

## XIX. COMMUNICATIONS BIOPHYSICS\*

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### A. MOTION OF MIDDLE-EAR BONES

Using stroboscopic illumination, we observed the motion of the ossicles through a microscope in anesthetized cats. With periodic acoustic stimuli amplitude measurements could be made with an accuracy of approximately 1/10 micron. The displacement amplitude was linearly related to sound pressure at the tympanic membrane up to rms pressures of at least 130 db re 0.0002 microbar (Fig. XIX-1). In the linear range the predominant movement of the stapes was pistonlike. At higher sound pressures the stapes motion became more complex. At these high stimulus levels components of the motion were observed which were similar to the two kinds of "rocking" that have been observed in middle ears of cadavers by von Békésy.<sup>1</sup> These components were small compared with the pistonlike movement for sound pressures in the linear range.

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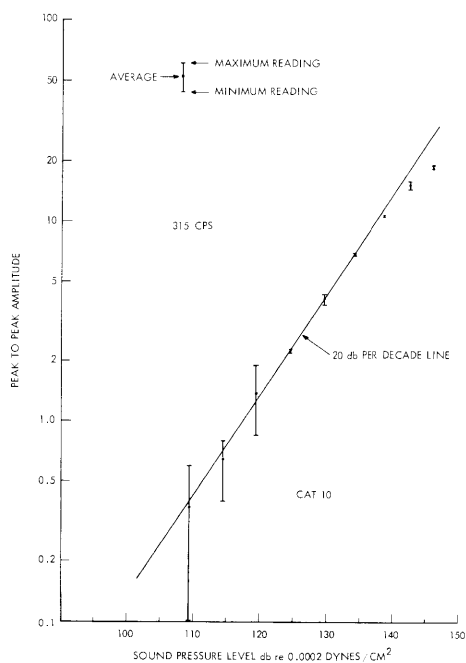


Fig. XIX-1.

Peak-to-peak amplitude of a point on the body of the stapes versus sound-pressure level. Tone stimulus, 315 cps. Units on the vertical scale correspond to  $0.72 \mu$  in the focal plane of the microscope, or to a calculated stapes movement of  $1.0 \mu$ .

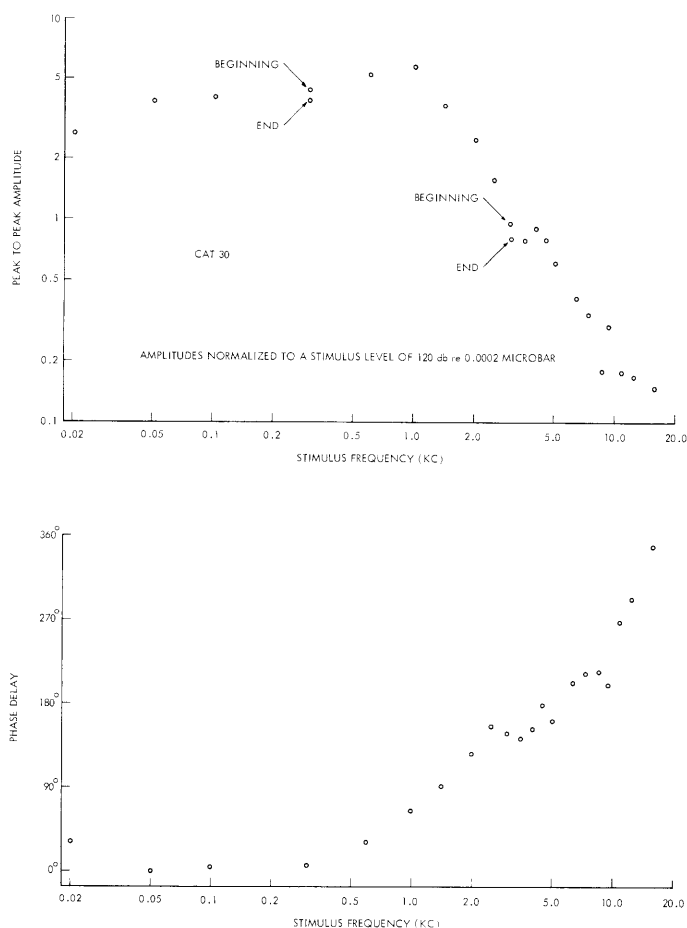


Fig. XIX-2.

Peak-to-peak amplitude and phase delay of the stapes movement. One unit on the amplitude scale corresponds to a measurement of  $0.42 \mu$  in the focal plane of the microscope or to a calculated stapes movement of  $0.57 \mu$ , or to a volume displacement of  $7 \times 10^{-7}$  cc based on an average footplate area  $1.26 \text{ mm}^2$ .

The amplitude and phase of the stapes displacement were measured as a function of frequency for pure-tone stimuli. Results from one cat are shown in Fig. XIX-2. These data are typical, except that the dips in the amplitude at 3 kc and 8 kc were not found in all cats. Measurements of electric responses near the round window of the cochlea indicate that the transmission of the middle ear is altered by the opening of the bulla and bony septum which is necessary in order to see the stapes. This surgical procedure changes the acoustic impedance of the middle-ear cavities with particularly striking

effect in the 4-kc region, so that these data cannot be considered to give an accurate description of the intact middle ear.

The techniques and results of this work are described in detail in a Master's thesis.<sup>2</sup>

J. J. Guinan, Jr., W. T. Peake

#### References

1. G. von Békésy, Experiments in Hearing (McGraw-Hill Book Company, Inc., New York, 1960), p. 113.

2. J. J. Guinan, Jr., Transfer Characteristic of the Cat's Middle Ear, S. M. Thesis, Department of Electrical Engineering, M. I. T., 1964.

#### B. RHYTHMIC FOREBRAIN POTENTIAL CORRELATED WITH CESSATION OF MOVEMENT IN THE RAT

A large rhythmic potential has been observed in sensory-motor cortex in the rat during periods of behavioral "freezing." This activity was studied<sup>1</sup> in animals with electrodes chronically implanted in caudate nucleus and hippocampus, as well as in neocortex. Subjects were trained to bar press in a conditioned emotional response situation, which included a special restraining apparatus. The emotional response was established by pairing an auditory conditioned stimulus with a shock unconditioned stimulus. The potential appeared only in the absence of the bar pressing, but the absence of bar pressing did not insure the occurrence of the potential. Visual monitoring showed that the potential is more highly correlated with periods of no movement than simply with the cessation of bar pressing. The large rhythmic potential was 9-10 cps and often reached amplitudes greater than 1 mv peak to peak. The potential has been observed for periods as long as 1 min, but it often occurred in short bursts wherein it took on a spindling appearance. Complete control of the potential has not yet been achieved, but the work thus far has revealed at least some of the sources of variability.

R. J. Clayton

#### References

1. This report gives a summary of an S. M. Thesis submitted to the Department of Electrical Engineering, M. I. T., May 29, 1964.

#### C. COMPARISON OF AUDITORY NERVE DATA FOR BULLFROG AND GREEN FROG

Single-unit activity in the eighth nerve of the green frog (Rana clamitans) has been studied<sup>1</sup> and the results compared with those of Frishkopf and Goldstein<sup>2</sup> for the bullfrog. Typical thresholds for single-unit responses to tone bursts are the same for both

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species; the most sensitive units respond to intensities as low as  $-50$  db re  $1 \mu\text{bar}$ . No unit in either species would respond to frequencies above 3000 cps. In both species the majority of units falls into two categories: the simple or high-frequency units are a relatively homogeneous group and show only excitatory characteristics; the complex or low-frequency group contains units that respond to acoustic and/or vibratory stimuli and their tone burst response can be inhibited by sound in a given spectral range.

