ARPA ORDER NO. 189-1

MEMORANDUM
RM-4877-ARPA
SEPTEMBER 1966

A DIGITAL-COMPUTER MODEL OF SPIKE ELICITATION BY POSTSYNAPTIC POTENTIALS IN SINGLE NERVE CELLS

R. J. MacGregor

PREPARED FOR:
ADVANCED RESEARCH PROJECTS AGENCY

The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

The model described in this Memorandum is one result of a study of the characteristics of information-processing in single nerve cells and of neural encoding mechanisms in the primate visual system. This model can provide general information about single-cell integrating processes which should be applicable to visual cells, and it will be used in an investigation of specific neural connections in the visual system now under way at RAND.

The model was formulated and the preliminary results obtained at RAND under a contract from the Advanced Research Projects Agency; all of the preliminary study and much of the background work were performed at the Department of Aeronautics, Astronautics, and Engineering Sciences, Purdue University, where the author was a graduate student.

SUMMARY

This Memorandum presents a digital-computer model of the spike-elicitation process of single nerve cells. To provide background information for this model, an idealized neuron is described, and the basic elements of single-cell neuroelectric behavior that are relevant to this study are discussed.

The computer model simulates the portion of the neuron at which spike potentials are initiated. Values for parameters have been specified on the basis of neuroelectric recordings so that the results obtained might be pertinent to actual nerve cells. Preliminary results are included which verify that the model is producing physiologically meaningful data. Input-output relations under regular input are also included for a wide range of input frequency and pulse amplitude, and plans for future uses of the model are mentioned briefly.

ACKNOWLEDGMENTS

The author would like to express his appreciation to Paul S. Lykoudis of Purdue University, Donald H. Perkel of The RAND Corporation, and George P. Moore of UCLA for their valuable encouragement and advice.

CONTENTS

SYMBOLS

$A, a, b, c, d, k, m, n, r, \alpha, \beta, \delta, \xi, \chi$ = parameters defined by Eqs. (2) through (6)

DT = model testing interval

E = transmembrane potential

EPSP = excitatory postsynaptic potential

ER = afterpotential

g = membrane conductance

IPSP = inhibitory postsynaptic potential

PSC = postsynaptic cell

PSP = postsynaptic potential

T = model time

t = time

V_c = spike threshold

τ = spike initiation time

τ_i = PSP initiation time

ω_o = mean PSC firing frequency

I. AN IDEALIZED NEURON

In this section an idealized neuron is described to provide background information for the model described in Section II. It is not intended to be a complete description of actual neural behavior or a critical examination of experimental evidence relating to the mechanisms described;* simplifications and assumptions have been made, and these are indicated.

PHYSIOLOGY

In the idealized neuron, shown in Fig. 1, the cell membrane is semipermeable and thus is able to sustain a difference in composition between the fluid inside the cell and that external to it. The cell is immersed in a fluid characterized by a relatively low concentration of potassium ions and relatively high concentrations of sodium and chloride ions. The relative concentrations of these ions in the intracellular fluid, on the other hand, are just the reverse (high K^+, low Na^+ and Cl^-). These differing ion concentrations in the external and internal fluids result in a potential difference across the cell membrane.

During the course of cell function, the permeability of the membrane to the different ions changes, resulting in a flow of ions through the membrane and consequent variation of the transmembrane potential. Recordings of these transmembrane-potential variations (and their correlations to physical parameters of sensory stimuli or muscle movement) are the basis of most investigations of neural encoding mechanisms and information-processing.

The idealized neuron can be divided into three regions on the basis of different electrical characteristics (see Fig. 1). Region I comprises the dendrites and soma (cell body) and is characterized by smooth, graded, low-level potential changes. Region II comprises the axon and termination fibers and is characterized by a train of discrete potential changes of large amplitude (spikes), which are essentially identical in

*References 1, 2, and 3 present more thorough discussions of the ideas discussed here.

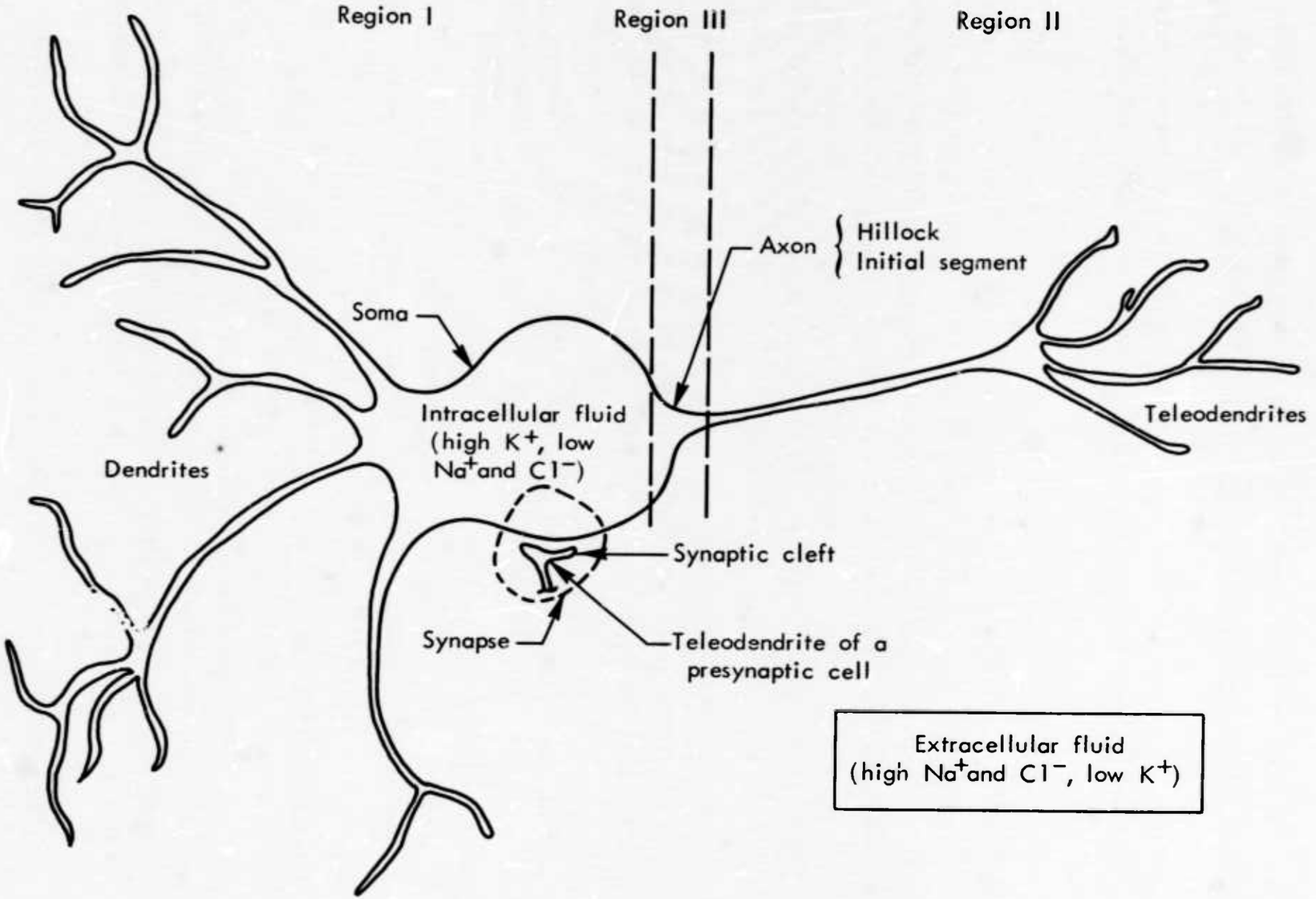

Fig. 1—Idealized neuron

form. Region III comprises the axon hillock (where the axon sprouts from the soma), in which incoming impulses are integrated and outgoing spike trains are initiated.

A description of the potential changes occurring in each of these regions and an indication of the ionic bases of these changes follows.

The Dendrites and Soma: Incoming Information

The information arriving at the soma and dendrites of a given cell is carried by the axonal terminations of preceding cells and is thus in the form of a time series of pulses.

A synaptic connection between neurons is functionally either excitatory or inhibitory. Figure 2 shows a recording of the potential change at the postsynaptic soma following a presynaptic pulse at an excitatory synapse; such a response is called an excitatory postsynaptic potential (EPSP). It is postulated that the following ionic process subserves these EPSPs: A chemical transmitter substance is released from the surface of a presynaptic axonal termination adjacent to the synaptic cleft by a spike in that axon. This transmitter diffuses across the synaptic cleft and causes a brief, very large increase in the permeability of the subsynaptic membrane to all ions.

Figure 3 shows a recording of the postsynaptic somatic potential following a presynaptic pulse at an inhibitory synapse (inhibitory postsynaptic potential, IPSP). The ionic hypothesis relating to these potentials is essentially the same as that for the EPSPs, except that the permeability change in the subsynaptic membrane is conceived as selective: Permeability to K^+ and Cl^- is increased (again greatly and briefly), while the larger Na^+ ions are prevented from passing through.

