Handbook of Sensory Physiology

Volume V/2

Auditory System

Physiology (CNS) · Behavioral Studies Psychoacoustics

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With 209 Figures

Springer-Verlag Berlin Heidelberg NewYork 1975

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ISBN 3-540-07000-1 Springer-Verlag, Berlin · Heidelberg · New York
ISBN 0-387-07000-1 Springer-Verlag, New York · Heidelberg · Berlin

Library of Congress Cataloging in Publication Data (Revised)
Keidel, Wolf Dieter. Auditory system. (Handbook of sensory physiology; v. 5). Includes bibliographies and index. CONTENTS: 1. Anatomy, physiology (ear). 2. Physiology (CNS), behavioral studies, psychoacoustics. 1. Hearing. 2. Ear. I. Neff, William D., joint author. II. Ades, Harlow Whitting, 1911— . III. Title. IV. Series. [DNLM: 1. Neurophysiology. 2. Sensation. WL700 H236] QP351. H34 vol. 5 [QP461] 591.1'82'08s [596'.01'825] 74—415

Printed in Germany.
Typesetting, printing and binding: Brühlsche Universitätsdruckerei Gießen

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Chapter 1

Cochlear Nerve and Cochlear Nucleus

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With 49 Figures

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Abbreviations

AP : Gross cochlear action potential.
CDT : Cubic difference tone ($2f_1 - f_2$).
CF : Characteristic ("best") frequency.
cn : Cochlear nerve (acoustic, auditory, nerve).
CN : Cochlear nucleus.
DCN, VCN, AVN, PVN : Dorsal, ventral, antero- and postero-ventral divisions of CN.
FRC : Frequency response curve (plot of firing rate versus frequency at constant SPL).
FTC : Frequency threshold curve ("tuning curve").
IHC : Inner hair cells of the organ of Corti.
OCB : Olivocochlear bundle.
OHC : Outer hair cells of the organ of Corti.
PST : Post or peri-stimulus time (applied to histogram).
$Q_{10\,dB}$: CF/bandwidth of FTC at 10 dB above threshold.
SON : Superior olivary nucleus
SPL : Sound pressure level relative to 2×10^{-4} dyne/cm^2 (2×10^{-5} N/m^2).

I. Introduction

The first recordings of single neurone activity in the auditory system were made from the cochlear nucleus of the cat, by Galambos and Davis (1943). In these experiments the authors were attempting to record from fibres in the cochlear nerve; subsequently, however, they concluded that the recordings had been from aberrant cells of the cochlear nucleus lying central to the glial margin of the VIII nerve (Galambos and Davis, 1948). The first successful recordings from fibres of the cochlear nerve were made by Tasaki (1954) in the guinea pig. These classical but necessarily limited results were greatly extended by Rose, Galambos, and Hughes (1959) in the cat cochlear nucleus and by Katsuki and co-workers (Katsuki *et al.*, 1958, 1961, 1962) in the cat and monkey cochlear nerve. Perhaps the most significant developments have been the introduction of techniques for precise control of the acoustic stimulus and the quantitative analysis of neuronal response patterns, notably by the laboratories of Kiang (*e.g.* Gerstein and Kiang, 1960; Kiang *et al.*, 1962b, 1965a, 1967) and Rose (*e.g.* Rose *et al.*, 1967; Hind *et al.*, 1967). These developments have made possible a large number of quantitative investigations of the behaviour of representative numbers of neurons at these levels of the peripheral auditory system under a wide variety of stimulus conditions.

Most of the findings discussed herein have been obtained on anaesthetized cats. Where comparative data are available, substantially similar results have been obtained in other mammalian species (*e.g.* guinea pig, monkey, rat). Certain significant differences have been noted in lizards, frogs and fish as would be expected from the different morphologies of their organs of hearing (*e.g.* see Flock, 1971; Frishkopf *et al.*, 1968; Furukawa and Ishii, 1967), and these will be discussed in the relevant sections. The direct effects of anaesthesia do not appear to be significant at the level of the cochlear nerve, as judged by a comparison with limited data obtained in the unanaesthetized cat (Rupert *et al.*, 1963) and in one fibre studied for a long period under normal and anaesthetized conditions (Simmons and Linehan, 1968). This is not the case at the level of the cochlear nucleus, where barbiturate anaesthesia can have a profound effect (Evans and Nelson, 1973a). Unfortunately, most cochlear nucleus studies have been carried out under pentobarbitone anaesthesia. Studies under anaesthesia do offer the advantage of being relatively free from the influences of the middle ear muscles and the efferent auditory system.

As a generalization, experimenters at this level of the auditory system now calibrate their acoustic system at the tympanic membrane, and except where noted, absolute stimulus levels will be given here in dB SPL at the tympanic membrane[1]. The experimental approach to the cochlear nerve and nucleus follows essentially that of Katsuki *et al.* (1958), that is, removal or retraction of the cerebellum in order that a microelectrode may be inserted into the target under direct vision. With precautions to ensure freedom from movements of the brainstem, recordings can be routinely made from individual cochlear fibres for several tens of minutes, and from cochlear nucleus cells for several hours. For the criteria and techniques used to distinguish between fibres and cells, and for more detailed technical information on the methods involved, the reader is referred to Rose *et al.* (1959), Kiang *et al.* (1965a), and Evans (1972b).

[1] In some laboratories (*e.g.* Kiang *et al.*, 1967, 1970), it has been the practice to express data in terms of p—p stapes displacement, inferred from averaged measurements of stapes motion on other animals of the same species.

II. Cochlear Nerve

A. Tonotopic Organization

Individual fibres of the cochlear nerve innervate relatively restricted areas of the organ of Corti (*e.g.* Lorente de Nó, 1933a; Spoendlin, 1971, 1972). In spite of a certain degree of twisting of the cochlear nerve (Lorente de Nó, 1933a; Sando, 1965), the distribution of fibres along the cochlea is projected in a tonotopic fashion to the cochlear nucleus (see Section III.B.1). It is not surprising, therefore, that penetrations of the cochlear nerve encounter fibres responsive to a more or less restricted range of tone frequencies (see Section II.D.1), and arranged systematically according to their optimal, or characteristic, frequencies (CFs). In the cat, the fibres are arranged such that microelectrode penetrations in the posterodorsal to anteroventral direction generally encounter fibres with high CFs first, then low CFs, and subsequently with progressively higher CFs. Thus, fibres with higher CFs are located superficially in the nerve, and those with lower CFs more centrally (Kiang *et al.*, 1965a; Evans and Rosenberg, unpublished observations). In the guinea pig, on the other hand, the twisting of the nerve appears to be less complete, so that penetrations in the same direction as in the cat encounter fibres with CFs progressively decreasing from high to low values (Evans, 1972b). A progression of frequency sensitivities in the reverse direction to that in the guinea pig is found in the monkey (Katsuki *et al.*, 1962).

B. Spontaneous Activity

All studies of single fibres in the cochlear nerve have reported activity in the absence of intentional auditory stimulation. While for any given fibre the mean rate remains relatively steady for long periods of time, between fibres it varies from less than a few spikes/sec to 100–120 spikes/sec (*e.g.* Nomoto *et al.*, 1964 in the Macaque; Kiang *et al.*, 1965a, in the cat; Rose *et al.*, 1971, in the squirrel monkey; Evans, 1972b, in the guinea pig). This range does not appear to rrelate to any degree of injury to the fibres themselves, in view of (a) the stability of the rate over long periods, and (b) the finding of fibres with high and low rates apparently adjacent in an electrode penetration. On the other hand, there is some relation between the spontaneous discharge rate and the threshold sensitivity of a fibre. In normal animals, there is a tendency for the most sensitive units to have rates of spontaneous discharge in excess of 15/sec (Kiang *et al.*, 1965a, 1970; Rose *et al.*,

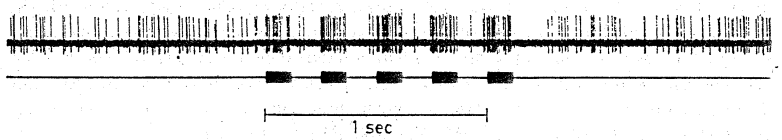

Fig. 1. Spontaneous and tone evoked activity of single cochlear nerve fibre. Cat. Tone at characteristic frequency, 9.5 kHz, 15 dB above threshold, indicated on lower trace. Positivity upward. Note: increase in spike discharge rate corresponding to duration of each tone burst; reduction in discharge rate at termination of stimuli

1971). In cats poisoned with kanamycin (Kiang *et al.*, 1970) and in guinea pigs in poor physiological condition (Evans, 1972b), the affected fibres with abnormally high threshold have low or no spontaneous discharge. These abnormal fibres apart, the distribution of spontaneous rates tends to be bimodal: about a quarter of the fibres have rates below 10/sec; the majority of the remainder discharges at rates in excess of 30/sec. Forty percent of all fibres in cat and squirrel monkey discharge at rates above 50/sec (Kiang *et al.*, 1965a; Rose *et al.*, 1971), and in the guinea pig, above 80/sec (Evans, 1972b).

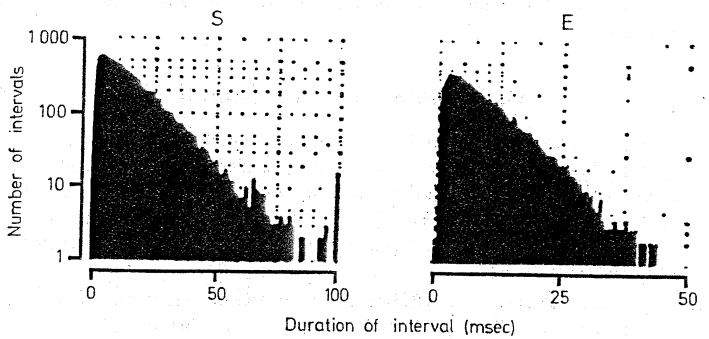

Fig. 2. Interspike interval histograms of spontaneous (S) and tone evoked (E) activity for a cat cochlear fibre. Tone at CF of fibre; 7.84 kHz. Histograms represent data collected from 5 min and 2 min of spontaneous and evoked activity, respectively. Note different time scales. (From Kiang, 1968)

The spontaneous discharge pattern of fibres in the cochlear division of the VIII nerve, in contrast to the vestibular division, is characteristically irregular (Kiang *et al.*, 1965a; Walsh *et al.*, 1972; see Fig. 1). Figure 2 shows the distribution of interspike intervals obtained from an analysis of several minutes of spontaneous discharge in a single cochlear fibre. The semi-logarithmic plot of the distribution has a nearly linear "decay", which may therefore be considered to be approximately exponential. This is characteristic of a Poisson process (Kiang *et al.*, 1965a). Furthermore, computations of joint interval statistics which indicate that the intervals between spikes are independent, are also compatible with this conclusion (Kiang *et al.*, 1965a). However, the observed interval distributions have fewer short intervals than would be expected on the basis of a Poisson process. This can be attributed to the absolute and relative refractory periods following each discharge, a conclusion supported by the observation that the modal values of the interspike interval histograms nearly all fall within the range: 4–7 msec irrespective of the rate of spontaneous activity (Kiang *et al.*, 1965a). A detailed analysis of the conditional probability of spontaneous discharge by Gray (1967) suggests that a cochlear nerve fibre has not *completely* recovered from the effects of the last discharge until after an interval of about 20 msec.

The mechanism underlying the spontaneous discharge is unknown. Apart from the possible case of the most sensitive units (see Section V.A; Wiederhold and Kiang, 1970), the influence of background acoustic noise can in the main be excluded.

Walsh *et al.* (1972) have suggested that the characteristic irregularity of the spontaneous discharge might relate to the stochastic excitation associated with chemical synaptic transmission. Most "blackbox" models of cochlear nerve activity incorporate a stochastic or probabilistic element in the neural spike generation process in order to account for the presence of spontaneous activity and the stochastic nature of the discharge pattern in response to steady tonal stimuli (see Section VI.A.3).

C. Response to Click Stimuli

In theory, a single click stimulus has uniform distribution of energy over the frequency spectrum, with energy minima at frequencies corresponding to multiples of the reciprocal of the pulse duration. Repetitive clicks generate concentrations of energy into spectral lines spaced at the repetition rate. At the rates of click presentation generally used in physiological experiments (10/sec or less), the spectrum can be treated as uniform.

In practice, however, clicks are generated by feeding an electrical pulse to an acoustical transducer. The spectral distribution is distorted by the frequency response of the system, and the time pattern of the stimulus is distorted likewise by delayed reflections and the "ringing" characteristics of the acoustic system. The introduction of carefully damped couplers and condenser microphones as transducers (*e.g.* Kiang *et al.*, 1965a; Molnar *et al.*, 1968) has minimised this problem.

A click stimulus evokes one or a few spikes discharges in a cochlear fibre (Fig. 3A). Although the time pattern of discharge differs from response to response even for stimuli well above threshold, on average the discharges occur at preferred times after the click, as is shown in the post-stimulus time (PST) histogram of Fig. 3B as a function of the time since the click stimulus. This average pattern of activity is characteristic of fibres with CFs below 3–4 kHz (Fig. 3B–D). For fibres with CF above 4 kHz, the periodic nature of the spike distribution is lost (Fig. 3E, F), apparently on account of the temporal "jitter" associated with the spike generation process (see VI.A.3). Figure 3 also indicates that the time interval between preferred periods is related to the CF of the fibre, and Fig. 4 shows that this relation is systematic: the time interval corresponds to the reciprocal of the CF. Furthermore, the latency of the first peak of the PST histogram is an inverse function of the CF (Fig. 5).

These findings are consistent with a travelling wave disturbance of the basilar membrane that takes time to propagate to the apical (lower frequency) regions of the cochlea and which exhibits a more or less damped oscillation to a click transient, the period of oscillation at a given location corresponding to the latter's optimum frequency (Békésy, 1960; Flanagan, 1962; Robles *et al.*, 1972; Wilson and Johnstone, 1972).

