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Nervous network seen as an AM/FM communications system

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THE NERVOUS NETWORK SEEN AS AN AM/FM COMMUNICATIONS SYSTEM

by

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ABSTRACT

The purpose of this paper is to make an attempt in explaining the selective property of the synapse. An analogy between the nervous network and the telephone circuit will be made in an effort to show the need for selectivity of the synapse. Using the available experimental evidences, a new synaptic mechanism will be hypothesized which will possess a selective property.

It will be shown that with this new explanation of the synaptic mechanism, the nervous network can be viewed as an AM and FM combination communication system. Noise, bandwidth, information capacity, and selectivity will be discussed and briefly compared with the most accepted explanations of the nervous system available today.

INTRODUCTION

In almost all physical communication systems selectivity is of prime importance. In wireless communication, the receiver is capable of selecting or "tuning-in" a particular transmitter station. In telephone communication, the transmitter dials the permutation of a set of numbers to select the receiver. In a complex and sophisticated communication system such as the nervous network the selectivity should be of major importance.

When approaching a red signal light, the right foot applies pressure to the brakes. When the telephone rings, the left hand reaches for the telephone while the right hand searches for a pencil. These are just a few examples where different stimuli excite different effectors, properly selected, so that the proper action be taken.

1. DESCRIPTION OF THE NERVOUS SYSTEM

A. The Nervous System: a Telephone Network

The nervous system is quite analogous to the telephone network. A single telephone circuit is made up of two remote stations, a microphone and a headphone; one central station or the exchange center; and the transmission lines connecting the central station to the remote stations. (See Figure 1.)

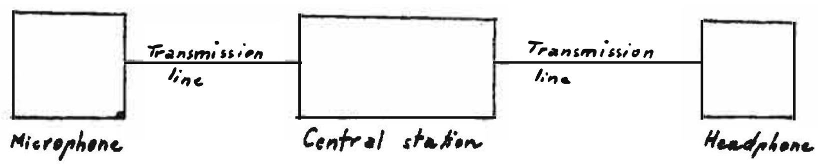
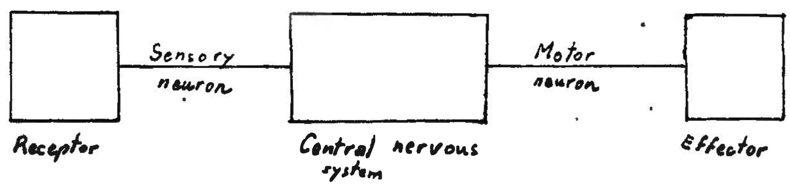


Figure 1. A single telephone circuit

Similarly, a simplified circuit of the nervous system includes two remote stations, a receptor and an effector; one central nervous system; and the transmission lines, known as neurons, linking the remote stations to the central station. (See Figure 2.)



Figues 2. A simplified circuit of the nervous system

B. The Components of the Nervous System

While the components of the nervous system have been described in many physiology texts, a brief description will follow to familarize the reader with their basic function.

1. The Receptor

The receptor is a special type of nervous tissue capable of being stimulated by a change in the environment. Where the microphone changes sound signals into electric signals, the receptor converts stimuli into electrical pulses keeping the frequency of pulses directly proportional to the logarithm of the intensity of stimulation. This is known as the Weber-Fechner Law.

2. The Effector

The effector is the structure that is set into activity as a result of stimulation by electrical pulses, e.g., muscles and glands.

3. The Central Nervous System

The central nervous system (CNS) is the center of all control functions. The CNS is made up of synapses and association neurons along with some supportive and connective tissues.

4. The neuron (Freygang, 1959)

The neuron is the structure that transmits information from the receptor to the CNS or from CNS to the effector depending on whether it is a sensory or motor neuron. It can often reach a length of several feet. A diagramatic view is shown in Figure 3.