The postsynaptic potentials (PSPs) shown in Figs. 2 and 3 are associated with synapses upon the soma. The PSPs are modified if the synapse is on a dendrite some distance from the soma, necessitating transmission of the signal along the membrane. This transmission is associated with a passive membrane (i.e., no permeability changes) and is referred to as "electrotonus." Equation (1) describes this process:[4,5]

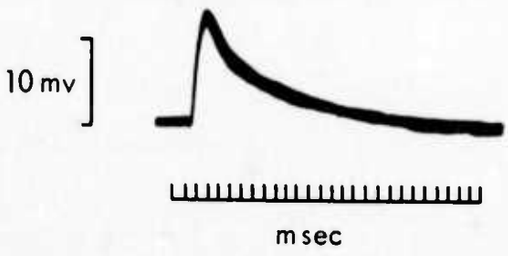

Fig. 2—Excitatory postsynaptic potential (EPSP)[2]

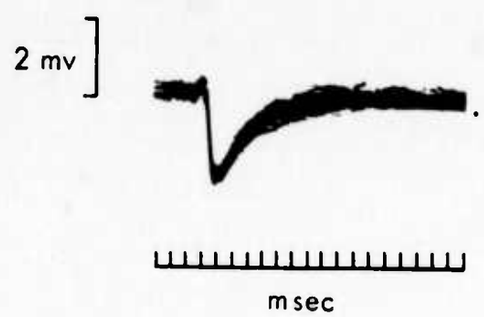

Fig. 3—Inhibitory postsynaptic potential (IPSP)[2]

$$\frac{\partial E}{\partial t} = \nabla^2 E - E \qquad (1)$$

where E is the transmembrane potential; the spatial coordinates implied by the Laplacian operator and the time, t, are normalized with regard to membrane parameters. In this process, PSPs are spread out in time and decreased in amplitude.[4] The effect of the location of the synapse, according to Rall,[6,7] is shown in Fig. 4.

Another influence on PSPs at their site of initiation is the transmembrane potential extant at the time of their arrival. The potentials are a reflection of ion concentrations and fluxes across the membrane, the magnitudes of which, in turn, depend on the potential which represents a driving force in the process. Excitatory (depolarizing) and inhibitory (hyperpolarizing) PSPs are associated with different combinations of membrane permeabilities and, therefore, ion fluxes and hence exhibit different dependencies on the transmembrane potential. The observed effect on PSP peak amplitude is shown in Fig. 5. The equilibrium potential of the EPSP is some 7 to 10 times farther removed from the normal resting potential than that of the IPSP.[2] Thus, this effect would appear to be more crucial in the latter.

The shapes of individual PSPs arriving at the soma, then, are determined by (1) the relative efficacy of the synapse at which the PSP originated (i.e., the width of the synaptic cleft, the surface areas of the membranes involved, and the mechanisms of transmitter release, action, and removal), (2) the length and geometry of postsynaptic membrane over which the PSP must be transmitted, (3) the properties of the postsynaptic membrane (essentially, the permeabilities to the different ion types), and (4) the transmembrane potential extant at the time of PSP initiation.

The amount of transmitter released per input pulse at a given synapse may depend on the frequency of firing in the appropriate termination; furthermore, a transient phase may occur when the firing of the presynaptic cell is started from rest.[2] These effects also influence the amplitude of the associated PSPs.

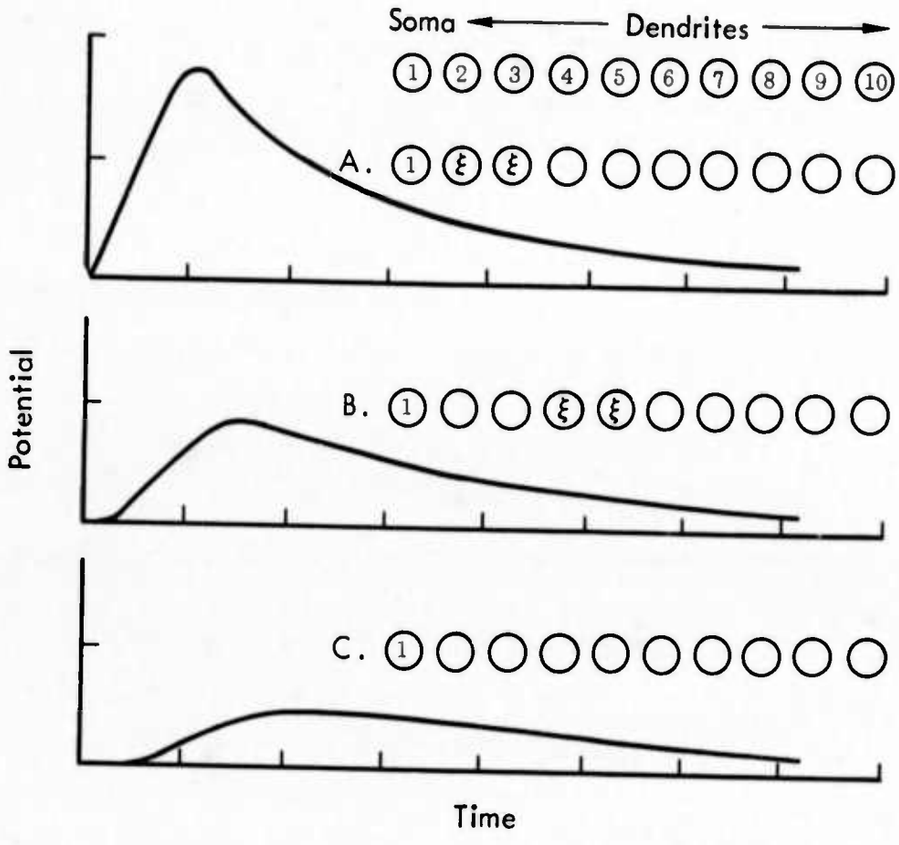

Fig. 4—Effect of dendritic location of synapse on EPSP[7] (marked circles indicate relative locations of synapses)

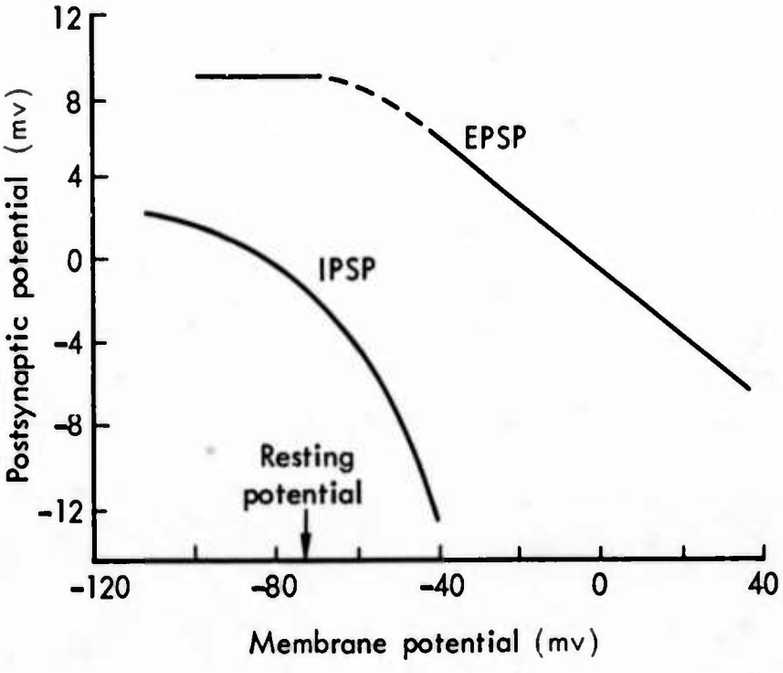

Fig.5—Dependence of PSP on potential [3]

The Axon and Its Terminations: Outgoing Information

The information transmitted down the cell axon to succeeding cells or muscles consists of a time series of essentially identical spikes.(8) Such a spike train is shown in Fig. 6.

The membrane-permeability changes associated with these trains of pulses are shown in Fig. 7. The permeability to Na^+ increases before the permeability to K^+. The former decreases to its normal value quickly but is nonetheless responsible for the large increase in intracellular potential.* The subsequent increase in permeability to K^+ is responsible for the sharp return of the potential to its resting level, and its relatively long-lasting tail probably is the basis of the hyperpolarized "afterpotential" (see Fig. 7).

Spike trains may differ greatly in the order and length of time intervals between spikes.(8) Furthermore, other cells transmit similar spike trains to the same postsynaptic cell. The spike-elicitation process may be sensitive to small differences among temporal patterns of input, and this sensitivity may be important in normal function.

The Axon Hillock: Information-Processing

The axon hillock (or "initial segment") is the part of the neuron at which the incoming PSPs are integrated and the outgoing spike trains are initiated. The amplitude and time course of an individual PSP arriving at the axon hillock are determined essentially by the factors listed above.

If the cell has not initiated a spike for a relatively long time, the hillock membrane may be considered passive. In this case, the incoming PSPs are combined via an operation which deviates from a linear algebraic summation only in a small effect resulting from the accumulated hillock membrane potential. (This operation is called "temporal summation" when all the PSPs are initiated at the same synapse and "spatial summation" when they come from different synapses.) A typical

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*The transmembrane equilibrium-potential values (internal minus external) of Na^+, K^+, and Cl^- are roughly +65, -95, -90 mv, respectively. A typical "resting potential" would be -70 mv.

