XV. COMMUNICATIONS BIOPHYSICS

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A. BIFREQUENCY ANALYSIS OF REPETITIVE AUDITORY STIMULI

Psychophysical experiments show that certain acoustic signals are described by listeners as having a low-pitched quality, although they contain no Fourier components in the corresponding portion of the spectrum (1, 2, 3, 4, 5). These results contradict the usual statement of Ohm's acoustic law, according to which a complex stimulus is analyzed with respect to its Fourier components during the listening process. Experimental evidence indicates that there is nonlinear action of the auditory system. Since these results are obtainable at near-threshold intensities, it is likely that at least some of the nonlinearity is neural in origin rather than mechanical.

A mathematical transform was developed which gives a simple representation of the aforementioned signals. The transform is a function of two variables, both of which have the dimension of frequency. The usefulness of this bifrequency transform for representing auditory signals derives from the close relation of one coordinate to Fourier frequency and of the other to the time-varying envelope of the signal.

A signal of special interest in auditory experiments is formed by gating (modulating) wideband noise with an electronic switch to form bursts of noise. Judgments can be obtained for changes in burst rate that are just noticeable. The spectral density of the bursts-of-noise signal remains identical to the spectral density of the unmodulated noise, independent of burst rate. If, however, the modulated signal is treated as a time-varying statistical signal, following the representation used by Booton (6), its periodic nature becomes evident. Booton's analysis includes a correlation function based on ensemble averages, rather than on averages over time, yielding the function of two variables

$$\phi(\tau, t) = \overline{x(t)\, x(t+\tau)}$$

where the bar indicates an average over the ensemble of the statistical function.

There is sufficient difference between the psychophysical and the physical situations with statistical inputs to indicate that the concept of taking an average over the statistical ensemble must be carefully examined. There is evidence that a listener's judgments are influenced both by past experience and instructional constraints. This psychophysical ensemble in which the stimulus appears may differ widely from the

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statistical ensemble from which the stimulus is drawn. Furthermore, the subject has for his stimulus only one member function of the statistical ensemble, so that use of a representation based on an average over the total ensemble loses validity. For statistically described signals of a periodic nature the average can be taken in a special manner, with the result that we have the correlation function,

$$\phi(\tau, t) = \overline{x(t)\, x(t+\tau)}^{\,T}$$

where the $\underline{\qquad}$ T indicates the operation of averaging products that are formed from pairs of samples spaced by intervals equal to the period, T, of the time variation. Thus, $\phi(\tau, t)$ could also be written

$$\phi(\tau, t) = \lim_{K\to\infty} \frac{1}{2K} \sum_{-K}^{K} x(t + KT)\, x(t + \tau + KT)$$

where K takes on integral values.

The Fourier transform of the correlation function results in a spectral density

$$\Phi(\omega, t) = \int_{-\infty}^{\infty} e^{-j\omega\tau}\, \phi(\tau, t)\, d\tau$$

that varies in time. Since $\phi(\tau, t)$ is periodic in t, $\Phi(\omega, t)$ is also periodic in t.
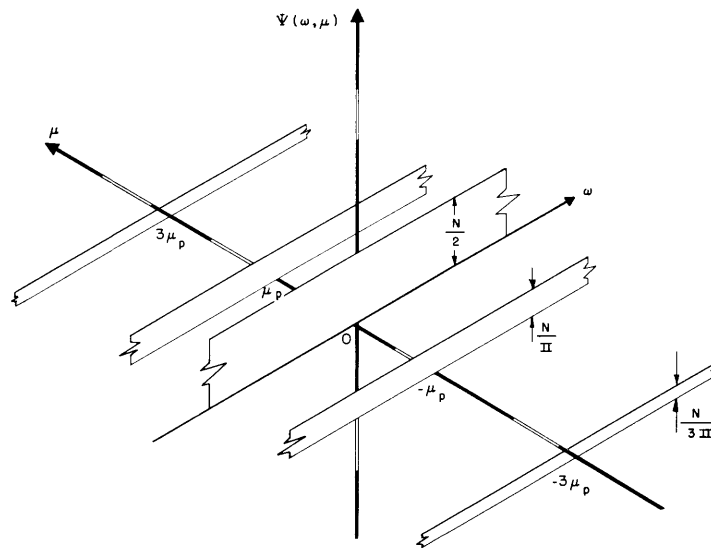

Fig. XV-1. $\Psi(\omega, \mu)$ for interrupted white noise (sound-time fraction = 0.5).