As in the bullfrog, most of the complex units in the green frog have best frequencies in the 200-400 cps range (Fig. XIX-3). The distribution of the best frequencies of simple

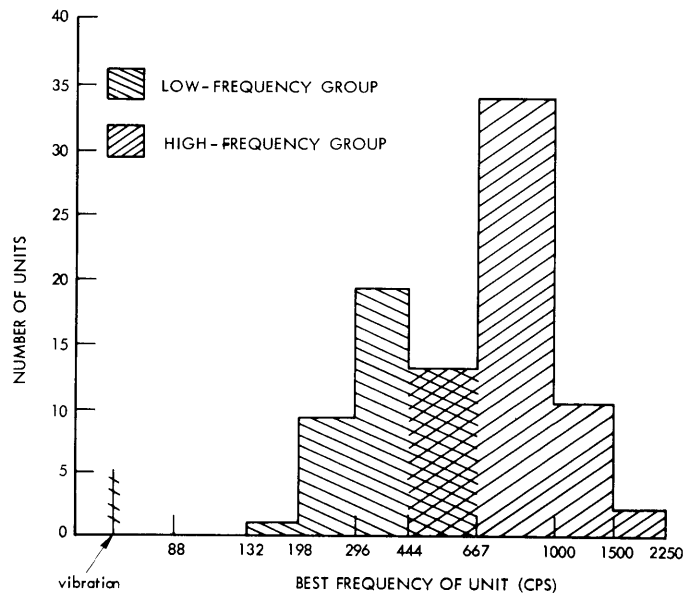


Fig. XIX-3. Histogram showing the number of units with best frequencies in the indicated intervals. Data obtained from 11 green frogs.

units is, however, quite different for the two species. For the bullfrog, Frishkopf and Goldstein found that the best frequencies for the simple units lie between 1000 cps and 2250 cps, with many units characterized by best frequencies above 1500 cps. In fact, they define 1000 cps to be the lower bound of their high-frequency group. Best frequencies for the high-frequency group in the green frog extend down to 650 cps, and most of the units in this group have best frequencies between 700 cps and 1000 cps.

Another difference in the data obtained for the green frog and for the bullfrog is the range of best frequencies for inhibition of the complex units. Frishkopf and Goldstein state that tuning curves for inhibition often show a minimum at 500 cps, with most sensitive range for the inhibitory stimulus between 500 cps and 600 cps. They stated that it may be significant that they found very few units with best excitatory frequencies in

this range. In contrast, the best inhibition frequency for complex units in the green frog is most often 700 cps and always lies between 650 cps and 1200 cps, the range in which most of the simple units of the green frog are most sensitive.

Approximately 10 units were found in the green frog which had very different response characteristics from those described by Frishkopf and Goldstein. These units did not form a homogeneous group. Some of them responded with bursts of impulses only at the turning on of a tone, at the turning off of a tone or at both the on and the off. Other units responded to tone bursts with a decrease in spontaneous activity, i. e., they were inhibited. Finally, three units were found which responded to low-frequency tone bursts with an increase in firing rate, and to high-frequency tone bursts with inhibition of spontaneous activity.

M. B. Sachs

#### References

1. M. B. Sachs, Characteristics of Primary Auditory Neurons in the Green Frog, S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, March 1964.
2. L. S. Frishkopf and M. H. Goldstein, Jr., Responses to acoustic stimuli from single units in the eighth nerve of the bullfrog, *J. Acoust. Soc. Am.* 35, 1219-1228 (1963).

#### D. RECENT STUDIES OF THE AUDITORY AND VOCAL BEHAVIOR OF THE BULLFROG

A previous report<sup>1</sup> described an "evoked-calling" technique for a behavioral study of the vocal and auditory performance of the bullfrog. This report<sup>2</sup> describes the methods used to analyze and synthesize recorded bullfrog croaks,<sup>3</sup> and includes a brief description of some results of evoked-calling experiments in which synthetic croaks were used.

##### 1. Gross Properties of the Bullfrog's Mating Croak

A typical bullfrog mating croak lasts approximately 0.8 second. There may be 3-15 croaks in a single mating call, with approximately 0.8-second silences separating the individual croaks. The temporal envelope of a single croak generally shows rise and fall times of ~150 msec. Each croak is a quasi-periodic sound, having a fundamental frequency of ~100 cps. The harmonic structure is fairly simple, usually showing energy concentrations in two frequency bands (formants), one centered around 250 cps, the other lying in the vicinity of 1000-1500 cps.

##### 2. Development of a Model Croak

For the detailed analysis presented here, we chose a series of 5 croaks, all of which were emitted by a single animal. This particular call was chosen because it reliably

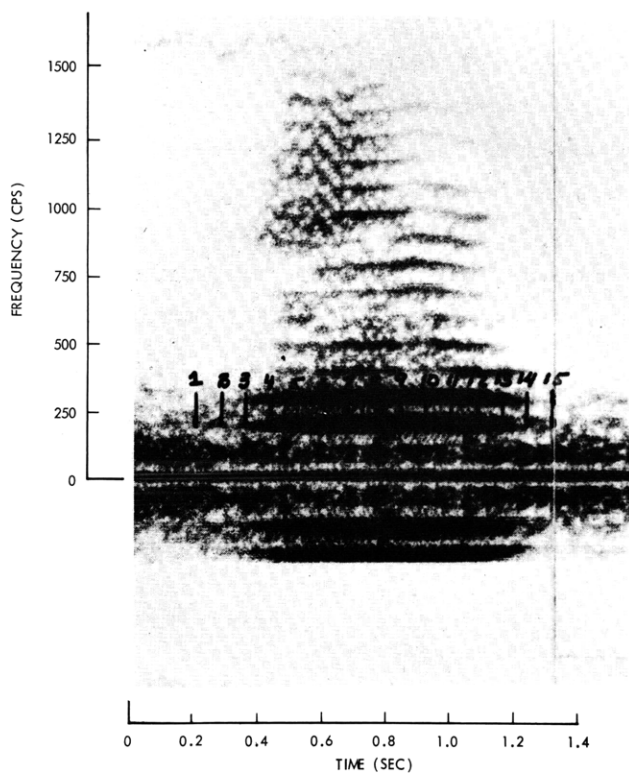


Fig. XIX-4. Sonogram of a bullfrog croak.

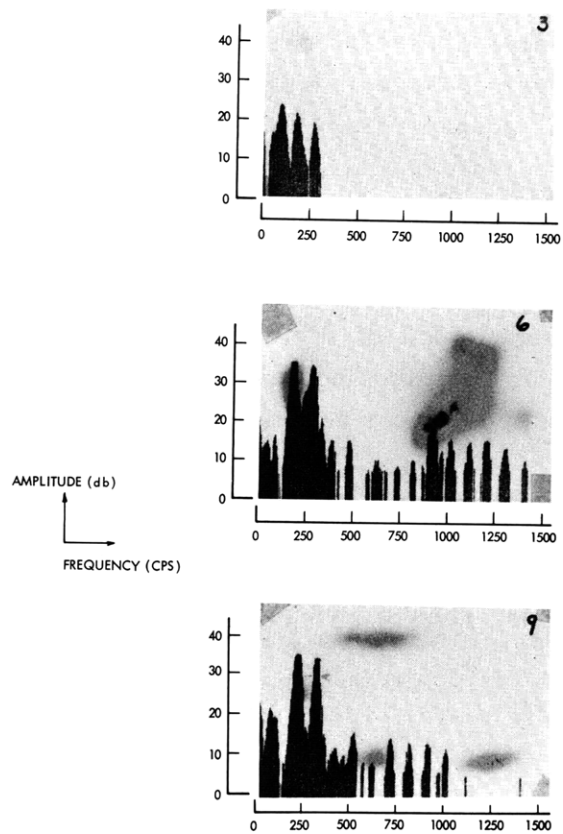


Fig. XIX-5. Sections of a bullfrog croak.

