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A. DESIGN PHILOSOPHY FOR PSYCHOPHYSICAL EXPERIMENTS RELATED TO A THEORY OF AUDITORY FUNCTION

Psychophysics should play a major role in the evolution of a theory of auditory function, together with anatomy and physiology. We feel that the psychophysical tests that will be most valuable for this purpose are those that can be related to the physiological information now available about hearing. In terms of this objective of relating psychophysical and physiological data, it is possible to argue for a "best" psychophysical test procedure.

A good deal is known about the mechanical properties of the ear,[1] and about the neural activity at the level of the acoustic nerve,[2] that is, about what might be called the peripheral auditory system. In particular, it is now clear that some information about the external acoustical stimulus is destroyed by the peripheral auditory system, and that psychophysical test performance is thereby fundamentally limited. By utilizing the available physiological information about the periphery in a statistical hypothesis testing formulation, the limits on performance imposed by the periphery in certain psychophysical tests could be described quantitatively, except, perhaps, for a few unknown parameters and functional forms. The more central system also imposes

limits on performance, but these more central limitations cannot be described quantitatively on the basis of physiological information, as present understanding of what is done centrally with the information available from the periphery is relatively incomplete. It may be that in some psychophysical tests, the dominant limitations on performance are peripheral; that is, the central processing is effectively as good as the mathematically optimal processing. If such is the case, the quantitative description of peripheral limitations for these tests should correctly describe the characteristics of the psychophysical data. Since some psychophysical data must be used to complete the formulation of peripheral bounds, the only fact that can really be demonstrated experimentally is that there exists a class of psychophysical tests in which the data are as if peripheral bounds were dominant. We can look for a class of psychophysical tests in which the data from one test are related to the data from another in the same way as they would be if peripheral limitations were dominant, but, even if we are successful, we cannot claim to have demonstrated that peripheral limitations are really dominant. However, this approach seems to be a legitimate and promising way in which to try to relate physiological and psychophysical phenomena.

If we subscribe to this approach, we must look first for psychophysical experiments that can be related to the statistical hypothesis testing formulation of peripheral bounds and hold some promise of being tests in which peripheral factors are dominant. Given these conditions, we can argue for several desirable attributes of psychophysical tests:

(i) The tests should involve discriminations rather than absolute recognitions.

(ii) The subject should be thoroughly informed about every aspect of the experimental design except the actual sequence of presentations to be used (the subjects used in the experiments described here were graduate students in electrical engineering, and hence had no difficulty in understanding a quantitative description of the stimuli).

(iii) The subject should be asked to choose from a finite and preferably small set of responses, say, two.

(iv) The stimulus parameters should unambiguously define which response is correct and the subject should be informed of which response was correct after each trial.

(v) The subject should be asked to use all of the information available to him to do as well as possible in terms of some scoring system.

(vi) There should be a minimum of different possible stimuli, say, two.

These points lead to consideration of two general types of discrimination tests, each of which involves only two possible stimuli and two possible responses. In one configuration, the subject is presented stimulus A followed by stimulus A (AA), or stimulus A followed by stimulus B (AB), and asked whether the two stimuli are the same or different. In the other configuration the subject is presented either AB or BA and asked in which position is B.

A series of experiments in frequency discrimination was run to evaluate the relative

merits of variations of these two presentations. Stability of performance was a major consideration in evaluating the various psychophysical test schemes, since unstable behavior was regarded as a clear indication that peripheral bounds were not dominant. We found that the symmetric presentations — those in which either pair occurred with a priori probability 1/2 — were better in terms of stability than the asymmetric. This conclusion was supported by the subjective feelings of the observers and the quantitative aspects of the experimental data. We also found that the High-Low (AB, BA) presentation was better in terms of stability than the Same-Different (AA, AB). The subjects preferred the (AB, BA) configuration because they felt that high-low was exactly the question they first answered in listening to the stimuli, whereas in the (AA, AB) configuration the stimuli all sounded different and they asked themselves "different enough?" The subjects' feelings were reflected quantitatively in the data, with the (AB, BA) data being significantly more stable than the (AA, AB). We feel that the two-alternative forced-choice experiment (AB, BA) would also be "best," given the goal of relating physiological to psychophysical data, in tests of discrimination other than frequency and in detection tests.

Further details of these arguments, the statistical hypothesis testing formulation, and the experiments referred to in this report may be found in the author's thesis.[3]

P. R. Gray

References

1. G. von Békésy's papers have been collected in Experiments in Hearing (McGraw-Hill Book Company, Inc., New York, 1960).

2. H. Davis, Advances in the neurophysiology and neuroanatomy of the cochlea, J. Acoust. Soc. Am. 34, 1377-1385 (1962).

3. P. R. Gray, A Design Philosophy for Psychophysical Experiments, S. M. Thesis, Department of Electrical Engineering, M. I. T., January 1963.

B. EVOKED RESPONSES IN RELATION TO VISUAL PERCEPTION AND OCULO-MOTOR REACTION TIMES IN MAN

[This report is a summary of an invited paper read at the Conference, "Sensory Evoked Response in Man," sponsored by the New York Academy of Sciences and Albert Einstein College of Medicine, New York, February 14-15, 1963. The paper will be published as a part of a Conference Monograph in the Annals of the New York Academy of Sciences.]

Responses evoked at the occiput in man by visual stimuli have been studied in relation to oculomotor reaction times, and in relation to some of the associated phenomena of visual perception. Sudden changes in the vertical position of a spot on an oscilloscope screen were used as stimuli and as tracking signals, and motor responses consisted of the corresponding redirections of gaze to the successively new positions of the spot.

For subsequent analysis, simultaneous recordings were made onto magnetic tape and paper of: (a) spot position, (b) eye position (monitored electro-oculographically), and (c) EEG potentials recorded bipolarly from a pair of midline parieto-occipital scalp electrodes.

Averages of parieto-occipital evoked potentials for a large number of stimuli were obtained from recordings made during visual tracking of the spot, and also from recordings carried out while gaze was maintained fixed at the center of the oscilloscope screen. Also, averaged responses, with eyes closed, to flashes of light from a strobo-scope were obtained. Oculomotor reaction times were determined by averaging of electro-oculographic potentials, and by crosscorrelation of the latter with the spot-position signals.

In separate psychophysical experiments with some subjects, an attempt was made to determine, by indirect means, the approximate time interval for subjective percep-tion of the stimuli, and for subjective perception of eye movements, for comparison with the latencies of various components of the parieto-occipital evoked responses.

Potentials evoked by the shifting spot of light were generally appreciably smaller, and greater in latency, than those evoked by bright flashes of light with the eyes closed, but the amplitude of certain components of the former (that is, those with an output at approximately 80-90 msec) was clearly increased during tracking for some subjects, an effect that may have been due to the fact that the fovea of the retina was more fre-quently stimulated during tracking than it was when the eyes were maintained fixed. Consideration of the latencies of these components suggests that they may represent nonspecific rather than specific evoked responses in the visual system. Comparison of averages of EEG responses with those of EOG responses established that the above-mentioned components appearing during tracking did not represent the electrical field, at the parieto-occipital scalp electrodes, of the EOG potentials, the amplitude of the latter being much larger than that of the EEG potentials. Suggestive, but not con-clusive, evidence for different forms of evoked responses for different directions of spot-shifts were obtained for some subjects.

A comparison, for one subject, of the results of the psychophysical experiments with those of the electrophysiological recordings provided some tentative evidence that the subjective perception of spot-shifts takes place, on the average, rather early (that is, within 50 msec), a finding that suggests that visual perception of simple stimuli may be more closely related to specific visual pathways than to nonspecific ones. Only minimal evidence of an early, specific response was, however, obtained in the present series of experiments for spot-shifts as visual stimuli. It appears probable that a component appearing in the averaged parieto-occipital EEG response at a constant interval of time after the mean oculomotor reaction time represents the same basic phenomenon as that of the "lambda waves" following eye movements

that have been described previously.

The findings from these electrophysiological and psychophysical experiments are discussed in relation to the question of quantization of time in the nervous system.

<div align="right">J. S. Barlow</div>

C. A MODEL FOR FIRING PATTERNS OF AUDITORY NERVE FIBERS

Acoustic signals are represented by sequences of spike potentials in the auditory (VIIIth) nerve. The form of this code and the encoding mechanism have been subjects of considerable interest in physiology. Recent experimental results of Kiang and others[1] have revealed the highly systematic structure of the spike activity of fibers in the VIIIth nerve of cats. These results have led to the work, summarized here, on the construction and testing of a model of the peripheral auditory system that relates the firing of an VIIIth-nerve fiber to sound coming into the ear.