A further Fourier transformation results in the bifrequency transform

$$\Psi(\omega,\mu) = \int_{-\infty}^{\infty} e^{-j\mu t} \, \Phi(\omega,t) \, dt$$

For a fixed ω, $\Psi(\omega,\mu)$ is a series of delta impulses at evenly spaced intervals in μ, owing to the periodic nature of $\Phi(\omega,t)$.

The steps involved in obtaining the bifrequency transform for a statistically described signal can be extended to the case of a signal which is a known function of time whose Fourier transform is $F(\omega)$. Now, no averaging is necessary and the resulting functions are

$$\phi(\tau,t) = f(t) \, f(t+\tau)$$

$$\Phi(\omega,t) = \int_{-\infty}^{\infty} e^{-j\omega\tau} \, \phi(\tau,t) \, d\tau$$

$$= f(t) \, e^{j\omega t} \, F(\omega)$$

$$\Psi(\omega,\mu) = \int_{-\infty}^{\infty} e^{-j\mu t} \, \Phi(\omega,t) \, dt$$

$$= F(\omega) \, F(\mu-\omega)$$

The second function is similar to one obtained by Ville (7). If f(t) is periodic, $F(\omega)$ is a series of delta impulses, and $\Psi(\omega,\mu)$ contains impulses in both variables. The form of the bifrequency representation is best demonstrated by a few simple examples.

The bifrequency transform of periodically gated white noise is shown in Fig. XV. 1. The sound-time fraction refers to the ratio of the length of a burst to the gating cycle. The transform takes the form of a number of "fences" parallel to the ω-axis. For a fixed ω, the function of μ is a series of impulses occurring at $\mu_p = 0$ and all odd multiples of μ_p, the gating frequency. The flat characteristic of white noise in the ω (Fourier frequency) dimension is retained, while the periodic nature of the modulation is manifest in the structure of Ψ in the μ (periodicity) dimension.

In Fig. XV-2 oscillographic traces of four signals are shown: a 100 per cent amplitude-modulated 5-kc signal, a suppressed-carrier-modulated 5-kc signal, the "missing fundamental"
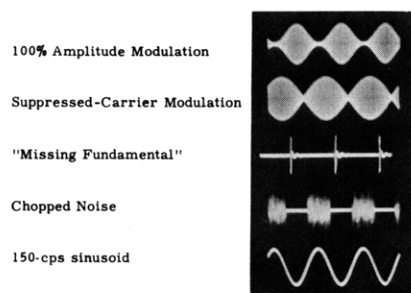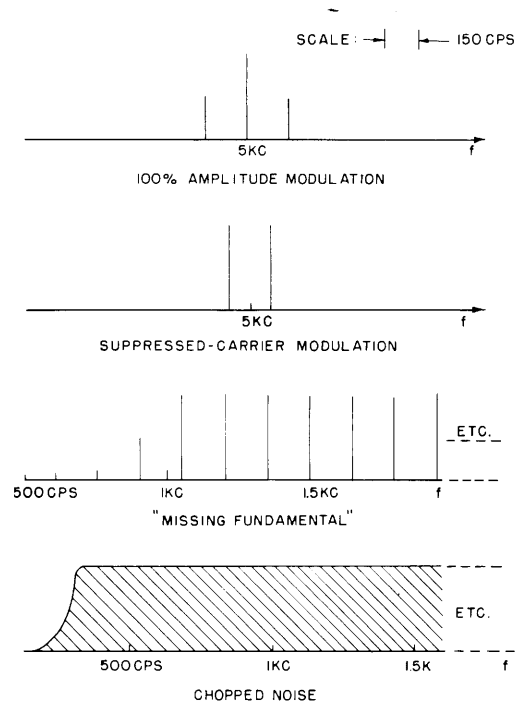

100% Amplitude Modulation

Suppressed-Carrier Modulation

"Missing Fundamental"

Chopped Noise

150-cps sinusoid

Fig. XV-2. Signal waveforms.

100% AMPLITUDE MODULATION

5KC

SUPPRESSED-CARRIER MODULATION

5KC

ETC.

500 CPS   IKC   I.5KC   f

"MISSING FUNDAMENTAL"

ETC.

500 CPS   IKC   I.5K   f

CHOPPED NOISE

Fig. XV-3. Spectral representation of signals.

SCALE →┤ ├— 150 CPS

PERIODICITY (CPS)

300

150

0

5 KC

FREQUENCY

100 % AMPLITUDE MODULATION

ETC.