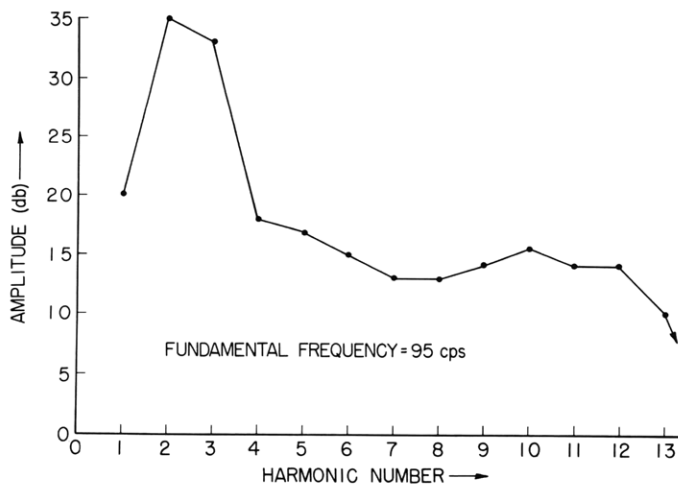


Fig. XIX-6. Average spectrum of a bullfrog croak.

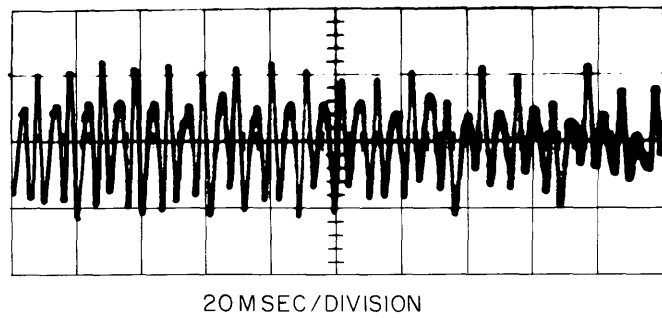


Fig. XIX-7. Representative waveform of a bullfrog croak.

evoked calling from our laboratory animals.

An example of a sonogram<sup>4</sup> of a single frog croak is given in Fig. XIX-4. Here spectral amplitude is represented by the intensity of the markings. Figure XIX-5 shows several sections through the sonogram at the times shown by the numbers in Fig. XIX-4. By taking a large number of sections and averaging the amplitude of each harmonic over all sections, an "average spectrum" is obtained as shown in Fig. XIX-6. Clearly, the low-frequency formant dominates.

Figure XIX-7 shows the semiperiodic pulselike structure of a sample croak waveform. The fundamental frequency (defined as the reciprocal of the interval between successive peaks) and the peak amplitude vary irregularly throughout the course of the croak. To study possible patterns in the frequency and amplitude variations, the croak waveform was recorded on chart paper with a pen recorder. The variations over a

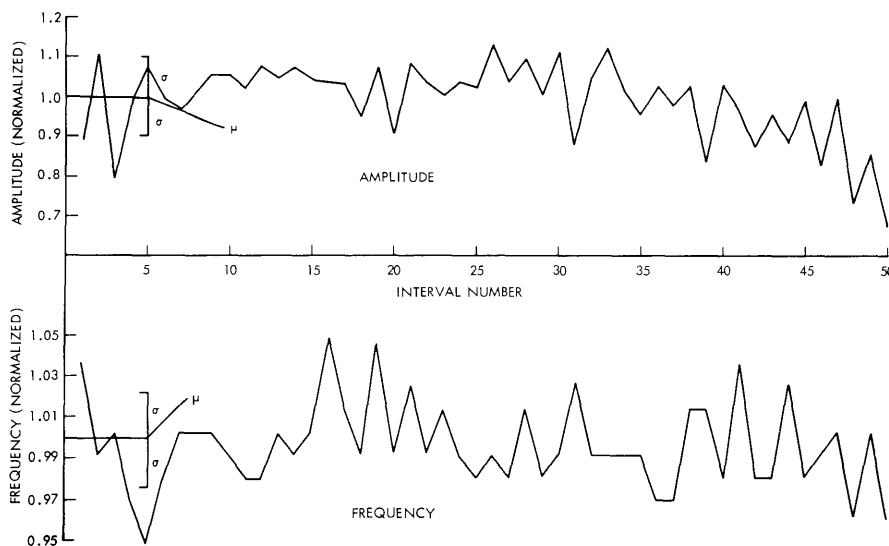


Fig. XIX-8. Variations of fundamental frequency and amplitude over a single croak.

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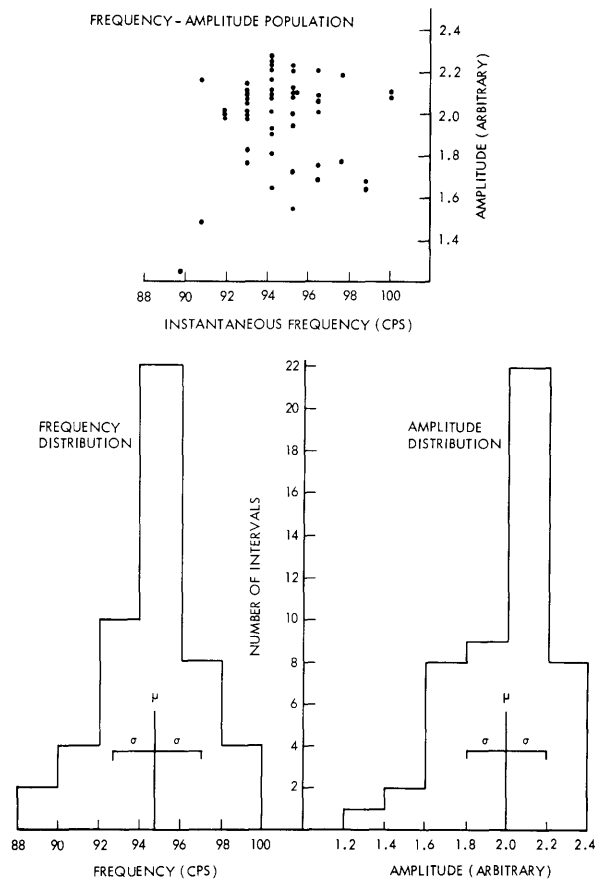


Fig. XIX-9. Some statistics of croak variations.

single croak of fundamental frequency and amplitude as determined from such a record are plotted in Fig. XIX-8. We were unable to find in these plots either a pattern or correlation between the amplitude and frequency. Some distributions of these parameters are shown in Fig. XIX-9. In the model croak the irregularities in frequency and amplitude were represented as uncorrelated Gaussian processes, with means and standard deviations given by the average of those for all 5 croaks.

### 3. Synthesis Approximations to the Model Croak

Several preliminary behavioral experiments influenced our attempts to synthesize croaks. We had some reason to believe that the structure and location of the low-frequency formant (first formant) was critical in evoking calling from our laboratory animals.<sup>1, 5</sup> We decided, therefore, to synthesize a close approximation to the first formant and to permit the amplitudes of higher frequency components to fall off monotonically, being careful to insure that the components in the range 1000-1500 cps were down at least 30 db from those of the first-formant harmonics.



