NEURONAL DISCHARGE AND SLOW POTENTIALS

THE RELATIONSHIP BETWEEN
NEURONAL DISCHARGE AND SLOW POTENTIALS
IN THE CAT CEREBRAL CORTEX

By

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SCOPE AND CONTENTS: The work reported in this thesis concerns a possible quantitative relationship between two bioelectric phenomena of the cat cerebral cortex: neuronal discharge and slow potentials. A review of literature dealing with research related to the present topic is given. This is followed by descriptions of the experimental procedure employed and the results obtained. A subsequent discussion in terms of current neurophysiological concepts relates present findings with those of other known research. The accompanying bibliography represents a fairly complete coverage of contemporary and recent experimental and theoretical work related to the present topic.

PREFACE

The present thesis is organized into four main sections. The first, Introduction, is a review of the literature dealing with recent research in areas related to the subject of this thesis. An attempt is made to explain the significance of the phenomena under study and to present concepts which may assist in the understanding of the work reported subsequently. The second section, Method, describes the three aspects of the procedure (animal preparation, recording technique and analysis) which were used to obtain the results presented in the third section. This section, Results, consists of a number of observations and statements derived from the present research; these are illustrated by a set of graphs which are representative of the data. Finally, in the fourth section, Discussion, the results are interpreted in terms of the introductory concepts and also in the light of other information bearing on the present study. As an afterthought, a brief Conclusion treats the results in the perspective of this line of research and comments on the possible consequences of this study. Items of Bibliography not specifically refered to in the text are included as background material, some of which influenced the organization of this thesis. Except where specified otherwise, review material and discussion is concerned solely with results obtained from cat preparations.

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INTRODUCTION

The living brain exhibits a range of electrical phenomena whose interrelation and significance to behavior of organisms is the subject of current research. A familiar form of electrical activity is the conventional electroencephalogram (EEG) recorded from the surface of the skin overlaying the skull (42). A similar record, the electrocorticogram (ECG), is obtained directly from the cortical surface. Electrical activity is also recorded from various brain centers such as the thalamus and the reticular formation in the brain stem (12) as well as the spinal cord (69). By means of micro-electrodes, external and internal electrical potentials may be recorded from neurons in the central nervous system (29, 37).

Two general forms of electrical activity are distinguishable in the cat brain: action potentials, which represent discharge of neuronal units, and the slow continuous potential wave forms like the ECG. The former are pulses with a time course of about 2 milliseconds while the latter are constituted of frequency components below 100 cycles/second (24). Analysis of the wave form in decerebrate cat cortex revealed the ECG to contain frequency components in the ranges 0.5 to 4 and 25 to 70 cycles/second (30). In other studies the frenquency range of the ECG components was found to be 6 to 10.5 cycles/second (36), and 12 to 25 cycles/second (10). It appears that the wave form

and the frequency components of slow potentials vary from one preparation to another while they are always slow compared to the action potential rate of change. Under certain conditions even slower changes of the resting potential are observed (12, 45, 68).

The record of electrical activity in the brain depends on the method which is used to obtain it. The recording system may be capacity coupled or direct, it may be mono-polar or bi-polar, it may record from the surface or depth, and utilize macro- or micro-electrodes. The distinction between recording methods is essential for the method often defines the scope of the study. The main components of the ECG are in the range below 5 cycles/second and the wave form, therefore, undergoes considerable distortion, both in amplitude and phase, in capacity coupled recording systems with time constants of one second or less.

The behavioral relevance of electrical potentials has been demonstrated both in clinical work and in animal experiments. It was shown, for example, that the cortical steady potential bears a definite relationship to the level of arousal and activity in freely moving rats. Cortical potentials were observed to shift positively in association with passive states (resting and sleep) and negatively in association with waking, responding to external stimuli and certain movements. Simultaneous recording from the reticular activating system in the brain stem, which is thought to influence cortical potentials, demonstrate

forms of electrical activity which correspond consistently to cortical potentials and behavior (12).

Apart from the demonstrated relationship between naturally occuring potentials and behavior it has also been shown that steady electrical currents induced in the cerebral cortex facilitate learning, if the current is anodal, and abolish memory traces, if the current is cathodal (44). For example, a steady anodal current induced in the motor cortex enables leg flexion in response to an arbitrary stimulus such as a tone (61). Conditioning of leg flexion during anodal polarization of cortex is accomplished in fewer trials than without polarization. Cathodal polarization of the same area, if administered shortly after the last conditioning trial, eliminates the conditioned reflex (44). On a neurophysiological level, induced currents modify the slow potentials in the cortex and change the discharge patterns of neurons (15). Examples of the effect of polarizing current on the neurophysiological level include the enhancement of the positive and depression of the negative phases of natural or evoked cortical potentials by cathodal polarization, and an opposite effect by anodal polarization (40, 57). The discharge rate of cortical neurons was shown to increase or decrease under the influence of anodal and cathodal polarization, respectively (4, 15). These studies further emphasize the significance of recorded brain potentials as manifestations of organized activity essential to the control of behavior.

Present knowledge of the mechanisms giving rise to brain potentials is incomplete, but findings to date point to the semipermeable nature of the neuronal membrane as the source of electrical energy. Membrane potentials are commonly measured at 70 millivolts (interior negative) although membrane potentials of about 90 millivolts have been encountered (24, 37). The various wave forms recorded from the brain are thought to be the result of partial spatio-temporal depolarization and hyperpolarization of the neuronal membranes due to interaction of neuronal units. For example, the ECG is believed to be a composite of excitatory and inhibitory post-synaptic membrane potentials generated in the soma and dendrites of cortical neurons, pre-synaptic depolarization, and synchronized all-or-none conduction in neuronal axons (18, 35, 56, 58, 65). Conduction in the dendrites is also believed to contribute to the ECG (13). Excitatory and inhibitory input to a neuron may originate in its own axon collaterals, in adjacent and inter-neurons or in more remote centers such as the contralateral hemisphere, the thalamic nuclei or the nonspecific activating system in the brain stem (8, 17, 52, 55).

Since the brain mass may be regarded as a volume conductor containing a fixed distribution of slow potential generators, the potential recorded extracellularly (and in some cases intracellularly) is the net activity of neuronal processes within the sensitivity range of the recording electrode (58). Extracellular detection of bioelectric activity in the brain is

possible at all because different parts of neuron membrane depolarize unequally at any one time (34, 13). Instantaneous and uniform depolarization of the entire neuron would not be detected in a volume conductor such as the brain mass. The extracellular biphasic form of the action potential has the form of a differentiated monophasic intracellular record (60). This appearance of the extracellular record is believed to be due to sequential depolarization of soma and dendrites, with a volume conductor inversion during the depolarization of the dendrites. Thus while partial neuronal depolarization makes the extracellular detection of its activity possible, the record so obtained is complicated by the neuron's spatially differentiated properties.

Records of slow extracellular potentials are, to a certain extent, ambiguous because of the distortion resulting from interaction of a distributed generator, the neuron, and the surrounding conductive medium. There are on the average 1000 excitatory and inhibitory synaptic inputs per neuron, with a decreasing density distribution from soma to dendrite tips (35). Since not all synaptic terminals originate in the same brain centers, the soma dendritic membrane is excited differentially to the extent that the various sources of synaptic input predominantly project on different areas of the soma-dendritic surface (22, 56). The localization of synaptic activity in neurons of the cortex is of significance not only to the process generating action potentials but also to the appearance of

polarizing and depolarizing membrane potentials in the cortical surface record. For example, depolarization of the membrane resulting from excitatory synaptic input to the apical dendrites appears as a negative potential on the cortical surface (13). However, negative surface potentials are also thought to be generated during hyperpolarization of the soma membrane by local inhibitory input and polarity inversion in the conductive medium (51, 60). Alternatively, surface positive potentials may be the result of dendritic hyperpolarization or soma depolarization. It follows, then, that the relative activity of excitatory and inhibitory synapses and their spatial distribution along the soma-dendritic surface are factors which are not always discernible in the record of electrical potentials of the cortex. It is apparent that the choice and location of electrodes as well as the mode of excitation of cortical neurons both determine the information content of recorded potentials.

Studies of cortical intracellular and surface slow potentials indicate a close relationship between the two phenomena and support the view that the ECG is a surface manifestation of the membrane transients of cortical neurons. Simultaneous intra-and extra-cellular microelectrode recording of potentials have demonstrated a close relationship between intracellular transients and extracellular slow potentials (60, 64). Similarly, simultaneous recording of spontaneous and evoked activity from the cortical surface and the interior of cortical neurons (somas) have been compared, and a statistical as well

as a qualitative analysis has shown a high correlation between the two records (17, 39, 65). The cortical surface record sometimes shows a phase shift with respect to the intracellular record. However, the phase shift distribution of the surface record is centered on the intracellular record and the order of time involved corresponds closely to the time associated with conduction in apical dendrites in the molecular layer of the cortex (39, 66). Thus it appears that microelectrode intra- and extra-cellular records as well as the gross electrode surface record represent essentially the same neuronal process although various factors are reflected differently in each. For example, while the intra-cellular record sometimes shows a very small field effect due to synchronized activity of adjacent neurons, the ECG reflects principally this synchronized activity (59). The microelectrode extracellular record, in contrast represents the potentials of a single neuron (particularly it's soma) although slow transients in the dendrites and, to a lesser extent, neighboring neurons are also represented (41). So far as timing is concerned, the intra- and extra-cellular records show better correspondence than either one with the surface record.

Although a relationship between cortical surface and neuronal membrane potentials has been demonstrated, the relationship of the discharge pattern of cortical neurons to these potentials is still in doubt. That a specific relationship between neuron discharge and slow potentials may exist is sug-

gested by the observation of intracellular depolarizing membrane potentials which occur at the time of neuronal discharge (24, 36). It is supposed that the mechanism giving rise to the discharge is triggered by postsynaptic membrane potentials when they attain threshold level at some critical, as yet unknown, site in the neuron. Normally, dendrites do not participate in the all-or-none activity of the neuron but are thought to function as integrators and propagators of excitatory and inhibitory membrane perturbations. However, an exception has been observed in the intracellular recordings from activitated hippocampal neurons, driven synaptically by repetitive stimulation, which display discharges in the absence of the usual post synaptic potentials. The interpretation given is that in this case dendrites not only participate in the all-or-none activity but that the discharges actually originate in the dendrites (58). Otherwise, that is, under biological levels of excitation, the dendritic complex is believed to be relatively passive when the soma-axon system discharges (65, 59). Also, while neuron membrane transients have been consistently linked with neuron discharges (with the exception of activated hippocampal neurons) the reverse is not true. Continuous intracellular recordings show that discharges occur during some depolarizing transients but not during others, without any recognizable pattern respecting the amplitude of the depolarizing transients (29, 30, 41). The relationship between the pattern of cortical neuron discharge and membrane potential (also extracellular potential or cortical surface potential), if a functional relationship exists at

all, promises to be probabilistic in nature.

Studies of cortical slow potentials and discharge patterns of cortical neurons reveal that variations in the discharge rate are at least loosely related to the phases of the potentials. From simultaneous recording of the normal cortical surface potentials and spontaneous (that is, not artifically stimulated) soma discharge it was noted that about half of the neurons recorded from showed particularly high discharge rates during positive phases of the potential. Other neurons discharged only some of the time during the positive phases but never during negative phases. No correlation between amplitude of the wave and magnitude of the change in discharge rate was observed. The surface positive waves were thought to be associated with depolarization of the neuronal soma (28). In a further study of the relationship between cortical slow potentials and neuron activity (visual cortex), the same workers found that neurons discharged significantly more often during positive than negative components of the evoked response, and concluded that discharge rate is related to the ECG (29). It was also observed that this relationship is most evident when the cortical steady potential is relatively positive. For example, the contrast between discharge rate during positive and negative phases was greatest when the cortical steady potential was about -1.2 millivolts. With the potential at about -3.1 millivolts the contrast was poor, and at -8 millivolts there was a reversal of the usual relationship, that is, in-

creased discharge during the negative rather than the positive phase of the potential. Polarity contrast and reversal such as was observed in this case is consistent with the above cited slow potential component enhancement and reversal during spontaneous and induced cortical potential shifts (57). If, as it is suggested,surface negativity is the result of apical dendrite depolarization, then the reversal of polarity may reflect a transition to detecting soma depolarization directly in the absence of the volume conductor inversion, which cannot occur while the dendrites are largely or completely depolarized. In such a case, in spite of the polarity inversion seen on the cortical surface, the basic relationship of discharge rate to membrane potentials would be retained.

A relationship between normal and induced cortical slow potentials and the occurence of neuron discharge has been noted in other studies as well. In a study of the direct cortical response (DCR) in the cat and squirrel monkey it was observed that neuron discharge, if at all, occured simultaneously with the positive spike of the DCR. A series of rhythmic waves following the primary components of the DCR were also associated with neuron discharge. (64). The post-stimulus histogram obtained by summing responses of a visual cortex neuron discharge to a light flash has an envelope which closely corresponds in form to the average evoked potential detected extracellularly. The histogram represents the likelihood of discharge on a time basis and holds for all components of the evoked response. The

correspondence is particularly close when the spontaneous discharge rate of the neuron is greater than zero. The suggestion is made that neuron discharge is related to the entire evoked potential complex probabilistically (27). A procedure consisting of averaging the ECG preceding and following the occurence of a cortical neuron discharge showed that in almost all cases neuron discharge is coincident with surface positive waves. Surprisingly, the average surface wave during injury discharge was also positive but of smaller amplitude. It is suggested that neuronal discharge mirrors the suppression-burst pattern of the ECG and that the latter modulates neuron discharge frequency (30). Neuronal all-or-none responses to thalamic stimulation during spontaneous and evoked surface negative waves were observed. The interpretation offered regards the long duration surface negativity as the result of hyperpolarization in depth which may be also responsible for the cessation of unit activity (51). Intracellular recordings from cortical neurons have demonstrated, first of all, a close time correspondence between the DCR and intracellular excitatory postsynaptic potentials and, secondly, that clusters of discharges frequently arise from the crest of depolarizing waves, although depolarization may or may not be accompanied by such discharges (65). A similar study of normal slow potentials amd intracellular recordings confirms these findings by observing that intracellular positive transients coincide with surface negative spindles and that cells fire (but not always) only

on peaks of depolarizing waves (36). Somewhat ambiguous results were obtained in the study of unit and slow potential responses in various centers of the brain during the conditioning of leg flexion to tone. It was found that extremely close correlation between unit activity and slow potentials is exceptional and that at subcortical sites no such correlation exists (10). Thus, while findings concerning the relationship of unit activity to slow brain potentials are not entirely consistent, the majority of studies support such a relationship, at least in a qualitative sense.

PURPOSE AND SCOPE

From a brief review of recent neurophysiological findings presented in the Introduction it appears that the subject of neuronal discharge and slow potentials as related phenomena has not received an adequate quantitative treatment. Apparently, the only observations of a quantitative nature have been made from visual inspection of data rather than numerical analysis. In one instance it is stated that there is no correlation between the normal cortical surface wave and the magnitude of the change in neuron discharge (28). In another instance, the post-stimulus histogram of evoked discharges to a light flash (visual cortex) is said to correspond closely in form to the average evoked response (27). In the latter instance a quantitative relationship between neuronal discharge and slow potentials is implied but is not demonstrated.

The primary purpose of the present study was to investigate quantitatively the relationship between normal cortical potentials and the discharge patterns of cortical neurons in the cat brain, the two types of electrical activity being recorded simultaneously by a single extracellular microelectrode with respect to the cortical surface. In other words, a correlation between normal neuronal discharge and slow potentials is sought. By computing the average discharge rate of neurons relative to discrete intervals of transcortical slow potential

it was anticipated that a functional relationship, or relationships, between the two types of electrical activity would emerge. After a preliminary analysis of data, the original purpose of this study was extended to a fairly detailed consideration of the time and frequency distributions of the slow potentials and neuron discharge, respectively.

A secondary purpose of this study was to obtain some indications regarding the susceptibility of neuronal discharge activity to possible modulating effects by extracellular slow potentials. The present research may be regarded as an initial attempt to investigate neuronal discharge and cortical slow potential as related phenomena on a quantitative basis.

METHOD

Preparation

Recordings from 32 neurons or neuron groups were obtained from the suprasylvian gyri of 9 decerebrate cats. The animals were put under ethyl chloride anesthetic and after a short pause were maintained on ether for the duration of the surgical procedure. The procedure consisted of tracheotomy, cannulization of the femoral vein, removal of the temporal muscles, decerebration and removal of a portion of the left parietal bone to expose the suprasylvian gyrus. Decerebration was performed with a U shaped instrument which was inserted through bilateral holes centered about 2 millimeters lateral to the sagittal crest and about 2 millimeters anterior to the lamboid ridge (26). The cut was made forward at an approximate angle of 45 degrees to the antero-medial surface of the parietal bone. The result of the procedure is to eliminate all brain stem and cranial nerve influences including and caudal to the level of the V th nerve. This is known as the mid-pontine pretrigeminal preparation (2). In the experiments of July and August (1967) the cuts were made steeper in order to preserve the V th nerve junctions. Such cuts seemed to yield more active preparations than those made at 45 degrees. Xylocaine injections and jelly were applied at wounds and fixation points lest deafferentiation was not complete.

Immediately following decerebration the preparation was

started on artificial respiration which was set for a 2 to 2.5 percent carbon dioxide content in the expired air. One half to one cc. of flaxedil (20 mg/ml) was administered through the femoral cannula every hour to minimize movement. The posterior part of the preparation rested on a heating pad to maintain body temperature at 37 degrees C; the temperature was monitored by a thermocouple which was inserted in the rectum. The animal's head was stabilized in a head clamp at such a height as to prevent the rib cage from resting on the table, in order to minimize movement due to breathing. A certain amount of longitudinal stretch of the preparation was secured by tying one of the hind legs to a peg. Pneumothorax was performed on one occasion only (July 19, 1967).

The lateral ventricles were drained in several experiments as a preventive measure against possible brain swelling. This practice was eventually discontinued because the preparations seemed to deteriorate more rapidly as a result; usually little or no data was collected in these experiments. The dura above the suprasylvian gyrus was removed to facilitate the penetration of microelectrodes into the cortex. To protect the exposed pia against drying and cold an initial procedure was to close the brain by cementing a disc to the parietal bone, with a central hole remaining for the admission of microelectrodes. This technique was later abandoned for fear of contaminating the brain with the cement solvent, but also because of difficulties in controlling breathing and blood pressure pulsations

in the brain. Consequently, an open brain technique was adopted which utilized a pressure disc as a local stabilizer of cortex. The surrounding cortex was protected against drying by a thin sheet of saline soaked cotton which exerted a minimal restraint on cortical pulsations and thus relieved the pressure under the disc. Most of the data were collected under such open brain conditions.

Data Collection

The arrangement of recording electrodes used is shown in Fig. 1. Neuronal discharge and transcortical potentials were both detected by a glass tube microelectrode for which a surface wick electrode served as reference. Electrical contact with the concentrated NaCl solution filled microelectrode was made by a non-polarizing Ag-AgCl wire. The electrode assembly was spring-suspended from an hydraulic drive which was micrometer controlled making fine vertical manouvering possible (63). Occasionally, tuning in on discharging neurons required horizontal as well as vertical adjustment. Horizontal adjustment was achieved by tilting the microelectrode to obtain an appropriate horizontal displacement of the tip. Since the hydraulic drive was itself suspended from a movable assembly, tilt of the microelectrode was controlled by a set of horizontal movements. Horizontal electrode manouvering, however, was rarely used since the likelihood of injury discharges was thought to be greater when lateral pressure was exerted on the adjacent cortex by the microelectrode shaft.