600

450

300   ETC.

150

0   IKC   I.5 KC

FREQUENCY

"MISSING FUNDAMENTAL"

PERIODICITY (CPS)

150

0

5KC

FREQUENCY

SUPPRESSED-CARRIER MODULATION

450

300

150

0   500 CPS   IKC

FREQUENCY

CHOPPED NOISE
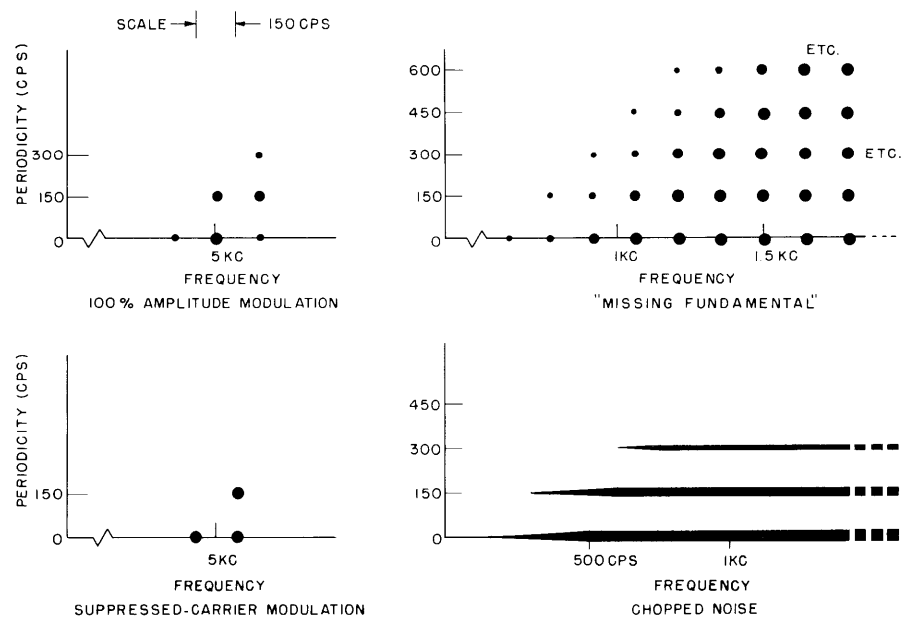
Fig. XV-4. Bifrequency representation of signals.

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signal of Schouten (1), and bursts of wideband noise. These signals have some quality of low pitch, although, as is evident in Fig. XV-3, their spectra contain no components in the low-frequency range. A representation of the signals in the bifrequency plane is presented in Fig. XV-4. A two-dimensional plot in only one quadrant of the μ-ω plane is used. The dots represent "impulses" in both the μ and ω variables, and the bars indicate impulse fences, with the thickness of the dot or bar corresponding roughly to the size of the impulse. In each case, the bifrequency transform has components with a periodicity coordinate of 150 cps.

The bifrequency transform is one of several possible mathematical representations of repetitive auditory signals that predict the results of psychophysical tests when conventional spectral representation fails to do so. Bifrequency transformation retains the conventional spectral picture, adding at the same time some temporal aspects that are so important in understanding the functioning of the auditory system.

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B. RESPONSES TO CLICKS RECORDED FROM THE ANTERIOR SUPRASYLVIAN GYRUS

Merlis and Lombroso (1) reported that in cats anesthetized with Dial, responses to clicks are recorded from a large portion of the anterior suprasylvian gyrus (Fig. XV-5). In their experiments, clicks delivered to one ear evoke comparable responses from anterior suprasylvian gyri on both sides. Later (2) they found that destruction of the cochlea opposite the stimulated ear resulted in a marked decrease in the size of the response on the side contralateral to the destroyed cochlea, as well as a slight increase on the side ipsilateral to the destroyed cochlea.

