XXVII. NEUROLOGY[*]

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RESEARCH OBJECTIVES

Physiology has had, first, biochemistry and, more recently, biophysics separated from it; these new disciplines deal with chemical and physical mechanisms within the biological organism. "Systems biology," the study of the organizational and control properties of these mechanisms, now constitutes the core of physiology. Our group, composed of medical scientists, engineers, and physiologists, is applying concepts and methods of communication and control theory to the analysis of neurological and biological systems.

Examples of design properties in biological systems that have been investigated here are the discontinuous or sampled-data characteristics of the human hand- and eye-tracking servomechanisms. Nonlinear scale-compression operators in the pupil and lens systems permit them to exhibit stability in one domain, and instability with complex limit cycles in another. Even-error signals have been found to be employed in the accommodation control system. The relationship of system behavior to underlying mechanisms has been explored by means of neurophysiological experiments on cats and crayfish, mechanical analysis of iris kinematics, pharmacological dissection, and by evaluating disease syndromes as naturally occurring interferences. Interaction between systems has been studied, in particular in the multiple-control system for eye movement. Certain inputs add algebraically; for others complete control shifts from one input to another. The ability to inject several different inputs may permit dissection and analysis of a system into component transfer functions.

As in any field of science, techniques must be developed pari passu with scientific advances. Our on-line digital computer provides function generation, real-time analysis, executive control of experiments, data editing, and display of results. It has further been used as part of a hybrid digital-analog simulation system. We have also established remote laboratories in three Boston hospitals, Massachusetts General Hospital, Massachusetts Eye and Ear Infirmary, and Boston University Medical Center where on-line digital-computer experiments are carried out with telephone lines for analog-data transmission. An adaptive-filter pattern-recognition scheme for electrocardiographic diagnosis is being reformulated as an on-line system in which we utilize both our own G.E. 225 computer and the IBM 7094 computer of the Computation Center, M.I.T.

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A. NONLINEAR OPERATOR IN THE PUPIL SYSTEM

"Biological adaptation" may be considered the acceptance of a new steady-state input level as the desired reference and the subsequent rearrangement of the feedback loop. This should be distinguished from both "input adaptation" and "task adaptation." The precognitive input predictor, which enables the hand- and eye-tracking systems to anticipate repetitive input signals and thus to eliminate delays in response, is an example of input adaptation. The hand's possessing an adaptive controller with the ability to compensate for a wide variety of loads and still perform skilled movements is a prime example of task adaptation.

An outstanding example of biological adaptation is found in the retina, which responds similarly, as seen by measurement of pupillary constriction to a step increase of 10 per cent in light intensity over a 6 $\log_{10}$ change in initial baseline light intensity. In Fig. XXVII-1 the left-hand block represents this division by the average light intensity, $\bar{I}$. The middle block represents a general operator for the remainder of the pupil system except for the right-hand block. This is the $\bar{A}$-multiplier and indicates multiplication of the penultimate signal by average area, $\bar{A}$, to yield the actual output, A or area.

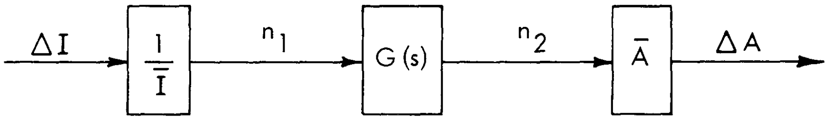

Fig. XXVII-1. Block diagram of the $\bar{A}$-multiplier.

In early linearization of the pupil signal the incremental dimensionless open-loop gain was defined as

$$G(s) = \frac{F_i}{F_e} = \frac{\Delta A \cdot \bar{I}}{\Delta I \cdot \bar{A}} = \frac{\Delta A/\bar{A}}{\Delta I/\bar{I}} \tag{1}$$

$$g(s) = \frac{\Delta A}{\Delta I} = \frac{I}{\bar{I}} \cdot G(s) \cdot \bar{A}. \tag{2}$$

Here, F_i is flux change controlled by iris response, F_e is flux change controlled by external intensity control, ΔI and ΔA are incremental changes in light intensity and in area, respectively, G(s) is incremental gain, and g(s) is incremental gain with the DC levels $\bar{A}$ and $\bar{I}$ ignored. As studies of nonlinear behavior of the pupil progressed, it was noted that the incremental gain definition was a good predictor, even in domains in which the underlying assumptions were no longer valid. It then became apparent that two nonlinearities in the pupil system compensated for range changes to normalize input and response. The first of these, the division by $\overline{I}$ and its impressive resultant scale compression, has been known experimentally for a long time.

The $\overline{A}$-multiplier does not seem to have been noted by previous workers. Although it first came to our attention when DC changes in $\overline{A}$ occurred secondarily to large changes in range of $\overline{I}$, this, of course, provides only a somewhat circular argument.

A more direct experimental approach is to change $\overline{A}$ by using another stimulus such as the near response; the pupil constricts synkinetically with lens accommodation to focus on a near object. Figure XXVII-2 shows the results of such an experiment, in which it is possible to see the constriction of the pupil with voluntary accommodation and the redilatation of the pupil with relaxation of accommodation. It is clear that identical light inputs (the pupil is receiving open-loop stimulation) cause area changes of very different sizes which are directly proportional to the actual DC level of area. Figure XXVII-3, a graph of ΔA as a function of $\overline{A}$ for several such responses, bears this out.

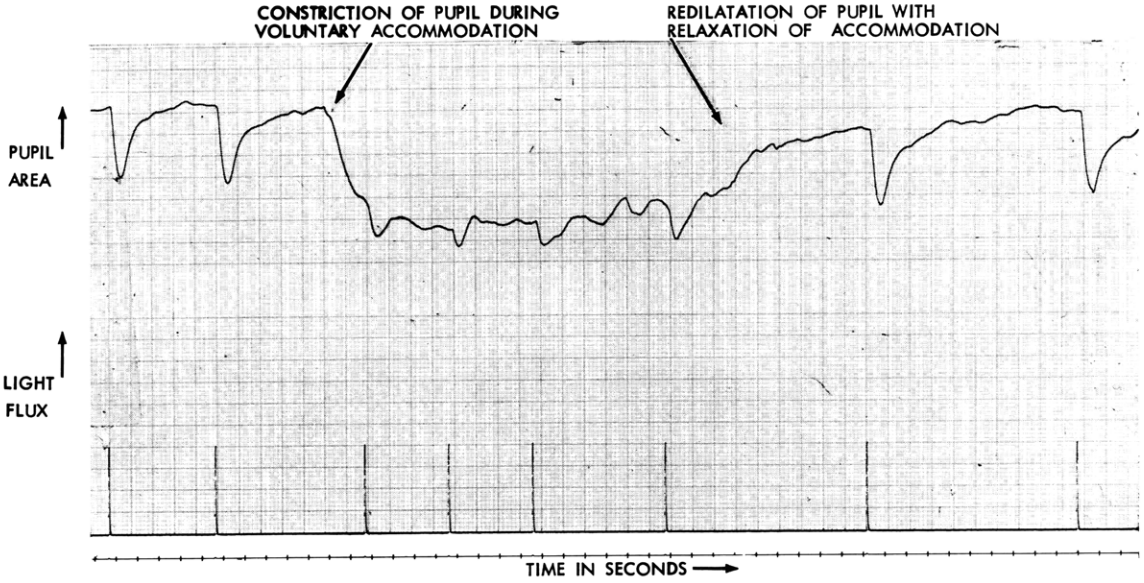

Fig. XXVII-2. Constriction and redilatation of the pupil during accommodation.