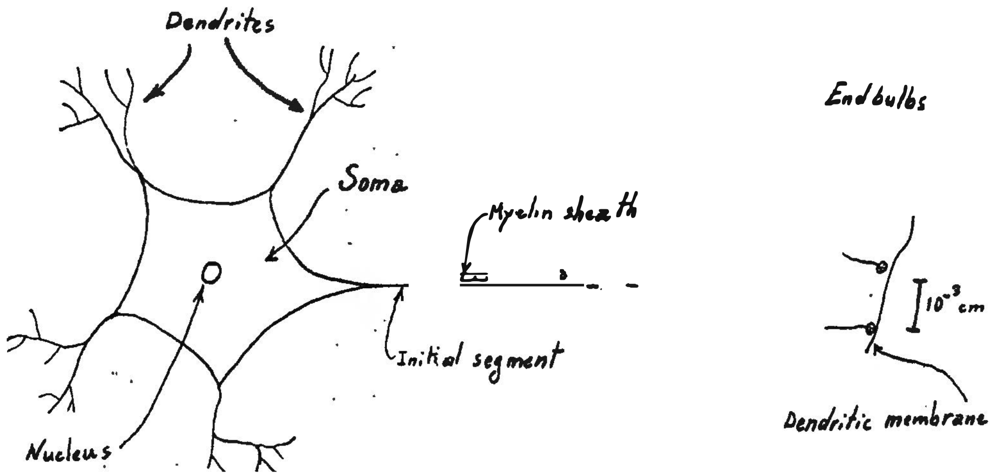


Figure 3. A diagramatic sketch of a neuron

The dendrites are long, tapering, branching structures that are attached to the soma. They reach a submicroscopic dimensions at their tips.

The soma is the widest part of the neuron, reaching a diameter of as much as O.1 mm. The nucleus of the neuron and much of the metabollic machinery is located in the soma.

The axon is the largest part of the neuron. It begins with a constricted portion or initial segment (IS), then becomes covered with myelin sheath, a fatty substance. The axon branches eventually and distributes endbulbs at the tips of its branches over the surface of the dendrite and soma of the motor neuron.

The internal (or protoplasmic) resistance of the neuron is about 50 ohms/cm, while the resistance across the membrane is about 4000 ohm cm^2. The membrane has a decay time constant of 4 msec. (Rall 1957). The capacitance of the membrane is about $1\ \mu f/cm^2$.

A steady, or membrane potential of - 70 to - 100 mv is found to exist across the ~~membrane~~ (Curtis and Cole 1952; Keynes and Martins - Ferreira 1953). The membrane thickness being about 75 A° (Robertson 1957), it would be expected that the membrane be a good dielectric material. Stämpfli and Will, 1957 showed experimentally that an increase of the membrane potential by 50% causes the membrane to break down resulting in a spark. This puts the membrane in the dielectric strength region of oils and paraffin.

5. The Synapse

The synapse is the junction or the gap between the endbulb and the motor neuron. The synaptic cleft is about 100 to 300 A° in the thickness (Robertson 1955; De Lorenzo 1959; Eccles 1961). The synapse is the relay of all nervous communications and thereby, is of great physiological interest.

In the telephone network the central station has the following functions:

a. Amplification It amplifies the weak incoming signal to separate it more distinctly from noise.

b. Unilateral property - It lets the signal go from the microphone to the headphone and not vice versa.

c. Selectivity - It guides the information to the intended headphone or headphones, through a patchboard set up.

In the nervous network the CNS, or more specifically the synapse, is responsible for the same functions.

a. Amplification It is a power amplifier. It amplifies the weak signal of the small endbulb to trigger an excitation in the large soma or even in the muscular organ. There is no attenuation of the information in the neuron, except at its terminals where a perfect matching exists to eliminate signal reflection.

b. Unilateral property - It lets the information go from presynaptic end to post synaptic terminal and not vice versa.

(Robertson 1955; De Lorenzo 1959). This property of the synapse is of no physiological significance (Guyton p. 632).

c. Selectivity - It relays the information to a selected group of neurons. This property of the neuron is suggested also by Fisher and Watkins, 1962, where they propose an FM system to handle the problem. They hypothesize a synapse where the post synaptic terminals are all sensitive to different and discrete frequencies. Depending on the frequency nature of the information, a particular neuron will be energized.

In the following sections a résumé of the experimental results will be given for the synapse, presynaptic terminal, and post synaptic terminal in an attempt to draw a more systematic conclusion about the mechanism of the synapse.

II. PRESYNAPTIC TERMINAL

In the central nervous system (CNS) the axon branches and distributes endbulbs at the dendrites or somas of motor neurons. The small synaptic cleft so formed serves as a mediater between the presynaptic terminal and the sub-synaptic membrane, about 200 A^{o} apart.

The endbulb is a structure filled with vesicles which, as revealed by the electron microscope, are 300 to 500 A^{o} in diameter (Birks, Huxley and Katz 1960). It is believed that these vesicles are either produced by mitochondria, or that they are portions of mitochrodria. It is further believed that these vesicles are filled with a transmitter substance; when the vesicles at the strategic end are excited, they rupture and discharge the transmitter substance in the synapse. Due to the rmal agitation, the vesicles are randomly moving inside the endbulb.. Hence, the probability of finding a vesicle at the strategic site is quite random but usually very large due to the large number of vesicles inside the bulb (Katz 1958).

