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AN ANALYSIS OF SPONTANEOUS IMPULSE ACTIVITY OF UNITS IN THE STRIATE CORTEX OF UNRESTRAINED CATS

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SUMMARY

1. Recordings were made from sixty-five cells in the visual cortex of unanaesthetized, dark-adapted cats and transferred automatically to computer input paper tape.

2. The activity of each cell was measured as a function of time (the running mean). The unit of time used was inversely proportional to the mean firing rate, in order to give comparable results for different cells.

3. For sixty-nine sections of discharge from fifty-two cells, the length of time recorded was sufficient to test for the long-term stability of the running mean. In twenty-six sections, various kinds of trend and long-term irregularity were found.

4. The interspike interval histogram was computed for the forty-one sections (from thirty-one cells) in which there were more than 2000 discharges. Only eight histograms approximated closely to the exponential form. A test was also made of the distribution of the longer intervals alone and in twenty-five sections they did not deviate significantly from the exponential form.

5. There was no significant correlation between the behaviour of the longer interspike intervals and the long-term stability or otherwise of the running mean.

INTRODUCTION

Cells in the visual cortex of unanaesthetized cats discharge even when the animal is in darkness (Hubel, 1959; Horn, 1962; Griffith & Horn, 1963; Murata & Kameda, 1963). Although this discharge often appears to be irregular, no studies have been undertaken to determine whether or not under scotopic conditions there are any systematic changes in impulse activity measured over a long series of successive fixed intervals of time. Levick & Williams (1964) made such a study of cells in the lateral geniculate body of cats anaesthetized with sodium pentobarbitone. The discharge of many units was observed to fluctuate, often quite markedly with time.

Small doses of sodium pentobarbitone were shown to produce changes in the mean firing rate so that variations in the level of anaesthesia during the experiment may have been responsible for some of the fluctuations. The effect of anaesthesia is, of course, eliminated when the unrestrained cat is used as experimental animal.

In a recent study of the spontaneous activity of cortical neurones in the isolated forebrain of unanaesthetized cats, Smith & Smith (1965) stated that when the interspike interval distributions were plotted on semi-logarithmic paper, all of the distributions possessed a definite point of gradient discontinuity. In a majority of the discharges there was a 'striking linearity' of the right-hand tail, that is, the longer intervals were distributed exponentially, and they concluded that the underlying stochastic process was Poissonian. If this conclusion is correct it would imply that when a cell has fired, and if it does not fire soon after, the time of occurrence of the next spike is not influenced by any changes of excitability that follow the preceding spike. Smith & Smith tested for long-term stationarity by counting spikes over successive 50 sec intervals. The discharge was found to remain stationary for as long as 15 min.

In the present study, in addition to measuring changes of impulse activity with time, interspike interval histograms of selected discharge sequences were plotted on semi-logarithmic paper and the distribution of the longer intervals was examined in some detail. Preliminary accounts of some of this work have been published (Griffith, Horn & Sassoon, 1965; Horn & Griffith, 1965).

METHODS

The recording techniques have been described in detail elsewhere (Horn, 1965). Briefly, a hole was drilled in the skull while the animal was anaesthetized. The hole lay over the visual cortex. An open-ended chamber was then attached to the skull and the animal allowed to recover from the anaesthetic. Some days later a microdrive (Horn, 1961) with a tungsten micro-electrode (Hubel, 1957) attached was mounted on the chamber. The microdrive, which was hydraulically operated, was connected by a length of polythene tubing to an oil reservoir outside the cage. A cathode follower was strapped to the cat's back. After amplification, the signals were monitored on a cathode ray tube and recorded on magnetic tape.

For some weeks before operation the animal had been trained to wear a pair of moulded plastic lenses (Evarts, 1963) beneath the eyelids. The outer surfaces of these lenses were painted black to exclude light. On the day of recording the cornea was anaesthetized with amethocaine drops (1 %), and the lenses inserted. The animal was placed in a shielded cage, the walls and door of which were solid. A hole in the roof insured adequate ventilation and allowed the leads to pass to and from the animal. A large square of black velvet was then placed over the whole cage. At least 1½ hr elapsed between the time the micro-electrode assembly was attached to the animal and contact lenses fitted, and the time that recording was begun. This is the length of time taken for cats to dark adapt (Barlow, FitzHugh & Kuffler, 1957). Units were detected by the presence of spontaneous activity, which is defined as that impulse activity which occurs in the absence of any deliberate sensory stimulation. Seven cats were used, none of which showed any evidence of discomfort from the procedures used in these experiments. No facilities were available for recording the electrocorticogram.

During one or more penetrations a current of approximately 10 μA for 5 sec was passed through the recording electrode and at the end of the experiment the animal was anaesthetized and killed by perfusing with normal saline followed by 10 % formol saline. Paraffin sections were cut at 12 μ and stained with cresyl violet. The lesions were identified and by correlating the depth of the lesion with the reading of the micrometer on the electrode drive, and making appropriate corrections for shrinkage, it was found that the recordings were made down to a depth of approximately 3 mm beneath the pial surface. The micrometer reading at which units were first encountered in a penetration was taken as zero. In three penetrations in which current was passed at this position the lesions were found in cortical layers I (2 lesions) and II.

Technique for analysing data. Data stored on magnetic tape were replayed and the discharges monitored on an oscilloscope. Units which could be discriminated from the base line, and from other units present on the record, were selected for analysis. The pulses stored on the length of magnetic tape to be analysed were delivered to a device (Griffith *et al.* 1965) which transferred this data on to punched paper tape. Signals from the magnetic tape recorder were amplified and fed into a four level gating circuit, by which spikes could be separated into different channels according to their height and polarity. The numbers of pulses present in up to three of these channels could then be counted over successive fixed intervals of time. These counts were then punched on to paper tape. The interval of time (1/110 sec) over which spikes were counted was fixed by the rate at which the punch operated (110 characters/sec). A special coding procedure was used to record the length of periods during which there were no impulses. In this way the temporal sequence of the discharge was preserved (for details, see Griffith *et al.* 1965).

The discharge of sixty-five cells was studied, broken down into eighty-eight sections. This procedure was necessary for a number of reasons. The record of the discharge was sometimes on two or three magnetic tapes so that the record was broken up in changing tapes. Occasionally large artifacts caused by the cat moving made it necessary to divide the record up into two or more sections. Finally, if a fast firing cell was held for a long period of time the paper tape record became so large as to be unwieldy and it was necessary to break the record up into small sections.