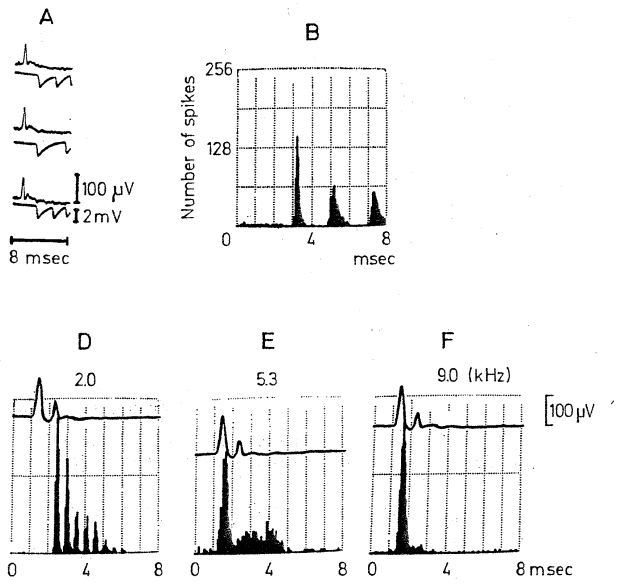

Fig. 3A, B. Response of single cat cochlear fibre to click stimuli. A: Continuous film record of responses to 3 successive clicks. Upper traces, record from electrode at round window showing click evoked AP response. Lower traces, spike discharges of fibre. Negativity upwards. Note temporal patterning of spikes. B: Poststimulus time (PST) histogram showing averaged temporal pattern of activity in response to 600 clicks. CF of fibre 0.54 kHz. C-F: PST Histograms for 4 more cat cochlear fibres of differing CF, in comparison with the AP response recorded from the round window. CFs indicated above plots. Linear ordinate scale: number of spikes: 256, 128, 64 and 128 for C-F, respectively. Note periodic envelope of PST histograms for the fibres with lower CFs (B, C, and D). Data samples, 1 min; clicks presented at same level in each case, at 10/sec. (From Kiang *et al.*, 1965a)

The earliest observed peak in the PST histogram (vd. Fig. 6) is obtained with rarefaction acoustic transients, *i.e.*: from a movement of the cochlear partition toward the scala vestibuli. With condensation transients, the peaks of the PSTHs occur at times which interleave with those for clicks of the opposite polarity (lower halves of each histogram in Fig. 6 compared with upper halves). This is consistent with the conclusion (Kiang *et al.*, 1965a; Weiss, 1966; Brugge *et al.*, 1969; Goblick and Pfeiffer, 1969; Duifhuis, 1970) that excitation corresponds with movements of the basilar membrane (and therefore associated hair cell structures) in one direction only. In fibres with a sufficient rate of spontaneous activity, the probability of discharge is reduced during periods corresponding to deflections in the non-exciting direction. Refractory mechanisms are not entirely responsible for this: the reduction of discharge can appear as the earliest sign of oscillatory activity (see Fig. 6: histograms at +5 and 30 dB). In all fibres, the combination of

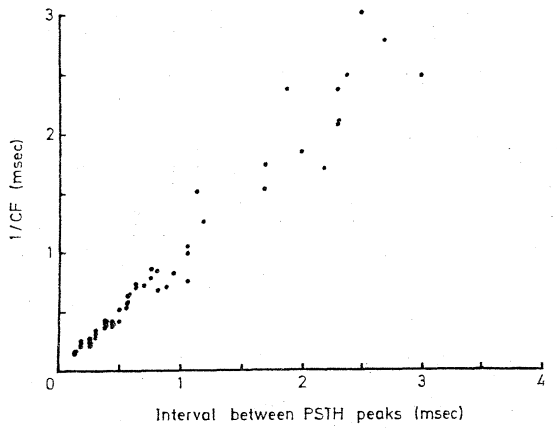

Fig. 4. Plot of reciprocal of CF against the interval between the PST histogram peaks in response to click stimuli, for 56 cat cochlear fibres (see text). (From Kiang *et al.*, 1965a)

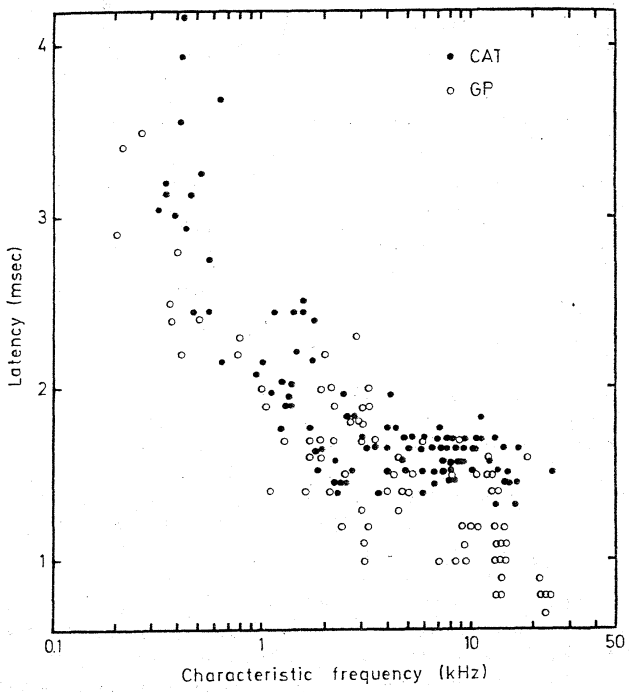

Fig. 5 (Legend see p. 9)

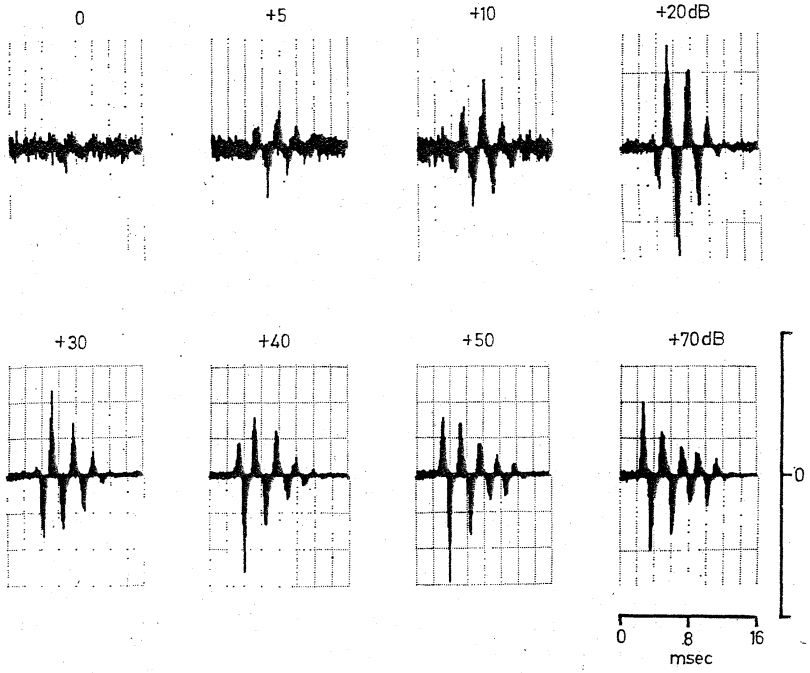

Fig. 6. Compound PST histograms of responses to click stimuli as a function of click level. Cat cochlear nerve. CF of fibre: 0.47 kHz. Click level expressed in dB relative to the "threshold" response level. Figure compiled from histograms of responses to rarefaction clicks and to condensation clicks (upper and lower halves of each compound histogram, respectively). Clicks: 100 μsec duration, 10/sec. Ordinate scales: linear number of spikes: 64 for 0—10 dB plots; 128 for 20 dB; 256 for 30—70 dB. (Data from Kiang *et al.*, 1965a)

PSTHs to transients of opposite polarity to form the compound PST histograms shown in Fig. 6, (Goblick and Pfeiffer, 1969) demonstrates most clearly the relationship between neural discharge pattern and presumed mechanical events.

Figure 6 also demonstrates how the pattern of discharge to a click is dependent upon the level of the stimulus. The positions of the peaks shift relatively little over an intensity range of 60 dB (Kiang *et al.*, 1965a; Goblick and Pfeiffer, 1969). On the other hand, at higher click levels, their relative heights change, an earlier peak with a latency of 2—4 msec appears, and the mode of the histogram occurs earlier.

Fig. 5. Latency of cochlear nerve response to click stimuli for fibres in the cat (filled circles, from Kiang *et al.*, 1965a) and the guinea pig (open circles, from Evans, 1972b) as a function of their CF. Rarefaction clicks of 100 μsec and 50 μsec duration, respectively, presented at 10/sec, at levels from 20—60 dB and from 20—80 dB, respectively, in electrical terms above minimum tone threshold (within 36 dB of click threshold for the cat data)

The number of spikes discharged in response to a click stimulus is a function of the stimulus level and the rate of click repetition (Kiang *et al.*, 1965a). With level, the average number of spikes discharged increases monotonically towards between one to a few spikes per click (fibres with low CF approaching the higher value) at low rates of repetition (10/sec). At higher rates, the number of spikes evoked per click decreases to an average value of about 0.1 at 1000 clicks/sec. The mean overall discharge rate, on the other hand, usually increases monotonically. The maximum *maintained* discharge rate obtained under optimum conditions rarely exceeds 100 spikes/sec for clicks (200/sec for tones) (Kiang *et al.*, 1965a; Moxon, 1968). Direct electrical pulse stimulation of the cochlea (Moxon, 1968) can evoke maintained discharge rates in excess of 500/sec. The limit on *maintained* discharge rate, therefore, appears to be set by the cochlear elements peripheral to the site of spike generation.

D. Response to Single Tonal Stimuli

In contrast to the responses of neurones at higher levels of the auditory system, the behaviour of single cochlear fibres is relatively simple as a function of frequency, stimulus level, and time, and the population of fibres is reasonably homogeneous in respect of these properties. The only response observed during continuous single tone stimulation is excitation (as in Fig. 1; cat: Kiang *et al.*, 1965a; squirrel monkey: Rose *et al.*, 1969; guinea pig: Evans, 1972b). The threshold stimulus level evoking this response is a relatively simple function of frequency; the firing rate is related monotonically to the stimulus level (except at very high levels, vd. later); the response adapts little with time; the interspike interval distribution is consistent with a Poisson process (Fig. 2E), superimposed on which, the temporal pattern of the discharges reflects the period of the sinusoidal stimulus at least for stimulus frequencies up to about 4 kHz. In short, the response properties of cochlear fibres to tone (and to click stimuli as observed above) can to a first approximation be predicted on the basis of the CF of the fibre (Kiang *et al.*, 1965a; Kiang, 1968).

Exceptions to these generalizations have been proposed, particularly from earlier studies. Thus, Tasaki, in the guinea pig (1954), and Nomoto *et al.*, in the monkey (1964), obtained data which they considered to indicate that there were two populations of fibres. These fibre populations were distinguished on the basis of responsiveness, threshold, shape of frequency threshold curve (FTC) and the firing rate versus stimulus level function. Later experiments with more adequate control of stimulus parameters have failed to uncover such differences; rather, they have provided the explanations for the earlier discrepant data (*e.g.* Kiang, 1968; Evans, 1972b). These will be discussed in Sections D.1. and 2. The only other contrary reports, as far as the present author is aware, is inhibition of the spontaneous activity of a few cochlear fibres described by Rupert *et al.* (1963) in the unanaesthetized cat and by Katsuki *et al.* (1962) in the monkey. Although Rupert *et al.* concluded that, on latency grounds, their fibres were primary, the illustrated responses have latencies which substantially exceed (by more than 10 msec) those obtained in studies on fibres under anaesthesia, and the possibility exists that these fibres were part of, or were influenced by, the descending, efferent

system. In the case of the latter study, it has been suggested by Kiang *et al.* (1965a) that the "spontaneous" activity was in fact evoked by ambient room noise and that the inhibition observed was an example of the suppression of stimulus-evoked activity discussed in Section II.E.1.a.

Against the above generalization of homogeneity of the mammalian cochlear nerve, recordings from the cochlear nerve of bullfrog and leopard frog (Frishkopf and Goldstein, 1963; Liff and Goldstein, 1970), lizard (Johnstone and Johnstone, 1969) and fish (Enger, 1963; Furukawa and Ishii, 1967) have demonstrated that at least two types of fibre can be clearly distinguished, which originate in anatomically and functionally separate transducer regions. Thus, in the frog and lizard, fibres can be separated into a "simple" population which cannot be inhibited by tonal stimuli and a "complex" population whose response to tonal or vibratory stimuli can be so inhibited. In fish, VIIIth nerve fibres have been sub-divided into two groups on the basis of their rate of adaptation to sound stimuli. Nevertheless, these different populations can also be distinguished on the basis of the CFs of the fibres, and fibres with similar CFs share similar properties.

1. Threshold and Response as a Function of Frequency

Rapid determinations of threshold of cochlear fibres as a function of frequency can be made by a variety of methods: by scanning across the relevant frequency range with continuous tones (Fig. 7), by the classical manner of successively approximating the frequency of a gated tone (with finite rise and fall time to avoid transients) towards the optimal frequency at each intensity until a change in rate of discharge is detected (Fig. 9), or by automatic or semi-automatic methods of "tracing" the threshold as the stimulating tone moves continuously across the responsive region (Kiang *et al.*, 1970; Evans *et al.*, 1970). These methods yield consistent results (*e.g.* Kiang *et al.*, 1965a), although small inexplicable changes in pure tone and noise threshold from minute to minute have been observed in some fibres, in contrast to their "neighbours" (Evans, Rosenberg, and Wilson, unpublished results). The arbitrary choice of a "threshold" criterion (*e.g.* the boundary of the response area in Fig. 7) enables the frequency threshold ("tuning") curve (FTC) to be delineated. The frequency corresponding to the minimum threshold (tip) of the FTC defines the "characteristic frequency" (CF) of the fibre.

Early studies of the minimum thresholds of cochlear fibres led to the conclusions that they were widely distributed (over a range as great as 60 dB) at any frequency (*e.g.* Kiang *et al.*, 1965a) or that they fell into two groups of high and low threshold corresponding to fibres innervating inner and outer hair cells respectively (*e.g.* Katsuki *et al.*, 1962). Subsequently, Kiang (1968) has shown that when sufficient data are collected from a single cat cochlear nerve (*i.e.* are not pooled across ears and animals) the distribution of thresholds becomes restricted to less than 20 dB at any frequency (Fig. 8). Within this limited range, there is some tendency for fibres with the lowest spontaneous discharge rates to have the highest thresholds (Kiang *et al.*, 1970). While there are considerable variations in distribution from animal to animal, the neural thresholds approach the average behavioral threshold for that species, with the exception of the higher frequencies (Fig. 8, interrupted line). These findings have been confirmed in the cat by Evans *et al.* (1970, and to

be published) and in the guinea pig (Evans, 1972b). Kiang and colleagues (Kiang *et al.*, 1967; Kiang, 1968) have pointed out that, unless the FTC is corrected for the frequency response of the sound system, it is possible to confound the low

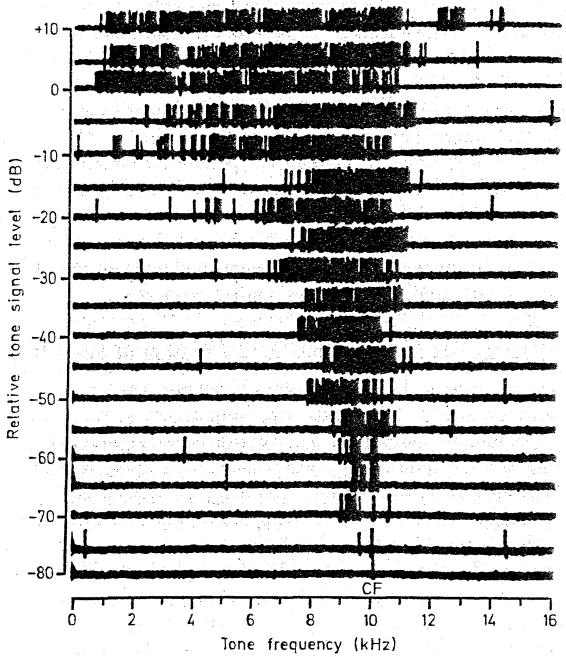

Fig. 7. Frequency sweep method of determination of frequency response area and Frequency Threshold Curve (FTC) of guinea pig cochlear fibre. A continuous tone is swept linearly in frequency, with 5 dB increments of signal level. Alternate sweeps are in the opposite direction. The pattern of spike discharges is built up on a storage oscilloscope. (Spikes are monophasically positive and 0.9 mV in amplitude.) Sweep rate: 14 kHz/sec. (From Evans, 1972b)

frequency high threshold segment of the FTC of a fibre with high CF (see Fig. 9) for a separate low frequency FTC of high threshold. This appears to be a satisfactory explanation for the high threshold population of fibres reported by Katsuki *et al.* (1962) in view of their being restricted to low CFs (below 6 kHz). In some guinea pigs, Evans (1972b) found a number of fibres which had abnormally high thresholds (above 70 dB SPL). Almost all of these, however, were derived from cochleas with evidence of pathological changes due to experimental interference or to circulatory insufficiency (from abnormally low systemic blood pressure or occlusion of the internal auditory artery) and were associated with a pathologically high AP threshold to clicks. The remainder had CFs above 12 kHz and were found in otherwise normal cochleas alongside low threshold fibres of similar

CFs. Like the other high threshold fibres, they had abnormally broad FTCs (see later, p. 18), and may relate (see Section VI.B) to the finding of a sporadic loss of outer hair cells in the basal turn of the cochleas of healthy guinea pigs (Wersäll, personal communication).