At certain synapses, it has been noted that a large quantity of acetylcholine (ACh) is present after a few continuous discharges. Since, at these same synapses it has been noted that ACh can excite the motor neuron very readily, it has been concluded that the vesicles are filled with ACh. Although there is no direct evidence that vesicles Contain ACh, the conclusion is good for certain synaptic regions. An isotonic solution of ACh of 0.1 M in a vesicle of 400 A^{o} in diameter will comprise 3,000 molecules of ACh (Castillo and Katz 1956; Katz 1958). It has also been estimated that the ACh content in an endbulb is 2.5×10^{-7} g (Brown 1953) and a single discharge liberates 10^{-10} g of ACh (Perry 1953; Emmelin and MacIntosh 1956.) Agreeing with these figures are Birks and MacIntosh, 1957, who observed that from one endbulb a maximum of 10,000 discharges can be obtained at a frequency of 20 pulses / second (pps).

This observation could also be used as a check to verify the presence of ACh in the vesicles, since after 10,000 discharges there will be no ACh left in the endbulb. Unfortunately, this in itself is not a sufficient reason - the maximum number of pulses that can be transmitted continuously in a neuron is also about 10,000 which could also account for the fatigue of the endbulb.

The intensity of the transmitted signal can be either great or small, depending on the number of endbulbs employed in transmitting the signal. As will be shown later when the intensity of transmitter signal is increased faster transmission is possible.

III. SYNAPTIC CLEFT

The synapse is an extracellular space of 100 to 300 A° (Guyton p. 622). For years the synapse has raised the curiosity of scientists who have tried to uncover a few of the many associated mysteries. It is only recently that through the help of electron microscope, microelectrodes, and sophisticated electronic instruments that definite progress is being made. Much more work needs to be done in this area to establish more firmly the present hypotheses.

Eccles and Jaeger, 1958, showed that the cleft resistance is about 100 ohms/cm and the surface membrane fronting it has a resistance of 500 ohms cm^2. It has not yet been possible to determine whether special electrical properties distinguish the presynaptic membrane from the subsynaptic membrane (Eccles 1961). However, Robertson 1955 and De Lorenzo 1959 have shown that in the crayfish the synaptic cleft is like a rectifier. In other words, the cleft has infinite conductance in the forward direction (toward effector) and zero conductance in the backward direction.

The transmitter substance released at the presynaptic end is transmitted across the cleft. The total synaptic delay is observed to be from 0.3 to 0.45 msec (Brooks and Eccles 1947). This delay includes the time lost in the release of the transmitter substance, the time of propagation of the transmitter substance across the cleft, and the time needed for the first depolarization of the post synaptic membrane.

A few of the most common chemicals present at the synapse are ACh, 5-hydroxytryptamine, aspartic, glutamic, cysteic, and certain amino acids. The complication arises when different chemicals are present at different synapses. For instance ACh is found in most synapses outside the CNS. Adrenalin is found in the neuro-muscular synapse of the sympathetic division of the autonomic system. In the CNS where the greatest amount of ACh is suspected, very little is found. (Guyton p. 627)

In most hypothesis it is assumed that the released transmitter substance diffuses to the subsynaptic terminal.

This assumption is reasonable because of the concentration gradient but in the presence of a potential greater than the half-wave potential across the cleft, it appears more likely that an electrolysis would take place. Assuming both presynaptic and subsynaptic terminals are at the same potential, an impulse of 150 mv at the presynaptic end will also appear across the cleft. Electrolysis would then occur if the half-wave potential of the transmitter solution is below 150 mv.

The half-wave potential of a solution is the potential necessary for a continuous decomposition to take place. it is given by the Nernst equation $E = E_{1/2} - \frac{0.0591}{n} \log \frac{i_d - i}{i}$ where

	E	is the voltage across the solution
	i	is the current through the solution
	n	is the number of electrons involved in the chemical reaction
	i_d	is the saturation current
and	$E_{1/2}$	is the half-wave potential

A typical plot is shown in Figure 4, for 3 different values of n.