Statistical procedures. The total number of spikes, N, present in a section was counted and also the time, T, in sec, between the first and last spikes of the sequence recorded on that section. The ratio $\lambda = (N-1)/T$ is referred to as the over-all mean rate of discharge. Two aspects of the discharge were examined in detail: (i) the running mean (see below) which gives a measure of the way in which the discharge varied in time, and (ii) the interspike interval histogram.

Running mean. By this is meant the number of spikes, n, present in successive intervals of time of constant length. Since there was a great deal of variability in the over-all mean firing rates, from 0·11 to 35·13/sec, there was no obvious unit of time to select as the basis of the running mean. It was therefore decided to use an interval in which the expected number of spikes is independent of the firing rate of the cell. If the over-all mean firing rate is λ, the expected number of spikes in an interval of length t is λt. If the interval selected is 100 times the mean interval (i.e. $100/\lambda$) then the expected number of spikes is always $\lambda . 100/\lambda = 100$. This selection allows the data from all sections to be treated in a standard way. Furthermore, the interval of time is large enough to make the random fluctuations in the numbers of spikes in an interval fairly small compared to the expected number.

One feature of a Poisson process of rate λ is that the number of spikes in a time t follows a Poisson distribution giving the probability

$$P_n = \frac{(\lambda t)^n}{n!}\,\mathrm{e}^{-\lambda t}$$

of getting exactly n spikes (Cox, 1962, p. 30). For large t, this distribution approximates to a normal distribution with mean λt and standard deviation $\sqrt{(\lambda t)}$. Thus with the choice $\lambda t = 100$, the standard deviation is 10, showing that the random fluctuations are fairly small. Also successive values of n are uncorrelated, this being a particular example of the complete lack of correlation in a Poisson process. The fact that the numbers n follow approximately a normal distribution and that successive values are, at least approximately, uncorrelated is also true for more general processes. It remains true for a renewal process (Cox, 1962, p. 40)—that is one in which the probability of firing depends directly upon the time the cell last fired, but not upon any previous time of firing.

The numbers n have a mean $\bar{n} \approx 100$. If the distribution of n is normal and successive values are uncorrelated, then successive values of $n-\bar{n}$ are equally likely to be both of the same sign or both of opposite sign. On the other hand, if the rate of firing were to show a long-term trend, then successive values of $n-\bar{n}$ are more likely to have the same sign. For example, if a cell fires slowly at first, but much faster later, then $n-\bar{n}$ will be persistently negative until the cell speeds up and will be positive after that.

Because of the preceding considerations, the number of times, A, that successive values of $n-\bar{n}$ had the same sign was counted and so was B, the number of times they had opposite signs. Cases in which either of the pair of $n-\bar{n}$ was exactly zero were rejected. On the assumption of complete lack of correlation, A should come from a binomial distribution and have probability

$$p(A) = \binom{A+B}{A} (\tfrac{1}{2})^{A+B}.$$

So the probability of getting as large a value as A is

$$P(A) = \tfrac{1}{2}^{A+B} \sum_{x=A}^{A+B} \binom{A+B}{x}. \tag{1}$$

Values of $P(A)$ for $A+B \leqslant 50$ are available in tabulated form (National Bureau of Standards, 1950), while for $A+B > 50$, $P(A)$ is sufficiently well approximated by the normal distribution of mean $\frac{1}{2}(A+B)$ and standard deviation $\frac{1}{2}\sqrt{(A+B)}$ (Cramér, 1955). Hence equation (1) may be used to give a test of significance to the positive deviation of A from its mean $\frac{1}{2}(A+B)$, either directly or, when $A+B > 50$, by testing the assumption that A comes from the stated normal distribution. Actually, because of the fact that, by definition, $\Sigma(n-\bar{n}) = 0$, there must be at least one occasion when adjacent values are on opposite sides of the mean, i.e. $B \geqslant 1$, so the test very slightly underestimates the significance level. The test is referred to as the side test, and significant correlations were accepted at the 5% level or less. It should be noticed that it was used as a single-sided test and thus did not test for cyclic activity (reflected in anomalously low values for A). Such low values of A occurred, in fact, at no more than chance level.

Interspike interval histograms. A convenient way of plotting an interspike interval histogram is to use semi-logarithmic scales, the ordinate giving the percentage of intervals (on the logarithmic scale) greater than the interval expressed in msec stated on the abscissa. A plot similar to this was used by Smith & Smith (1965). A useful method of displaying the deviation from a standard distribution is to plot results in such a way that if they follow the standard distribution they always give the same graph. Any deviations from the standard distribution may then easily be detected. It can be shown (Cox, 1962, p. 5; Griffith *et al.* 1965) that for a Poisson process the probability that an interspike interval is greater than τ, where τ is expressed in units of the mean interval, is given by the equation

$$P(\tau) = \mathrm{e}^{-\tau}$$

or

$$\log P(\tau) = -\tau \log \mathrm{e}.$$

Thus, for a Poisson process a plot of $\log P(\tau)$ against τ is a straight line with slope $-\log_{10}\mathrm{e} = -0{\cdot}4343$.

A cursory examination of the plots revealed that the tail of some of them appeared to lie along a straight line, although it was not always obvious where the tail began. In a number of cases it was suspected that, although the tail was approximately straight there was some deviation from linearity at the far right end of the tail, that is, there were more of the longest intervals than would be expected for an exponential distribution. Each histogram was composed of thirty-three bins, so that there were thirty-three points on each graph. The point at which the tail of the histogram begins is arbitrary. Nevertheless, a decision has to be made about its position in order to test for linearity. The following procedure was adopted. A straight line was fitted by least squares to points 9, 11, 13..., 25 of the histogram semi-logarithmic plot. The successive points are, of course, correlated because they are plots of the cumulative sums of the bins of the histogram, not the bins themselves. For this reason the even points were omitted as they would have given negligible extra information. The rate of firing was then determined which, with a Poisson process, would have given the same straight line plot as the fitted one. From this rate, the probabilities were calculated for getting various possible numbers of the very longest intervals, point 33. These numbers follow a binomial distribution. This theoretical distribution was then used to see whether the actual number of the longest intervals found was significantly different from the expected number.