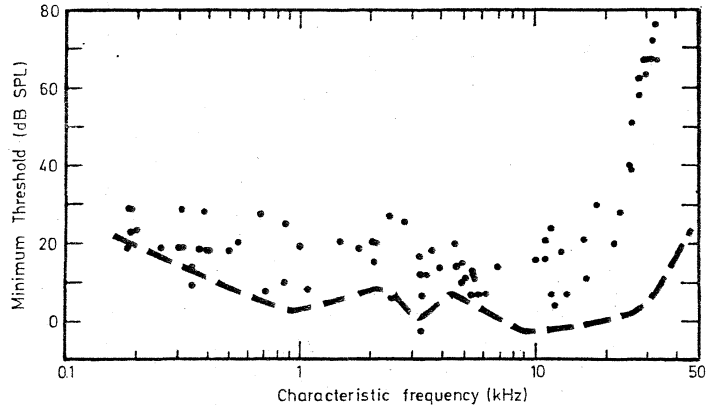

Fig. 8. Minimum pure tone thresholds of cochlear fibres from a single cat versus their CF (from Kiang, 1968), compared with a curve indicating the average behavioural threshold (interrupted line). Thresholds in dB SPL at the tympanic membrane. Open bulla. (Behavioural thresholds from the free-field measurements of Neff and Hind, 1955, and corrected for the outer ear response and to open bulla conditions using the data of Wiener *et al.*, 1965, and Guinan and Peake, 1967, respectively)

Figure 9 shows the similarities between the FTCs of single cochlear fibres of cat (Kiang *et al.*, 1967), guinea pig (Evans, 1972b) and squirrel monkey (derived from the data of Rose *et al.*, 1971). The thresholds in each case are given in SPL measured at the tympanic membrane. Plotted in this way on a logarithmic frequency scale, the shapes of the FTCs are systematically related to their CF. The curves become increasingly narrow and asymmetrical with higher CF, particularly for fibres with CFs above 2 kHz[2]. In these cases, the high frequency cut-off is steeper than the low-frequency cut-off and becomes steeper with increasing tone intensity, whereas the low frequency cut-off suddenly decreases to less than 10 dB/octave beyond about 30—60 dB above the minimum threshold. Fibres with CFs below 2 kHz have more nearly symmetrical FTCs and frequently exhibit an inflexion in the high frequency cut-off 20—30 dB above threshold. Discrete plotting of the FTCs as in Fig. 9 renders the tips artificially sharp; more detailed plots show that the tips are in fact rounded (Kiang *et al.*, 1970; Evans *et al.*, 1970). The 3 dB bandwidths of the FTCs are approximately half the 10 dB bandwidths.

[2] These systematic differences in the shape with CF largely disappear if the data are plotted on a square-root frequency scale (Ross, personal communication). Likewise, the 10 dB bandwidth values (Fig. 13C), when computed on a square root frequency basis, cluster about the same value (0.4) irrespective of CF (Evans, 1972b).

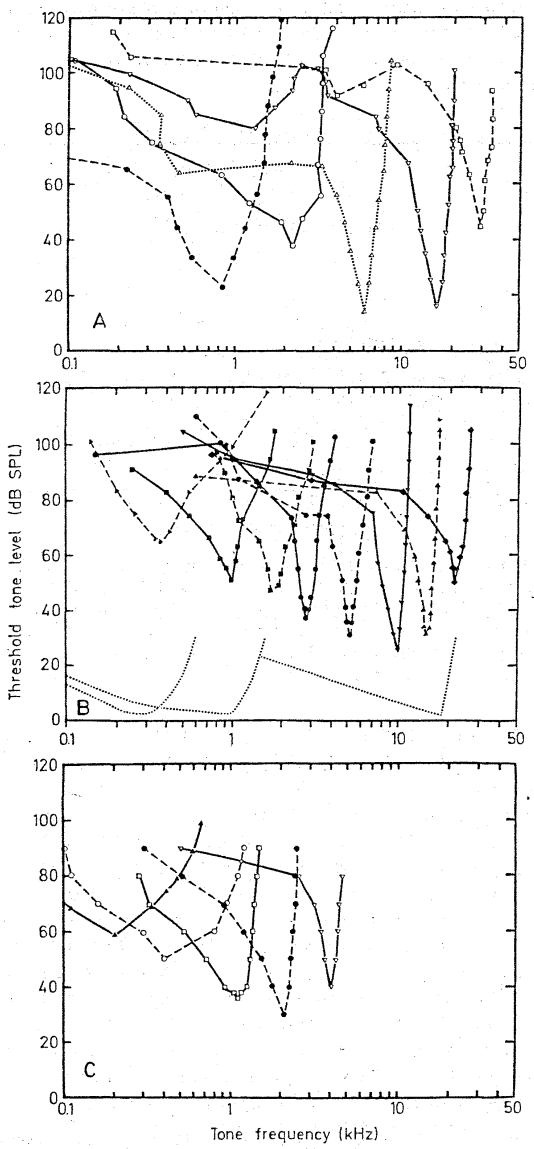

Fig. 9A—C (Legend see p. 15)

The values of the slopes of the low and high frequency cut-offs measured over the portion of the FTCs between 5 and 25 dB above threshold are shown in Fig. 10A and B, respectively. In both cases, the slope values increase initially at least with CF and reach maximum values of between 100—250 dB/octave and between 100—600 dB/octave, respectively, at CFs of about 7—10 kHz. The slopes for the high frequency cut-offs represent the minimum slopes; as already mentioned, they become steeper with increase in signal level, approaching values of 1000 dB/octave, in some cases.

It is a common and convenient practice to express the relative sharpness of the FTCs in terms of the "Q_{10dB}" value. This is the CF divided by the bandwidth measured at 10 dB above minimum threshold. The values for cat, guinea pig and squirrel monkey are shown in Fig. 10 C. They reach a maximum of between 4—10 for fibres of intermediate CF, *i.e.*, of about 7—10 kHz.

The limited data available on fish (Furukawa and Ishii, 1967) and lizard (Johnstone and Johnstone, 1969) indicate that their FTCs are substantially broader than those of mammals. In the frog, however, fibres in both simple and complex populations can have FTCs as narrow as those of mammalian fibres of comparable CFs (0.1—1.5 kHz; Frishkopf and Goldstein, 1963: bullfrog). The Q_{10dB} values of these fibres are as high as those of mammals: 1—3 (Liff, 1969: leopard frog).

A discussion of the above various indices of frequency selectivity in comparison with psychophysical and behavioural data and basilar membrane data will be deferred to Section VI.A.1, C.1. However, two points regarding Fig. 10 deserve comment at this stage. The first concerns the finding of an intermediate range of CFs at which the slopes of the low and high frequency cut-offs, and the relative sharpness of the FTCs, are maximal. This range, approximately from 7—10 kHz, corresponds to the most sensitive region of the behavioural audiograms for the cat (*e.g.* Miller *et al.*, 1963) and guinea pig (Heffner *et al.*, 1971); to the region where minimum tone thresholds are found for the cochlear fibres of the cat (Fig. 8; Kiang, 1968) and guinea pig (Evans, 1972b); and to the region where the elevation of cochlear nerve threshold by stimulation of the olivocochlear bundle is greatest (Wiederhold and Kiang, 1970; Wiederhold, 1970; Teas *et al.*, 1972; see Section V.A.). The second point is to emphasize that the data in Fig. 10 are pooled not only across species but animals. In a study of the slopes and bandwidths of populations of fibres in the cat, measured with a semi-automatic plotting technique, Evans, Wilson, and Rosenberg (1970) (also, Evans and Wilson, 1971, and unpublished data) have observed small but systematic differences between animals. Of greater significance is the observation that even within a cochlear nerve of a single animal (cat and guinea pig), the range of slopes and bandwidths at a common CF is substantial and approaches a factor of 4 in some cases (Evans, 1972b; Evans and Wilson, 1973). This variation in sharpness from fibre to fibre at a

Fig. 9A—C. Representative Frequency Threshold Curves of cochlear fibres from A: cat (after Kiang *et al.*, 1967), B: guinea pig (from Evans, 1972b), and C: squirrel monkey (derived from data of Rose *et al.*, 1971). Dotted lines in B: basilar membrane frequency response curves (corrected to SPL at the tympanic membrane) from Békésy (1944) and Johnstone *et al.* (1970), arbitrarily arranged on the ordinate scale

common CF correlates to some extent (at least in the guinea pig) with the threshold of the fibre. Thus, the lower the threshold, the sharper the FTC tends to be (Evans, 1972b; Evans and Wilson, 1973).

On top of the systematic variation in shape of the FTC of cochlear fibres with their CF (as plotted on a logarithmic frequency scale), therefore, there are variations from fibre to fibre and from animal to animal. The latter, non-systematic, variations, (at least in the material of Kiang *et al.*, 1965a, 1967; Evans *et al.*, 1970, in the cat; Evans, 1972b, in the guinea pig) do not fall into two well-defined populations, as was reported by Katsuki *et al.* (1959) for the cat. The latter authors described two kinds of response area: symmetrical and asymmetrical, which appeared to correlate to a certain extent with high and low threshold, respectively, and which were held to relate to the innervation of inner and outer hair cells. As has already been mentioned, it is clear that the high threshold, symmetrical, FTCs of low CF may be accounted for by the absence of correction of their FTCs for the response of the sound system at the tympanic membrane. Similar considerations may be responsible for the remaining differences in shape of FTCs of higher CF in their data, or they would appear to represent the *extremes* of the variation

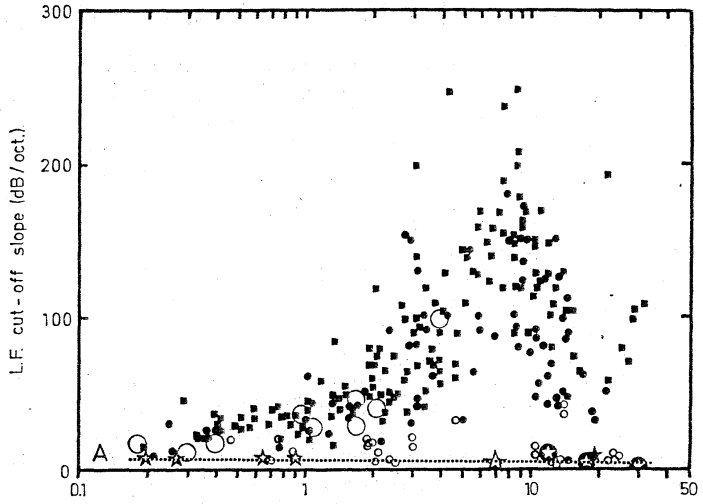

Fig. 10A

Fig. 10A—C. Measurements of slopes of low frequency cut-offs (A), high frequency cut-offs (B), and relative sharpness (C), of FTCs of cochlear fibres from cat, guinea pig, and squirrel monkey, versus their CF. Slopes measured over region 5—25 dB above minimum threshold. Relative sharpness measured as the Q_{10dB} value, *i.e.*: CF/bandwidth of FTC at 10 dB above minimum threshold. Symbols indicate animal and source. Cn: cochlear nerve data for cat, from Evans and Wilson, 1971; guinea pig (GP) from Evans, 1972b, and squirrel monkey (SM) from Fig. 9C. Small open circles: values for fibres with pathologically high thresholds in guinea pig (see text). Star symbols: analogous measurements from basilar membrane frequency response data of von Békésy (1944: B) in guinea pig, Rhode (1971, 1973: R) in squirrel monkey; Wilson and Johnstone (1972: W) and Johnstone *et al.* (1970): J) in guinea pig

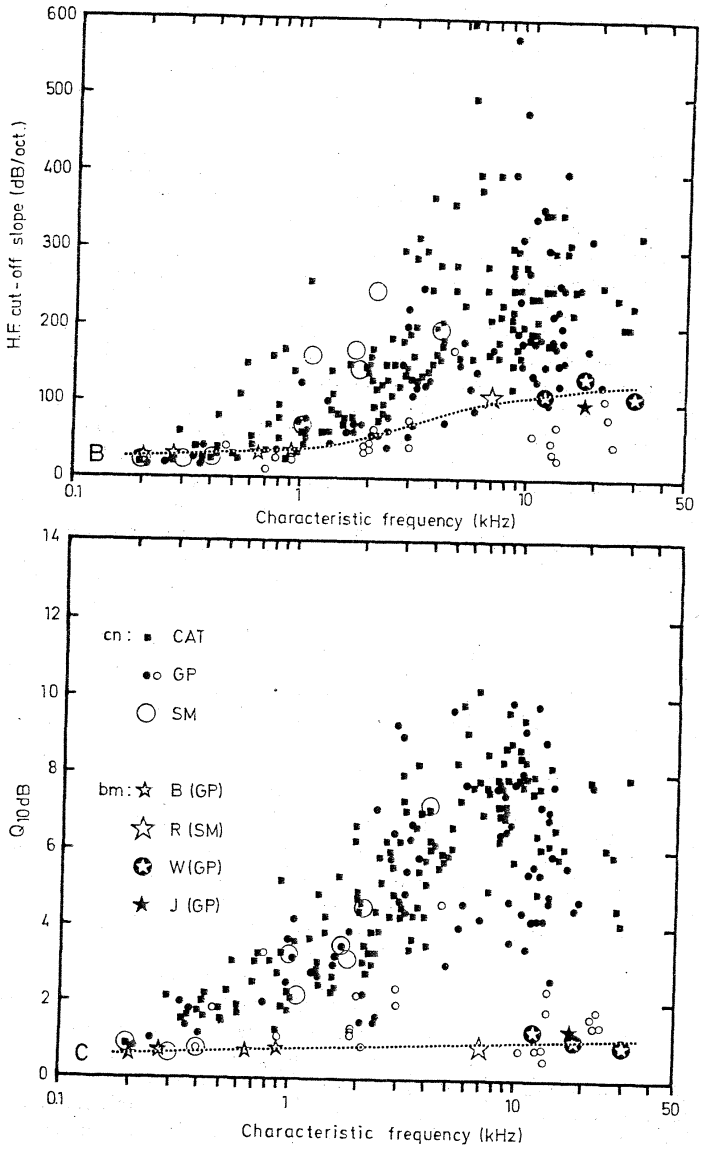

Fig. 10B and C

noted above. In this connection, it is of interest that the same authors were unable to differentiate into two groups, on the basis of shape, cochlear fibres in the monkey, on account of the "variety of intermediate types" (Katsuki *et al.*, 1962, p. 1402).

In all of the above considerations, the group of fibres mentioned earlier (p. 13) with pathologically high thresholds (*i.e.*: above 70 dB SPL) has been excluded. These were obtained in the guinea pig only, under conditions of apparent and presumed cochlear pathology (Evans, 1972b). The FTCs of these fibres are clearly anomalous, being very broadly tuned, and resemble the normal FTCs shown in Fig. 9B but with the narrowly tuned lower threshold tip section (20–40 dB) missing. Measurements of the cut-off slopes and the relative sharpness of these fibres are given as the open circles in Fig. 10A–C, indicate their anomalous degree of tuning.

That anoxia can selectively decrease the sharpness of tuning of single cochlear fibres has been shown in recent experiments in the cat (Evans, 1974a, c). *Reversible* loss of the low threshold, sharply tuned segment of the FTC, leaving behind the high threshold broadly tuned segment, can occur after only a few minutes of *hypoxia*. Local instillation of KCN (at concentrations of less than 10^{-3} M) into the scala tympani, or intra-arterial injection of Frusemide, a potent ototoxic diuretic, can produce identical reversible effects on the FTC without apparent action on the cochlear microphonic (Evans and Klinke, 1974; Evans, 1974c, d). Other influences can also modify the threshold and shape of the FTC. Electrical stimulation of the olivocochlear bundle and prior exposure to long-term high level tonal stimuli at the CF cause a relatively greater elevation of the threshold at the CF than at other frequencies; that is to say, the FTC becomes less sharp (Kiang *et al.*, 1970). The addition of background noise at increasing levels produces a progressive elevation in the tip of the FTC (Kiang *et al.*, 1965), but without substantial loss of tip bandwidth until saturation of the discharge rate makes determination of response threshold difficult (Evans, 1974d). It is interesting that under conditions of *continuous* noise stimulation, the saturation discharge rate becomes progressively reduced as the level of background noise is raised (Evans, 1974d).

