

XVII. COMMUNICATIONS BIOPHYSICS

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RESEARCH OBJECTIVES

The Communications Biophysics group continues to study in a quantitative manner the electrical activity of the central nervous system and, in particular, certain probabilistic aspects of this activity (1 and 2).

The systematic investigation of evoked responses from the auditory system has been carried further by enlarging our stimulus repertory. Varying the rate of presentation and the on-off characteristics of tone-pips and of bursts of noise has brought out certain temporal and organizational features of the auditory system (3, 4, 5, 6).

Our psychoacoustic studies have, in the main, involved simple judgment procedures in response to relatively complex auditory stimuli (7); in addition, an informational analysis of auditory reaction times has been carried out (8).

Our cooperation with the Neurophysiological Laboratory of the Neurology Service of the Massachusetts General Hospital centers, as in the past, around the use of correlational techniques in the processing of EEG data and of evoked responses to flashes in both man and cat (9, 10).

In this program and in our auditory studies our special-purpose computing devices have proved increasingly useful. As our experience with these devices grows, we become better able to assess the best means of supplementing the experimenter's sensory and analytical capacities and of matching computation methods to data more appropriately. Our greatest specific need in this area is for a considerable speed-up in our data-handling procedure in order to bring the time spent in computing somewhere near the time consumed by data-taking.

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A. DETECTION OF RESPONSES TO CLICKS IN AWAKE SUBJECTS BY AN AVERAGING PROCEDURE

Davis (1) reported in 1939 that auditory stimuli delivered to awake human subjects evoke electric responses from the head. It was found consistently that this response is largest at the vertex of the skull. A similar response, evoked in light sleep, was found by Davis, et al. (2) and named the K-complex. In a recent paper, Roth, Shaw, and Green (3) reported that the K-complex was evoked in all subjects in light sleep. They were not able to obtain the response in deep sleep. In awake subjects visually discernible responses were observed in the EEG's of about 20 per cent of all subjects.

There is considerable evidence that the K-complex is connected with a general arousal response. The electrical event is often accompanied by movement and sometimes by awakening. The response seems, moreover, to be nonspecific in origin (2, 3); auditory, visual, tactile, and painful stimuli are all capable of eliciting a similar response. The work of Moruzzi and Magoun (4) on the role of the nonspecific sensory system in maintaining states of sleep and wakefulness seems relevant. We have undertaken an investigation of the effect of intensity and rate on the average response to auditory clicks obtained from the vertex in awake subjects.

The device used to obtain an average waveform was described earlier by Barlow (5). Consider two waveforms, concurrent in time, one a series of periodic pulses, and the other an arbitrary function. Consider the ensemble obtained by segmenting the arbitrary function at the times of the pulses. By the "average waveform" is meant the function obtained by averaging this ensemble. Obviously, any event that is time-locked to the pulses will be emphasized by this procedure at the expense of events that are not

