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On the Frequency Limits of Binaural Beats*

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The report describes measurements of the frequency limits of binaural beats and outlines a theory of binaural beats, based on synchronous discharges in the two auditory nerves. Two sinusoids of frequencies f_1 (fixed) and f_2 (variable) were led separately to the two ears; and the difference $\Delta f = |f_1 - f_2|$ that marked the disappearance of the fluctuating loudness or roughness that is characteristic of binaural beats was determined. Δf was maximal (approximately 35 c.p.s.) for frequencies in the neighborhood of 400 c.p.s. Binaural beats were heard above 1000 c.p.s., but careful attention was required and Δf was small. The shape of the curve relating Δf to f_1 provides an explanation for the fact that determinations of the upper frequency limit of binaural beats have not been in agreement; the upper frequency limit depends markedly on Δf. The theory, given to account for the fact that Δf is smaller both at low and at high frequencies than it is near 400 c.p.s., combines elements of the Hill-Rashevsky theory of the excitation of neurons with elements of Wever's volley theory. At low frequencies neurons can discharge in some degree of synchrony with the stimulus wave form, yet fail to coincide within the time interval necessary for synaptic summation. At high frequencies the neurons must take turns discharging, and relatively few can participate in any given volley. At intermediate frequencies, however, each neuron participates in many volleys and the neurons participating in each volley fire almost simultaneously. The result is that at intermediate frequencies synchrony is relatively precise in each afferent pathway and, when the two afferent streams join in a common neural center, beats appear.

INTRODUCTION

When two sinusoids of somewhat different frequencies are led separately to the two ears, the listener hears a tone that periodically shifts its subjective location, that fluctuates in loudness, or that seems "rough"—or he hears two tones. Which of these subjective effects he reports depends upon the frequencies of the two sinusoids. Although the term is sometimes reserved for the fluctuations in loudness, *binaural beats* serves to designate the triad of subjective effects, or, more accurately, the continuum of subjective effects of which three stages can be described as shifts, fluctuations, and roughness.

Binaural beats have been important in auditory theory because they constitute a demonstration that the discharges of the neurons of the auditory nerve in some way preserve information about the phase of the acoustic stimulus. The fluctuations in loudness, for example, occur at a rate equal to the difference between the frequencies of the stimulating sinusoids. The only parsimonious explanation of this fact requires that the afferent flow in each auditory nerve vary at the corresponding stimulus frequency. The fluctuations of loudness are then understood as the result of the superposition of the two varying trains of afferent impulses in some common neural center or centers. Roughness can be regarded simply as fluctuation of the output of the common center at a rate faster than higher neural centers can readily follow. Shifts of localization can be explained by relating the location of the sound image in phenomenal space to the location, within the common neural center, at which the trains of impulses from the two ears reinforce each other.[1] But nothing can be explained without the postulate that the afferent impulses in one way or another follow the stimulus frequency and preserve information about the stimulus phase. The study of binaural beats has therefore been relevant to, and influenced by, two theoretical issues: (1) frequency *vs.* place as the basis of pitch perception, and (2) phase *vs.* intensity as the basis of sound localization.[2]

For both the frequency theory of pitch perception and the phase theory of sound localization, a primary question has been: is the field of the theory restricted to the lower end of the scale of stimulus frequency? What is the highest frequency at which the auditory

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[1] Such hypotheses have been described by: E. G. Boring, "Auditory theory with special reference to intensity, volume and localization," Am. J. Psychol. **37**, 157–188 (1926); G. v. Békésy, "Über das Richtunghören bei einer Zeitdifferenz oder Lautstärkenungleichheit bei beiderseitigen Schalleinwirkungen," Physik. Zeits. **31**, 824–835, 857–868 (1930); H. Wallach, personal communication (1942); and L. A. Jeffress, "A place theory of sound localization," J. Comp. Physiol. Psychol. **41**, 35–39 (1948).