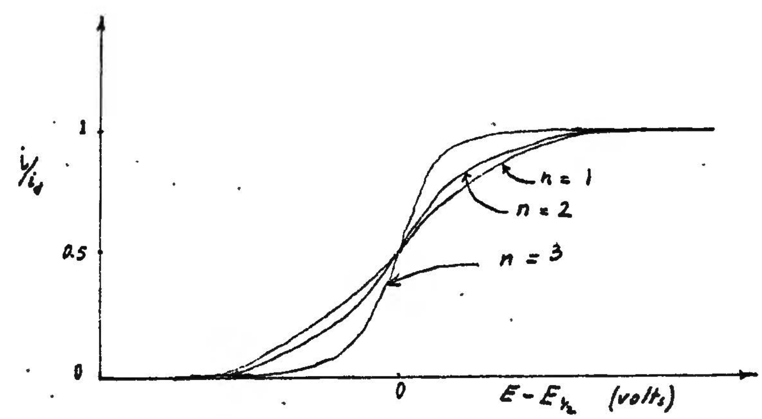


Figure 4. - Theoretical current potential curves

In general the half-wave potential is concentration independent, while the current associated with it is concentration dependent. A solution of higher concentration will have a higher current flow at the half-wave potential than otherwise.

A list of half-wave potential values for inorganic substances are made available by Delahay 1957 and Latimer 1952. Unfortunately, organic substances are not so well categorized but Kolthoff and Lingane, 1952, have listed a large number of them. In the above references over 30 substances, organic and inorganic, have been found to have half-wave potentials within the range of usefulness for this synapse.

IV. POST SYNAPTIC TERMINAL

The transmitter substance reaching the post synaptic membrane generates an excitatory post synaptic potential (EPSP) which has normally a very small amplitude and a decay time constant of 1-120 msec. Since all membranes have a threshold level for excitation, it is not until the EPSP attains this depolarization threshold that an impulse is created at the motor neuron (Eccles 1953; Coombs, Eccles and Fatt 1955; R. M. Eccles 1955; Machne, Fadiga and Brookhart 1960; Nishi and Koketsu 1960; Spencer and

Kandel 1960).

The EPSP caused by one package or quantum of transmitter substance is almost always very small and well below the required threshold to generate an impulse (Guyton p. 629). However, the threshold level of depolarization may be attained by either temporal summation or spatial summation or both. Spatial summation occurs when bombardments from separate presynaptic terminals summate with each other to form a stronger signal. Temporal summation occurs when the EPSP superimposes on the remaining tail of the preceding EPSP (Lloyd 1946; Eccles 1953).

The effect of the spatial summation is greatest when the EPSP is formed by several simultaneous bombardments. The probability for getting a true miniature EPSP becomes very small as the synaptic bombardment becomes more random (Nishi and Kotetsu 1960). This is effective in reducing the probability of the depolarization of the neuron by random noise.

Characteristically, receptor organs fire repetitively so that under natural conditions synapses are activated by trains of pulses. The relationship between frequency of presynaptic impulses and rate of discharge of transmitter substance has been observed (Curtis and Eccles 1960); the relationship appears in Figure 5.

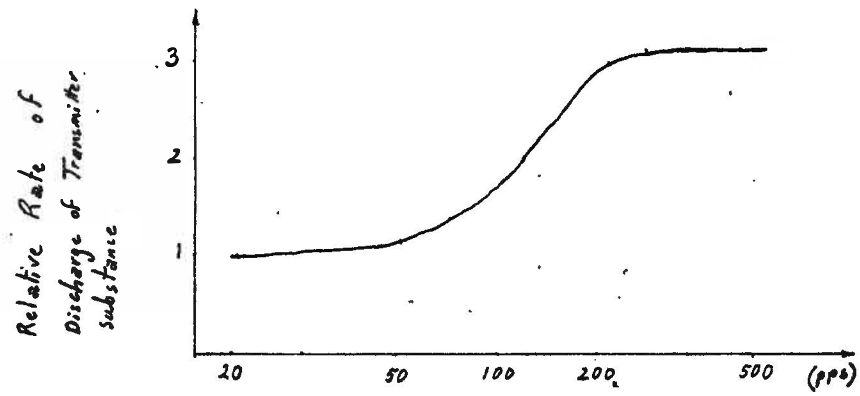


Figure 5 - Relationship of rate of discharge of transmitter substance and the frequency of presynaptic (stimulation - Curtis and Eccles 1960)

The curve shows that up to 300 pps the amount of transmitter substance released is related to frequency. Above 330 pps a plateau is reached corresponding to release of three times as much transmitter substance as at 20 pps.