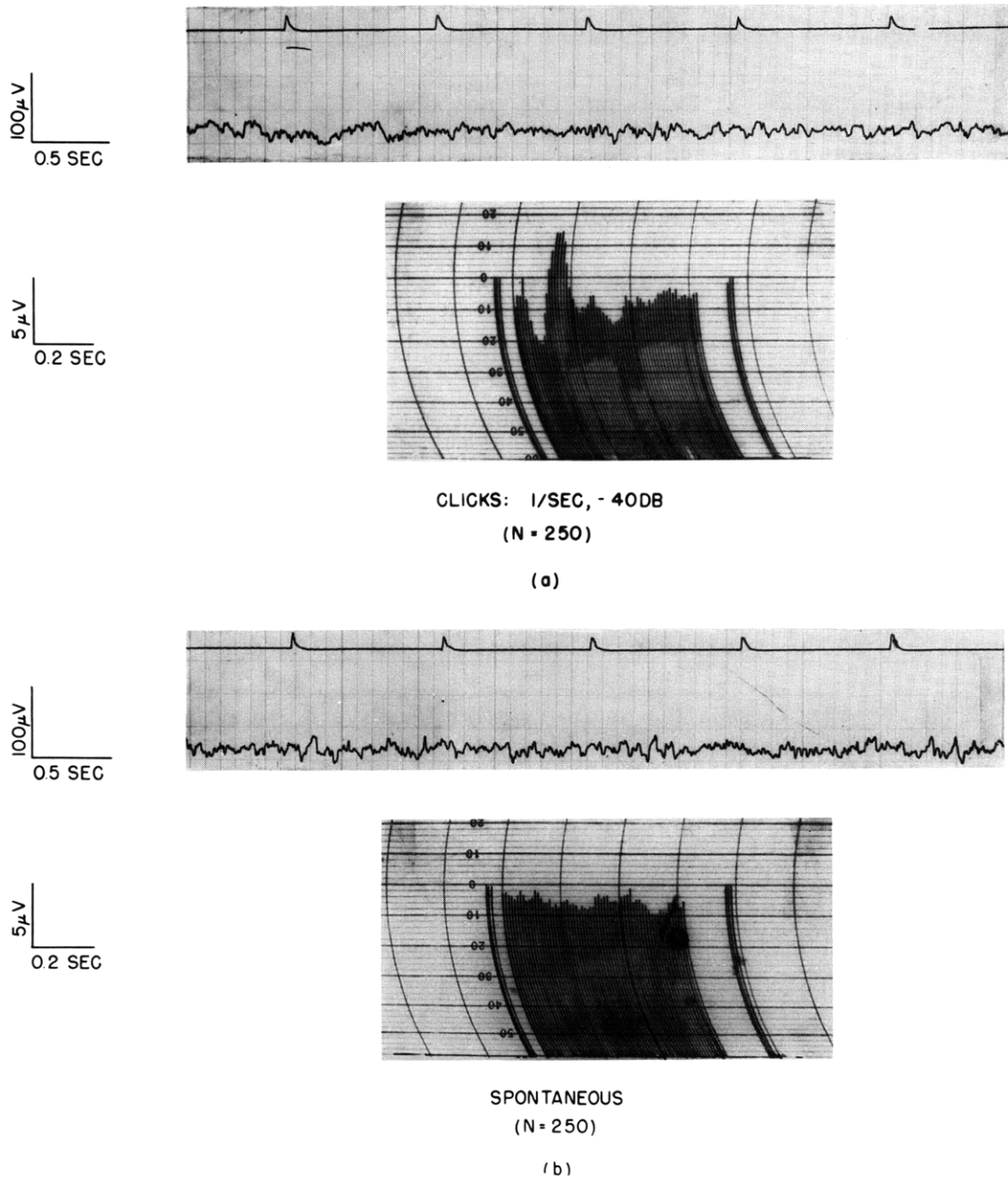


Fig. XVII-1. The upper records of (a) and (b) show ink traces obtained from the vertex with and without clicks, respectively. The pulse channel, recorded simultaneously, indicates in (a) the times of click presentations and in (b) serves as a comparable time reference. Pulse rate, 1/sec; click intensity in (a), -20 db.

The lower records are the average waveforms obtained, by the procedure indicated in the text, from a sample of 250 intervals, of which a few are shown in the ink records directly above. Consecutive lines are separated by 10 msec. The zero potential line is at -6 on the graph. Negativity at the vertex is represented in ink records and average responses by an upward deflection.