[2] Early in its history, the study of binaural beats was relevant to a third issue, the relation between beats and difference tones. Binaural *Stösse*, probably the fluctuations of loudness, were in fact discussed by H. W. Dove ["Nachtrag zu den Combinationstönen," Reportorium d. Physik **3**, 404–405 (1839)] and others [see G. W. Stewart, "Binaural beats," Phys. Rev. **9**, 502–508 (1917)] well before Silvanus Thompson's ["On binaural audition," Phil. Mag. (5 ser.) **4**, 274–276 (1877)] "discovery" of binaural beats.

nerve follows frequency? What is the highest frequency at which it preserves phase? This Janus-faced question led, naturally, to determinations of the upper frequency limit of binaural beats. The determinations go back at least as far as Rayleigh's, and they continue to the present.[3]

Rayleigh heard reasonably good binaural beats at 640 c.p.s. but obtained results of a "nondescript character" at 768 c.p.s. He concluded that phase differences are "probably the principal basis on which discriminations of right and left are founded—at any rate below c' (256)." Lane[4] found binaural beats up to 800 or 1000 c.p.s. Stevens and Sobel[5] gave 750 to 800 c.p.s. as the limit. Chocholle and Segal[6] gave 900 c.p.s. But Wever's students, Loesch and Kapell,[3] report binaural beats at 2500 c.p.s. And, with stimulus tones only slightly separated in frequency, Wever[3] himself reports shifts of localization up to 3000 c.p.s. Moreover, when two sinusoids of the same frequency, with constant difference of phase, have been used, the upper frequency limit of the localization effect has been reported still higher.[7]

PROBLEM

It is implicit in Wever's discussion, and it appears from the foregoing juxtaposition of results, that the disagreement among the determinations of the upper frequency limit of binaural beats may be due to the fact that different experimenters have used stimulus tones separated by different intervals on the frequency scale. If the beats or shifts become more and more pronounced as the frequency separation decreases, then trying to determine an upper frequency limit is something like trying to decide where an asymptotic curve reaches its asymptote. Slightly different criteria lead to widely divergent answers, and the answers are as arbitrary as the criteria.

We have therefore approached the problem of frequency limits of binaural beats by introducing frequency separation explicitly as a variable. We have determined, as a function of the frequency (f_1) of one of the sinusoids, the greatest frequency separation ($\Delta f = |f_1 - f_2|$) at which we could detect binaural beats. Since Δf is small relative to f_1, it is permissible to regard the relation as one between Δf and f, where f designates the frequency region in which both f_1 and f_2 lie.

[3] Lord Rayleigh, "On our perception of sound direction," Phil. Mag. (6 ser.) **13**, 214–232 (1907); E. G. Wever, *Theory of Hearing* (John Wiley and Sons, Inc., New York, 1949), pp. 427–428; and J. G. Loesch and B. L. Kapell, "The frequency limit for the perception of binaural beats and for cyclic binaural localization," thesis, Princeton University (1948).

[4] C. E. Lane, "Binaural beats," Phys. Rev. **26**, 401–412 (1925).

[5] S. S. Stevens and R. Sobel, "The central differentiation of synchronized action potentials in the auditory nerve," Am. J. Physiol. **119**, 409–410 (1937). Abstract.

[6] R. Chocholle and J. Segal, "Les battements binauraux," C. R. Soc. Biol. Paris **141**, 237–239 (1947).

[7] O. C. Trimble, "The theory of sound localization: a restatement," Psychol. Rev. **35**, 515–523 (1928).

PROCEDURE

The two tones were generated by resistance-capacitance tuned oscillators and fed separately to dynamic earphones (Permoflux PDR-8), mounted in "doughnut" sockets and supported by a headband. The sound pressure levels at the entrance to the ear canal were reasonably near the nominal values indicated in Fig. 1. Measurements made with a probe tube at the entrance of *JCRL*'s left ear canal deviated from the nominal values by less than 5 db.

The procedure in each of two sets of observations (*A* and *B* in Fig. 1) was to set the tone for one ear at a predetermined frequency (f_1) and intensity and the tone for the other ear at the same intensity, and then to adjust the frequency of the latter, either up or down the scale, until the dividing point (f_2) between fluctuation (or roughness) and smoothness was decided upon. The listener made the adjustment without looking at the dial of the oscillator, varying the frequency back and forth until he was confident of his determination. He then measured Δf by connecting a "detector" to the two earphone lines in order to obtain a difference tone of frequency Δf, and then adjusting a third oscillator (calibrated for very low frequencies) until it made, with the difference tone, a simple Lissajous figure. We served as our own listeners, working through the matrix of test conditions in each set of observations in random sequence. Figure 1 indicates the values of the 13 frequencies f_1, and Table I gives other conditions of observation.

