EXCERPTUM

Acta physiol. scand. 1971. 81. 540—556

From the Department of Physiology, Karolinska Institutet, Stockholm, Sweden

Unit Responses in the Rat Cochlear Nucleus to Tones of Rapidly Varying Frequency and Amplitude

By

AAGE R. MØLLER

Received 5 October 1970

Abstract

MOLLER, A. R. *Unit responses in the rat cochlear nucleus to tones of rapidly varying frequency and amplitude.* Acta physiol. scand. 1971. *81*. 540—556.

The response of single units in the cochlear nucleus of the rat to sweep tones (FM sounds) and short tone-bursts (AM sounds) has been investigated. It was found that the response pattern to FM sounds became more restricted with regard to tone frequency at a certain rate of tone-frequency change. The probability of firing within a narrow frequency range surrounding the unit's CF became frequently more than ten times greater than that at low sweep-speeds.

For a certain range of higher sweep-rate, cycle histograms become narrower and higher than at low sweep-rates. The range of frequency change where the peaks had maximal height was found to lie in the region between 1 and 15 MHz/sec for units with CF from 5 to 30 kHz. This effect was found to persist over a sound-intensity range of more than 60 dB, but was less marked at very low intensity levels. The threshold of the units investigated did not become lowered at any rate of frequency change.

The cycle histograms of the response to sounds of constant frequency and variable duration (AM sounds) differed significantly from that to FM sounds. Only occasionally was an increase in height of the cycle histograms seen when the duration of the sounds was narrowed and the repetition rate increased.

The response areas of single units at different levels in the auditory system have been studied in numerous previous investigations, using pure tones with a constant or slowly varying frequency. In many studies, a unit's response area has been expressed by its threshold as a function of tone frequency (tuning curves, *cf.* Kiang 1965), but it has been claimed that the responses above threshold offer a more representative description of the characteristics of a neuron than threshold values. Iso-rate functions which show the sound intensity required to evoke a certain increase in firing rate represent one way of describing a unit's response area above threshold. Such curves however are essentially parallel to the turning curres (*cf.* Møller 1969 a). Other authors have plotted the response area as a function of tone frequency, with the sound intensity as parameter (see *e.g.* Hind *et al.*, 1967).

Although most natural sounds have a more or less rapidly changing spectral distribution, only a few neurophysiological investigations on the response to frequency-modulated sounds have been reported in the literature. Suga (1965) studied the threshold of single units in the cochlear nucleus and inferior colliculus to FM sounds similar to the echo-locating sounds of flying bats. In his detailed studies of units in the cochlear nucleus, he found no appreciable difference between the threshold of FM sounds and that of tones of constant frequency. Watanabe and Ohgushi (1968) examined the threshold to FM sounds in different parts of the ascending auditory pathways. Though they found no specificity of the neurons in the cochlear nucleus with regard to direction of FM sweep, at higher levels in the auditory pathway they found a rather pronounced directionality in a number of units. These features were especially marked in the auditory cortex (AI), which agreed with earlier findings by Whitfield and Evans (1965). Erulkar *et al.* (1968) investigated the response of cochlear nucleus units to stimulation with trapezoidally FM modulated sounds above threshold. They found only slight differences between the responses to slow and to fast sweep-rates in units in the cochlear nucleus.

In a previous investigation (Møller 1969 b), similar sounds were used. The range of the frequency sweep, however, extended over a much wider frequency range than it did in the above-mentioned studies. It was found that the response areas of single neurons in the cochlear nucleus to tones of constant or slowly varying frequency (the static response areas) differed significantly from those obtained with tones whose frequencies varied rapidly (the dynamic response areas). The intensity of the sounds was 20—30 dB above threshold. At low sweep-rates, the distribution of nerve impulses as a function of tone-frequency was in accordance with the unit's response area to tones of constant frequency. At higher sweep-rates, however, more discharges were evoked near the unit's characteristic frequency (CF) than was the case at lower sweep-rates. This was illustrated in the cycle histograms of the responses to sounds with triangulary modulated frequencies. In these histograms a peak occurred at a tone-frequency which was equal to the unit's CF. The height of the peak reached a distinct maximum at a certain sweep-rate. Above this sweep-rate the peak again became wider and lower. The mean firing rate changed only slightly with sweep-rate, and in several units not at all (Møller 1969 b).