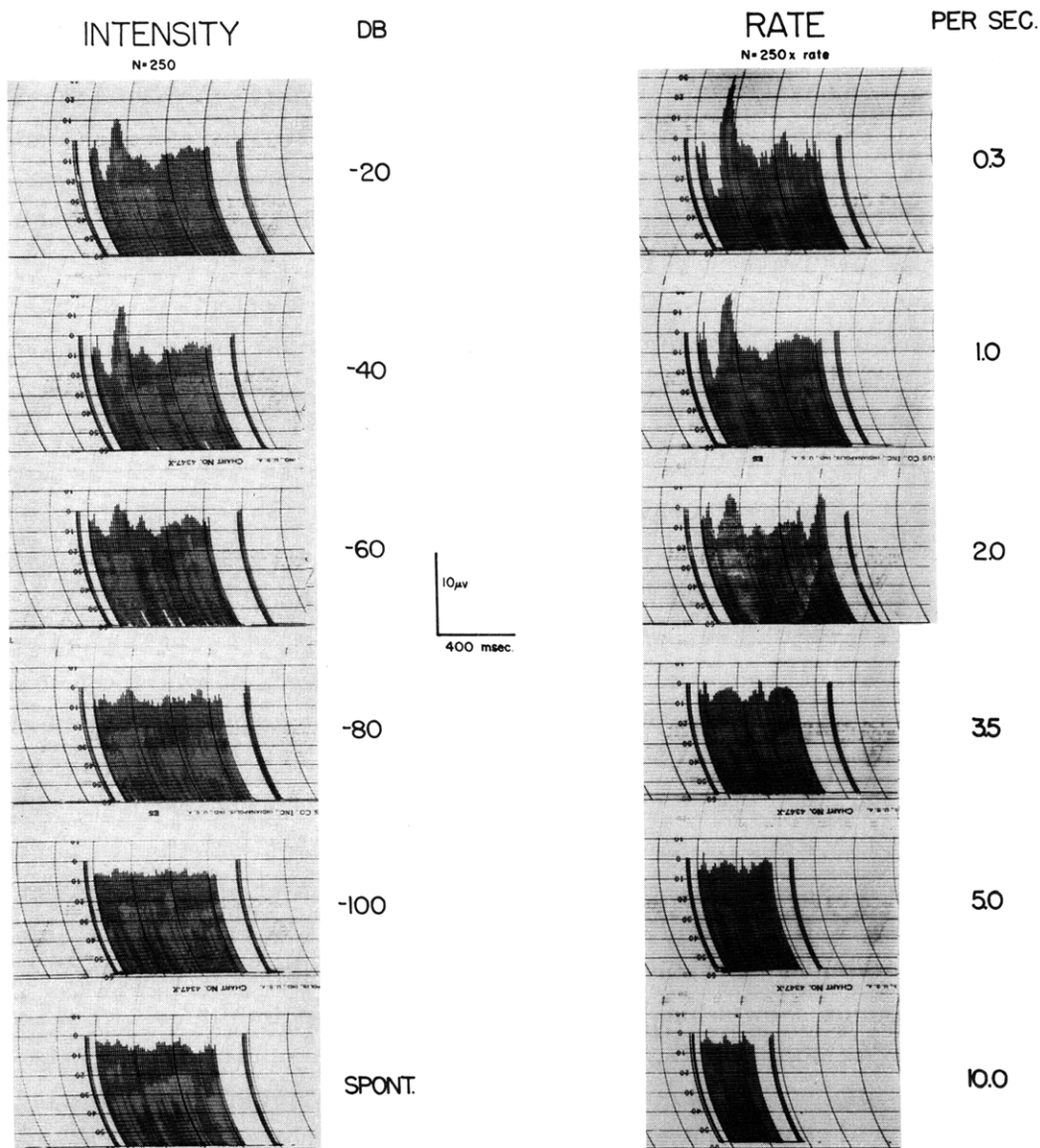


Fig. XVII-2. Left column: Average response to clicks as a function of click intensity. Rate of presentation, 1/sec; sample size, 250 in each case. Successive lines are separated by 10 msec. The zero potential line is at -6 on the graph. Right column: Average response to clicks as a function of click rate. Click intensity -20 db; sample size is given by 250 times the rate, varying from 75 at 0.3/sec to 2500 at 10/sec. All else is the same as for the column on the left. Negativity at the vertex is represented in all graphs by an upward deflection. (H-436).

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correlated with the pulse. This method is ideally suited to the detection of small responses that are ordinarily obscured by the "on-going" activity.

Clicks were presented monaurally to the awake subject. The electrodes were located on the vertex and over the mastoid process behind the unstimulated ear. The subject's eyes were open throughout the experiment. The psychophysical threshold for clicks was determined for both ascending and descending intensities. Clicks were presented at several intensities and rates. In each condition a five-minute sample was recorded.

Figure XVII-1 compares sections of the ink record with the average waveforms obtained from the same data. In Fig. XVII-1a clicks were delivered to the subject at a rate of one per second. In Fig. XVII-1b no clicks were presented. On the basis of the ink records the two cases appear rather similar; in particular, no responses are apparent in Fig. XVII-1a. The average waveforms, however, clearly demonstrate the existence of a response in the one case but not in the other.

Figure XVII-2 shows the effect of intensity and rate on the response, as obtained from one subject. The psychophysical threshold was -90 db. We observe that a response is present at -80 db but not at -100 db; a close correspondence between the physiological and psychophysical thresholds for clicks is thereby demonstrated in this case. The waveform of the response at higher intensities agrees, in general, with the description that Davis (1) gave in 1939. An early negative component at 30-40 msec is followed by a prominent positive peak, and then by a large negative peak (a negative potential is represented by an upward deflection on the graph); this triphasic response is over in about 200 msec and is followed by a slow positive wave that lasts about 300 msec, as reported by Roth, et al. The slow wave itself has a complex structure, as can be seen from the intensity series. Several small peaks occur at consistent latencies in this interval. It should be kept in mind that there is a considerable amount of variability in the latency and form of the response among different subjects.