Sound enters the outer ear, impinges on the eardrum, and is transmitted through the middle-ear structures to the fluids of the cochlea or inner ear. The fluid motion results in motion of the cochlear partition, which in turn results in forces on and/or movements of the auditory receptor cells or hair cells. The hair cells are thought to be transducer elements whose function is to produce local excitation of nearby VIIIth-nerve fibers. The spike potentials resulting from this excitation are transmitted to the brain via the VIIIth nerve.

Figure XV-1 shows a model of this system. The "Mechanical System" represents the functional relationship between an acoustic pressure input to the ear and a displacement of the cochlear partition and is assumed to be representable as a linear system over a range of approximately 80 db of sound intensity. The transfer function of this part of the system for a particular point along the cochlear partition is assumed to be given by the work of von Békésy[2] for frequencies below approximately 2 kc. The "Transducer" is intended to represent the functional relationship between the displacement of the cochlear partition at a point along its length and the output of a hair cell at that point. The final block shows a stereotyped or idealized "Model Neuron." In this model the output of the transducer is summed with noise at the input of the neuron. This noise is included to account for both the spontaneous activity and the probabilistic response behavior characteristic of VIIIth-nerve fibers. The existence of this noise (additive to the membrane potential) can be justified to some extent on the basis of extrapolations from some empirical evidence that is due to Verveen.[3] The sum of the
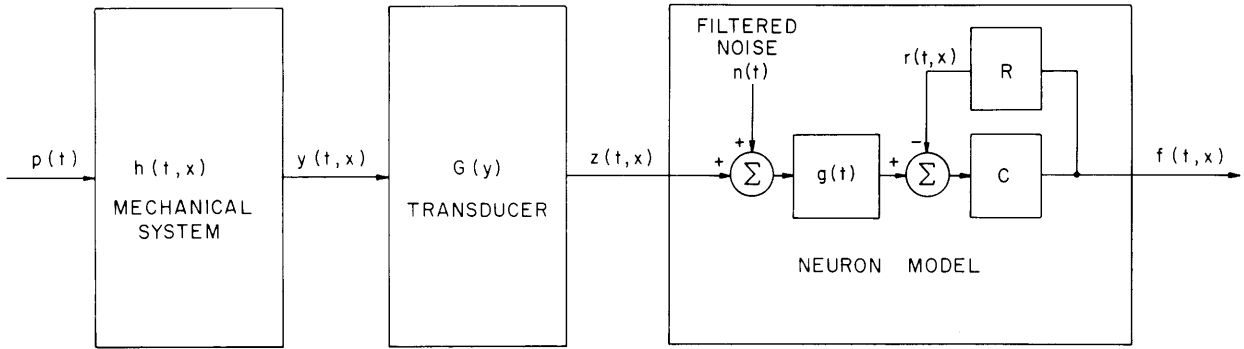
p(t), Pressure at the ear drum

y(t,x), Displacement of the cochlear partition

z(t,x), Output of hair cell

f(t,x), Action potentials of fiber

h(t,x), Impulse response of the cochlear partition at a point x cm from the stapes

G(y), A function relating the output of a hair cell to displacement of the cochlear partition at a point x cm from the stapes

g(t), Impulse response of a linear filter

r(t,x), Threshold of the neuron model at time t

Fig. XV-1. Model relating the firing patterns of fibers in the auditory nerve to acoustic stimuli.

noise and the input to the neuron is filtered and then compared with a threshold in the box labelled "C." If the threshold is exceeded, then a spike is defined as occurring, and the threshold is reset to some larger value, by the box labelled "R."
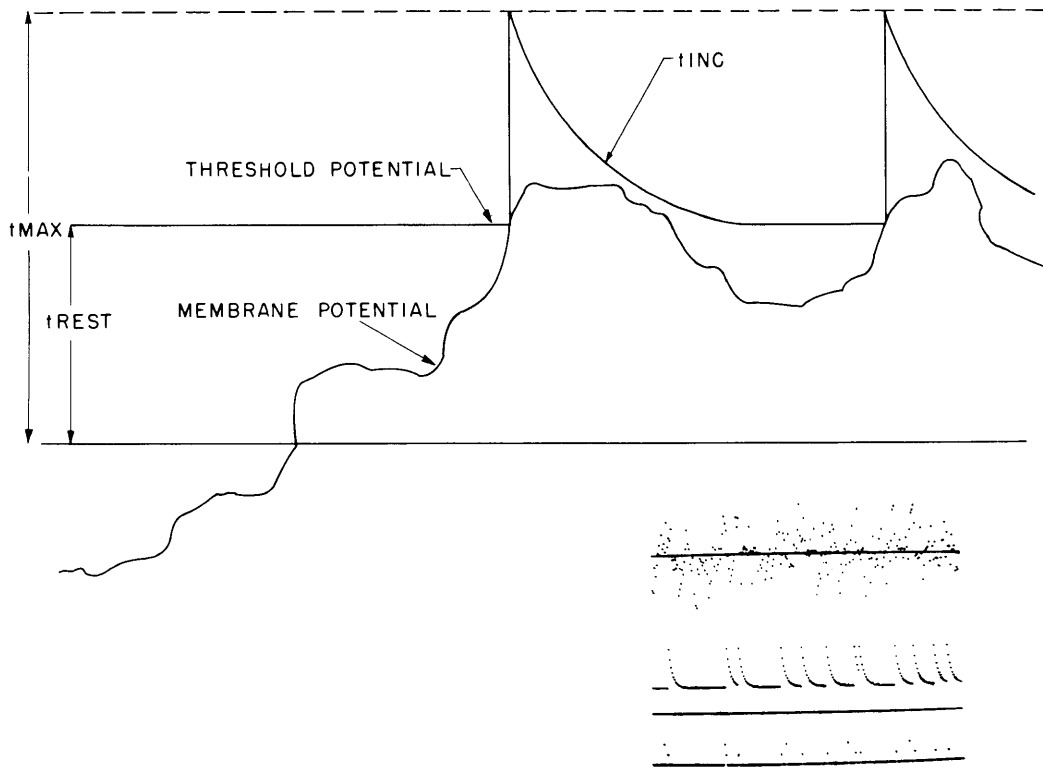

Fig. XV-2. Threshold and membrane potential of the model neuron as a function of time.

Figure XV-2 shows both the noisy membrane potential of the model neuron and the threshold as a function of time. The threshold is reset to some large value (tMax) upon the occurrence of a spike and decays to its resting value (tRest) with a decrement (tInc). In the lower right-hand corner there is a representation of the membrane and threshold potentials generated by the TX-2 computer simulation of this system. The top trace shows the noisy membrane potential. The center trace shows the threshold as a function of time. The bottom trace of dots shows the times of occurrence of spikes and a set of time markers.

The fundamental assumptions in this model are:

(i) The mechanical system is assumed to be representable by a linear system.

(ii) A point-to-point relation between the displacement of the cochlear partition and the neural excitation is assumed. A particular neural fiber is assumed to be excited by a neighboring hair cell, which in turn responds to the displacement of the cochlear partition at a point along its length.

(iii) The process of neural excitation is represented by a simple model neuron. This model is probabilistic and characterized by threshold and refractory effects.

(iv) The effects of efferent fibers on the peripheral system are ignored.

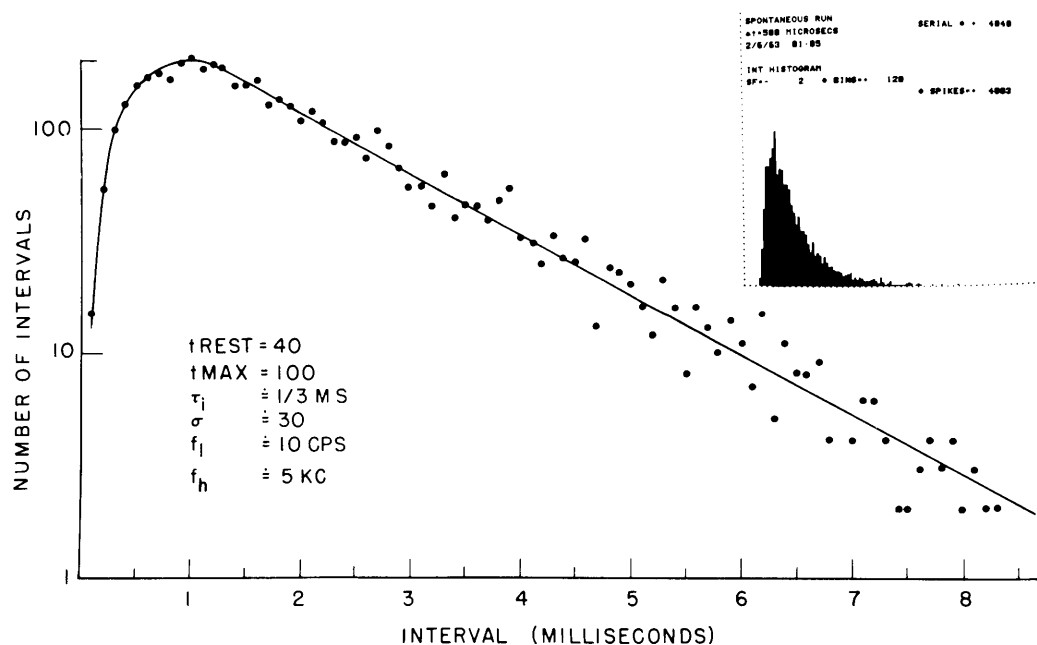This model has been simulated on the TX-2 computer at Lincoln Laboratory, M.I.T.,