Complementary to the above descriptions of the frequency *sensitivity* of cochlear fibres, are representations of their frequency *response*, *i.e.* response rate versus frequency curves, (FRCs). These have been studied in most detail by Rose and his coworkers in the squirrel monkey (Rose *et al.*, 1967, 1971; Hind *et al.*, 1967; Hind, 1972), and examples are shown in Fig. 11. Each curve depicts the average *maintained* discharge rate (measured over several seconds continuous tone stimulation) as a function of frequency at a constant sound pressure level at the tympanic membrane. The FTCs of Fig. 9C were obtained from these iso-intensity rate curves by plotting the frequencies and stimulus levels evoking a constant rate of response near threshold, in other words by using as a criterion of "threshold", an isorate condition just above the spontaneous firing rate.

The considerably different appearance of these curves from the FTCs arises partly from the linear frequency scale, but mainly from the manifest non-linearity of the response rate as a function of stimulus level, with its limited dynamic range, which will be described in detail in the next section. Thus, comparing the FRCs of Figs. 11C and 12A, from two fibres of similar CF, the two sets of curves look very different. Fig. 12C, however, shows that the FTCs derivable from the two sets of data

(Curves *c* and *a* respectively) are in fact very similar. Figure 12B shows, from the same fibre as 12A, a plot based on the number of discharges synchronized to the stimulus waveform (see Section II.D.4). It has been claimed (Rose *et al.*, 1971; Møller, 1972) that the differences between the plots of Fig. 12A and B indicate that the frequency selectivity is much more pronounced with respect to stimulus

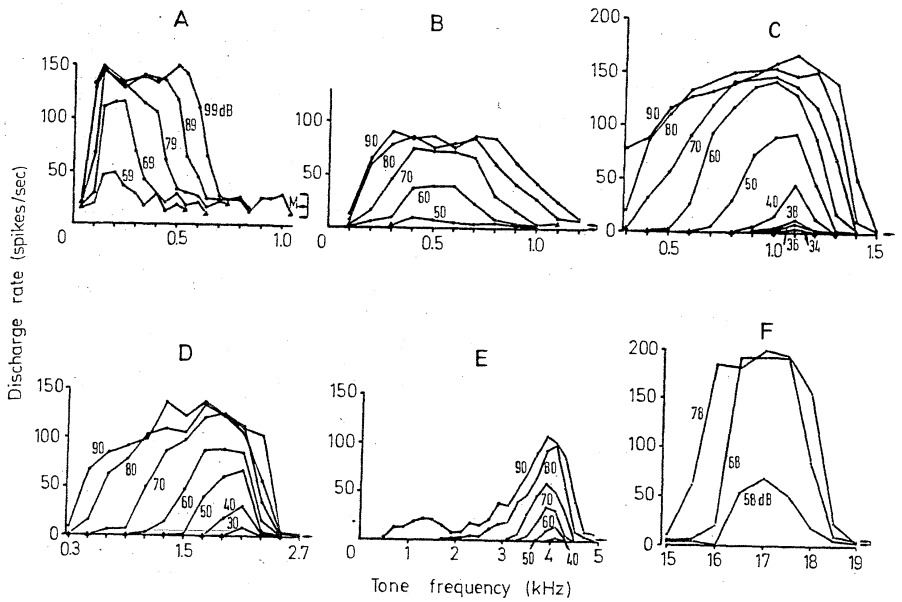

Fig. 11. Iso-intensity frequency response curves of 6 squirrel monkey cochlear fibres. Mean rate of discharge to several seconds of continuous stimulation at frequencies and intensities (in dB SPL) indicated. Note linear frequency scale and different expansions. Range of spontaneous discharge rates and means indicated by brackets and M (or arrow) respectively. Triangular points: no significant degree of synchronization of activity to cycles of stimulus. (From Rose *et al.*, 1971)

locking than to mean discharge rate. Figure 12C, Curve *b*, however, shows a plot analogous to a FTC derived from the curves of Fig. 12B using a constant synchronized rate criterion (50 synchronized spikes/sec). (The ordinates of the two plots have been shifted for convenient comparison.) If anything, the "synchronized isorate contour" (Curve *b* in Fig. 12C) is less sharp than the FTC based on a mean rate criterion (Curve *a*).

Similarly, it has been claimed that the broadening of the FTCs with increase in stimulus level is an indication of degradation of cochlear filtering properties at suprathreshold levels. If, however, isorate contours with higher rate criteria are plotted as in Fig. 13, these do not exhibit systematic changes in shape and band-

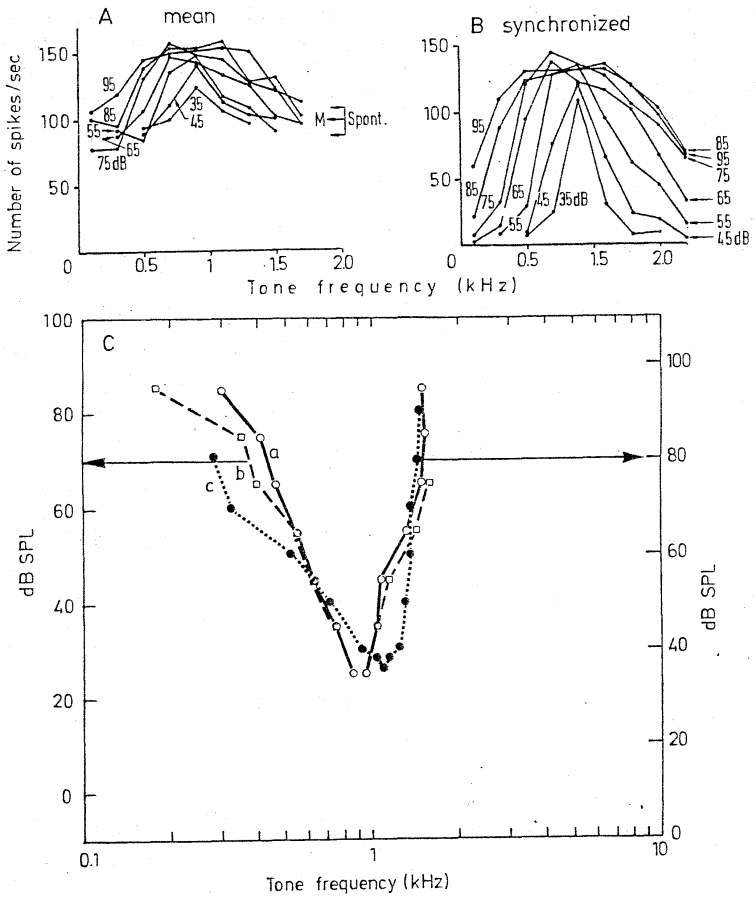

Fig. 12A—C. Relationship between FRCs (using mean and synchronized discharge rate measures), FTC and analogous plots. Squirrel monkey cochlear nerve. A: iso-intensity frequency response curves for a cochlear fibre with a high spontaneous discharge rate (range and mean indicated to right of plots). B: plots of the "synchronized" discharge rate for the same fibre, *i.e.*: the number of spikes discharged during the more effective half-cycle of the stimulus minus the number during the less effective half-cycle, expressed as a rate per sec. (From Rose *et al.*, 1971.) C: iso-rate intensity versus frequency curves (analogous to FTC but using suprathreshold response criteria) derived from FRCs of A and B compared with FTC of a fibre with low spontaneous discharge rate (derived from Fig. 11C). (a) (open circles): iso-rate contour for discharge rate of 120 spikes/sec (20% above spontaneous rate) for frequency response curves in A. (b) (open squares): iso-rate contour for "synchronized" discharge rate of 50 spikes/sec derived from frequency response curves in B. (c) (filled circles): FTC derived from iso-intensity frequency response curves of Fig. 11C (8 spikes/sec criterion of "threshold"). Curves a and c use the right hand ordinate. Note similarity between the 3 FTCs, compared with marked differences between the iso-intensity frequency response plots

width, at least within the range of stimulus levels before saturation of the rate response precludes accurate measurement. The isorate data of Sachs and Kiang (1968) also support this conclusion. Above these relatively high levels, the filtering properties may indeed deteriorate; the evidence for this and the consequences will be discussed later (Section VI.A.1).

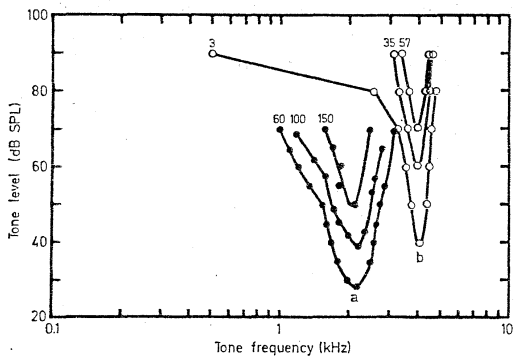

Fig. 13a, b. Iso-rate response contours for two cochlear fibres. Mean discharge rate, in spikes/sec, indicated above respective curve. a: Cat (Evans, Rosenberg, and Wilson, unpublished data). Mean spontaneous rate: 50 spikes/sec. b: Squirrel monkey; derived from Fig. 11E (data from Rose *et al.*, 1971). Negligible spontaneous discharge rate. The difference in bandwidth between a and b probably reflects individual variation and that with CF, rather than any species difference (see Fig. 10)

In summary, the above considerations emphasise the care necessary to relate and interpret various measures of cochlear fibre activity as a function of frequency. Viewed thus, the data point more to systematic changes in shape of the cochlear filtering characteristic with the CF of a fibre than to differing individual characteristics suggestive of differences in cochlear innervation pattern, as suggested by Hind (1972) on the basis of FRC data alone. The FTC and suprathreshold isorate data indicate the characteristics of the cochlear filter function from which has been eliminated the non-linear response characteristics of the cochlear nerve excitation process. The FRC, on the other hand, indicates the limits which may be set upon the central representation of the cochlear filtering by the non-linear rate behaviour of the cochlear fibres. In particular, it indicates the surprisingly limited dynamic range of the system through which, in terms of discharge rate, the results of peripheral filtering are transmitted to the central regions of the auditory nervous system, at least in the anaesthetized animal (see Section VI.D.1).

2. Response as a Function of Intensity

To a first approximation, the discharge rate of a cochlear fibre is a monotonic function of stimulus intensity, as shown in Fig. 14 (Katsuki *et al.*, 1962; Nomoto *et al.*, 1964; Kiang *et al.*, 1965a; Kiang, 1968; Evans, 1974d). The maximum

discharge rate, and dynamic range, like the spontaneous discharge rate, differs from fibre to fibre, but, generally, the higher the spontaneous discharge rate, the higher the maximum discharge rate (Kiang *et al.*, 1965a). The dynamic range, in terms of stimulus level, ranges from 20—50 dB. Figure 14A shows that the rate-intensity function for a single fibre may also differ to a small extent depending on the stimulus frequency (Evans, Rosenberg, and Wilson, unpublished observations; Evans, 1974d). In general, for frequencies at and above the CF, or as in Fig. 14A only above the CF, the functions are less steep than those for frequencies below the CF. Not all fibres show these systematic differences with frequency (Fig. 14B). Similar rate functions are illustrated by Wiederhold (1970; Fig. 6), and can be derived from the data of Rose *et al.* (1971). This dependence of the rate function on frequency is likely to be responsible for the systematic shift of the peak discharge rate of some FRCs towards lower frequencies with increase in stimulus level above threshold (*e.g.* see Fig. 11C—E).

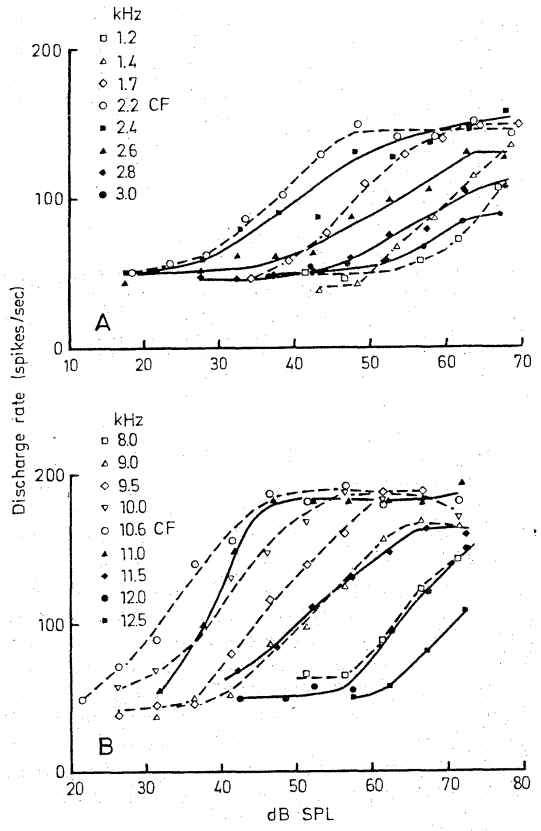

Fig. 14. Discharge rate versus stimulus intensity curves for two cat cochlear fibres, with CFs of 2.2 kHz (A, same fibre as in Fig. 13a) and 10.6 kHz (B). Open symbols and interrupted lines denote curves for frequencies at or below CF; filled symbols and continuous lines, for frequencies above CF. Note: in A, systematic differences in slopes of rate functions between frequencies above and below the CF. (Evans, Rosenberg, and Wilson, unpublished data)

Nomoto *et al.* (1964) described two groups of fibres possessing what was termed a "crossed ramp" and "parallel ramp" type of rate-intensity function respectively. These two types are consistent with those of Fig. 14A and B respectively, although the data of Nomoto *et al.* are less complete. Nomoto *et al.* regarded the existence of the two types as evidence for different kinds of cochlear fibres: specifically, the external spiral and internal radial fibres respectively. This speculation however, has not been well received (*e.g.* Kiang *et al.*, 1965a). Clearly, there is room for a more systematic study of these rate functions and their significance.

At very high stimulus levels (90 dB SPL and above) the maintained discharge rate can *decrease* with increase in stimulus level, *i.e.*: the rate response becomes non-monotonic. Kiang *et al.* (1969) and Kiang and Moxon (1972) have reported a curious phenomenon at these levels, where within a few dB, the discharge rate drops towards the spontaneous rate and rises again to a maximum. This notch in the rate-intensity function is found in fibres of widely differing CF at comparable sound pressure levels, although it is said to occur at somewhat lower levels for tones below the CF. Its characteristics could be accounted for by interference between two-out-of-phase excitation processes, one with low threshold accounting for the lower portion of the rate intensity function, and a higher threshold process responsible for the portion above approximately 90 dB SPL. In support of this hypothesis, for fibres of low CF and at low frequencies (where phase relations can be observed), substantial changes in the relative phase of the discharge pattern occur as the stimulus level is raised through the region of the notch. (See also discussion in Section VI.B).

3. Response as a Function of Time

Figure 15 shows the typical time-course of discharge of cochlear fibres to short duration tone (A) and noise stimuli (B). The rate of firing reaches a maximum within a few msec of stimulus onset and adapts at a increasingly slower rate with time. At the cessation of the stimulus, the firing rate drops below the spontaneous level transiently before recovery (as in Fig. 1). This pattern of response is characteristic of all cochlear fibres and, in qualitative terms, is relatively independent of the nature and parameters of the stimulus, *i.e.* tone, noise, frequency and intensity, and whether the efferent innervation of the cochlea is intact or not (Fig. 15B; Kiang *et al.*, 1965a; Kiang, 1968). However, the magnitudes of the transient excitation and suppression, following the onset and termination of the stimulus, depent on the level, and for the transient suppression, on the duration of the tonal stimulus. Thus, near threshold, the former becomes less marked (Fig. 15B, — 70 dB), whereas the duration and degree of the latter increase with the level and duration of the signal.