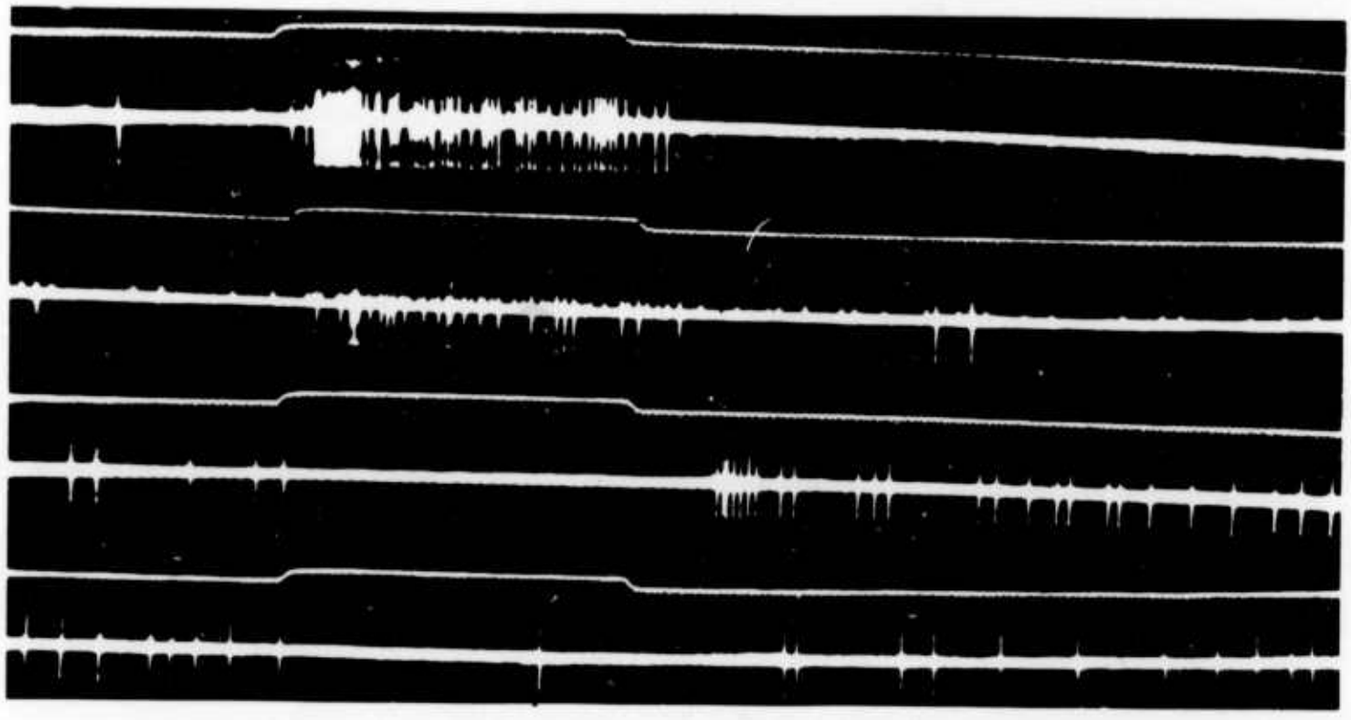

Fig. 6—Spike trains in lateral geniculate nucleus [9]

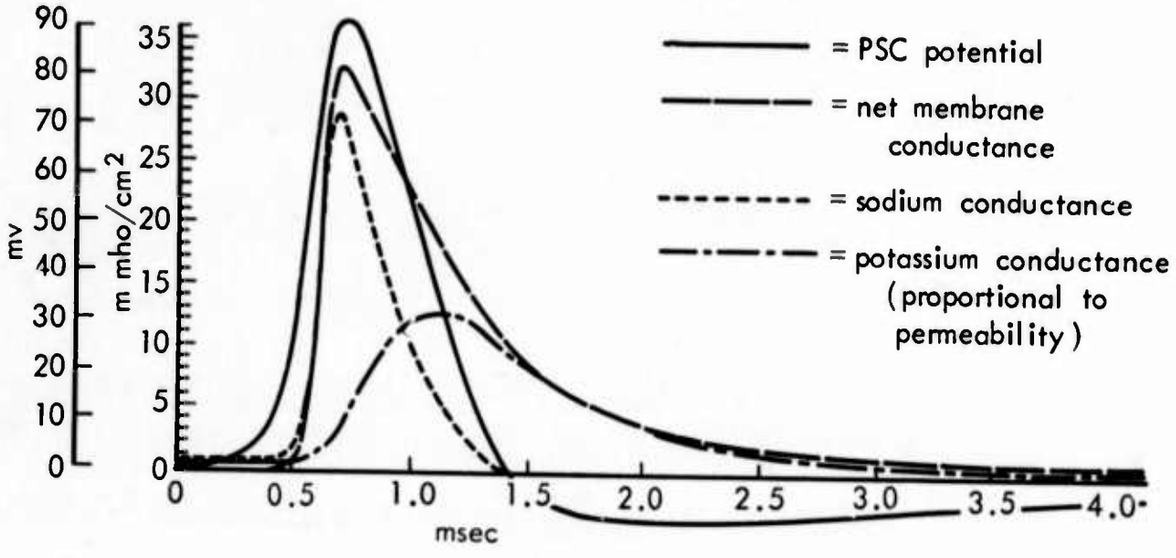

Fig. 7—Spike potential and associated permeability changes [10]

recording of such a summation process is shown in Fig. 8. This process continues until the potential at the hillock exceeds a certain critical value called the "threshold" potential. If this potential is exceeded, the permeability changes shown in Fig. 7 and the concomitant spike ensue.

In normal operation, the cell transmits a series of spikes, and the passive-membrane mechanism is modified by two occurrences which follow a spike: First, the threshold potential is essentially infinite for a finite period of time following a spike, so no two spikes may be closer together in time than that interval; the threshold then declines essentially exponentially to its resting value.[11] Second, the permeability changes associated with the pulse have two ramifications: (1) they bring about a spike afterpotential which is significantly different from the resting level (see Fig. 7) and upon which incoming PSPs are superimposed, and (2) they affect the time courses (and indirectly the amplitudes) of any PSPs arriving at the hillock during their existence. The effect of any PSP arriving during the large Na^+ permeability change associated with the spike is very nearly obliterated. The permeability value drastically alters the shape and magnitude of the PSP and simply incorporates it into the spike. Also, any driving force associated with the PSP is quite small relative to that of the spike. However, as the spike potential rapidly diminishes, PSPs arriving at its later stages are again significant and the marked influence of the "tail" of the K^+ permeability change on their time courses is critical to the integrating mechanism. This increased K^+ permeability diminishes the EPSP and facilitates the IPSP. Figure 9, taken from Ref. 12, illustrates this effect on excitatory input. (The curves in (b) of Fig. 9 are obtained by subtracting the afterpotential from a superposition of the afterpotential and single EPSPs initiated at several different time intervals after the spike.) It should be noted that both of these postspike influences, the raised threshold and the increased permeabilities (with the consequent afterpotential and influences on the excitatory and inhibitory PSPs), tend to reduce the effectiveness of a given set of PSPs for releasing another spike. Hence, the set of effects collectively determines the "relative refractory period."

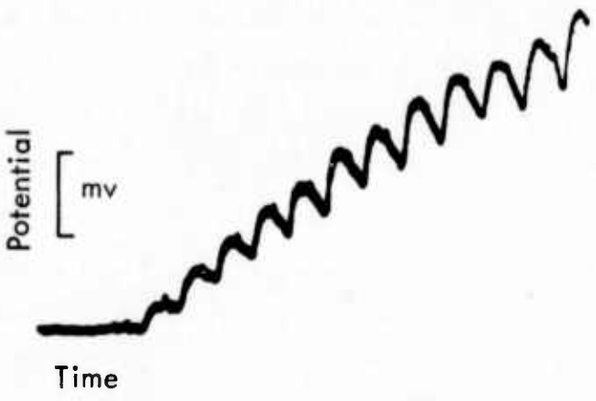

Fig. 8—Subthreshold summation process [2]

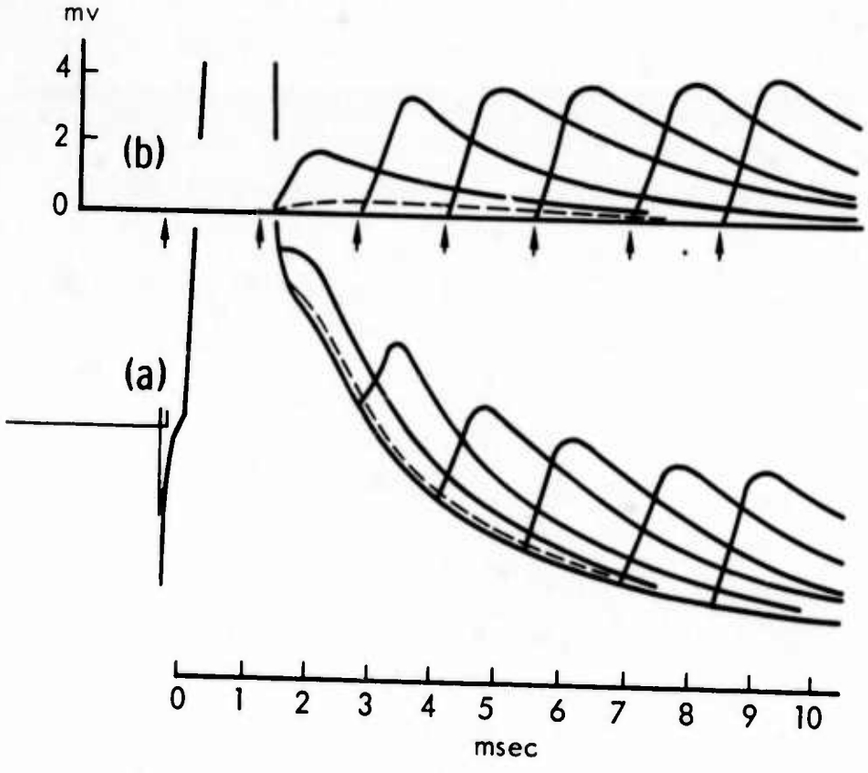

Fig. 9—Postspike EPSP modification [12]
(arrows indicate initiation times
of single EPSPs)

In summary, then, the spike-triggering mechanism (comprised of (1) PSP summation and (2) permeability changes triggered at a threshold potential) occurring across an active membrane differs from that across a passive membrane essentially by exhibiting the phenomena of absolute and relative refractoriness.