RESULTS

A histogram of the over-all mean firing rate of fifty-seven units is given in Fig. 1. A unit whose discharge was recorded on more than one section of paper tape was included in this histogram only if the over-all mean rate for each of the sections fell into the same bin, and then only a single value was recorded. The modal firing frequency was less than 5 spikes/sec. In Fig. 2 the over-all mean firing rates which are included in Fig. 1 are plotted against the depths at which the units were recorded. There appeared to be very little correlation between firing rate and depth, but there was a preponderance (eight out of nine) of units firing faster than 10 spikes/sec between 1·0 and 1·5 mm. Within these limits is contained cortical layer IV which receives coarse projection fibres from the lateral geniculate body (O'Leary, 1941; Sholl, 1955) the cells of which usually fire faster than 10 spikes/sec (Fuster, Herz & Creutzfeld, 1965). It is possible, therefore, that the majority of units recorded between 1·0 mm and 1·5 mm were geniculo-striate fibres. This view is supported indirectly by the observation that within the superficial cortical layers (0·0–0·5 mm), which do not receive coarse geniculo-striate axons, only units which fired more slowly than 10 spikes/sec were encountered (eight units).

Running means

A minimum of 700 spikes was required in order to apply the side test. The test was applied to sixty-nine sections of discharge from fifty-two units. On the basis of this test successive values of the running mean were uncorrelated in forty-three sections, an example of one of which is shown in Fig. 3*A*. In the section illustrated in this Figure, 3721 spikes were counted in 181 sec. The filled circles represent the observed number of spikes present in successive periods of 4·86 sec, the expected number being 100. There was no significant correlation between successive points and this finding is consistent with the view that the running mean values may be regarded as being stationary in time. For purposes of comparison, a sequence of running means for a set of events which follows a Poisson process is given in Fig. 3*B*. The sequence was generated on the Atlas computer using the theoretical formula for the probability of finding 0, 1, 2,... spikes in an interval of 1/110 sec (Cox, 1962, p. 30). An uncorrelated sequence of numbers with these probabilities was produced by a pseudo-random number subroutine, from which the running means were computed.

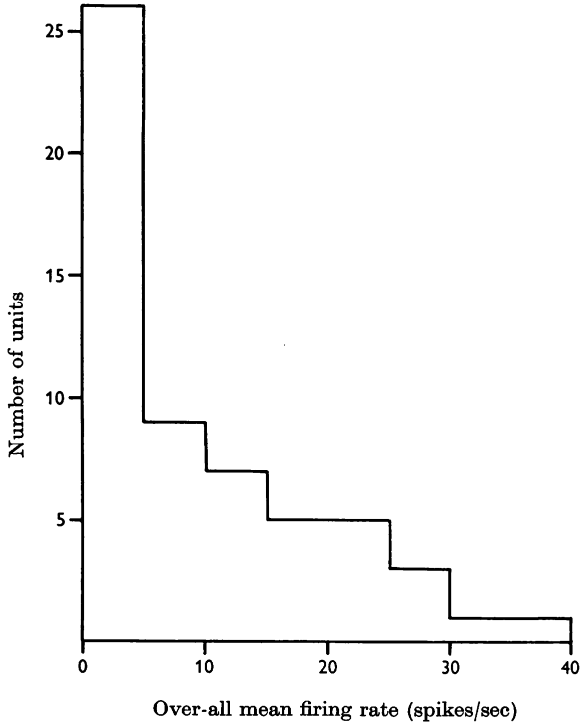

Fig. 1. Distribution of over-all mean firing rates (λ spikes/sec) of fifty-seven units. Where the discharge of a unit was divided among two or more sections of paper tape, the unit was included in this histogram only if each value of λ fell in the same bin, and then only one value was recorded.

In twenty-six sections successive values of running means were correlated. Several types of trends were observed, some of which are shown in Figs. 4 and 5. During the section of discharge illustrated in Fig. 4*A*, the over-all mean rate was 3·35/sec. The discharge was studied for 15 min 46 sec and for the first 6 min 30 sec the unit fired at a rate which gave consistently fewer spikes for each running mean value than the expected 100. The rate of firing then abruptly changed and for the remainder of the section the firing rate was increased giving running mean values which on only two out of eighteen occasions fell below the expected value.

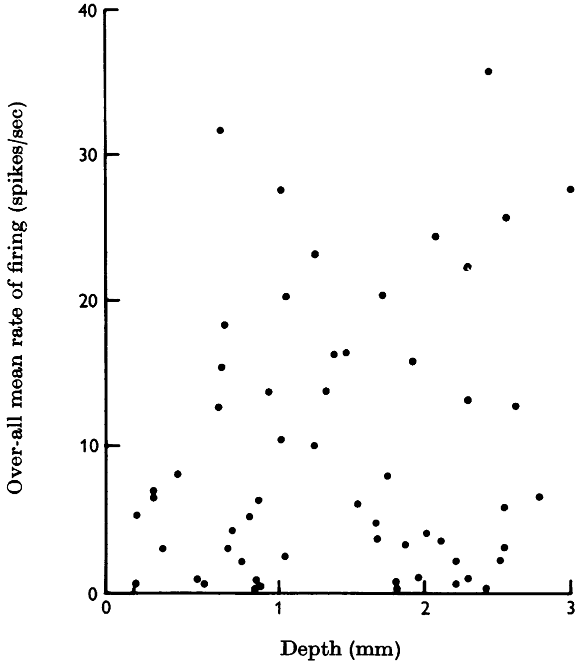

Fig. 2. A plot of over-all mean firing rate (of the fifty-seven units included in Fig. 1) against the depth at which each unit was recorded. Depth is measured in mm relative to the point at which units were first encountered in the course of a penetration.

In the section of discharge illustrated in Fig. 4*B* the number of spikes present/unit of time initially fell considerably below the expected value. The number gradually increased to a maximum of more than twice the expected number, and then declined. In other sections the running means passed through one or more irregular cycles. The running mean values of Fig. 4*C*, for example, initially decreased then gradually increased relative to the expected number, remaining stable at this higher level for approximately 13 min and then fell to values below 100 again.