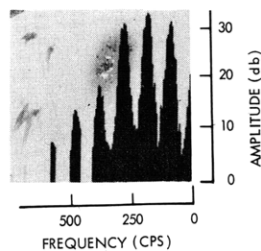
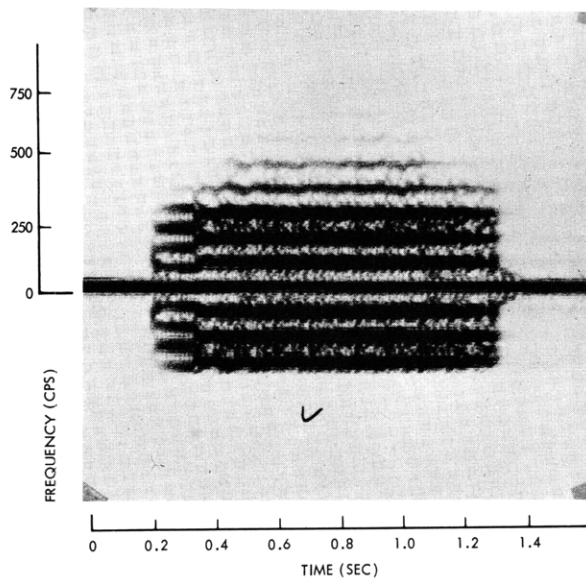


Fig. XIX-10. Sonogram and section from synthesized croak P1.

not modulated in any way. The gross temporal characteristics of both sounds were made similar to those of a bullfrog croak. The spectra of these sounds appear in Figs. XIX-10 and XIX-11, where "P1" refers to the modulated sounds, and "P2" refers to the other. The sections in these figures were taken from the middles of the sounds.

P1 sounds (to humans) much like a real bullfrog croak; P2, unsurprisingly, sounds quite mechanical, and not very "froggy" at all. The laboratory animals called to both of them, however, at a calling level comparable to that obtained when the natural croaks were presented. Thus, imitating the irregularities of the natural bullfrog croak is not necessary to evoke calling. This makes it possible to synthesize sounds in a much more convenient way simply by superposing a few sinusoids corresponding in frequency to the harmonic components of the first formant of the model croak. To do this, we used a device constructed for lecture-demonstration purposes in the Department of Electrical Engineering, M. I. T., which provides 10 sinusoids at each of the first 10 harmonics of a fixed fundamental frequency, which in all cases was chosen to be effectively

In our first attempts to synthesize bullfrog croaks we used POVO<sup>6</sup> (POle Analog of the Vocal Organs), a speech analog device kindly made available by the Speech Communication Group of the Research Laboratory of Electronics. In essence, POVO consists of cascaded tuned circuits (resonators), whose natural frequencies may be chosen to correspond to the center frequencies of the formants to be synthesized. These tuned circuits are excited by pulse trains of the desired fundamental frequency. A single resonator of appropriate bandwidth and center frequency excited by a 100-pps pulse train reproduces fairly accurately the first-formant spectrum (first through sixth harmonics) of the model croak. Using this arrangement, we generated two sounds. The amplitude and repetition rate of the first sound were modulated with white noise to imitate the irregularities described above. The excitation of the second sound was

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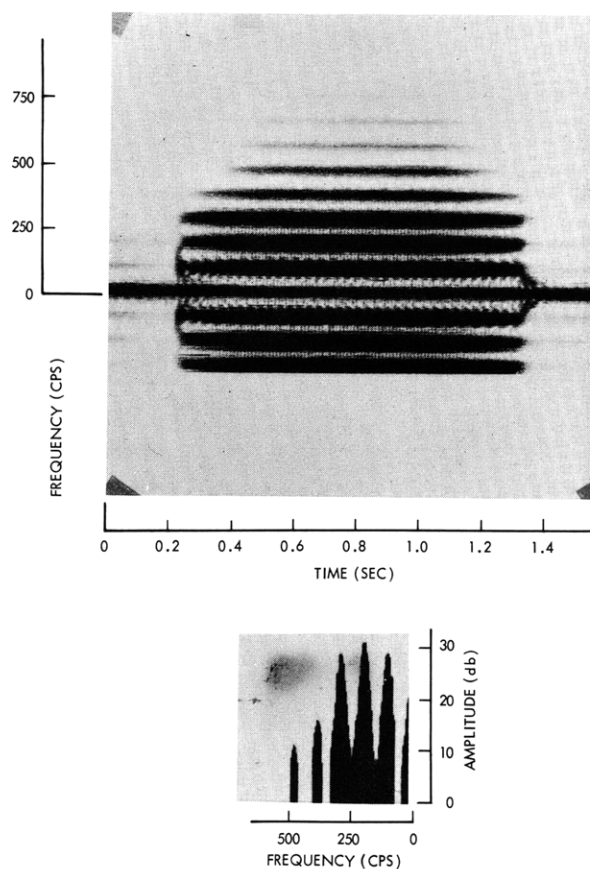


Fig. XIX-11. Sonogram and section from synthesized croak P2.

100 cps. The relative phases and amplitudes of these sinusoids can be adjusted independently.

This Fourier Synthesizer was used to generate two groups of sounds. The first group consisted of three sounds, each reproducing the amplitude relations of the first 5 harmonics of the model croak, but each having different phase relations among its harmonics. The second group consisted of a number of sounds, each of which contained at most 3 harmonics, corresponding in frequency to the first-formant harmonics, but in each of these cases the harmonic amplitudes were significantly different from those of the model croak. Care was taken in all cases to insure that the amplitudes of the harmonics outside the first-formant range were down at least 50 db from those of the first-formant components.

Figure XIX-12 gives a compendium of representative waveforms. Shown here are one of the 5 model croaks, P1 and P2, and a Fourier-Synthesizer reproduction of the model spectrum.

4. Evoked Calling to Synthesized Croaks

Calling from our laboratory bullfrogs was evoked by both POVO-generated sounds, P1 and P2. Fourier-synthesized croaks, in which only the low-frequency formant was present, evoked no calling. A representative spectrum of such a croak is shown in Fig. XIX-13. All harmonic components above 500 cps are down at least 55 db.

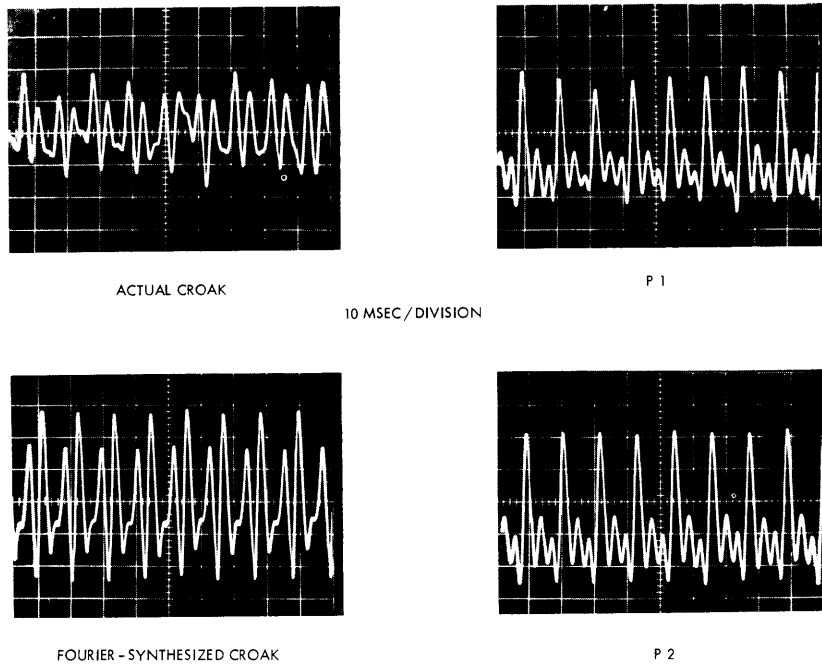


Fig. XIX-12. Summary of representative waveforms.