In addition, Curtis and Eccles showed in 1960 the relationship between frequency of the presynaptic pulses and its effect of EPSP as a function of time of application of the pulses. A summary of the results is shown in Table

Table 1. Relationship between frequency at presynaptic region formation of pulses at post synaptic terminal

Frequency of pulses pps	Total number of pulses	Relative size of EPSP	Formation of impluses
100	40	negligible	no
400	40	1.4	yes
640	40	1.4	yes
100	3200	1.2	yes
400	3200	1.5	yes
640	3200	1.8	yes

The above data shows clearly a direct relationship between presynaptic pulse frequency and the probability of occurrence of an impulse at the motor neuron. In general, the probability of generating impulses is high for frequencies over 300 pps. However, for frequencies below 300 pps the time of application of the impulses increases the probability of triggering an impulse at the motor neuron.

Hagiwara and Taski, 1958, and other investigators have shown that a similar relationship exists between the size of the presynaptic impulse and the probability of generation of an impulse at the subsynaptic terminal.

Perhaps a reasonable deduction would be that the frequency and the amplitude of the presynaptic pulses are directly related. In other words, when the frequency of the pulses is increased by the receptor, the pulses superimpose at the presynaptic terminal to form pulses of larger amplitudes. There is no conclusive experimental evidence supporting this argument, but Brock et al, 1952, has shown that at the presynaptic terminal the pulses get wide due to a longer decay time constant, similar to the post synaptic region. Hence, a temporal summation could occur at the presynaptic terminal just as in the subsynaptic terminal.

Because of the absolute refractory period where the threshold level is infinite and the long decay time constant of the pulses, the motor neuron is limited in its upper frequency range. Also, because of its pulse shaping character and its deficiency in information coding and decoding mechanism, the nervous network is not making best use of the available bandwith.

Adrian and Bronk, 1929, and Denny-Brown, 1929, were first to show that individual motor neurons would discharge up to 50 pps, when subject to a continuous and assynchronous synaptic bombardment of a sufficient intensity. Under such conditions it can be assumed that spatial and temporal summations of the EPSP's build up until they reach the threshold of the motor neuron and so generate an impulse. This demonstration has been also explained by the hypothesis of the rhytmic discharges (Kolmodin and Skoglund 1958). In the conducted experiment, it was shown that when the membrane potential was decreased to -51 mv from a normal of -58 mv, an impulse was generated and then followed by a repolarization. When the repolarization was rebuilt to -51 mv a second impulse was triggered. Increasing the intensity of synaptic bombardment caused an increase in the frequency of discharge, but a higher level of depolarization (-49 mv) was required to discharge an impulse.

The motor neuron, like the receptor, will discharge repetitively for as long as the level at EPSP is above threshold.

It has also been shown that a current depolarization threshold exists at the post synaptic terminal. A 20 mμ A current is shown to be just below threshold for generating an impulse (Coombs, Curtis and Eccles 1957). This current threshold was also noted by Hoorweg, 1892, and Weis, 1901. Lapicque called this critical current rheobase. The 20 mμ A current happens to be also the current that would flow through the membrane at the depolarization threshold potential.

The somas and dendrites of most neurons are much less excitable than the nonmedullated initial segment (IS). The depolarization threshold is two to three times higher for the some-dendritic spike than for the IS spike (Lorente De Nó 1947; Fatt 1957; Cragg and Hamlyn 1955; Anderson 1960). In view of this, the synapses of the dorsal root fibers are very unfavorably located.

V. TRANSMITTER SUBSTANCES and EFFECT of DRUGS on EPSP

There are many chemicals that can act as a transmitter substance in creating EPSP's. However, acetylcholine (ACh) is one that is most widely recognized, mainly because in certain instances, is can cause excitation. In the CNS, ACh or ACh-like drugs have a far less powerful effect in stimulating the neurons than in the autonomic ganglia. (Guyton p. 627). Other common transmitter substances at different synapses are norepinephrine and 5-hydroxytryptamine.

Neurons are, in general, very responsive to changes in pH of the surrounding interstitial fluids.