The preparation, electrode assembly and the first stage of amplification were all shielded from electromagnetic interference by a surrounding copper screen. A representation of the amplification and recording system is shown in Fig. 2. The biopolar signal from the cortical electrodes was fed through a high input impedance preamplifier to a differential d.c.amplifier, for a voltage amplification of about 500. Additional amplification, when necessary, was achieved with oscilloscope amplifier (output terminal at back of scope). The signal consisted of slow transcortical potentials and superimposed action potentials which were subsequently isolated by passing the double record through a high pass filter. The isolated action potential signal was then further amplified in a second scope (monitor). Auditory pulses triggered by slightly-above-noise-level action potentials aided in locating and tuning in on discharging neurons.

Recordings of transcortical slow potentials were made direct (not capacity coupled)with a high cutoff at 10 KC. This frequency band preserves the form of transcortical and action potentials intact. The unfiltered signal (slow potentials with superimposed action potentials) was recorded FM on channel #1 (rolls off at 625 cps) of a 4 channel tape recorder (Ampex) while the isolated action potentials were recorded direct on channel #4. Voice markers and polarizing current signals (when used) were recorded on channels #3 and #2, direct and FM, respectively. To limit the amplified potentials to the

operating range of the tape recorder and to counteract system instability, the voltage offset control on the d.c. amplifier required adjustment, sometimes during actual recording. Changes in the average transcortical potential, polarization of the Ag-AgCl electrodes, amplifier drift and fluid conditions in the vicinity of the surface electrode are believed to have contributed to system instability.

Analysis

Data was comprised of simultaneous tape recordings of transcortical slow potentials and action potentials of neuron discharges. The slow potentials record was contaminated both by low and high frequency noise. Predominant noise frequencies were 60 cycles/second, radio frequencies from a local station, superimposed action potentials, and system drift. On one occasion (August 9, 1967) amplifier instability (with input shorted) appeared to have rhythmic components of 8-10 seconds, 16 seconds and 24 seconds per cycle, with amplitudes of 50 to 100 percent of the slow potential signal peak to peak value. Although low amplitude, high frequency noise would probably have no significant effect on the results, it was essential to eliminate the superimposed action potentials as well as the large amplitude, low frequency system drifts. Consequently, the signal was cleaned up after being passed through a band pass filter whose characteristics are shown in Fig. 3. The filter was designed to pass 0.1 to 10 cps frequencies with minimum

amplitude variability and phase shift. Most of the data was analysed repeatedly at time constant settings (low cutoff) of 4, 8 and 16 seconds. Thus, while filtering was inevitable, the transcortical slow potential signal remained essentially a d.c. record, particularly at the filter time constant setting of 16 seconds.

The record of action potentials consisted of high frequency low amplitude noise from which the pulses representing neuron discharge arose. In some records the train of pulses was of approximately uniform amplitude, apparently representing the activity of one neuron only. Other records consisted of a series of distinct large amplitude pulses and several superimposed series of smaller pulses, presumably the activity of neighboring neurons. Such records could be used as single neuron data, by gating only the tallest pulses, or as neuron group records by gating at a low level to include several pulse series. Because action potential amplitude variations in some records were considerable, care was taken to set the gating level so as to differentiate consistently between the different neuron discharge series without losing counts as a result of sub-threshold pulse amplitude dips.

The principle of analysis was to compute the average rate of neuron discharge as a function of slow potential amplitude. This was accomplished by a) dividing the slow potential peak to peak range into a set of equal potential intervals, b) obtaining the time spent by the slow potential in each interval, c) also

the corresponding discharge count per interval, and d) dividing values of discharge count by corresponding values of time: to arrive at the average discharge rate per slow potential level. Since the absolute amplitudes of the slow potentials are to a certain extent dependent on particular experimental setups, the ability to compare different functions rested on the possibility of displaying them in a standardized form. The scale adopted for this purpose uses the mean of the time distribution for the alignment of functions and the standard deviation as a scale factor.

The discharge count and slow potential time distributions were computed on a 1024 channel pulse height analyser (Nuclear Data, Model ND-150M). The slow potential signal was resolved into less than 256 intervals, usually less than 50, otherwise depending on the type of analysis desired. The discharge distribution was obtained by feeding both the action potential and slow potential records from tape into a set of inputs from which the analyser computed the potential levels at instants of discharge occurence and incremented corresponding registers. A rerun of the slow potential record with a standard frequency pulse (instead of the action potential record) produced the slow potential time distribution. The register contents of the analyser were tabulated on an analyser driven electric typewriter. The data was then key punched on unit record cards and processed by a specially written program on an IBM 7040 computer. Processing included calculation of means and standard

deviations of distributions, discharge rates, abscissas in terms of standard deviations, and normalization of the distributions to peak values. For certain data analysed polaroid camera snapshots of slow potential and discharge count distribution were taken directly from the analyser display screen.

RESULTS

The discharge rate functions (with respect to slow transcortical potential level) have been computed for 25 single neurons and 7 neuron groups from the suprasylvian cortex of decerebrate cats. There are usually 2 or 3 neurons per group. Following is a description of the characteristics observed in the forms of functions relating the two types of neuronal activity. It will be noted that all rate functions and distributions refered to below are plotted on a transcortical slow potential abscissa and the polarity indicated is that of the cortical surface. The unit of the abscissa is the standard deviation (SD) of the slow potential time distribution, and zero corresponds to the distribution mean. Neurons from different depths and locations in the suprasylvian gyrus are not distinguished in the results.

1. No single functional form describes all relationships between discharge rate and slow potential level, either in the case of single neurons or neuron groups studies. However, all rate functions in this study conform to one of the following descriptions.

a) Linear. Sixteen of the 32 functions have this form (Fig. 4). The discharge rate is usually a monotonic, positive function of the cortical surface phase of the slow potential amplitude and the individual rate values group

in such a way as to form approximate straight lines. This is particularly applicable in the range of slow potential between the 10 percent values of the slow potential time distribution. Some of the functions show a slight flattening at the positive ends and a wide scatter of point values in the slow potential range beyond the 10 percent limits.

b) Exponential. Eight of the remaining 16 discharge rate functions have this form (Fig. 5). These functions are characterized by monotonically increasing, positively accelerating discharge rates with respect to the surface phase of the transcortical slow potential. The same functions approximate straight lines on semi-log plots (Fig. 6).

c) Sigmoid. Five of the remaining 8 discharge rate functions have this form (Fig. 7). Three of these rise rapidly at relatively low potential levels and then seem to saturate gradually (Fig. 7,A), while the other two do not discharge at all in the lower range of the slow potential (Fig. 7,B).

d) Concave up. Two functions belong to this category (Fig. 8). The functions show a high rate of neuron discharge at both positive and negative phases of the slow potential level and a minimum near the mean. Data for the two

neurons was collected when activity reappeared after a cortical depression caused by polarization with cathodal current. Prior to the depression, data on 8 neurons and 1 group were collected and the functions for these are linear (7), exponential (1) and sigmoid (1). Thus, the behavior of neurons of the same preparation was radically different before and within half an hour after onset of the cortical depression.

e) Concave down. Only one rate function is of this form (Fig. 9). Recordings in this case were made under the usual conditions but there was a brief cessation of heart beat during surgery. The yield from this preparation was small and the slow potential waveform was characterized by sharp, large amplitude spindles unlike the slower transitions seen in most of the other waveforms.

2. Group Functions. Discharge rate functions of neuron groups do not differ in form from functions of single neurons. Rate functions computed both for a group and a single member of that group are almost identical in form, although the rate of the former is greater by a factor of about 3 (Fig. 10). All 7 neuron groups studied have either (approximately) linear or exponential discharge rate functions.

3. Threshold. Different neurons show initial discharge at different levels of the slow potential. From the relative shape of the discharge count and slow potential time distributions, and also from the rate functions, it is evident that some neurons do not begin to discharge until a fairly high potential level is attained, while others discharge over the entire slow potential range. Three functions with different threshold characteristics (no specific neurophysiological mechanism implied) are shown in Fig. 11. Discharge threshold similarities are observed in the functions of neurons from the same preparations. For example, rate functions of neurons from August 11, 1967 preparation (excepting those obtained after cortical depression) show a high discharge threshold, while the neurons from the July 28, and August 9, 1967 preparations are characterized by low thresholds. All 7 neuron group rate functions have a low discharge threshold.

While most neurons, after attaining threshold, show a gradual increase in discharge rate with increasing slow potential level, certain neurons seem to discharge at relatively high rates even at minimum levels of slow potential. The discharge rate, in such cases, also increases monotonically with slow potential level (Fig. 11, C).

4. Filter Effect. A comparison of the distribution and rate functions obtained with different capacity coupling time constants makes it possible to assess the extent of distortion introduced by such coupling. Three sets of results corresponding to

different time constants are shown in Fig. 12. While the general slopes of the rate functions corresponding to 4 and 16 seconds time constants are similar, that of the 8 second time constant is flatter. Apart from filter distortion, such flattening could be the result of misalignment of the discharge rate and slow potential time distributions due to amplifier drift in the time intervening between analysis of discharge count and slow potential time. But, as far as it goes, consistency of this nature is observed in the results of most of the neurons and neuron groups studied. Thus, the degree of uniformity between results obtained with different time constants suggests that the effect of capacity coupling on the distributions and rate functions is small and, for the present purpose, negligible. Nevertheless, only results obtained with the 16 second time constant capacity coupling are used to illustrate statements, since these are most nearly like the results which would be obtained with direct coupling of the slow potential signal.

Distortion of the slow potential signal and, consequently, the rate function at the upper frequency end of the filter cannot be assessed from a comparison of the results from different capacity coupling analyses. But such distortion may be assumed to be negligible since high frequency content of the slow potential waveform is usually very small. Power spectrum analyses of the transcortical slow potential wave form was performed on records obtained from different preparations. Since the slow potential signal was capacity coupled for this analysis, only a distorted

picture is obtained from frequencies below about 1 cycle/second. It is evident, however, that at frequencies above 5 cycle/second, the contents are extremely small and in most cases there is zero power above 10 cycles/second. Samples of power spectra of slow potentials from two preparations are shown in Fig. 13. It appears therefore, that the slow potential waveform is preserved largely intact while the system instabilities and higher frequency noise are largely eliminated.

5. Fine Structure. A casual inspection of the discharge count and slow potential time distributions, and the resultant discharge rate functions, of the neurons studied reveals a general presence of apparent irregularities and discontinuities. Under low slow potential resolution (less than 20 points peak to peak) as these results were initially studied, the discontinuities were largely masked or, where they persisted, they were initially thought to be a random scatter of points. The purpose of this section, however, is to explore the possibility that a pattern in the structure details of the distributions and rate functions exists. To carry this exploration out more effectively and to confirm previous results, the data from several neurons were re-analysed at higher resolution. Also, a more detailed study of the slow potential time distributions was made. The data selected for this purpose show good consistency with respect to the various filter time constants, while the rate functions are of the most common types, that is, linear and exponential.

The rate function shown in Fig. 14 appears at low reso-

lution to be made up of two linear segments with a sharp upward displacement of the right segment. At the resolution shown, however, the entire function seems to consist of an alternating series of local minima and maxima. Corresponding to each local maximum in the rate function there is a local maximum in the discharge count distribution and a less distinct one in the slow potential time distribution. A similar occurence of minima and maxima is observed in group functions (Fig. 15). The appearance of corresponding local maxima in the two distributions suggests the possibility that they are a manifestation of definite "prefered" activity states of neurons, where the discharge count is accumulated within a narrow band of slow potential. Since the appearance of definite activity states is more pronounced in the discharge count distribution than in the potential time distribution, the result is a sequence of local maxima in the rate function. It may be observed that the difference in the magnitude of the maxima in the two distributions increases toward the positive potential limit, where the time spent by the potential is small while the discharge rate is highest.

The view that local maxima in the distributions and rate functions reflect actual neuronal processes, rather than experimental errors, is supported by the following observations.

a) Repeated analysis. Reanalysis of data under higher resolution of slow potential seems to confirm and match the maxima from previous analyses (Fig. 16).

b) Different filter settings. Fair agreement regarding location and form of maxima is observed in distributions and rate functions obtained from analyses of the same data using different capacity coupling time constants (Fig. 17).

c) Split record analysis. Results obtained from separate analyses of 2 or 3 non-overlaping time spans of neuron activity records are fairly similar in the location and magnitude of maxima. The discharge count distributions of two equal time spans from the activity record of a single neuron are shown in Fig. 18.

d) Short interval analysis. The slow potential time distribution maxima are usually more distinct in distributions obtained from the analysis of short record spans rather than long ones (Fig. 19). A possible reason for poor definition of maxima in the long interval time distributions can be seen in Fig. 20. Shown is a sequence of snapshots of 5 second duration slow potential time distributions taken at different times in the activity record of a neuron. It seems that the slow potential follows a definite level to level transition pattern and that this pattern changes in the course of time. A similar sequence of 10 second time distributions from a recording of a different neuron is shown in Fig. 21.

Questions are raised concerning the extent to which the slow potential time maxima are specific to levels of potential and the stability of relative positions of the maxima. In the first place, a certain degree of potential level specificity would be essential to produce the maxima in the long duration potential time and discharge count distributions. In the second place, rearrangementof some of the snapshots of Fig. 20 makes it easier to recognize what appears to be a recurring pattern of slow potential transitions (Figs. 22, 23). Recurring transition patterns can also be identified in the distributions of Fig. 21 (C and H, D and J). While relative positions of the maxima are comparatively stable, the entire distributions may be located in different slow potential ranges (for example C and H of Fig. 21), suggesting that the patterns are to a certain extent independent of the slow potential level. It should be added, however, that while the time distributions of the various transition patterns are generally quite different, some common features are often identified in all, and that the predominant difference between time distributions is often in the amplitudes rather than the locations of the local maxima.

It is difficult to obtain a reliable representation of the discharge behavior of neurons with the approach used to study short interval slow potential activity. The number of discharges occuring in an interval of time such as 5 seconds is too small to give distributions with clearly defined features. But a study of the average discharge rates of neurons over consecutive 30 second intervals reveals large fluctuations in the rate. The

time course over which such fluctuations occur (about 1 minute) is comparable to the time required for the slow potential to change from one predominant transition pattern to another (Fig.24).

6. Slow Potential Induction. A description of the circuit and operation of a unidimensional slow potential neutralizer and voltage inducer is given in Appendix I. The circuit was used effectively in several experiments in that a high degree of slow potential neutralization has been achieved. The effect of neutralization and induction of potentials on the discharge pattern of cortical neurons is presently indeterminate and, therefore, additional work in this area shall be required. But, to the extent that the study has been carried, the operation of the neutralizing curcuit has led to two significant observations regarding the properties of cortical slow potentials. First, unidimensional neutralization of slow potentials is possible without any apparent destructive effect on the cortical tissue. Second, the current needed to achieve slow potential neutralization is less than 10 microamperes peak to peak. Expressed as current density at the cortical surface this current value is equivalent to about 1 microampere per square millimeter.

DISCUSSION

It is generally held that synaptic excitatory and inhibitory input of cortical and extracortical origin produces complex patterns of standing waves in soma-dendritic membranes of cortical neurons. The net excitation states of neurons depend on the type, intensity and geometry of synaptic input as well as the resting membrane potential. The all-or-none neuronal activity is believed to be initiated at the first axon segment of the neuron by membrane depolarization to which the greatest contribution is made by synapses located on the soma and the least by those located on tips of dendrites. Activity of neurons spreads by all-or-none conduction in axons to form complex feedback loops resulting in more or less synchronized activity of large populations of cortical neurons. The algebraic sum of synchronized conduction in afferent and efferent axon pathways, together with the resultant depolarization and hyperpolarization in large populations of neurons constitutes the cortical slow potential. The complexity of the process generating these potentials is not always apparent from recordings because the potentials do not represent unique combinations of factors contributing to the bioelectric activity of the cerebral cortex (54).

In this study, cortical slow potentials were recorded between an extracellular point near the neuron soma and the cortical surface, where the reference electrode presumably sees the synchronized activity on apical dendrites. In cases where

recordings were made from neurons with dendritic extensions all the way to the cortical surface, the potential record is that of the soma potentials with respect to the surface portion of the dendritic tree. Most of the neurons studied, however, were deep lying (below.5 mm from the surface) so that the recorded potentials simply represent the slow activity of deep neuron somas relative to the activity of apical dendrites. But the dendritic tree, because of its relatively large surface area, is likely to follow the potentials of the surrounding medium. This is probably also true for the neuronal axon. Consequently, recording extracellularly produces essentially a record of the soma potentials with respect to the dendritic complex of the neuron. It is to be expected, however, that as the distance between the microelectrode and surface reference electrode increases the potentials recorded in this manner are less representative of the soma activity because of the interposed generators of slow potentials belonging to other neurons. Nevertheless, it is likely that the slow potentials recorded in this study represent membrane activity of the soma with respect to its dendrites (and, possibly, the axon).

If a definite relationship between discharge frequence and the potential across some critical portion of a neuron exists, then that relationship can at best be detected as an approximation with the present technique, for two principal reasons. First, the slow potential recorded by the microelectrode partly represents activity of neighboring neuronal processes so that the record is not a pure representation of single neuron soma activity. The

notion that adjacent neurons contribute to the slow potential records is supported by frequent observations in neuron discharge records of low amplitude pulses which are almost certainly representative of discharges in adjacent neurons. Also, recordings of neuron group discharge activity would not be possible if the influence of neighboring neurons would not make itself felt at the microelectrode tip. Second, according to neurophysiological theory, the trigger mechanism initiating discharges is situated in the vicinity of the first axon segment, in which case the axon-soma potential is likely to be the important one. At the same time, it is probable that the electrical transients of the medium induce potential fluctuations in the axon relative to the soma. Thus, if the discharge frequency of the neuron were a function of the axon-soma potential, such interference would partly obliterate this relationship in view of the present recording method. A similar argument could possibly account for the apparently probabilistic nature of the relationship between neuron discharge and slow potentials.

In view of the above considerations it is somewhat surprising to find the degree of regularity seen in the forms of rate functions of most of the neurons studied. In the majority of cases the relationship of discharge rate to slow potentials is very nearly linear or positively accelerating, without any sharp distinctions between the two forms. There is a possibility that the rate functions are basically exponential in form but do not always appear as such because of recording limitations. Such a neuron would in part function as an exponential analog-

to-frequency converter, a transformation that would be complementary to other bioelectrical processes found in the nervous system, particularly in peripheral sense receptors.

The rate functions of several neurons studied (Figs.8 and 9) are exceptional in form and a consideration of possible causes follows. What differentiates the function of Fig. 8 from those of most other neurons from the same preparation is the increasing discharge rate toward the surface negative end of the slow potential range. Since discharges are thought to result from excitatory postsynaptic potentials, and since excitatory input to the dendrites gives rise to surface negative potentials, it is possible that excitatory input to the dendrites initiates in them all-or-none responses which are then propagated to the soma. Similar dendrite initiated discharges have been infered from the study of activated hippocampal neurons (58). Under normal conditions, discharge activities is believed not to involve extensive participation of dendrites; therefore an increase in effectiveness of the dendritic synapses in the neuron of Fig. 8 may be assumed to have occured. Because part of the function shows the usual increasing rate with increasing positive surface potential (some depolarization) it may also be necessary to assume at least a partial dissociation between somatic and dendritic inputs.