Fig. XV-3. Histogram of intervals between spikes generated by the model in the absence of a stimulus. The time constant of the decay of the threshold to its resting value is 1/3 msec. The noise spectrum is flat from 10 cps to 5 kc.
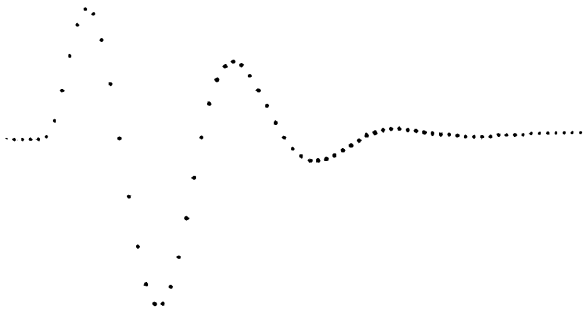
Fig. XV-4.

Impulse response of the cochlear parti-
tion at a point whose characteristic fre-
quency is 500 cps. Dot separation is
100 μsec, and successive maxima of the
response are separated by 2 msec. This
particular impulse response corresponds
to $F_3(t)$ (see Flanagan[4]).

CLICK RESPONSE OF MODEL
WITH NONLINEARITY
Δt=100 MICROSECS   CF=500~
2/6/63   22·40

SERIAL ● ✦   4028

PST HISTOGRAM
SF=-   3   ● BINS=✦   140

● SPIKES=✦   3725

⊢ 2 MILLISECONDS

Fig. XV-5. PST histogram of the click response of the model for a fiber
whose characteristic frequency is 500 cps.

and statistics of the spontaneous activity and response of the model to a variety of acoustic stimuli have been studied and compared with the VIIIth-nerve data obtained by Kiang and others.[1]
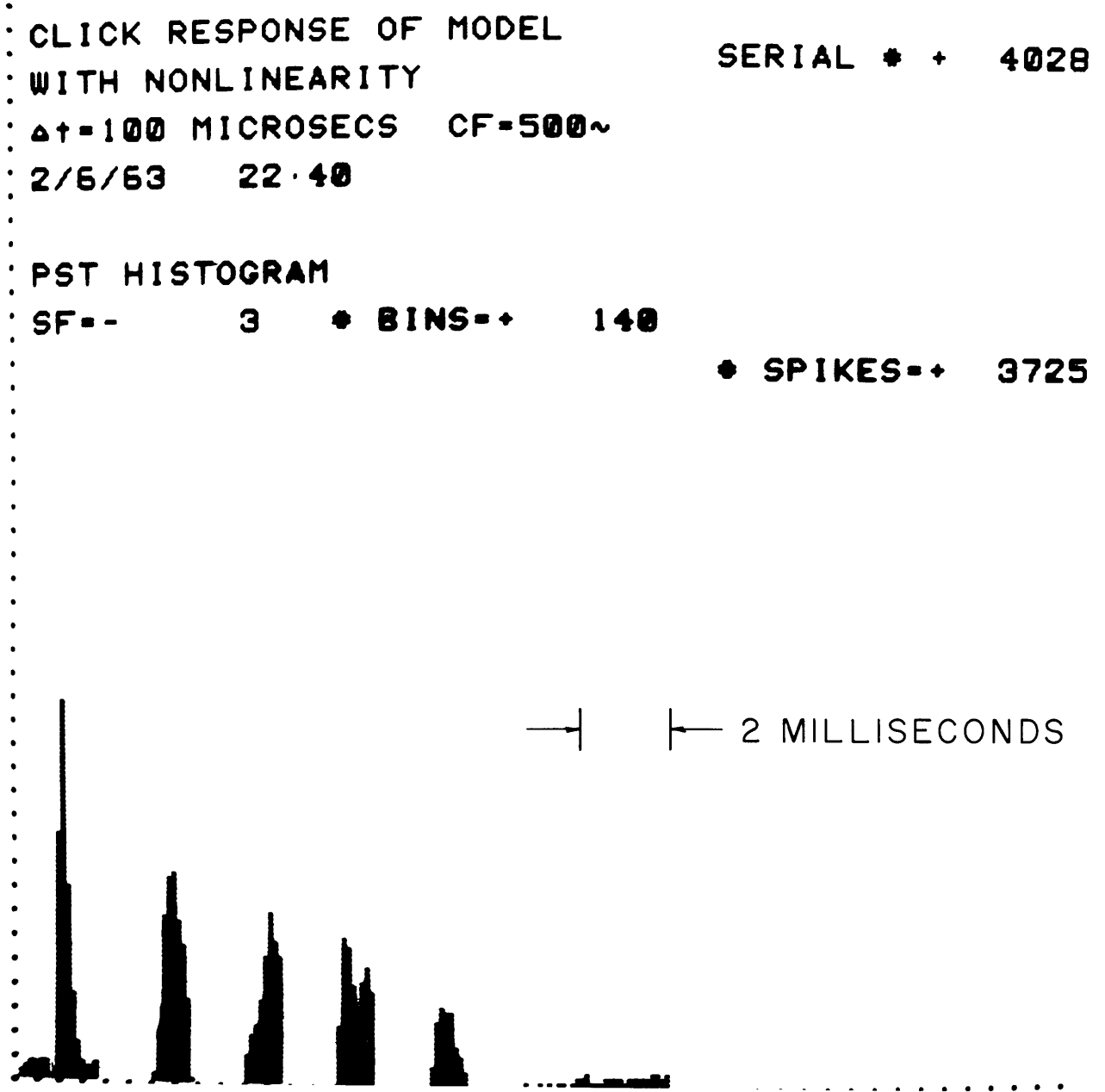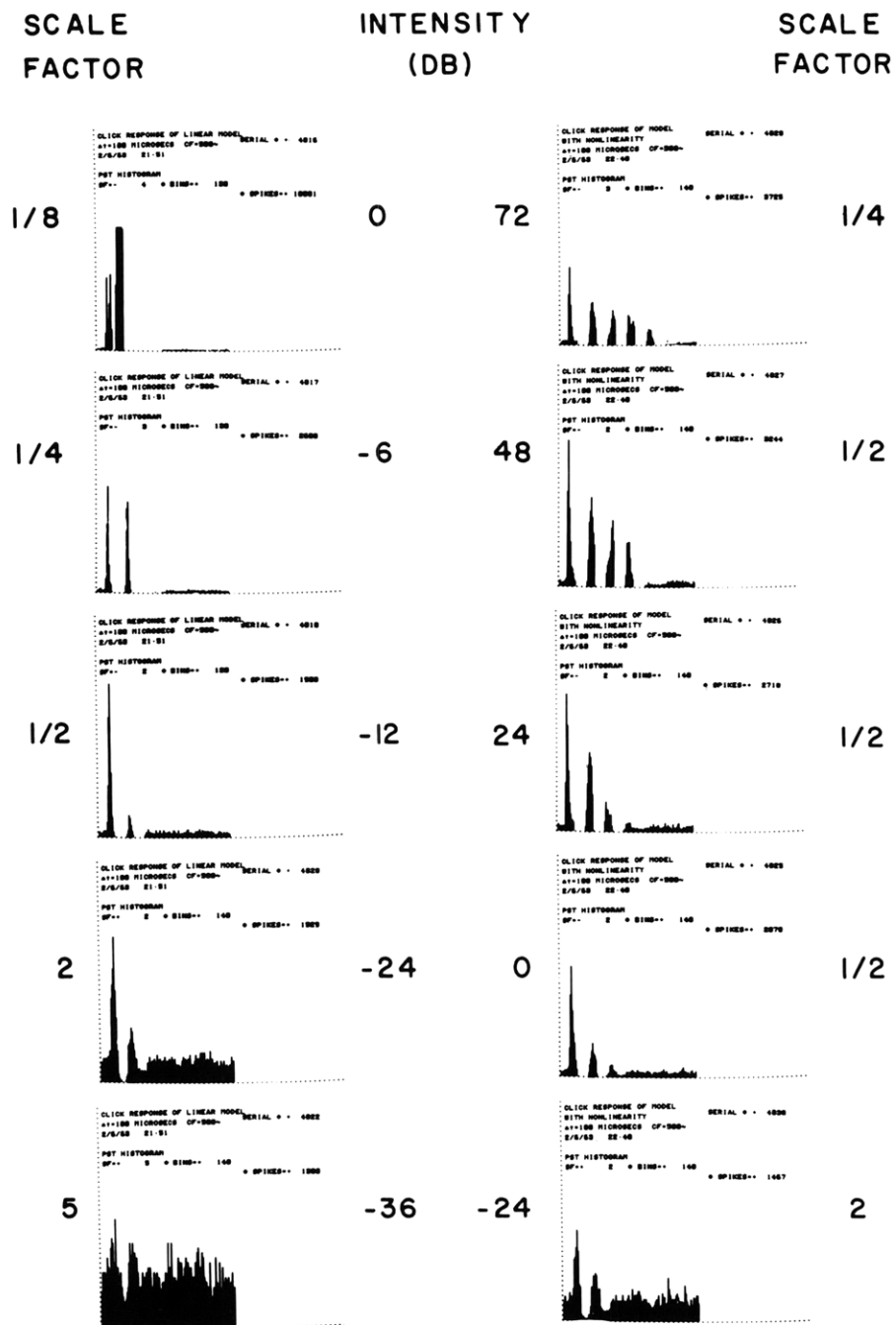
Figure XV-3 shows a histogram of interspike intervals of the spontaneous activity generated by the model. The insert shows this histogram as photographed from the TX-2 oscilloscopic output. The rest of the figure shows the interval histogram plotted in semi-logarithmic coordinates. Notice that the tail of the distribution is linear with these coordinates, or exponential on linear coordinates. For very short intervals, the the number of firings decreases to zero, a reflection of the refractory properties of the model. This general form of the distribution of intervals in the spontaneous (or unstimulated) case is characteristic of VIIIth-nerve fibers.