The rate functions show a marked decrease in response amplitude with increasing rate for all response components, with the exception of the early negative peak. The effect of rate on this peak is strikingly different in that its amplitude is affected relatively little. This suggests that the early peak and the remainder of the response have different origins. We have not yet been able to determine the source of the early peak. Whereas the late response was observed to some degree in all the subjects tested, the early peak was seen clearly in only two cases.

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B. THE PACING OF EEG POTENTIALS OF ALPHA FREQUENCY BY LOW RATES OF REPETITIVE FLASH IN MAN

After the early observations of Bartley and Bishop (1) on the rabbit, many workers described in the experimental animal a series of apparently rhythmic waves that follow the primary cortical response evoked by sensory stimulation. A similar phenomenon has also been noted in the human EEG. The present study in man was designed to determine whether these waves are a part of the train of events set up by the stimulus or are a "rebound phenomenon" of the alpha rhythm that returns after brief suppression by the flash. If the latter is the case, there would not necessarily be any relationship between the phase of the returning rhythm and the specific primary response which is time-locked to the stimulus. If, however, the train of waves is itself a part of the response, it might well be expected to have the instant of each of its recurrent positive and negative phases determined by the flash.

We have examined this phenomenon in normal man by means of the averaging technique described previously (2, 3, 4). Using scalp electrodes, we made recordings simultaneously on an ink-writing oscillograph and on a 7-channel tape recorder, the flash being signaled from the photocell onto one of the channels. Averages were then obtained

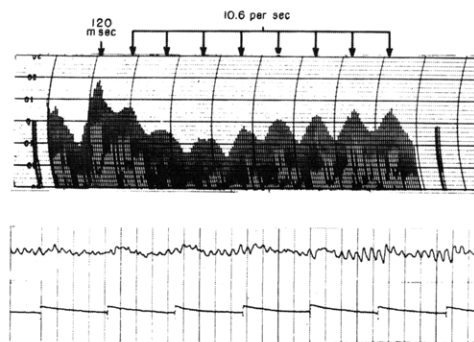


Fig. XVII-3. Averaged response to 70 flashes at a rate of 1.2/sec. Right parieto-occipital recording. Steps of delay, 5 msec.

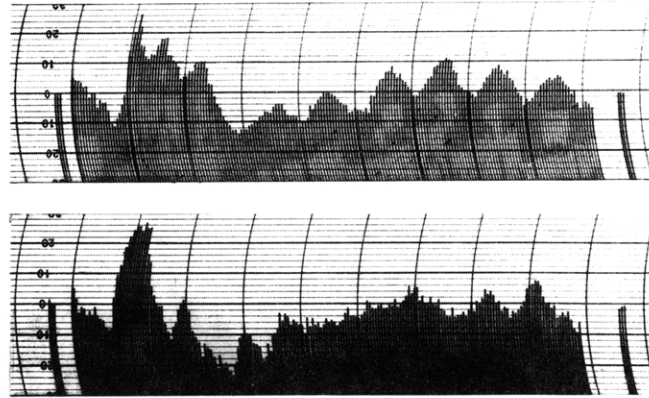


Fig. XVII-4. Averaged responses of two subjects to periodic flashing. Midline parieto-occipital recording. Length of sample, 1 min; flash rate, 1.2/sec; steps of delay, 5 msec.

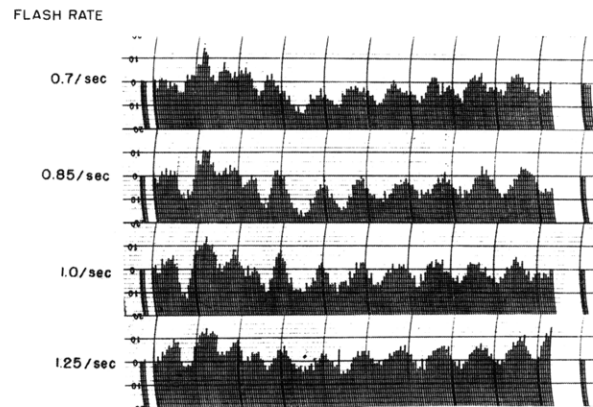


Fig. XVII-5. Averaged responses of one subject for different flash rates. Left parieto-occipital recording. Length of sample, 1 min; steps of delay, 5 msec.