DISCUSSION

The properties of the idealized neuron are based on the electrical activities of real nerve cells. However, real cells do deviate from the idealization in several ways.

Some nerve cells may be subdivided into several zones, each of which exhibits electrical characteristics differing from those of the others.[13,14] Furthermore, some cells exhibit various duplications of regions; for example, two axons which may simultaneously carry different spike patterns,[15] or more than one triggering section.[2,14] Neurons exhibit great diversity in their branching, geometry, and distribution of dendrites.[16] The responses of many cells depend on input history prior to the last postsynaptic spike.[2,3,14] At least one investigator, Wall, believes that the dendritic[17] and axon-termination[18] regions are sites of integration mechanisms which are not contained in the subsynaptic membrane changes and electrotonus of this idealized cell. Randomness and spontaneous activity appear in some cells,[19,20] and real neurons sometimes interact nonsynaptically.[14,21]

Furthermore, there is diversity in the degrees to which single cells exhibit any or all of these phenomena,[3] and neuron parameters, although usually comparable for similar cells in a given species, vary among species and different locations in the same animal.[2,3]

The relative importance of these facets of neural function is for the most part a matter of speculation. However, the mechanisms of the idealized neuron do seem to be common to most cells and probably describe with reasonable accuracy the gamut of function in at least some.

II. A MATHEMATICAL MODEL OF SPIKE ELICITATION

INTRODUCTION

The model described here simulates the elicitation of trains of spikes by postsynaptic potentials (PSPs). Values of all the parameters used here have been chosen on the basis of neurophysiological findings, specifically, on electrical recordings from cat motoneurons. In this regard, the model differs fundamentally from the numerous more abstract models designed to examine global properties of networks or random collections of neuron-like elements. This model also differs from other realistic models, such as the electronic analogs of Harmon,[22] Lewis,[23] and Jenik,[24] and the digital simulation of Perkel,[25] in several respects, including the dependence of PSP amplitude on membrane potential.

THE MODEL*

The state of the triggering section of the postsynaptic cell (PSC) at any instant in time is completely determined by the values at that time of two variables: the transmembrane potential, E, and the PSC threshold, V_c. The value of V_c at any time, t, is given by

$$V_c(t) = V_{c_\infty}\left\{1 + ae^{-b(t-\tau)}\right\} \qquad t > \tau \tag{2}$$

where V_{c_∞}, a, and b are parameters characteristic of the PSC, and τ is the time of occurrence of the last PSC spike. The value of E at t is determined by

$$E(t) = ER + \Sigma EPSP_i - \Sigma IPSP_i \tag{3}$$

where ER is the afterpotential, and EPSP and IPSP are excitatory and inhibitory postsynaptic potentials, respectively. The values of these variables at t are determined by

*The values of parameters appearing in Eqs. (2) through (6) have been chosen to make those equations match experimental data.

$$ER(t) = A\left\{e^{-c(t-\tau)} - ke^{-d(t-\tau)}\right\} \qquad t > \tau \qquad (4a)$$

$$EPSP_i = \xi_j\left\{e^{-\alpha(t-\tau_i)} - e^{-\beta(t-\tau_i)}\right\} \qquad t > \tau_i \qquad (4b)$$

$$IPSP_i = \delta_j\left\{e^{-\eta(t-\tau_i)} - e^{-\chi(t-\tau_i)}\right\} \qquad t > \tau_i \qquad (4c)$$

where A, c, k, and d are parameters characteristic of the PSC; α, β, η, and χ are parameters characteristic of the PSC and the location on the cell at which the appropriate hypothetical synapse occurs; ξ_j and δ_j are parameters determining the relative efficacy of the given synaptic junction; and τ_i is the initiation time of the i^{th} EPSP or IPSP.

At any given time, the triggering section is characterized by one of two states: the PSC is either initiating a spike (State 1), or it is not (State 2). It is said to be in State 1 if and only if $E > V_c$; otherwise, it is in State 2.

Incorporated Physiological Features

As indicated by Eq. (3), spatial* and temporal summations of the individual EPSPs and IPSPs occur in the model. The amplitudes of the PSPs, ξ_j and δ_j, are made to depend (via Eqs. (5a) and (5b)) on the average potential, $\bar{E}$, which would exist over the time interval in which they are initiated in the absence of those PSPs which are initiated in that interval:

$$\xi_j = \xi\{1 + m\bar{E}\} \qquad (5a)$$

$$\delta_j = \delta\{1 + m\bar{E}\} \qquad (5b)$$

*Here, spatial summation is equivalent to adding EPSPs from separate input channels.

where ξ and δ are parameters characteristic of the appropriate synaptic junctions, and m represents characteristics of both the PSC and the input channel.

An absolute refractory period is incorporated in the model by simply assuming the triggering section to be in State 2 for an interval following the occurrence of a spike.

Following the initiation of a PSC spike (i.e., the existence of State 1) at a time t^*, several modifications are made in the operation of the model. First, the value of the variable τ is reset to t^*. Thus the potential ER exhibits the common spike afterpotentials via Eq. (4a), and the threshold V_c declines exponentially after rising as determined by Eq. (2). Second, all input-channel initiation times are updated so that all EPSPs and IPSPs initiated prior to t^* have no effect after t^*. Third, the values of α and η, which determine the amplitudes and time courses of PSPs initiated after t^*, are made to vary as follows:[†]

$$\alpha = \alpha_\infty\{1 + re^{-n(t-\tau)}\} \tag{6a}$$

$$\eta = \eta_\infty\{1 + re^{-n(t-\tau)}\} \tag{6b}$$

where α_∞ and η_∞ are parameters characteristic of the PSC and the location of the synapses, and r and n represent the PSC solely. These modifications collectively define the relative refractory period.

FORTRAN Program and Machine Operation

The program allows for up to 100 input channels (excitatory or inhibitory). Any given channel must fire at equal, regular intervals, and the parameters ξ, α, β, δ, m, η, and χ are the same for all pulses in one channel. However, these values, the firing frequency, and the initiation and cessation times may be set independently for each channel.

[†]These relations have been used to make the model forms of Eqs. (4) match the data of Fig. 9. It appears reasonable to interpret them as reflections of the potassium-permeability tail (see Fig. 7).

All other parameters characterizing the PSC may be set at the initiation of a run, and they apply to all input channels where appropriate.

The logic of the program and the details of its execution may be seen in Fig. 10. It should be noted that although the model takes the time continuum into a set of discrete values, it does contain a mechanism for focusing on the times of spike occurrence and obtaining those times to any desired degree of accuracy.

The program output may contain either subthreshold potential values, PSC spike times (or, equivalently, ordered interspike intervals), or both. Furthermore, output at either level may be in the form of punched cards* and/or direct printout of numbers and/or graphs.

DISCUSSION OF MODEL

The model, in essence, represents only the triggering mechanism of the idealized neuron of Section I. It would appear that the validity of the triggering mechanism under discussion is quite well established and that the verisimilitude of the model at this level is high.

If the model is conceived to represent an entire neuron, the validity of the idealized neuron becomes much more significant. Since the PSPs are thought to arise from firing in presynaptic cells and to be transmitted over postsynaptic membranes, the relation of the model's programmed PSP characteristics to those in a real postsynaptic cell is crucial if the model results are to be interpreted as neuronal input-output functions. The relative importance of dendritic PSP interaction also becomes significant.(4)

The model has several shortcomings. For example, it contains no allowance for habituation or accommodation in the postsynaptic cell. Furthermore, the model input is expressed only in the form of PSPs; consequently, the possibility of other influences (e.g., ephaptic and nonsynaptic subthreshold transmission) is not readily incorporated.