Figure XV-4 shows the response of the cochlear partition to a short click determined by Flanagan[4] from the data of von Békésy. In this case, the response is given for a point along the cochlear partition whose characteristic frequency is 500 cps. Figure XV-5 shows the response of a model fiber that is assumed to innervate a hair cell at the same spot on the cochlear partition. The response is in the form of a PST (Post Stimulus Time) histogram. This histogram shows the number of firings that occur at a time t after the onset of a stimulus. The peaks in this histogram are separated by an interval of 2 msec and correspond to the times of the maximum positive deflections in the response of the cochlear partition at the 500-cps point to the click. This general form of the model PST histogram agrees quite well with the form of similar histograms computed from the VIIIth-nerve data.

Figure XV-6 shows PST histograms of the click response of the model for two different forms of the transducer as a function of sound intensity. The histograms on the left side show the results for a linear transducer, that is, the output of the transducer is proportional to its input. Note that there is a 36-db range between the intensity at which a response first appears to be visible in the PST histogram and the intensity at which the response of the model becomes stereotyped (that is, the model responds to the largest positive deflection of the cochlear partition every time a stimulus is presented.) This behavior does not agree with the observed response of VIIIth-nerve fibers. Since the envelope of the impulse response of the cochlear partition decays at a rate exceeding 20 db per cycle of oscillation, there can be at most two or three peaks in the PST histogram when a linear transducer model is used. The linear transducer function thus yields PST histograms that are at variance with the empirical evidence of Kiang and others. The histograms on the right side of Fig. XV-6 show the results obtained for a transducer model that is a nonlinear saturation function. The results obtained with the nonlinear transducer model agree qualitatively with the results of Kiang and others.

One of the puzzling results of the investigations of Kiang and others indicates that

SCALE
FACTOR

INTENSITY
(DB)

SCALE
FACTOR

1/8   0   72   1/4

1/4   -6   48   1/2

1/2   -12   24   1/2

2   -24   0   1/2

5   -36   -24   2

$\Delta t = 100 \mu sec$

$CF = 500 cps$

Fig. XV-6. PST histograms of the click response of the model for two different transducer functions vs intensity of click. The left-column histograms were computed for a linear transducer. The right-column histograms were computed for a nonlinear transducer $\left[G(y) = y \dfrac{k}{k + |y|} \right]$.

the sensitivity of neurons responding to sinusoids at their characteristic frequency increases as a function of frequency (at a rate of approximately 40 db/decade) in the range 100 cps-2 kc. Such a change in sensitivity is seen at higher auditory centers[5] and even in the human audiogram,[6] but it was surprising to encounter this effect so close to the periphery, particularly since the mechanical part of the system does not exhibit so large a change in sensitivity. Preliminary results tend to indicate that this effect can be explained by the model. That is, the model predicts a change in sensitivity as a function of frequency which is qualitatively the same as the change in sensitivity seen in VIIIth-nerve fibers, but the quantitative results depend upon the definition of the threshold of firing of a unit and a knowledge of the exact parameters of the system.

To summarize, this model of the peripheral auditory system seems capable of fitting certain available VIIIth-nerve data over a considerable range of stimuli. The important constituents of the model are a linear bandpass filter, followed by a nonlinear saturation function, followed by a probabilistic threshold device with refractory properties.

T. F. Weiss

References

1. N. Y-S. Kiang, T. Watanabe, Eleanor C. Thomas, and Louise F. Clark, Stimulus coding in the cat's auditory nerve, Ann. Otol. Rhinol. Laryngol. 71, 1009-1016 (1962).

2. G. von Békésy, Experiments in Hearing, edited by E. G. Wever (McGraw-Hill Book Company, Inc., New York, 1960).

3. A. A. Verveen, Fluctuation in Excitability (Drukkerij Holland N. V., Amsterdam, 1961); Axon diameter and fluctuation in excitability (in press).

4. J. L. Flanagan, Models for approximating basilar membrane displacement, Bell System Tech. J. 39, 1163-1192 (1960).

5. J. E. Hind, Unit activity in the auditory cortex, Neural Mechanisms of the Auditory and Vestibular Systems, edited by G. L. Rasmussen and W. F. Windle (Charles C. Thomas, Springfield, Ill., 1960), p. 203.

6. J. C. R. Licklider, Basic Correlates of the Auditory Stimulus, Handbook of Experimental Psychology, edited by S. S. Stevens (John Wiley and Sons, Inc., New York, 1951), p. 995.

D. CORTICAL FACILITATION FOLLOWING ONSET OR TERMINATION OF A LIGHT

The present report concerns the shock-evoked response complex (SERC) recorded from the primary visual cortex. This response has been the subject of considerable study. The complex of deflections is obtained whether one delivers the "test" shocks to the optic nerve, chiasm, tract, the lateral geniculate body or the optic radiation. (These deflections are usually numbered as illustrated in Fig. XV-8, trace D.[1,2]) There is general agreement that deflection no. 1 is related to the volley of impulses in nerve

fibers that feed into the cortex, and that deflections no. 3, no. 4, and no. 5 are measures of intracortical events resulting from this influx. The SERC for a given size of test shock may be modified by changing the animal's physiological state, or by changing conditions of retinal stimulation. The most striking modification of this SERC is an enhancement, which has been demonstrated under a number of conditions, including arousal by reticular stimulation or other means,[3,4] presentation of a continuous diffuse illumination,[5] and retinal deafferentation.[6] Besides these effects which last long, there are transient changes in the SERC following a sensory or arousing stimulus. In this report we shall deal with such a transient effect; specifically, with a strong enhancement following the onset or termination of the presentation of a light. The effect is most clearly demonstrated when the shocks are delivered to the optic radiation rather than to more peripheral loci in the afferent pathway, and it is abolished by deep barbiturate anesthetization. The experiments were performed with unanesthetized cats with mid-pontine pretrigeminal brain-stem sections.