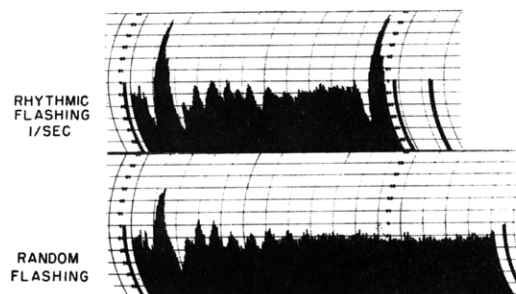


Fig. XVII-6. Averaged responses of one subject to rhythmic and to random flashing. Midline parieto-occipital recording. Length of sample, 3 min; steps of delay, 5 msec.

as the tapes were played back repeatedly.

Figure XVII-3 shows the average of 70 responses obtained from a bipolar recording from parieto-occipital electrodes. The first prominent downward deflection is seen to be maximal at 75 msec, and it is followed by an upward wave, reaching its peak at 120 msec. As the interval from the flash increases, the averaged response of this man's occiput is clearly delineated, and it is seen that the rhythmic discharge is indeed a part of the response, and that the phases of its rhythm are locked in a temporal relationship with the flash.

Among twenty subjects recorded, considerable variation has been found in the form of the after-discharge, as recorded with bipolar linkages. In some individuals it is more rhythmic than in others. Two examples illustrating this variation are shown in Fig. XVII-4.

The next point examined was whether or not this cortical rhythm was a harmonic phenomenon attributable to the fact that we were using a rhythmically repeated flash. Therefore, several different flash-rates of slow repetition rate were used on the same subject and the frequency of the evoked rhythm was measured. Figure XVII-5 shows the responses from one individual at four different flash rates. These responses show that the frequency of the after-discharge is the same for the four rates, and, therefore, it is not a harmonic of the flash rate; also the rhythm at all rates is phase-locked with the flash. Another check was made by using an arrhythmically recurring flash. A circuit was, therefore, constructed to trigger the stroboscope in a random manner and the same subjects were again recorded with the source of periodicity removed. The time intervals between successive flashes ranged from 800 msec to 2 sec. The upper section of Fig. XVII-6 shows the response of an individual to rhythmic stimulation at 1 flash per second, and the lower section shows the response of the same man to random flashing. The rhythmic after-discharge is essentially the same in each case and is evidently not a mere harmonic of a periodic stimulus. These records were averaged over a 3-minute sample, and in the upper trace the periodic primary response is on the right, time-locked, by the interval between flashes, to the one on the left. In the lower trace, since the flash was random, no constant time relationship exists between successive primary responses; hence they are represented only once.

[This report was presented as a paper at the Annual Meeting of the American Electroencephalographic Society, Atlantic City, New Jersey, June 1956.]

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C. CORRELATORS FOR THE INVESTIGATION OF NEUROELECTRIC ACTIVITY

Because of the increasing use of autocorrelation and crosscorrelation techniques as means for investigating and interpreting electrical activity in biological systems, a study was undertaken of the various schemes for computing the correlation coefficients in order to determine which method, in terms of speed, economy, versatility, and reliability, should be used as the basis for the construction of an improved correlator.

At present, the Communications Biophysics group utilizes the analog correlator that is described in detail in reference 1. The correlation function to be calculated is defined by the integral

$$\phi_{12}(\tau) = \frac{1}{T} \int_0^T f_1(t) f_2(t+\tau) dt \quad (1)$$

which in the limit as T becomes infinite tends toward the usual definition of the correlation function on a time-average basis. The operations that must be performed to carry out the mathematical operation defined by Eq. 1 are: (a) delay of $f_2(t)$ by a fixed time τ_1 , (b) continuous formation of the product of $f_1(t)$ with the delayed signal $f_2(t + \tau_1)$, (c) integration of the continuous product over the finite time interval $0 < t < T$, and (d) division by T to obtain the value of the correlation function $\phi_{12}(\tau)$ at $\tau = \tau_1$. The correlation function is then built up by performing the calculation of Eq. 1 at a sequence of values of τ . A correlation function consisting of 200 points is common in biological work.