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*The punched interspike-interval cards can be fed directly to a statistical spike-train-analysis program (PANCHO) developed at RAND by D. H. Perkel.(26)

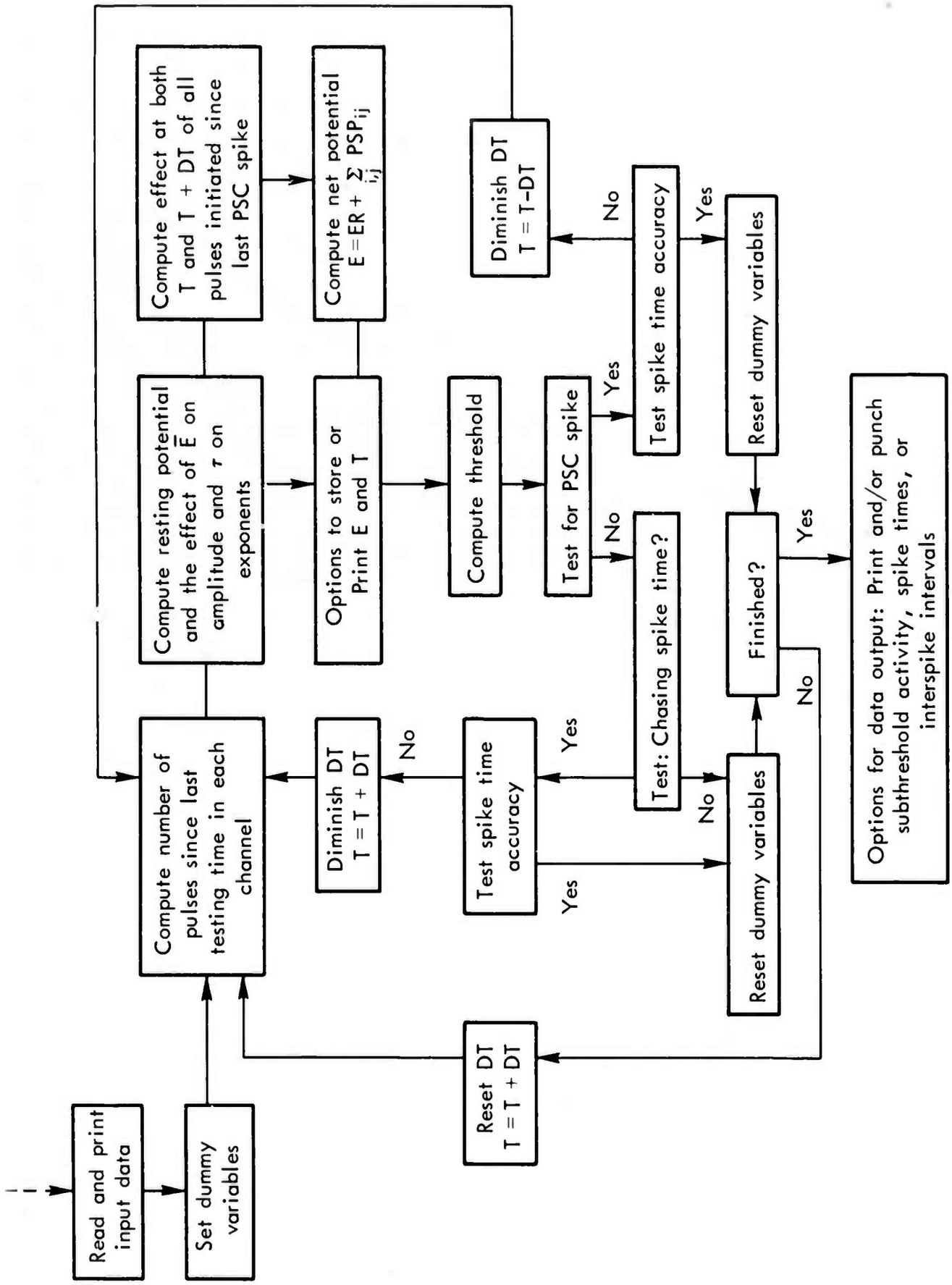

Fig. 10—Model flow diagram

If one is considering an excitatory synapse on a dendrite, the relation of the transmembrane potential at the dendrite to that at the hillock must be specified before the dependence of the EPSP amplitude on the variable $\bar{E}$ can be specified. On the other hand, if most inhibitory synapses end directly upon the soma, as is suggested by Eccles,[2] it is reasonable to assume that the potential across such a synapse is the same as that across the hillock membrane (and is thus represented by $\bar{E}$).

Since each input channel must fire at constant intervals, there is a limit to how much the input temporal pattern may be varied when such input is to be considered active over relatively long time periods. However, since each input channel may be initiated and stopped arbitrarily, and all parameters and input characteristics are specified by the operator, it is possible to examine variable input patterns over short periods.

It is possible that if the testing interval (DT) is too large, some spikes may be missed. However, it is felt that this possibility will become significant only when an EPSP is followed very closely by an IPSP. Further investigation is needed on this point.

Many interesting questions may be examined, despite the built-in restrictions of the model. For example, input-output relations for the simplest possible case of one excitatory input through the gamut of amplitude and frequency obtained from this model may be compared with those of previous models and related to neural data; phase effects (relating both to PSP initiation time relative to postsynaptic-spike occurrence and to relative initiation times of different PSPs) may be examined; and the relative efficiency of synapses located at various distances from the soma may be explored (at least to a first approximation) by altering the appropriate PSP exponents.

It is anticipated that results will be quite sensitive to the values given to various parameters in the mechanism, and that this may provide information on the effects of individual variations in actual neuron populations.

PRELIMINARY RESULTS AND PLANS

Preliminary Results

The results given here are those of trial runs, the sole purpose of which was to establish that the model was operating correctly and reproducing the functional forms of neuroelectric data accurately.

Figure 11 shows an EPSP obtained from the model (see Eq. (3b)), along with an average of several actual EPSPs. (The curves are comparable to that in Fig. 2.) Figure 12 shows several calculated IPSPs and an average of several actual IPSPs* (see also Fig. 3). All the calculated IPSPs were assumed to have the same synaptic efficacy (i.e., the same δ); the amplitudes were made to change by varying the transmembrane potential extant at the time of their initiation (see Eqs. (4c) and (5), and Fig. 5). The spike afterpotential obtained via Eq. (4a) is compared to an actual recording in Fig. 13.

Figure 14 exhibits the dependence of the calculated EPSP on the time interval between PSC spikes (see Eqs. (4b) and (6)). The average of actual data showing this effect, upon which the choice of values for r and n was based, may be seen in Fig. 9.

The summation process of Eq. (3) is displayed in Fig. 15. Curves (a) and (b) reflect temporal summation in that only one excitatory channel is used in both cases. The synaptic strength (i.e., α of Eq. (4b)) is higher in (b), the difference being such that the summation process is seen to saturate in (a) with no spikes initiated, while the threshold is attained in (b) with the implication of spike initiation and the onset of the afterspike modifications discussed on pp. 14 - 16. Curve (c) of Fig. 15 reflects spatial summation in that three separate excitatory input channels are used. The channels have identical characteristics except for their initiation times. Again, spikes are initiated.

Figure 16 shows an interaction between one excitatory channel and the inhibitory mechanism and illustrates the effect of cessation of input activity. (The hyperpolarized tail exhibited reflects the after-

*No attempt was made to incorporate the small depolarization exhibited in the actual data.