In those units whose discharge was divided into two or more sections the distributions of running means often varied from section to section. A unit of this kind is illustrated in Fig. 5. The total period of recorded activity of this unit was 32 min 54 sec. Because of the large number of spikes counted over this period, the discharge was divided into three sections, *A*, *B* and *C* in that order in time. To avoid duplicating any of the activity, 6 sec of the discharge was erased from the magnetic tape between Fig. 5*A* and *B*, and 5 sec between Fig. 5*B* and *C*. For each section the side test indicated significant correlation between successive values of the running means, but the course taken by these numbers varied from one section to the next. The over-all mean values, however, were relatively stable at 14·90/sec (Fig. 5*A*), 15·97/sec (Fig. 5*B*) and 14·40/sec (Fig. 5*C*).

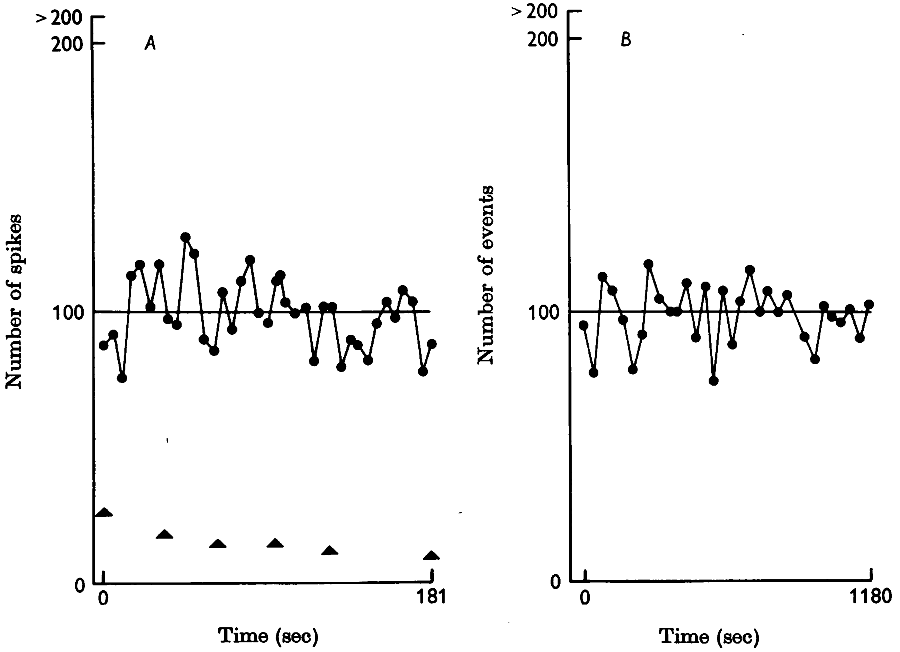

Fig. 3. In this Figure and in Figs. 4 and 5 are shown sequential distributions of running means (filled circles). A sequence commences at time 0 sec and adjacent points are joined by a straight line. The expected number of spikes in each unit of time is always 100. The unit of time is 100 times the over-all mean interval (i.e. $100/\lambda$). In all these Figures (except Fig. 3*B*) the peak to peak amplitude of the spike measured at various times during a discharge is indicated by filled triangles. The amplitude in mV of the first spike of a sequence is stated in the legend of each Figure. Amplitudes at the beginning and end of a section are always plotted. *A*. This unit (section 34) fired 3721 times in 181 sec giving an over-all mean rate, λ, of 20·56 spikes/sec. The unit of time ($100/\lambda$) in this instance therefore is 4·86 sec. The side test for sequential correlation was not significant at 5%. Spike height at 0 sec was 1·2 mV and gradually declined. *B*. Sequence of running means for a computer-generated Poisson process. The sequence lasted 19 min 40·27 sec during which 21,628 events occurred giving λ = 18·32 events/sec. The side-test was not significant.