The definition of the correlation function on the time-average basis is meaningful only if the statistics of the time signals $f(t)$ are approximately time-invariant over the observation time T . In general, T should be chosen to be at least four or five times the maximum range of the correlation variable τ in order to reduce the errors arising from truncation.

If instead of an analog method a digital scheme is used, the correlation function becomes

$$\phi_{12}(\tau) = \frac{1}{N} \sum_{n=1}^N f_1(t_n) f_2(t_n + \tau) \quad (2)$$

where the sequence of operations is the same as in the analog case, except that the

operation of integration is replaced by summation. In the digital method the signals must first be sampled at discrete, evenly spaced times, t_1 , t_2 , t_3 , and so on, and then the value of the signal at these instants quantized to a digital number in binary form. The sequence of operations a, b, c, d are then performed on the digital numbers. In order to reduce the error in the correlation resulting from a finite sampling size, the number of samples used in the calculation is usually chosen to be greater than 1000. The effect of sample size on the correlation is discussed in reference 3.

Several correlators have been built (1, 2, 4, 5) that utilize a variety of schemes that range from pure analog to pure digital forms. The scheme or method chosen for calculation depends very heavily upon the form of the input data, the desired form of the output data, the time scale of the problem, and factors such as the economy, versatility, and reliability of the equipment with which the computation is to be realized. Because of the large amount of experimental data that need to be processed, the emphasis is on the reduction of total computation time to as low a figure as is practicable within the aforementioned constraints.

This problem logically falls into two parts: first, choosing the amount of data to be correlated, and the number and time separation of the computed correlation values; and second, designing a correlator which will perform the single correlation computation as rapidly as possible. Solution of the first part of the problem resides in the intelligent use of the correlator, while that of the second part is solely a function of its design. This report is concerned primarily with the second part of the problem.

Since much information was available on the present analog correlator design that is in use, the approach to the problem was to compare computation of correlograms by analog techniques similar to those employed in the present computer with computation by digital techniques. Combination or hybrid systems that use both analog and digital parts were also studied.

A fundamental limitation exists on computing speed because of the bandwidth limitation of approximately 10 kc on the input signal. This limitation was caused, primarily, by the use of a magnetic tape recorder that utilizes frequency modulation for the data storage. Recognizing this limitation and using a set of operating specifications based on the current and projective use of the present correlator, we outlined with sufficient detail an analog correlator.

The study showed that a digital correlator working at a maximum sampling rate of 50,000 samples per second could perform at about the same level (speed, versatility, and accuracy) as its analog counterpart. The next question to be answered was "At what cost in complexity could such a digital system be realized?" The answer to this question rests on the number of binary digits that is necessary to represent the quantized input data to the correlator.