This paper is concerned with the coding of sweep-tones in single units in the cochlear nucleus of the rat, and is an extension of the above-mentioned study (Møller 1969 b). The present paper describes in greater detail the relationship between rate of frequency change and the distribution of nerve impulses in a wide range of sound-intensity. To assess whether or not it is the transient character of the response to FM sounds that is responsible for the most localized response to fast FM sweeps, the response pattern to FM sounds is compared with the response to sounds of constant frequency and variable duration.

Methods

White rats weighing from 250—350 g were used in this investigation. The rats were anesthetized by intraperitoneal injection of urethane (1.5 g/kg b.w.). Temperature was maintained near 37° C in the normal way. The trachea was cannulated and a hole was made in the

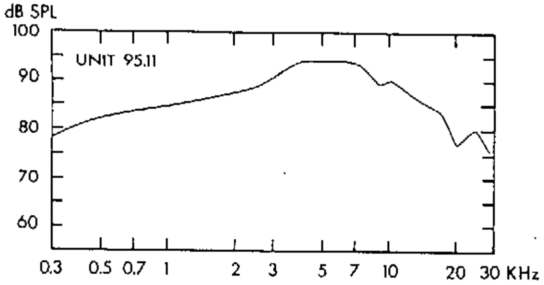

Fig. 1 A. Frequency response of the sound system. Sound-pressure level (in dB re 0.0002 μb), measured close to the eardrum of a rat, is shown as a function of tone-frequency. The graph shows the sound-pressure for a 1 volt RMS input to the earphone in a typical experiment.

occipital part of the skull. The outer ear was removed and the head was mounted in a head-holder (described earlier, Møller 1969 a). Part of the cerebellum was sucked away to make the cochlear nucleus visible, and the animal was then placed in a sound-proof box. Recordings were made using glass micropipettes of a tip diameter of 1—5 μm and filled with 3.0 M KCl. The electrode was positioned by visual control through a Zeiss Epitcknoskop. The electrode was advanced in 2 μm steps with a Stålex micromanipulator controlled from outside the sound-insulated box. The potentials led off from the microelectrode were amplified and recorded on magnetic tape. During the experiments, the spike pattern was analyzed by an Intertechnique DIDAC 800 physioscope set to produce cycle histograms by triggering it at a certain phase of the modulation wave. This served the purpose of guiding the experimenter in choosing suitable stimulus parameters. Afterwards, the final analysis was made from the tape-recorded spike train, using the same analyzer (see Møller 1969 b). The sound source consisted of a 1 inch condenser microphone (B & K type 4131) connected to the ear via the hollow ear bars of the head-holder. The sound pressure near the ear drum was measured with a probe microphone (B & K 4134). The frequency characteristic of the complete sound-generating system is shown in Fig. 1 A. The frequency-modulated tones were generated by a Wavetek function generator (type 112) which was frequency-modulated with another Wavetek generator (type 110). The frequency-modulated tones used in this investigation were similar to those used in a previous investigation (Møller 1969 b), but in the majority of the experiments reported on in the present investigation, trapezoidal modulation was used instead of triangular modulation.

Triangular frequency modulation implies that the tone frequency changes continuously during the entire modulation cycle, while the frequency of a trapezoidally modulated tone changes

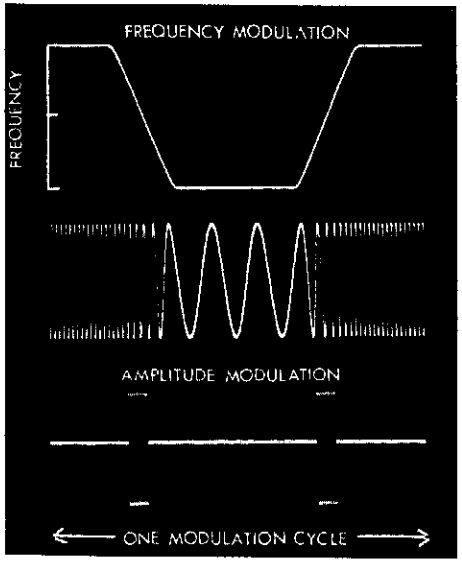

Fig. 1 B. The wave-form of the trapezoidally frequency-modulated sound (above) and the amplitude-modulated sound. For both types of modulation, one complete cycle of the modulation is shown.

only during a certain fraction of the modulation cycle but otherwise is steady. When using triangular modulation of constant extent of frequency deviation, the repetition rate and the rate of changes in tone-frequency are linked together. Trapezoidal modulation, however, makes it possible to vary the rate of tone-frequency change independently of the rate of the modulation.