Caffein, theophylline, and theobromine, which are found in coffee, tea and cocoa, respectively all increase neural excitability, presumably by reducing the threshold level for excitation of the post synaptic terminal (Guyton p. 633)

There is a different class of transmitter substance which inhibits the effect of the excitatory transmitter substance. Strychnine has the property of inhibiting the action of the inhibitor substance, so that the excitability of the system stays high. (Guyton p. 633)

VI. POTENTIAL BIASING SYNAPSE

A few of the experimental facts along with the deductions made thus far have been put together in an attempt to explain the operation of the nervous circuit. A summary of the basic operation of the nervous network is shown in flow chart ~~form in Figure 6.~~

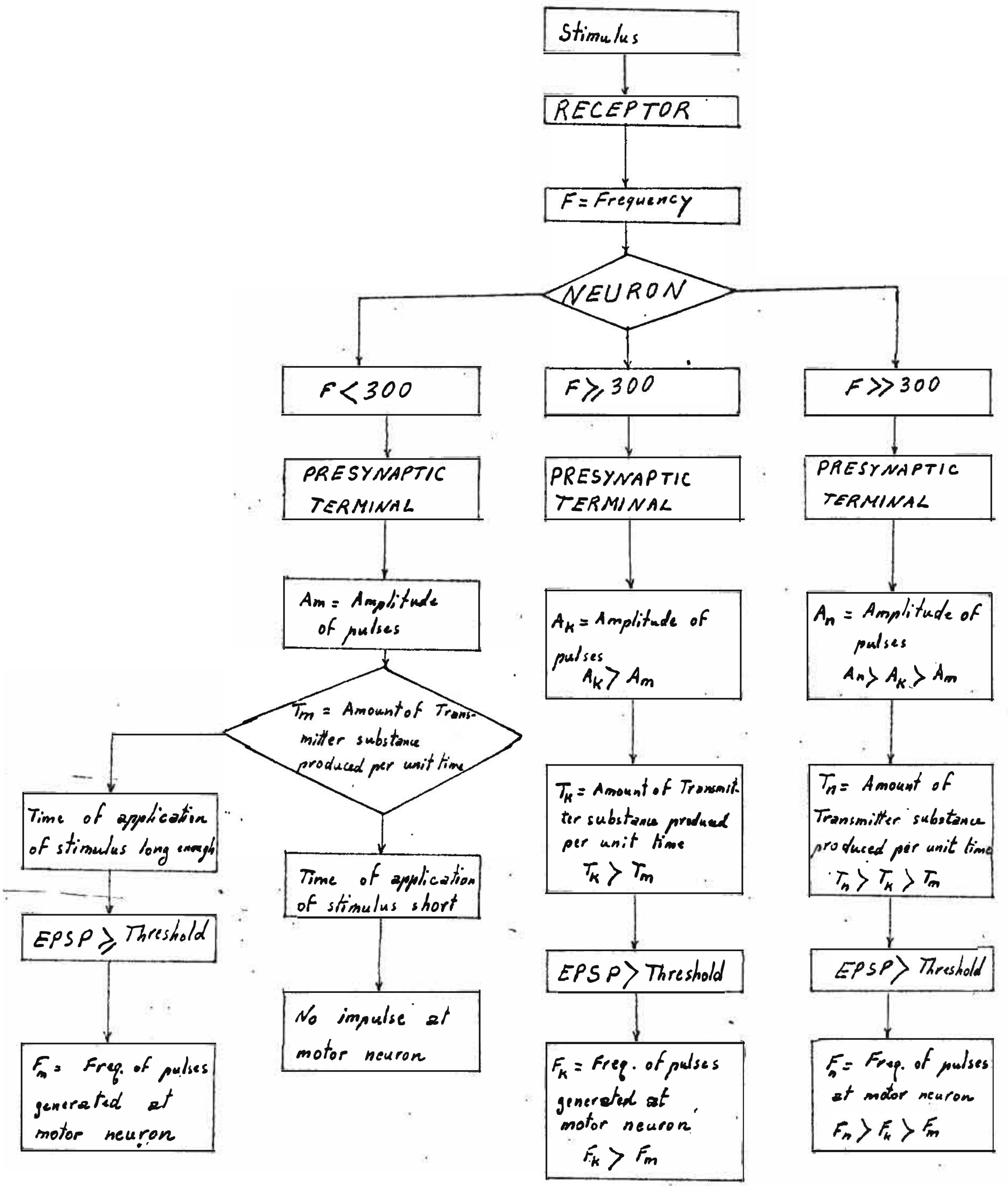


Figure 6 - Flow chart diagram for the conduction through the neural circuit

When a train of pulses of frequency F and amplitude A appear at the presynaptic terminal, it causes the endbulb to discharge transmitter substance in the synaptic media. Here, the transmitter substance can propagate across the cleft in the two main different modes. It can either transmit by diffusion or by a forced ionic influence, just as in an electrolysis. It is this latter mode of transmission to which most attention is given in the remainder of this paper.

In an attempt to explain the operation of a potential biasing synapse, a multi-synapse is illustrated in Figure 7 with hypothetical values for the membrane potentials. The assigned values are well within specifications, since membrane potentials vary from - 60 to - 100 mv.