The locus of this $\overline{A}$-multiplier is of interest. We know that changes of $\overline{A}$ that are secondary to light-intensity, accommodation or noise changes produce the same effect. This application of the "multi-input analysis" method suggests that only those portions of the pupil system that are common to all three inputs can serve as the location of the $\overline{A}$-multiplier, that is, either the Edinger-Westphal nucleus or the motor nerve and

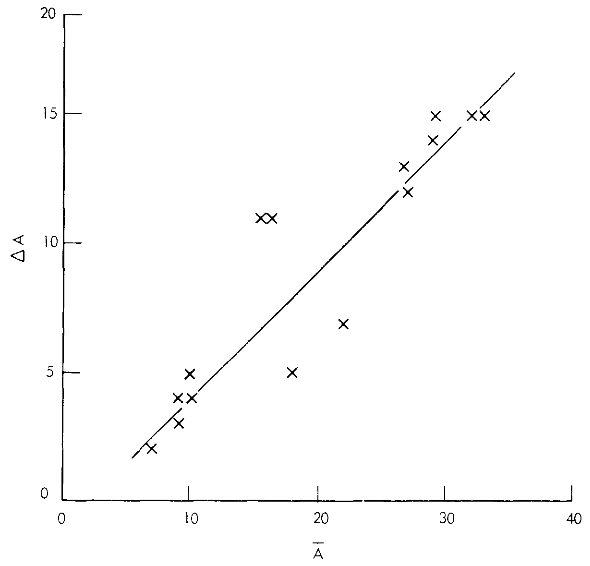

Fig. XXVII-3. Change in area as a function of $\overline{A}$.

neuromuscular apparatus elements.

We have used pharmacological methods to further dissect the system in preliminary experiments. If local drugs are placed on the cornea to change pupil area, then the $\overline{A}$-multiplier continues to have the same action. Under these conditions, since the iris has no proprioceptive feedback mechanisms and visual feedback is eliminated with the optical open-loop technique, the central nervous system and the motor neuron and motor nerves cannot be involved. We are left with the neuromuscular apparatus as the locus of the $\overline{A}$-multiplier. It may be that the sphincter muscle is more excitable when stretched, or that the active contractile components contract more vigorously when stretched, or that series elasticity (with a hard-spring nonlinearity) permits more of the contractile force to express itself as dimension change when stretched.

A latent nonlinearity that acts to "linearize" the pupil system over a wide range of output levels has been defined and discussed. By using the multi-input analysis technique, together with open-loop and pharmacological "dissection" of the pupil system, this nonlinearity has been localized to the effector organ, the iris muscle.

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B. DOUBLE OSCILLATIONS IN THE PUPIL SERVOMECHANISM

The interesting phenomenon of two simultaneous pupil oscillations, each with its own gain, phase lag, and frequency, is shown in Fig. XXVII-4. Such oscillations were first noticed during environmental clamping of the pupil servomechanism.[1] The pupil-area curve of Fig. XXVII-4 can be approximated by Eq. 1. The phase-plane plot of Eq. 1 is shown in Fig. XXVII-5.

$$p(t) = 3.5 \sin 2\pi(0.183)\, t + \sin 2\pi(1.28)\, t \qquad (1)$$

The oscillations of Fig. XXVII-4 were achieved by inserting a "clamping box" in the pupil servomechanism loop. The "clamping box" provided adjustment of gain and phase delay. The phase delay of the "clamping box," however, is a nonlinear function of frequency.

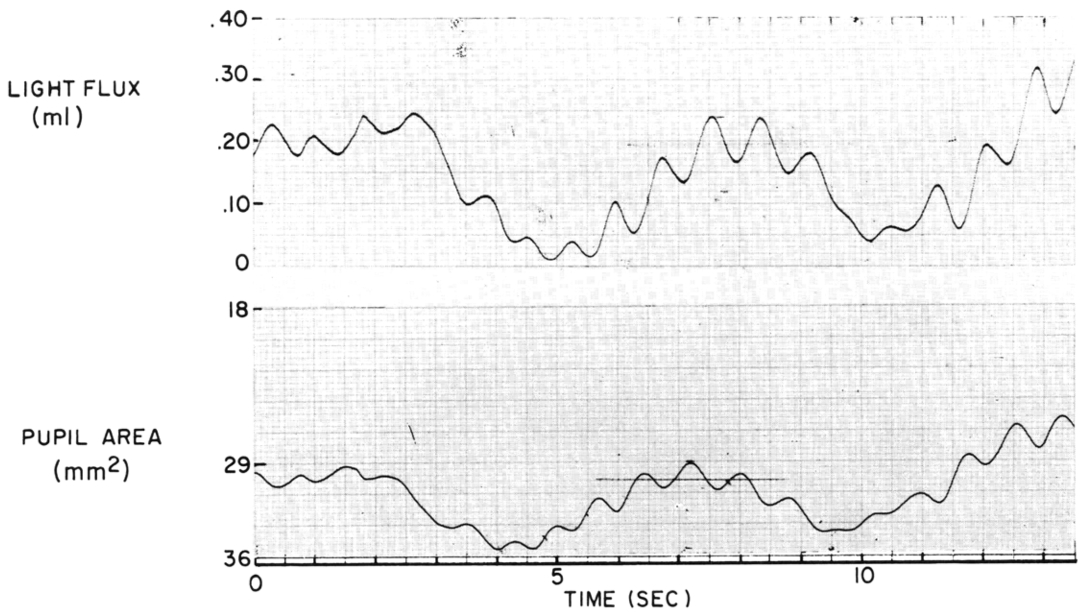

Fig. XXVII-4. Double oscillations of the pupil servomechanism.

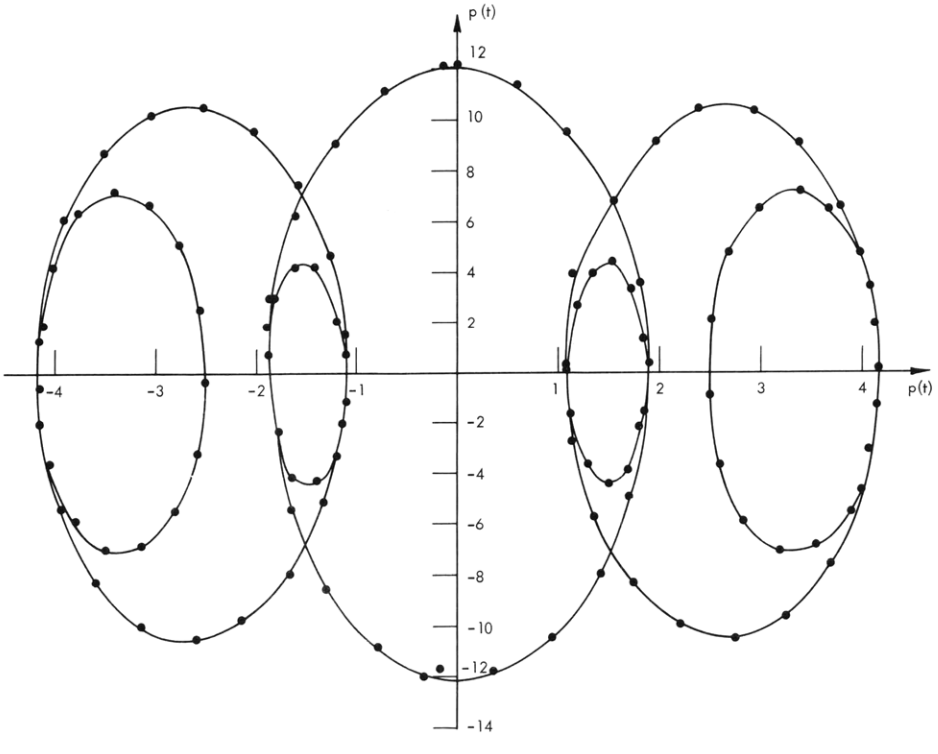

Fig. XXVII-5. Phase-plane plot of Eq. 1.