The tones used in the experiments were usually frequency-modulated linearly in the range of 1 : 5, *e.g.* 1 kHz to 5 kHz, and occasionally 1 : 10 symmetrically around the unit's characteristic frequency. The rate of frequency-change was varied by varying the repetition rate of the modulation (usually in the range from 0.1 to 200 Hz). This type of frequency-modulated sound produces a mean excitation within a certain frequency band, independent of the sweep-rate. When the sweep-frequency is doubled, for example, the tone passes the unit's response area twice as fast, but its duration is only half as long. For trapezoidal modulation, various wave shapes were used in order to alter the fraction of the modulation cycle where the tone-frequency varied.

Sounds of variable duration and constant frequency (AM sounds) were produced by gating the Wavetek-type 112 generator with triangular waves from the Wavetek-type 110 generator. The duty cycle (ratio between tone and silence) could be varied by adjusting the trigger level-control on the Wavetek 112. Usually, a duty cycle of 1 : 10 was used. The frequency- and amplitude-modulated signals are illustrated in Fig. 1 B. In additional investigations, continuous tones of constant frequency, generated with a Hewlett-Packard tone generator, were superimposed on the FM tones. The sound system had two channels with independent attenuators.

The DIDAC 800 was modified in such a way that its address register could be reset by the trigger pulse immediately before it initiated the sweep. This made it easier to make cycle histograms, since each trigger-pulse automatically reset the sweep to its initial position before initiating a new sweep. This left the experimenter free to use a fraction of the channels of the analyzer in order to obtain optimal time-resolution in the analysis.

Integrated histograms were also produced. From these the total number of discharges, as well as the number of discharges contained in each peak of the histogram, were determined.

Results

The results of the present study are based on analysis of spike data from 55 units in 15 animals. Only units from which satisfactory recordings were made for periods of time longer than 30 min were included. Recordings from many of the units were made over periods of 2 hrs or longer.

When the frequency of a tone varies slowly, an auditory unit's discharge frequency varies as a function of tone-frequency in a manner similar to the response area of the unit measured with steady tones. The response evoked by a tone whose frequency was equal to that of the unit's CF could be suppressed in most units by a second tone of a slightly higher frequency. In some units, a tone whose frequency was lower than the unit's CF had a similar, but usually less pronounced effect. In many of the units which had spontaneous activity, a similar depression of the spontaneous activity was seen for tones in a limited range above the unit's CF. This depression has previously been termed inhibition, but the results of recent investigations (see *e.g.* Hind, 1970) suggest that it may be a form of modulation rather than a neural inhibition, in the sense in which it is usually defined.

Fig. 2 shows typical responses of a unit in the cochlear nucleus to trapezoidally frequency-modulated tones. The figure shows histograms of the response to one min of stimulation at two different sweep-rates, a slow rate (0.1 sweep/sec) and a fast sweep-rate (6.4 sweeps/sec) which latter is near that of maximal sharpening. The corresponding rates of change in tone frequency are 7.3 and 470 kHz/sec respectively. It can be seen that the peaks in the histograms are much higher at a

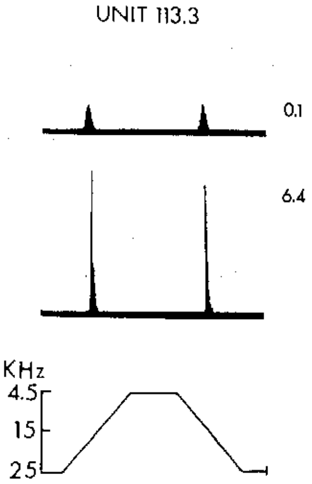

Fig. 2. Cycle histograms of the responses to trapezoidally frequency modulated tones with a rate of 0.1 and 6.4 sweeps/sec, corresponding to a rate of change in tone-frequency of 7.3 and 470 kHz/sec, respectively. In the lower part of the figure, the shape of the frequency-modulation is illustrated.

sweep-rate of 6.4 (lower histogram) than at 0.1 sweeps/sec (upper histogram). In addition, the peaks in the lower histogram are much narrower than those in the upper. The unit's CF was 15.0 kHz. The intensity of the tone at the CF was 50 dB SPL or 15 dB above the threshold of the unit. The tone-frequency of the stimulation varied symmetrically around the unit's CF.