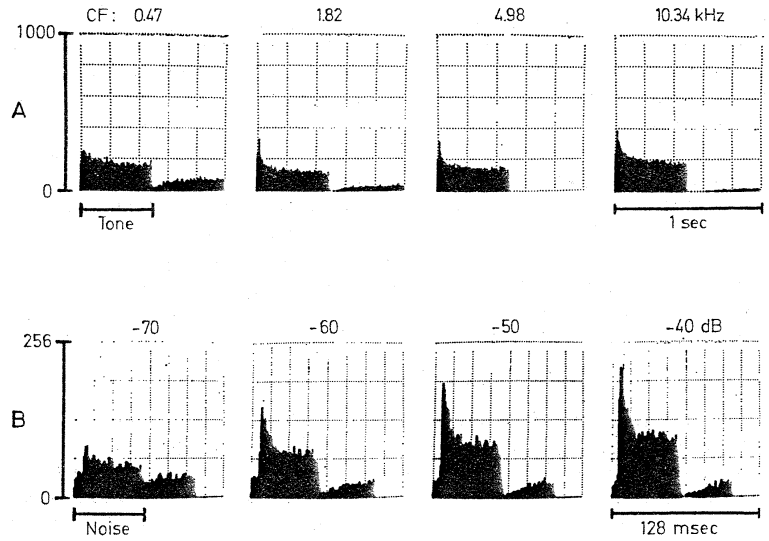

Fig. 15A, B. Time-course of response of cat cochlear fibres to tone and noise bursts. PST histograms. A: 4 different fibres of the CF indicated. Linear ordinate scale, number of spikes per bin; 2 min data; tone at CF, 0.5 sec duration, presented 1/sec. B: Effect of level of stimulus on time-course (similar for tones and noise bursts). 50 msec noise burst beginning approx. 2.5 msec after zero time of PST, repetition rate: 10/sec. Relative signal level indicated above each PST histogram. (From Kiang *et al.*, 1965a)

4. Response to Low Frequency Tones

Responses of cochlear fibres to tones of frequency lower than 4–5 kHz preferentially occur during a restricted segment of the cycle of the sinusoidal stimulus, *i.e.* the discharges are "phase-locked": Fig. 16, (Tasaki, 1954 in the guinea pig; Rupert *et al.*, 1963; Kiang *et al.*, 1965a in the cat; Katsuki *et al.*, 1962; Rose *et al.*, 1967 in the monkey; Frishkopff and Goldstein, 1963 in the bullfrog; Furukawa and Ishii, 1967 in the fish). This phenomenon has been studied most thoroughly by Rose and his colleagues in the squirrel monkey cochlear nerve (Rose *et al.*, 1967, 1968, 1971; Anderson *et al.*, 1971; Hind, 1972).

The probability of discharge of a fibre (irrespective of its CF) to a sufficiently intense low frequency tone appears to be a function of the displacement of the cochlear partition in one direction (Figs. 16B, 17, 18). Thus "folded" time histograms ("period histograms"), of the distribution of discharges relative to the period of the stimulus sinusoid, mirror the effective half-cycle of the stimulus (Figs. 17 and 18), and a compound histogram (Fig. 16B) can be constructed by repeating the analysis with inversion of the polarity of the stimulus (Arthur *et al.*, 1971). Thus, while the mean discharge rate is given by the FRC, the cadence of discharge is governed by the cadence of the stimulus cycles and the ability of the fibre to "follow" the stimulus (Fig. 17).

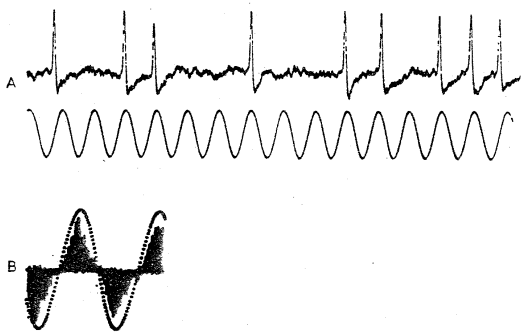

Fig. 16A, B. Synchronization of responses of cochlear fibres to low-frequency tones. A: continuous film record of response of guinea pig fibre to tone of 0.3 kHz, near threshold. B: compound period histogram (see text) of response of cat cochlear fibre to continuous tone at CF of 1.498 kHz, 63 dB SPL. (From Arthur *et al.*, 1971.) Waveform of stimulus tone superimposed. Continuous tone of 76 sec duration

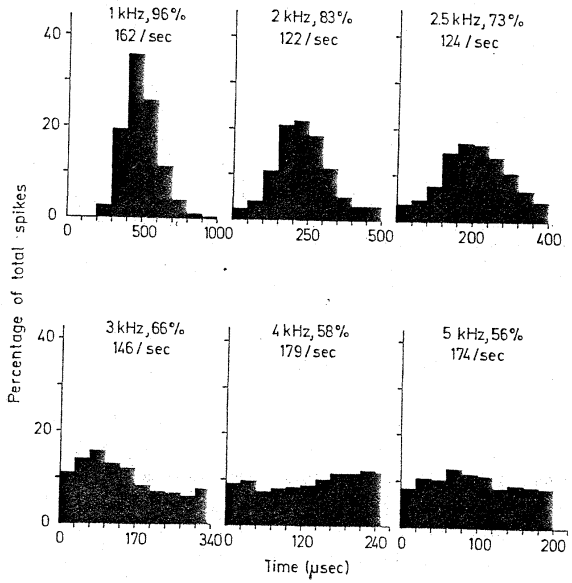

Fig. 17. Degree of synchronization of response of cochlear fibre to tones of differing frequency. Squirrel monkey. CF of fibre: 4 kHz. Tones presented at 90 dB SPL at frequencies indicated above period histograms. Scale of each histogram and bin width adjusted to span one period of stimulating tone. Ordinate scales: percentage of the total number of spikes falling in respective bin. Percentage figure above each histogram: "coefficient of synchronization" *i.e.* number of spikes in most effective stimulus half-cycle as percentage of total (100% = complete synchronization; 50% = no synchronization). Mean discharge rate in spikes/sec indicated over each histogram. Note maximum degree of synchronization to lowest frequency; progressive reduction in degree with increase in tone frequency. Spontaneous discharge rate: 64 spikes/sec. (From Rose *et al.*, 1967)

Figure 17 shows the progressive loss of synchronization between discharge pattern and stimulus cycle as the stimulus frequency is increased. In the case illustrated, this loss occurs in spite of the greater effectiveness of the higher frequencies in terms of the mean discharge rate. In the experience of Rose *et al.*, (1967), phase-locking fades out for most fibres for frequencies above 4–5 kHz though they do report significant synchronization in some fibres at frequencies up to 12 kHz.

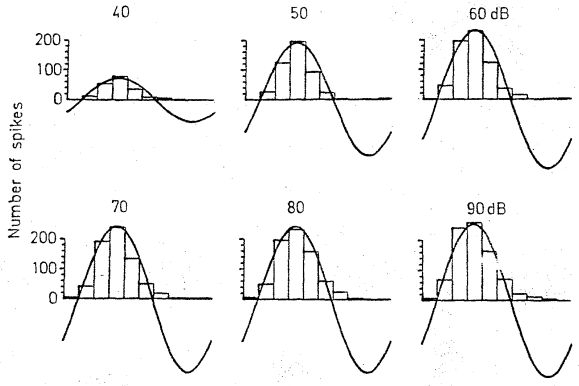

Fig. 18. Synchronization of response of cochlear fibre with level of tone at CF (1.1 kHz). Squirrel monkey. Stimulus level in dB SPL indicated above each period histogram. Period of histogram: 912 μsec. Histograms fitted by sinusoids of constant phase but differing amplitudes. Note preservation of stimulus waveform in period histogram even at stimulus levels above the level producing saturation of the rate response (70 dB SPL). The FRC of this fibre is shown in Fig. 11C. (From Rose *et al.*, 1971)

Many spontaneously discharging fibres display a detectable degree of phase synchronization at stimulus levels 10–20 dB below the threshold for an increase in mean discharge rate (Rose *et al.*, 1967; Evans, 1972b). This synchronization, in addition, is maintained at stimulus levels above those producing a saturation of the mean discharge rate (Fig. 18). These considerations mean that the dynamic range over which phaselocking is obtained is far in excess of the 20–50 dB limit for the mean discharge rate.

It is clear from Fig. 16A and from interspike interval histogram analyses (Fig. 19) that a fibre does not discharge once every cycle of a low frequency stimulus waveform but predominantly to integral multiples of the waveform cycle (Rose *et al.*, 1967). Exceptions to this generalization occur at very low stimulus frequencies where multiple discharges sometimes occur, and at higher frequencies, where the refractoriness of the fibre eliminates interspike intervals below about 0.7 msec (Rose *et al.*, 1967). At lower stimulus levels (or at frequencies where the stimuli are less effective, as in Fig. 19A, F), there is an increase in the relative proportion of longer intervals, corresponding to the decrease in mean rate. It is clear that, for intervals longer than 0.5 msec, it is not refractoriness which determines

whether or not a cycle is effective. Rose *et al.* (1967) calculated the conditional probability of discharge and found it to be nearly constant at any one frequency *irrespective (after the refractory interval) of when the previous discharge occurred.* In their words (Rose *et al.*, 1968) "... a sinusoidal stimulus acts in general as if it consisted of as many individual stimuli as there are cycles". They concluded, therefore, that the events determining the effectiveness of a cycle took place *peripheral* to the spike generation process which is assumed to be responsible for the properties of refractoriness.

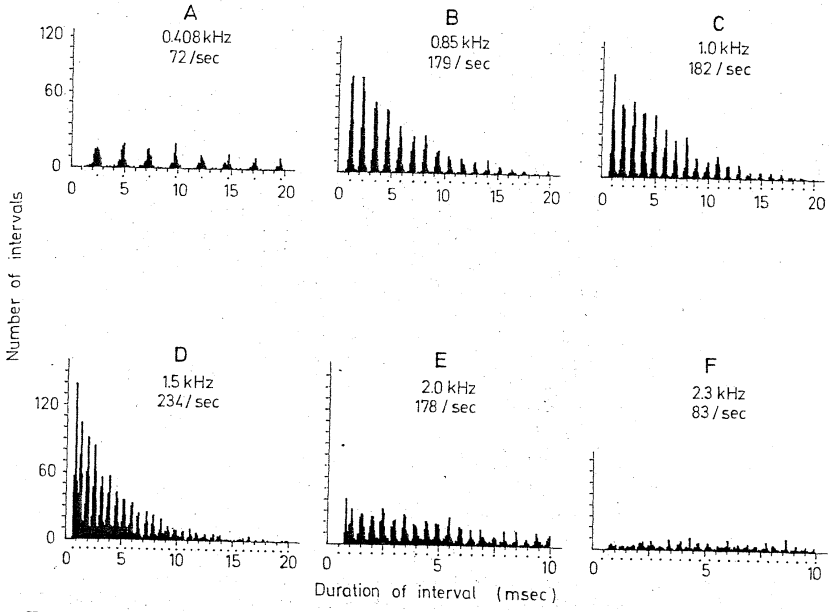

Fig. 19. Interspike interval distributions of response of single cochlear fibre to tones at different frequencies. Squirrel monkey. Tone frequency and mean response rate (in spikes/sec) indicated above each histogram. Intensity of all tones: 80 dB SPL; tone duration: 1 sec. Data comprise responses to 10 presentations of stimulus. Bin width: 100 μsec. Dots below abscissa indicate integral multiples of period of stimulating tone. CF: approx 1.6 kHz. Note different time scales of E and F. (From Rose *et al.*, 1968)

The phase of the stimulus cycle at which the probability of discharge is maximum differs systematically from fibre to fibre according to the CF, and, for a single fibre, according to the stimulus frequency (Pfeiffer and Molnar, 1970; Anderson *et al.*, 1971). Pfeiffer and Molnar (1970) computed the phase lag (relative to the round window CM) of the fundamental component from Fourier analysis of period histograms obtained from cat cochlear fibres. For fibres of CF lower than 2 kHz, this was an approximately linear function of frequency, although a better

fit to the data was obtained by two straight lines intersecting at a point close to the CF in some but not all cases (Fig. 20). For fibres with CF above about 1.1 kHz, the phase lag increased more rapidly with frequency for frequencies above the CF; for fibres with lower CF, the reverse tended to occur. Goldstein *et al.* (1971) have

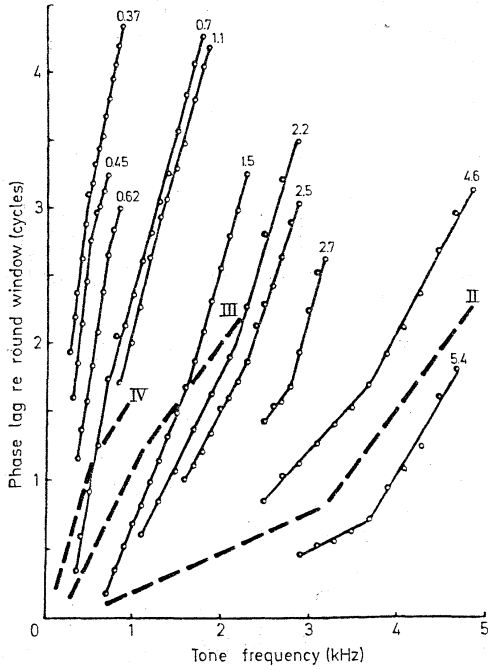

Fig. 20. Phase of response synchronization relative to round window cochlear microphonic potential for 11 cochlear fibres from the cat. Computed by Fourier transform of period histograms obtained at different frequencies of continuous tone stimulation at constant intensity. CF of fibres (in kHz) given above each plot. Note break-point occurring at about CF for each fibre. II, III, IV: phase characteristics of cochlear microphonic potential recorded by differential electrodes in second, third, and fourth turn, respectively, of guinea pig cochlea. (From Pfeiffer and Molnar, 1970)

reported similar findings. From more limited data in the squirrel monkey, Anderson *et al.* (1971) obtained linear phase versus frequency plots from which they derived a total time delay (acoustic plus cochlear plus neural) for each fibre (Fig. 21 A). On the assumptions that the middle ear transmission delay could be neglected, and that the neural transmission amounted to 1 msec (the asymptote of Fig. 21 A), they obtained the estimated "travel times" of the cochlear disturbance to the points of innervation of the cochlear partition shown in Fig. 21 B. The interpretation of this "travel time" is, however, made difficult by the suggestion

of Goldstein *et al.* (1971) and Duifhuis (1972) that the measured delay must include a factor corresponding to the "response time" of the cochlear filter (see Section VI.A.1).

In contrast to the behaviour with frequency, Pfeiffer and Molnar (1970) and Anderson *et al.*, (1971) showed that the phase lag between response and stimulus was relatively unaffected by stimulus level. For most fibres studied in the material of Anderson *et al.* (1971), the phase lag increased with stimulus level (less than

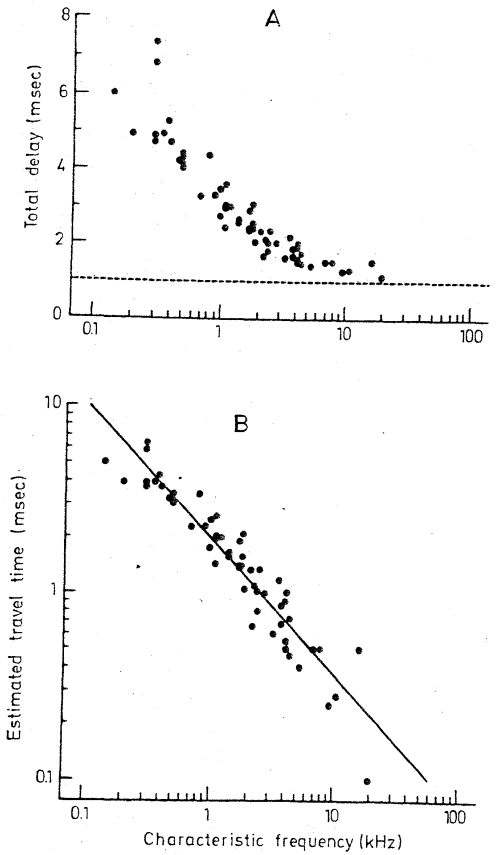

Fig. 21. A: Delay times of synchronized spike responses. 58 cochlear fibres in squirrel monkey. Delays computed from slope of phase versus frequency curves (as in Fig. 20) for each fibre, and plotted against CF of fibre. Values corrected for acoustic delay in sound system, and, therefore, represent travel time in cochlea plus synaptic and neural conduction delays. B: Cochlear travel times calculated from data of A, after subtracting 1 msec average neural delay estimated from asymptote of A (interrupted line), and plotted against each fibre's CF. (From Anderson *et al.*, 1971)

90°) for frequencies below the CF, and *vice-versa*. At frequencies at or near the CF, little or no change of relative phase with level occurred (*e.g.* Fig. 18). On the other hand, as has already been mentioned (Section II.D.2), at *very high* stimulus levels very large changes in response phase have been reported to accompany dramatic changes in the discharge rate (Kiang *et al.*, 1969; Pfeiffer and Molnar, 1970).