Inasmuch as we were looking for the maximal separation of f_1 and f_2 at which binaural beats could be detected, we were not immediately concerned with the shifts of localization that appear when the difference between the frequencies of the two sinusoids is very small. The subjective effects with which we were primarily concerned were (a) periodic fluctuations of loudness heard when the frequency separation was greater than 2 but less than 10 c.p.s., (b) a characteristic roughness heard when the frequency separation was greater than 20 c.p.s. but less than Δf, and (c) a smooth, bitonal sensation heard when the frequency separation was greater than Δf.[8] As the frequency separation was increased and the fluctuation or roughness faded out, the tonal image divided into two parts, and the parts separated and migrated from the center of the head to the two ears. The separating parts were distinguished, of course, by increasing divergence in pitch as well as in location in phenomenal space.

[8] In those observations that resulted in Δf's below 10 c.p.s., fluctuation of loudness became less marked as the frequency separation was increased and faded out, leaving a smooth tonal sensation, without the appearance of roughness. In the observations that yielded Δf's above 20 c.p.s., the beats became too rapid to be described as fluctuations of loudness before they faded out. For Δf's between 10 and 20 c.p.s., it is difficult to say whether the subjective effect on the "non-smooth" side of the dividing point was one of rapid fluctuations of loudness or of course-grained roughness.

Although the acoustic stimuli were quite simple, the subjective sound presented itself for description in several ways. It was necessary to make a number of preliminary observations before starting the series for which data are to be presented. The one of us with the least listening experience had, in fact, to spend approximately 15 hours over a period of three weeks, trying out and discarding various sets and criteria of judgment, before he could achieve consistent results.[9] The criterion for Δf finally decided upon was the transition of the sound image from fluctuation or roughness to smoothness.

RESULTS

The curves of Fig. 1 show the relation between Δf and f_1. Regardless of the sound-pressure level, Δf is maximum when f_1 is in the neighborhood of 350 to 500 c.p.s. Both at lower and at higher frequencies f_1, Δf is smaller and, with a given frequency separation, the beats are less marked.

The results obtained with f_1 and f_2 above 1000 c.p.s. require qualification. In the observations of Experiment 1 (Fig. 1*A*) at 1000, 1188, 1300, and 1412 c.p.s., *JCW* reported beats in 4 of 32 trials, *JCRL* in 25 of 32, and *JMH* in 18 of 32. Hearing them appeared to depend upon being properly set and upon not being fatigued. It was almost impossible to locate the beats without some hypothesis about the rate at which they would occur. *JCRL* and *JMH* therefore adopted the procedure of finding the beats with the aid of Lissajous figures on an oscilloscope, and then of determining whether or not the beats could be followed without such aid. Once they were found they could usually be followed through slow variations in rate introduced by perturbing the frequency of one of the oscillators.[10] *JCW*, on the other hand, simply adjusted the frequency of the variable tone back and forth in the neighborhood of f_1 until he heard beats, or until he concluded that none were to be heard. Δf was recorded as zero when no beats were detected. As a result of this inhomogeneity of procedure, the average values of Δf shown for $f_1 \geqslant 1000$ c.p.s. in Fig. 1*A* are hybrid quantities. In Experiment 2 (Fig. 1*B*) *JCW* adopted the procedure used by *JCRL* (*JMH* did not participate in Experiment 2), and beats were reported in every trial at 100 db and at 80 db. Even in Experiment 2, however, the 60-db averages for $f_1 \geqslant 1000$ c.p.s. are hybrid: in 19 of 32 trials no beats were detected.

The observations with f_1's from 177 through 840 c.p.s. form homogeneous matrices, determinations of Δf having been completed in each experiment under all combinations of the conditions listed in Table I. The average value of Δf for each treatment of each of the main variables is shown in Table I, and quadratic analyses of the homogeneous parts of the two sets of observations are summarized in Table II. The root-mean-square error for a typical observation, estimated from the residual error (Error 4) and therefore particular to the observers and test conditions actually used, is between 3 and 5 c.p.s. Since each of the datum points in Fig. 1 is based on 24 observations, the root-mean-square error for a typical point is of the order of 1 c.p.s. It is evident from the magnitudes of the listener variance and of the interactions involving listeners, however, that considerable latitude must be allowed if the results are to be generalized to a population of listeners.