Fig. 3 shows the variation in the height of the peaks in the histograms of the responses of the unit shown in Fig. 2 to trapezoidally frequency modulated tones in a large range of sweep-rates. The tone-frequency varied from 4.5 kHz to 25 kHz. The change in tone-frequency occupied 60 % of the modulation cycle. Fig. 3 A, B and C represent the responses for sound intensities of 25, 15 and 5 dB above threshold at CF respectively. The responses to rising tone-frequency are represented by solid lines, and those to falling tone-frequency by dashed lines. It can be seen that the peaks in the histograms of the responses to FM tones increase in height when the sweep-rate is successively increased from low sweep-rate up to a certain optimal sweep-rate. Above this optimal rate, on the other hand, the height of the peaks in the histograms decreases rapidly. The figure also shows that, for higher sound intensities, the maximum peak height is reached at a higher sweep frequency. At a sound level of 25 dB above the unit's threshold the height of the peaks in the histograms reaches a maximum at a sweep frequency of about 12 Hz, which corresponds to a rate of change in tone-frequency of about 0.9 MHz/sec. At lower intensities, the maximum in the histograms occurs at a somewhat lower sweep-rate, but the shape of the curves is almost independent of sound intensity in the investigated range (A, B and C in Fig. 3). It can also be seen from these curves that the direction of the sweep has little influence on the response, except at very high sweep-rates.