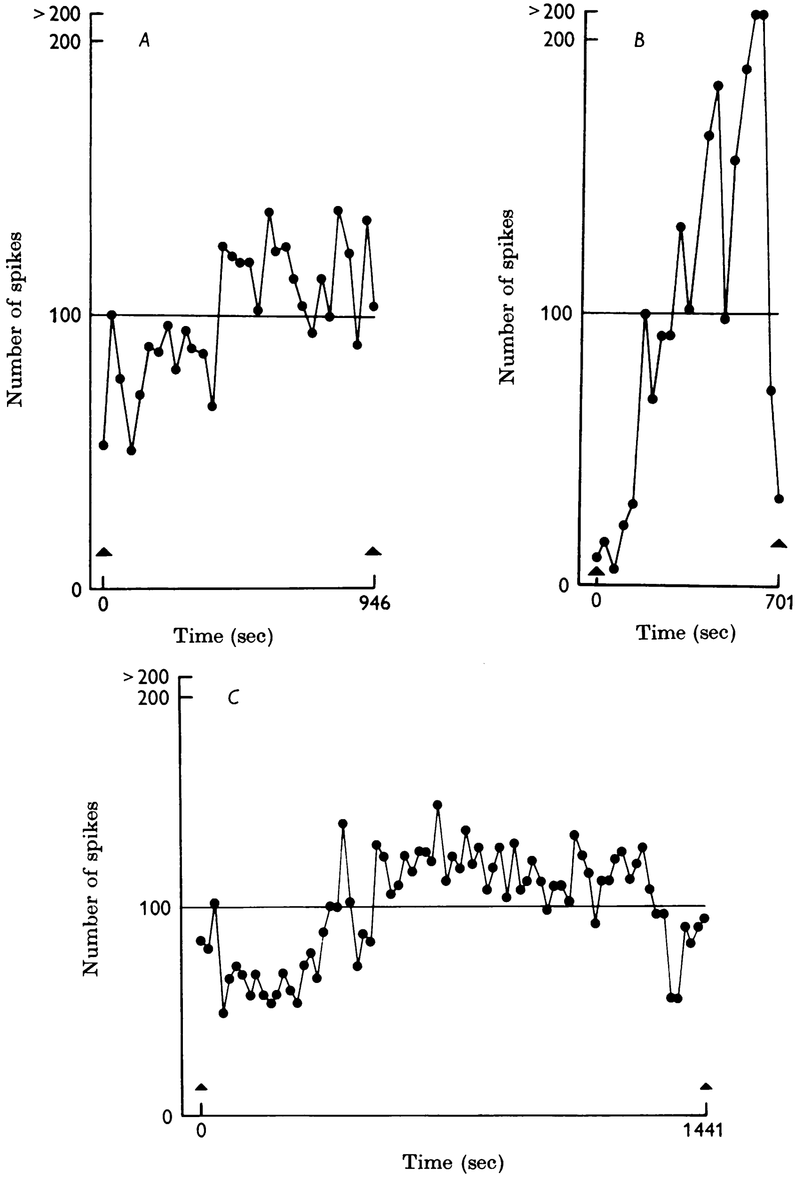

Fig. 4. *A*. The firing rate of this unit (section 35) showed a step-like change which is reflected in the distribution of the running means. The duration of the section was 15 min 46 sec during which 3172 spikes were counted giving $\lambda = 3{\cdot}35$ spikes/sec and $100/\lambda = 29{\cdot}85$ sec. The side test was significant with $P < 1{\cdot}0\%$. Spike height was constant throughout at 0·6 mV. *B*. Duration of discharge (section 7) 11 min 41 sec, total spike count 2143; $\lambda = 3{\cdot}06$ spikes/sec and $100/\lambda = 32{\cdot}68$ sec. The side test was significant with $P < 5\%$. Spike height at time 0 sec was 0·5 mV. *C*. Duration of discharge (section 22) 24 min 01 sec, total spike count, 7500; $\lambda = 5{\cdot}21$ spikes/sec and $100/\lambda = 19{\cdot}19$ sec. The side test was significant at $P < 0{\cdot}1\%$. Spike height stable throughout at 0·3 mV.

Fluctuations in the values of running means may be physiological or they may be artifacts due, for example, to mechanical stimulation of the neurone by the recording electrode. The latter factor was taken into account by measuring spike height at intervals (15–60 sec according to the length of discharge) throughout the period of recorded activity, since changes of spike height accompany movements of the electrode. Spike height is plotted on a linear scale as filled triangles in Figs. 3–5. Where successive points have the same height above the abscissa, spike height was constant in the intervening period; where adjacent points have different heights, spike height changed gradually in the interval. The amplitude was stable throughout the periods of recording shown in Figs. 4*A*, *C* and 5*C*, though the running means showed systematic fluctuations. On the other hand, quite marked changes in amplitude occurred during most of the period illustrated in Fig. 3*A* though the running mean showed no systematic drifts. The running mean values plotted in Fig. 4*B* increased and then decreased while the spike amplitude gradually increased. There is thus no reason to suppose that an irritative effect of the electrode on the neurone, as manifest by changes in spike height, can account for all of the fluctuations in spontaneous activity that have been described.

Another factor that might be correlated with changes in the running means is the over-all mean firing rate—more slowly firing cells might, for example, be associated with stationary firing activity. However, the proportion of cells with over-all mean firing rates of less than 10/sec was 0·67 in those sections in which the running means were stationary and 0·61 in those in which they were not.

Histograms

Histograms were computed only for those sections of discharge that contained at least 2000 intervals. There were forty-one such sections, of which thirty-one were from different cells. For each histogram the observed distribution was (i) compared with the theoretical exponential distribution having the same mean interval and (ii) tested for linearity of the right hand tail containing the longer inter-spike intervals.

Comparison with exponential distribution. Some of the plots of the histograms appeared, on visual inspection, to lie quite close to the expected values for an exponential distribution. A χ^2 test was therefore run on the original data from which these plots were constructed, the data being arranged in nine groups. It was found that for all histograms the observed distribution deviated significantly from that expected for an exponential distribution. The deviation was so large as to be significant even at a 0·1 % level.

In spite of this result, it was undoubtedly true that some of the experi-

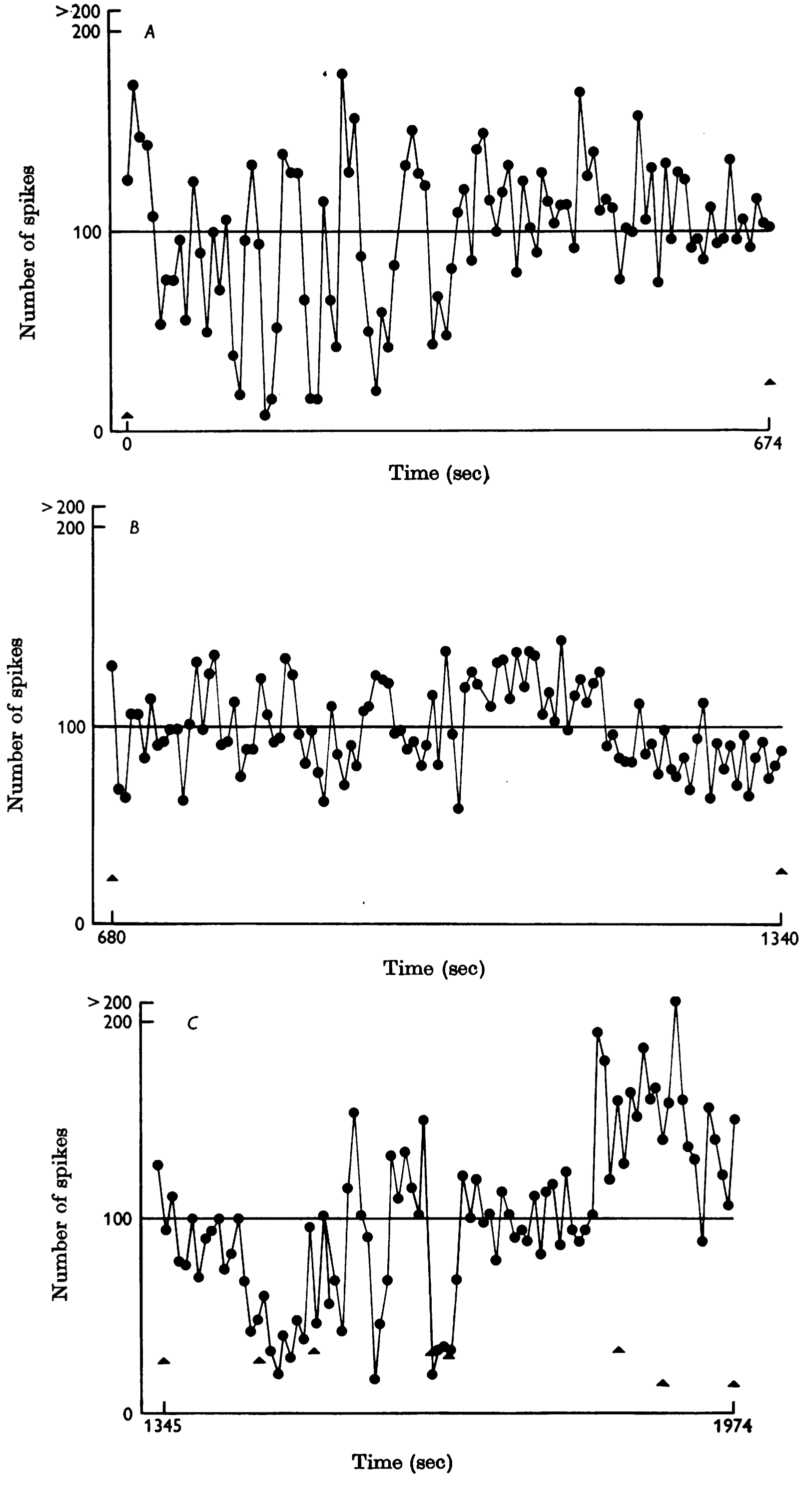

Fig. 5. For legend see opposite.