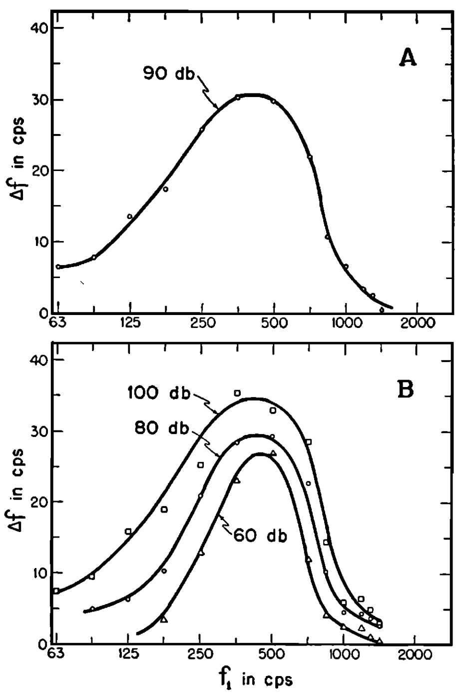

FIG. 1. Frequency limits of binaural beats: Δf is the maximal frequency interval between two sinusoids, applied separately to the two ears, for which binaural beats are reported, and f_1 is the frequency of one of the sinusoids. The parameter is sound-pressure level in db re 0.0002 microbar. *A*, Experiment 1; *B*, Experiment 2.

DISCUSSION

The upper frequency limit of binaural beats depends upon the intensity of the stimulus tones. It depends upon their frequency separation. There are considerable differences among listeners. And there is a practice effect. But the important thing is that the beats do not vanish abruptly as f is increased.

The clarity and obviousness of the beats follow the course of Δf. They decrease rapidly as f is increased from 500 to 1000 c.p.s., but above 1000 c.p.s. they level

[9] Actually, one criterion of judgment was discarded even though it did lead to consistent results. With that criterion, which had to do with the countability of the beats, the curve relating Δf to f_1, for 125 c.p.s. $\leq f_1 \leq$ 707 c.p.s., approximated a horizontal straight line at $\Delta f \simeq 8$ c.p.s.

[10] For future work with slow binaural beats, we should favor an arrangement that would record simultaneously the listener's rhythmic marking of the beats and the difference tone derived from the two stimulus waves. The correlation between the two records would provide an objective index of the listener's performance.

TABLE I. Average values of Δf for various conditions of observation.

Variable	Treatment	Mean Δf in c.p.s. Exper. 1	Exper. 2
Frequency f_1	177	17.2	11.6
	250	25.7	19.0
	354	30.3	28.9
	500	29.9	30.0
	707	21.9	21.0
	840	10.7	10.5
Listener	*W*	27.4	20.5
	L	19.7	19.9
	H	20.8	
f_2 re f_1	>	23.4	20.4
	<	21.9	20.0
Ear receiving tone 1	*r*	23.1	20.0
	l	22.2	20.4
Repetition	1	21.6	
	2	23.7	
Intensity	60 db		13.9
	80 db		20.7
	100 db		25.9

out. As f goes beyond 1100 or 1200 c.p.s., the beats become more and more difficult to observe—they require more attention, they are harder to find and harder, once found, to hold on to. But just where they vanish is difficult to say. Instead of trying to determine an upper frequency limit, therefore, it may be better to regard as critical the frequency at which the curves of Fig. 1 have their steepest negative slopes. This frequency, which is more precisely determined, is between 750 and 850 c.p.s.

If we limit our discussion to the effects of sinusoidal stimuli, it seems reasonable to conclude that the afferent neural representation of stimulus phase is better in the neighborhood of 300 to 600 c.p.s. than at higher or at lower frequencies. At higher frequencies rotation among several fibers would be required to provide synchrony between nerve volley and stimulus wave form. At lower frequencies each cycle of the stimulus wave form lasts several milliseconds, and the discharges of various neurons may stay in step with the stimulus yet fail to coincide with one another within the interval, less than 1 millisecond, for synaptic summation.[11] How these factors may favor synchrony in the region of 400 c.p.s. is illustrated in Fig. 2.