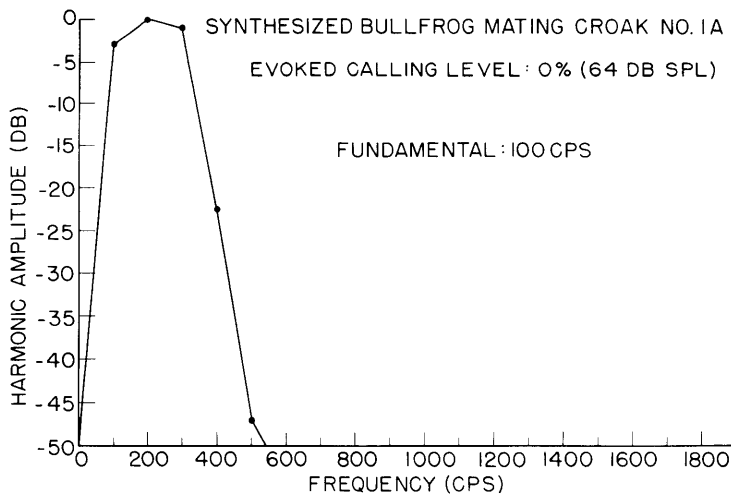


Fig. XIX-13. Harmonic amplitudes of a synthesized low-frequency formant croak.

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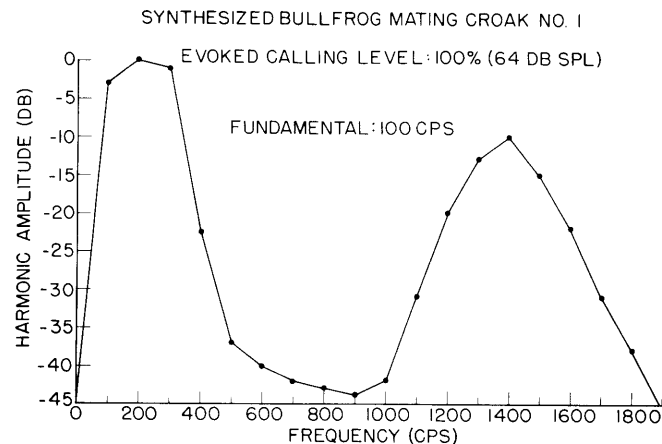


Fig. XIX-14. Harmonic amplitudes of a synthesized two-formant croak.

To initiate calling, energy corresponding to a high-frequency formant must be added. The synthesized croak whose spectrum is shown in Fig. XIX-14 has evoked calling comparable to that of natural croaks. For this croak, the peak of the second formant was arbitrarily placed at 1400 cps and its amplitude, relative to that of the first formant, at -10 db. Presentation of just the high-frequency formant by highpass filtering has not evoked calling.

Calling on the part of our animals to the POVO-generated croaks P1 and P2, as well as to natural croaks, is contingent on the presence of energy in the range 1000-1500 cps. Calling to these sounds ceases if they are sharply lowpass-filtered at 500 cps. From these studies we have concluded that to initiate calling by our laboratory bullfrogs we must simultaneously present energy in the ranges 100-400 and 1000-1500 cps.

M. J. Murray, R. R. Capranica

References

1. R. R. Capranica, M. Sachs, and M. J. Murray, Auditory discrimination in the bullfrog, Quarterly Progress Report No. 71, Research Laboratory of Electronics, M. I. T., October 15, 1963, pp. 245-265.
2. Further details will be found in M. J. Murray, Analysis and Synthesis of the Mating-Croak of the Bullfrog, S.B. Thesis, Department of Electrical Engineering, M. I. T., 1964.
3. A tape recording for analysis was kindly provided by Mr. C. M. Bogert, Curator of the Museum of Natural History, New York, N. Y.
4. G. Fant, Modern instruments and methods for acoustic studies of speech, Acta Polytech. Scand., Nucleonics, Series No. 1, Swedish Contributor No. 2, 1958.
5. R. R. Capranica, Auditory discrimination in the bullfrog, Proposal for Ph. D. Thesis, Department of Electrical Engineering, M. I. T., 1963.
6. K. N. Stevens, R. P. Bastide, and C. P. Smith, Electrical synthesizer of continuous speech, J. Acoust. Soc. Am. 27, 207(A) (1955).

## E. PSYCHOACOUSTICS OF BINAURAL UNMASKING AND ECHOLOLOCATION SYSTEMS OF BATS

Most of the results presented in this report were obtained by students in connection with thesis work. Specifically, the results described in section 1 were obtained by H. S. Colburn, those in section 2 by L. R. Rabiner and C. L. Laurence, those in section 3 by G. E. Wien, and those in section 5 by A. W. W. Clay, Jr.

### 1. EXPERIMENT ON TIME-INTENSITY RELATIONS IN BINAURAL UNMASKING

Variations in the binaural-masked threshold have been explored as a function of simultaneous shifts in interaural time delay and interaural amplitude ratio in the target signal. The purposes of this study were: (a) to fill an important gap in the data on binaural unmasking; (b) to test certain predictions of the equalization-and-cancellation (EC) model<sup>1</sup>; (c) to relate the topic of binaural unmasking to the topic of time-intensity trading.<sup>2</sup> The target signal consisted of a 500-cps tone and the masking signal of broadband Gaussian noise. The noise was presented at 90 db SPL and was identical in both ears. The combinations of interaural time delay  $\tau_s$  and interaural amplitude ratio  $a_s$  for the tone consisted of all pairs from the sets  $\tau_s = 0.00, 0.25, 0.50, 0.75, 1.00$  msec and  $a_s = \check{0}, \pm 6, \pm 12, \pm 20, \pm \infty$  db. The results (averaged over various subjects and various methods for obtaining the thresholds) for the values  $\tau_s = 0.25$  msec and  $\tau_s = 0.75$  msec are shown in Fig. XIX-15.