An alternative explanation for the biphasic form of the function of Fig. 8 would be based on the assumption that discharges are generated normally at the axon-soma site but because of the increased effectiveness of dendritic synapses the polarity of the recorded potential is inverted. Such an explanation would

also require the assumption of a dissociation between somatic and dendritic inputs to account for the positively rising section of the rate function.

The rate function of Fig. 9, like that of Fig. 8, is also biphasic but contains descending rather than ascending rates with increasing positive and negative slow potential amplitude. The form of the rate function of Fig. 9 can be rationalized within the same framework used for the interpretation of the function in Fig. 8. The high discharge rate at the mean potential level may be due to simultaneous excitatory input to soma and dendrites. A suitable balance of excitation in both neuron regions would result in a small net transcortical potential which would, nevertheless, be associated with a high rate of discharge. A reduction in net dendritic excitation would be manifested as a positive slow potential shift and a decrease in discharge rate. Similarly, a reduction in the net excitation of the soma would be manifested as a negative slow potential shift and a similar decrease in discharge rate. Further, if discharge rate is a stronger function of somatic rather than dendritic excitation, as suggested by theory, then the rate of decrease of discharge accompanying negative shift of the potential would be greater than that accompanying positive shift. This effect is actually observed in Fig. 9.

There is no inconsistency in the suggested causes of the forms of the functions in Figs. 8 and 9, provided that in the first case it is assumed that somatic and dendritic inputs are mutually exclusive, while in the second case the excitation at

each site is maximal when input to both sites occurs simultaneously, resulting in high discharge rate. It seems that irregular forms of rate functions such as those of Figs. 8 and 9 result from data collected from preparations in various states of deterioration. It has been found, for example, that a deteriorated state of the preparation is often associated with an increased overall discharge rate of neurons (36). Deviations from the common forms of the rate functions seem to be most marked for neurons from which recordings were made in the last stages of the experimental session. The degree of irregularity also varies from one preparation to another.

The similarity between the distributions and rate functions of single neurons and neuron groups (Fig. 10) is interpreted as an indication of at least local synchronism in the activity of cortical neurons. Such synchronism could be a reflection of coordinated activity in the multiplicity of radiations originating subcortically, or it could be due to spread of excitation between adjacent neurons. It seems likely that the synchronism is primarily a property of cortical radiations since the latencies between discharges in a group record are of a very short order, perhaps too short to be accounted for by spread of excitation. Synchronized input probably originates in the thalamus which is regarded as the principal pacemaker for cortical rhythms (7).

A wide range of discharge thresholds is encountered in the rate functions of the neurons studied. As an extension of the concept of threshold it may be worth noting that in some prepara-

tions there seemed to be a complete absence of spontaneous neuronal discharge in the presence of apparently normal slow potential activity. Possibly, in such preparations the discharge threshold is raised to such an extent as to render common excitation levels incapable of initiating neuronal discharge. It is known, for example, that even in normal cortex certain neurons ("idle cells") exhibit normal slow potential activity but no discharge activity (37).

Suggestions of the discrete nature of cortical slow potentials can be found in the reports of various studies of cortical electrical activity. In a study of intracellular potentials of cortical neurons it was noted that the character of the potential waves is fairly stereotyped as long as the membrane potential remains constant, and that the waves are made up of stepwise rising and descending potentials (36). In an investigation of the relationship between intracellular and surface potentials it was observed that spontaneous excitatory potentials are composed of several excitatory postsynaptic potentials(EPSPs) of a "unitary" character and that the single EPSPs can be recognized to summate during spindle depolarization (18). Intracellular recordings of responses to single stimuli applied to the ventro lateral nucleus of the thalamus show that each response consists of 3 consecutive EPSPs (17). In a study of cortical evoked potentials a series of short latency spikes was observed in the starting phase of the primary negative wave (64). Finally, in a study of the direct cortical response (DCR) it was noted that

the depolarization wave suggest a stepwise process (66).

Additional suggestions of the discrete nature of cortical slow potential activity are found in the results of the present study, which seem to indicate that relatively stable and recuring excitation sequences characterize neuronal activity. The observation in the present case is extended to considerations of neuronal discharge and an analysis of short and long duration samples of slow potential. It would seem that while the results are more reliable when obtained from long rather than short sample analysis, those of the short sample analyses provide a clearer indication of the stepwise process. Also,because the average excitation state of neurons seems to vary with time, all but the most radical features of the discrete transition process are obliterated in long duration sample analyses. This would explain the poor accentuation of maxima in the distributions from long duration sample analyses, particularly in the time distributions of slow potential where more gradual inhibitory input would tend to flatten the maxima.

The infered excitation sequences represented by the maxima in the short sample slow potential distributions may be generated intracortically or they may stem from subcortical rhythmic activity. It has been noted, for example, that cortical spindle waves are accompanied by synchronized activity in the thalamus (18). Since a certain degree of local synchronism appears to exist (see above) there is a likelihood that the excitation sequences are generated subcortically. Excitation sequence gene-

ration may consist of discrete intensity changes and/or co-ordinated excitation in different fibre groups. The likelihood of the latter process is supported by an apparent differentiation of inputs to cortical neurons observed in other studies. Evidence for a differentiated input organization is provided, for example, by the ability to produce only a simple negative component of the surface cortical response by weak stimulation (56) and the observation that peak positive and negative amplitudes of cortical slow potential waves are quite independent (60). Whatever the origin of the discrete rhythmic activity it is unlikely that the stepwise transitions in the slow potential are due to individual synapses, since the number of maxima observed in the distributions is typically between 10 and 15 while the average number of synapses activating a neuron is estimated at about 1000. It appears, therefore, that rhythmic excitation is imparted to the neuron through sets rather than individual synapses.

Polarization with steady currents has been shown to alter the discharge rate of cortical neurons. The effect of anodal polarization is immediate and appears as an increase in discharge rate; the effect of cathodal polarization takes longer to develop and results in a decrease of discharge rate. In one study of the polarization effect in cortical neurons no noticable change in discharge rate was observed for currents below 200 microamperes (15). However, polarization effects with smaller currents were observed during incidental operations in the present study, and it may be assumed that the minimum value of polarization current

that will produce a noticable effect will depend on the experimental conditions.

The possibility of influencing neuronal discharge by polarization without any apparent damage to the cortical tissue raises questions concerning the possibility of slow potentials affecting the discharge of neurons. Specifically, the question is whether this low amplitude electrical activity plays a role in the function of the brain. According to the preliminary results of this study, cortical slow potentials can be counteracted by currents of less than 10 microamperes. If it were certain that currents of this order of magnitude have no significant effect on cortical neurons, it would follow that extracellular slow potentials are an epiphenomenon without any feedback effect on the activity of neurons. There is evidence, however, that potentials of magnitudes comparable to those of cortical slow potentials play a role in synaptic excitation processes. For example, potential buildup at a synapse during periods of high activity may reduce the effectiveness of incoming impulses by decreasing the efficiency of transmitter release (69). But, such potentials are both internal and specific in their action and the electrical fields involved may be much greater than either of those produced by extracellular slow potentials or polarizing currents of less than 10 microamperes. As far as can be determined from an initial study of this phenomenon, cortical slow potentials have no detectable effect on the discharge rate of cortical neurons.

CONCLUSION

The results of the present study are consistent with previous qualitative observations that cortical neurons show variability in their discharge rates which appear to be related to the phases of the cortical slow potentials. While the present approach to the study of the relationship between discharge rate and slow potential amplitude is limited in its possibilities to describe an exact relationship between the two phenomena, the results obtained support the likelihood that such a relationship exists. It appears that any attempt to find a functional relationship will have to go hand in hand with an attempt to identify precisely the site where the slow potentials are directly related to the discharge activity, and the development of a recording technique that will make it possible to detect these potentials. If the surface or transcortical slow potentials are truly the net result of complex activity of neuronal aggregates then the relationship of the discharge activity of single neurons to the slow potential generated by aggregates is likely to be probabilistic in nature, at best.

The discrete character of neuronal slow potential activity, suggestions of which are found in numerous reports of neurophysiological studies, also appears in this study. The same data when viewed under greater resolution of the slow potential than has been used for the illustrations, exhibits an even finer structure of discrete activity. Again, because of the limited scope of

this study, the higher resolution analysis cannot be fully exploited at the present. Under appropriate conditions it may be possible to demonstrate the activity of small synaptic sets or even of individual synapses, and make inferences from such analysis about the nature of neuronal connections.

There is no evidence, either in this or other known studies, that extracellular slow potentials have any significant influence on the behavior of cortical neurons. While slow potentials can be neutralized with appropriately generated polarization currents, in no known instance have such small currents as are required for this purpose been found to have any effect on neuronal discharge activity. A more precise statement about the effect of slow potentials on neuron activity must await further investigation.

The present study may well be regarded as an initial step in the attempt to describe the relationship between graded and all-or-none activity of neurons in quantitative terms.

SUMMARY

The present study is an investigation of a possible quantitative relationship between the spontaneous discharge pattern of cortical neurons and the slow potentials of the cortex. Records of the activity of 32 neurons or neuron groups were obtained from the suprasylvian gyri of 9 decerebrate cats. Simultaneous recording of discharge and transcortical slow potentials was made with a single microelectrode refered to the cortical surface directly above the recording point.

The predominant functional form of the relationship between average neuronal discharge rate and transcortical slow potential amplitude was found to be linear (16); other common functional forms were exponential (8) and sigmoid (5). The rate functions corresponding to 3 of the neurons studied were of irregular form and are thought to be due to the deteriorated condition of the preparations at the time of recording. Some rate functions showed neuronal discharge only above certain levels of the slow potential while others showed discharge throughout the slow potential range. Groups of neurons, as recorded by a single microelectrode, were found to behave in a manner similar to that of single neurons. A series of local maxima was observed in the rate functions, and corresponding ones in the distributions of slow potential time and discharge count; these are attributed to a possible discrete and patterned nature of slow potential transitions.

An initial procedure to evaluate the effect of cortical slow potentials on the discharge activity of neurons led to the observations that slow potentials can be locally neutralized without apparent damage to neural tissue, and that the currents required for this purpose are about one order of magnitude smaller than the steady currents which are known to produce noticable effects on neuron discharge. Thus far no indication has been found to suggest that extracellular slow potentials play a role in the all-or-none activity of neurons in the cat cortex.

APPENDIX I

An electronic circuit (voltage clamp) for the manipulation of cortical potentials was constructed and is shown schematically in Fig. 25. The effectiveness of the circuit lies in the amplification of the slow potential signal detected between two microelectrodes (or a microelectrode and a surface reference electrode) and by generating a current which is proportional in magnitude but opposite in polarity to the detected signal. The generated current is then fed back into the cortex through a surface polarizing electrode, effecting a neutralization of slow potentials to less than 10 percent of the normal slow potential amplitude. The degree of neutralization is controlled by a gain adjustment on the operational amplifier. Induction of static and dynamic potentials in the cortex is possible by application of the desired signal to a second input at the operational amplifier. Neutralization and induction of potentials is both unidimensional and local.

Effectiveness of the circuit operated as a potential neutralizer is shown in Fig. 26. Starting with a normal slow potential signal the circuit is then switched on at low gain (clamp on) without any noticable effect on the potentials. The gain is then progressively increased resulting in graded slow potential neutralization, as is shown in the consecutive segments of the record in Fig. 26. The effect of the neutralizing circuit on the cortex surrounding the microelectrode tip

was explored with a second microelectrode. A map of the residual potentials as percentages of normal potentials is represented by the areas of the dots in Fig. 27. A graded effect of the neutralizer with distance from the microelectrode tip is observed. It should be mentioned that the mapping of the cortical potentials of Fig. 27 was performed on a preparation under nembutal anesthetic, unlike all other results of this study which have been obtained from decerebrate preparations.

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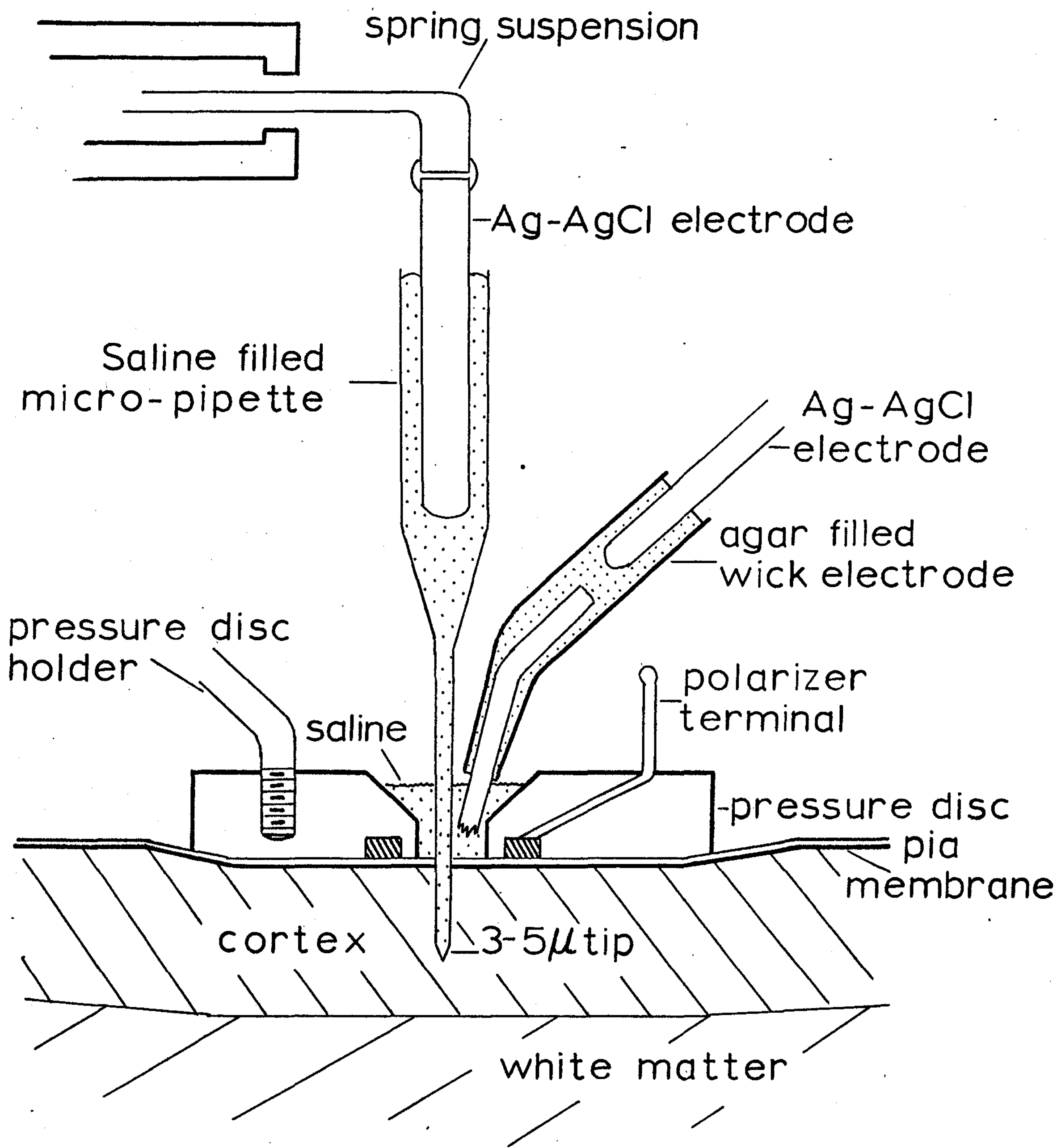
Recording Electrodes

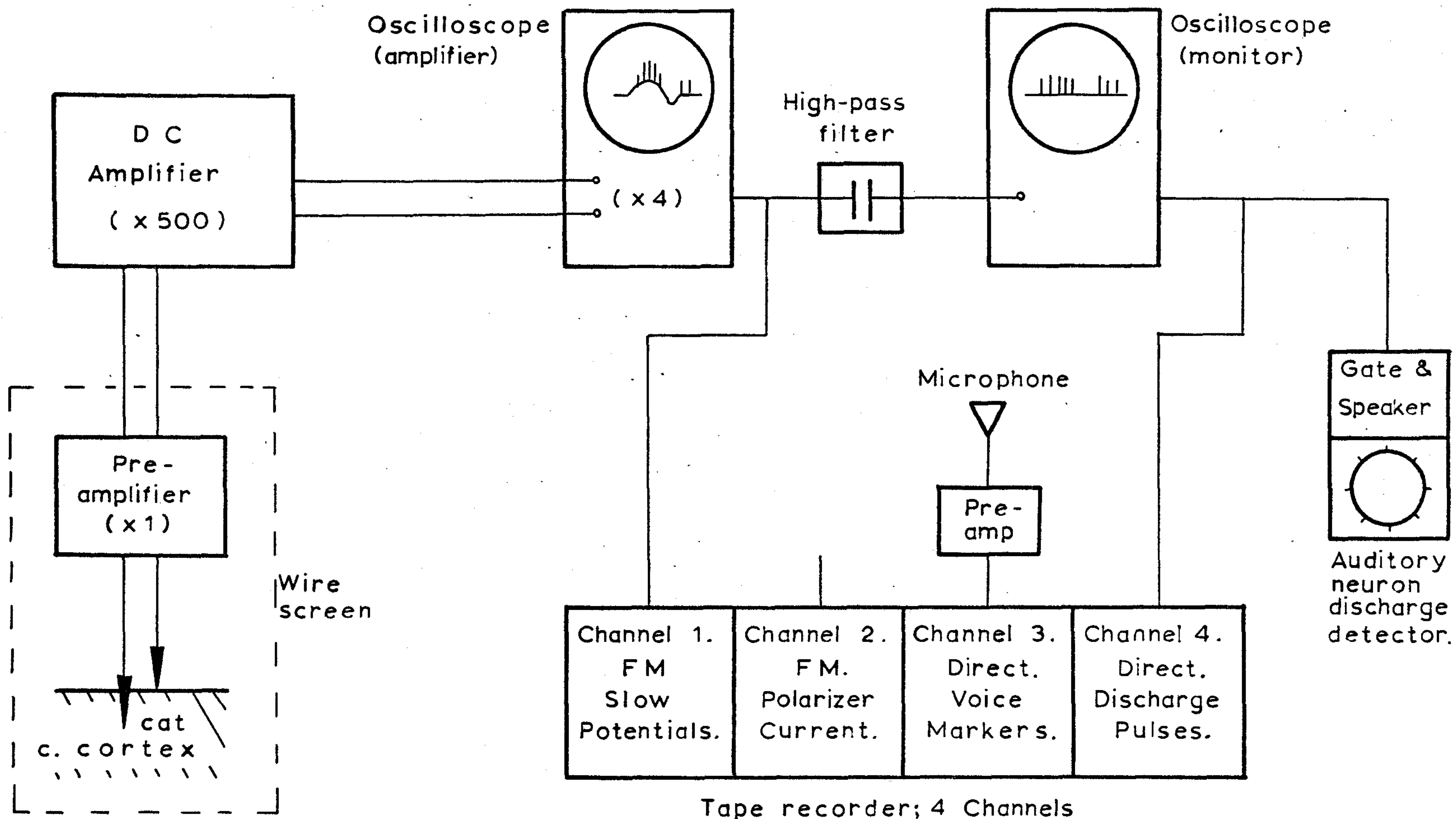


H.L., Nov.'67.

Not to scale.

Fig. I.