THEORY OF SYNCHRONY AND BINAURAL BEATS

Figure 2 may be regarded as a simplified and highly schematic theory of synchrony in the auditory nerve. The acoustic stimulus is represented by the sinusoids $S(t)$ in the first line of the figure. Since it appears probable that the process through which the stimulus excites the neurons of the auditory nerve involves rectification (cf. Békésy's[12] eddies), the first operation applied to the stimulus wave form is non-linear. For simplicity, half-wave rectification is chosen for the illustration. Other asymmetrical non-linearities yield qualitatively similar results. The rectified wave form is indicated by the blackened half-cycles $R(t)$.

No physical event is determined exclusively by other events of the same instant. The determination is in part a function of the past. This consideration is introduced into the schema of Fig. 2 by deriving the excita-

TABLE II. Summary of analyses of variance.

Source of variation	Experiment 1 *n*	Variance	Experiment 2 *n*	Variance
Frequency ($F=f_1$)	5	1413	5	1637
Listener (L)	2	837	1	14
Ear receiving tone 1 (E)	1	31	1	7
Direction of adjustment of f_2 re f_1 (D)	1	76	1	5
Repetition (R)	1	158		
Intensity (I)			2	1731
$F\times L$	10	149	5	104
$F\times E$	5	12	5	32
$F\times D$	5	33	5	53
$F\times R$	5	47		
$F\times I$			10	52
$L\times E$	2	7	1	55
$L\times D$	2	19	1	29
$L\times R$	2	483		
$L\times I$			2	17
$E\times D$	1	6	1	3
$E\times R$	1	8		
$E\times I$			2	18
$D\times R$	1	44		
$D\times I$			2	58
$F\times L\times E$	10	51	5	7
$F\times L\times D$	10	43	5	17
$F\times L\times R$	10	39		
$F\times L\times I$			10	50
$F\times E\times D$	5	67	5	12
$F\times E\times R$	5	10		
$F\times E\times I$			10	12
$F\times D\times R$	5	8		
$F\times D\times I$			10	32
$L\times E\times D$	2	29	1	80
$L\times E\times R$	2	22		
$L\times E\times I$			2	22
$L\times D\times R$	2	98		
$L\times D\times I$			2	2
$E\times D\times R$	1	115		
$E\times D\times I$			2	3
Error 1*	133	45.1	133	26.0
Error 2	99	30.1	99	17.5
Error 3	47	17.0	47	10.2
Error 4	10	21.7	10	13.1

* Error 1 includes all interactions; Error 2 includes interactions of second and higher orders; Error 3 includes interactions of third and higher orders; Error 4 is the residuum after the third-order interaction (not shown) has been taken out.

[11] In the curves for low sound-pressure levels in Fig. 1, the decline of Δf to the left of the maximum may be attributed in part to the fact that loudness, and presumably neural flux, decrease with decreasing frequency. At 100-db sound-pressure level, however, loudness is almost independent of frequency within the frequency range covered by the observations, and it does not seem reasonable to attribute the decline in Δf entirely to paucity of nerve impulses.

[12] G. v. Békésy, "The vibration of the cochlear partition in anatomical preparations and in models of the inner ear," J. Acous. Soc. Am. **21**, 233–245 (1949). [Transl. of "Über die Schwingungen der Schneckentrennwand beim Präparat und Ohrenmodell," Akust. Zeits. **7**, 173–186 (1942).]

