The microelectrode technique, by permitting observations of the spike trains from single sensory neurons, has broadened our understanding of sensory information processing by the central nervous system. Since technical limitations prohibit the maintenance of prolonged electrical contact with a single neuron, a relatively brief sample of the single-unit record is often the basis for characterizing the stimulus-response characteristics of a unit. If unit discharge characteristics are invariant over time, a sample record obtained at any time would be sufficient to characterize the unit's response. On the other hand, if unit discharge characteristics do vary over time, a sample record may give a restricted view of a unit's response to sensory stimulation.

Changes in the level of anesthesia (2) or arousal (8, 23) are correlated with changes in single-unit responses to sensory stimulation. But even if the experimental procedure is carefully controlled to minimize state changes, there is little data which indicate the degree to which the stimulus-response function is time invariant. The small amount of data which are relevant to this issue come mainly from investigations of stochastic properties of neuronal discharges (13, 25). The results of these experiments indicate that a sizable proportion of sensory neurons show significant changes in discharge rate independent of intentional changes in sensory stimulation or physiological state. This implies that the stimulus-response function might undergo simultaneous changes, although the nature of such changes has received little attention.

The present study is concerned with some properties of spike trains recorded from single neurons of the medial geniculate body (MGB) of locally anesthetized paralyzed cats. Two questions were considered: 1) Do the discharge rates of single neurons change independent of intentional changes in stimulus and physiological conditions? 2) If the discharge rates are not stable, how are rate changes related to the pattern of discharges, i.e., how are they reflected in the poststimulus time histogram?

**METHODS**

**Subjects and surgical procedures**

The subjects were 14 cats (3.0-5.0 kg) free of middle ear infection. Initial anesthesia was produced with an intravenous injection of sodium thiamylal (Surital) and subsequent injections of this short-lasting barbiturate maintained a surgical level of anesthesia for approximately 1 hr. An endotracheal tube, coated with a long-lasting local anesthetic (Zyljectin), was inserted under laryngoscopic control and 0.4 mg of atropine methyl sulfate was injected subcutaneously to prevent respiratory congestion. In five animals both tympanic membranes were punctured with an 0.125-mm-diameter wire, and in another the bullae were exposed and opened using a dental drill. The purpose of these procedures was to prevent a change in pressure within the middle ear which could alter acoustic transmission (21, 26). Results from these animals did not differ from animals which did not undergo these procedures. The animal was mounted in a stereotaxic instrument with blunt, hollow ear bars which did not
damage the tympanic membranes. All wound edges and pressure points were infiltrated with Zyljectin. Respiration rate and volume were adjusted prior to paralysis to correspond to the cat's breathing patterns. The animal was then paralyzed with 2 ml (40 mg) of gallamine triethiodide administered through a catheter in the femoral or radial vein. Paralysis was maintained by supplementary 40-mg doses. Rectal temperature was maintained at 36-38 C by a circulating warm-water pad. All surgical and experimental procedures were carried out with the cat enclosed in an acoustically dampened room (IAC 1202).

Recording procedure

The ECoG was monitored from a cortical screw overlying the marginal or suprasylvian gyrus. Microelectrodes were made of electrolytically sharpened tungsten wire covered with glass insulation with impedences of 5-15 megohms. Units were located by presenting clicks as the electrode was advanced in steps of approximately 5 μ every 10-40 sec. The electrode was advanced with an electrical drive controlled by the experimenter outside the acoustic room. The signals from both microelectrode and skull screw were amplified by Tektronix type 122 preamplifiers and displayed on an oscilloscope. Pulses coincident with unit discharges and stimulus onset were led to a LAB-8 digital computer for further processing. Data recording was delayed 1-2 hr after the administration of the paralyzing agent to permit the effects of general anesthesia to dissipate.

Acoustic stimulation

Acoustic stimuli were presented binaurally through Telephonic TDH-49 speakers mounted on the end of the hollow ear bars to form a closed cavity. Stimulus intensity was measured through a 0.6-cc coupler connecting the hollow ear bar with a B and K impulse sound-level meter (2204) fitted with a one-half-inch condenser microphone (4134). Measurements of stimulus intensity showed variations of less than 2 dB during the entire experiment. Two types of acoustic stimulation were presented. 1) Clicks mixed with white noise (click stimulation). White noise was added to 0.1-msec pulses by a Grason-Stadler white-noise generator (901B). Most click stimulation was presented with a white-noise background of 77 dB and click intensity of 98.5, dB re:0.0002 bar. The period between successive clicks was generally 530 msec. 2) Amplitude-modulated white noise (AMWN). AMWN was produced by switching the output of a Grason-Stadler noise generator (455C) through a Grason-Stadler electronic switch (829E) using long (250 msec) rise and fall times. This produced a white-noise signal whose amplitude varied continuously during each complete stimulus cycle of approximately 530 msec. The amplitude envelope of the signal is depicted in Figs. 4A and 5A. The maximum intensity of the AMWN was 92 dB re:0.0002 bar; the minimum intensity was 77 dB.