We have corroborated these findings and have attempted to elucidate the mechanisms underlying these rather surprising phenomena. For click stimuli of high intensities, it
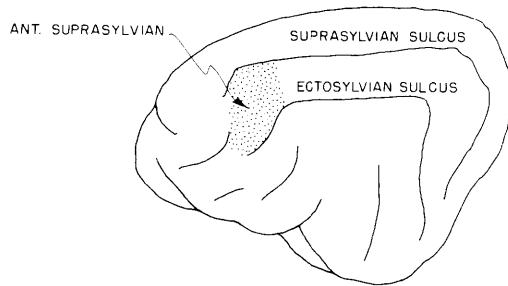
Fig. XV-5. Map of a cat's brain (left side); the stippled area represents the anterior suprasylvian gyrus.

is possible that an airborne click stimulates the "unstimulated" ear. The bulla on the unstimulated side was opened in an acute preparation. The responses that were recorded resembled those observed after destruction of the "unstimulated" cochlea. When the hole in the bulla was resealed with bonewax, the response at both cortices became similar again. When the bonewax was removed, the response at the contra-lateral cortex was again greatly reduced. This procedure was repeated several times, and the results were identical. These same procedures, including destruction of one cochlea, have essentially no effect on auditory responses recorded from the ectosylvian gyrus on either side. It seems reasonable, therefore, to suppose that there is a path-way from each cochlea to the contralateral anterior suprasylvian gyrus with a much smaller, if any, projection to the ipsilateral anterior suprasylvian gyrus and that most of the response recorded from the ipsilateral anterior suprasylvian gyrus is attributable to cross-stimulation (acoustic leakage) of the other ear.

We have used both monopolar and vertically-oriented, concentric, penetrating electrodes in an effort to check whether or not the potentials recorded at the anterior suprasylvian gyrus are local in origin. Although we did not make an exhaustive exami-nation, for the numerous points that we did examine, the monopolar electrodes do not show reversals of polarity as they penetrate the anterior suprasylvian gyrus and the bipolar electrodes do not essentially demonstrate potential differences at any pair of points when they are pushed through the cortex. These results indicate that most of the responses recorded at the anterior suprasylvian gyrus are not locally generated but represent electrical spread from elsewhere. The potentials may originate in some small part of the anterior suprasylvian gyrus that has not yet been tested, or they may come from areas that lie entirely outside the anterior suprasylvian gyrus.

Experiments involving the use of strychnine, or chronic preparations in which one cochlea was destroyed, have given equivocal results.
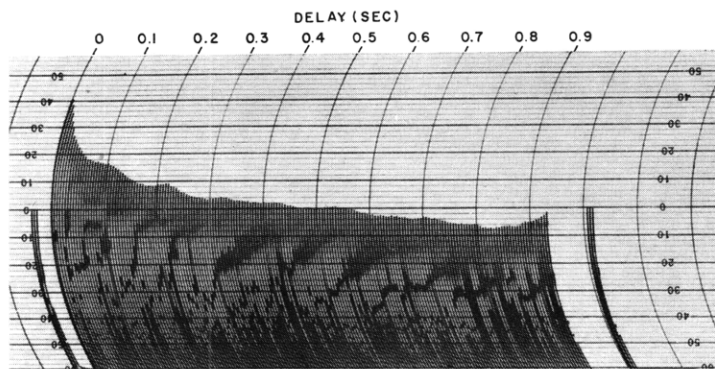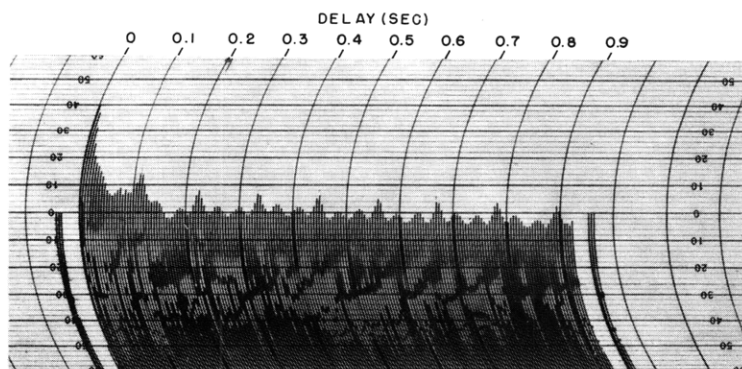
N. Y. S. Kiang