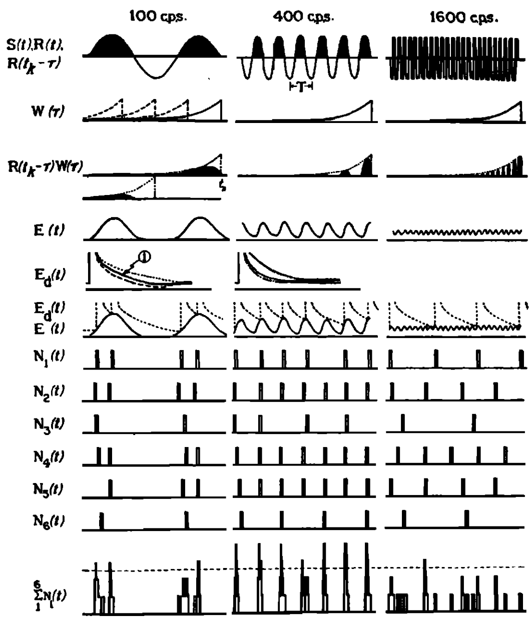

FIG. 2. Schematic illustration of mechanism underlying synchrony: The stimulus waveform is rectified (line 1), then passed through the low pass filter of which the weighting function is shown in line 2, to determine the excitatory function $E(t)$ (line 4). Interaction between $E(t)$ and the recovery curves of several neurons (line 5) determines when the neurons discharge (lines 7–12). When the discharges of the individual neurons are superposed to form volleys (line 13), it is evident that synchrony is more marked at 400 c.p.s. than at 1600 or at 100 c.p.s. This corresponds to the fact that the curves of Fig. 1 have maxima in the neighborhood of 400 c.p.s.

tory function $E(t)$ from $R(t)$ with the aid of a weighting function. The process is illustrated in lines 2, 3, and 4 of the figure. For simplicity, an exponentially declining weighting is used. Again, other reasonable forms yield qualitatively similar results. It is important, however, to make the weighting function reach back in time about as far as does the one we have selected; it has a time constant T equal to the reciprocal of the stimulus frequency for which synchrony is to be maximized. For the determination of $E(t_k)$, the excitation at the particular instant t_k, the weighting function assigns a weight to the contribution of each instant in the past of t_k. The weight is $W(\tau)$, where τ is distance into the past.[13] The contribution that is weighted is $R(t_k-\tau)$, the value of R at the instant τ-seconds before t_k. $E(t_k)$ is obtained by multiplying $R(t_k-\tau)$ by $W(\tau)$ and integrating the product over τ. Thus the ordinate of line 3 is the product of the blackened ordinate of line 1 by the ordinate of line 2; and the ordinate of line 4 is the blackened area of line 3. In general,

$$E(t)=(1/T)\int_0^\infty R(t-\tau)W(\tau)d\tau.$$

$E(t)$ is the function that governs the activation of the neurons of the auditory nerve.

The rule that determines when a particular neuron fires is simple. The neuron discharges whenever its threshold $E_d(t)$ is equal to $E(t)$. $E_d(t)$ cannot be less than $E(t)$ because discharging puts the neuron into a refractory state, which is to say that $E_d(t)$ is elevated again just as soon as it drops to $E(t)$. In line 5 of Fig. 2, six arbitrary but reasonable threshold recovery curves are shown, one for each of six neurons. The curve labeled 1 is shown again in line 6, this time in interaction with the function $E(t)$ from line 4. Whenever $E_d(t)$ touches $E(t)$, the neuron discharges and a new cycle is started. The discharges are represented by the rectangular pulses N_1 in line 7. N_2 through N_6 are generated by following the same procedure with $E(t)$ and the five unnumbered recovery curves.

Line 13 of the figure shows the result of superposing the discharges of the six neurons. (We shall not take conduction time into account in this discussion. We can therefore shift our attention from the peripheral to the central ends of the neurons, yet retain the same temporal patterns of discharge.) It is evident that, for any process dependent upon excitation at regular intervals, the pattern at 1600 c.p.s. is inadequate. The train of composite pulses at 400 c.p.s., on the other hand, shows definitely regular recurrence and only slight modulation of amplitude. At 100 c.p.s., some regularity prevails, but there are two main bursts of activity for each cycle of stimulation and, since the discharges of the six neurons are more scattered than they were at 400 c.p.s., the bursts are lower in amplitude.

As a final step, we assume that the summated activity of the six first-order neurons must reach a threshold value, indicated by the dashed line, before it produces effects in higher order neurons. To get a rough picture of the activity in the higher order neurons, we can ignore all of line 13 except the peaks that get above the threshold. If we now regard binaural beats as arising from the superposition of two such trains of impulses, one train from each ear, we see that the beats would be much better at 400 c.p.s. than at 1600 or at 100.