A consideration of these findings in relation to questions of cochlear mechanics and innervation will be deferred to Section VI.A. and B.

E. Response to Complex Sounds

1. Two-tone Stimuli

a) Two-tone Suppression. Perhaps the best known phenomenon arising from the interaction between two tones at this level is that known as two-tone inhibition or suppression, which is found in many species (*monkey:* Nomoto *et al.*, 1964; Hind *et al.*, 1967; *frog*: Frishkopf and Goldstein, 1963; Liff and Goldstein, 1970; *bat:* Frishkopf, 1964; *cat:* Kiang *et al.*, 1965a; Kiang, 1968; Sachs and Kiang, 1968; Sachs, 1969; Arthur *et al.*, 1971). As will be made clear subsequently, the term *suppression* is to be preferred, to distinguish the phenomenon at the cochlear nerve from that with different characteristics at the cochlear nucleus and higher levels of the auditory system, where lateral inhibitory influences can be clearly inferred (*e.g.* Galambos, 1944; Greenwood and Maruyama, 1965).

The phenomenon entails the suppression of activity evoked by one stimulus (tone or noise) by a second tone over a restricted range of frequencies and intensities (Fig. 22). Its properties have been described in detail by Sachs and Kiang (1968), and Arthur *et al.* (1971). The former authors were able to demonstrate suppression in every fibre examined (*cf.* Nomoto *et al.*, 1964). The situation most commonly examined is where the response to a continuous tone (CT) at the CF of a fibre is reduced by a second tone, generally of higher level, within a band of frequencies adjacent to or even slightly overlapping the excitatory response area of the fibre (Fig. 22B). This implies that the second, (suppressing) tone can, on its own, produce either no response or excitation (Fig. 22A, C). Figure 22B also indicates the asymmetry of the suppressive frequency bands, extending down towards the CT intensity only on the high frequency side. There is some evidence that with an exciting CT stimulus at a higher level, the suppressive frequency bands are shifted vertically upwards from the situation shown in Fig. 22B, so that the degree of overlap is greater (Nomoto *et al.*, 1964).

There is a non-monotonic relationship between the response to, and the intensity of, the "suppressing" tone (Fig. 22C; Arthur *et al.*, 1971). This would be expected as the latter progressed through the suppressive sideband into the excitatory response area (vertically upwards in Fig. 22B).

Hind *et al.* (1967), Brugge *et al.* (1969), and Arthur *et al.* (1971) have shown that the discharge pattern under conditions of two-tone suppression retains phase-locked information of *both* tones. Thus compound period histograms (*vd.* Fig. 16B)

obtained under these conditions can be approximated by a waveform containing the two frequency components comprising the stimulus (as in Fig. 24).

The suppression has a latency of the same order as excitation, *i.e.* it occurs within a few msec of the onset of the suppressing tone (Nomoto *et al.*, 1964; Arthur *et al.*, 1971). For the initial part of the suppressing tone, the suppression

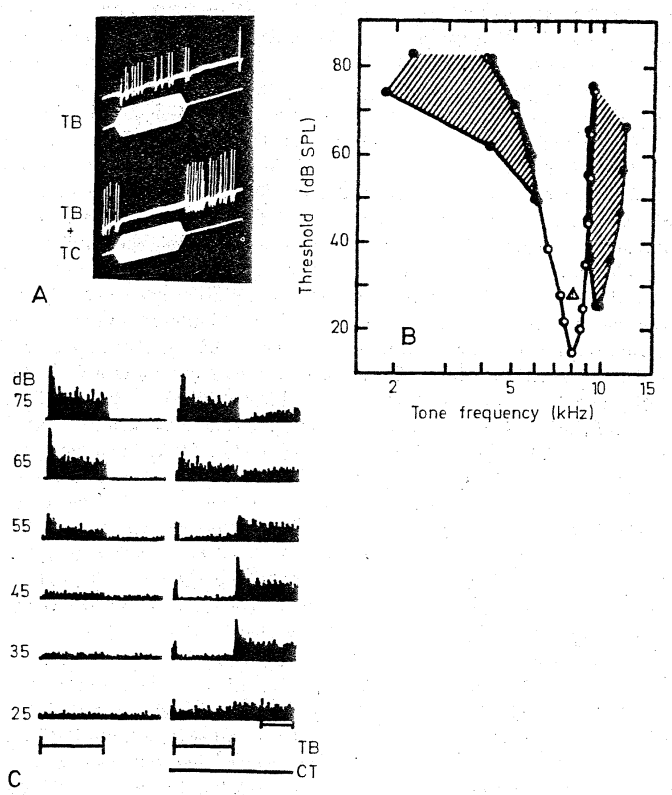

Fig. 22A—C. Two-tone suppression in cochlear fibres. A: continuous film records of response of fibre to tone burst (TB) at 0.8 kHz, 80 dB SPL (upper record) and to identical tone burst superimposed upon exciting continuous tone (CT) at 11.3 kHz, 77 dB SPL (lower record). Monkey. (From Nomoto *et al.*, 1964.) B: Frequency response areas of single-tone excitation (open circles) and of tones which suppress response to continuous tone of the frequency and level indicated by the triangle (filled circles and hatched areas). Continuous outlines represent "threshold" response criteria of more than 20% above the spontaneous discharge rate and 20% below the response to the CT alone for excitatory and suppressive areas, respectively. Cat. (From Arthur *et al.*, 1971.) C: PST histograms of response to 100 msec tone bursts alone (left) and superimposed on continuous tone at CF (right) as a function of level of tone burst. Continuous tone: 8.08 kHz, 28 dB SPL; tone burst frequency: 8.893 kHz. Repetition rate: 5/sec. Average of 128 responses. Time bar: 50 msec. Cat. (From Arthur *et al.*, 1971)

may be complete, but a greater or lesser degree of adaptation ensues. The time course of this "adaptation" is generally slower than that of excitation of the fibre (Fig. 22; Liff and Goldstein, 1970). On termination of the suppressing tone, a prominant rebound of discharge occurs (Fig. 22C) comparable to the excitatory transient at the beginning of the response to a steady tone.

A matter of some controversy (*e.g.* Moushegian *et al.*, 1971) is whether two tone suppression can produce a *maintained* depression of the activity of a fibre *below the spontaneous discharge level*. Sachs and Kiang (1968) claimed that this did not occur for more than the initial several hundreds of msec, although certain of their records (*e.g.* Fig. 2, −40 dB of Sachs and Kiang, 1968) suggest that it can occur for a few seconds, at least. All the above observations are, however, consistent with the hypothesis (Arthur *et al.*, 1971) that the initial suppression below the spontaneous discharge rate is characteristic of the cochlear fibre behaviour which follows the termination of excitation, *i.e.* postexcitatory depression (Section II.D.3). On this basis, the time-course of the suppression below the spontaneous level will depend upon the duration of the excitation preceding the onset of the two-tone suppression. The fact that, in the usual two-tone suppression paradigm, there has been at least several seconds of continous excitation before the application of the suppressing tone would ensure that in these circumstances the time course of the suppression below the spontaneous level would exceed that of excitation (as observed by Liff and Goldstein, 1970). In the case of the data of Sachs and Kiang (1968), the unsuppressed excitation had been continuously present for over 20 sec before the onset of the suppressing tone. This explanation also enables an understanding of the observation of Nomoto *et al.* (1964) that when the time order of the stimuli was interchanged, *i.e.* a tone burst at the CF was superimposed on a continuous tone which was suppressive in the usual two-tone paradigm, a transient suppression below the spontaneous level was not obtained. The suppression produced in the two-tone situation, therefore, occurs as if the exciting tone had merely been interrupted or abruptly attenuated. On this view, the transient total suppression and the transient excitatory "overshoot" corresponding to the onset and termination, respectively, of the suppressing tone are both effects identical to those occurring when a single exciting tone is turned off and on, respectively.

The mechanism by which the effects of an exciting tone are suppressed is still obscure. It is clear that it does not involve the descending efferent (inhibitory) pathway, because two-tone suppression can be recorded from fibres in the peripheral stump of the sectioned cochlear nerve (Frishkopf and Goldstein, 1963; Kiang *et al.*, 1965a) and after section of the crossed and uncrossed olivocochlear tracts and their subsequent degeneration (Kiang, 1968). The anatomical (*e.g.* Spoendlin, 1971) and physiological evidence is equally overwhelming against a lateral inhibitory mechanism involving synaptic connections between hair cells and/or afferent fibres. Thus, the latency, time-course, and quantitative characteristics differ from those associated with lateral inhibition in other systems, *e.g.* Limulus eye (Furman and Frishkopf, 1964; Sachs, 1969; Liff and Goldstein, 1970; Arthur *et al.*, 1971). Furthermore, the application of strychnine is without effect (Nomoto *et al.*, 1964). The possibility exists, however, of electrotonic interaction between the unmyelinated segments of outer spiral and inner radial fibres at the habenula perforata, where the two sets of fibres become intimately opposed

(*e.g.* Spoendlin, 1972). Arthur *et al.* (1971) have suggested that any interaction must occur peripheral to the stage of rectification associated with generator or action potential initiation, because of the preservation of waveform interaction in the spike discharge patterns. However, Sachs (1969) claims that a shunting model of electrotonic interaction (*e.g.* Furman and Frishkopf, 1964) is not supported quantitatively by the data on two-tone suppression. An alternative possibility has been suggested by the similarities between two-tone suppression in the cochlear nerve and an analogous reduction of the cochlear microphonic, where the latter could be modelled qualitatively by a system comprising a non-linearity associated with one or two filtering processes (Engebretson and Eldredge, 1968; Pfeiffer, 1970). In Pfeiffer's model, designed to account for two-tone suppression at the cochlear nerve level, the nonlinearity is sandwiched between an input filter of low frequency selectivity (equivalent to that of the basilar membrane) and an output filter with a sharper frequency selectivity (equivalent to that of the FTC). The model generated asymmetric suppressive side bands overlapping the excitatory response area, and, in addition, a significant intermodulation distortion component at a frequency of $2f_1 - f_2$ (where f_1 and f_2 are the frequencies of the two primary tones). This product is in fact observed at the cochlear nerve level (Goldstein and Kiang, 1968; see below).

b) Excitation by Tone Combinations. Nomoto *et al.* (1964) were the first to demonstrate that two tones of appropriately differing frequencies, neither of which alone excited a cochlear fibre, could, when presented together, nervertheless evoke a response. This phenomenon has since been investigated in detail by Goldstein and Kiang (1968) and by Goldstein (1970, 1972) who have shown its relation to the most conspicuous combination tone perceived under these conditions, namely one of frequency $2f_1 - f_2$, where f_1 and f_2 are the frequencies of the primary tones and where $1 < f_2/f_1 < 2$. Two examples are shown in Fig. 23, where the frequencies of two tones outside the response area of the fibre are so arranged that the frequency $2f_1 - f_2$ coincides with the CF of the fibre. A brisk response is obtained, which in the case of the fibre of low CF is time-locked to the cycle of a reference $2f_1 - f_2$ signal generated electrically from the two primary signals (Fig. 23B).

The response to the tone combination behaves as if a component of the $2f_1 - f_2$ frequency were actually present in the stimulus (Goldstein and Kiang, 1968). Thus, the responses are phase-locked to individual cycles of a reference $2f_1 - f_2$ signal (when the combination tone frequency was below 4 kHz) as in Fig. 23B; the synchronized responses can be cancelled by adding a tone of appropriate phase and frequency $2f_1 - f_2$ to the stimulus ensemble; the response discharge rate shows a similar dependence upon signal level as for single tone stimuli.

In other aspects also the cochlear fibre data are analogous to psychophysical data (Zwicker, 1955; Goldstein, 1967, 1970). In particular, the degree of synchronization of the cochlear nerve activity with the $2f_1 - f_2$ frequency is not strongly dependent upon stimulus level, as if the stimulus contained a combination tone with nearly constant relative amplitude. Furthermore, the response to the combination tone decrements with separation of the frequency of the primaries at an estimated rate of the order of 100 dB per octave and above, in terms of equivalent stimulus change (Goldstein and Kiang, 1968) and the level of a cancelling $2f_1 - f_2$ tone (Goldstein, 1970). This frequency dependence indicates that the site

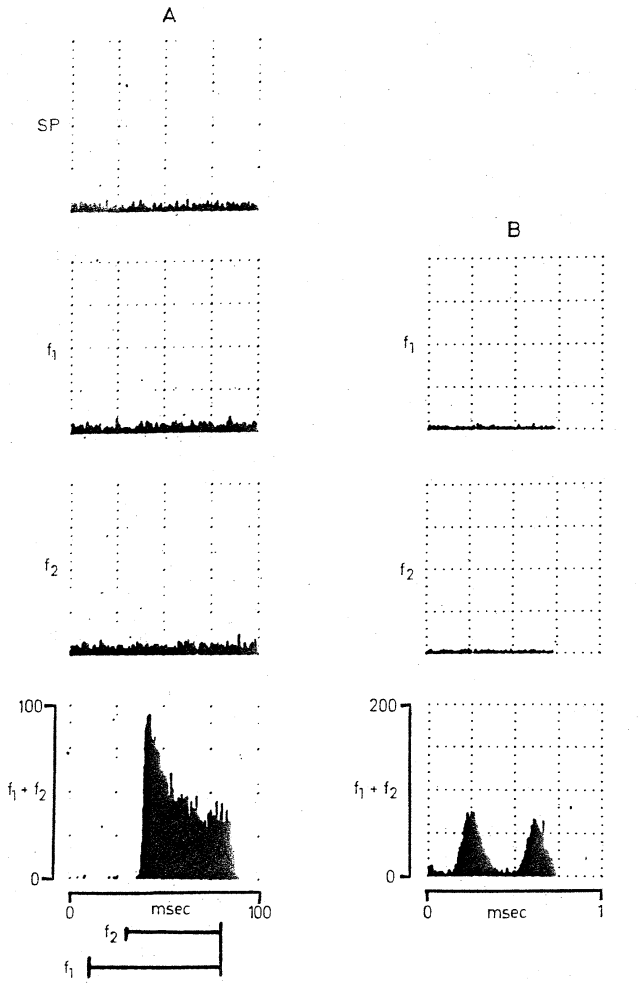

Fig. 23 A, B. Excitation of cat cochlear fibres by combination tone $2f_1 - f_2$ (see text). A: Time histograms of spike activity in presence of: no stimulation (SP); tone 1 alone, at 10.00 kHz, 59 dB SPL (f_1); tone 2 alone, at 12.15 kHz, 69 dB SPL (f_2); Tone 1 and tone 2 together ($f_1 + f_2$). Presentation time and duration of the two tone bursts indicated under lowest histogram. Repetition rate: 10/sec. Note vigorous response to combination of tones ($2f_1 - f_2$ falls on CF of fibre: 7.88 kHz) in comparison with negligible response to either tone alone. B: Period histograms of response to two tones alone (f_1: 5.5 kHz and f_2: 4.13 kHz) and to combined tones ($f_1 + f_2$), of fibre with low CF (2.69 kHz). Each histogram is synchronized to the fundamental frequency of the harmonically related (4 : 3) primary tones. The response to the tone combination exhibits a period of synchronization equal to about half the histogram period, *i.e.*: corresponding to the $2f_1 - f_2$ combination tone (2.76 kHz), close to the CF of the fibre. Spontaneous rate: 5 spikes/sec. (From Goldstein and Kiang, 1968)

of the generation of the distortion product must be central to the middle ear (because of the latter's relatively level frequency response) and that the process responsible for the distortion must be not simple overloading but an "essential" (*i.e.* level-normalized) odd-order nonlinearity (Goldstein and Kiang, 1968; Goldstein, 1970). In one curious respect, however, the neurophysiological and psychophysical data disagree: the measured phase of the psychophysical combination tone changes with the level of the primary stimuli, whereas that obtained in the cochlear nerve recordings does not (Goldstein, 1971: QPR No. 100, p. 202; Goldstein, 1972). There is as yet no explanation for this discrepancy.