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1. J. K. Merlis and C. Lombroso, Third International Congress of EEG and Clinical Neurophysiology, August 17-22, 1953. Abstract No. 54, Suppl. III, EEG Jour., p. 70.
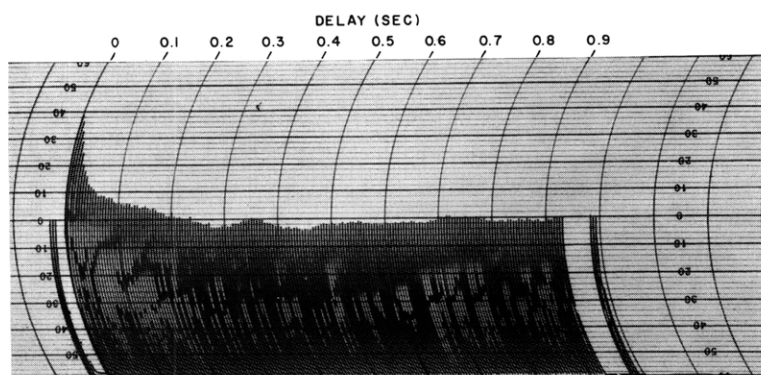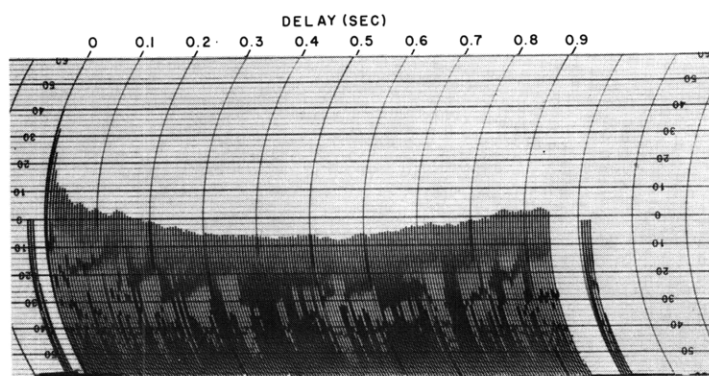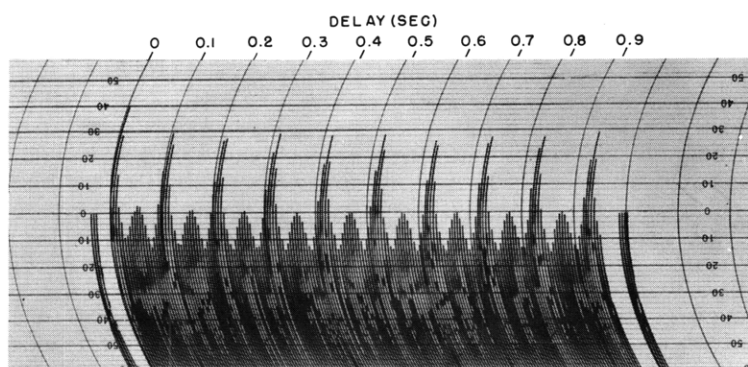2. J. K. Merlis, Personal communication.
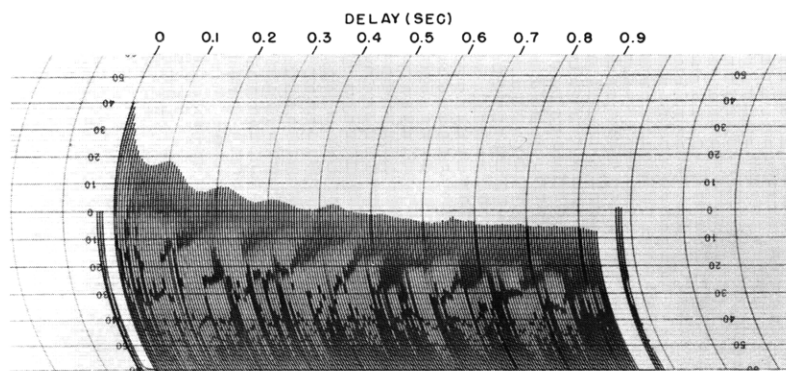
Fig. XV-6. Autocorrelations from an anterior location on the lateral gyrus:
(a) without stroboscopic stimulation; (b) with stroboscopic stimu-
lation, flash rate about 1 per second; (c) with stroboscopic stimu-
lation, flash rate about 9 per second. Length of sample, 1 minute;
steps of delay $\Delta\tau$, 5 msec.

Fig. XV-7. Autocorrelations from lateral geniculate body. (a) without strobo-
scopic stimulation; (b) with stroboscopic stimulation, flash rate
about 1 per second; (c) with stroboscopic stimulation, flash rate
about 10 per second. Length of sample, 1 minute; steps of delay
$\Delta\tau$, 5 msec.