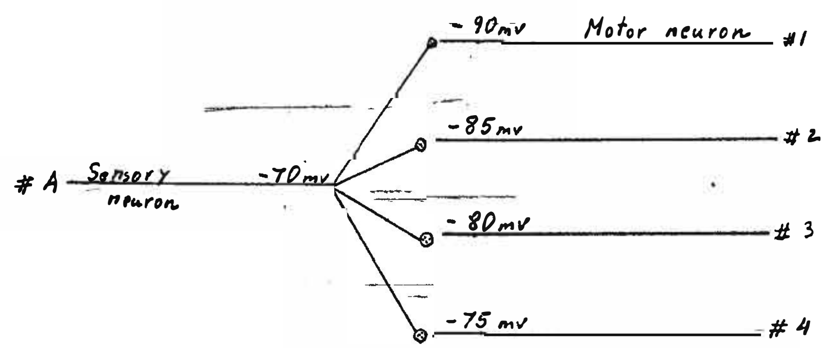


Figure 7 - Schematic representation of a multi-synapse

When an impulse of 135 mv appears at the presynaptic terminal a spike of 135 - 70 = 65 mv of net height will result. In essence, during this time, a potential difference of 65 - (- 90) = 155 mv will exist across neurons # A and #1. Assuming, also, that the half-wave potential of the transmitter solution is about 150 mv, it is clear that a decomposition will take place, the current of which will be a function of the concentration of the transmitter solution. During the decomposition quanta of transmitter solution will reach the subsynaptic membrane as the pulses appear at the presynaptic region. The EPSP's thus formed will superimpose to overcome the threshold. Both temporal and spatial summations are effective just as in the chemical transmitter synapse.

When the same analysis is repeated for neurons # 2, #3, and #4 it is found that neurons #3 and #4 are not excited. The result of this analysis is summarized in Table 2. These results show that with a chemical switch such as described above, selectivity is established at the synapse.

Table 2. Tabulated potential values at a synapse

Resting potential of sensory neuron (mv)	Pulse height (mv)	Stimulated potential of sensory neuron (mv)	Resting potential of motor neuron (mv)	Potential difference between motor and sensory nerve endings at the synapse (mv)	Potential across synapse compared to 150 mv decomposition potential	State of the synapse conduction
-70	135	65	-75	140	smaller	no conduction
-70	135	65	-80	145	smaller	no conduction
-70	135	65	-85	150	equal	conduction
-70	135	65	-90	155	larger	conduction

If neuron #3 were to be energized, the receptor would be required to increase its output frequency which in turn would increase the pulse height at the presynaptic terminal. Once the pulse amplitude grows large enough to creat a potential difference across the synapse equal to the half-wave potential, neuron #3 will be energized.

It is interesting to note that an impulse appearing at the post synaptic region cannot trigger the sensory neuron. First, because the post synaptic region is not capable of liberating transmitter substance; second, the potential difference across the synapse is always below the half-wave potential.

To summarize, the proper biasings of the neurons at the synaptic terminals, the half-wave potential of the particular transmitter solution, and the frequency output of the receptor give full control to the nervous network in transmitting the information to the proper effectors.

VII. THE NERVOUS NETWORK AN AM/FM COMMUNICATIONS SYSTEM

In general, AM stands for amplitude modulation and FM for frequency modulation. When in a train of pulses the information is in the amplitude variations of the pulses, the system is an AM system. When the information is in the frequency variations of the pulses, the system is an FM system.

The nervous system uses both of these techniques in transmitting information. It is FM in the transmission lines and AM at the synapses to establish selectivity. Figure 8 illustrates in flow chart form the neural circuit of a potential biasing synapse. The AM and FM sections are also labeled.