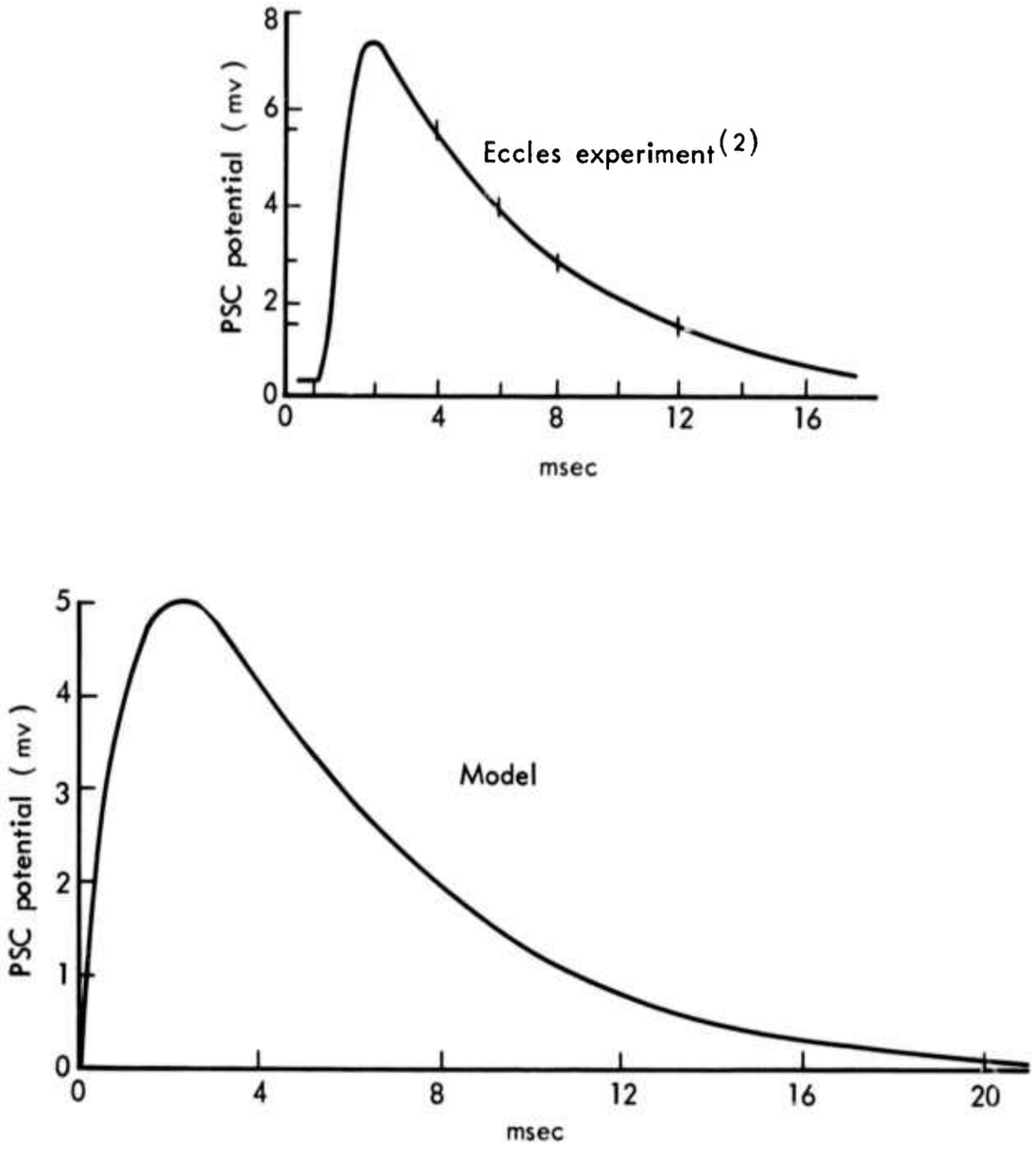

Fig. 11—Model and experimental EPSPs

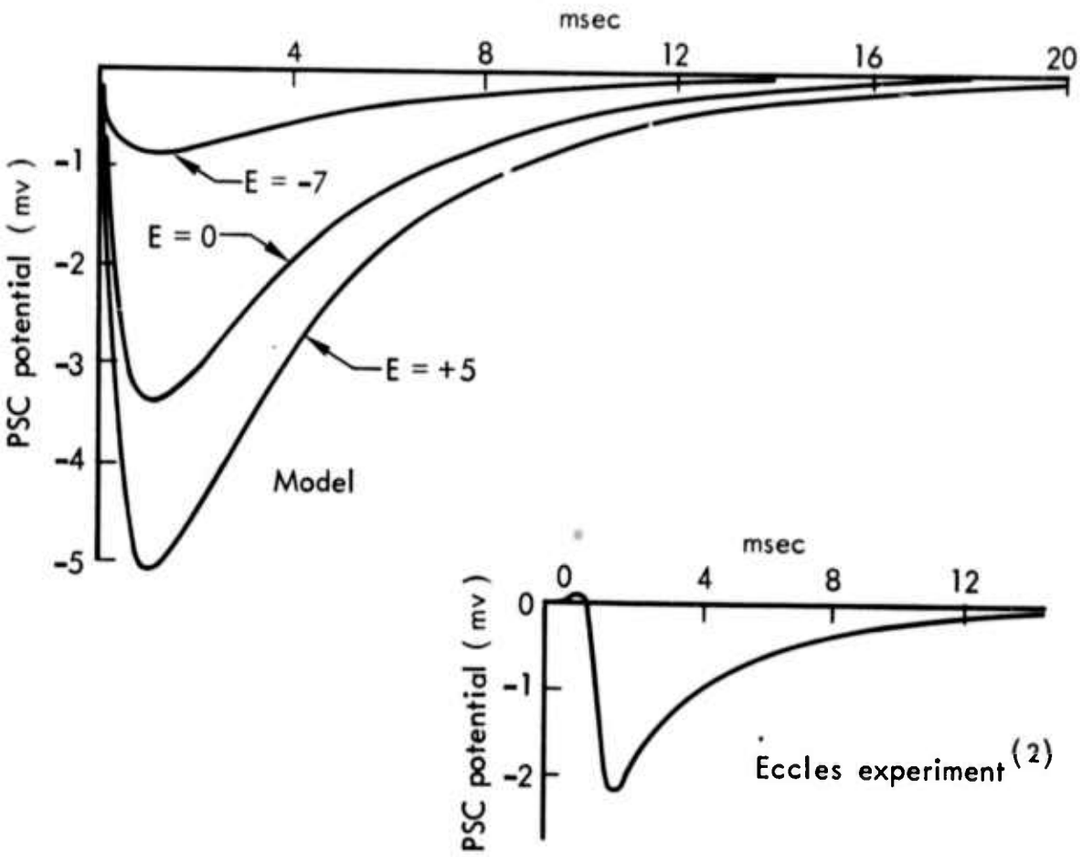

Fig. 12—Model and experimental IPSPs

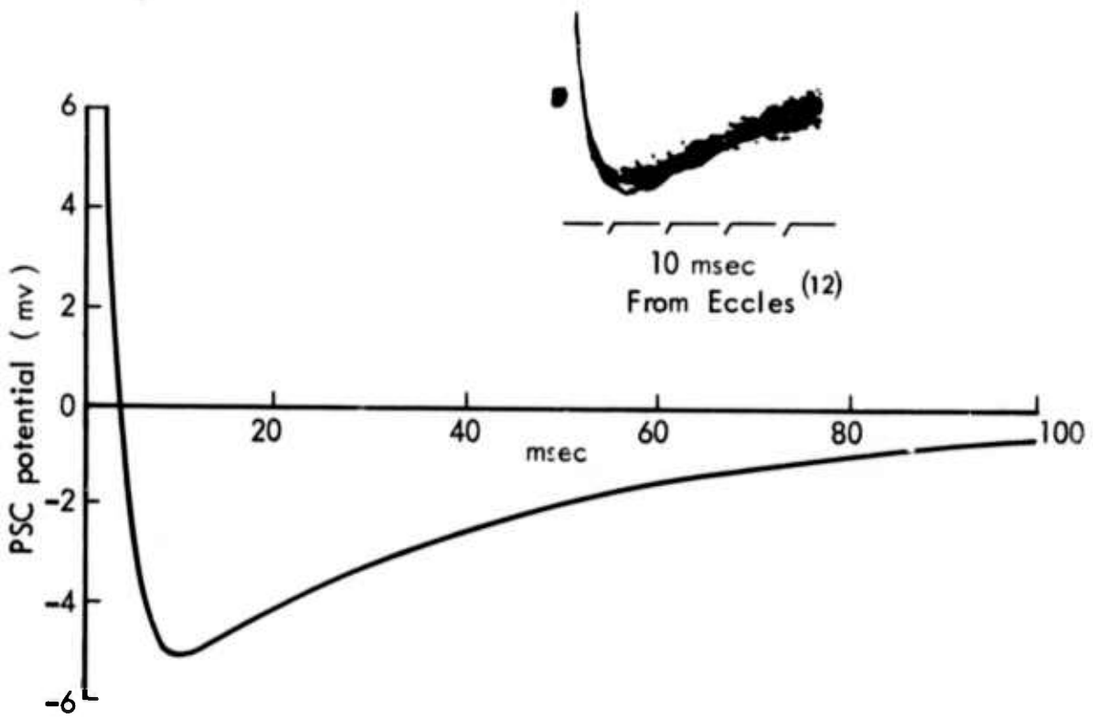

Fig. 13—Model and experimental afterpotentials

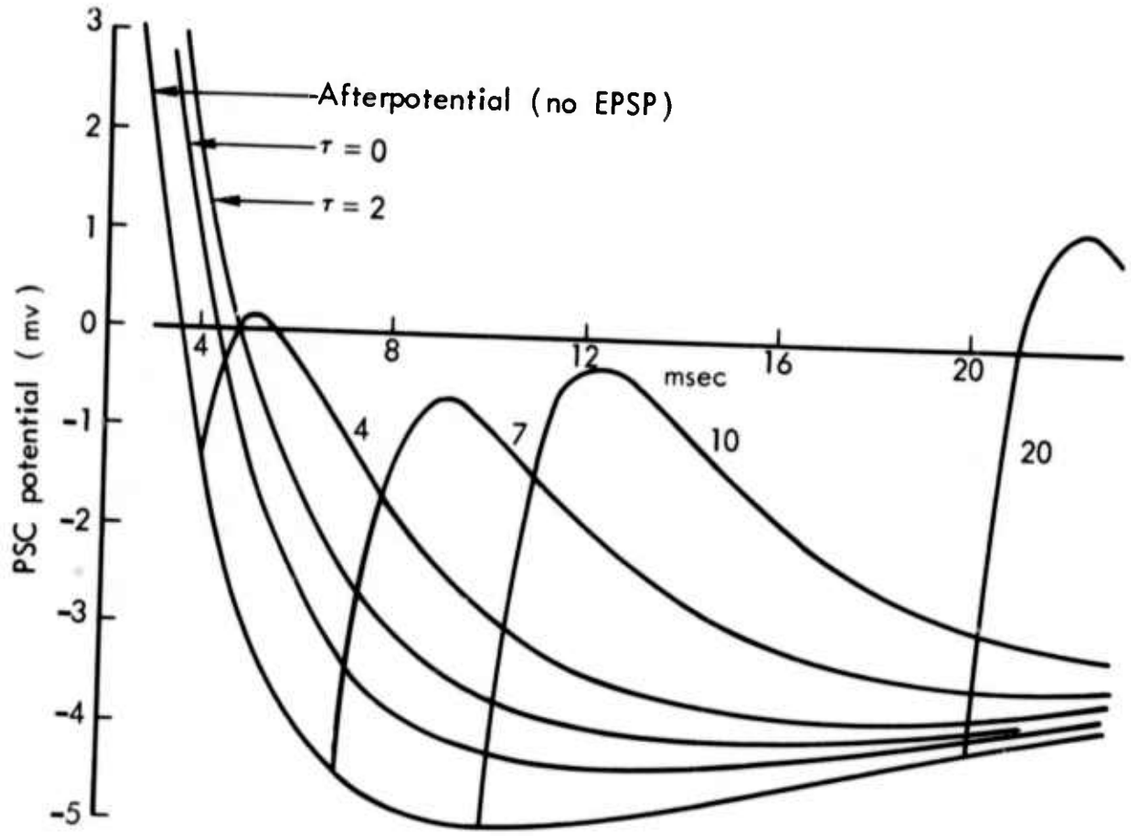

Fig. 14—Postspike effect on model EPSP

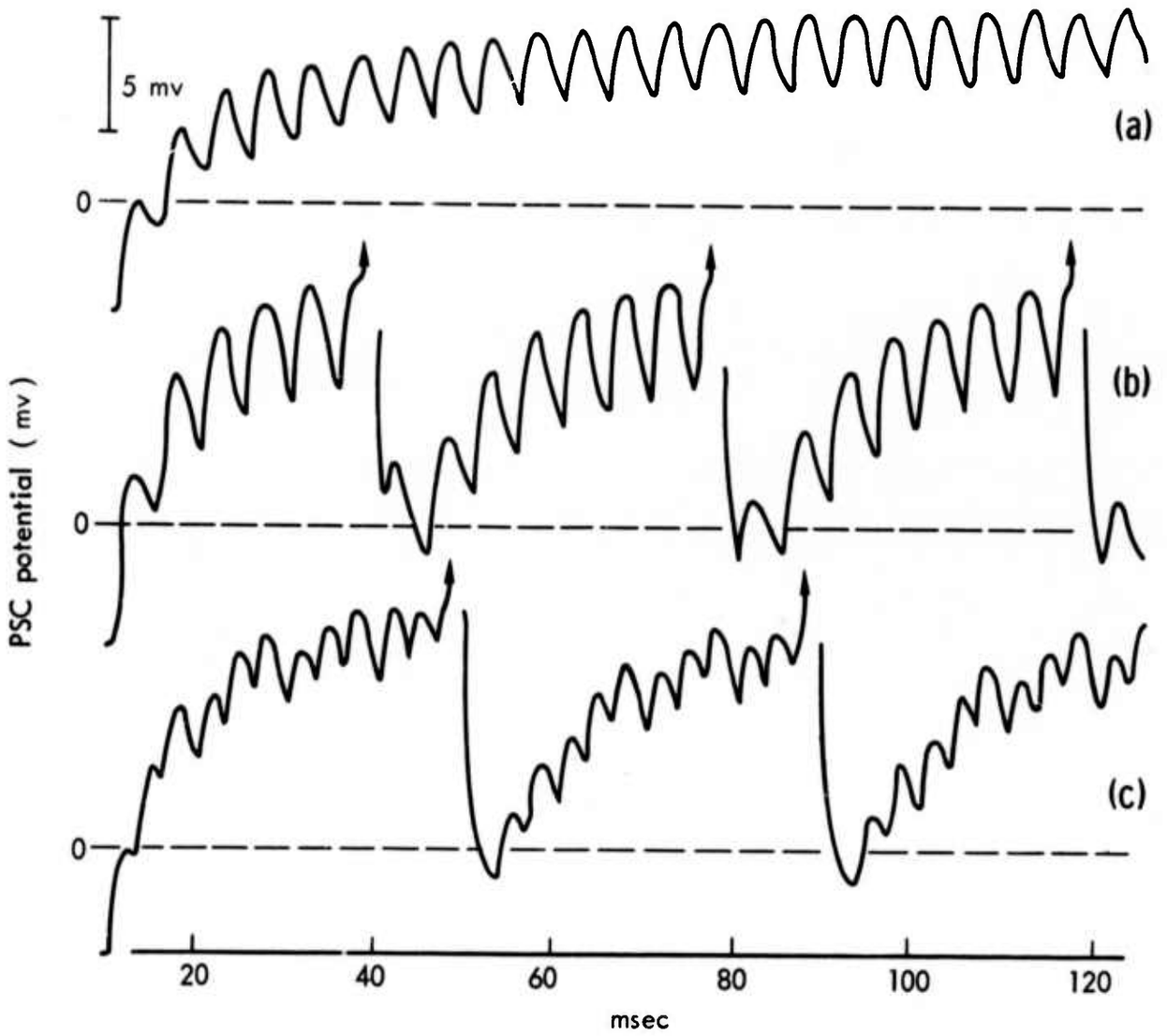

Fig. 15—Spatial and temporal summation in model

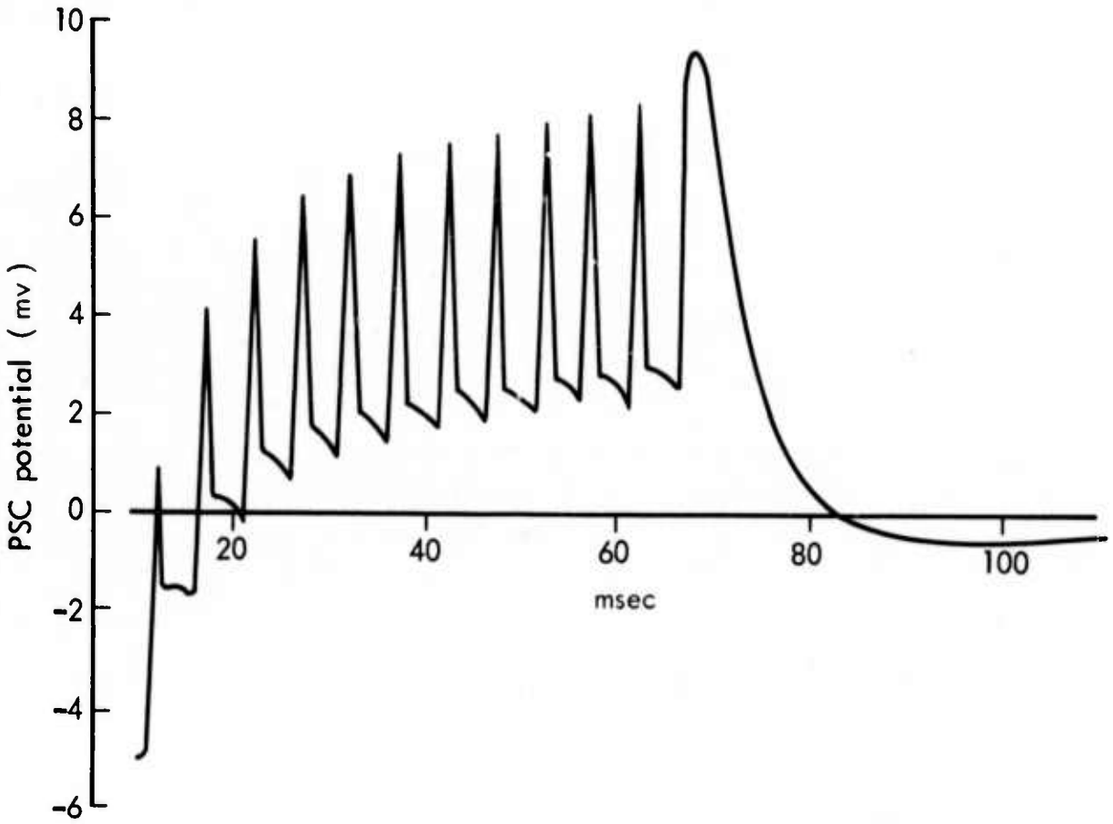

Fig. 16—EPSP and IPSP interaction in model

potential of a spike which has occurred at time t = 0, rather than a long-lasting IPSP.)

Input-Output Relations With Regular Input

Here, the case of one excitatory input firing at a constant, regular frequency is considered. Figure 17a shows PSC mean firing frequency as a function of regular input frequency and strength. It is seen that the response varies with input frequency at a given strength in a stepwise manner. Each plateau on such a "staircase" is associated with a constant number of input pulses necessary to produce a PSC spike. (Figure 17b shows the same data in a different form.) The dependence of PSP amplitude on potential was deleted for the present cases.

One "transition" region, corresponding to $\xi = 22$ and input frequency between 220 and 250 pulses/sec, was examined in some detail, as may be seen in Fig. 17a. An interesting result is the difference in response quality between the plateau and transition regions. In the former, the responses in all cases attained a single steady-state interspike interval and maintained this interval indefinitely. The characteristics of the brief transient were dependent on the phase of the first input pulse relative to an output spike which occurred at time zero, but the steady-state interval achieved was characteristic of the input frequency and strength only and was independent of this phase, as may be seen in Table 1.