Recording was by a monopolar electrode (silver ball or cotton wick soaked in NaCl solution), with the neutral electrode on the skin of the neck. Shocks were delivered by concentric electrodes. The light source was a Westinghouse 47 bulb placed in the end of a hollow cylinder, 18 cm long and 3 cm in diameter. At the other end of the cylinder was a glass diffuser that was placed directly in front of the cat's eyes at a distance of approximately 8 cm. The bulb was excited by a 6-volt dc source. The electrocortical
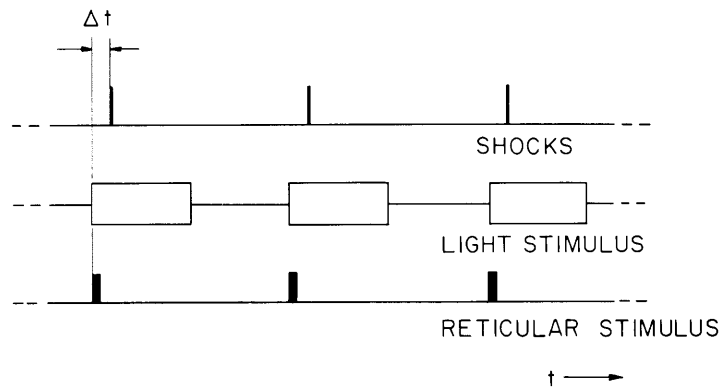

Fig. XV-7. Temporal pattern of stimuli. Top line shows the timing of the shocks to the optic pathway. Stimuli are delivered repetitively at the rate of 1 per 2 seconds or 1 per 4 seconds. In control conditions the cat is in the dark. When light or reticular stimulation is coupled with the shocks the time sequence is as shown, with $\Delta\tau$ the time between the onset of the electric signal to the light, or the train of shocks to the reticular formation (represented by a solid bar) and the shock to the optic pathway. (For the time course of the light onset see Fig. XV-8.) Duration of the light stimulus is 1 sec; duration of the train of shocks to the reticular formation, 0.1 sec.

activity was recorded on magnetic tape and processed by the ARC-1 average response computer.

Figure XV-7 illustrates the temporal pattern of stimuli used in the experiments. The average waveform of cortical responses to the onset of the light is shown in Fig. XV-8, trace A. Figure XV-8, trace B shows, on the same time and amplitude scale as in trace A, the average of responses to the light together with a single **shock** to the optic
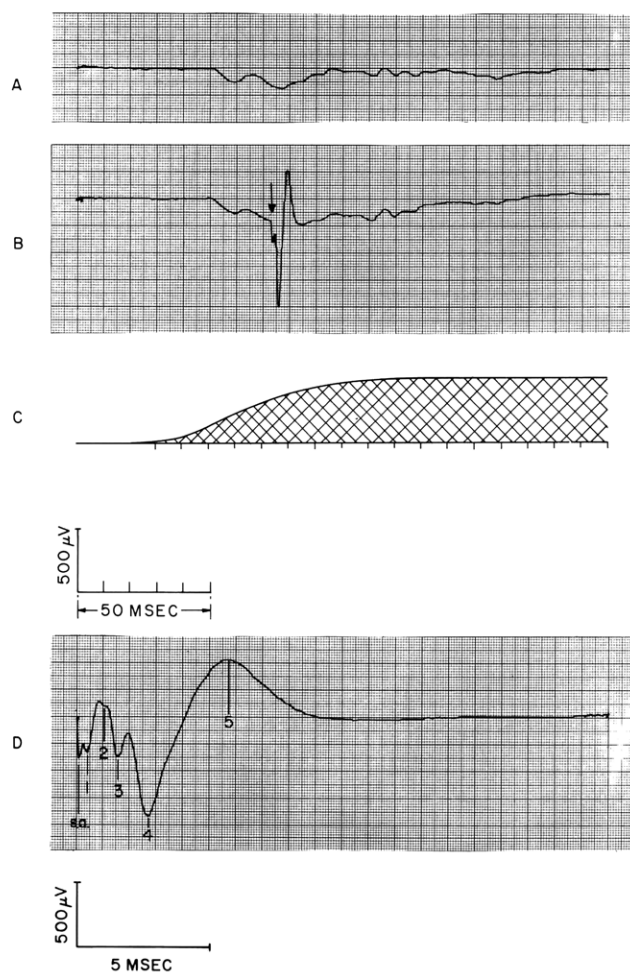

Fig. XV-8. Evoked responses from primary visual cortex. A: average of responses
to the onset of the light. B: average of responses to the onset of the light
together with a shock to the optic radiation homolateral to the recording
electrode delivered at the time indicated by the arrow. C: time course
of the light as measured by a photomultiplier tube. The trace starts at the
onset of the electric signal to the bulb. D: detail of the part of the wave-
form in B following the shock. The shock artefact (s. a.) and characteris-
tic deflections of the shock-evoked response complex (SERC) are indicated
in this and subsequent figures. The shocks are 4 v in amplitude, and 0. 2
msec in duration, and presented once every 4 seconds. In this and subse-
quent figures the number of responses in each average is 32.

radiation delivered at the time marked by the arrow. Figure XV-8, trace C shows the time course of the onset of the light. It is clear that the SERC is larger and of much shorter duration than the response to the light alone, so that large changes in the sizes of its deflections cannot result from an addition of these two responses. Figure XV-8, trace D shows a more detailed view of the SERC on a different time scale.

The enhancement effect is illustrated in Fig. XV-9. Figure XV-9, trace A shows the SERC (shocks delivered to the optic radiations) with control (dark) conditions. Figure XV-9, trace B shows the SERC when the shocks are delivered 150 msec following the electric signal to the light source. (Note that there is an approximate 30-msec delay between this event and the light onset, see Fig. XV-8, trace C.) It is interesting to

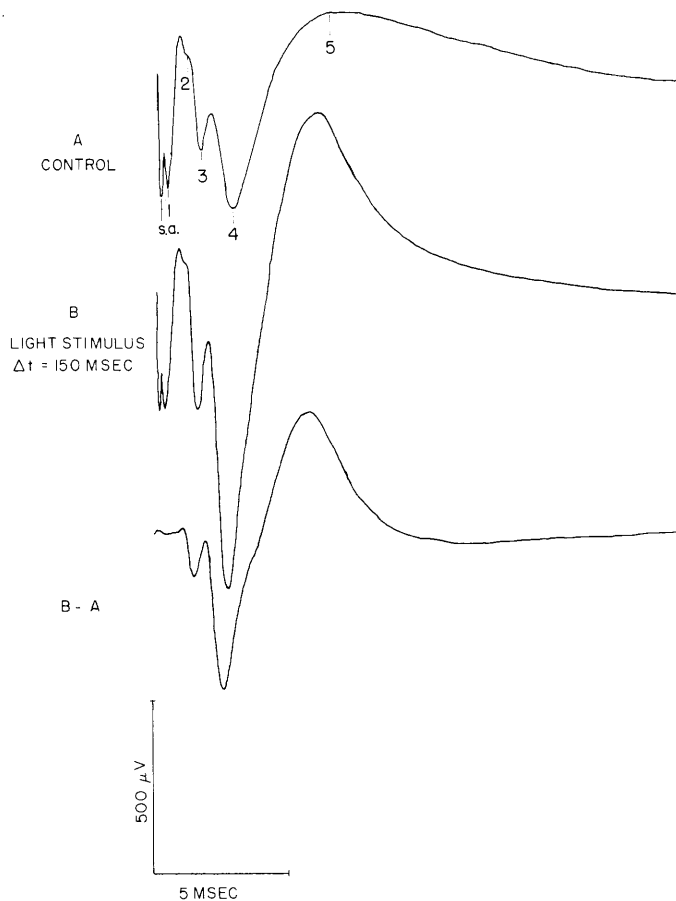Fig. XV-9. Enhancement of the SERC by the onset of a light. A: average of responses to shocks to the optic radiation under control conditions of darkness. B: average of responses to shocks together with the presentation of light. The third trace is the difference between the waveforms obtained in B and A. The shocks were given 150 msec after the electric signal to the light. Other stimulus parameters are the same as in Fig. XV-8.
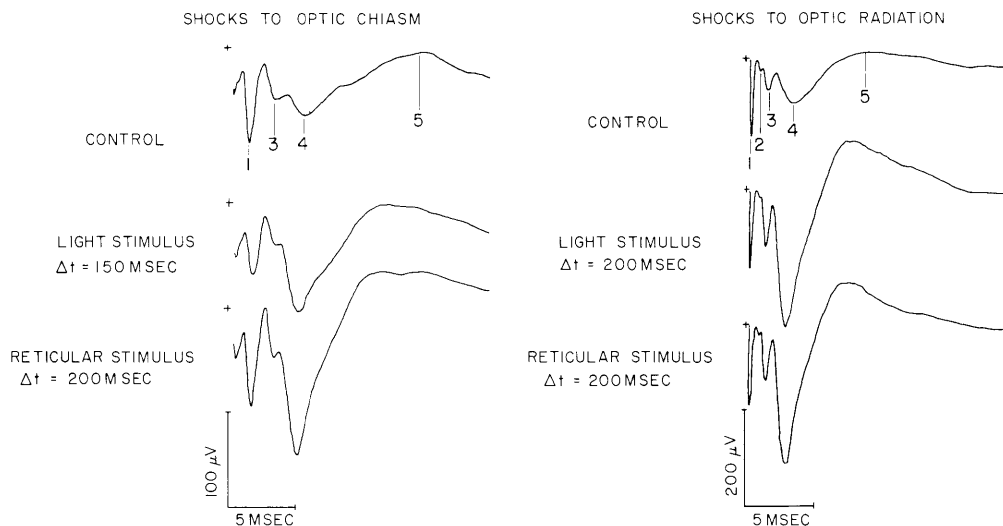
Fig. XV-10. Modification of the SERC by the onset of a light and by reticular stimulation. Left column shows averages of responses to shocks to the optic chiasm, and their modification by the onset of a light and by the onset of a train of shocks to the reticular formation. Right column gives similar results for shocks delivered to the optic radiation. The stimuli were delivered repetitively at a rate of 1 per 2 seconds. The shocks to the chiasm were 4 v in amplitude, 0.2 msec in duration; those to the optic radiation were 3 v in amplitude, 0.2 msec in duration. Reticular stimuli were 0.1-sec trains of shocks having 2-volt amplitude, 300/sec rate, and 0.2-msec duration.