mental data was not very far from the expected form. Therefore, a method was needed to give a quantitative estimate of the deviation between the observed distribution and the exponential one. However, χ^2 cannot be used just as it stands because its value is dependent not only upon the deviation of the distribution from an exponential one, but also upon the actual number, ν, of intervals which were counted in a given experiment. Thus, suppose that the probabilities for each group used in the χ^2 test are p_i on the assumption that the distribution is exponential. Suppose, however, that the probabilities are really $p_i+\lambda_i$. If the observed histogram follows exactly the distribution given by the latter theoretical probabilities, then the number of interval lengths occurring in the ith group is $f_i = \nu(p_i+\lambda_i)$.

Thus $$\chi^2 = \Sigma\frac{(f-\nu p_i)^2}{\nu p_i} = \Sigma\frac{\nu^2\lambda_i^2}{\nu p_i} = \nu\,\Sigma\frac{\lambda_i^2}{p_i}.$$

Hence $$\chi^2/\nu = \Sigma\frac{\lambda_i^2}{p_i}.$$

Thus χ^2/ν is approximately independent of ν and gives some estimate of the deviation of the observed interspike interval distribution from that expected for an exponential one. In agreement with this it was found that the quantity χ^2/ν was indeed small (less than 0·10) in the eight cases where visual inspection showed the plot of observed values to be close to the theoretical line. The detailed results for these cases and also for a few which, on the basis of visual inspection, were not expected to be so close are shown in Table 1. The running mean was stable in all except two (Table 1, sections 22 and 70) of the histograms that are closely fitted by an exponential distribution.

Four histograms are shown in Figs. 6 and 7. For all of these the observed distributions (filled circles) differ significantly, on the basis of the χ^2 test,

Legend to Fig. 5

Fig. 5. All sections of discharge came from one unit, recorded on a continuous length of magnetic tape. Spike counts were punched on to three pieces of paper tape (*A*, *B* and *C*). The discharge commenced at time 0 sec on *A* and ended after 1974 sec (32 min 54 sec) at the end of *C*. In transferring the data on magnetic tape to paper tape it was necessary to erase from the magnetic tape 6 sec of discharge between the end of *A* and beginning of *B* and 5 sec between the end of *B* and the beginning of *C*. Data were calculated separately for each section. *A*. Duration 11 min 13·5 sec, spike count 10,036; λ = 14·90 spikes/sec and $100/\lambda$ = 6·71 sec. The side test was significant at the 5 % level. Spike height initially 2 mV. *B*. Duration of discharge 11 min 43 sec, spike count 10,545; λ = 15·97/sec and $100/\lambda$ = 6·26 sec. The side test was significant, $P < 0{\cdot}1\,\%$. Spike height initially 6 mV. *C*. Duration 10 min 28·83 sec, spike count 9055; λ = 14·40 spikes/sec and $100/\lambda$ = 6·94 sec. The side was significant at 1 %. Spike height was initially 7 mV.

from the theoretical distributions (interrupted lines). However, on visual inspection, the fit appears to be very good for the histogram of Fig. 6*A*, fairly poor for the histogram of Fig. 6*B* and very poor for both the histograms of Fig. 7. These appearances correlate well with the values of the parameter χ^2/ν which is 0·030 for Fig. 6*A*, 0·175 for Fig. 6*B* and 0·672 and 0·664 for Fig. 7*A* and *B* respectively.

TABLE 1. The distribution of interspike intervals was compared with a theoretical exponential distribution by a χ^2 test with 7 degrees of freedom. On the basis of this test all of the observed distributions differed significantly from the exponential one. The value of the parameter χ^2/ν was less than 0·10 for eight histograms all of which appeared on visual inspection to approximate closely to the straight line corresponding to the exponential distribution. The values of χ^2 and χ^2/ν are given for these histograms and for a number of others in which the fit was not expected to be so close. The histograms of sections 34 and 62 are illustrated in Fig. 6 (*A* and *B* respectively) and of sections 39 and 18 in Fig. 7 (*A* and *B* respectively). With 7 degrees of freedom and $\chi^2 = 24·3$, $P < 0·1\%$. ν refers to the number of intervals used in the histogram of a section of paper tape, the section number of which is given in the table

Section	ν	χ^2	χ^2/ν
1	12,308	9,815·8	0·798
2	3,154	531·4	0·168
3	2,692	363·9	0·135
16	2,643	67·75	0·026
18	11,211	7,440·7	0·664
22	7,519	256·5	0·034
23	2,227	46·4	0·021
24	3,651	37·7	0·010
25	2,840	308·1	0·108
29	2,810	154·8	0·055
33	2,036	181·6	0·089
34	3,720	112·5	0·030
39	6,679	4,489·1	0·672
62	2,541	445·1	0·175
70	6,492	301·7	0·046
91	2,223	489·8	0·220

In some neurones after-potentials can be recorded for as long as 100 msec following the discharge of a single spike (Coombs, Eccles & Fatt, 1955). Within this period, therefore, the probability of discharge of another spike is likely to be influenced by the antecedent discharge. If the neurones which were recorded in the present series show these after potentials then it might be expected that the interspike interval histograms of fast firing cells (λ greater than 10/sec) would be less likely to follow an exponential distribution than those of the slowly firing ones. Of the eight histograms that are nearly exponential, in only two (25 %) was the over-all mean firing rate less than 20/sec. This percentage may be compared with the percentage (88 %) which fired at this rate (< 20/sec) among the thirty-three sections whose interspike interval distributions did not follow the exponential distribution closely. Thus our results did not follow the expected pattern, though it must be conceded that in three of the eight