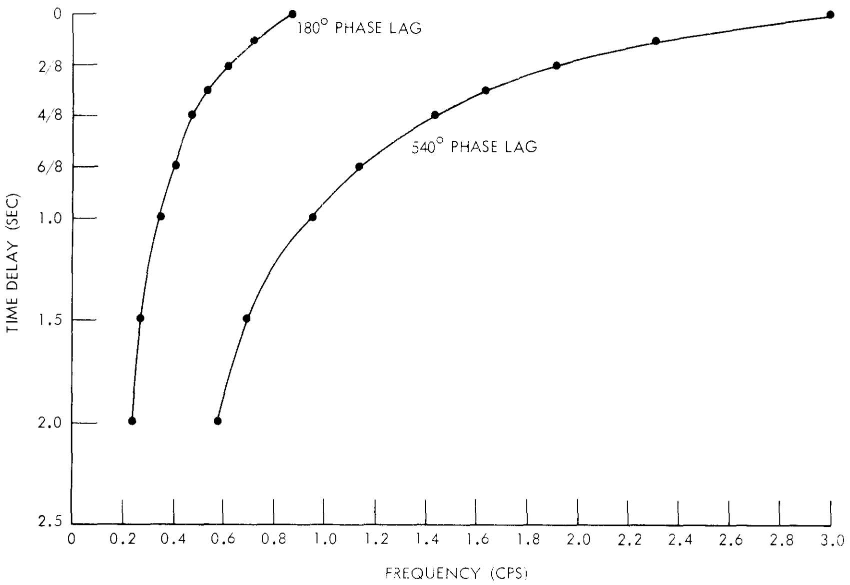

Fig. XXVII-6. Predicted frequencies of double oscillations.

When the "clamping box" is composed of an amplifier and a delay line, arbitrary gain and phase as a linear function of frequency can be induced.[2] By using the phase response of the pupil servomechanism, the additional phase delay required to produce a total delay of 180° and 540° can be calculated. Thus the frequencies of oscillation as a function of time delay can be predicted. These predictions are shown in Fig. XXVII-6 for 180° and 540°.

Experiments are under way to see whether or not sustained double oscillations occur at frequencies that are comparable with those predicted in Fig. XXVII-6. One difficulty still remaining in the experimental procedure is the lack of control over mean pupil area. Once the pupil drifts into saturation, either fully opened or fully closed, the oscillations cease.

D. U. Wilde, L. Stark

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1. L. Stark, Environmental clamping of biological systems: Pupil servomechanism, J. Opt. Soc. Am. 52, 925-930 (1962).

2. The G.E. 225 computer, programmed and operated by Allen A. Sandberg, is used as the delay line of variable delays.

C. ACCOMMODATION TRACKING

In a previous report[1] experiments were described which were designed to elucidate the nature of the error signal on which the accommodative system operates.

We have found that control of extraneous clues is the one most important factor in determining an experimental situation in which the accommodative system makes approximately 50 per cent errors.

An attempt was made to eliminate all clues in the following manner: Horizontal target movement was minimized by use of a horizontal line target and a variable diaphragm. Vertical target movement was minimized by control of head position, precise initial alignment of the target by means of a plastic reference grid, and matching the symmetry of blur in extreme positions. At times difference in size of blur at the near and far positions could be eliminated by symmetrically enlarging the step. The subject wore a set of headphones that produced a relatively loud sound at 360 cps to mask any auditory clues made by the movement of the target.

1. Results

A series of experiments was run in which the target remained in position until focus was accomplished. Subject A showed initial tracking errors of 41 per cent and 50 per cent in two trials of approximately 100 stimuli under white-light illumination. In Fig. XXVII-7 the percentage of initial errors in successive sets of 10 trials is shown. It can be seen that the average error is approximately 50 per cent, and that no trends or learning occurred.

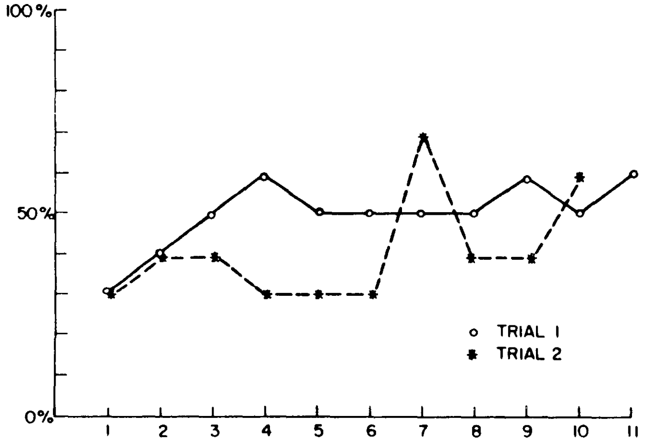

Fig. XXVII-7.
Percentage of erroneous initial tracking attempts (ordinate) in successive 10 trials vs sequence of sets of 10 trials (abscissa).

To confirm the randomness of the response system, the number of intervals between successive failures was analyzed. Figure XXVII-8 shows these intervals as a distribution function with a logarithmic ordinate scale. By assuming that the occurrence of correct initial response is random, the probability of getting n successive correct initial responses is given by

$$P_n = \left(\frac{1}{2}\right)^n. \tag{1}$$

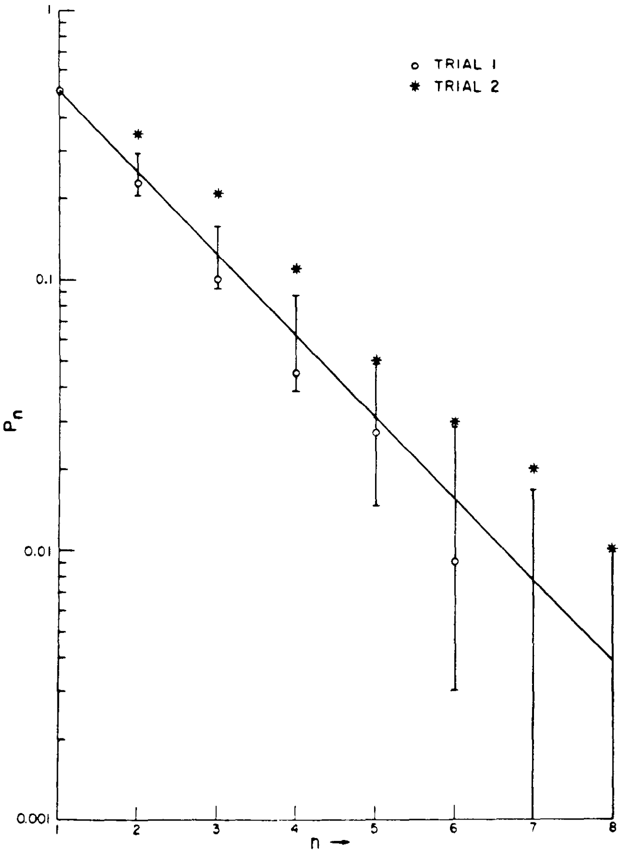

Fig. XXVII-8. Probability of getting n successive correct responses (P_n) versus n. Straight line is predicted from the theoretical equation (1).