observe that only deflections no. 3, no. 4, and no. 5 are modified significantly. The differential waveform of Fig. XV-9 illustrates this point. A similar enhancement effect may be demonstrated following termination of the light.

The rate of presentation of the light is important in determining the extent of enhancement. For rates of 1 per second, or greater, the enhancement is small. In several cases a considerably greater enhancement was observed for the rate of 1 per 4 seconds than for the rate of 1 per 2 seconds. The enhancement effect is obtained for a wide range of light intensities, and can be demonstrated with the stimulating light shining directly into the animal's eyes, or with the light overhead.

In a number of experiments we have attempted to enhance the SERC by reticular stimulation. In these midpontine pretrigeminal preparations such an enhancement is possible, but difficult to obtain. The effect is extremely sensitive to the location of the stimulating electrode in the reticular formation. When an enhancement is obtained it occurs in the period following the onset of the train of shocks to the reticular formation, and cannot be demonstrated during a continuous reticular stimulation. This enhancement is greatest if the test shocks are delivered to the optic pathway approximately 200 msec after the onset of

the train of shocks to the reticular formation. A 100-msec train of shocks to the reticular formation seems to provide as much enhancement as a longer one. Figure XV-10 shows enhancement of the SERC for shocks to the optic chiasm and enhancement of the SERC to shocks to the optic radiations following reticular stimulation (third waveform in each column). Note that in both cases the size of deflection no. 1 is practically unchanged, while deflections no. 3, no. 4, and no. 5 are enhanced.

Figure XV-10 also shows corresponding modification of the SERCs for shocks to the optic chiasm and optic radiations following the onset of a light (second waveform in each column). For shocks delivered to the optic radiations results are very similar to those obtained with reticular stimulation. However, for shocks delivered to the optic chiasm the modification is more complex; deflection no. 1 is smaller than in the control, while the later events show some enhancement.

We interpret these results as follows: Following the onset or termination of a light there is a facilitation of the neurons of the primary visual area of the cortex. This facilitation is demonstrated by the "test probe" of a shock to the optic radiations. There is an enhancement of the intracortical events 3, 4, and 5 in the SERC when the test shock is delivered in the appropriate time interval following the onset or termination of the light. The modification of the SERC when the test shock is delivered to the chiasm demonstrates an inhibitory effect which is caused by the retinal activity following the onset of the light. (Arduini and his co-workers[6,7] have hypothesized and demonstrated that such an inhibition exists.) This inhibitory effect is evident in the decrease of deflection no. 1 (see Fig. XV-10). The facilitation of the cortical neurons following the flash is still evident in enhancement of the later deflections.

The mechanism of the enhancement effect is being investigated. Similarity of the waveforms for enhancement following the light onset and following a reticular stimulation suggests that the effects may involve the reticular formation. An important feature of the enhancement is that it disappears completely following deep anesthetization by Nembutal, which would not be at variance with this suggestion. However, there are findings that cast doubt upon a reticular involvement. First, there is the difficulty of obtaining the enhancement by reticular stimulation in the midpontine preparation, contrasted with the constancy and ease of the demonstration of enhancement following onset or termination of light. Second, the interval between light onset (or termination) and the time of delivery of the test shock for greatest enhancement is considerably shorter than the corresponding interval between the onset of the train of shocks to the reticular formation and the test shock. Finally, it appears that the enhancement following reticular stimulation is diminished more by a very light dosage of barbiturate anesthetic than the enhancement produced by transients in the light. None of these findings provides conclusive evidence one way or the other.

Further studies include a detailed investigation of the enhancement as a function of the time between the light onset (or termination) and delivery of the test shock. The question whether the facilitation of cortical neurons is limited to the primary visual area is also being investigated.

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References

1. G. H. Bishop and J. O'Leary, Potential records from the optic cortex of the cat, J. Neurophysiol. 1, 391-408 (1938).

2. F. Bremer and N. Stoupel, Analyse oscillographique comparée des réponses des aires de projection de l'écorce cérébral du chat, Arch. ital. Biol. 95, 1-19 (1957).

3. F. Bremer and N. Stoupel, Facilitation et inhibition des potentials évoqués corticaux dans l'éveil cérébral, Arch. internat. Physiol. Bioch. 67, 240-275 (1959).

4. S. Dumont and P. Dell, Facilitation réticulaire des mécanismes visuels corticaux, EEG Clin. Neurophysiol. 12, 769-796 (1960).

5. H. T. Chang, Cortical responses to stimulation of lateral geniculate body and the potentiation thereof by continuous illumination of the retina, J. Neurophysiol. 15, 5-26 (1952).

6. A. Arduini and T. Hirao, Enhancement of evoked responses in the visual system during reversible retinal inactivation, Arch. ital. Biol. 98, 182-205 (1960).

7. A. Arduini and M. H. Goldstein, Jr., Enhancement of cortical responses to shocks delivered to lateral geniculate body. Localization and mechanism of the effects, Arch. ital. Biol. 99, 397-412 (1961).

E. STUDY OF THE HANDWRITING MOVEMENT

An experimental system to investigate the detailed properties of pen displacement and velocity as a function of time during handwriting has been put into operation. A commercial handwriting transmitter (Telautograph) has been modified so that its output signals, voltages from two precision potentiometers mechanically coupled to the pen, may be sampled, converted to digital form, and written on magnetic tape by the TX-0 computer. The analysis of these data is carried out by the IBM 7090 computer of the Computation Center, M. I. T.

Data analysis proceeds as follows. The x and y coordinate sequences are first recovered by solving the equations of mechanical constraint of the pen and then differentiated to yield the pen velocity vector function. A segmentation into strokes is carried out by using the zeros of the y velocity as segmentation points. A parametric description of the strokes thus obtained is determined on the basis of the following models.

1. Model A

This model matches half-wave sinusoidal segments $\dot{x}_m(t)$, $\dot{y}_m(t)$ to the experimentally obtained functions $\dot{x}(t)$ and $\dot{y}(t)$. It corresponds closely to that of Eden[1] with the

exception that his slope parameter σ has been replaced by a phase-shift parameter ϕ for mathematical convenience.

Approximating Equations

$$\left.\begin{array}{l} \dot{x}_m(t) = \dot{X} \sin\left[\omega(t-t_0)+\phi\right] + \dot{X}_c \\[2ex] \dot{y}_m(t) = \dot{Y} \sin \omega(t-t_0) \end{array}\right\} \qquad t_0 < t \le t_2$$

Constraints

$$\omega = \pi/(t_2-t_0) \tag{1}$$

$$\dot{x}_m(t_0) = \dot{x}(t_0) \tag{2}$$

$$\dot{x}_m(t_2) = \dot{x}(t_2) \tag{3}$$

$$\int_{t_0}^{t_2} \dot{x}_m(t) \, dt = \int_{t_0}^{t_2} \dot{x}(t) \, dt \tag{4}$$

$$\int_{t_0}^{t_2} \dot{y}_m(t) \, dt = \int_{t_0}^{t_2} \dot{y}(t) \, dt, \tag{5}$$

where t_0 and t_2 are the experimentally determined segmentation points.

2. Model B

This model is an extension of Model A which allows for differences between the acceleration and deceleration sections of any stroke. The x-velocity amplitude, the frequency, and the phase shift between x and y velocities are allowed to take on different values over the two ranges.