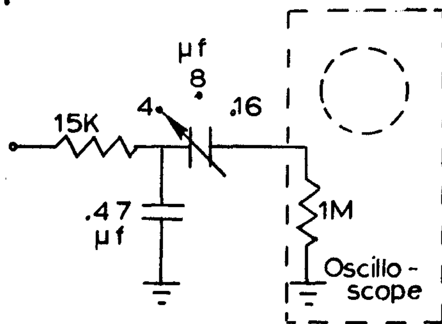
Recording System



H.L., Nov. '67.

Fig. 2.

Slow Potential Filter
Characteristics



+ 10
0
-50
-100
Degrees
Phase Shift

1.0
0.5
0
Relative magnitude
Attenuation

0·2 0·3 0·5 1·0 3·0 5·0 10·0 20·0 30·0 50 60 100
Sine wave frequency - cycles/sec.

H.L., Nov.'67.

Fig. 3

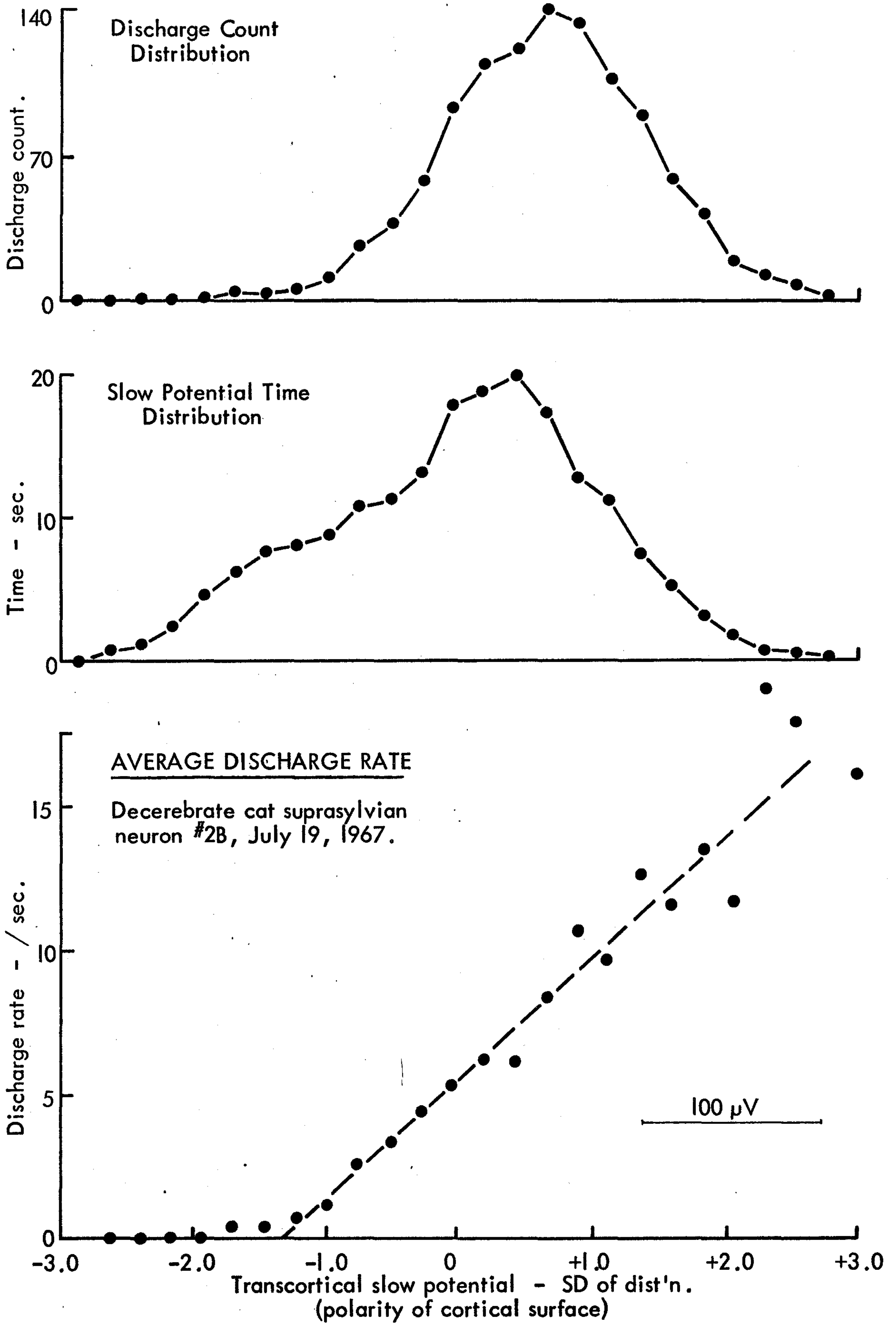
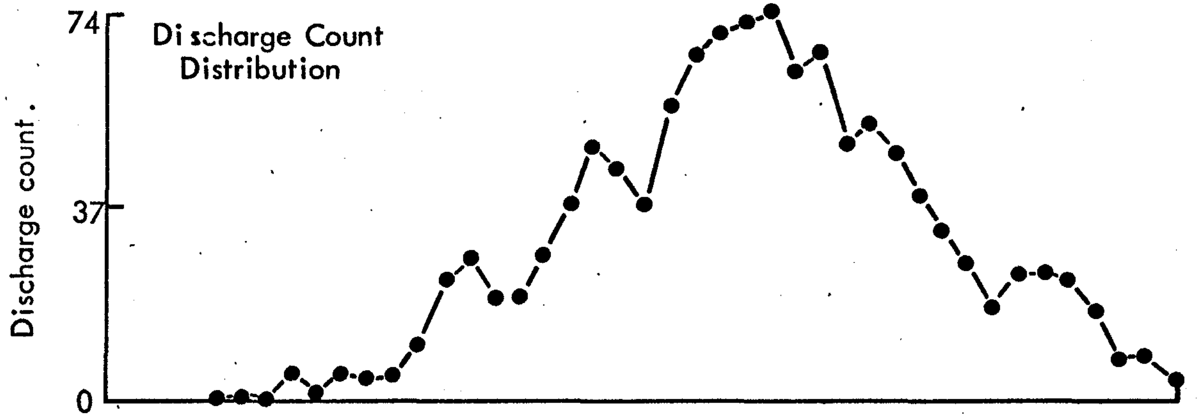
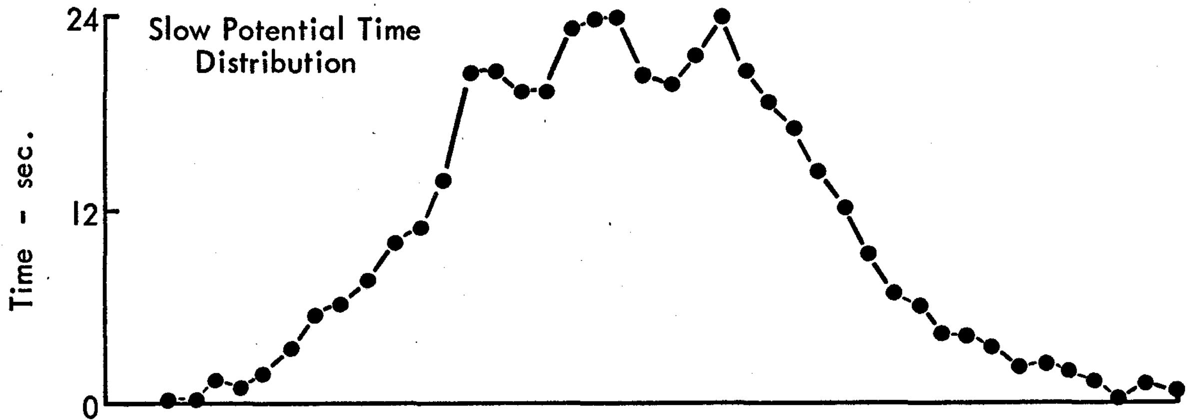


Fig.4.





AVERAGE DISCHARGE RATE

Decerebrate cat suprasylvian
neuron #4, Ayg. 11, 1967.

10

5

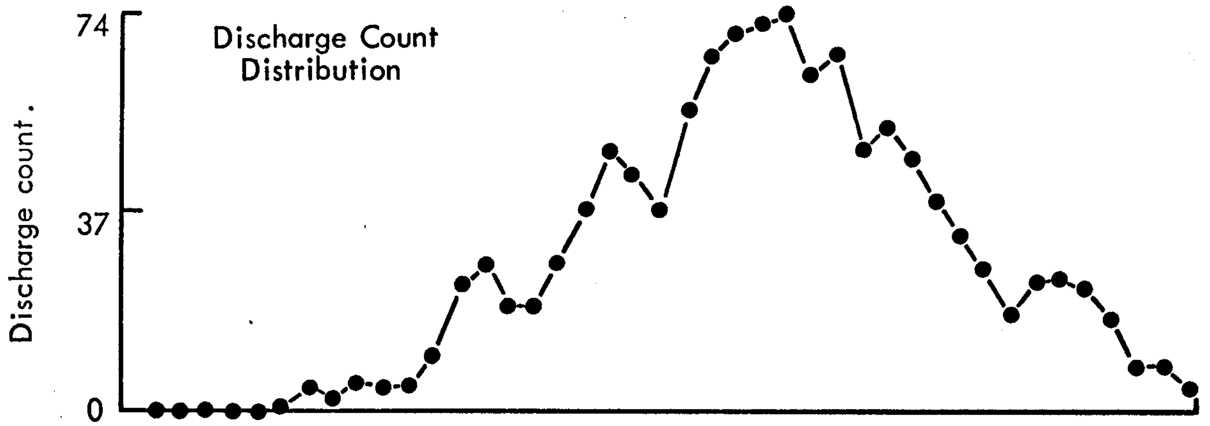
0

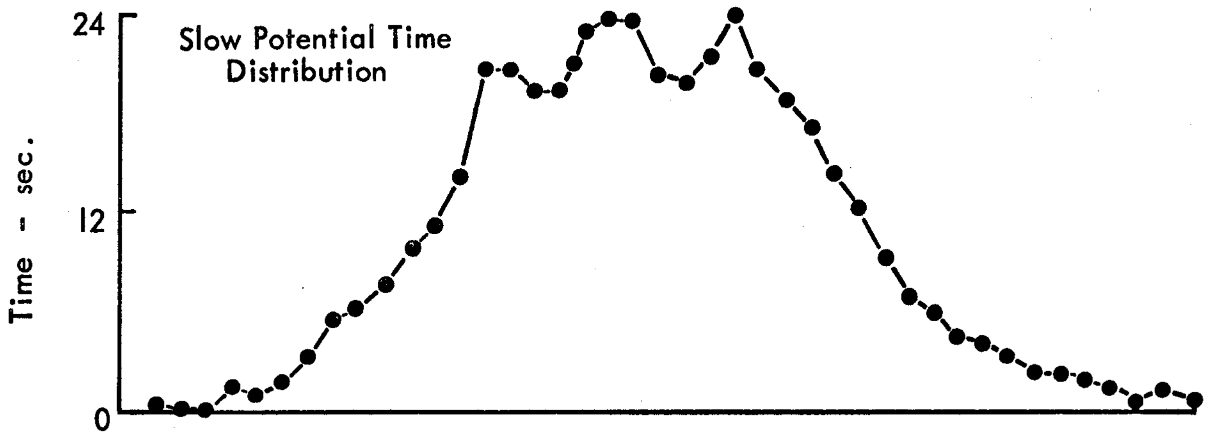
Discharge rate - / sec.

250 μV

-3.0 -2.0 -1.0 0 +1.0 +2.0 +3.0

Transcortical slow potential - SD of dist'n.





10.0
3.0
1.0
0.3
Discharge rate - / sec. (log plot).

AVERAGE DISCHARGE RATE

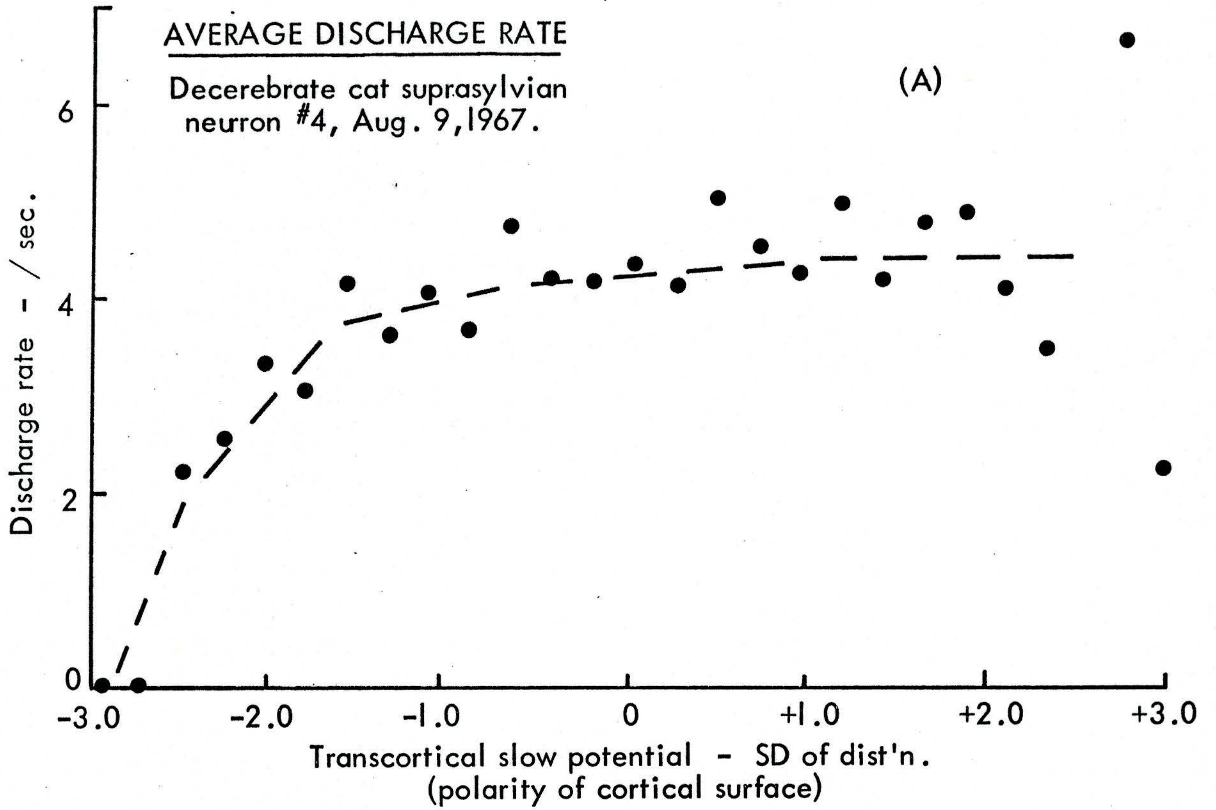
Decerebrate cat suprasylvian
neuron #4, Aug. 11, 1967.

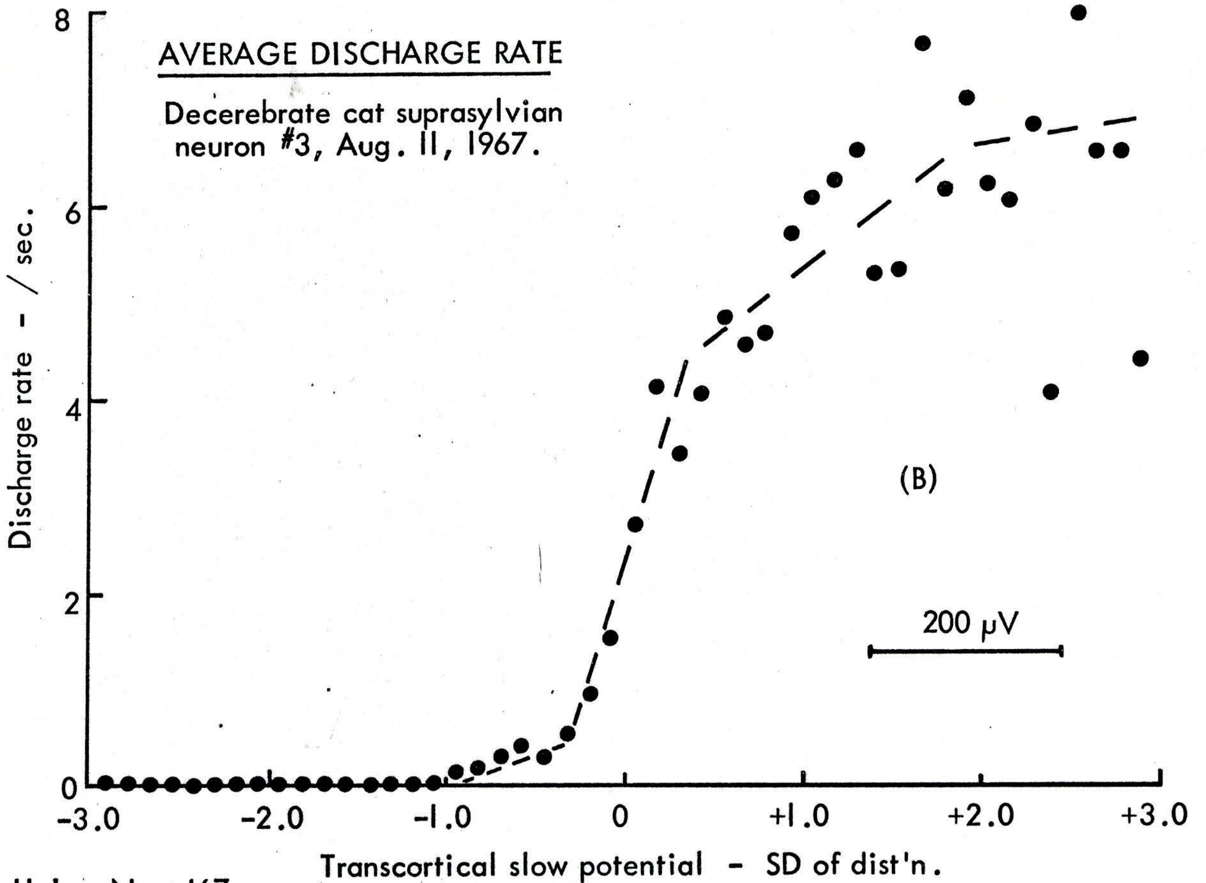
250 μV

-3.0 -2.0 -1.0 0 +1.0 +2.0 +3.0

Transcortical slow potential - SD of dist'n.

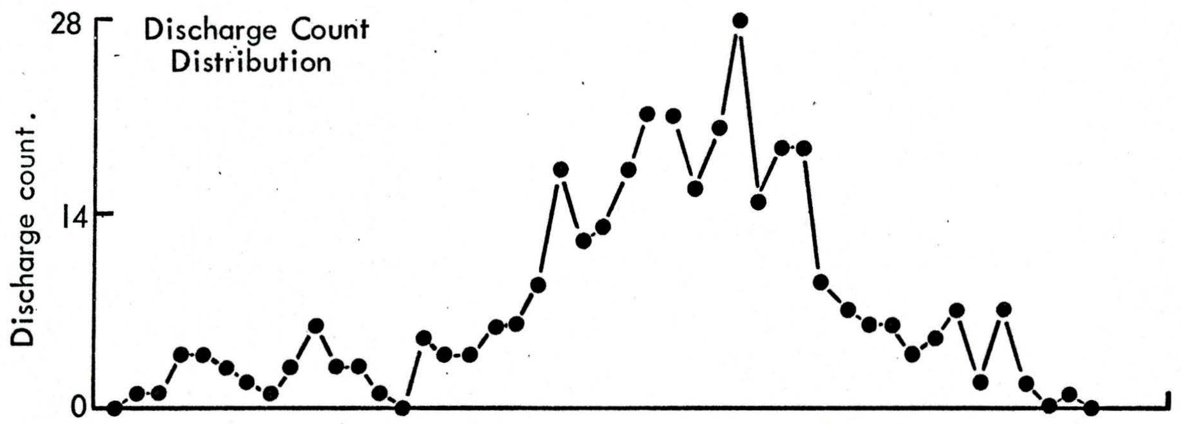
H.J. Nov.'67.