C. CORRELATION STUDIES OF EFFECTS OF VISUAL STIMULATION
UPON ANESTHETIZED CATS

Simultaneous recordings with and without stroboscopic stimulation were made from
the lateral geniculate nuclei, and from several points on the lateral gyrus (visual cortex)
of cats under nembutal anesthesia. Autocorrelations of depth and surface recordings
and crosscorrelations of depth with surface recordings were obtained. Crosscorrelation
of stimuli with recorded activity by the method described previously (1, 2) was used to
obtain averages of responses evoked by visual stimulation at these two-way stations of
the visual pathway. Examples of results obtained with unipolar recordings are shown
in Figs. XV-6, 7, 8, and 9. Figure XV-6 shows how the autocorrelation from an
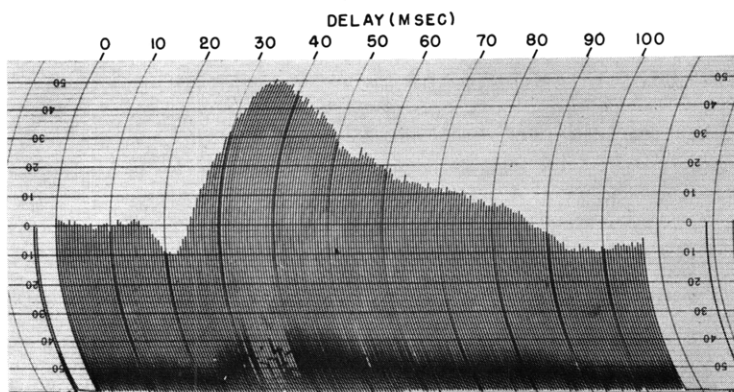anterior position on the lateral gyrus is altered as a result of stroboscopic stimulation

Fig. XV-8. Averaged response from anterior lateral gyrus to 180 strobo-
scopic stimuli at a rate of 1 per second. Steps of delay $\Delta\tau$,
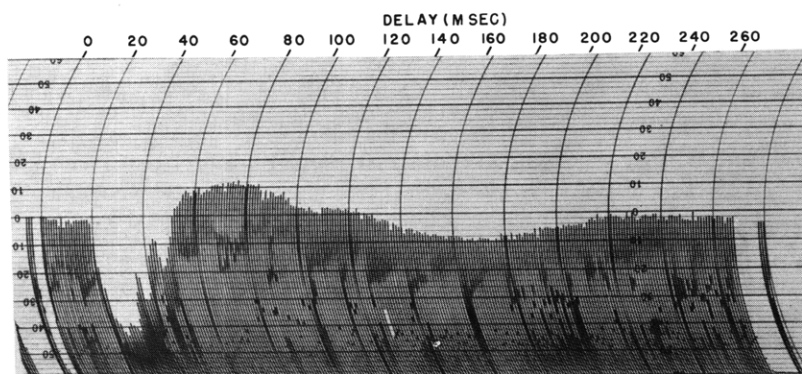0.5 msec. (Same cat as in Fig. XV-6.)

Fig. XV-9. Averaged response from lateral geniculate nucleus to 60 strobo-
scopic stimuli at a rate of 1 per second. Steps of delay $\Delta\tau$, 1 msec.

at approximately 1 and 9 flashes per second, respectively. With a stimulation rate of 9 per second, a new rhythm of the same frequency as the stimulus appears in the correlogram; there is also present a rhythm of three times the stimulus frequency. Figure XV-7 shows, for another cat, the alteration of the autocorrelation from the lateral geniculate nucleus, by the imposition of stimuli of about 1 and 10 flashes, respectively. At a flash rate of 10 per second, there is a rhythm of twice the stimulus rate, in addition to the rhythm at the same frequency as the stimulus. (For an example of the autocorrelation of a mixture of a sine wave and its second harmonic, see Fig. XIX-6a, Quarterly Progress Report, January 15, 1956, p. 144.)

Figure XV-8 indicates the averaged response obtained from 180 successive photic stimuli at 1 flash per second, from an anterior position on the lateral gyrus for the same cat from which the results of Fig. XV-6 were obtained. The steps of delay $\Delta\tau$ are 0.5 msec. The latency of onset of the surface positivity is 17 msec, the peak of surface positivity occurs at 22 msec, and the peak of the surface negativity occurs at 36 msec. Figure XV-9 shows the averaged response from 60 flashes, at a rate of 1 flash per second from the lateral geniculate nucleus of another cat, at a different level of anesthesia. The steps of delay $\Delta\tau$ are 1 msec. Latencies in this case are as follows: onset of positivity, 18 msec; peak of positivity, 26 msec; and peak of negativity, 75 msec.