There have been attempts to account for some, at least, of these phenomena on the basis of the non-linear threshold detector mechanism in the cochlear nerve spike generation process (de Boer *et al.*, 1969). Such a process alone, could not, however, account for the excitation of a fibre by a combination of two tones, each outside the response area. In addition, the hypothesis of de Boer *et al.* (1969) is not consistent with the other physiological findings, in particular: the absence of cubic intermodulation products higher than the primary frequencies predicted by the hypothesis (de Boer, 1970, p. 246); the observed degree of synchrony of cochlear fibres to the combination tone component (Goldstein, 1972); and the interspike interval histograms obtained by Goldstein and Kiang (1968), (Hall 1971).

Boerger and Gruber (1970) have reported that some but not all cochlear fibres of low CF in the cat could be excited by multicomponent signals consisting of the 3rd to 6th harmonics of a fundamental which coincided with the CF, but which was absent from the signal (*i.e.* a "residue" or "missing fundamental" signal). None of the components, individually, evoked responses, whereas responses could be evoked by the composite signal at levels comparable to the threshold level for tones at the CF. These low relative thresholds were obtained from fibres with low CFs, *i.e.* about 0.2 kHz. The absolute levels were well below those expected to produce significant amounts of difference tone through distortion in the ear (see *e.g.* Goldstein, 1970). Boerger and Gruber have suggested that this phenomenon may be related to the perception of the "missing fundamental" with similar stimuli by man. On the face of it, this would seem unlikely, in view of the finding (Licklider, 1954) that whereas the percept can be masked by signals at the frequencies of the components, it cannot be masked by signals at the frequency of the perceived fundamental.

c) Interaction of Responses to Two Tones: Linear and Non-linear Aspects. A detailed investigation of the effects of two tone stimulation on the discharge pattern of the cochlear fibres of the squirrel monkey, with analogous techniques to those described in Section II.D.4 above, has been made in Rose's laboratory (Hind *et al.*, 1967; Rose *et al.*, 1968; Brugge *et al.*, 1969; Rose *et al.*, 1969; Rose, 1970; Hind *et al.*, 1970). The findings appear to hold for tones which are related or unrelated harmonically. The above authors have shown that, within certain limits, the time-pattern of discharges reflects, to a first approximation, a rectified version of the waveform of the combined stimulus tones.

Figure 24 illustrates the nature of the interaction when the relative amplitude (A) and relative phase (B) of the two component tones is varied over appropriate

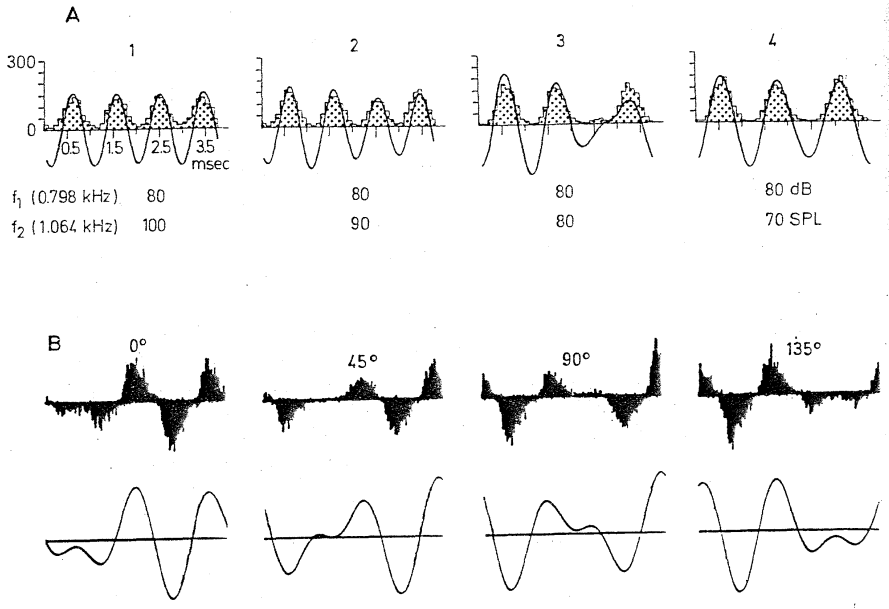

Fig. 24 A, B. Interaction of two tones as a function of relative amplitude and phase. A: Period histograms of activity of a squirrel monkey cochlear fibre in response to a tone of 0.798 kHz at fixed intensity (80 dB SPL) combined with a 1.064 kHz tone at intensities: (1) 100 dB SPL, (2) 90 dB SPL, (3) 80 dB SPL, and (4) 70 dB SPL. Analysis of responses to two presentations of tone combination, each of 10 sec duration. Duration of histogram corresponds to the period of the fundamental frequency of the two harmonically related (3 : 4) tones (*i.e.*: 0.266 kHz). Ordinate: linear number of spikes in respective bin. Note almost complete domination of discharge patterns by more intense tone in 1 and 4. Each histogram is fitted by a waveform obtained by linear addition of the two primary waveforms (f_1 and f_2) in the same relative phase as that for the waveforms fitting the responses to each primary alone, but at arbitrary relative amplitudes (see text). (From Brugge *et al.*, 1969.) B: Compound period histograms of activity of a cat cochlear fibre in response to a combination of two exciting tones of frequencies 0.538 and 0.807 kHz. Relative phase between primary stimulus tones indicated above the histograms. Lower half of each histogram obtained by repeating analysis with polarity of stimulus inverted in a manner analogous to that of Figs. 6 and 16B. (Duration of the histograms corresponds to the period of the fundamental frequency of the two harmonically related (2 : 3) tones, *i.e.*: 0.269 kHz.) Waveforms beneath histograms obtained by linear addition of the two primary waveforms at fixed (arbitrary) amplitudes and of the same relative phase as in the stimulus, leading to the response indicated in the appropriate period histogram. (From Goblick and Pfeiffer, 1969)

values. Interaction occurs over a range of relative intensities restricted to 20 to 30 dB. At each end of the range, the discharge pattern (as indicated by the period histogram) is dominated by the more effective tone. Thus, in the case illustrated by Fig. 24, this occurs when the f_2 tone is 20 dB higher in level than the f_1 tone (Fig. 24, A.1) and when the level of f_1 is 10 dB higher than that of f_2 (Fig. 24, A.4).

At intermediate relative levels, the discharge pattern reflects the interaction between the two component tones. These discharge patterns can be fitted, to a first approximation, by a linear addition of two waveforms of the same frequencies of the stimulus tones but of arbitrarily chosen relative amplitude and phase, as shown by the superimposed waveforms of Fig. 24A. Within this limited range of relative stimulus levels, Rose *et al.* (1971) showed that a reasonable fit could be obtained by adjusting the amplitudes of the matching sinusoidal components in the same ratio as in the stimulus. From this, it would appear that the amplitude ratio of the effective stimulating waveform of the cochlear transduction process changes very nearly as the ratio in the delivered sound.

Likewise, changes in the relative phase of the two stimulus components (Fig. 24B) introduces changes in the discharge pattern which can be fitted by linear addition of two sinusoids with the same changes in relative phase (Brugge *et al.*, 1969; Goblick and Pfeiffer, 1969). In many cases, good fits could be obtained to the empirical combined tone period histograms by using as a starting point the phase of fits to the responses to the individual tones.

These patterns of interaction described above are maintained over a wide range of absolute levels of the two component stimuli, even at high levels where the discharge rate of the fibre is saturated. Under the latter conditions, the period histograms indicate that the complex waveform is preserved at the excitation process (as in the single tone situation illustrated in Fig. 18) in spite of saturation of the spike generation process (Brugge *et al.*, 1969).

Interaction between two tones can be demonstrated at frequencies inside and outside the frequency response area for the fibre. The absolute stimulus levels required for interaction to occur, however, appear to be related to the frequency response area, but not in a simple fashion (Hind *et al.*, 1967). It appears from the data of Hind *et al.* (1967) that, for frequencies well inside the response area, the levels of a tone required for it to achieve a certain degree of synchronization of the response in the presence of another effective tone are to a large extent governed by its effectiveness in driving the fibre on its own. This is not the case for peripheral frequencies, however, which can be more effective in terms of their dominating of the discharge pattern that their rate response would predict.

Indeed, tones at peripheral frequencies which have no effect on their own on the discharge rate can nevertheless dominate the discharge *pattern*. In this connection, Hind *et al.* (1970) made the interesting observation that under these conditions, the discharge rate evoked by the combined stimuli tends towards the rate for the tone alone which is dominating the discharge pattern. Thus, the discharge rate to combined stimuli can be substantially less than that for the most effective tone alone, if the latter is paired with a tone of peripheral frequency which alone is relatively ineffective. The possible relationship of this to the two-tone suppression phenomenon discussed above has been suggested by Hind *et al.* (1970). It is clear from their data, however, that domination of the discharge *rate* by a second tone of peripheral frequency can occur even when the discharge *pattern* has not been dominated by the second tone.

Thus, stimulation of a fibre (66-107-2 in Hind *et al.*, 1967, Table I) with a second tone of 3 kHz at 90 dB SPL reduced the discharge rate to 54%, whereas the coefficient of synchronization of the discharge pattern to the second tone was only 57.9%, compared with a value of

87% for the other tone. (50% = no synchronization; "100%" = complete synchronization.) For comparison, a tone of 3 kHz at 80 dB SPL had no significant effect on discharge rate and gave a synchronization coefficient of 55%.

A clear understanding of these interaction phenomena obviously awaits further data.

Another curious feature of the interactions is that the relative effectiveness of the constituents of a two-tone combination depends on the absolute level of the two. If a given relative level difference is maintained while the absolute levels are changed, both the relative phase and amplitudes of matching constituent waveforms have to be adjusted for the combination to fit the period histograms. In particular, Hind *et al.* (1967), Brugge *et al.* (1969), and Rose *et al.* (1971) observed that the component of a tone pair which was less effective at lower stimulus levels could dominate the discharge pattern of the response at higher levels. This non-linearity in relative effectiveness of phase-locking amounted to 5–12 dB when the levels of both components tones were changed by 50–70 dB (Rose *et al.*, 1971). Over a smaller dynamic range, *e.g.* 20 dB, these amplitude and phase non-linearities become negligible (as already noted). It is interesting to note that, in the illustrated examples of this phenomenon in the above reports, the initially "less effective" tone was the *lower* frequency tone in each case.

From a study of the interspike interval distributions obtained under two tone stimulation, Rose *et al.* (1969) observed that the predominant intervals corresponded, as would be expected, to that of the period of the stimulating waveform excursions. It was concluded that the probability of occurrence of a spike discharge was a function of the amplitude of the excursion (in one direction only). Thus, when one or other primary dominated the response to the combined tones, the predominant intervals were grouped around the integral multiples of the period of that primary. On the other hand, when the two tones contributed about equally to the combined response, the predominant intervals corresponded to the overall period of the complex sound (*i.e.* that of the fundamental frequency of two harmonically related tones), or integral multiples thereof. In addition, smaller numbers of intervals were observed corresponding to frequencies higher than the lower primary. The values of these latter intervals were critically dependent upon the relative phase and amplitude of the primaries, in contrast to those corresponding to the fundamental period.

The possible significance of the above findings, on the patterns of response evoked by stimulation with more than one tone, in relation to the coding of information pertaining to perceived combination tones will be discussed later (Section VI.C.3., D.1).

It must be emphasised that the above data were obtained under conditions of maintained (ca. 10 sec) stimulation (including the response to the onset of the tone). While it does seem unlikely that the conclusions derived will not hold for stimuli of shorter duration, some of the more puzzling features (*e.g.* in relation to the rate response) could conceivably be determined by adaptation phenomena.

2. Noise Stimuli

The responses of cochlear fibres to broadband noise stimuli have been analysed in two different ways, both of which have given rise to similar conclusions on the nature of the cochlear filter.

The first approach has examined the time-structure of the suprathreshold discharge pattern of cat cochlear fibres and its correlation with the waveform of the noise stimulus (de Boer, 1968, 1969, 1970; de Boer and Jongkees, 1968). By an ingenious procedure of "reverse" or "triggered" correlation, where the cross-correlation function between the waveform of the noise stimulus and the ensuing spike discharge pattern is computed, these authors have been able to derive the impulse response of an hypothetical linear cochlear filtering system "seen through" the non-linear excitation process of the cochlear nerve (de Boer and Kuyper, 1968). From the impulse response, the frequency response of an equivalent linear filter was computed and found to approximate to the observed pure tone FTC within the 10–20 dB range of the method. In other words, under broadband conditions, the discharge pattern is determined by a filtered version of the noise signal, the characteristics of the filter approximating to that of the FTC of the fibre. This result is of course limited to fibres with CFs below 4 kHz, as beyond this frequency, the phase-locking of the discharge pattern to the stimulus drops out. This correspondence between the computed filter function and the FTC obtained for a relatively wide range of noise levels, in one case, over a range to 60 dB above threshold (de Boer 1969, 1970). De Boer and de Jongh (1971) and de Jongh (1972) have simulated the hypothetical filter (computed from the cross-correlation function between noise stimulus and spike discharge pattern), used this simulated filter to filter a pseudorandom (*i.e.* repetitive) noise waveform, and then compared the actual moments of discharge with this filtered waveform. A result of such a

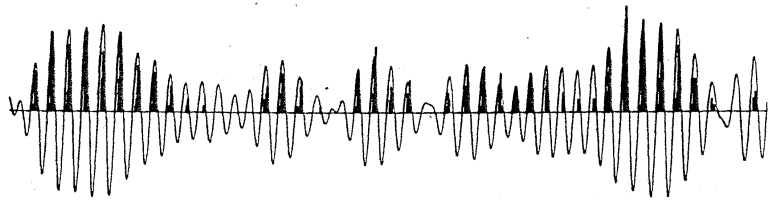

Fig. 25. Time-pattern of discharges of cat cochlear fibre to pseudo-random broadband noise stimulus. Bars: time histogram of average number of spike discharges related of the period of repetition of the pseudo-random noise stimulus. Waveform: filtered version to the stimulus waveform. Characteristics of the filtering operation simulate those of the particular cochlear fibre whose responses are indicated in the superimposed histogram (see text).
(From de Jongh, 1972)

comparison averaged over many repetitions of the waveform is shown in Fig. 25. While the authors interpret their data in terms of the efficacy of "zero crossings" of the waveform, the similarity between this situation and that described in Section II.D.4 and E.1 above is such to suggest the more obvious explanation that, to a first approximation, the probability of discharge is proportional to the amplitude of unidirectional excursions of the filtered waveform presumed to be acting at the site of excitation (see Section VI.A.3).

In this connection, it is interesting to note that a better fit between the filtered waveform and the spike discharge would have been obtained if the waveform had been subjected to a

downward dc shift. Rose *et al.* (1971) comment that this was sometimes necessary to obtain an adequate fit between the spike discharge patterns and simulating waveforms in their two-tone interaction data. The significance of this dc shift is not clear.