Data analysis

During acoustic stimulation, both synch pulses and unit discharge timing pulses were led to a LAB-8 computer. The synch pulses were coincident with occurrence of the pulse which produced clicks or at a fixed phase of a stimulus cycle during AMWN stimulation. The times of occurrence of both the synch pulses and spike discharges were recorded by the computer with a resolution of 100 μsec. For purposes of later analysis the data was gathered on-line in a series of 128 consecutive stimuli, a "block." After each block had been gathered, the data were transferred to digital tape, which required 30-60 sec. Discharges occurring during the transfer were not recorded although acoustic stimulation continued. A minimum of 4 blocks of data were recorded for each unit; usually 8 blocks, and in a few instances up to 32 blocks, were recorded. These data were subjected to analyses off-line as described in the RESULTS section.

Histology

At the completion of an experiment, the animal was sacrificed with an overdose of anesthetic and perfused with formal-saline. The brain was cut in 50-μ sections on a freezing microtome. Sections were stained with cresyl violet and those containing electrode tracks were traced at a magnification of 20 times for identification of recording sites.

RESULTS

Physiological state

Every effort was made to maintain the animal in good physiological condition throughout the 12–19 hr duration of the experiment.1 In the first 1–2 hr following surgery, the ECoG changed gradually from high-voltage slow waves with spindles to low-voltage fast waves, and generally re-

1 In similar preparations having pupillary motility, habituation and discriminative conditioning of pupillary dilatation have been demonstrated, reinforcing the notion that this preparation is within reasonably normal physiological limits (15).
mained desynchronized throughout the experiment.

Location of units

The electrode tracks through the MGB could generally be well localized although the precise location of the deepest point of the electrode tip could not be identified with absolute certainty. The location of units in the dorsal-ventral dimension was estimated with reference to the bottom of the track and recorded depth measurements from the microdrive. Recording loci are presented in Fig. 1. The ventral region of the parvocellular part of the MGB is recognized anatomically as the major MGB component of the auditory pathway (11, 18). Although this region is most clearly differentiated from the dorsal region of the parvocellular MGB in Golgi material (11), differentiation was possible in Nissl-stained sections. We identified the ventral MGB as an area of greater cellular density than the dorsal MGB. It was located in the ventral and lateral regions of the nucleus, bounded medially by fibers of the brachium of the inferior colliculus, and dorsally (in the anterior portion) by horizontal fascicles separating it from the dorsal division. Furthermore, in a separate experiment performed in this laboratory, a lesion in the inferior colliculus produced dense terminal degeneration (Fink-Heimer method) within the MGB which was confined to the region identified above as the ventral MGB (W. Lippe, personal communication). This is in agreement with previous reports (10, 11, 17). Only data from units located within the ventral division are included in the present communication.

General characteristics of unit activity

The amplitudes of unit potentials ranged from 150-800 μV, and were generally 400-600 μV. Discharges from only those units which were very well isolated from their neighbors, had initially negative deflections, and showed no obvious signs of injury (i.e., high-frequency bursting) were included in this study. Discharge waveform was monitored on an oscilloscope throughout the experiment and data acquisition was terminated if any of these conditions deteriorated. The sampling of units included in this study was not random since units with very low discharge rates were seldom studied due to the difficulty of statistically analyzing small numbers of discharges. Furthermore, most units were restricted to the middle third of the ventral division of the MGB, which corresponds approximately to A4.0-5.0 of the Snider and Niemer atlas (20).