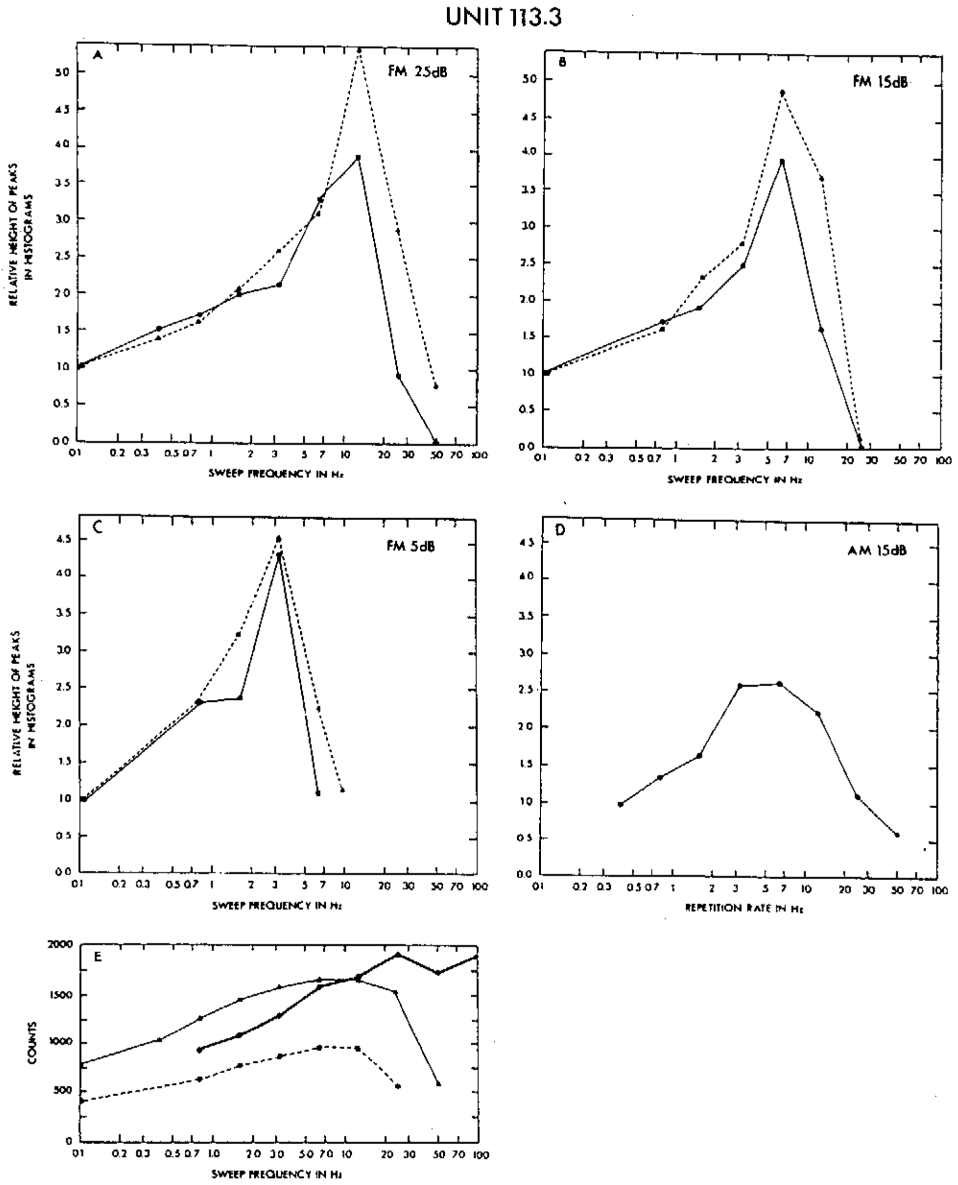

Fig. 3. Responses of a unit whose CF was 15.0 kHz. The unit showed no spontaneous activity. *A—C:* Relative height of the peaks in the cycle histograms of the response to trapezoidally frequency-modulated tones, shown as a function of sweep-rate in Hz. The tone frequency changed during 60 % of the modulation cycle. The graphs were obtained at three different sound-intensities, as indicated by legend numbers (in dB re threshold at CF). Continuous lines represent rising frequency sweep, and dashed lines falling frequency sweep.

D: Relative height of the peaks in the cycle histograms of the response to repetitive tone-bursts. The ratio between sound and silence was 1:10 throughout the range of repetition rates shown in the graph. The sound-intensity of each burst was 15 dB above the unit's threshold at CF.

The total number of spikes evoked during a one-minute recording period is shown in Fig. 3 E as a function of sweep frequency. The thin continuous line represents the response at 25 dB and the dashed line the response at 15 dB above threshold. Both curves show a broad maximum, located in the range of the same sweep frequency as that of the maximum in the height of the peaks in the histograms, but this maximum is much less pronounced.

The height of the peaks in the histograms of the responses to short tone bursts (AM sounds) is shown in Fig. 3 D as a function of repetition rate. The tone-frequency of the bursts was equal to the unit's CF, and the intensity was 15 dB above its threshold. The curve has a maximum around a repetition rate of 3—7 Hz, but in this case the maximum is much broader, and not as high as for the curves showing the response to FM sounds (Fig. 3 A to C). The ratio between tone and silence was kept constant at 1: 10 in the range of repetition rates used. The duration of the tone thus varies in accordance with the repetition rate.

The unit whose responses are shown in Fig. 2 and 3 had a tuning curve of the normal type with a very steep high frequency skirt (*cf.* Møller, 1969 a), and it had no spontaneous activity. When a 15 kHz continuous tone (the unit's CF) was sounded together with a tone of slowly varying frequency, the histograms of the unit's response showed a typical area of suppression above the unit's CF.

The response of another unit which behaved in a slightly different way is shown in Fig. 4. This unit had a CF of 22.0 kHz and a moderate degree of spontaneous activity. The response of this unit to trapezoidally frequency-modulated tones was studied in the intensity range from 25 to 65 dB above its threshold at CF (45 to 85 dB SPL at 22 kHz). The tone varied from 4.5 kHz to 30 kHz, and the variation occupied 15 % of the modulation cycle. The relative height of the peaks in the cycle histograms of the response to FM sounds is shown in Fig. 4 A, B and E. The corresponding total spike counts during one minute of stimulation are shown with heavy lines in Fig. 4 C, D and G. In these graphs the number of nerve impulses contained in each of the two peaks in the histograms is also shown, the thin continuous lines representing the responses for rising tone-frequency and the dashed lines those for falling tone-frequency.