In general, the data from this experiment were found to be consistent with the EC model. In particular, the apparently absurd prediction that the thresholds for the cases  $(\tau_s, a_s)$  and  $(\tau_s, 1/a_s)$  are equal was substantiated within experimental error.<sup>3</sup> The comparison of these data with data on time-intensity trading will be made by using the present data to determine contours of constant threshold in the  $(\tau_s, a_s)$  plane and then comparing these contours with the conventional published time-intensity contours. Inasmuch as the new contours are based on a detection criterion and the conventional contours are based on a lateralization criterion, this comparison should be useful in specifying in what manner the binaural unmasking phenomenon is related to the separation of the noise and tone images within the head. For a detailed discussion of the work completed thus far, the reader is referred to the thesis of H. S. Colburn.<sup>4</sup>

### 2. EXPERIMENTS ON BINAURAL UNMASKING AS A FUNCTION OF INTERAURAL TIME DELAYS OR INTERAURAL PHASE SHIFTS IN THE MASKING NOISE

The binaural-masked threshold has been explored as a function of the interaural time delay or phase shift in the masking noise for a variety of tone frequencies. The purpose of these experiments was to extend the previous data of Jeffress, Blodgett, and Deatherage at 167 cps and 500 cps.<sup>5,6</sup> Such an extension was deemed to be important

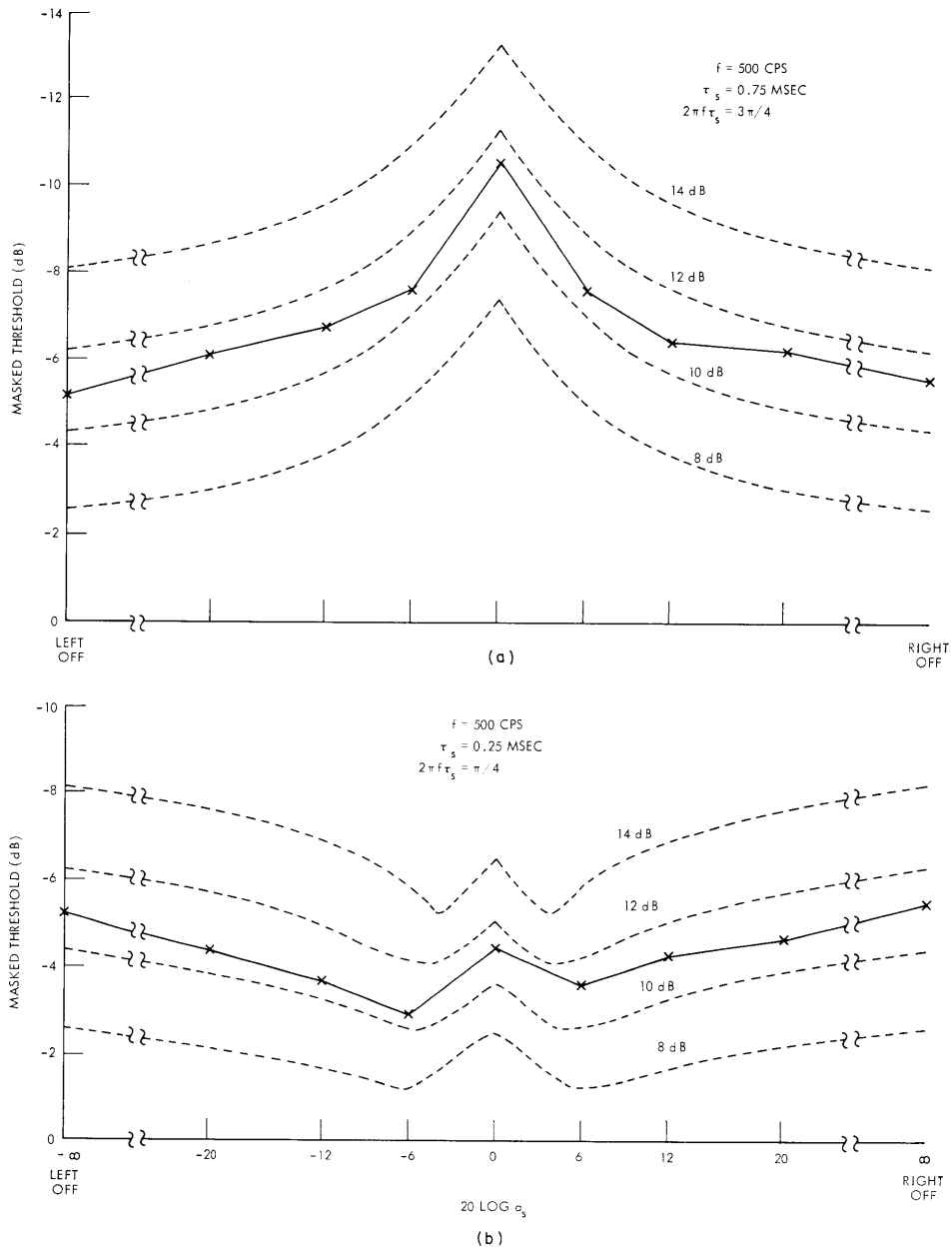


Fig. XIX-15. Variations in binaural-masked threshold as a function of interaural time delay  $\tau_s$  and interaural amplitude ratio  $a_s$  of the signal tone. The threshold for the case ( $a_s=1$ ,  $\tau_s=0$ ) is represented by 0 db. When  $a_s \neq 1$ , the threshold is defined by the signal level in the louder ear. The condition  $\tau_s > 0$  corresponds to the signal in the right ear leading the signal in the left ear. The condition  $a_s > 1$  corresponds to the signal in the left ear being louder than the signal in the right ear. Data points are indicated by crosses. Dashed curves are theoretical curves derived from the EC model by choosing specific values (indicated on the curves) for the difference between the thresholds for the cases ( $a_s=1$ ,  $\tau_s=0$ ) and ( $a_s=1$ ,  $\tau_s=1/2f$ ). In this experiment, this value was actually 11.5 db.

because of the failure of the EC model to explain certain aspects of the previous data and because the previous data were relatively meager. One point of particular interest was the inability of the model to provide an adequate explanation of the fact that at 167 cps (where the noise delay  $\tau_n$  was varied over the interval  $0 \leq \tau_n \leq 3.0$  msec) the threshold was found to be independent of  $\tau_n$  in the region  $0.6 \leq \tau_n \leq 3.0$  msec. It was conjectured that the breakpoint  $\tau_n = 0.6$  msec at which the threshold curve changed its behavior was related to the time width of the head and the fact that presenting a stimulus in which  $\tau_n$  was greater than this width made extraordinary demands on the auditory system. No conjecture was offered, however, as to why the threshold curve should remain flat after this breakpoint.

In the present time-delay experiment, binaural-masked thresholds were measured as a function of  $\tau_n$  for  $\tau_n$  in the region  $0 \leq \tau_n \leq 10$  msec and for tone frequencies of 167, 297, 500, 694, and 1040 cps. In the phase-shift experiment, binaural-masked thresholds were measured as a function of the interaural phase shift in the noise for phase shifts in the region  $0-180^\circ$  and for tone frequencies of 200 and 400 cps. In both experiments, the

noise was broadband Gaussian noise with an over-all power level of approximately 90 db SPL, and the interaural amplitude ratios for the tone and noise were maintained at unity. (In general, phase-shifted noise and time-shifted noise cannot be equated; however, if one assumes reasonable values for the width of the critical band, for the present discussion these two experiments can be grouped together.) The average results of the time-delay experiment for the frequencies  $f = 694$  cps and  $f = 297$  cps are shown in Fig. XIX-16.

The implications (with respect to the flattening problem) of these experiments can be summarized roughly as follows: (i) for frequencies  $f \geq 500$  cps, there is no flattening; (ii) for  $167 \leq f \leq 400$  cps, the flattening is very pronounced; (iii) for frequencies at which the flattening occurs, the regions of  $\tau_n$  over which the threshold remains flat are given approximately by  $n/f + h \leq \tau_n \leq (n+1)/f - 2h$  ( $n$  an integer), where  $h$  is  $\sim 0.6$  msec. In addition to

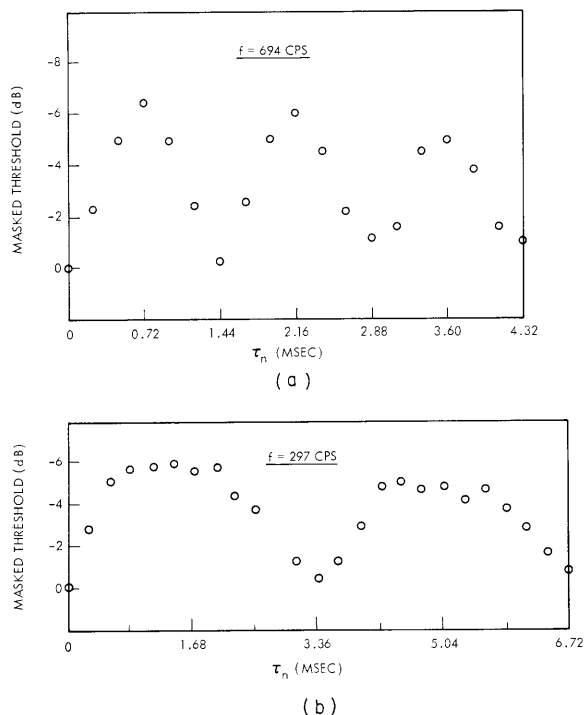


Fig. XIX-16.