By introducing more neurons into the picture, by letting the recovery curves vary with time, by taking further account of non-linearity in the excitation of higher order neurons by first-order neurons, and by other obvious means, it is possible to bring the schema into line with known physiological and anatomical facts without losing the basic result, i.e., that synchrony is better for middle frequencies than for high or for low. It is interesting to note, however, that the disappear-

[13] For a discussion of weighting functions, see James, Nichols, and Phillips, *Theory of Servomechanisms* (McGraw-Hill Book Company, Inc., New York, 1947), pp. 30–40. In Fig. 2 we have reversed the scale of τ in line 2 for convenience: with the scale reversed, we can think of moving the weighting function along the time scale in the way suggested by the dotted curves. As we move W, we multiply its ordinates by the corresponding ordinates of R (the blackened curve) in the line above and keep a continuous record of the integral of the product. We plot the integral of the product as an ordinate in line 4, directly below the leading edge of W. The weighting function thus serves as a moving window through which $R(t)$ acts to produce $E(t)$.

ance of synchrony at high frequencies depends upon some limitation of the number of neurons available for rotational discharge. According to the schema, any neuron is more likely to discharge on the uphill half-cycle of $E(t)$ than upon the downhill half-cycle, no matter what the frequency. Given enough neurons, the volley would show synchrony within half a cycle. The defect of synchrony at high frequencies must therefore be attributed to a perturbing factor. In Fig. 2 the factor is paucity of neurons: synchrony is disrupted by what communication engineers recognize as quantization noise and what computation people call the noise of rounding-off. It may be that random fluctuations of sensitivity in the receptive and neural mechanisms ('neural "noise") contribute to the disruption of synchrony. Such fluctuations would tend to scatter the discharges throughout the cycle, and they would have more effect at high frequencies than at middle and low frequencies. But the introduction of random factors cannot entirely overcome the tendency, inherent in the schema, for the neutral discharges to keep in step with the stimulus. It therefore appears reasonable for binaural beats to be heard even at very high frequencies. The ultimate limitation upon their being heard at high frequencies may lie either in the number of peripheral neurons available for rotation or in the sensitivity of the higher centers that mediate the listener's response. Hence, although it is possible to conclude from simple theoretical considerations that the shapes of the functions shown in Fig. 1 are reasonable, it does not appear feasible to deduce a theoretical upper frequency limit for binaural beats.

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San Diego County Fair Hearing Survey

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A phonographically recorded test of the ability to hear pure tones was given to 3666 people at the San Diego County Fair in the summer of 1948. Absolute thresholds were determined at five frequencies and masked thresholds at two frequencies. The results were analyzed according to the age, sex, musical training, and past noise environment of the listeners, and according to their statements as to whether or not they had difficulty in hearing. As expected, auditory sensitivity was found to decline with age; women were found to be more sensitive than men for the higher frequencies; and men who worked in noise showed greater than normal losses at high frequencies. The data indicated, in addition, that musically trained men and women possess greater hearing sensitivity than do men and women without musical training, and that the 20–29 year old males tested at San Diego in 1948 appeared to have a greater loss at the high frequencies than did most males of the same age group who were tested in surveys before the war.

INTRODUCTION

IMPROVEMENT in the operational efficiency of an electronic system (such as sonar, radio, and radar) in which a human operator is an indispensable component can be obtained by bettering either the equipment or the operator or both. The efficiency of the operator can be increased in two ways—by better selection and training of the operator himself, or by modifying the equipment to better fit the physiological and psychological capabilities of the operator. As a possible means of selecting operators for systems requiring good hearing, a phonographically recorded test of hearing sensitivity which was suitable for administration to groups of subjects was devised. To evaluate this test, to gather information on hearing sensitivities, and to acquaint the public with the human factors of military research, the test was administered to visitors at the 1948 San Diego County Fair.

Previous large scale hearing surveys determined hearing losses as functions of age, sex, frequency,[1] and awareness of hearing difficulties.[2] More specific studies have been made on hearing losses as functions of prolonged exposure to noise.[3–5] At least one study has been made relating hearing loss to musical training.[6] These

[1] Steinberg, Montgomery, and Gardner, "Results of the World's Fair hearing tests," Bell Sys. Tech. J. **19**, 533–562 (1940); J. Acous. Soc. Am. **12**, 291–301 (1940).
[2] W. C. Beasley, J. Acous. Soc. Am. **12**, 114–121 (1940).
[3] W. A. Rosenblith, J. Acous. Soc. Am. **13**, 220–225 (1943).
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