Responses to acoustic stimulation

The PSTH was employed to evaluate unit responses to sound. Clicks mixed with white noise were presented to 54 units, 53 of which showed a clear response to the click. The PSTH consisted of complex series of peaks and troughs following the click, but the extent to which these reflect the waveform of the stimulus or modulation due to neural mechanism cannot be determined from the present data. Despite the complexity of the shapes of the PSTHs, two characteristics stand out. First, 53/54 units displayed a short-latency (10-25 msec) modulation of neural discharges. In 29/53 units this took the form of an initial peak (increase in discharge rate) (e.g., Fig. 2A), and in 24/53 units there was an initial trough.
FIG. 2. Relationship between discharge rate and discharge pattern for unit F800. Clicks (98.5 dB) were presented binaurally on a background of continuous white noise (77 dB) at the rate of 1/530 msec. Discharge rate is presented by serial counts histograms (B), the construction of which is explained in the text. Discharge pattern is presented by poststimulus time histograms (A and C). Data depicted were gathered into eight blocks of 128 clicks each during continuous click stimulation. Blocks were separated in time by periods of 30–60 sec, during which the discharge data was transferred to digital tape; stimulation was not interrupted during data storage. PSTHs were constructed using a 5-msec bin and are 530 msec in length. PSTH ordinates in this and following figures are normalized and calibrated in spikes per bin per stimulus (S/B/C). A: PSTH constructed from all 8 blocks of data, 1,024 clicks presented; number of discharges = 5,083. 4 denotes the initial discharge (latency 15–25 msec), 3 denotes the second discharge (latency 35–45 msec), and 2 denotes the period of background activity (latency 255–530 msec). B: serial counts histograms which present the number of discharges following clicks (ordinate) as a function of the serial order of clicks (abscissa). Each point on the ordinate in this and following figures represents the sum of discharges to consecutive pairs of clicks, rather than to individual clicks, in order to slightly “smooth” the display. Divisions at the bottom denote the eight data blocks. 1 is the serial counts histogram for the entire PSTH depicted in A, giving the number of spikes to each pair of clicks for the entire 530-msec interval between clicks. The discharge rate depicted by this histogram was unstable. The first two blocks had the lowest discharge rate (LDR), while the third and fourth blocks had the highest discharge rate (HDR). B, 3, and 4 are serial counts histograms constructed from subintervals following click stimulation corresponding to the period of background activity (2), second discharge (3), and initial discharge (4). See text for discussion. Calibration: 1 and 2, eight spikes; 3 and 4, four spikes. C: poststimulus time histograms constructed from the two highest discharge rate blocks (HDR), the two lowest discharge rate blocks (LDR), and the difference between these two histograms (HDR – LDR). HDR: 256 clicks and 1,529 spikes; LDR, 256 clicks and 1,037 spikes. The difference histogram reveals that the difference in spikes between the HDR and LDR data was not randomly distributed across the PSTH. See text for discussion.

(decrease in discharge rate). In most cases the initial trough was followed by a prominent peak in the PSTH (e.g., Fig. 3A), but in a few instances there was an inhibition only. The shape of the remainder of the PSTH was not obviously correlated with the occurrence of an initial peak or trough. Second, neuronal discharges showed little tendency for the 10/sec rhythmic activity seen in the click-evoked potentials and PSTHs of both single (I) and multiple-unit activity in the barbiturate-anesthetized preparation. In only one unit’s discharge pattern was a periodic afterdischarge clearly evident and a suggestion of limited repetitive afterdischarge was seen in three others. The PSTH of 25 of the remaining 49 units showed a long-latency peak approximately 100 msec following the stimulus, but there was no tendency for repetitive afterdischarge.

The response to amplitude-modulated white noise (AMWN) cannot be described simply. In 7/19 units the PSTH approximated the amplitude envelope of the stimulus (Fig. 4A). Discharges from the remaining 12/19 units exhibited more complex responses (e.g., Fig. 5A).
FIG. 3. Relationship between discharge rate and discharge pattern for unit A200. Clicks (98.5 dB) were presented binaurally on a background of continuous white noise (77 dB) at the rate of 1/1,060 msec. Data depicted were gathered during continuous click stimulation into five blocks of 100 clicks each, separated by approximately 30–60 sec, during which time data was transferred to digital tape; stimulation was not interrupted during data storage. PSTHs were constructed using a 10-msec bin, and are 1,060 msec in length. Ordinates are given in spikes per bin per stimulus. A: PSTH constructed from all five blocks of data, 500 clicks presented; number of discharges = 10,879. B: serial counts histograms presenting the number of discharges to each consecutive pair of clicks (ordinate) as a function of the serial order of the clicks (abscissa). Divisions at the bottom denote the five data blocks. 1 is the serial counts histogram for the entire PSTH depicted in A. This discharge rate was unstable. The second block has the lowest discharge rate (L) and the fifth block, the highest rate (H). 2, the serial counts histogram constructed from the subinterval following click stimulation corresponding to the period of background discharges (latency 310–1,060 msec). 3, the serial counts histogram for the subinterval of the initial discharge in response to click stimulation (latency 30–50 msec). Calibrations: 1 and 2, 20 spikes; 3, 5 spikes. C: poststimulus time histograms constructed from all data in the highest discharge rate block (H), the lowest discharge rate block (L), and the difference between them (H – L). H: 100 clicks and 2,374 spikes; L: 100 clicks and 2,103 spikes. See text for discussion.