Widrow (6) showed that the amplitude may be quantized extremely coarsely at the

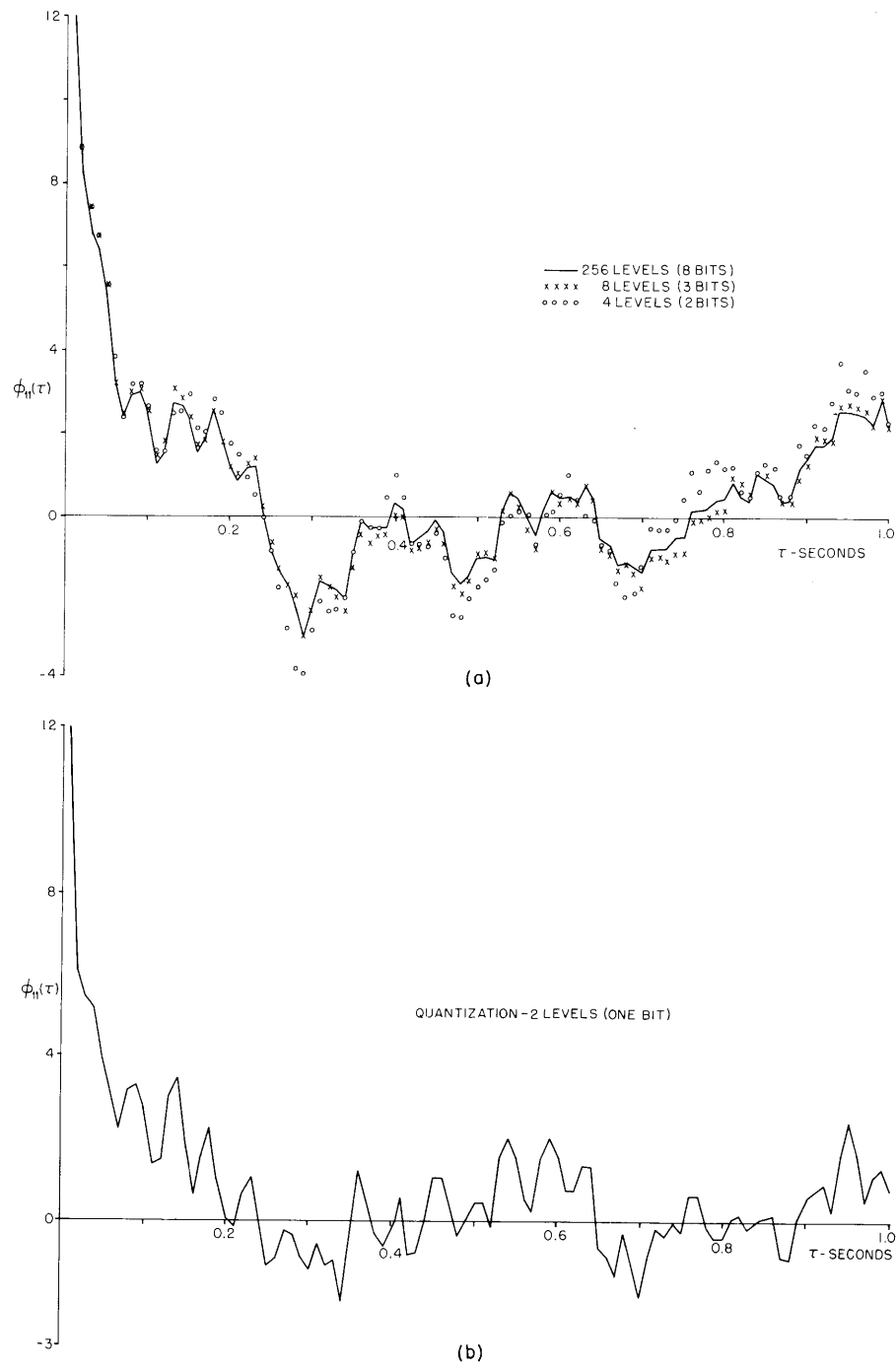


Fig. XVII-7. Effect of quantization coarseness on the autocorrelation function of an electroencephalogram (650 sample pairs used for the correlation).

