Youtz and Stevens). The ranges were so chosen that the central component of the resulting spectrum was twice as large, equal, and half as large as the two adjacent side-bands. These ranges were 15, 22, and 29 cycles, respectively, and the central component had a frequency of 1000 cycles in each case. The observers adjusted the frequency of a steady tone until it sounded equal in pitch to the modulated tone. Figure 99 shows the distributions of the settings. The wider scatter of the judgments at the wider ranges demonstrates that pitch becomes less certain as the extent of the vibrato is increased.

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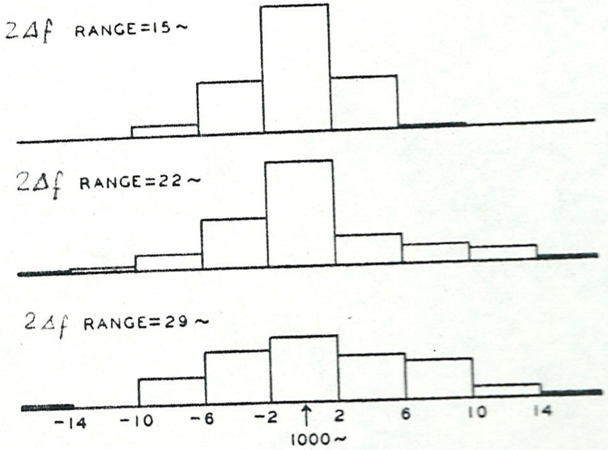

Fig. 99. The distributions of judgments of observers who set a pure tone to equal a tone (1000 cycles) modulated in frequency at the rate of 8 per second. The ranges of modulation are indicated on each plot. (After Youtz and Stevens.)

Closer analysis of the results from individual observers in this experiment revealed evidence that, when the range of modulation was 29 cycles, the separate components of the spectrum stood out sufficiently to cause occasional close groupings of the settings around one of the two large side-bands. Even more direct, however, is the evidence from the verbal reports of the observers. When they raised the frequency of the test tone up to the value of pitch which they thought they detected in the modulated tone, they found that the pitch of the modulated tone had apparently moved still higher. Then, when they moved the pitch of the test tone on up to the new pitch in the modulated tone, they found that this pitch had unaccountably shifted back to its original value. In other words, whenever they had set the test tone to the pitch of one of the large components of the vibrato, the pitch of the other component stood out so clearly as to make the setting seem erroneous. The observers never could make a single pure tone match, at one time, all the pitches in the modulated tone. From this fact, we may conclude that, when the range of a vibrato is sufficiently wide, the individual components of the tone stand out well enough to be identified separately.

BEATS

Whenever two tones, of nearly the same frequency, are sounded together they produce beats at a rate equal to the difference between their frequencies. Beats occur because the continuous change in the relative phase of the two tones leads to alternate periods of reinforcement and cancellation. However, beats do not occur unless the two tones affect the same system. If the ear were a really perfect analyzer of sound, if Ohm's law held exactly, we should never perceive beats. It is only because the two tones force into vibration overlapping regions of the basilar membrane that an alternate waxing and waning of sound is heard. This lack of sharp tuning in the ear also underlies, as we have already noted, the effects produced by modulated tones. In fact, we can classify beats as a kind of hybrid modulation in which the spectrum contains only two