Stability of discharge rate

The procedure and rationale for determining discharge rate stability have been given in greater detail in a previous paper and will be described only briefly. A 5- to 40-min sample of the discharge was collected during acoustic stimulation. This sample was usually divided into approximately 68-sec increments (a block), during which time 128 stimuli were presented. The number of discharges occurring in each stimulus cycle (i.e., between two successive synch pulses) was tabulated. A display of the number of discharges per stimulus cycle as a function of time constitutes the “serial spike counts histogram” (SCH); examples of SCHs are provided in Figs. 2B–5B and these will be discussed below. A visual analysis of the SCH yields some information regarding discharge rate stability, but a more objective evaluation is mandatory.

One method of determining whether significant changes in rate have occurred is to subject the spike counts data to an analysis of variance. A parametric analysis of variance test (F test) requires that the distribution of spike counts be normal (5). We have previously investigated the distributions of spike counts, and have found them to be normal only rarely (8, 23). The same results obtained in the present experiment. There-
FIG. 4. Relationship between discharge rate and discharge pattern for unit J200. Amplitude-modulated white noise (AMWN) was presented continuously with each stimulus cycle requiring 530 msec. The intensity of this stimulus varied from 92 to 74 DB. The amplitude envelope of the AMWN is shown below the PSTH in A. Data depicted were gathered into eight blocks of 128 AMWN cycles, separated by the time needed to store data on digital tape. The PSTH (A and C) were constructed using a 5-msec bin and are 530 msec in length; ordinates are calibrated in spikes per bin per stimulus cycle. A: PSTH constructed from all eight data blocks, 1,024 AMWN cycles presented; number of discharges = 5,475. B: Serial counts histogram for all data. The discharge rate was unstable; discharge rate increased, the first block having the lowest rate (L) and the eighth block the highest rate (H). Calibration: 12 spikes. C: Poststimulus time histograms constructed from data of the highest (H) and lowest (L) discharge rate data blocks and their difference (H - L). H: 128 stimulus cycles and 971 spikes; L: 128 stimulus cycles and 380 spikes. See text for discussion.

fore, use of a parametric analysis of variance would be inappropriate and, accordingly, we have employed a nonparametric statistical test, the Kruskal-Wallis one-way analysis of variance on ranks (19).2 A significant change in rate was considered to have occurred some time during the recording of a unit’s discharges if the probability of obtaining the computed Kruskal-Wallis statistic was equal to or less than 0.05.

Serial counts histograms in Figs. 2B, 1, 3B, 1, 4B, and 5B illustrate discharge rates which met this criterion. The discharge rates of 47/53 units recorded during click stimulation and of 18/19 units recorded during AMWN stimulation displayed significant changes. Thus, stable unit discharge rates were uncommon under both conditions of stimulation.

Relationship between changes in discharge rate and discharge pattern

CLICK STIMULATION. The finding that the discharge rate of MG units changed over time led us to inquire into the relationship between rate and the click-evoked discharge pattern, i.e., the poststimulus time histogram (PSTH). Since both the discharge rate and PSTH are computed from the same spike train for each unit, changes in dis-
FIG. 5. Relationship between discharge rate and discharge pattern for unit M400. Stimulation conditions were the same as in Fig. 4. Discharges from this cell were gathered into 32 blocks of 128 AMWN presentations each. The PSTH (A and C) were constructed using a 5-msec bin and are 530 msec in length; ordinates calibrated in spikes per bin per cycle. A: PSTH assembled from all 32 data blocks, 4,096 AMWN cycles presented; number of discharges = 10,659. B: serial counts histogram for all data; the bottom row is continuous with the top row. The discharge rate was unstable. Data blocks having the highest and lowest discharge rates are denoted, respectively, by H (Hx, Hy) and L. Discharge rate during block Hy was much higher than that of any other block. C: PSTH constructed from data of the five highest discharge rate blocks (including block Hy but not block Hx), the five lowest discharge rate blocks, and their differences (Hy - L). Hy: 640 AMWN cycles and 2,666 spikes; L: 640 AMWN cycles and 1,072 spikes. D: PSTH constructed from data of the same high discharge rate blocks as in C, except that block Hx has been substituted for block Hy; the PSTH for the lowest rate blocks is unchanged. Hx-L, the difference histogram. Hx: 640 AMWN cycles and 2,487 spikes. See text for discussion.