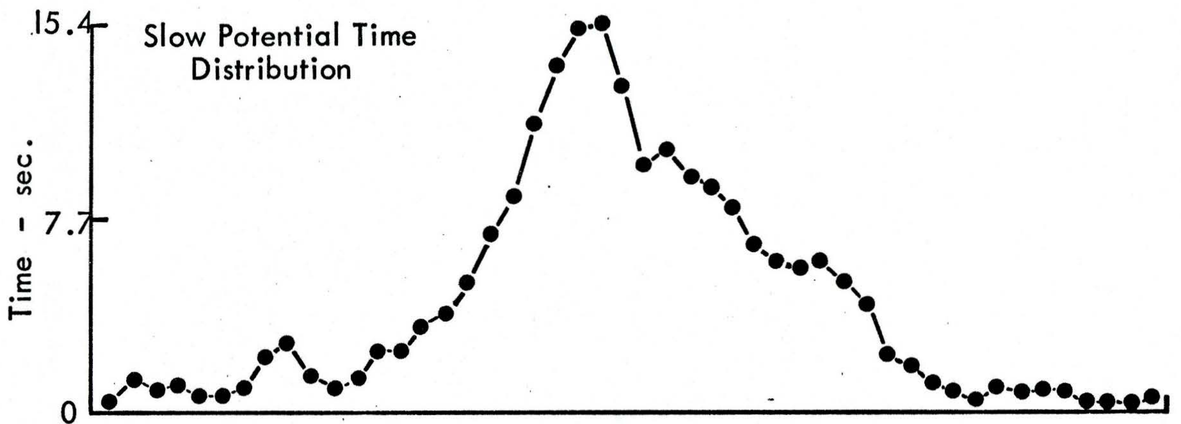


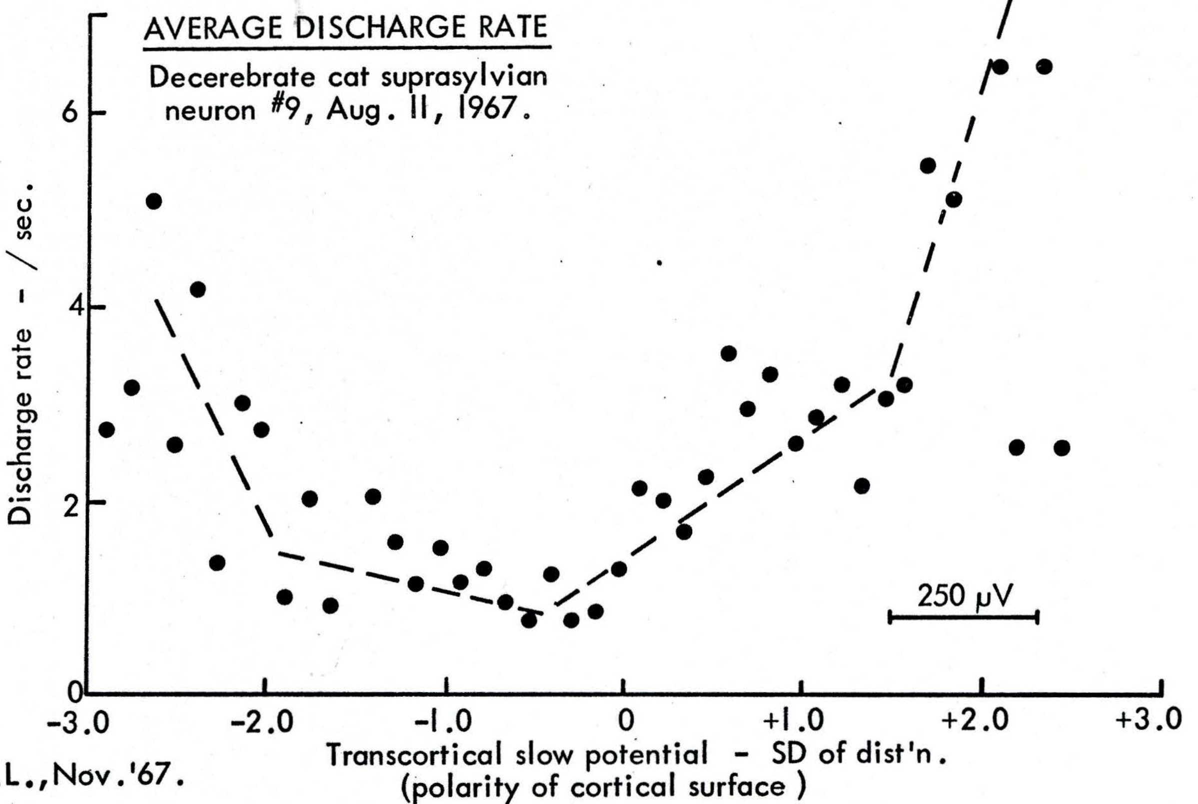


H.L., Nov.'67.

Fig. 7.

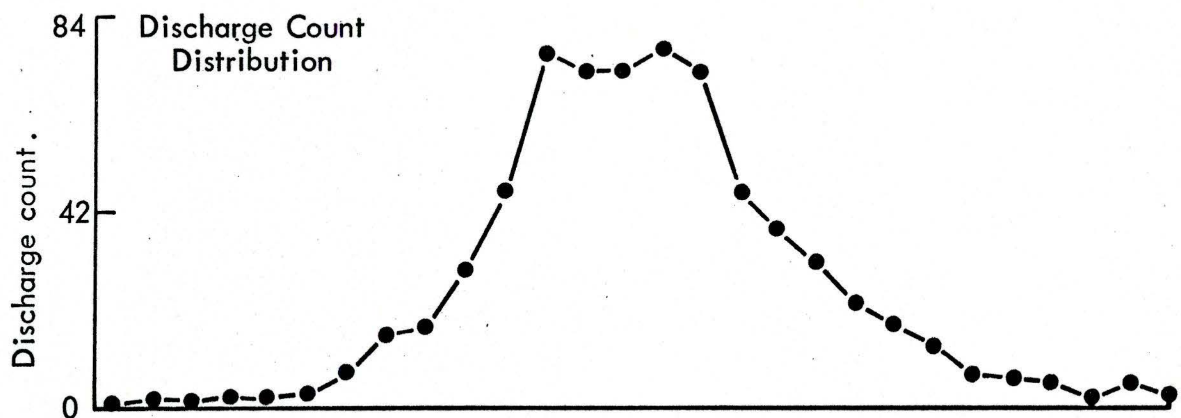


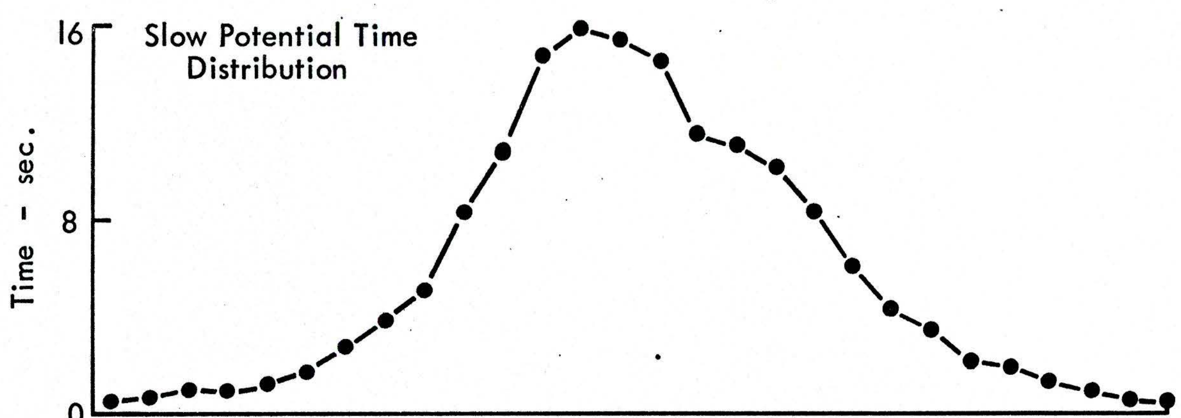


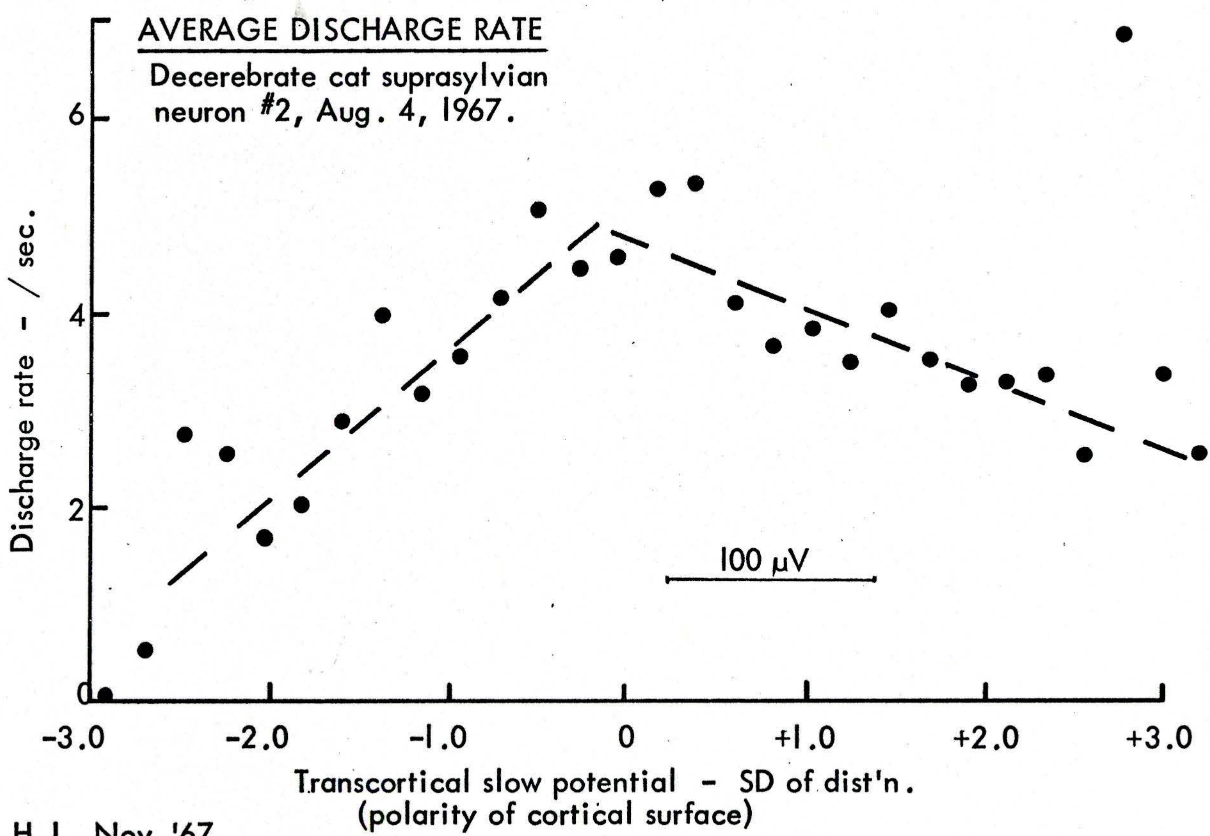


H.L., Nov.'67.

Fig. 8.

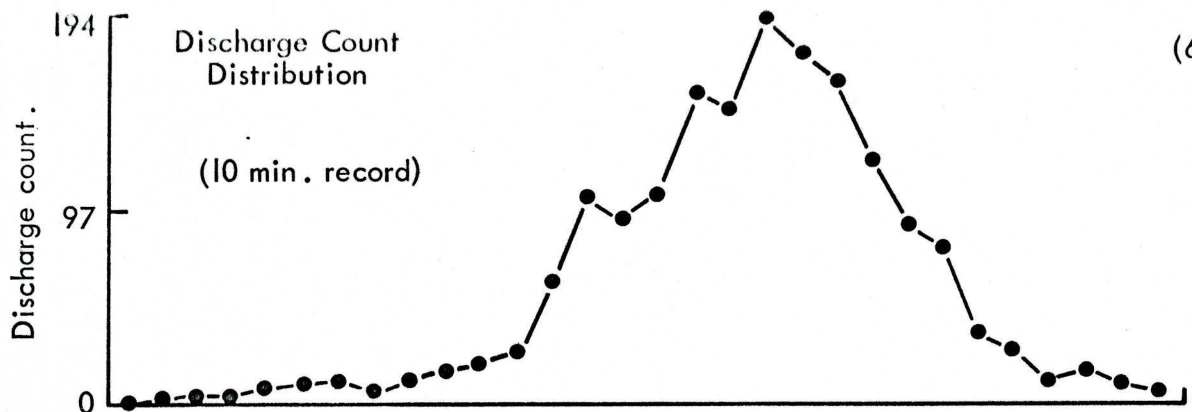


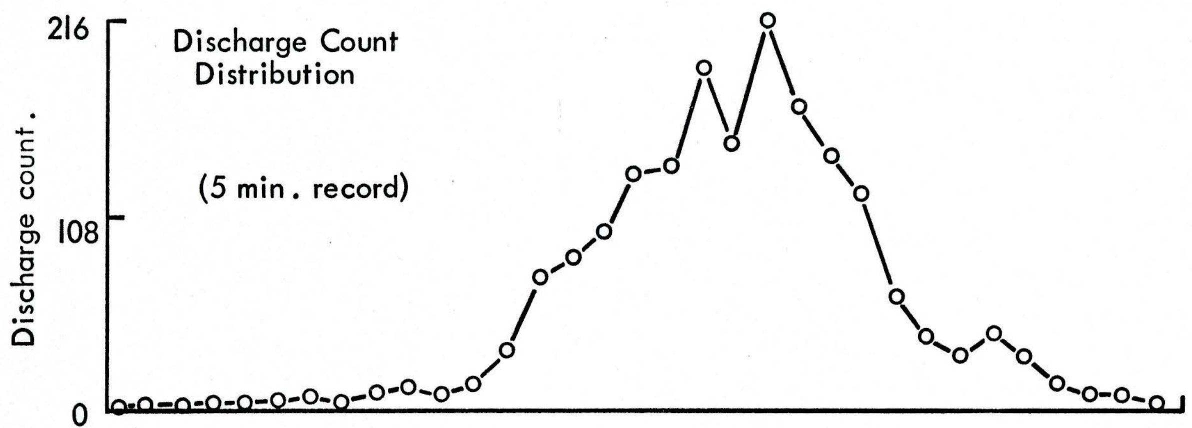




H.L., Nov.'67.

Fig. 9.





25
20
15
10
5
0

AVERAGE DISCHARGE RATES

Decerebrate cat suprasylvian

single neuron of a
neuron group

#5G, Aug. 11, 1967.

250 µV

Discharge rate - /sec.

-3.0 -2.0 -1.0 0 +1.0 +2.0 +3.0

Transcortical slow potential - SD of dist'n.

H.L., Nov.'67.

Fig. 10.

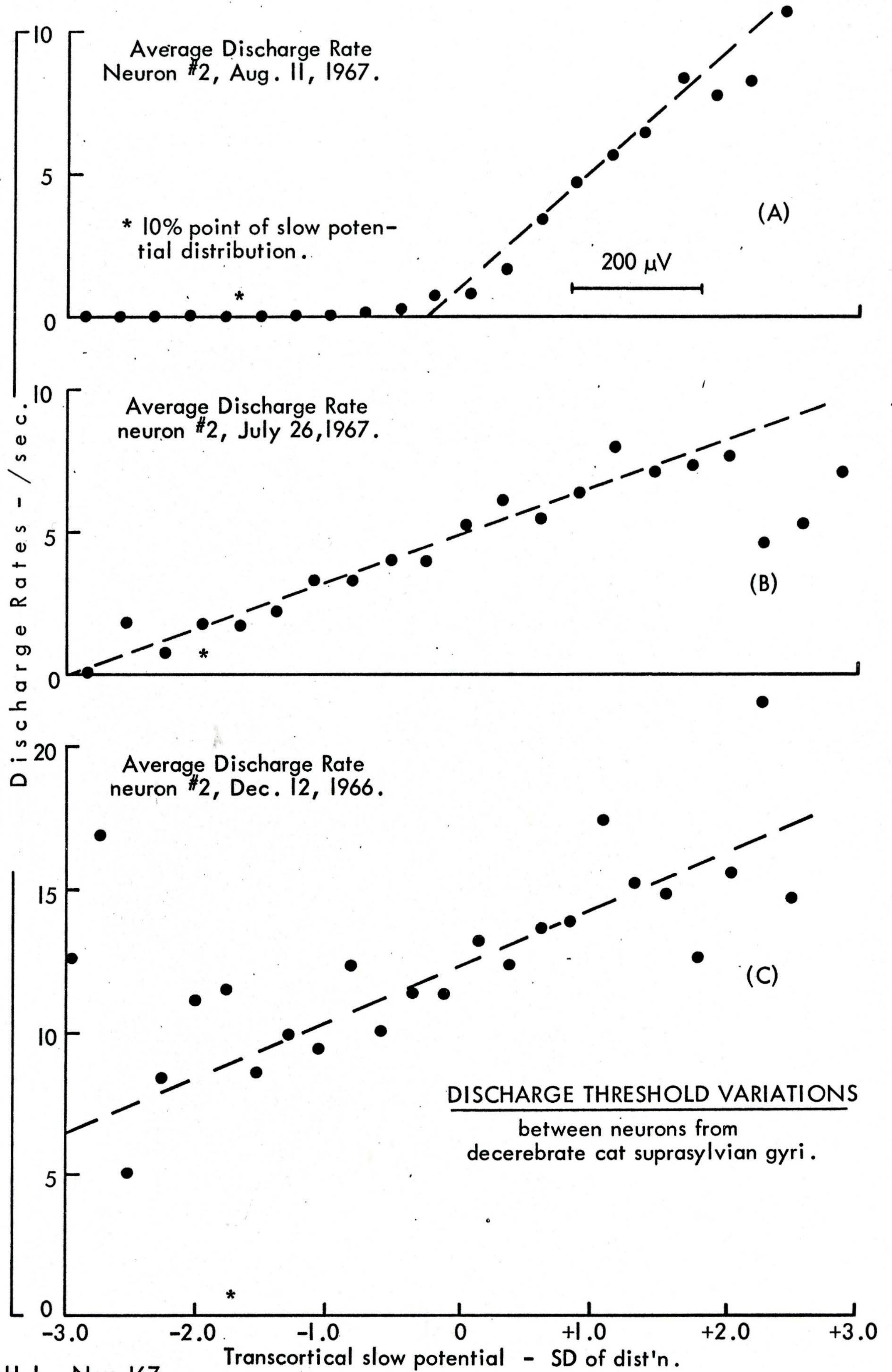
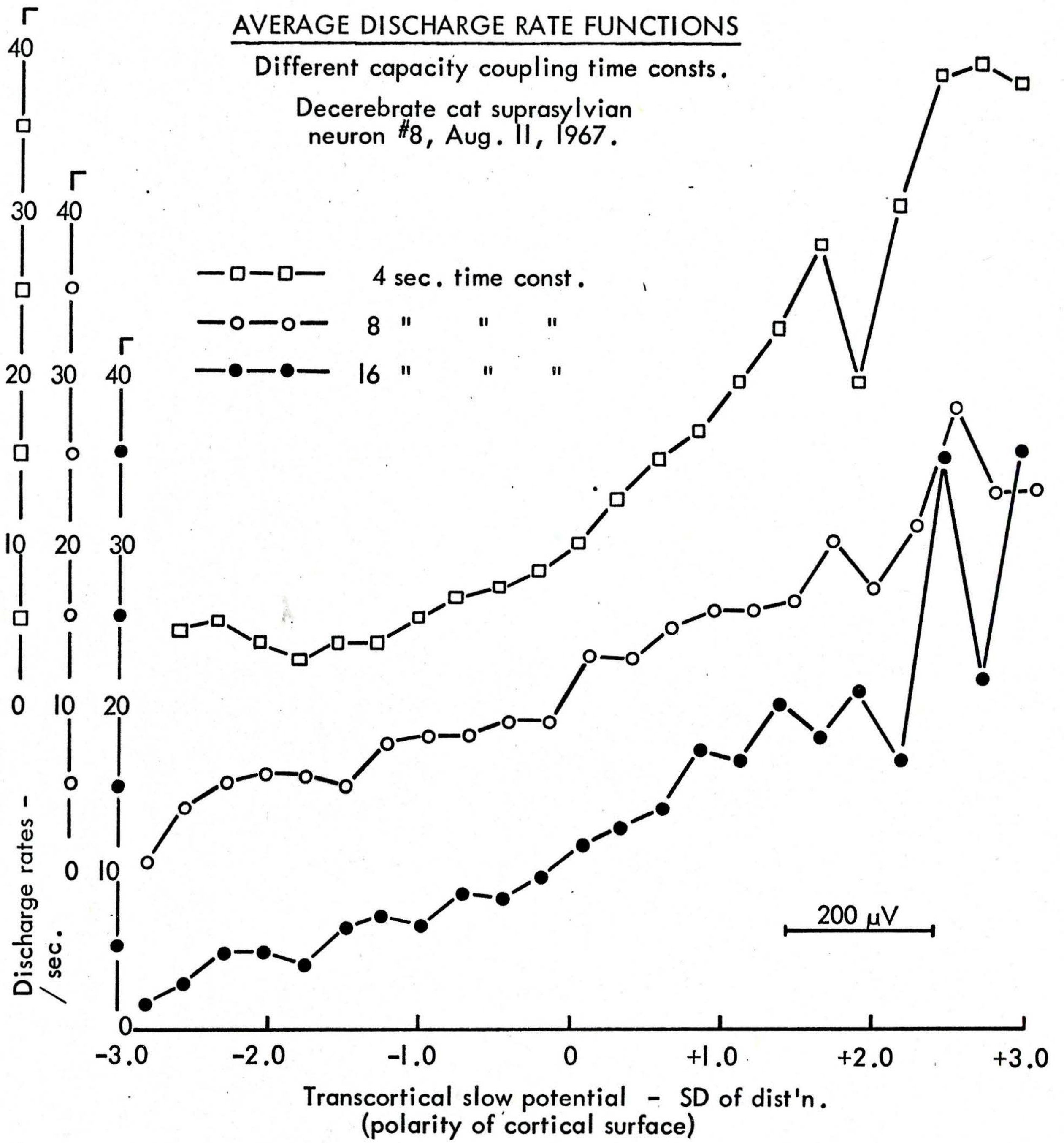