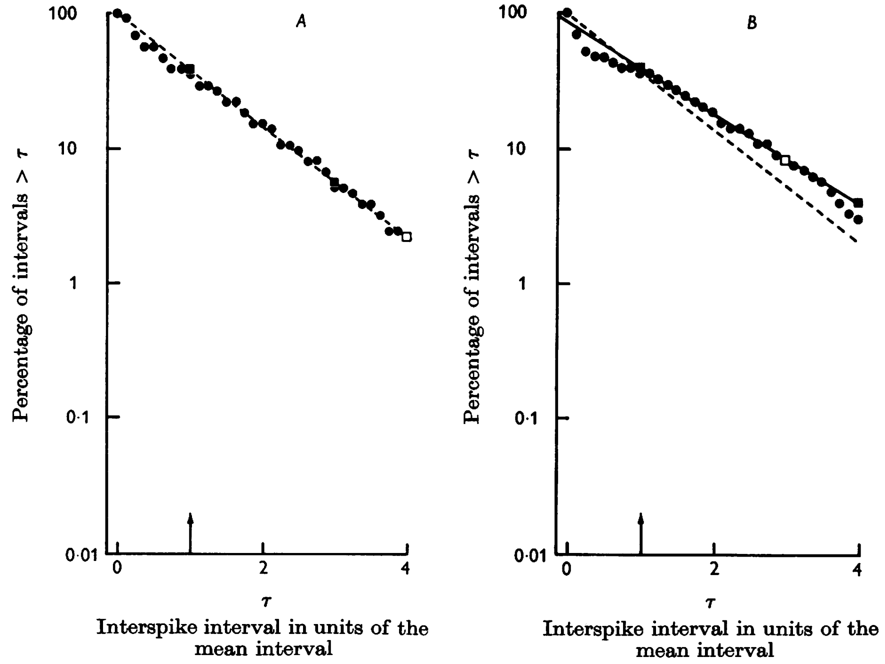

Fig. 6. In constructing the histograms shown in Figs. 6 and 7 time was broken down into units of the over-all mean interval ($1/\lambda$) and the range over which the histograms extended was from 0 to 4 times this interval. The percentage of intervals (on a logarithmic scale) greater than that stated on the abscissa is indicated by filled circles. The theoretical line corresponding to the exponential distribution is shown by the interrupted line. The straight line, which was fitted to points 9, 11, ..., 25 by least squares regression, was drawn to include the two points on the line corresponding respectively to the mean interval and 3 times the mean interval. The expected value for point 33 (4 times the mean interval), assuming the longer intervals were exponentially distributed, was calculated and also plotted. All three points fall on the same straight (continuous) line. The positions of these points are plotted as squares, open if the observed values coincide with them, otherwise filled. The arrow on the abscissa indicates the position of the mean interval. *A*. In this histogram (section 34) the line fitted to the tail coincided with the theoretical (interrupted) line and is not shown. The histogram was constructed from 3720 intervals, the over-all mean interval, $1/\lambda$, being 48·64 msec. The expected number of intervals greater than 4 times mean interval was 87 and the observed was 84. The difference between the observed and expected values was not statistically significant. In testing for the closeness of fit of the experimental data with the theoretical exponential distribution, χ^2 had the value 112·5, indicating significant differences between the two distributions. However, the fit appears on visual inspection to be quite good and this view is supported by the low value of $\chi^2/\nu = 0{\cdot}030$. The distribution of running means for this section is shown in Fig. 3*A*. *B*. On visual inspection the theoretical exponential line is seen not to be fitted well by the experimental data and consistent with this the value of χ^2 is 445·1 and χ^2/ν is 0·175. This histogram (section 62) was constructed from 2541 intervals, the value for $1/\lambda$ being 60·75 msec. The longer intervals were not distributed exponentially. The expected number of intervals greater than $4/\lambda$ was 103·66, the observed number (75) being significantly ($P < 1\%$) less than this value. The running means were stable in time.

near-exponential histograms (e.g. Fig. 6*A*) there was a slight deficiency of intervals shorter than the mean interval, relative to the theoretical distribution.

The eight histograms in which the parameter χ^2/ν was less than 0·1 (Table 1) all came from different units, three of which were recorded in the first millimetre of penetration and four of them deeper than 1·5 mm.

Distribution of longer intervals. If a cell fires at time zero but not again till time t, the probability $p(t)$ per unit time would naturally be expected to become constant and independent of t, when t is very large. This would imply, in particular, that for any cell the distribution of sufficiently long intervals should be exponential, and the experimental values in the graph should lie along a straight line. As described above (see methods) the constancy of $p(t)$ at large t was tested by comparing the observed and expected values for point 33 of the histogram. These two values were not different at the 5 % level of significance in twenty-five histograms. In Fig. 7*A*, for example, the observed number of intervals greater than 4 times the mean interval was 528 which is not significantly different from the expected number of 505·69. The two values were significantly different in the remaining sixteen histograms, fourteen of them having more (e.g. Fig. 7*B*) and two having fewer (e.g. Fig. 6*B*) of the longest intervals than expected for an exponential distribution.

The running means were stable in fourteen of the twenty-five histograms (56 %) in which the longer intervals were exponentially distributed and stable in six of the remaining sixteen histograms (38 %) in which the longer intervals are not so distributed. These differences are not statistically significant.

A longer interval is defined as an interval greater than that represented in the eighth bin of a histogram. If the influence of a single spike on a succeeding spike lasts for up to 100 msec, it might be expected that in a majority of the histograms in which the longer intervals are exponentially distributed these intervals will all exceed 100 msec. Data on the two groups of histograms are set out in Table 2.

Of the histograms whose longer intervals were all more than 100 msec, eighteen (64 %) had exponential tails, while for those whose longer intervals started at less than 100 msec, seven (54 %) had exponential tails. These results mean that, as far as the data in Table 2 is concerned, a histogram whose tail starts with long or short intervals (relative to 100 msec) is equally likely to have its tail exponential. In this connexion it is of interest to note that, of the seven histograms mentioned above, six of them approximated fairly closely to an exponential distribution throughout.