The responses in the transition regions were similarly independent of initial phase (see Table 1) but did not exhibit a uniform firing pattern. Firing patterns within the transition regions exhibited a cascaded effect: Upon departing from a single-interval plateau, the response was seen to display a periodic, multimodal, interspike-interval pattern. The number of modes, n, decreased monotonically, approaching a minimum of two about half-way to the next plateau, then increased monotonically, apparently without bound, until the next unimodal plateau was reached. An interesting facet of this behavior is that the values of n determined another series of steps within the transition region, each of which was characterized by a transfer efficiency (i.e., number

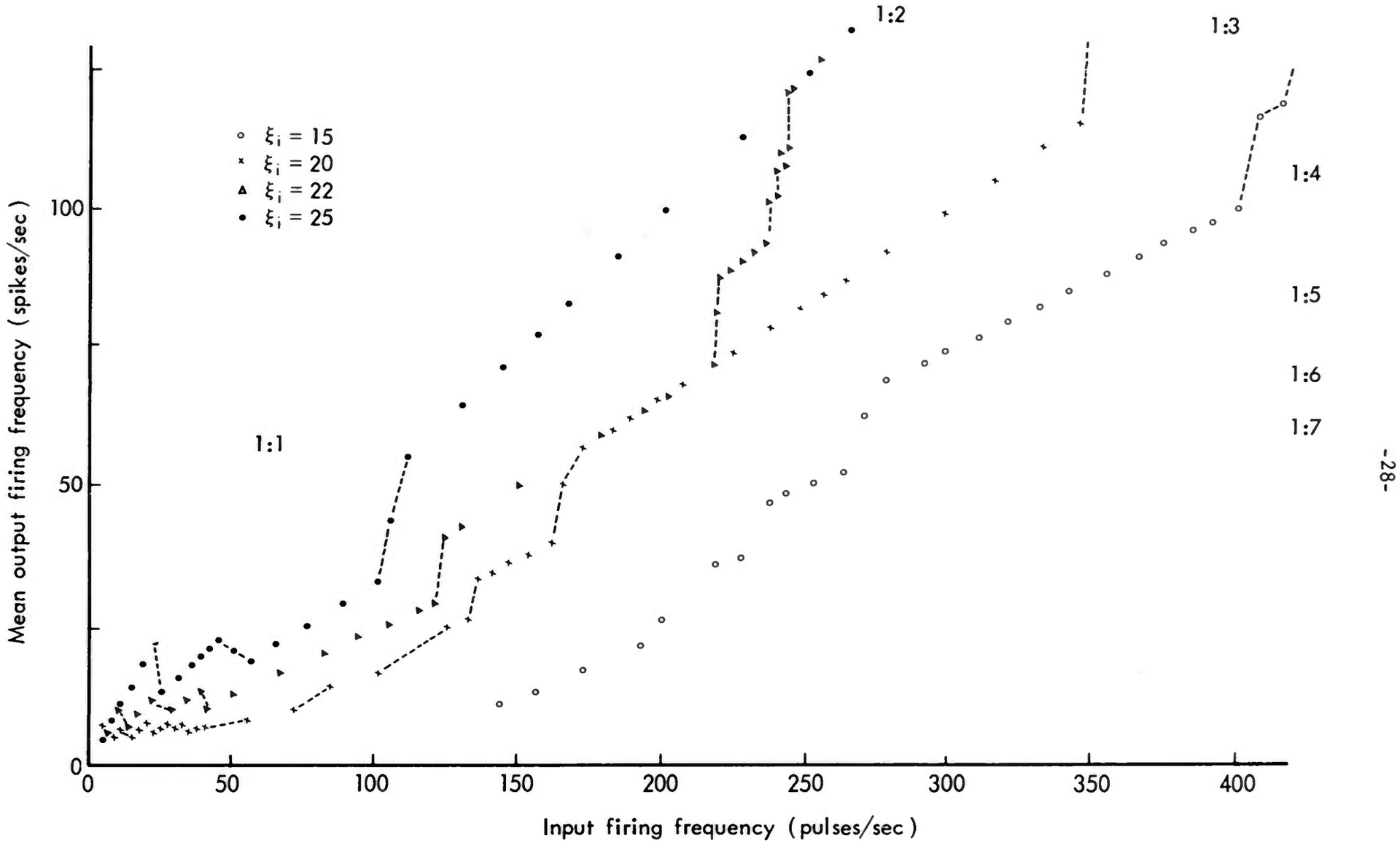

Fig. 17a—Input-output relations with regular input

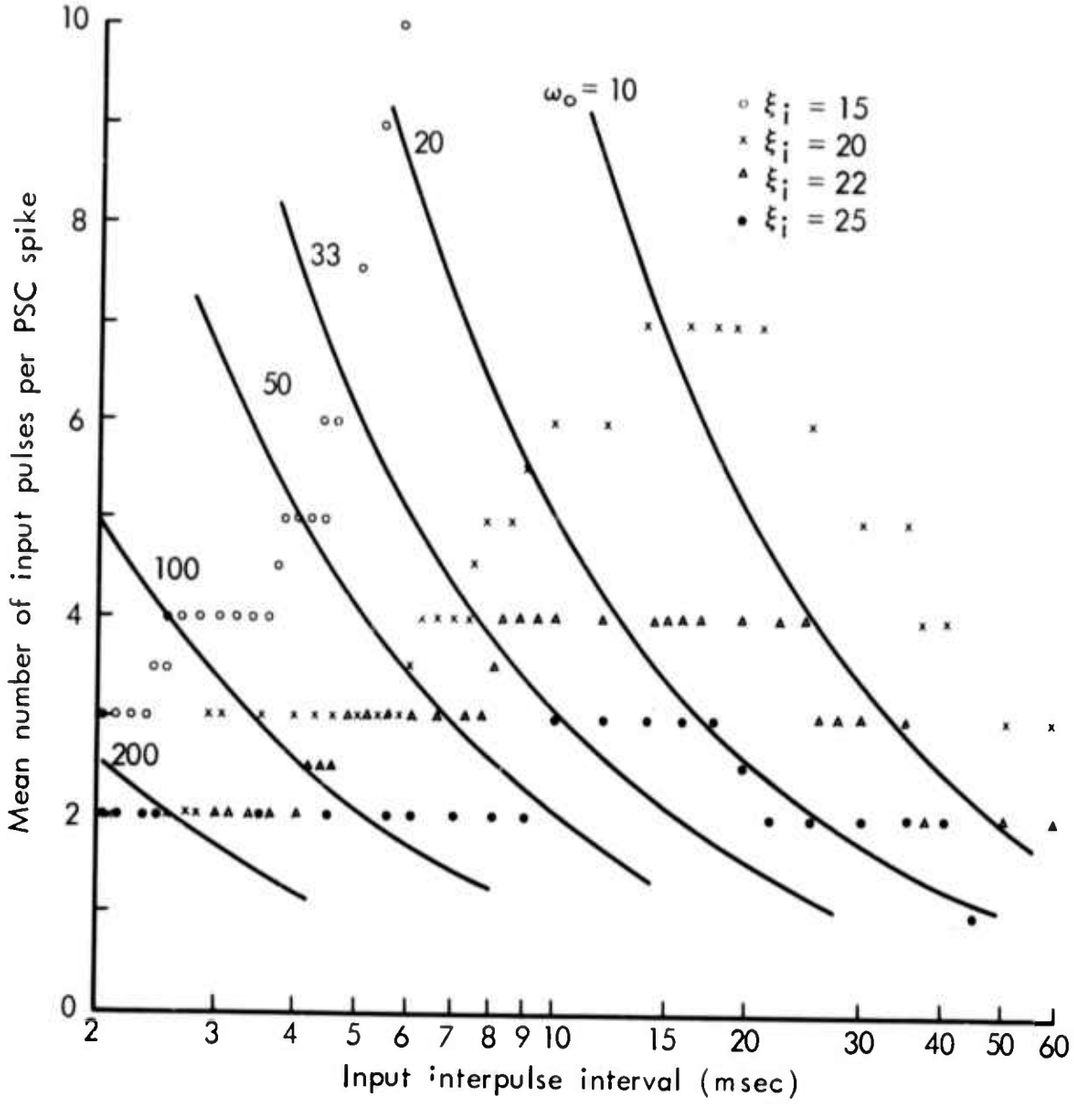

Fig. 17b—Input-output relations with regular input

Table 1

INPUT-OUTPUT RELATIONS FOR A SAMPLE CELL

Freq.	Input: Time of First Pulse	Output: Spike Times (msec)			Output: Spike Intervals (msec)		
200	1	11.71	26.56	41.55	....	14.8	15.0
		56.56	71.55	86.56	15.0	15.0	15.0
200	5	15.54	30.56	45.55	....	15.0	15.0
		60.56	75.55	90.56	15.0	15.0	15.0
200	13	18.88	33.57	48.55	....	14.7	15.0
		63.56	78.55	93.56	15.0	15.0	15.0
238	2	10.82	20.07	31.78	....	9.2	11.7
		41.07	52.78	62.07	9.3	11.7	9.3
238	5	10.31	19.06	20.59	....	8.7	11.5
		39.87	51.58	60.87	9.3	11.7	9.3
238	11	15.94	24.94	36.58	....	9.0	11.6
		45.87	57.58	66.87	9.3	11.7	9.3

of input pulses per output spike) a fraction of 1/n removed from the closest unimodal plateau. This phenomenon is shown in Fig. 17 and has also been reported by Harmon.[22]

As indicated above, the amplitude of EPSPs depends on the frequency of input firing. This must be kept in mind when extrapolating information from Fig. 17a or 17b that is to be applied to a given synapse in different frequency regions.*

Future Plans

This model is intended to be used to examine subthreshold activity and input-output relations for different types of input patterns, and the sensitivity of these processes to the values of PSC parameters. These results are then to be compared with those of previous models and to neuroelectric data. Specifically, the relative effects of concentrated and distributed input are to be explored, and questions pertinent to a specific retinal organization model will be investigated.

*Reference 27 contains an analysis of these and other results.

It would be desirable to obtain a catalogue of input-output relations associated with different input patterns. The extent to which such a catalogue will be developed depends on the comparison of preliminary results with experimental data, the intricacy of the phenomena encountered, and the questions that will be indicated by preliminary results, should those results prove to be physiologically meaningful.

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10 ABSTRACT

A simulation of the information-processing function of nerve cells. The computer model simulates the portion of the neuron at which spike potentials are initiated. Values for parameters were specified on the basis of neuroelectric recordings so that the results obtained might be pertinent to actual nerve cells. Trial runs verify that the model is accurately reproducing the functional forms of neuroelectric data. Input-output relations under regular input are given for a wide range of input frequency and pulse amplitude.

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