Fig. 11.

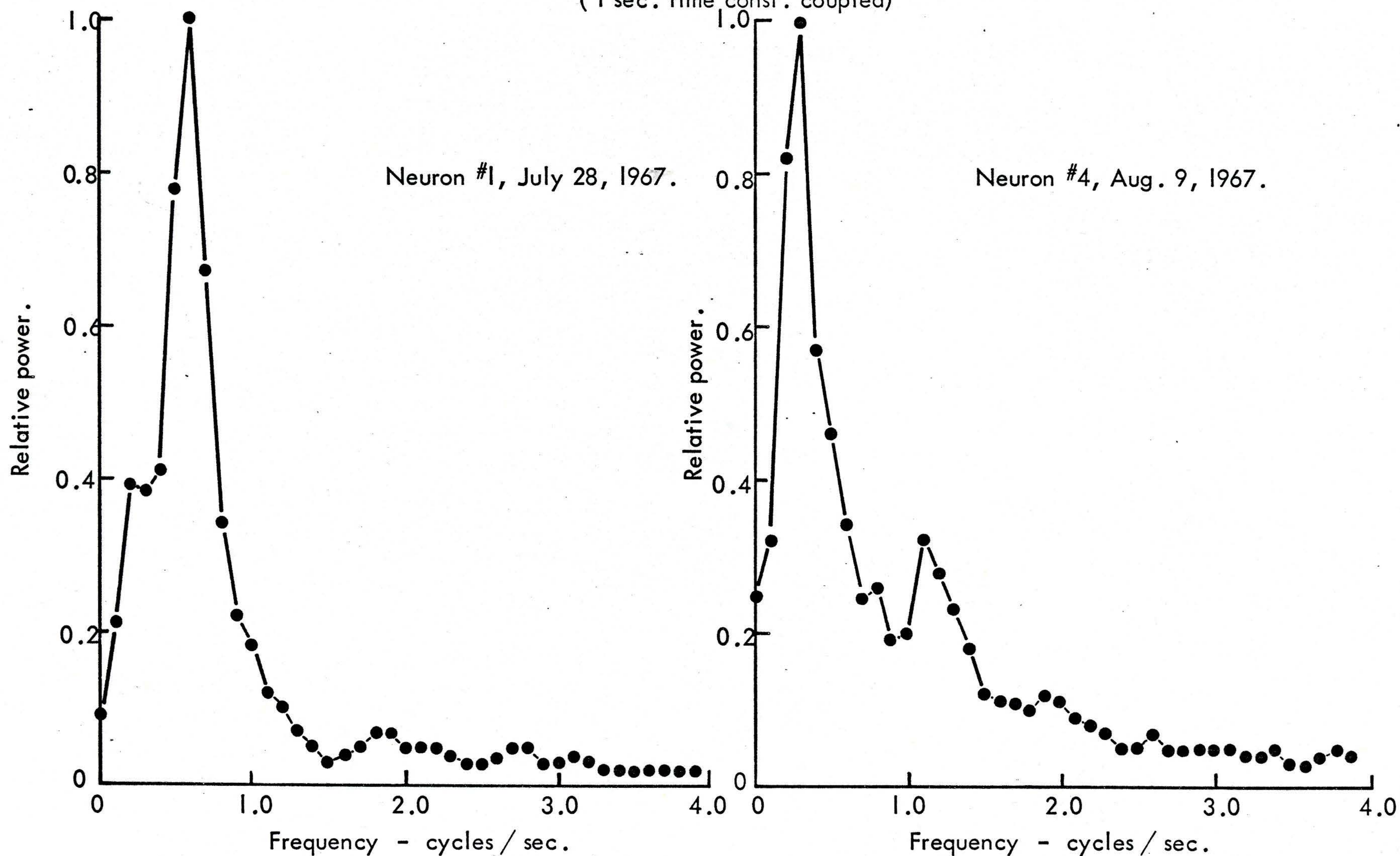


H.L., Nov.'67.

Fig. 12.

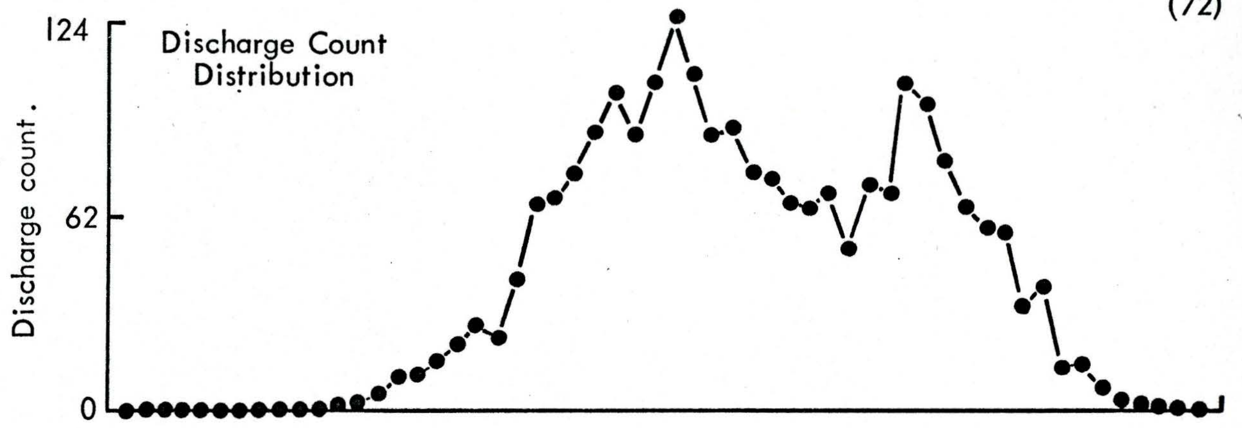
SLOW POTENTIAL POWER SPECTRA

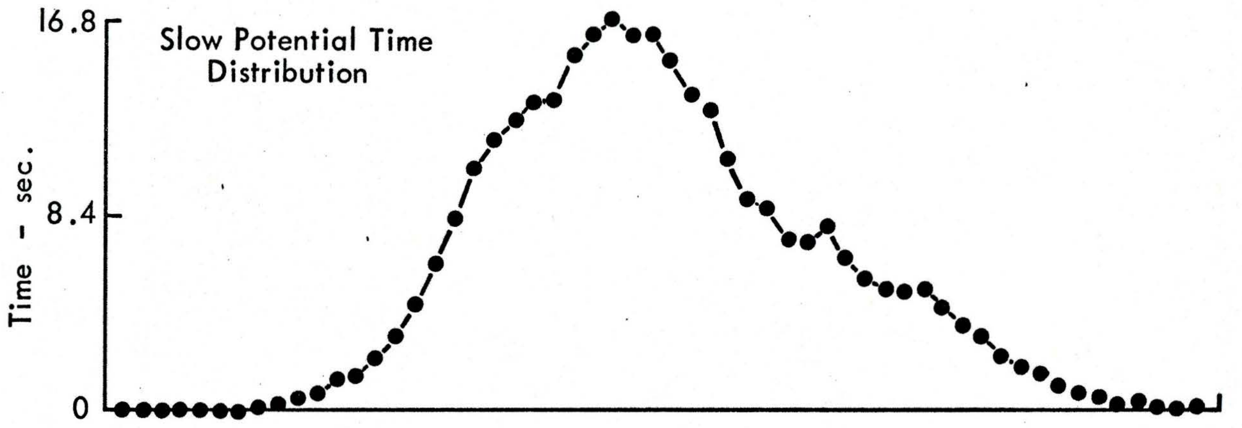
(I sec. time const. coupled)



H.L., Nov.'67.

Fig. 13.





30
20
10
0
Discharge rate - / sec.

AVERAGE DISCHARGE RATE

Decerebrate cat suprasylvian
neuron #1, July 28, 1967.

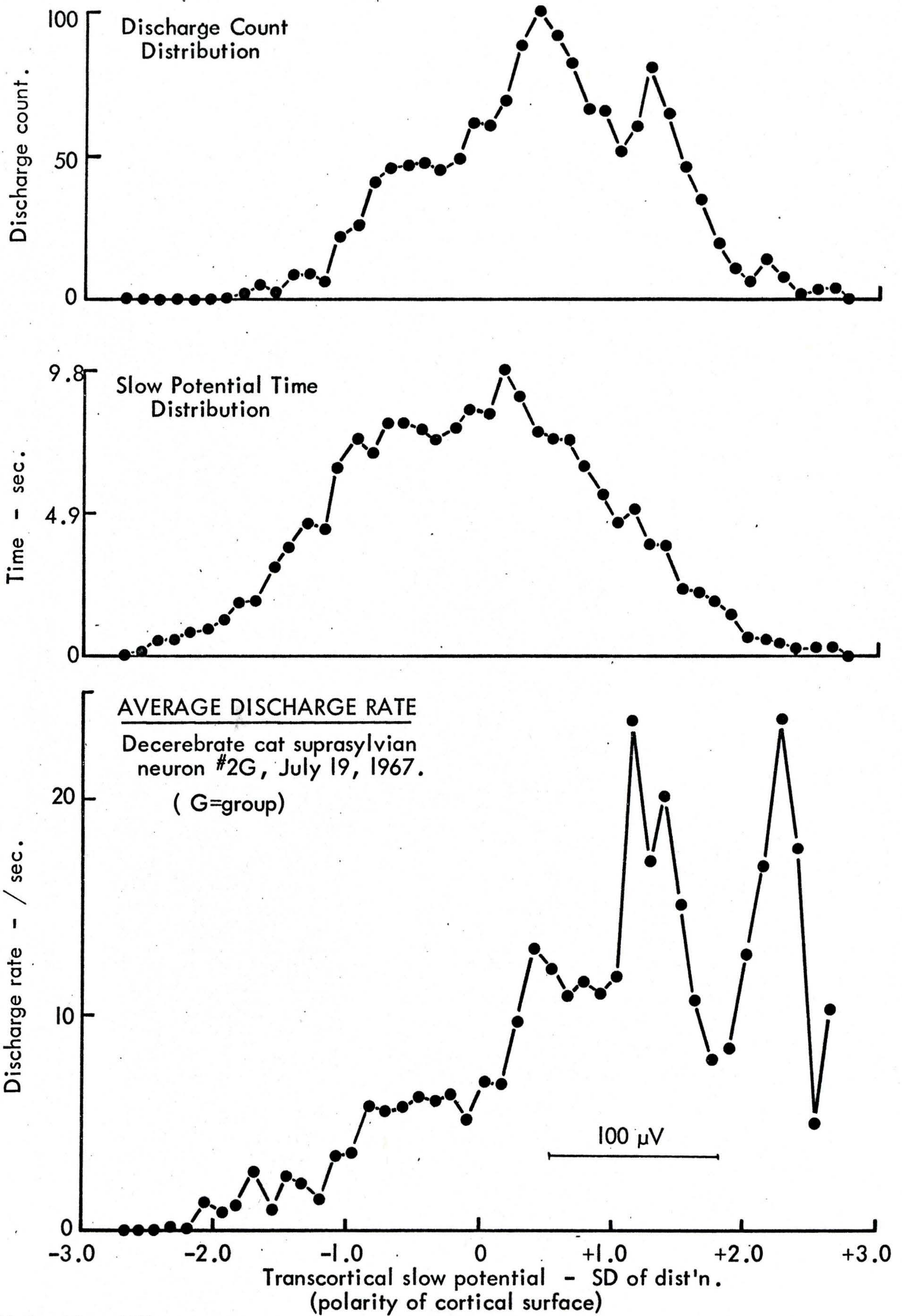
200 μV

-3.0 -2.0 -1.0 0 +1.0 +2.0 +3.0

Transcortical slow potential - SD of dist'n.

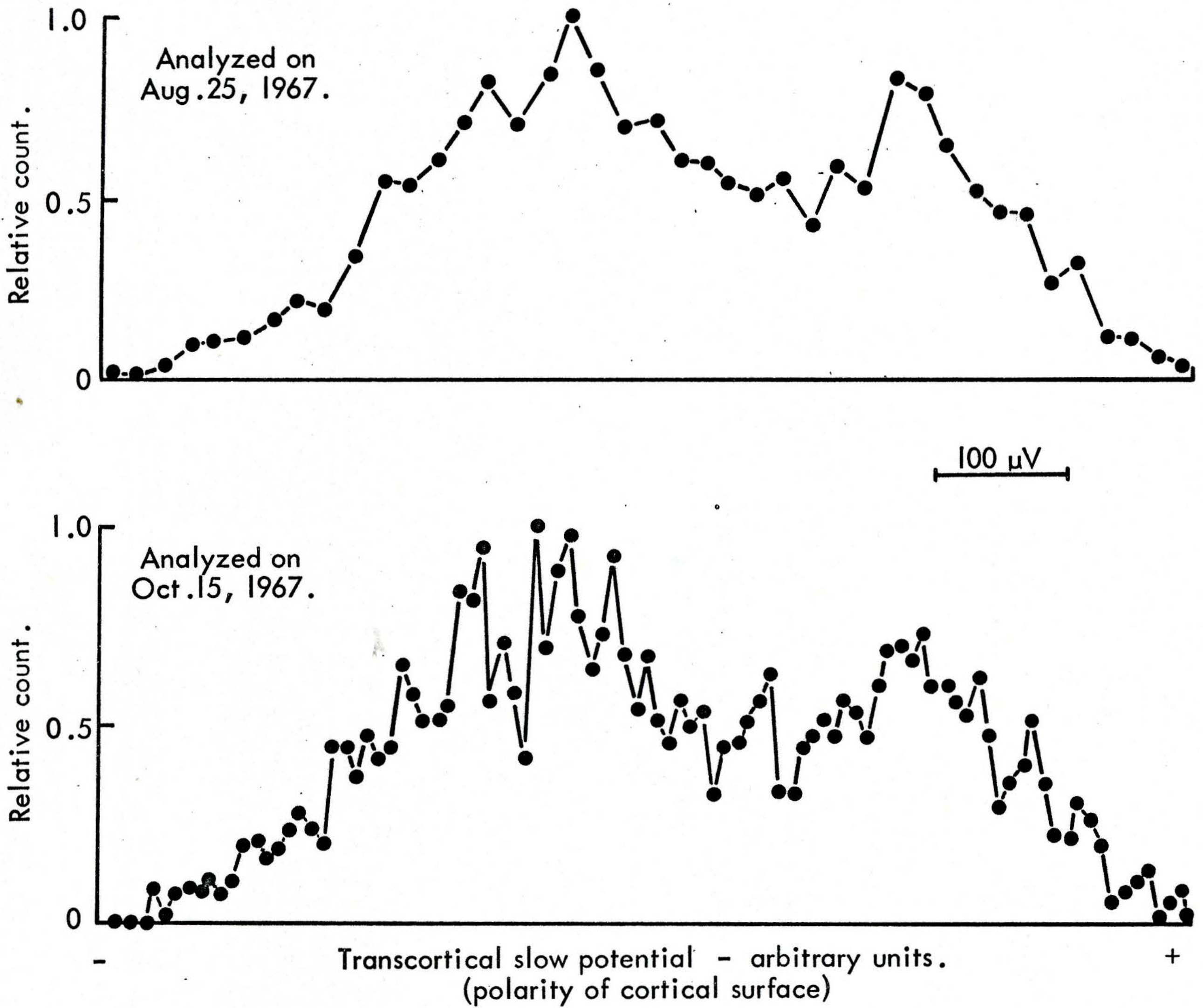
H.L.,Nov.'67.

Fig. 14.



H.L., Nov.'67.

Fig. 15.



H.L.,Nov.'67.