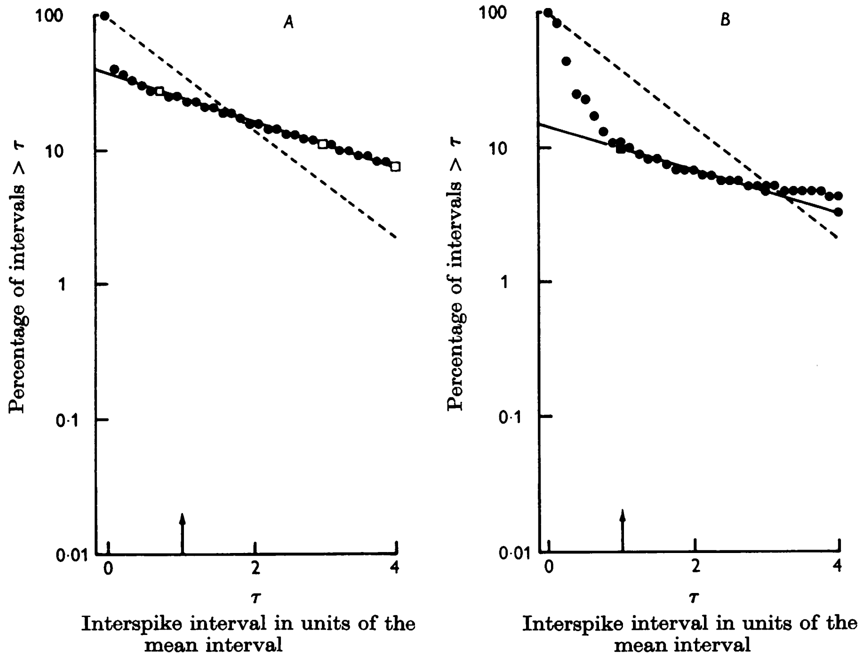

Fig. 7. *A*. The section (39) of discharge from which this histogram was constructed contained 6679 intervals. The over-all mean interval was 653·36 msec. The observed distribution did not fall close to the theoretical exponential distribution ($\chi^2 = 4489{\cdot}1$; $\chi^2/\nu = 0{\cdot}672$). The longer intervals were distributed exponentially, the expected value for point 33 being 505·69 and the observed value 528 (*P* not significant). The running mean was not stable in time. *B*. 11,211 intervals were used to construct this histogram (section 18), $1/\lambda$ being 54·35 msec. The observed and theoretical exponential distributions differed ($\chi^2 = 7440{\cdot}7$; $\chi^2/\nu = 0{\cdot}664$). The longer intervals were not distributed exponentially since more were in bin 33 (505) than was expected (375·46). The difference was significant ($P < 1\%$). The running mean was not stable in time.

TABLE 2. Distribution of histograms according to whether or not the longer intervals were exponentially distributed and whether or not the longer interspike intervals included intervals less than 100 msec. A longer interval is one which exceeds those present in bin 8 of the interspike interval histogram. The intervals in bin 9 were never less than 40 msec in any of the histograms

	Number of histograms		
Duration of interval in bin 9 (msec)	With exp. tail	Without exp. tail	Totals
More than 100	18	10	28
Less than 100	7	6	13
Totals	25	16	41
Expected number > 100	$\frac{28.25}{41} = 17$	$\frac{28.16}{41} = 11$	—
Expected number < 100	$\frac{13.25}{41} = 8$	$\frac{16.13}{41} = 5$	—

DISCUSSION

The changes in spontaneous activity which have been described are similar to those observed at the lateral geniculate body of the anaesthetized cat by Levick & Williams (1964). It is thus highly unlikely that all of the changes which we have encountered can be attributed to variations in the sleep/wakefulness cycle (Evarts, 1962).

Cyclic activity was observed very rarely (in three out of sixty-nine sections). The period in each case was approximately 15, 86 and 136 sec respectively. These results contrast with the relatively frequent occurrence of such discharge patterns in the lateral geniculate body of the cat (Levick & Williams, 1964) and rabbit (Arden & Söderberg, 1961) and in thalamic somatic sensory neurones of monkeys (Werner & Mountcastle, 1963). This apparent discrepancy may reflect differences in the technique of analysing the data, because all the above workers averaged spike discharges in real time. In the present analysis only cyclic activity with a periodicity of approximately a multiple of 100 times the mean interspike interval would have been detected.

Only a minority of interspike interval histograms approximated to an exponential distribution over the whole range, whereas in a slight majority of sections the longer intervals appeared to be distributed exponentially. An exponential histogram always occurs when the underlying process is Poisson. However, if the process is not stationary, in particular if the running means are not stable, then it cannot be Poisson even if it generates an exponential histogram. As the running means in the present study were not all stable it is clear that in this, as in the studies mentioned above, the condition of stationarity is not always fulfilled. Indeed two of the eight units whose interspike interval histogram followed closely an exponential distribution showed non-stable running means as did more than one third of those histograms with exponential tails. On the other hand the running mean was stationary in almost two thirds of the histograms where the longer intervals were not distributed exponentially. Thus a unit in which the interspike interval histogram is approximately exponentially distributed in part or in whole may not have a stable running mean and conversely.

In those cases where the running mean is stable and the tail exponential, it is possible that, for the longer intervals, the time of occurrence of a spike is independent of the time of the preceding spike. In a minority of the histograms (six out of twenty) where conditions of stability in time exist, the tail was not exponential. In four of these there was a preponderance of the very long intervals and in two a deficiency of them. These interspike interval distributions might occur if for the longer intervals (which in these six units were all greater than 60 msec) the cell tended to fire at random, but that some inhibitory or excitatory process operated and respectively reduced or increased the likelihood of some of the discharges. Where such processes were absent the cell would tend to fire at random provided it did not fire very shortly after the preceding spike.

We are, however, left with twenty-one histograms for which the running means drifted. In this situation there is no simple statistical model which can be used to represent the process which might generate such interspike interval histograms. However, it is possible that the process is stationary over short periods, with a long-term fluctuation superimposed on top of this. The simplest example would be one which is 'Poisson' but with a slowly varying probability of firing, i.e. in which the probability $p(t)$ of firing per unit time is independent of the last time of firing but changes with time. Such a process would have a non-stable running mean and would not necessarily give rise to an exponential histogram. In fact such a process, especially in combination with the inhibitory and excitatory effects mentioned above, could certainly give rise to our experimental results. This is not to say, however, that it is responsible for them.

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