In this unit there is a marked difference between the response to rising and falling tone-frequency, especially at the highest intensity used. In particular, the maximum height of the peaks in the cycle histograms in Fig. 4 A, B and E reveals a greater dependency on the intensity, and this is much more pronounced for rising frequency sweep than for falling sweep. At the lowest intensity used (25 dB above threshold), the maximum in the height of the peaks in the histograms occurs around 12 Hz (Fig. 4 E), corresponding to a rate of change in tone-frequency of 4 MHz/sec. At this sound intensity, increasing and decreasing frequency sweeps yield similar

---

E: Total number of spike counts during 1 min of stimulation. The thin line represent FM sounds, continuous line of 25 dB, and dashed line of 15 dB above threshold at the unit's CF. Heavy line represents the response to AM sounds with a sound level of 15 dB above the unit's threshold.

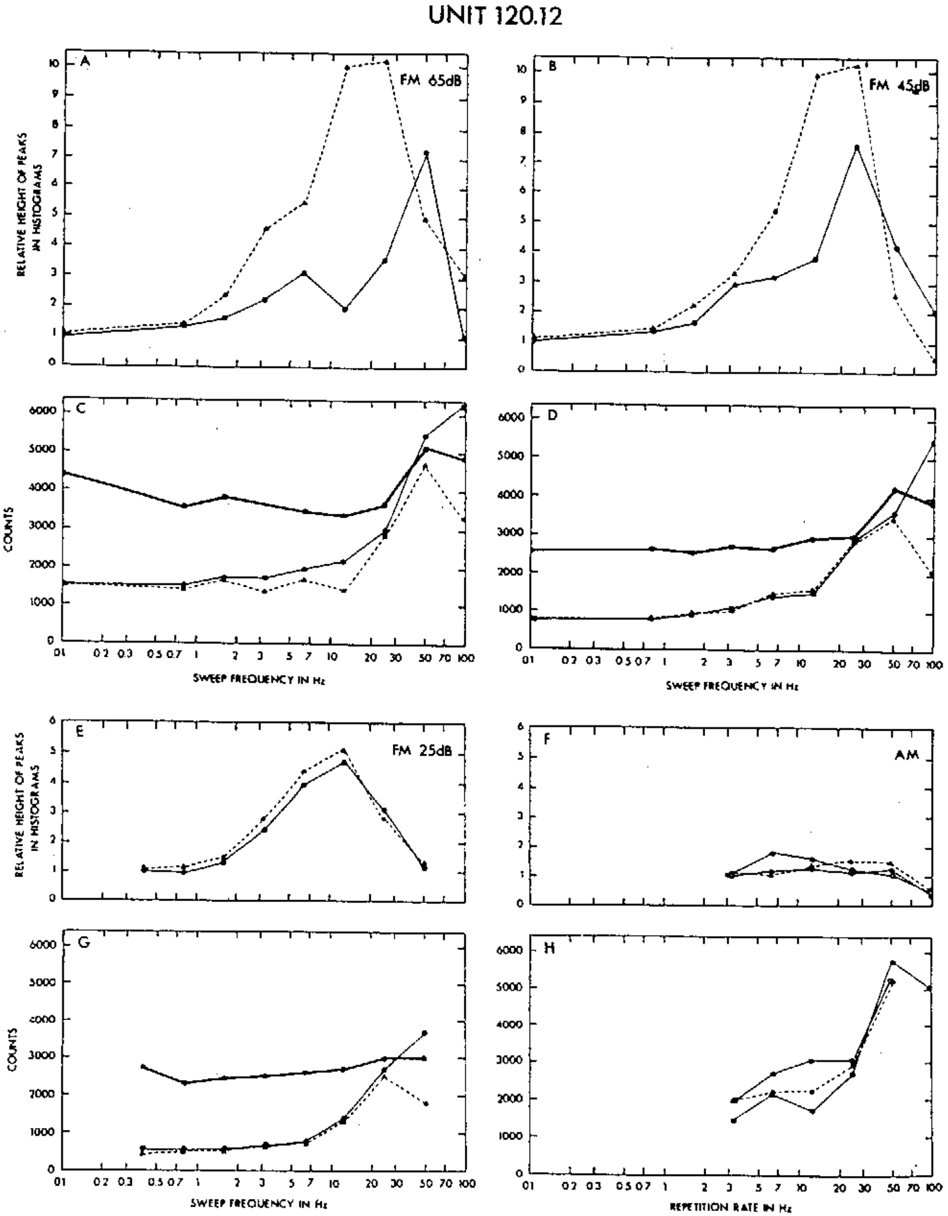

Fig. 4. Responses of a unit whose CF was 22.0 kHz. The unit showed a moderate degree of spontaneous activity.

A, B and E. Relative height of the peaks in the cycle histograms of the response to trapezoidally frequency-modulated tones, shown as a function of sweep-rate in Hz. The frequency varied during 15 % of the modulation cycle. The sound level was 65, 45 and 25 dB, respectively, above the threshold of the unit at CF. Solid lines represent rising frequency sweeps, and dashed lines falling frequency sweeps.

C, D and G. The corresponding total number of spikes during 1 min of stimulation (heavy lines) and the number of spikes contained in each peak for rising (thin continuous lines) responses. At an intensity of 45 dB above threshold, the histogram peaks corresponding to decreasing frequency sweep have a broad maximum between 25 and 50 Hz. The maximum for the increasing tone-frequency sweeps has moved up to 20 Hz and is smaller than for the decreasing tone-frequency sweeps (Fig. 4 B). When the intensity is further increased to 65 dB above threshold, the maximum for increasing frequency sweep has moved further up in frequency, to about 50 Hz, while the location of the broad maximum of the relative height of the peaks in the histograms of the responses to decreasing tone-frequency sweep has remained almost unchanged.