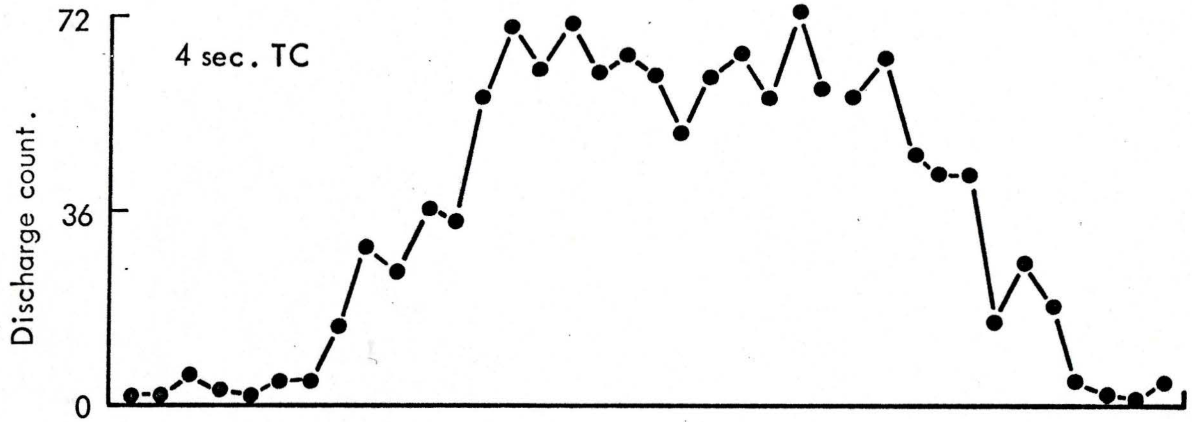
DISCHARGE COUNT DISTRIBUTIONS

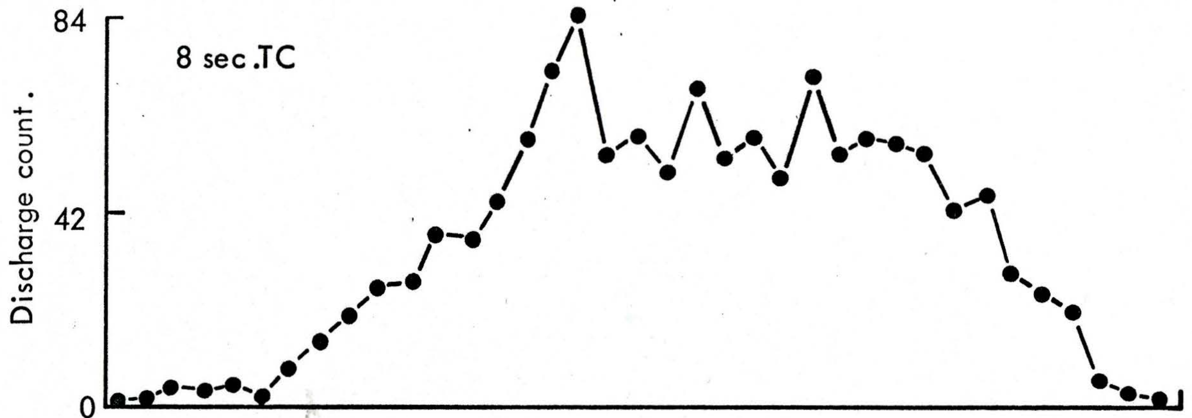
Decerebrate cat suprasylvian neuron #1, July 28, 1967.

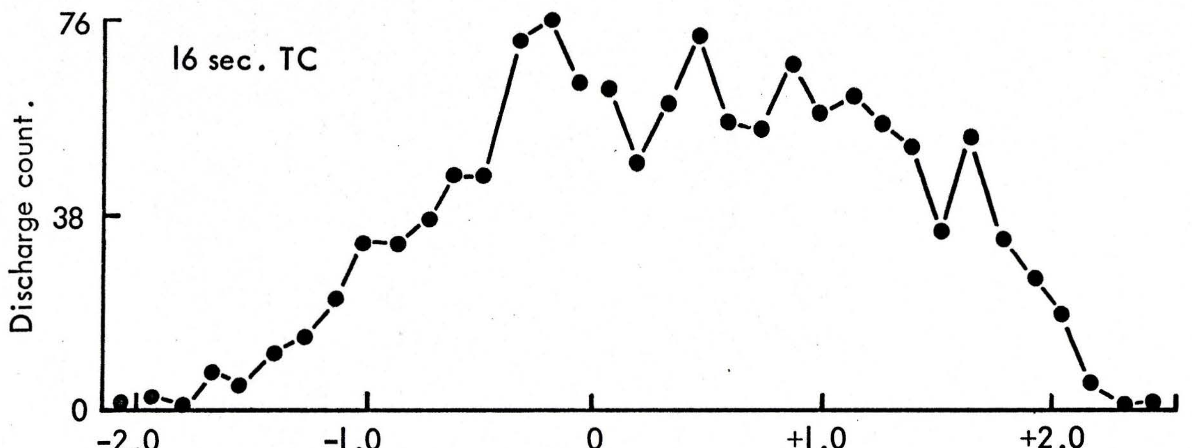
Fig. 16.

DISCHARGE COUNT DISTRIBUTIONS

Different filter time constants (TC).







Transcortical slow potential - SD of dist'n.
(polarity of cortical surface)

H.L.,Nov.'67.

Decerebrate cat suprasylvian neuron #1G, Dec. 23, 1966.

Fig. 17.

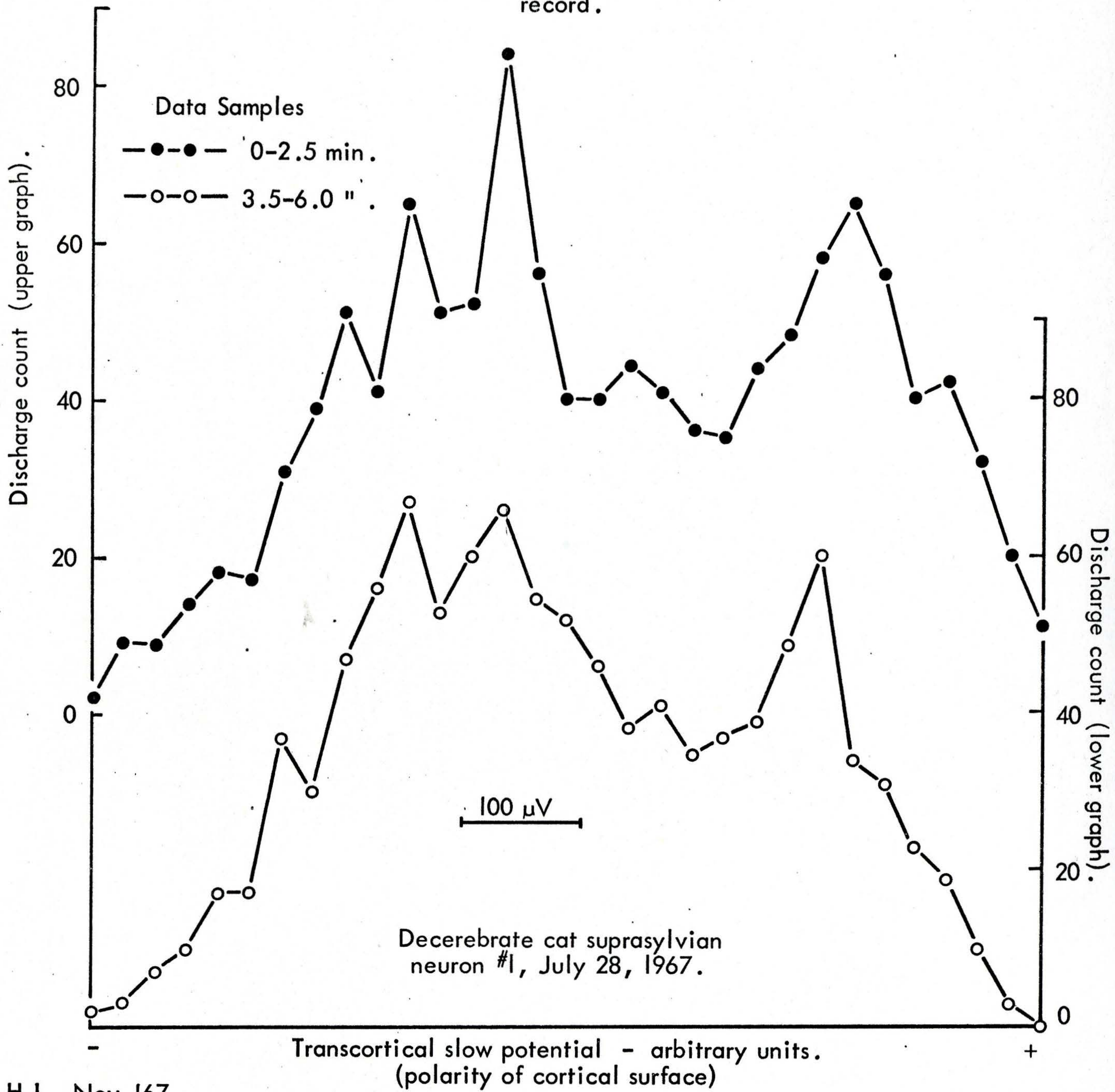
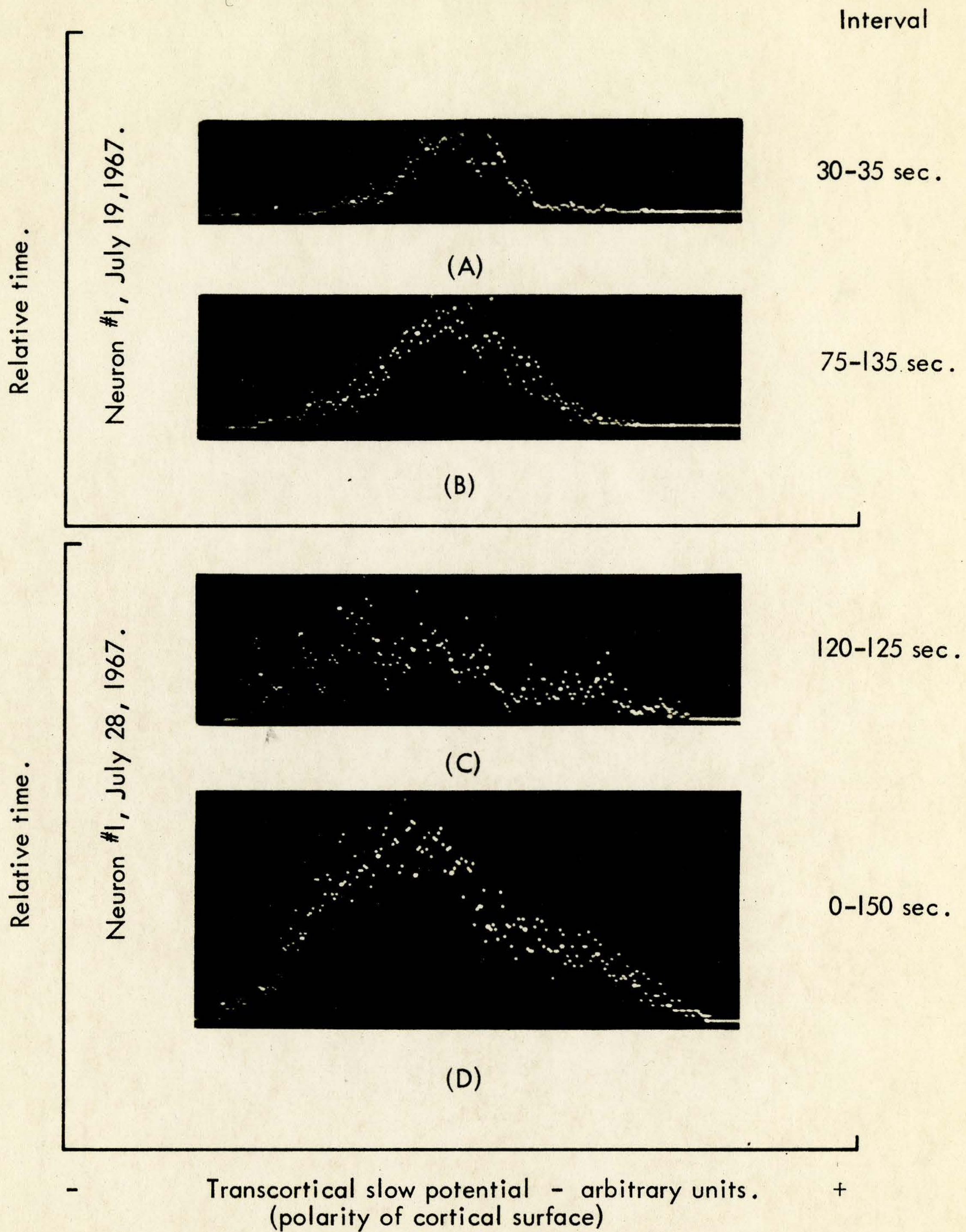


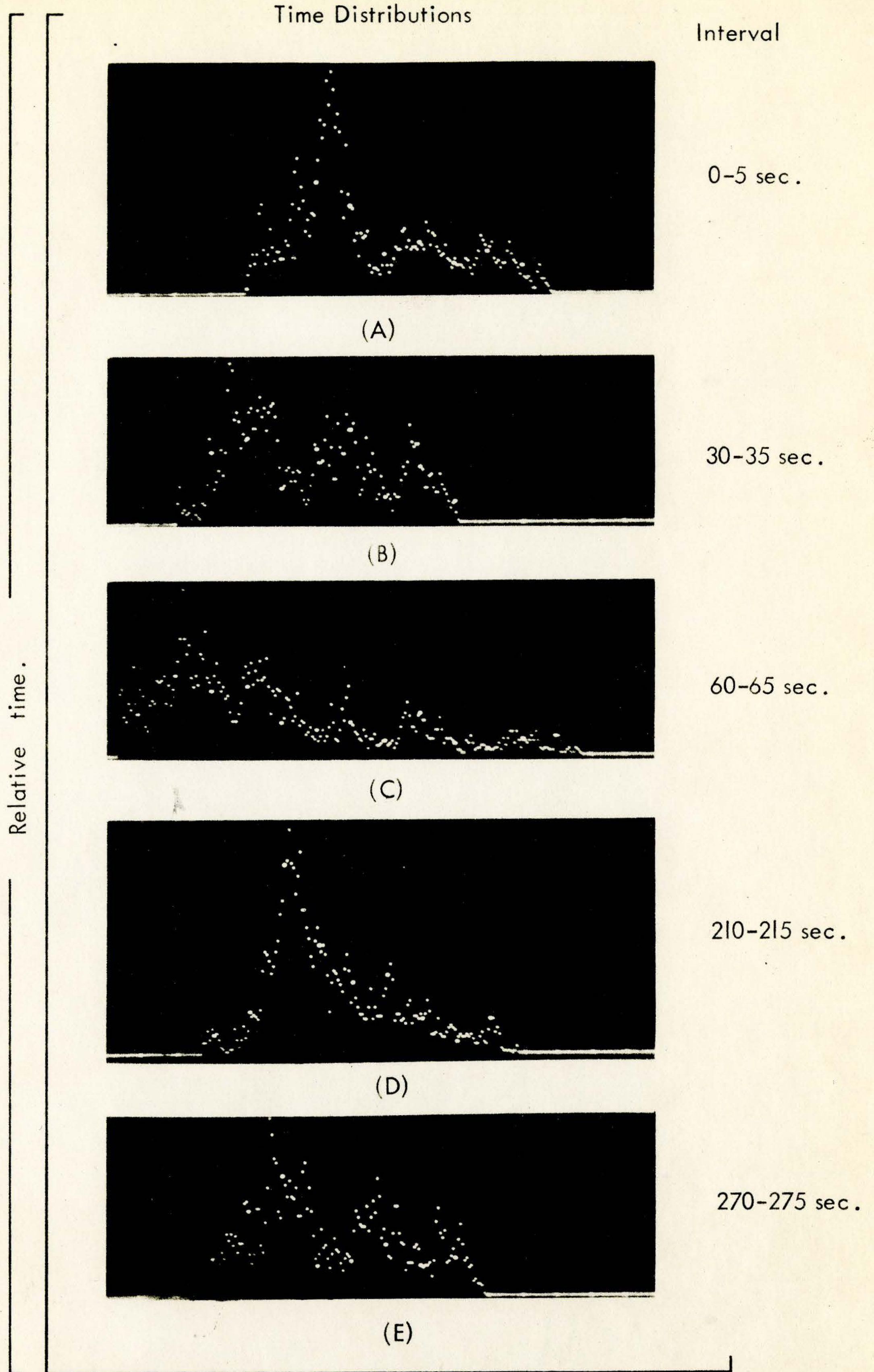
Fig. 18.

SLOW POTENTIAL TIME DISTRIBUTIONS



H.L.,Nov.'67.

Fig. 19.

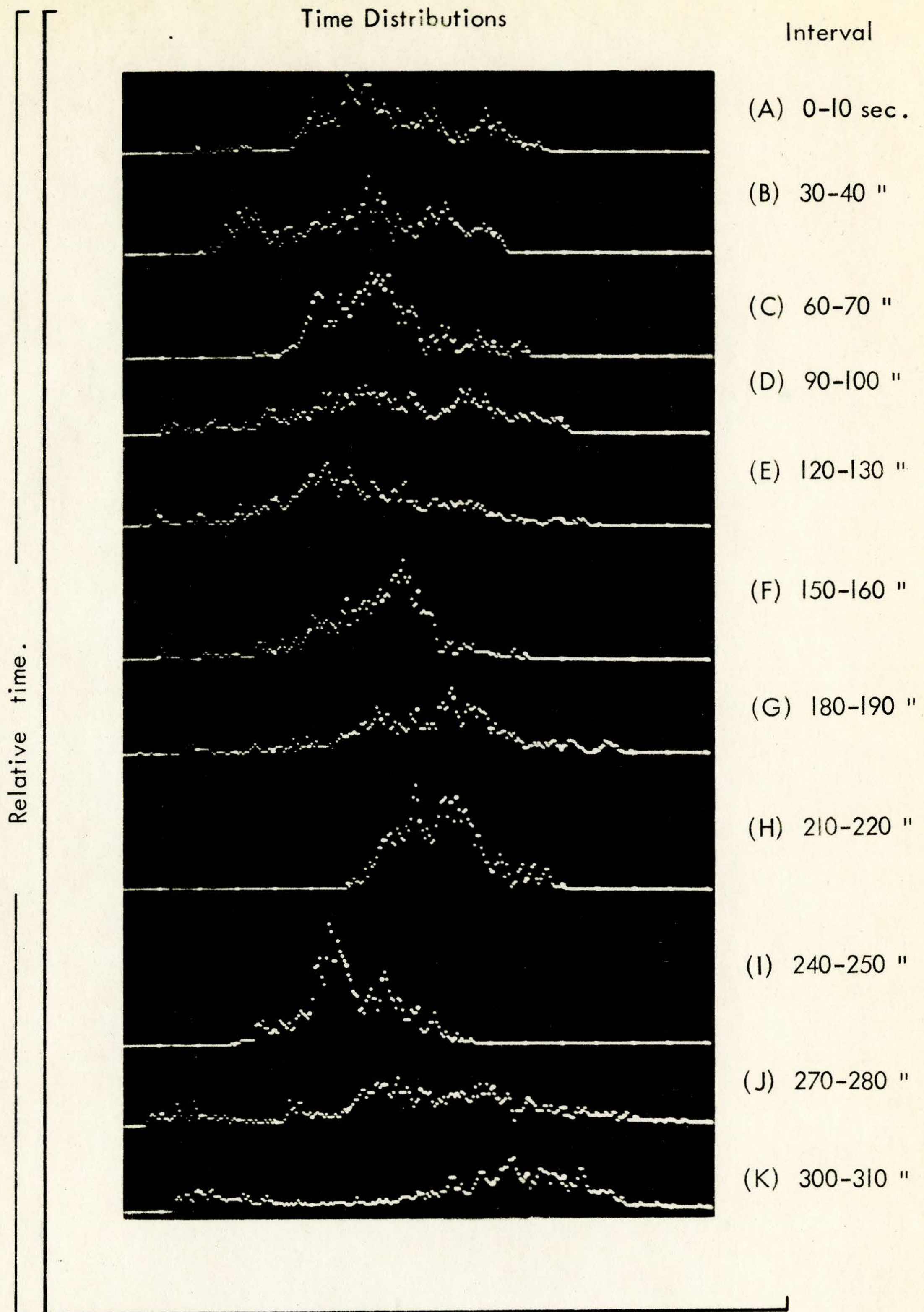


Neuron #1, July 28, 1967.