charge rate must be reflected as some change in the PSTH. The PSTH is simply a display of the temporal distribution of the rate over the stimulus cycle interval. In this study PSTHs have been normalized to ease comparison; their ordinates are spikes per bin per stimulus cycle (S/B/C) instead of simply spike counts. Thus changes in discharge rate will be reflected in the PSTH as changes in S/B/C, which is referred to as ΔS/B/C.

How is the change in discharge rate distributed throughout the PSTH; is it distributed randomly or nonrandomly to each bin of the PSTH? To answer this question, the number of spikes in each block of the spike train was counted. On the basis of this count, blocks with the highest and lowest counts were selected and are called the high-discharge rate (HDR) and low-discharge rate (LDR) portions of the spike train. As the discharge rates of these units showed significant changes, statistically these highest and lowest rate portions of the spike train were also significantly different. From these spike train segments two PSTHs were constructed, one from the HDR segment and the other from the LDR segment. To evaluate how the change in discharge rate was distributed throughout the PSTH, the difference histogram was computed by subtracting the number of spikes in bins of the LDR histogram from the number of spikes in the corresponding bins of the HDR.
For example, if the additional spikes occurring during the HDR portion of the spike train were distributed randomly to the PSTH, then each bin of the difference histogram (HDR PSTH minus LDR PSTH) would vary randomly about the mean $\Delta S/B/C$. On the other hand, a nonrandom distribution would be revealed as a difference histogram having definite peaks and troughs.

Figure 2 shows such an analysis of data from unit $F800$. The PSTH constructed from eight blocks of data is shown in Fig. 2A; it consists of two initial peaks, labeled 4 and 3, respectively, followed by a period of reduced discharge, after which a maintained level of discharge occurs, 2. The SCH for the total spike train from which the PSTH was constructed is given in Fig. 2B. It reveals that discharge rate varied over time; in particular, the rate was lower during the first two data blocks (LDR) than the following two blocks (HDR). Separate SCHs were also computed for restricted portions of the PSTH, specifically for the initial peaks, 4 and 3, and the maintained discharge, 2. These are displayed in Fig. 2B and denoted by numerals corresponding to their respective portions of the PSTH. These SCHs suggest that the spike discharges added during the HDR part of the total spike train were allocated to the maintained level (Fig. 2B, 2) and also to the initial peak (Fig. 2B, 4). A small increment is also seen for the second peak (Fig. 2B, 3).

This method of display provides a resume of the results which is somewhat difficult to analyze visually. The difference histogram is easier to interpret. PSTHs from the HDR and LDR parts of the spike train are displayed in Fig. 2C, as is their difference histogram (HDR – LDR). The difference histogram is easier to interpret. PSTHs from the HDR and LDR parts of the spike train are displayed in Fig. 2C, as is their difference histogram (HDR – LDR). The difference histogram shows clearly that the change in overall rate is not randomly distributed to each bin in the PSTH. Rather, the $\Delta S/B/C$ is related to the absolute value of $S/B/C$ for each bin in the total histogram (Fig. 2). That is, bins of the total PSTH having the largest $S/B/C$ values generally receive a greater proportion of additional spikes occurring during the HDR portion of the spike train than bins having the smallest $S/B/C$ values.

This type of analysis was computed for 31 units which showed significant changes in DR and in only 6 units did $\Delta S/B/C$ appear to be distributed randomly to each bin of the PSTH. In all others (25/31), the change in rate appeared to be distributed nonrandomly. In 14/25 units, the $\Delta S/B/C$ values for bins in the difference PSTH were generally large for large $S/B/C$ values and small for small $S/B/C$ values, as was the case for unit $F800$ whose data are illustrated in Fig. 2.