In cooperation with the Medical Acoustics Research Group at the Massachusetts General Hospital, recordings for correlation analysis similar to those described above are being made in anesthetized cats in which a lesion has been previously made by ultrasonic radiation in the lateral geniculate nucleus on one side, the second, unirradiated side being used as the control (3). Correlograms obtained from these recordings will be discussed at a later time.

M. A. B. Brazier, J. S. Barlow

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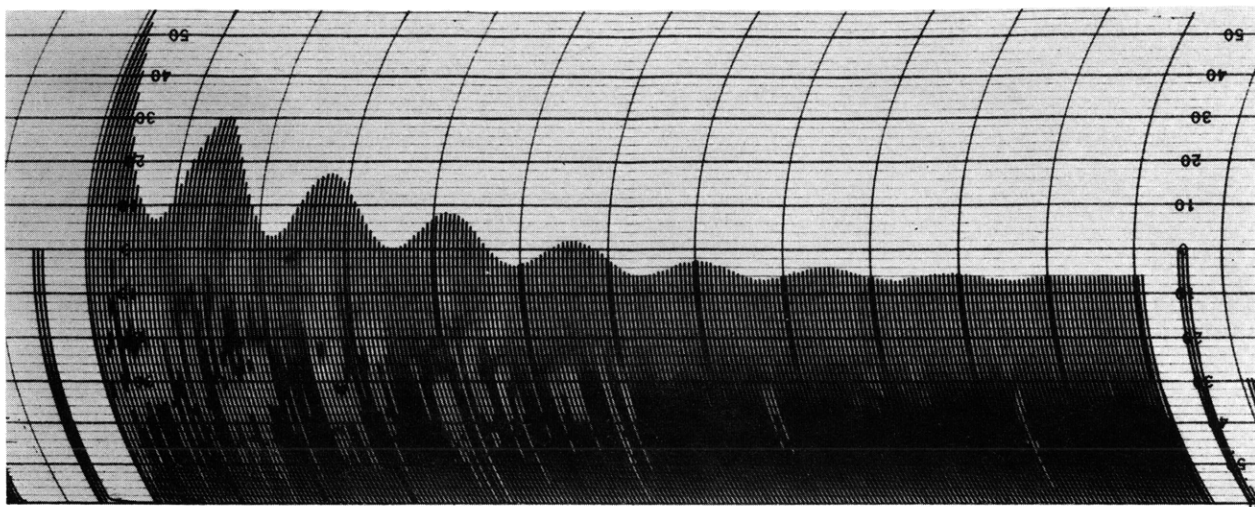
Fig. XV-10a. Autocorrelation of brain potential (between electrodes at left temporal location and chin) recorded while clicks were presented (at 1 per second) to the right ear. Correlation is plotted against delay of the sample with respect to itself. The analyzed sample was 4 minutes long; the delay step (between successive lines of the record) is 4 msec. Zero correlation is shown by the three lines at the beginning and end of the record.
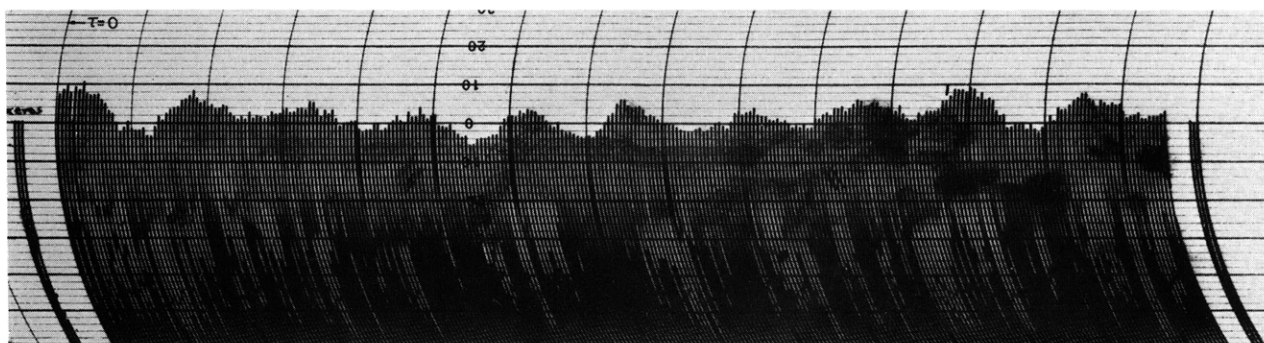
Fig. XV-10b. The result of crosscorrelating the same sample with pulses occurring at the times of the stimuli. The delay step is again 4 msec.
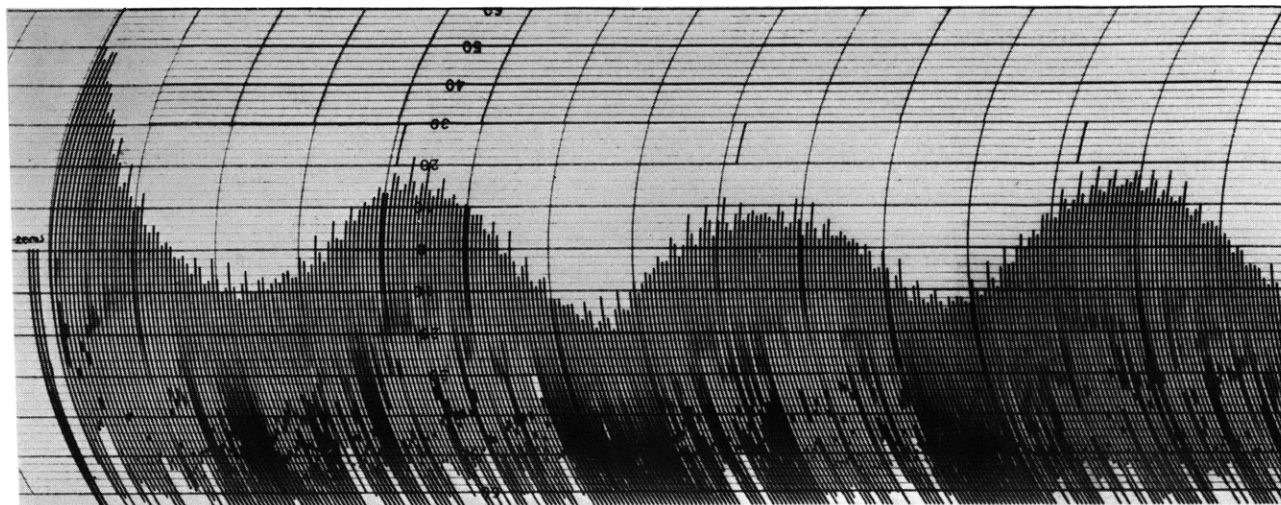
Fig. XV-11.   Autocorrelation of brain potential (electrodes at left temporal location and chin) recorded while clicks were presented to the right ear at the rate of about 3 per second.   The analyzed sample was 4 minutes long; the delay step is 4 msec.   (Compare this autocorrelation function with Fig. XV-10a; the time scale and electrode locations are the same.)   The vertical lines above the correlation indicate the repetition rate of the stimulus.   The fast component that is super-imposed on the record represents the autocorrelation of line-voltage pickup (60 cps).