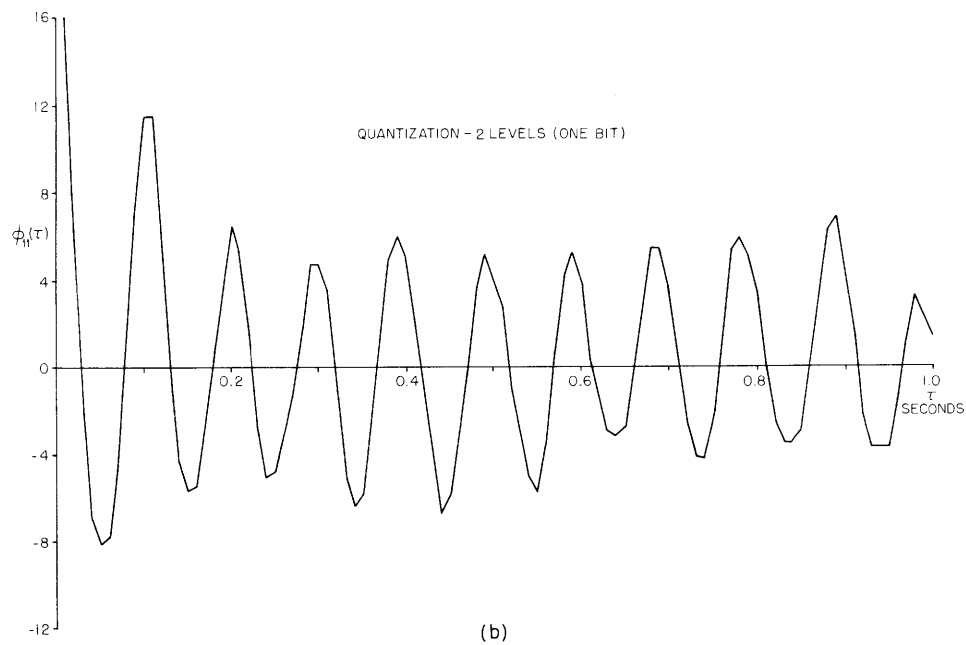
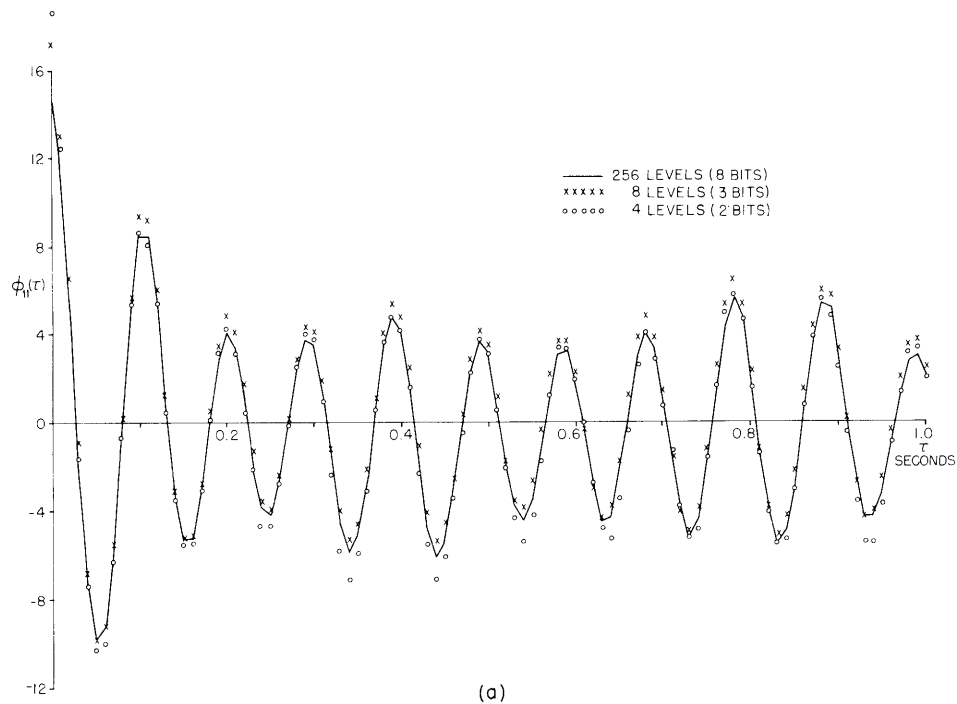


Fig. XVII-8. Effect of quantization coarseness on the autocorrelation function of another electroencephalogram (650 sample pairs used for the correlation). This correlation represents as much regularity as is usually found in similar tracings (see Fig. XIX-3, Quarterly Progress Report, Jan. 15, 1956, p. 142).

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sampling instants and still retain sufficient information to give a good correlation measurement. The theory for correlation is based on gaussian distributions for the data. For the investigated biological signals, we found that the actual distributions could be closely approximated by gaussian distributions.

A series of digital correlations was carried out on the Whirlwind computer to observe the effects of coarse quantization on the resultant correlation function. The results of several of these runs are shown in Fig. XVII-7 and Fig. XVII-8. These correlations were carried out on two sets of data and represent, approximately, the extremes in the correlogram characteristics. The results are rather startling when it is realized that only 650 sample pairs were used in calculating each correlation point. From these results, we conclude that three-bit quantization gives a sufficiently accurate correlation. Two-bit quantization introduces some error in amplitude but not in the over-all correlation characteristic. It is felt that no conclusions can be drawn on the basis of the present data but that a larger sample size should be tried. Theory shows that two-bit quantization, with a quantizing box size of $q = 1.56\sigma$, should be accurate to 5 per cent for all normalized correlation coefficients less than 0.83. In all cases the frequency information in the correlation function appeared to be unaffected.

The surprising results of the one-bit quantization are of some value in pointing out the possibility of a real time correlator of moderate simplicity. A Master's thesis is being initiated for the construction and investigation of a one-bit correlator that will be capable of continuous presentation of a correlation function of 25 points.

On the basis of the quantization studies and additional studies of the effects of saturation tendencies in the quantizer, physical designs for several digital machines can be carried out. These designs can then be compared, as to complexity, economy, reliability, and versatility, with the equivalent analog machines. Then a decision can be made about the configuration of a proposed improved correlator.

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