In another 11/25 units, however, the relationship between $\Delta S/B/C$ and $S/B/C$ was more complex. In Fig. 3, high (H) and low (L) discharge rate segments of the record are shown in the SCHs, and the PSTHs corresponding to these portions of the record are shown in section C of the same figure. In this example the correspondence between the $S/B/C$ and $\Delta S/B/C$ is much less clear than in Fig. 2. The $\Delta S/B/C$ values for the first peak (which has the largest $S/B/C$ values) are no larger than those for the background (the “flat” part of the PSTH), which has much lower $S/B/C$ values than the first peak. However, the trough following the first peak, which has the lowest $S/B/C$ values in the PSTH also, has low $S/B/C$ values in the difference histogram. Thus, while the relationship between $S/B/C$ and $\Delta S/B/C$ values is not as clear as in the group of units described above, it is not random and in fact does show a tendency for $\Delta S/B/C$ to increase as $S/B/C$ increases. Thus, the analysis of unitary responses to click stimulation suggests that $\Delta S/B/C$ and $S/B/C$ exhibit a positive correlation for most units.

**AMWN STIMULATION.** Although the difference histogram technique using click PSTHs indicates a positive correlation between $\Delta S/B/C$ and $S/B/C$, a more powerful method of statistically evaluating these results is desirable. Click stimuli produce only short duration changes in the PSTH, resulting in only a few high and low $S/B/C$ values, while the majority of $S/B/C$ values is unaffected by the stimulus. In order to perform a statistical analysis, a greater
dispersion of values is advantageous. Amplitude-modulated white-noise (AMWN) stimulation produces a more continuous change in stimulus intensity than does click stimulation, one which we hoped would be reflected in a greater dispersion of S/B/C values than for click stimulation; indeed, this was the case.

AMWN was presented to 19 units; 1 unit did not respond to this stimulus and 1 showed a stable discharge rate, reducing the sample size to 17 units. A typical result is shown in Fig. 4. The PSTH of unit J200 roughly approximates the envelope of the stimulus (Fig. 4A). The SCH was comprised of eight blocks of which the first and last were selected as those exhibiting the lowest and highest discharge rates, respectively (Fig. 4B). (Although the SCH shows recurrent peaks indicating episodes of high discharge rate, alternating with periods of lower rate, the unit discharge was not characterized by bursting.) The PSTHs constructed from the high- and low-rate blocks both resemble the total PSTH, but the difference histogram (H—L) reveals that additional high-rate spikes were not randomly distributed. Although the variance within this histogram is still appreciable, the relationship between the ΔS/B/C and S/B/C can be determined more easily than for click stimulation. ΔS/B/C values appear to be positively correlated with the S/B/C values of the total PSTH.

Visual inspection of the difference PSTHs for all 17 units revealed only one unit for which ΔS/B/C values were independent of S/B/C values. In the other 16 units, these variables were positively correlated, i.e., bins having high S/B/C values received more of the “added” spikes during the high-rate part of the spike train than those having low S/B/C values.

In 10/17 units, the relationship between ΔS/B/C and S/B/C values is well illustrated by unit J200 whose data are presented in Fig. 4. In 6 other units, however, the relationship was less clear, although ΔS/B/C values were positively correlated with S/B/C values. An example of this finding is illustrated by Fig. 5. The PSTH approximated the stimulus envelope but the unit discharged less during the decreasing than the increasing phase of amplitude modula-

The SCH shows rather moderate changes in discharge rate with the exception of one block labeled “Hy” in which the rate was several times that of most other stimulus blocks (Fig. 5B). PSTHs constructed from high (H) and low (L) discharge rate (DR) blocks are displayed in Fig. 5C; the high-rate PSTH included the extreme Hy block. The difference histogram (Hy—L) is not random, but it differs markedly from the total PSTH; in particular, the region corresponding to minimal discharge in the total PSTH (minimum stimulus intensity) displays relatively greater discharge in the difference histogram.

It is possible that these results were due to the inclusion of the Hy block which has an abnormally high rate. A second high DR PSTH was constructed, substituting block Hx for block Hy; Hx was not extreme in its values (Fig. 5B). The new Hx and difference histograms are shown in Fig. 5D; (the I. histogram was unchanged). The difference histogram (Hx—L) still is markedly different from the total PSTH, but the resemblance is closer than for the Hy—L PSTH because the discharges during the period of minimal stimulus intensity are reduced. Nevertheless, the peak associated with increasing stimulus amplitude (far right) is still no larger than the peak associated with decreasing stimulus amplitude (far left), unlike the total PSTH. Therefore, the inclusion of the “odd” Hy block cannot account for the failure of the ΔS/B/C values to correlate as well with the S/B/C values as in the previous example.