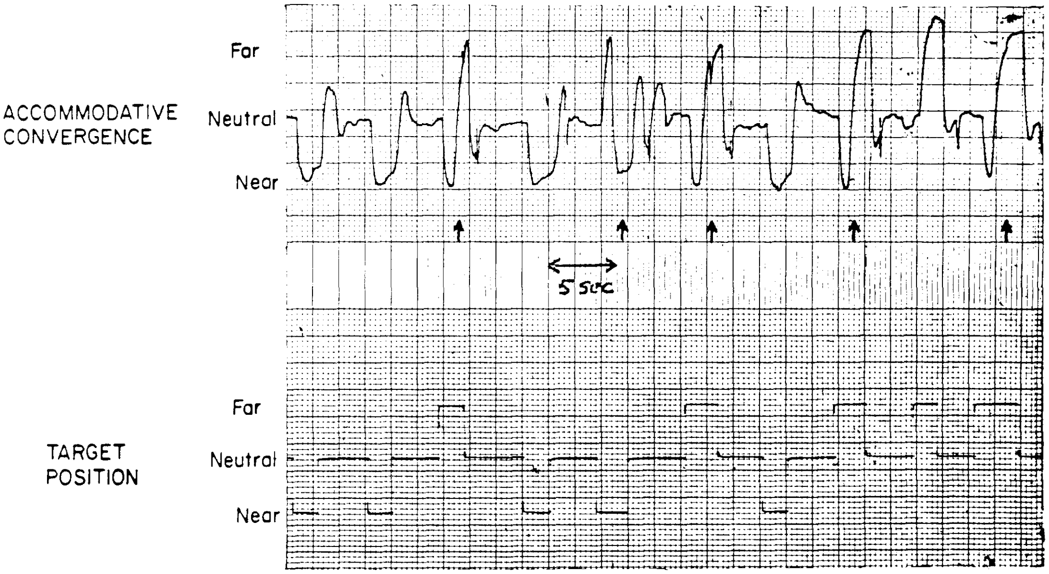

Fig. XXVII-9. Ten responses with 5 initial errors from a typical experiment.

Therefore, if n = 1, $P_n = \frac{1}{2}$ or 50 per cent. If n = 4, $P_n = \frac{1}{16}$ or 6.25 per cent. This means that the chances of getting 4 successive correct initial responses are 16 to 1. Figure XXVII-8 illustrates the theoretical straight line resulting from Eq. 1. The vertical bars represent a standard deviation of ±1. The experimental data closely follow the theoretical line, further illustrating that the errors of initial tracking follow a chance or random pattern. Figure XXVII-9 shows 10 responses with 5 mistakes taken from a typical experiment. The subject was aware of all erroneous responses, as well as of oscillations.

When the target was illuminated with red light, subject A showed a similar frequency of initial errors. Although two other subjects showed clear responses to all stimuli, they made no initial errors, thereby indicating their inability to eliminate all perceptual clues.

Many trials on each subject emphasized and re-emphasized the difficulty involved in eliminating all perceptual clues. Of three subjects, subject A was the only one for which it was possible to eliminate all perceptual clues, and even for him it was not possible in all experiments.

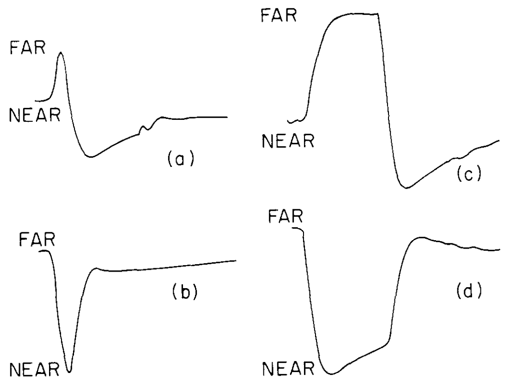

Fig. XXVII-10.

(a) and (b) Averaged responses to pulse stimuli. (c) and (d) Step stimuli. Note the difference in response shape and delay time depending on direction. Near-to-far delay time, 0.34 sec; far-to-near delay time, 0.21 sec.

The delay time or latent period between change in target position and vergence movement was studied by averaging 20 responses by means of a digital computer. Subject A was presented with 20 step stimuli (target allowed to come into focus) and 20 pulse stimuli (200-msec presentation). Figure XXVII-10 illustrates these average responses, including the delay times.

2. Discussion

If one were to consider the accommodative system as an automatic control system, the crux of this study would seem to revolve around the characteristics of the information flow between retinal blur on the one hand and brain, ciliary muscle, and medial recti on the other hand. It is assumed that the brain, in some manner, compares the characteristics of a given retinal image with those of a well-focused retinal image, and any discrepancy is registered as an error signal. The question that this study poses is whether the signal flow of the accommodative system, stripped of its connections with other clue systems, contains information about the magnitude and direction of the error (an odd-error signal) or only about the magnitude of the error (an even-error signal).

In studying accommodation, it was assumed that fluctuations in accommodation were faithfully reflected by changes in vergence. Experimental and clinical studies regarding the linearity and constancy of this AC-to-A ratio (accommodative convergence to accommodation ratio) would appear to support this assumption.[2-5] Nonaccommodative vergence movements such as fusional vergence were eliminated by use of a monocular viewing system.

The results of the study stress the importance of eliminating all extraneous clues by controlling the following factors:

(a) learning (by use of random-target presentation);
(b) horizontal and vertical target movement;
(c) auditory clues;
(d) blur symmetry and size in both near and far positions; and
(e) illumination uniformity and size clues.

If these conditions are met, the initial-tracking-direction component of the accommodative system seems to operate on a trial-and-error basis and thus produces approximately 50 per cent errors in initial judgment.

From reanalyzing published data, as well as from our own experiments, we conclude that it is easy to attain 100 per cent correct accommodative responses. It is only through painstaking attention to every detail of the stimulus that all clues may be eliminated and the randomness of the system appreciated. Here, too, the experience and skill of the subject are essential in isolating and eliminating each extraneous clue.

A. Troelstra, B. L. Zuber, D. Miller, L. Stark

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D. EXPERIMENTS ON ERROR AS A FUNCTION OF RESPONSE TIME IN HORIZONTAL EYE MOVEMENTS

Previous studies of eye movements have suggested that further investigation be carried out regarding the error related to response time in tracking a horizontally moving target.[1-3] In the present experiments we used square-wave frequencies, primarily of 0.4 cps and 0.5 cps, since these were found to give optimum prediction, as well as delayed responses.[1] The target moved through a constant angle of ±5 degrees. Prediction of a target's movement usually results in error, as shown in Fig. XXVII-11a; a delay of 80 msec or more usually produces little, if any, error. Figure XXVII-11b shows the error plotted as a function of response time for a typical experiment. A χ^2 analysis showed that the frequency of the occurrence of error greater than 5 per cent is significantly higher in prediction than in delay, $\chi^2 = 40.08$, $p < 0.001$. This corroborates earlier results,[3] for which $\chi^2 = 21.9$, $p < 0.001$.

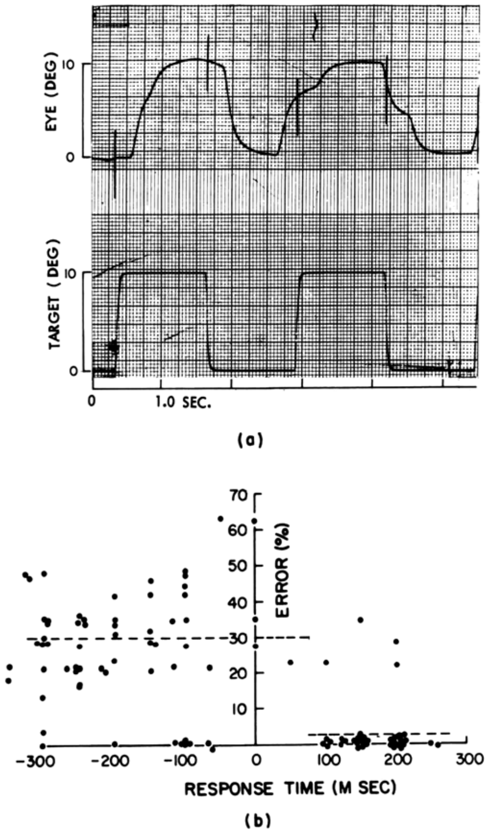

Fig. XXVII-11.