Variations in binaural-masked threshold as a function of the interaural delay  $\tau_n$  of the noise. The threshold for the case  $\tau_n = 0$  is represented by 0 db.

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helping specify the flattening phenomenon, the time-delay experiment has served, along with recent experiments by Langford and Jeffress,<sup>7</sup> to specify other characteristics of the threshold curve. For example, as a result of all of these experiments, it is now well established that the threshold dependence on  $\tau_n$  has the general form of a damped periodic function for which the period is equal to the period of the tone. It also appears that the degree of damping can be predicted from the value of the critical bandwidth.<sup>8</sup> The phase-shift experiment, on the other hand, has served to relate the difference between the thresholds for the cases "signal in phase-noise out of phase" and "signal out of phase-noise in phase" to the flattening phenomenon. For further details the reader is referred to the theses of L. R. Rabiner<sup>9</sup> and C. L. Laurence,<sup>10</sup> and the work of Durlach<sup>1</sup> and Jeffress.<sup>5-7</sup>

### 3. PRELIMINARY EXPERIMENT ON ADAPTATION TO MAGNIFIED INTER-AURAL TIME DELAYS

In many psychoacoustic experiments involving time parameters, the data appear to undergo a change in character when the time parameter is of the order of the time width,  $h$ , of the head. An example of such a "critical point" has already been cited above in connection with binaural unmasking. A second example (probably closely related) is furnished when one stimulates the two ears with broadband noise signals differing only in time delay,  $\tau$ , and asks the subject to report on the position of the subjective image inside his head. The image occurs in the center of the head for  $\tau = 0$  and progressively moves across to the leading ear as  $\tau$  increases to  $h$ . As  $\tau$  increases beyond  $h$ , however, the image tends to remain "locked" at the leading ear. A third example is found in the study of localization cues for tone stimuli. Letting  $T$  denote the period of the tone, one finds that for  $T > h$ , the dominant interaural cue is the interaural time delay, whereas for  $T < h$ , the dominant interaural cue is the interaural intensity difference.

In each of these cases, the fact that the critical point is roughly equal to the time width of the head appears to be more than a coincidence. One wonders, in fact, if the processing mechanisms in the auditory system were not developed in a manner that takes specific account of the head width. This leads one to conjecture that there might be a close correlation between the head width and the critical points for various head widths. One way of exploring this question is to see if a given subject can be adapted to an artificially large head width (which has the effect of magnifying the interaural time delays) and determine whether or not these critical points are shifted accordingly.

The specific experiment that was attempted was styled after that of R. Held in which subjects were fitted with pseudophones that rotated the interaural axis in the horizontal plane.<sup>11</sup> In the present experiment, pseudophones were constructed which had the effect of expanding the interaural distance by a factor of three and reducing the interaural attenuation caused by head shadowing. A photograph of this apparatus is shown in Fig. XIX-17. The tests performed on the subjects (before and after "adaptation training"<sup>12</sup>) consisted



of localization tests and binaural unmasking tests at frequencies in the interval 100-600 cps. The results on localization were somewhat ambiguous in that one subject showed appreciable adaptation (even in the region where the interaural delay was substantially greater than 0.6 msec), while two other subjects showed only very minor adaptation. The results on binaural unmasking showed no change attributable to the adaptation training, i. e., the critical point that occurred at approximately  $\tau_n = h$  before training occurred at almost the same point after training. If the critical point in the masking data had shifted, one could draw a relatively firm conclusion. From the fact that it did not shift, one can only conclude that either the head width is not related to the critical point or the relevant processing mechanisms are "wired in" and cannot be changed by learning or the equipment and/or the adaptation training were inadequate. For further details on this project, the reader is referred to the thesis by G. E. Wien.<sup>13</sup>



Fig. XIX-17. Apparatus used for "head-stretching" experiment. Signals are picked up by microphones at end of the horizontal bar, amplified by circuitry in boxes, and presented to subject through earphones (unseen) contained in acoustical ear muffs.

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4. THEORETICAL WORK ON BINAURAL UNMASKING

In addition to the experimental results outlined above, two theoretical results have been obtained.

1. The EC model has been extended to apply to data describing the variations in threshold as a function of the interaural correlation of the masking noise.<sup>14</sup> The data considered are those of Robinson and Jeffress in which the correlation was controlled by varying the amount of independent noise fed to the two ears.<sup>15</sup>

2. As described in section 2, if the signal tone has a frequency  $f \leq 400$  cps, the variation of the masked threshold with the interaural time delay  $\tau_n$  of the noise exhibits a