In summary, an analysis of the pattern of discharges during AMWN stimulation has revealed that a change in rate does not result in discharges being randomly distributed to all bins of the PSTH. Instead, there is a positive correlation between ΔS/B/C from the difference histogram and the S/B/C from the total PSTH.

To statistically evaluate the relationship between these variables, a linear regression between the ΔS/B/C (dependent variable) and the S/B/C (independent variable) was computed. This statistical approach provides a more objective index of the relationship than does visual analysis of the histograms. The regression was computed bin by bin (i.e., each data point in the re-
Regression analysis was specified by two coordinates, bin 1 of the difference PSTH and bin 1 of the PSTH computed from the entire sample. The regression lines are plotted in Fig. 6 for each of the 17 units. A point on each line indicates the mean $\Delta S/B/C$ and mean $S/B/C$ values for the corresponding unit. All regression lines have positive slopes which were statistically significant ($P < .05$) in 15/17 of the units. In spite of the nonlinearities which are present for some units (e.g., Fig. 5) and undoubtedly account for some scatter in the regression lines, the positive slope of the regression lines confirms the visual analysis using the difference PSTH, namely that an increase in overall discharge rate produces a greater increase in bins with high $S/B/C$ than bins with low $S/B/C$.

**DISCUSSION**

**Rate stability**

The discharge rates of units in the ventral division of the medial geniculate body were characteristically unstable. In previous studies, discharge rates in this nucleus recorded during click stimulation have been found to change in the absence of intentional background stimulation (8, 23c). In the present study, rate changes occurred during stimulation by clicks mixed with white noise and also during stimulation by amplitude-modulated white noise. Therefore, changes in discharge rate in the presence of an acoustic stimulus are not limited to a single stimulus condition.

Rate instability is not a property of MGB units alone. Using different analysis techniques and spike trains of approximately 1 min in duration, Werner and Mountcastle (25) found a "nonoscillatory dependency" in 15/101 spike trains recorded from ventrobasal units, which is perhaps similar to the rate instability reported here. Nakahama et al. (13) found that 19/35 units recorded in the ventrobasal complex, lateral geniculate body, mesencephalic reticular formation, and red nucleus had nonstable discharge rates. The proportion of units with nonstable discharge rates in the present report was far greater than those reported in the previous studies, but the results are not directly comparable due to different analysis techniques and lengths of time of data collection. Nevertheless, rate instability is clearly not confined to the medial geniculate body.

The importance of rate stability has been discussed in several reviews (9, 16). Statistical analyses of spike trains can produce clues about connectivity of neurons (6) and spike production mechanisms (4). But the results of such statistical tests depend on both the time variant and time invariant properties of the spike train. Unfortunately,
the contribution of these two properties to the outcome of the statistical analysis often cannot be separated, thus producing ambiguous results (4, 7).

The mechanisms responsible for rate changes were not studied directly in the present experiment, but consideration of its causes is possible in light of some of the procedures which were employed. Two obvious candidate mechanisms relate to a) changes in the state of the animal and b) changes in the effective acoustic stimulus. State changes have already been discussed. The animals' ECoGs were desynchronized throughout the experiment, ruling out gross alterations in state. However, the possibility that the arousal level of the animals changed within the desynchronized state cannot be excluded (24).

Changes in acoustic stimulation seem very unlikely. Measurements of stimulus intensity did not vary significantly over a period of 5–6 hr or from day to day. Since all experimental procedures took place inside an acoustically dampened room in which only the cat was present, the subject was shielded from extraneous noise. The cats might have heard their own respiration despite the presence of masking noise, but as this was constant throughout the experiment it could not account for the observed changes in rate. Accumulation of mucus in the endotracheal tube or water condensation in the return line to the respirator produced audible gurgling during the recording of discharges from two units, which were excluded from analysis. Respiratory noise was carefully checked before and after recording discharges of every unit to control for this source of variability. Given that the acoustic stimulus at the tympanic membrane was invariant, a change in the transfer function of the middle ear could also produce changes in effective stimulus intensity at the oval window. Although the middle ear muscles are capable of modifying the transfer function of the middle ear, the animals were completely paralyzed. The level of paralysis was checked following data collection for each unit by monitoring muscle tonus and watching for spontaneous movements. These did occur during recordings from three units in which a supplemental injection of the paralyzing agent had been overlooked and these data were rejected and not analyzed. A final possible source of variation in transmission through the middle ear is due to changes in middle ear pressure (21, 26). Although changes in middle ear pressure have not been demonstrated to occur in the paralyzed preparation, the possible occurrence of this source of variability was eliminated in six animals in which both tympanic membranes were punctured or bullas opened. There was no systematic difference between the data obtained from these cats with respect to either discharge-rate stability or to the relationship between discharge rate and the PSTH. On these grounds, we believe that the observed phenomena cannot be attributed to stimulus variability.