(a) Typical responses to target movement showing both delay and prediction.
(b) Plot of percentage error as a function of response time for a typical experiment (square wave, 0.4 cps).

In order to determine the time at which the subject no longer depends on remembered target position (with resultant error) and is able to apply information obtained after the target's movement to correct his responses, we were led to study the delayed responses between 0 msec and 130 msec, the minimum response time. Thus, we employed a new method, one that yielded fewer predictive and more delayed responses than the previous technique.[1-3] This second method, used in a study of motor coordination,[4] presented a predictable target for a short period of time which alternated with an unpredictable target (a summation of three square waves) for a short period of time. With this method, more time delays were observed.

The results showed that median error of 15-25 per cent falls off to zero error after an 80-msec delay, indicating that information is unable to be correctly assimilated in a shorter period of time. Figure XXVII-12 shows the median and interquartile range of four experiments. (At 180 msec of response time very few points were available for determining the mean and interquartile range, which may account for the fact that it is not in agreement with the rest of the data.) A χ^2 analysis showed that the frequency of error greater than 5 per cent between 0 msec and 80 msec after the movement of the target was higher than after an 80-msec delay ($\chi^2 = 17.1$, $p < 0.001$). This is a shorter time delay than found earlier[3] in which χ^2 analysis of the difference of responses greater than 5 per cent error between those occurring earlier than 130 msec and after that time was equal to 7.08, $p < 0.001$. The present experiment with this same time delay showed $\chi^2 = 5.2$, $p < 0.05$ but >0.02. Thus there is a suggestion that some modification of responses may take place within the earlier proposed minimum response time.

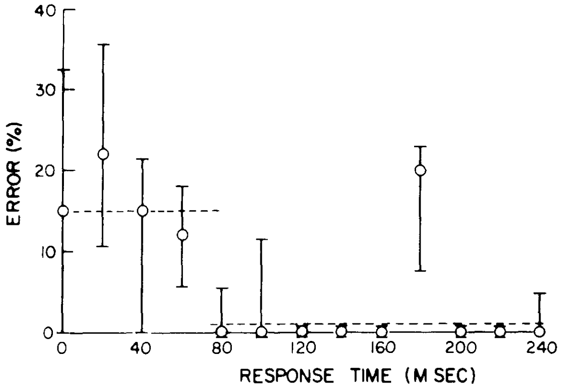

Fig. XXVII-12. Median and interquartile range of percentage error as a function of response time for 4 experiments. Only delayed responses are shown (square waves, 0.4 cps and 0.5 cps).

We noted that even with this second method, relatively few responses occurred between 0 msec and 100 msec (Fig. XXVII-13). This seems to be in agreement with an

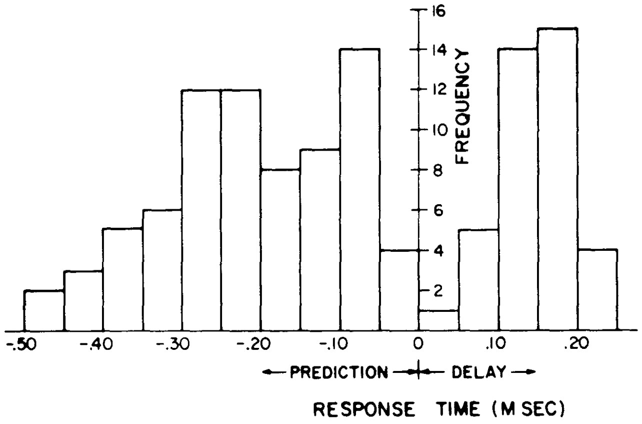

Fig. XXVII-13. Histogram of the frequency of occurrence of eye-movement response times for target motions (square wave, 0.4 cps).

earlier eye-movement experiment[1] for which histograms of response times at similar frequencies also show fewer responses in that time span. This phenomenon may indicate an inhibition of response in that period of time for possible correction; for those responses that do occur, error usually results. Further investigation of these findings is planned.

Anne Horrocks, L. Stark

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E. OPTOKINETIC NYSTAGMUS IN MAN: THE STEP EXPERIMENT

This experiment is a continuation of work reported in Quarterly Progress Reports No. 70 (pages 357-359) and No. 71 (pages 286-290). The apparatus used in this experiment is shown in Fig. XXVII-14. The subject looks through a telescope at a visual field reflected from a galvanometer mirror. Eye-movement recordings are made from the left eye, which is also used for calibration. The experimenter controls the angle of the mirror so that the subject sees either stimulus A or stimulus B through the lenses

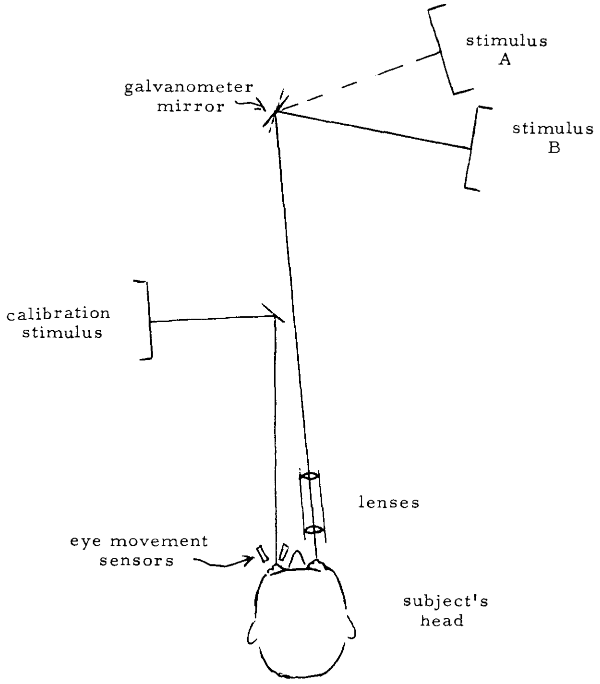


Fig. XXVII-14. Experimental apparatus.

forming the telescope. This apparatus can also be used for velocity feedback experiments, in which the eye position drives the galvanometer. In this case, the slow phase velocity will add a velocity component to the field movement.

In the step experiment, stimulus A consisted of a uniformly moving, vertically striped field. This field, as seen by the subject through the lenses, is 30° in diameter. Stimulus B was a dark, featureless space. The experiment consisted of applying a DC step to the galvanometer, which resulted in rapidly switching from stimulus B to A, or stimulus A to B. From unpublished experiments performed in this laboratory we have found that the optokinetic nystagmus response is binocular and identical in each eye, whether the stimulus is uniocular or binocular. Monitoring the left eye, which during the course of the experiment sees nothing except a dark blank field, is equivalent to monitoring the right eye, which sees the striped field. Figure XXVII-15 shows some responses to variable-width pulses applied to the galvanometer. The vertical line on the records shows the appearance of the stripes. A few responses are shown to the stripes that are being turned off (off step). Both on and off steps are random in time. In this experiment, there is no fixation point. The subject is directed to maintain a forward gaze on the center of the field. In this situation, the slight drift seen in the beginning of the record is normal.

