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would not change the position of the side-bands in the spectrum of the tone, but it would alter their relative amplitudes. As the range increases, the amplitude of the outer side-bands grows larger, making the spectrum effectively wider. How does the width of the spectrum affect our sensation? Within certain limits, it appears to determine the *richness* of a tone. Thus, as the range is increased steadily from zero, a point is eventually reached at which the tone appears, to the musical ear, maximally rich. Then, after further increase, the richness gives way to an experience of increased complexity.

Both these approaches were used by Ramsdell in order systematically to determine the critical values of rate and range for maximal richness and for singleness of pitch. He employed trained musicians as observers, because the judgment is essentially a musical one, and he gave them instructions, at one time, to increase the rate of modulation until they achieved a tone of apparently unitary pitch, such as would be satisfactory in a singing voice. At another time they were asked to vary the range until they obtained maximal richness. The results for four different frequencies are shown in Fig. 97. The circles show the values obtained when the rate was increased from a low value up to the rate which just gave singleness of pitch. The upper part of the curve has been dotted to represent the rates at which a gliding pitch is no longer detected and all that remains is a complex mass of tones. The almost vertical lines represent the results of adjusting the range of modulation to give maximal richness. At the intersections of the two functions we have what might be called the *richest, singlest* note obtainable under frequency-modulation.

How, then, do these critical values of rate and range compare with those of actual vibratos produced by good musicians? On the plot for the 500-cycle tone in Fig. 97 is indicated the rate and range of a group of 20 voices studied by Metfessel. About half his cases fell within the limits of this circle (provided we may assume that all the notes he studied were sung at 500 cycles). Here we see that most vocal vibratos are just fast enough to produce a note which appears unitary in pitch, and

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that they cover very nearly the optimal range for maximal richness. The violinists studied by Hollinshead produced vibratos, most of which fell within the oval figure. The rates are very nearly the same as those of the singers, but the range is definitely

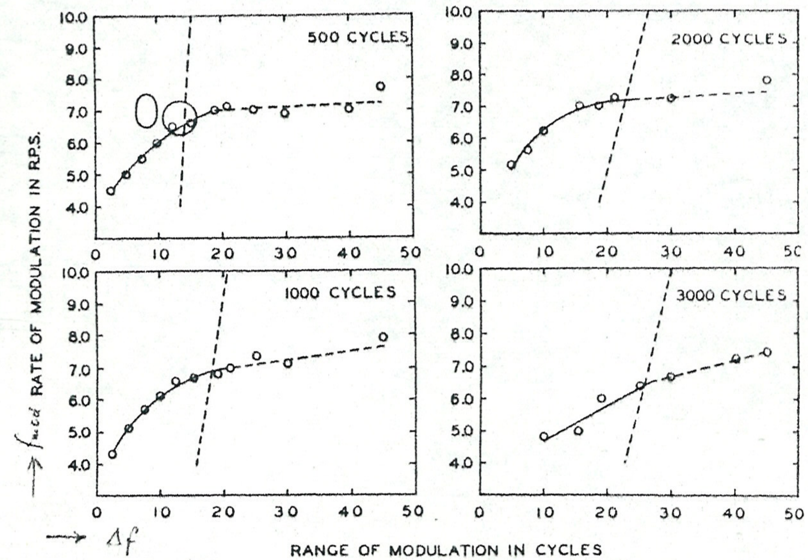

Fig. 97. The critical rates and ranges of frequency-modulation producing singleness of pitch (circles) and maximal richness (vertical dotted lines). (After Ramsdell.) In the plot for 500 cycles, the large circle represents the rate and range of vibrato in the voices of accomplished singers, and the oval shows the rate and range of vibrato produced by expert violinists.

smaller. The rates could be lower without the listener's being able to hear the tone as having a gliding pitch, but the range would have to be almost doubled to obtain maximal richness.

Explanation of all the effects of frequency-modulation cannot be made at present. Probably the most interesting problem demanding clarification is why, as the rate of modulation is increased, we go from a situation where the pitch is obviously gliding up and down to one in which the only thing apparent is a series of intermittent impulses resembling rapid beats. At slow rates, the steady components beat with each other and cause the maximum of the disturbance on the basilar membrane to glide back and forth, in the manner already indicated. That

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