The total number of discharges varies only slightly as a function of sweep frequency (heavy line in Fig. 4 C, D and G). The number of discharges within each peak in the histograms shows, however, a marked increase in the sweep-range from 15 to 100 Hz (Fig. 4 C, D and G, continuous and dashed thin line). This implies that a large fraction, or almost all nerve impulses are located within the two peaks in the histograms at high sweep frequency. From Fig. 4 A, B and E, however, it follows that the sweep frequency where the total number of nerve impulses reaches its maximum is significantly higher than the frequency where the heights of the peaks in the histograms are maximum.

In Fig. 4 F, the relative height of the histograms of the response to AM sounds is shown. (The AM sounds were of the same type as used in the experiment depicted in Fig. 3). The curves represent the responses to different sound-intensities of the AM-sounds: Open circles represent 65 dB, triangles 45 dB, and filled circles 25 dB above the unit's threshold.

From Fig. 4 F, it can be seen that the unit's response pattern to repetitive tone-bursts of constant frequency is almost independent of the repetition rate, and thus of the duration of the tone-bursts. Moreover, the response pattern changes remarkably little when the intensity is changed from 25 to 65 dB above threshold. The total number of nerve impulses contained in the peaks in the cycle histograms during 1 min of stimulation can be seen in Fig. 4 H. The curves are similar to those in Fig. 4 C, D and G, representing FM sweep. During one cycle of FM modulation, the tone passes the unit's excitatory area twice. In the case of AM sounds, the unit is excited only once for every tone burst. In order to facilitate the comparison of the response pattern to these two types of modulation, the repetition rate in the case of AM sounds refers to pairs of sound-bursts (*cf.* Fig. 1 B).

In order to ensure that the changes found in the response pattern with increasing sweep-rate were not influenced by the concomitant increase in the repetition rate of the modulation, the slope of the trapezoidal modulation was varied and cor-

---

and falling (thin dashed lines) tone-sweep. The vertical scale refers to the total spike counts. For the spike counts in each peak, multiplied by a factor of two in order to facilitate the comparison of the total spike counts and the number of spikes contained in each peak.

F. The relative height of the peaks in the histograms of the response to AM sounds as a function of repetition rate. The different symbols indicate intensity of the tone-bursts, open circles 65 dB, triangles 45 dB and closed circles 25 dB above threshold at the unit's CF.

H. The corresponding spike counts contained in the peaks in the histograms of the response to AM sounds. The symbols correspond to those in graph F.