Approximating Equations

$$\begin{aligned} \dot{x}_m(t) &= \dot{X}_1 \sin\left[\omega_1(t-t_0)+\phi_1\right] + \dot{X}_c & t_0 < t \le t_1 \\[2ex] &= \dot{X}_2 \sin\left[\omega_2(t_2-t)-\phi_2\right] + \dot{X}_c & t_1 < t \le t_2 \\[2ex] \dot{y}_m(t) &= \dot{Y} \sin\left[\omega_1(t-t_0)\right] & t_0 < t \le t_1 \\[2ex] &= \dot{Y} \sin\left[\omega_2(t_2-t)\right] & t_1 < t \le t_2 \end{aligned}$$

Constraints

Equations 2-5 of Model A and

$$\omega_1 = \pi/2(t_1-t_0)$$

$$\omega_2 = \pi/2(t_2 - t_1)$$

$$\dot{X}_1 \cos \phi_1 = \dot{X}_2 \cos \phi_2 \qquad \text{(continuity at } t=t_1)$$

$$\omega_1 \dot{X}_1 \sin \phi_1 = \omega_2 \dot{X}_2 \sin \phi_2 \qquad \text{(continuous derivative at } t=t_1),$$

where t_0 and t_2 are experimentally determined segmentation points, as above, and t_1 is mathematically unconstrained but experimentally determined by minimizing the rms error between the experimental and matching functions.

3. Discussion

Writing samples produced by two input methods were obtained from one subject and processed. The first utilized the handwriting transmitter mentioned above in which the writing is executed on a horizontal surface (Input 1). In the second the writing is executed on the vertical face of the TX-0 computer oscilloscope (Input 2). The rms error ratios (rms error/rms signal) have been calculated to obtain an indication of the matching accuracy for both velocity and displacement functions and are given in Table XV-1. The extension of these results to include data from different subjects is under way at the present time.

Table XV-1. Matching accuracy of handwriting models.

Model		Input 1[a]	Input 2[b]
A	Displacement Error	.047	.046
A	Velocity Error	.232	.112
B	Displacement Error	.039	.045
B	Velocity Error	.175	.088

[a]Average of 9 samples

[b]Average of 4 samples

It is immediately apparent that a relatively poor match in the velocity domain will, when integrated, result in a quite acceptable match in the displacement domain. Hence, for Input 1, the input method of major interest, while Model A can be considered adequate in the displacement domain, it appears inadequate for the study of the detailed

intrastroke kinematics that are observable only in the velocity domain. Model B clearly effects a significant improvement for the velocity error over Model A. The differences between the two models for Input 2, for which the major part of the writing movement is executed by the elbow and the upper arm rather than the wrist and fingers, are much reduced and thus indicate that the kinematics of the segments of positive and negative acceleration within any stroke are much more alike. The smaller errors obtained for Input 2 indicate that this mode of writing is smoother and corresponds more closely to a harmonic oscillator system.

For Model A five parameters $[\dot{X}, \dot{X}_c, \dot{Y}, \omega, \phi]$ and for Model B eight parameters $[\dot{X}_1, \dot{X}_2, \dot{X}_c, \dot{Y}, \omega_1, \omega_2, \phi_1, \phi_2]$ are required to be known for the regeneration of any stroke. In each case the validity of the approximation is revealed by the close match between the original and regenerated two-dimensional handwriting patterns. The representations also achieve a reduction in the information storage per word over function samples at the minimum sampling frequency for perfect signal recovery if the velocity function is considered bandlimited at 20 cps.

The usefulness of the models for recognition work is primarily determined by the statistical properties of the above-given parameters. Experimental studies of the variations in stroke parameters with writer and context, as well as their consistency in the absence of such variations, are now being carried out. It is desired to determine the conditional probability densities $p(v_j/s_i)$, where v_j is the jth parameter and s_i is the ith stroke group, and strokes are grouped according to topological similarities. If the information content of the parameters is sufficiently high, that is, if $p(v_j/s_k) \gg p(v_j/s_l)$ for all $k \neq l$, then reliable recognition of which stroke group the sample belongs to may be expected. The strong statistical constraints in sequences of particular strokes are to be used in the final identification of the individual letters.

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References

1. M. Eden, Handwriting and pattern recognition, IRE Trans., Vol. IT-8, pp. 160-166, 1962.

F. STROKE ANALYSIS OF DEVANAGARI CHARACTERS

Recent studies[1] of the characteristics of English cursive handwriting have raised the question whether writing systems unrelated to English might be a useful complementary study. For this purpose, the Devanagari script of India offers interesting possibilities because in its present form it has been fairly static for more than a thousand years, despite the development of closely related scripts, such as Bengali and Gujarati, which are much faster to write.

It is only in the past hundred years that mechanical methods of writing have become widespread in the West; and during the past decade strenuous efforts have been made to develop a satisfactory typewriter for Indian languages. Meanwhile, typesetting equipment that can produce aesthetically satisfying printed material is also being sought. At the present time, only hand-set type fonts making use of 400-800 pieces of type come close to looking authentic, and such useful devices as linotype have basic structural limitations that prevent them from accommodating such a variety of symbols.

Devanagari writing (used for Sanskrit, Hindi, Marathi, Punjabi, and in modified form for Gujarati and Bengali) is syllabic. That is, the unit of writing is the consonant (or consonant cluster) combined with the following vowel, which is written to the left, right, above or below. This combination is called an akshar. For example,

$$\text{stri} \Rightarrow \text{श} + \text{ट} + \text{र} + \text{ई} \Rightarrow \lceil + \text{ो} + C + \wedge + \overline{} \Rightarrow \text{स्ट्री}$$

Vowels have a special written form when they appear without a preceding consonant.

1. Research Objectives

The aim of this research, then, is to study the structure of the Devanagari symbols with a view toward understanding whether and how the consonants and consonant clusters (a brief survey uncovered 221 distinct clusters) can be generated, and described, distinguished or selected, in a consistent manner.

A consonant (or cluster) appearing alone is read as containing the "intrinsic" vowel, /ə/. Frequency studies in Hindi and Marathi show that the most frequent occurrences are of a single consonant with /ə/, and therefore we shall study the writing of the 33 Devanagari consonants first.

In this report a stroke analysis appropriate to Devanagari is presented, together with the joining rules for normal writing. These rules form a complete set with respect to generation of the consonants, as shown in Fig. XV-11.

2. Development of the Set of Basic Strokes

In contrast to English cursive script, penlifts occur in Devanagari even in the writing of a single "letter." Strokes are written from left to right and from top to bottom. There are very few exceptions. It is possible to develop most of the strokes by applying two kinds of transformations to a basic Straight Stroke $\downarrow$ /A/ and Curved Stroke $\subset$ /B/. We call the operator Reflection (about a vertical), α. We call the operator Rotation, β (Rotation by 45°, β_1; Rotation by 90°, β_2). Applying β_1 and β_2 to /A/, we get

$$A \downarrow \quad \beta_1 A \searrow \quad \beta_2 A \rightarrow \quad \beta_1\beta_2 A \nearrow \quad \beta_2^2 A \uparrow \quad \beta_1\beta_2^2 A \nwarrow \quad \beta_2^3 A \leftarrow$$
$$\beta_1\beta_2^3 A \swarrow$$

Of these, only the first four occur. They are labelled (for convenience, and to avoid

subscripts): /A/, /D/, /L/, /Q/. Applying a and β_2 to /B/, we get

$$\text{BG} \qquad \beta_2 \text{B}\cup \qquad \beta_2^2 \text{B}^{\circlearrowleft} \qquad \beta_2^3 \text{B}\curvearrowright$$

$$\alpha\beta\, \supset \qquad \alpha\beta_2 \text{B}\upsilon \qquad \alpha\beta_2^2 \text{BC} \qquad \alpha\beta_2^3 \text{B}\curvearrowright$$

Of these, all occur except the last. They are labelled (again, for convenience): /B/, /E/, /J/, /N/, /H/, /M/, /K/. Two other strokes ς /f/ and $\wr$ /g/ are reflections of each other. Two miscellaneous strokes $\wr$ /C/ and $\smile$ /P/ complete the set of 15 Basic Strokes.

The stroke sizes have been quantized to two levels. For the larger, we use upper-case labels; and for the smaller, we use lower-case labels. (Concerning the third Basic Stroke see II (iii) below.)

A. | a.', B.C b$^\text{c}$, c.$^{)}$J, d.\, e.U, F.ς, g.?, h.$\supset$,

J.$\supset$j.$\supset$, k.$^\text{c}$, ℓ.–, m.$^{\cup}$, n.$^{\cap}$, p.$\smile$, q./ .

For three strokes, both large and small sizes occur. In all other cases only the smaller size is utilized.