In summary, it seems unlikely that either gross state changes or changes in effective stimulus intensity are likely to account for the rate changes observed in this experiment. Two other possible mechanisms include changes in blood pressure, which was not monitored, and the mechanical influence of the recording electrode on neuronal activity consequent to possible changes in its position relative to the neuron. Mechanical influences have been demonstrated in the lower auditory system (22). We have observed significant correlations between spike amplitude and discharge rate, which might be expected if electrode position affects discharge rate. However much more extensive and systematic controlled observations would be necessary to provide strong support for this explanation of the present findings. It is also conceivable that these changes in discharge rate reflect normal neuronal functioning.

Relationship of discharge rate and pattern

Although the causes of changes in discharge rate in the present study are unknown, the relationship between changes in discharge rate and the pattern of unit firing is of interest. In the present study, increased discharge rate was not distributed equally to each bin of the PSTH. Bins having most counts under low-rate conditions received a disproportionately greater number of counts under high-rate conditions than bins having fewest counts. This
finding seems to hold for click stimulation and was verified statistically for amplitude-modulated white-noise stimulation. This relationship is quite different from that reported by Mountcastle, Poggio, and Werner (12) for one unit in the VB complex. The spontaneous discharge rate increased gradually over a period of 1 hr, and the increased rate appeared to be added to the evoked discharge. A regression of the change in rate for a given stimulus intensity and the response to the same stimulus would have yielded a regression line with 0 slope.

The relationship between discharge rate and pattern in the auditory system has also been investigated by Bureš and Burešová (3) who manipulated the background rate of units in the inferior colliculus of the rat with extracellular polarization. In 40% of the units the increase in rate was additive, i.e., an approximately equal number of spikes were added to each bin of the click-evoked PSTH; this corresponds to a "random" allocation of counts in the present experiment, a finding which was extremely rare in this study. Another 40% of the colliculus cells exhibited a "multiplicative" relationship, i.e., counts added to the PSTH were allocated preferentially to bins having higher count values during low-rate portions of the spike train. We found a much higher percentage of proportional allocation of spikes; the regression analysis between S/B/C and ΔS/B/C for AMWN stimulation was significantly positive in 15/17 cases. This discrepancy might be due to differences in brain locus, species employed, the use of polarization to increase discharge rate, or stimulus conditions. Whatever the differences in the two sets of findings, it is clear that the nonrandom allocation of discharges to the PSTH under conditions of increased discharge rate is not confined to one level of the auditory system.

Bureš and Burešová (3) have pointed out that the multiplicative relationship has interesting implications. If one considers the peaks of the PSTH to represent "signals," and the background maintained discharge level as "noise," then the multiplicative or proportional relationship results in a constant S/N ratio in the face of an increase in discharge rate, i.e., the peaks do not become "submerged" in the background discharge activity. General increases in the discharge rate of units in sensory nuclei (e.g., lateral geniculate body, medial geniculate body) are known to occur during an increase in arousal (8, 14). It is possible that neuronal mechanisms responsible for the positive correlation between S/B/C and ΔS/B/C function during heightened arousal to maintain the processing of sensory system data which otherwise would be altered or degraded.

**SUMMARY**

Extracellular potentials from single units in the medial geniculate body of locally anesthetized, paralyzed cats were recorded for periods up to 3 hr while presenting click or amplitude-modulated white-noise stimuli. The discharge rates of the vast majority of units were found to change significantly in the absence of intentional changes in acoustic stimulation or physiological state. The relationship between discharge rate and discharge pattern was not random. Comparisons of low- and high-rate segments of a spike train revealed that additional discharges occurring during the high-rate segment were distributed disproportionately to the peaks rather than the troughs of the poststimulus time histogram. These results were discussed in relation to maintenance of a constant signal-to-noise ratio during increases in discharge rate.

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