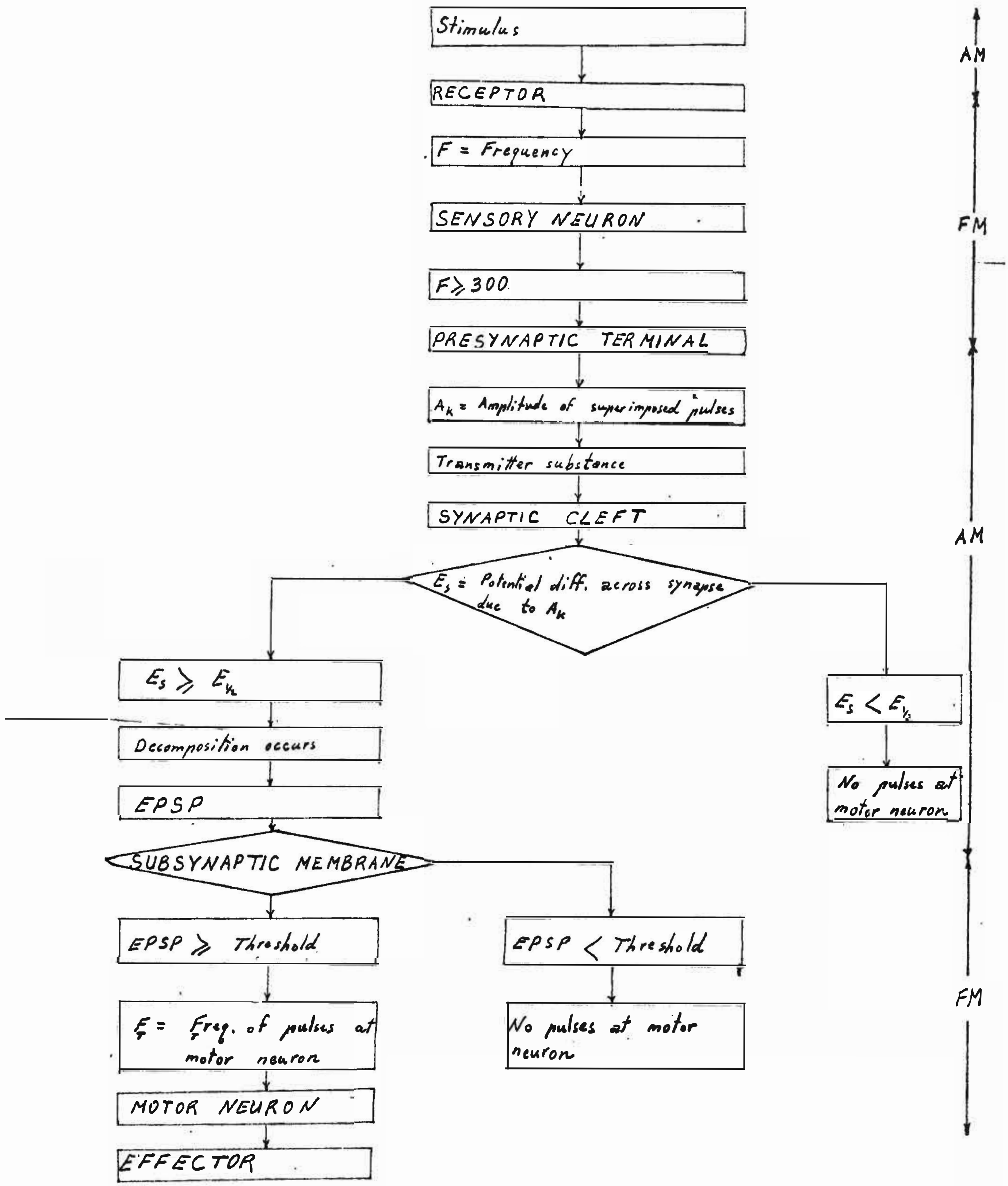


Figure 8 - Flow chart diagram for the neural circuit with potential biasing synapse

VIII. DISCUSSION

The necessity for the synapse derives mainly from the functional separation between neural elements. Nature must have had better reasons for inserting this synapse between any two consecutive neurons or cells. In most physical communication networks the following properties are associated with the system: speed of communication, selectivity, noise level, band width capacity, size, repairability, and cost. The last three are of lesser importance in the discussion of the mechanism of the nervous network.

The electrical transmitting synapse, where the synaptic cleft is a rectifier (Robertson 1955; De Lorenzo 1959), has a very fast conduction property at the synapse, but outside this there are no other useful communication properties.

The chemical transmitting synapse, where the information is transmitted across the cleft by diffusion of the transmitter, has a fast conduction and a low noise property. The threshold at the post synaptic terminal serves essentially the same purpose as a threshold in electronic counters. The post synaptic region has also the ability of storing the the miniature EPSP's and amplifying them by temporal summation so that a large cell can be triggered.

The potential biasing synapse is essentially a chemical transmitting synapse with the ability to be selective with properly biased neurons.

In this paper, an attempt was made to show the transmission properties of the synapse. The different theories explaining the synaptic mechanism were discussed. Clearly, there are fascinating problems for investigations, but before these problems are explored fruitfully the transmitter substance will need to be identified.

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