A distinctive feature of Devanagari is the top line that "ties" together the character (and is written last). Certain characters have a broken top line, and for these /(r)/ is added to the linear-form description of the character.

One other symbol, /s/, is used to signify a penlift. Where this is redundant information (the penlift being due to the direction in which the previous stroke was written), /$\not{s}$/ is used.

3. General Comments on Characteristic Features of the Strokes

We shall list some characteristic features of the strokes in a purely descriptive manner. Then we shall discuss some cases in which contextual clues are relevant to the role of the individual stroke in forming the characters. Relatively simple rules suffice to indicate whether the larger or smaller size of a given stroke is to be used in a given situation. Thus the same code could unambiguously apply to both. Similarly, in certain contexts a variant on the usual form (or shape) of a stroke is used. To simplify reading, we have retained the lower- and upper-case designations in the "linear forms" given in Fig. XV-11.

I. Characteristic Features of the Strokes

    (i) Written from top to bottom: A B c d F g h

        Written from left to right: d e l p q

        Written from right to left: c F m n

        Written from bottom to top: J k q

    (ii) Initial movement downward: A c d e m p

          Initial movement to right: d g h J p q

          Initial movement to left: B F k

          Initial movement upward: n q

  (iii) Requiring counterclockwise movement: B e f j m p

          Requiring clockwise movement: c g h n k

  (iv) Positioning in letter space: Height

              Always found at same distance below top line: A a B c F G J k 1 m p

              Height in character can vary: b d e h n q

The rarity of strokes written leftward or upward, as indicated in I (ii), is even more striking when the relative frequency of these strokes is taken into consideration.

The data of I (iv) indicate a high degree of redundancy, in that most strokes are not found except in certain regions of the letter space and may perhaps explain the readability of the script despite its complexity.

II. <u>Notes on Certain Strokes</u>

    (i) /A,a/ Both large and small forms are always written from the top line

              As an initial stroke, it occurs only as /a/

              As medial or final stroke, it occurs only as /A/

It is interesting to note that none of the characters has a vertical line segment except that hanging from the top line.

    (ii) /B,b/ As an initial stroke this occurs only as /b/, starts from the top line only in sequence /bb../. Otherwise it is written in the middle of the letter space.

              In medial position the form is /b/ in context /abh/; otherwise B as in aB, aBJ, aBn, aBjc.

    (iii) /c/   This stroke has two forms. It is written (J) when followed by /1/; otherwise it is written (Ɔ).

    (iv) /e/   In context /le../ the form is (↜) instead of the normal (∪).

    (v) /J,j/ In context /aBJ/ the form is (Ɔ̇); i.e., /J/. Otherwise (ᴐ), /j/.

    (vi) /1/   Always written at mid-height in letter space. The group /..1A../ is frequent and is uniformly written ⊣ .

4. General Rules of Formation of Characters from Strings of Strokes

The rules presented below may be considered a preliminary set. As formulated at present, they deal with the construction of the consonants. They have been left flexible, however, in order to accommodate the numerous and complex cases of conjunct characters. A significant feature of the rules is that transitional strokes are obviated except with /A/.
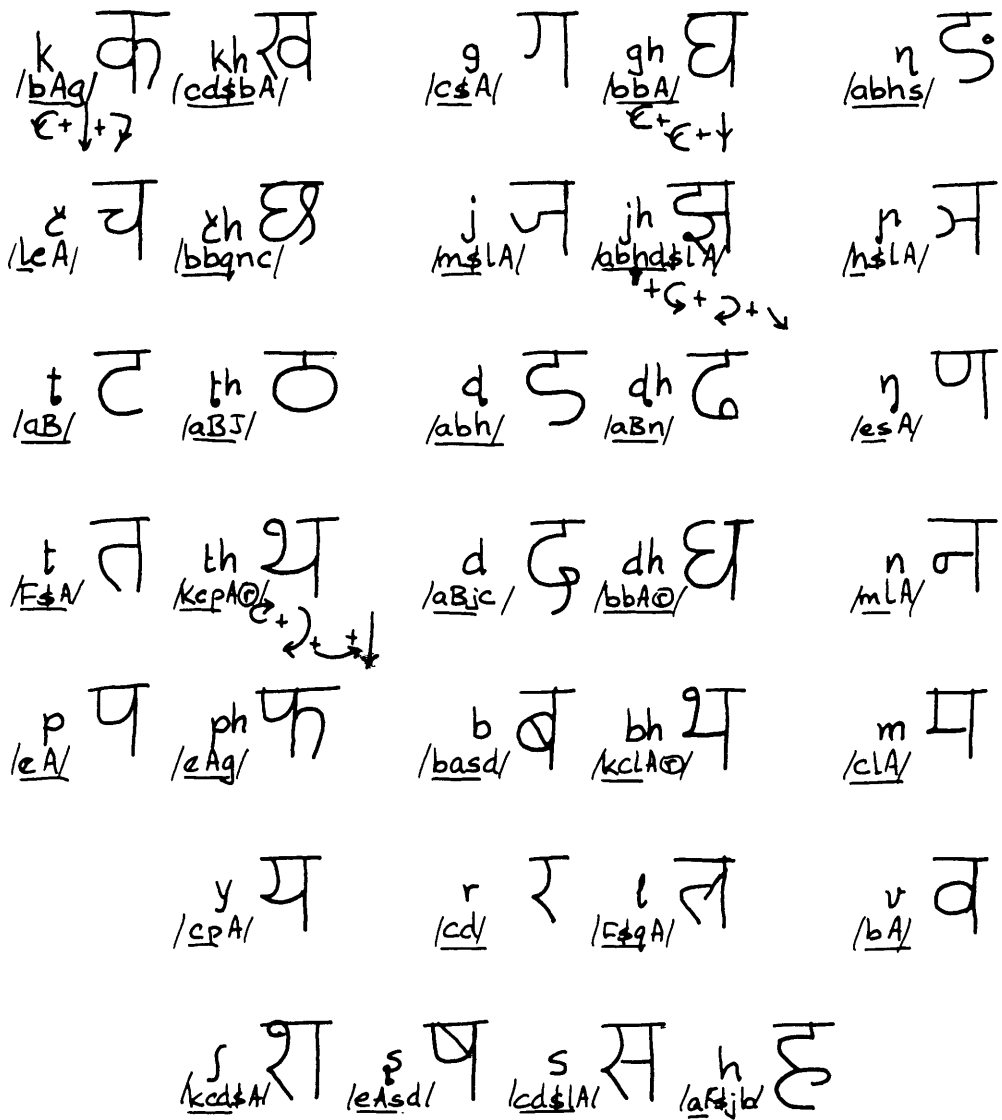
Fig. XV-11.   The 33 Devanagari consonants and their "linear" representation.

III. General Rules

(i) The highest point of the first stroke is always at the top line, except that initial /b/, /F/, /h/, /ℓ/, /m/ are written at mid-height. (Note that initial /bb../ is written from the top line.)

(ii) Strokes always commence from the end point of the previous stroke except as in III (v) below.

(iii) Mark /ʂ/ implies a penlift that is due to the direction of stroke, and is a redundant instruction. Mark /s/ implies a penlift that is due to the fact that the character has two segments, and implies a space left between the segments.

(iv) After the listed strokes comes the conventional top line. In cases in which the additional instruction /(r)/ is added, it implies that the top line is written over the right half of the character only.

(v) Added transitional strokes are used before and after /A/ as follows:

IV. Examples of Operation of the Rules

/b: * /bb: ℇ /bA/: ⟨ /bbq: ℰ⟩ /bbqn: ℰ⟩ /bbqnc: ℰ⟩ /bbqnc/: ℰ⟩

In the first example, * implies uncertainty till the sequence is known.

5. Remarks

The work reported here provides a means of uniquely generating the 33 consonants of the Devanagari alphabet from a set of 15 Basic Strokes. In Fig. XV-11 the stroke descriptions, which are essentially linear representations of two-dimensional characters, are underlined to the point where unambiguous identification is possible.

This work can be logically extended to the study of akshar formation and the adaptation of the present strokes and rules to this far more complex situation. In another direction lies the comparison of the script described in this report, as used in Sanskrit, Hindi, Marathi, and Punjabi, with related scripts. Gujarati on the West coast of India, and Bengali in the East, have developed written alphabets that are obviously offshoots of Sanskrit-Devanagari. The study of these scripts in relation to their parent writing form is not only of anthropological interest but also provides an opportunity for a comparative study of the cognitive roles of the constituent strokes in the related-but-different formations.

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References

1. M. Eden and M. Halle, The Characterization of Cursive Handwriting, Information Theory—Fourth London Symposium, edited by C. Cherry (Butterworths Scientific Publications, Washington, D. C., 1961).