H.L., Nov.'67.

SNAPSHOTS OF SLOW POTENTIAL TRANSITIONS

Fig. 20.

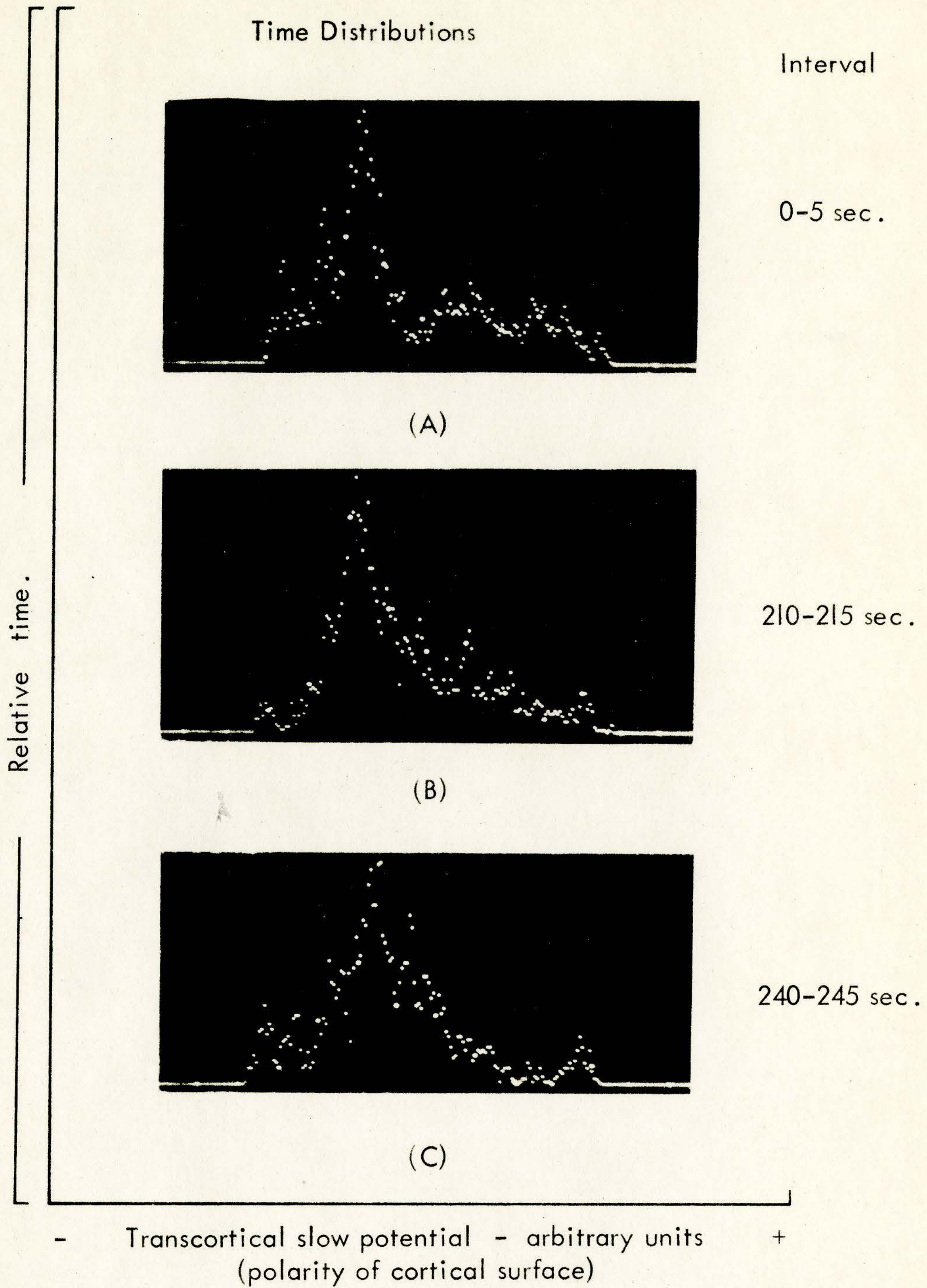


H.L., Nov.'67.

SNAPSHOTS OF SLOW POTENTIAL TRANSITIONS

Decerebrate cat suprasylvian neuron #7, Aug. 11, 1967.

Fig. 21.



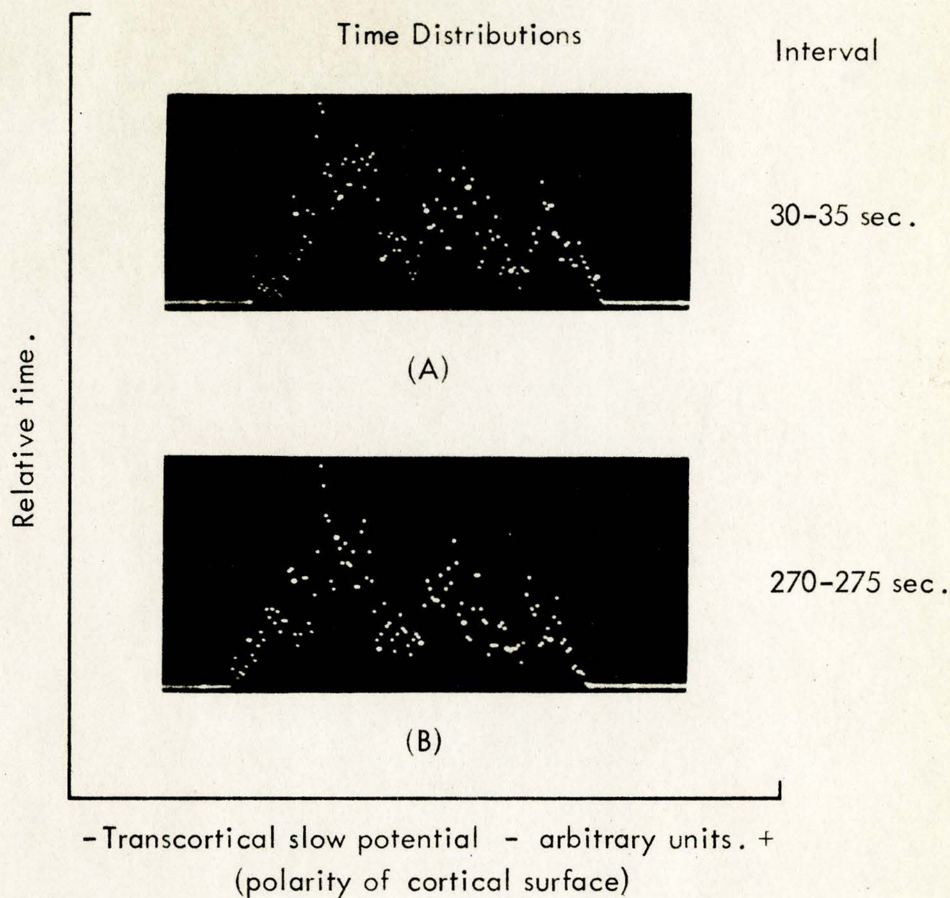
H.L., Nov. '67.

SNAPSHOTS OF SLOW POTENTIAL TRANSITIONS

Aligned for comparison.

Decerebrate cat suprasylvian neuron #1, July 28, 1967.

Fig. 22.



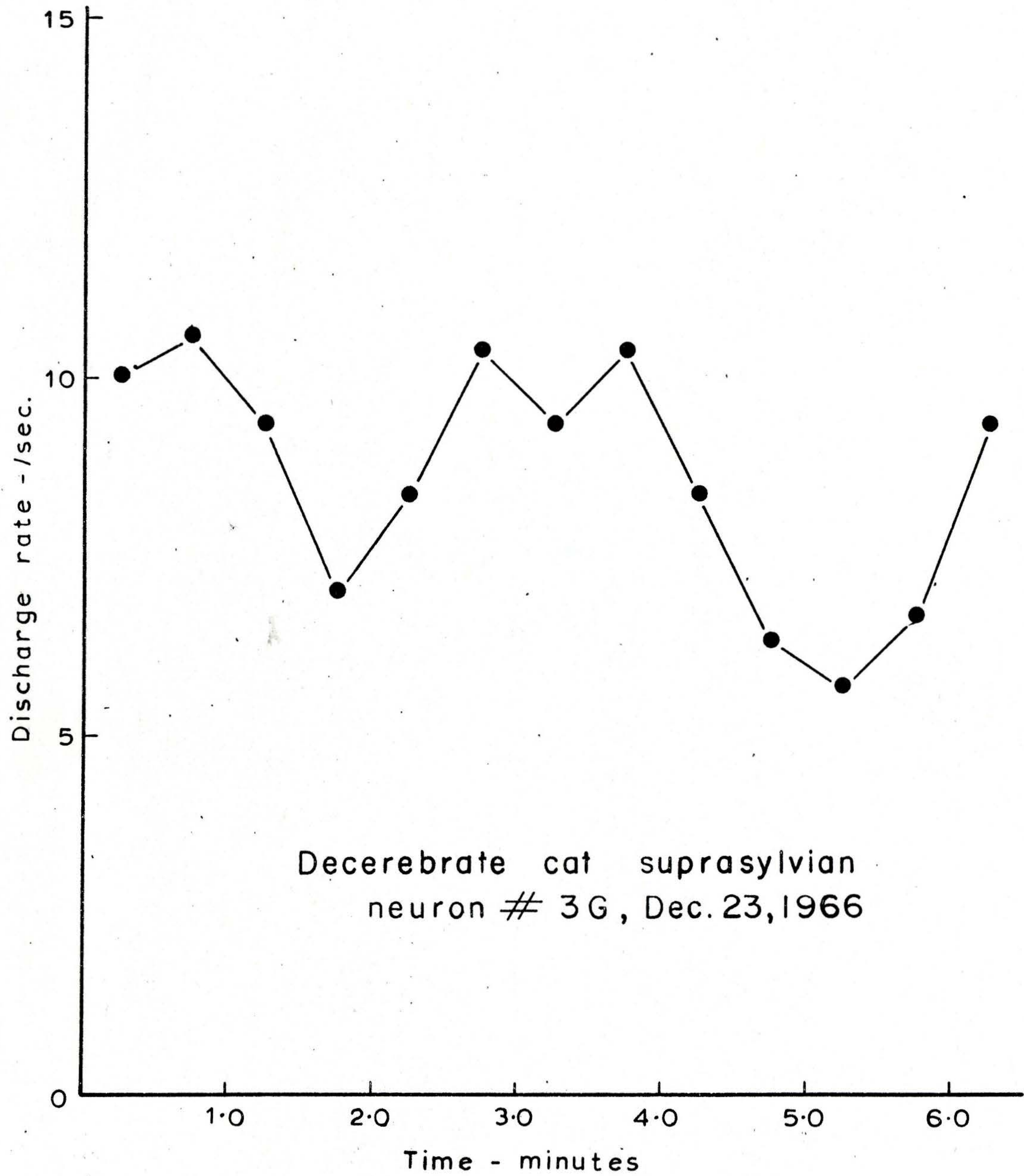
SNAPSHOTS OF SLOW POTENTIAL TRANSITIONS

Aligned for comparison.

Decerebrate cat suprasylvian neuron #1, July 28, 1967.

H.L., Nov.'67.

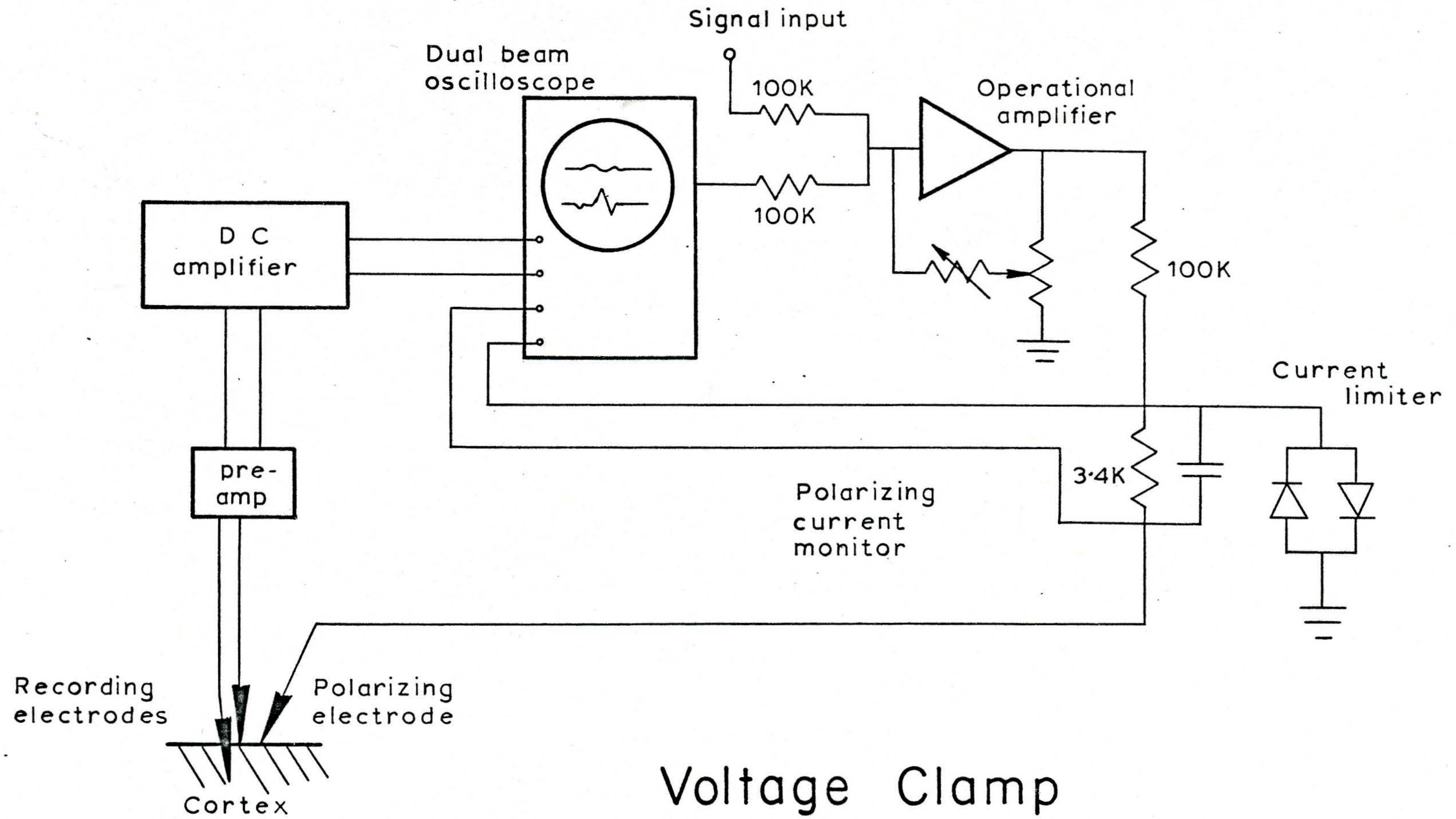
Fig. 23.



H.L., Nov.'67.

Fig. 24.

H.L., Nov. '67.



Voltage Clamp

Fig. 25.

CLAMP GAIN CONTROL

TRANSCORTICAL POTENTIAL

1

CLAMP ON

2

3

4

5

DEC. 12, 1966

Fig. 26.

VOLTAGE CLAMP MAPPING

CAT CEREBRAL CORTEX (NEMBUTAL)

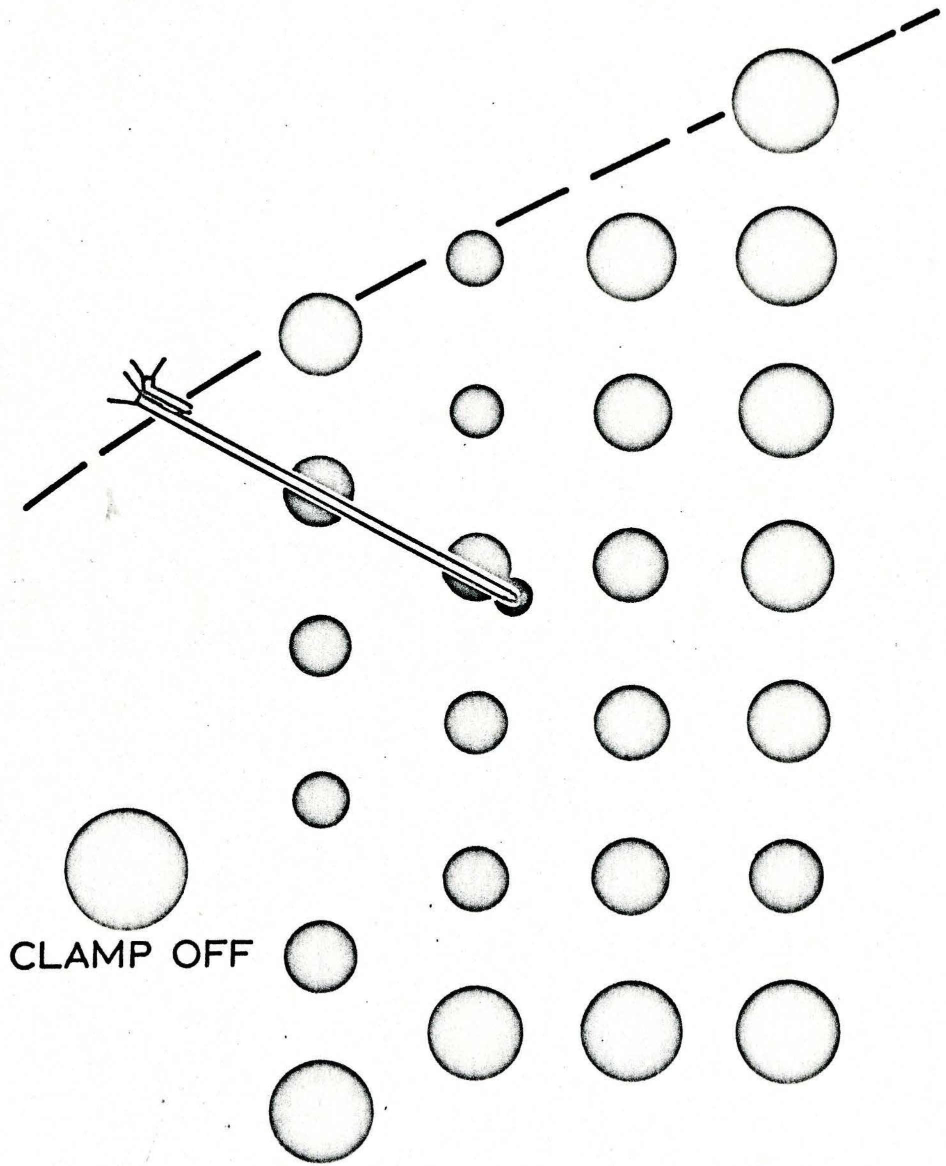


Fig. 27.