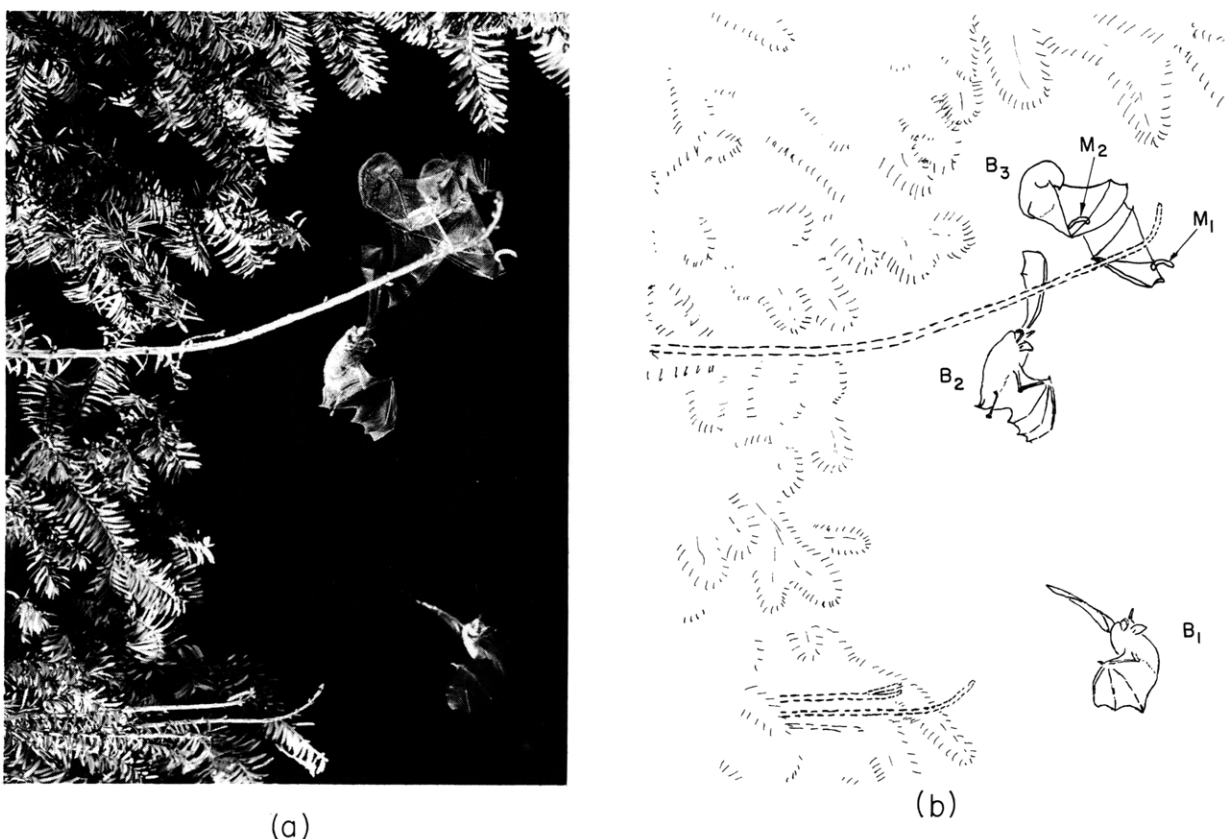


Fig. XIX-18. *Myotis lucifugus* intercepting a tossed mealworm in the presence of a yew branch: (a) multiflash photograph; (b) line drawing traced from the photograph. Four flashes are shown. Only the first three are reproduced in the drawing. (The letters refer to the objects and the numerical subscripts to the time sequence.) At flash 3, the bat has caught the mealworm in its tail membrane. In flashes 3 and 4, the bat is upside down and is reaching into its tail membrane to grasp the mealworm with its mouth. In flashes 2, 3, and 4, the bat and mealworm are within 1 ft of the nearest part of the yew branch. (Photograph and drawing obtained from F. A. Webster.)

flattening for certain regions of  $\tau_n$ . It has recently been observed that this flattening is consistent with the EC model, provided that one augments the model with the hypothesis that the stimuli undergo a time contraction when  $\tau_n$  is in the region of flattening. If, for simplicity, we restrict the values of  $\tau_n$  to the region  $h \leq \tau_n \leq 1/2f$ , this time contraction is described by the transformation  $t \rightarrow (h/\tau_n)t$ . In addition to making the EC model consistent with the available data, this hypothesis has been used to predict results for which there are no available data. Experiments designed to test these predictions are now under way. A brief description of this theoretical work can be found in an informal memorandum.<sup>16</sup>

## 5. RESULTS RELATED TO BAT-ECHOLOCATION SYSTEMS

This project, conducted in collaboration with F. A. Webster,<sup>17</sup> consisted of two parts: (i) construction of an ultrasonic "scattering range" to measure the reflective properties of targets; and (ii) preliminary experiments on the bat's ability to overcome "clutter."<sup>18</sup> The scattering range was not only needed to measure the clutter situation faced by the bat in part (ii) of this project but also as a general tool for the whole bat program. This range has been completed and appears to be adequate for measuring the ultrasonic scattering properties of moths, fruit flies, mealworms, etc. In order to facilitate the analysis of the behavioral results on target discrimination by Myotis lucifugus,<sup>19</sup> comparative measurements have been made on mealworms and various types of spheres. The results of the clutter experiments, although very preliminary, indicate that the bat may transmit special signals when faced with extreme clutter situations. A picture of a Myotis pursuing and catching a mealworm in a background of "yew clutter" is shown in Fig. XIX-18. For further details on this work, the reader is referred to the thesis by A. W. W. Clay, Jr.,<sup>20</sup> to Webster and Durlach,<sup>19</sup> and to the publications of D. R. Griffin and F. A. Webster.<sup>21</sup>

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### Footnotes and References

1. N. I. Durlach, Equalization and cancellation theory of binaural masking-level differences, *J. Acoust. Soc. Am.* 35, 1206-1218 (1963).
2. See, for example, G. Moushegian and L. A. Jeffress, Role of interaural time and intensity differences in the lateralization of low-frequency tones, *J. Acoust. Soc. Am.* 31, 1441-1445 (1959).
3. By symmetry, one would expect that the thresholds for the cases  $(\tau_s, a_s)$  and  $(-\tau_s, 1/a_s)$  would be equal and the thresholds for the cases  $(-\tau_s, a_s)$  and  $(\tau_s, 1/a_s)$  would be equal. The experimental results show that the thresholds for all four cases are equal.
4. H. S. Colburn, Time-Intensity Relations for Binaural Masking, S. M. Thesis, Department of Electrical Engineering, M. I. T., May 1964.

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5. L. A. Jeffress, H. C. Blodgett, and B. H. Deatherage, The masking of tones by white noise as a function of the interaural phases of both components. I. 500 cps, J. Acoust. Soc. Am. 24, 523-527 (1952).

6. L. A. Jeffress, H. C. Blodgett, and B. H. Deatherage, Masking and interaural phase. II. 167 cps, J. Acoust. Soc. Am. 34, 1124-1126 (1962).

7. L. A. Jeffress, private communication. (The results of the work of Langford and Jeffress are scheduled to appear in J. Acoust. Soc. Am., August 1964.)

8. For a prediction based on the EC model, see N. I. Durlach, J. Acoust. Soc. Am. 35, 1206 (1963), Fig. 8; see also Langford and Jeffress, J. Acoust. Soc. Am. in press.

9. L. R. Rabiner, Binaural Masking – The Effects of Interaural Delay of the Noise on the Detection of Tones, S.M. Thesis, Department of Electrical Engineering, M. I. T., May 1964.

10. C. L. Laurence, Studies of Masking Noise Phase Delays in Binaural Masking Level Differences, S. B. Thesis, Department of Physics, M. I. T., May 1964.

11. R. Held, Trained Shifts in Binaural Direction Finding, Ph. D. Thesis, Harvard University, 1952.

12. "Adaptation training" consisted primarily of actively moving about in the anechoic chamber while wearing the hat, with various acoustical stimuli being presented through loudspeakers.

13. G. E. Wien, A Preliminary Investigation of the Effect of Head Width on Binaural Hearing, S.M. Thesis, Department of Electrical Engineering, M. I. T., May 1964.

14. N. I. Durlach, Note on binaural masking-level differences as a function of the interaural correlation of the masking noise (J. Acoust. Soc. Am. in press).

15. D. E. Robinson and L. A. Jeffress, Effect of varying the interaural noise correlation on the detectability of tonal signals, J. Acoust. Soc. Am. 35, 1947-1952 (1963).

16. N. I. Durlach, Time Contraction – A Possible Solution to the 'Flattening Problem' in Binaural Masking (unpublished, May 1964).

17. F. A. Webster is the principle investigator for the "Bat-Echolocation Project," Sensory Systems Laboratory, Cambridge, Massachusetts.

18. "Clutter" is defined as interference from unwanted echos.

19. See F. A. Webster and N. I. Durlach, Echolocation Systems of the Bat – Progress Report on Experimental Studies Conducted at F. A. Webster's Laboratory (1 November 1961-1 September 1962), Report 41G-3, Lincoln Laboratory, M. I. T., August 1963.

20. A. W. W. Clay, Jr., The Effects of Clutter on the Echolocation System of Bats, S. B. Thesis, Department of Electrical Engineering, M. I. T., May 1964.

21. See, for example, D. R. Griffin, Listening in the Dark (Yale University Press, New Haven, 1958); F. A. Webster, Acoustical Control of Airborne Interceptions by Bats, Proc. International Congress on Technology and Blindness, American Foundation for the Blind, 1963.