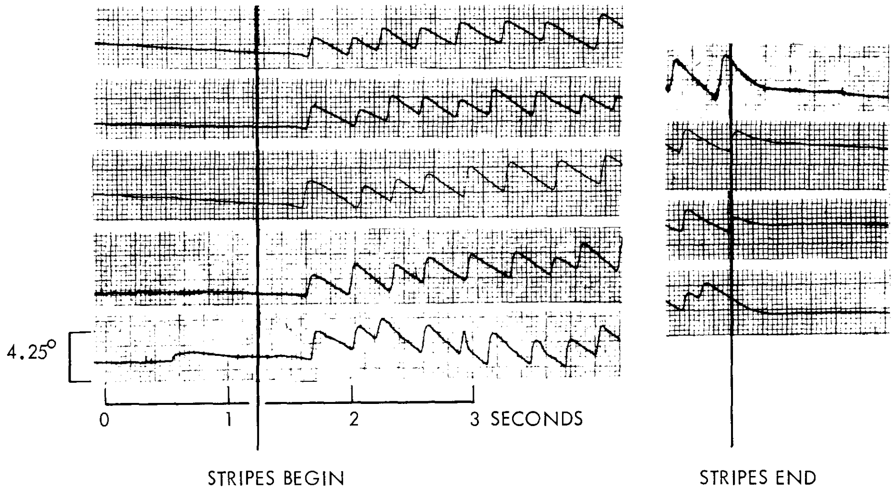


Fig. XXVII-15. Responses to variable-width pulses.

Four features of the on-step responses have been noted:

(i) The response begins with a fast phase.

(ii) This fast phase moves the eye away from the position of forward gaze toward the direction from which the stripes appear.

(iii) The response time, measured to the beginning of the fast phase, is approximately 300 msec.

(iv) A suggestive slow phase lasting only approximately 80 msec seems to precede the first fast phase.

Three features of the off-step responses have been noted:

(i) The last phase is a slow phase.

(ii) The response time, measured to a point of approximately zero velocity, is again approximately 300 msec.

(iii) There does not seem to be any "afternystagmus" persisting beyond a normal response time after the stimulus ceases.

From this experiment we conclude that optokinetic nystagmus is a reflex response with two components, a fast phase and a slow phase. This finding is in agreement with the magnitude correlations, published in Quarterly Progress Report No. 71 (pages 286-290), in which the lack of correlation between the fast phase and the preceding slow phase was shown. This suggests that the fast phase is not a positional servo correction to forward gaze error caused by the slow phase. The present experiment contains further evidence against the interpretation that the function of the fast phase is a positional correction for the error introduced by the preceding slow phase. The first response is a fast phase, which itself throws the eye into positional error.

Thus it seems that optokinetic nystagmus is a curious sort of double response. The fast phase, saccadic in nature because of its high velocity, is not a positional correction in the same sense as the saccade in normal eye tracking. The slow phase is not functionally the same as smooth tracking, as evidenced by the quantitative addition of the slow phase with a smooth tracking response (Quarterly Progress Report No. 71, pages 286-290).

E. G. Merrill, L. Stark

F. REMOTE ON-LINE COMPUTER DIAGNOSIS OF THE CLINICAL ELECTROCARDIOGRAM: SMOOTHING OF THE ELECTROCARDIOGRAM

Rapid advances in digital-computation techniques now make it possible to approach the problem of automatic diagnosis of clinical electrocardiograms with confidence that a solution will be found. This problem is being explored by a cooperating group from the Neurology Section of the Electronic Systems Laboratory and the Department of Biology, M.I.T., and the Division of Medicine of the Boston University School of Medicine. The objective of these studies is to develop a program for automatic on-line digital-computer interpretation of the electrocardiogram by using pattern-recognition techniques. Achievement of this goal has profound implications for improved clinical practice and efficiency, for improved reproducibility of interpretation, and for the development of new methods of investigation and validation of results of current interpretation problem areas.

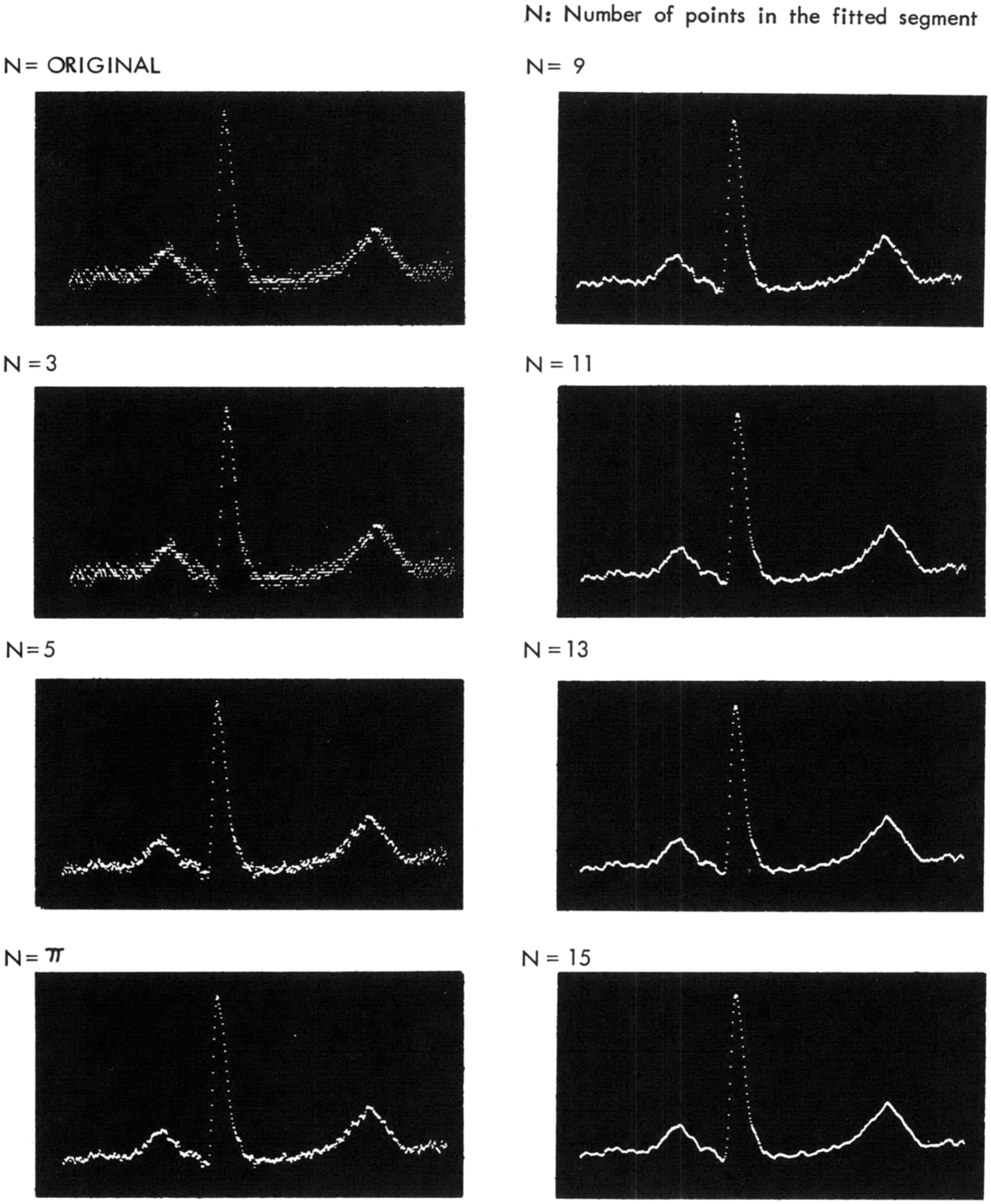
In this on-line diagnostic system the electrocardiogram is relayed instantaneously from Boston University Medical Center over DC paired telephone lines to our laboratory at M.I.T. where it enters a G.E. 225-IBM 7094 computer complex through the analog-to-digital converter of the G.E. 225 computer. The electrocardiographic signals originating at the Medical Center, however, are obscured by noise, and smoothing of these tracings is necessary to facilitate the computer pattern-recognition analysis by adaptive matched-filter techniques.