D. CORRELATIONAL ANALYSIS OF BRAIN POTENTIALS UNDER CONDITIONS OF AUDITORY STIMULATION

We are investigating the effects of auditory stimulation on the electrical activity detected by gross electrodes placed on the scalps of human subjects. The observed activity is analyzed with the aid of an analog correlator by the following computational methods:

1. autocorrelation of the activity detected at a single location;

2. crosscorrelation of activity recorded simultaneously from two locations;

3. crosscorrelation of the observed activity with brief rectangular pulses occurring at the times of the stimuli. These methods and the corresponding instrumentation have been described by Barlow and Brown (1) and by Barlow and Brazier (2).

Data from one subject (H-398) were analyzed. The subject lay on a cot in a darkened anechoic chamber. Electrodes were located over the left temporal area and at the top of the head (vertex). The reference electrode was on the chin. Clicks were delivered at rates of about 1 per second and 3 per second to the right ear.

Autocorrelation of the activity recorded from the awake subject, stimulated at 1 per second, shows, at both locations, a predominant component at about 9.5 cps (Fig. XV-10a). Crosscorrelation of this same activity with the stimulus exhibits the same 9.5 per second rhythm (Fig. XV-10b). It appears, therefore, that each occurrence of the stimulus disrupts the rhythm which, thereafter, reorganizes in fixed phase with respect to the stimulus. A similar phenomenon was observed by Bishop and O'Leary (3) at the visual cortex of the rabbit, in response to shocks delivered to the optic nerve.

At a stimulation rate of 3 per second, the predominant rhythm detected at the temporal location is about 3 per second; however, the two frequencies (of stimulus and response), although they are close, appear to differ significantly (Fig. XV-11). A mixture of two rhythms (3 per second and 9 per second) is observed at the vertex.

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