In an electrocardiogram, the frequency components of the information signal are relatively low, approximately 0.2-100 cps.[1] The general standard for a clinical electrocardiograph is that the frequency response at 40 cps does not fall below 4 db of the DC response.[2] Unfortunately, the majority of clinical electrocardiographs do not meet this standard,[3] having a poor upper limit of frequency response. Langner and others[4-6] and Kerwin,[7] however, have emphasized the clinical importance of high-frequency components in the electrocardiogram, particularly for myocardial infarction. According to the present standard, set by the American Medical Association, frequency components in the electrocardiogram higher than 100 cps can be presumed to be non-informational noise and may be removed if necessary. If the high-frequency components do not interfere with the analysis of the electrocardiogram, they may be retained, since they may reveal factors of clinical significance that are still not well recognized.

As we reported[8] the logic for our point-recognition technique needs the first and/or second derivative of the original signal to detect the QRS complex that corresponds to the electrical activation of the cardiac ventricle. This means that the discrimination of the QRS complex from the other components is most certain by using these derivative functions, particularly if the electrocardiographic record is free from the higher frequency noise that originates in analog tape-recorder systems.

Two methods for eliminating high-frequency noise – curve fitting by the least-squares method, and the moving-average method – have been adapted for the electrocardiogram. The smoothing effect and the signal degradation produced by these procedures is a fundamental, controversial problem. It is clear that the problem is related to the length of segment to be fitted and with the functions assumed for the least-squares method, and with the weighting function, as well as the length of the segment, for the moving-average method. The measure of signal degradation largely depends on how one subsequently analyzes the signal for diagnostic purposes.

Figures XXVII-16, XXVII-17, and XXVII-18, show the effect of the length of the segment to be fitted or averaged. The function used for the least-squares method is a quadratic curve (parabola), and the weighting function for the moving-average method is a straight line, that is, no weighting on any points. Before and after the smoothing procedure these electrocardiograms were plotted on the auxiliary oscilloscope of the IBM 7094 computer. The amplitude of the QRS complex gradually decreased, as shown in Fig. XXVII-19, as the segment to be fitted or averaged became longer. This was particularly prominent in the moving-average method. The longer the segment, the wider the duration of the P, QRS, and QT complexes. This is more apparent in the moving-average method than in the least-squares method. If some weighting were put on the value of the center point in the segment, this greater degradation of the signal would be lessened in the moving-average method. In order to have the same smoothing effect as that provided by the 15 points (0.025 sec) used for the least-squares parabola method, the length of segment to be averaged was found to be approximately 6 points (0.01 sec) for the moving-average method. The derivatives of the electrocardiographic signal were most efficient in discriminating the QRS complex from the other components, as the amplitude of QRS complex could be smaller than the T wave. As shown in Fig. XXVII-18, however, the discrimination of the QRS component by the derivative was very poor before the smoothing procedure, but after smoothing by moving-average method the discrimination was nearly perfect. Figure XXVII-20 shows the result of Fourier analysis of an electrocardiogram before and after the smoothing procedure by the moving-average method in which the length of segment was 0.0015 sec (9 data points). The sampling rate was 600 points per second in these experiments, that is, 6 points per 10 msec. The computation time was less than 12 sec for



N: Number of points in the fitted segment

N= ORIGINAL

N= 9

N = 3

N = 11

N = 5

N = 13

N = π

N = 15

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Fig. XXVII-16. Smoothing of electrocardiogram, least-squares parabolic method.

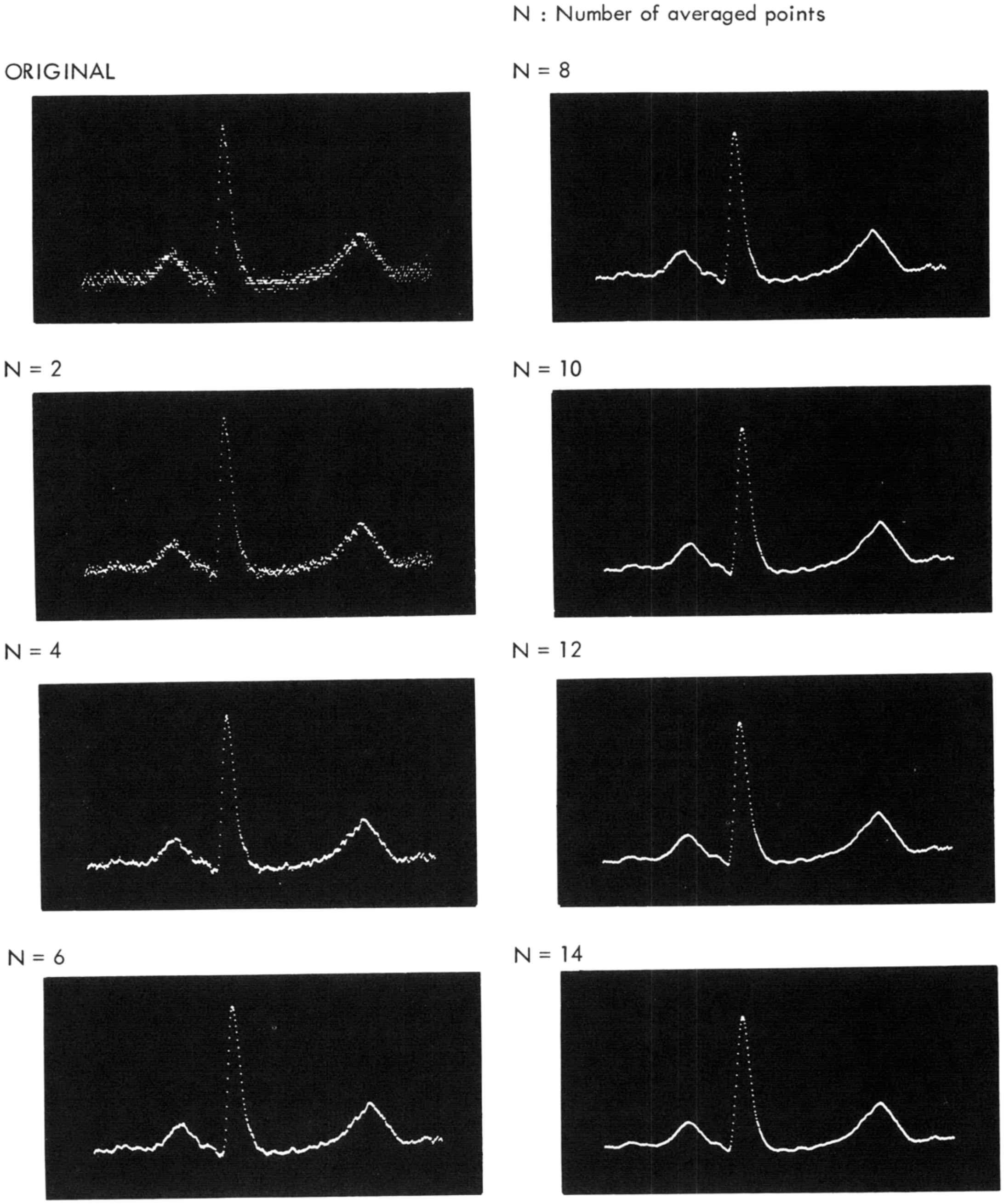

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Fig. XXVII-17. Smoothing of electrocardiogram, moving-average method.

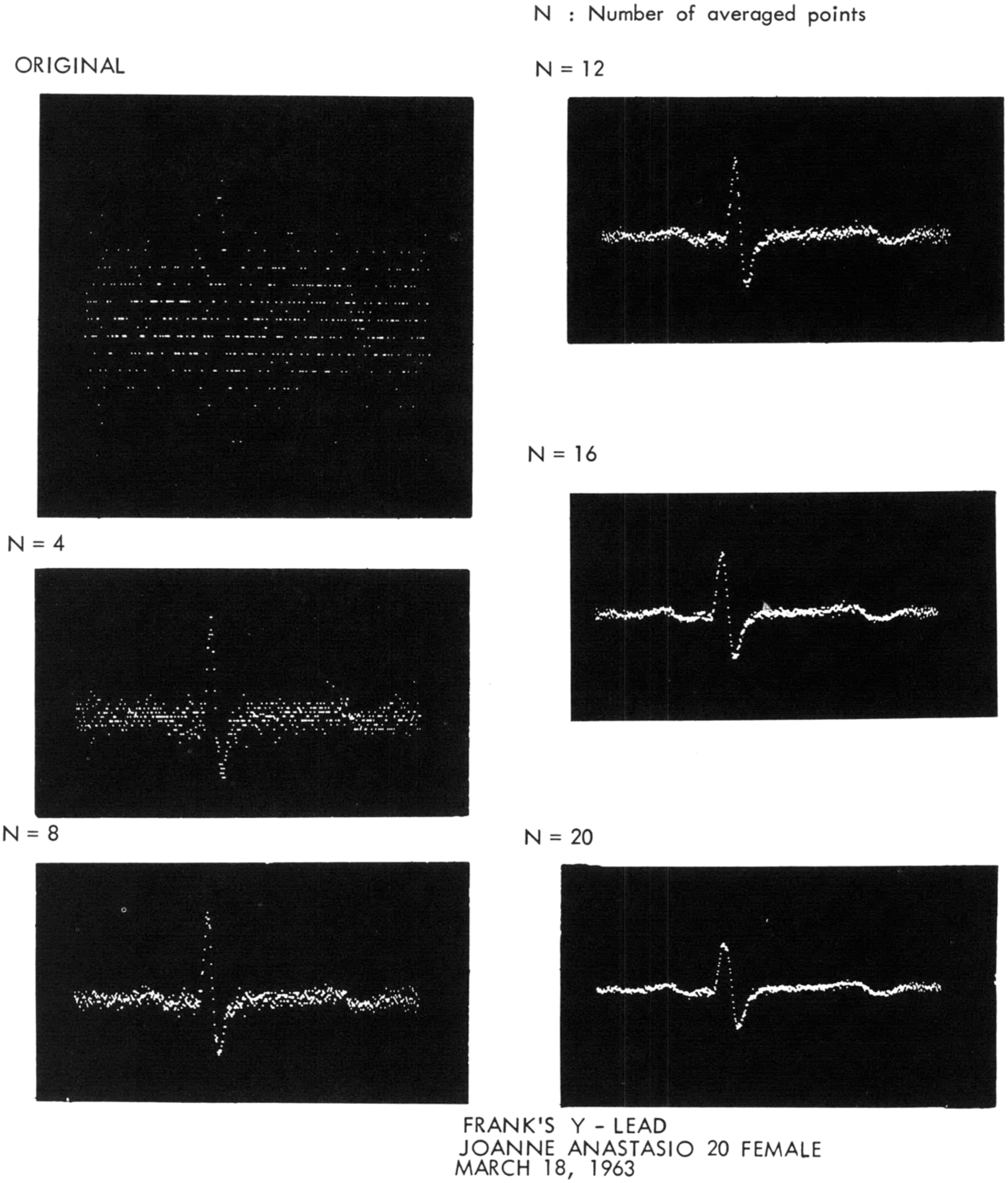

Fig. XXVII-18. Effect of smoothing by moving-average method on first derivative of electrocardiogram.

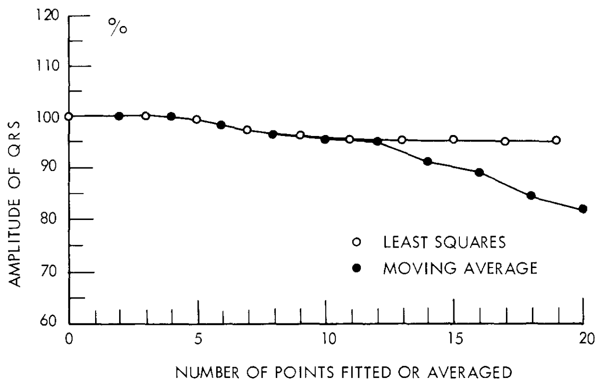

Fig. XXVII-19. Relation of amplitude of QRS complex to segment length.

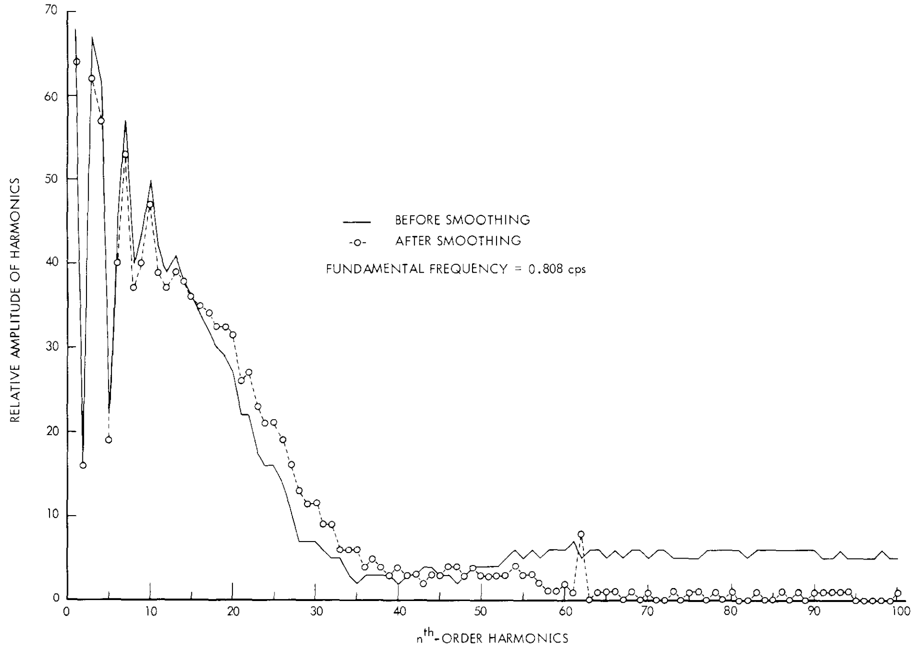

Fig. XXVII-20. Fourier analysis of electrocardiogram before and after smoothing (moving-average method).

the smoothing procedure for the X, Y, and Z components of a vectorcardiogram 2 sec long. At present, we are unable to recognize any significant difference between the smoothing effects of several high-order curve fittings as far as the electrocardiogram is concerned.

We found that either the method of the moving average or the least-squares parabola was quite satisfactory for the analysis of the electrocardiogram if the characteristics of each smoothing procedure were well understood. When these techniques were used properly, there was no preference found for one method over the other. The length of the segment to be smoothed, the weighting factor, and the degree of the curve to be used should all be considered in achieving the best results.

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