The second approach has been to examine the relation between the threshold of response to broad band noise and to pure tone stimuli (Evans *et al.*, 1970; Evans and Wilson, 1971, 1973). Using the same criterion of "threshold" for tone and noise stimuli (an audio-visual indication of increase in discharge rate above the spontaneous rate, evoked by gated stimuli of 100 msec duration), the data of Fig. 26M were obtained for cat cochlear fibres of CF ranging from 0.2 to over

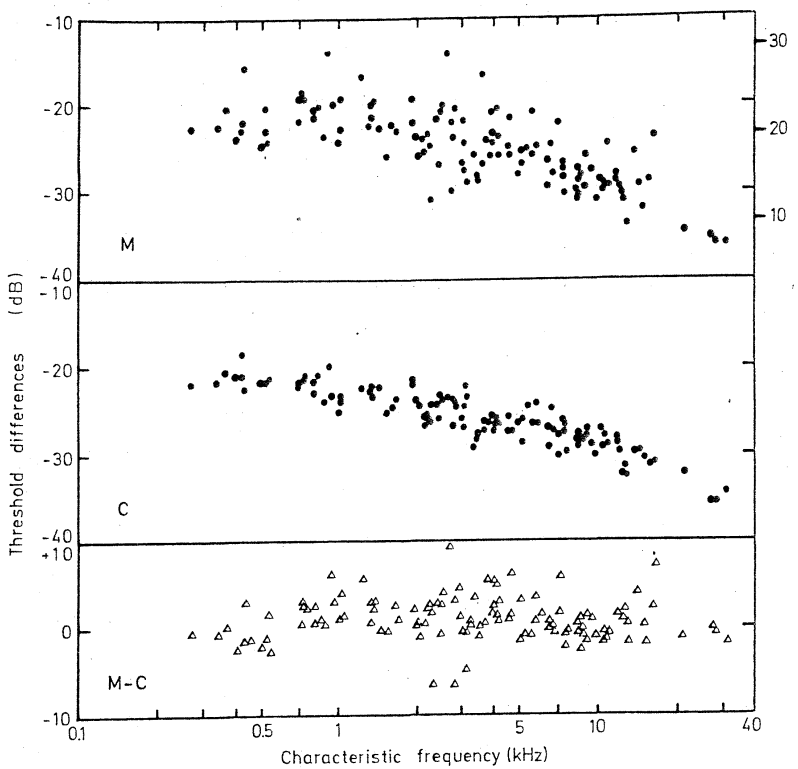

Fig. 26. Difference between noise and tone thresholds for 118 cochlear fibres from 5 cats, plotted against the CF of each fibre. M: measured values of noise threshold intensity relative to threshold of tone at CF, noise intensity being expressed in terms of r.m.s. power in 1 Hz bandwidth. (Right ordinate gives the values measured using a full noise bandwidth of 21.5 kHz.) C: corresponding values computed from FTC of each fibre using expression: $10 \log_{10}$ ("effective bandwidth" of FTC). The "effective bandwidth" is the bandwidth of the equivalent rectangular filter (equal in area to the FTC plotted on linear power and frequency coordinates as in Fig. 27). M—C: differences between corresponding measured and computed values. (After Evans and Wilson, 1971, 1973)

30 kHz. These show that, with noise level expressed as spectral level (*i.e.*, power in 1 Hz bandwidth), the noise threshold was 13—36 dB below the threshold of a tone at the CF. (Measured with a noise bandwidth of 21.5 kHz, the r.m.s. noise threshold was 7—30 dB higher than that of the tone). On the assumption that the pure tone FTC represented the frequency response function of a *linear* filter, the predicted threshold difference between noise and pure tone stimuli could be computed from the FTC of each fibre (see Fig. 26C and legend). The similarity between the observed and computed threshold differences (Fig. 26M—C) suggests that, within the limits of experimental error, and within the limited range of the method (10—20 dB), the overall frequency filtering characteristics of the cochlea act as a linear filter of bandwidth consistent with that of the pure tone FTC. The latter conclusion thus extends that of de Boer to fibres of all CFs.

These two studies therefore indicate that, within limits, the relative threshold and the discharge pattern of the response to noise can be predicted in principle from the filtering characteristics of a fibre, as defined by the pure tone FTC.

3. Stimuli with Multiple-Component Spectra: "Comb-filtered" Noise

When a stimulus with a wide-band spectrum (noise or click) is mixed with a delayed version of itself, a signal results which has as its spectrum a sinusoidal distribution of energy with regard to frequency, *i.e.* a series of peaks and valleys of energy evenly spaced on a linear frequency scale, a so-called "comb-filtered" noise spectrum (see Fig. 27). The spacings of the peaks and valleys of energy depend upon the delay (*e.g.* see Wilson, 1967, 1970). Multicomponent stimuli of this kind give rise to a sensation of pitch (Wilson, 1967, 1970), are generated whenever broadband signals reach the ear via direct and reflected routes, and are utilized by the blind for providing ranging cues (Bassett and Eastmond, 1964; Wilson, 1967). Experiments utilizing comb-filtered noise to stimulate single cochlear fibres (Evans *et al.*, 1971; Wilson and Evans, 1971; Evans and Wilson, 1973) have demonstrated that fibres of the cochlear nerve of the cat respond to multicomponent stimuli in the manner of linear band-pass filters of the same width and shape as the FTC; that lateral inhibition is not involved in the filtering; and that the frequency selectivity of these filters corresponds to that observed in psychophysical measurements with the same stimuli.

Figure 27 illustrates the response of a single cochlear fibre to comb-filtered noise spectra adjusted and switched so that a peak and valley of the spectrum alternately coincides with the CF of the frequency threshold curve, for two different spacings of the spectrum (A and B, respectively). The mean level of the noise spectrum is about 10 dB above the threshold level for noise. At the widest spacing of the spectrum (Fig. 27A), there is a marked difference in the discharge rate between the periods of time (100 msec in each case) when an energy peak (thin continuous line) and an energy "valley" (interrupted line) overlie the inverted FTC (thick continuous line). At progressively closer spacings of the spectral peaks and valleys, the ratio of discharge corresponding to peak and trough responses decreases until a spacing is reached (Fig. 27B) where this ratio becomes unity; *i.e.* the discharge is unaffected by the position of the spectral peaks and troughs relative to the FTC. This point indicates that the fibre is no longer capable of resolving the separate peaks of the spectrum. Inasmuch as these stimuli are analogous to the

luminosity gratings employed in studies of the visual system (*e.g.* Campbell *et al.*, 1969), we can say that the fibre has reached the limit of its "grating acuity". These responses can be quantitatively matched by the responses of a linear band-pass filter of identical frequency response characteristics to that of the fibre's FTC. The

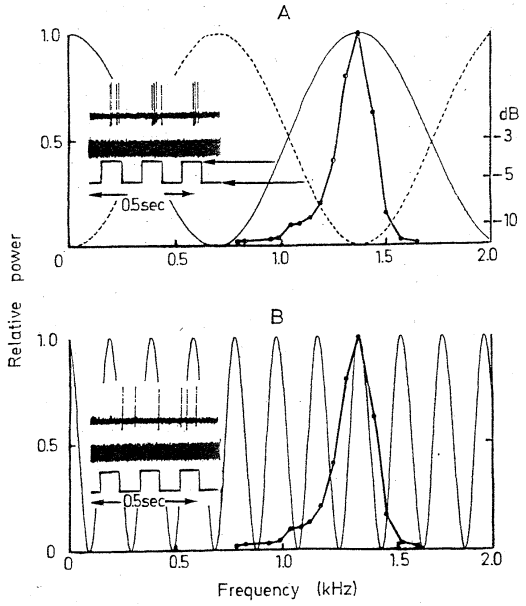

Fig. 27 A, B. Response of cat cochlear fibre to comb-filtered noise stimuli, widely (A) and narrowly (B) spaced. Filled circles and thick continuous line: FTC of fibre plotted as a bandpass filter function in linear relative power and frequency coordinates. A: Widest spacing. Thin continuous sinusoid: envelope of "normal" comb-filtered noise spectrum, with the first energy peak of the spectrum coincident with CF of fibre (1.37 kHz). Dashed sinusoid: envelope of "inverted" spectrum, *i.e.*: with energy minimum at CF of fibre. Inset: continuous film record of spike discharges in response to comb-filtered noise, alternated every 100 msec between normal and inverted conditions according to the switching waveform shown on the lowest trace. Middle trace shows oscillogram of comb-filtered noise stimulus. B: Narrowly spaced spectrum, with peak spacing of 0.2 kHz. Envelope of normal spectrum only shown (thin sinusoid). Otherwise as in A. Note discharge unrelated to alternation of normal and inverted spectra (see text). (From Evans and Wilson, 1973)

fact that this match obtains for all spacings is evidence against the involvement of lateral inhibition in the production of the fibre's narrowly tuned FTC. Lateral inhibition would be expected to produce systematic deviations from the predicted linear filter values such that the response to widely spaced spectra was reduced and that to intermediate spacings was enhanced (vd. Ratliff, 1965 for an analogous case in vision).

A comparison of the limit of "grating acuity" (established as above) for cat cochlear fibres covering a wide range of CFs, with analogous psychophysical measurements (Wilson and Evans, 1971; Evans and Wilson, 1973) suggests that the limits upon the frequency resolving power of the auditory system for multicomponent signals are already largely determined at the level of the cochlear nerve (see Section VI.C.1).

4. Effect of Noise on Responses to Click and Tone Stimuli

Kiang *et al.* (1965a) have demonstrated that the responses to click and tone burst stimuli can be attenuated and finally abolished as the level of a background broadband noise stimulus is progressively raised. In both cases, the initial component of the click and tone responses is attenuated relatively more than the later components.

From the data of Kiang *et al.*, the total "masking" of the click and tone responses appeared to be obtained when the level of the continuous noise stimulus was high enough to cause saturation of the fibres' *maintained* response. Interestingly, this rate was substantially lower than the discharge rate evoked by the *onset* of the tone alone (see p. 18 and Evans, 1974d). Whether this represents an "exhaustion" of some metabolic process, or what the nature of the interaction is, waits upon more data.

III. Cochlear Nucleus

A. Introduction

While all fibres of the cochlear nerve terminate in the cochlear nucleus complex (Stotler, 1953; Powell and Cowan, 1962), the cells of the nucleus receive greatly differing numbers of terminals and modes of termination (*e.g.* Cajal, 1909; Poljak, 1926; Lorente de Nó, 1933a, b; Stotler, 1949; Rasmussen, 1957; Harrison and Warr, 1962; Powell and Erulkar, 1962; Harrison and Irving, 1965, 1966; Osen, 1969; Cohen *et al.*, 1972). For the purpose of this review the simplest and morphologically most conspicuous anatomical subdivision (Fig. 28) will be utilized, namely into dorsal (DCN) and ventral (VCN) divisions, with the latter further subdivided into anteroventral (AVN) and posteroventral (PVN) nuclei. It must nevertheless be remembered that there are at least 9 distinct cell types within the complex (Osen, 1969, in the cat), and that their distribution is not limited by the boundaries of these divisions.

In contrast to the relatively homogeneous properties of cochlear fibres, the behaviours of different neurones of the cochlear nucleus exhibit great variety. To a first approximation, the properties of cells in the VCN differ little from those of the primary fibres, whereas cells in the DCN show a great variety of differences. While such differences were noted in the earlier studies of the cochlear nucleus (*e.g.* Galambos and Davis, 1943, 1944; Rose *et al.*, 1959; Moushegian *et al.*, 1962) it is only recently that they have been related systematically to location within the nucleus. Pfeiffer and Kiang and their colleagues (Pfeiffer and Kiang, 1965; Kiang *et al.*, 1965b; Kiang, 1965; Pfeiffer, 1966b; Kiang *et al.*, 1973) have

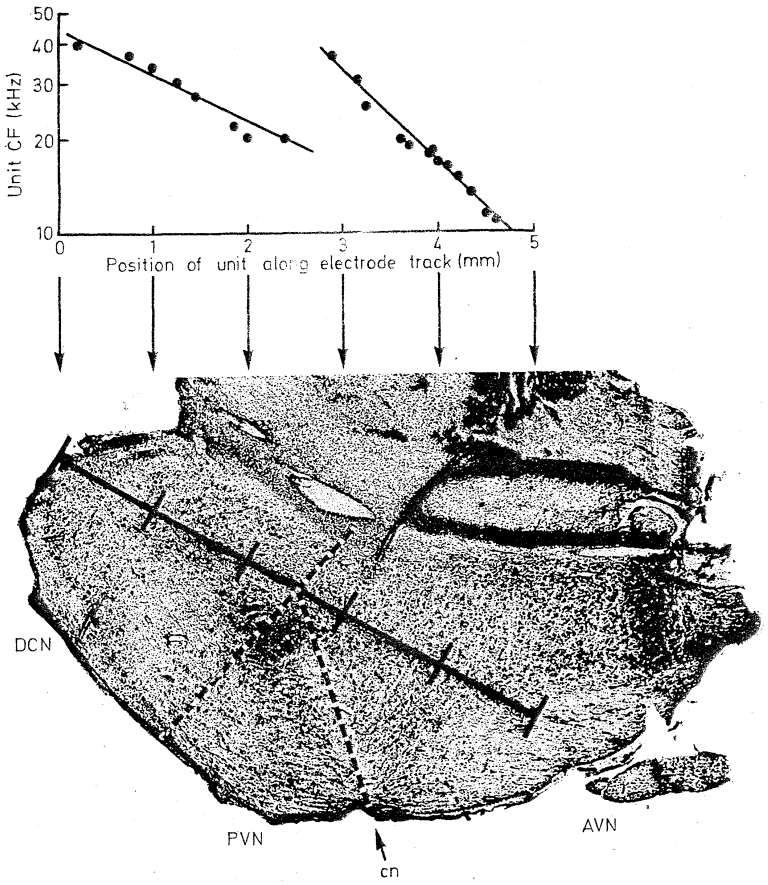

Fig. 28. Gross and tonotopic organization of the cochlear nucleus (cat). Sagittal section through medial region of CN (and adherent cerebellum dorsally) stained with Thionine. Caudal and rostral to left and right respectively. Major subdivisions into dorsal (DCN) and antero- (AVN) and posteroventral (PVN) nuclei indicated approximately by interrupted lines. Incoming and branching cochlear fibres indicated by cn and arrow. Solid line and cross-bars indicate electrode track and mm depth from dorsal surface. Above is plotted the CFs of 21 units found at the indicated depths

undertaken a classification based on the interspike interval statistics of the spontaneous activity and on the time course of the response to tones at the CF about 20 dB above threshold. Evans and Nelson (1966a, b; 1973a, b), in a complementary study of unit responsiveness as a function of stimulus frequency (*e.g.* Figs. 30–32), have shown that there are systematic differences in the distribution

of inhibitory and excitatory influences. Their survey was carried out with tones within 20–40 dB of threshold.

All attempts at classification of response properties face a number of difficulties. In the first place, many anaesthetic agents (including barbiturate and urethane) have a profound effect on the responses of neurones in the DCN (Evans and Nelson, 1973a, b). Such anaesthetics tend to obliterate the differences in properties between the DCN and VCN, and it is unfortunate that all studies of single units in the DCN, with the exception of those by Evans and Nelson (1973a, b) have been carried out under barbiturate or urethane anaesthesia. Secondly, the response properties of many cells in the cochlear nucleus, unlike those of the cochlear nerve, are modified *qualitatively* by changes in stimulus parameters such as frequency, intensity, and repetition rate. Thirdly, different microelectrodes may sample different populations of cells, and, in any case, less accessible and less extensive regions (such as the nuclei lateralis and interstitialis of Lorente de Nó, 1933b) and small-celled areas (*e.g.* the molecular and granular layers of the DCN) are likely to be under-represented. On the other hand, the use of large tipped electrodes by most workers who have explored the CN minimised the chance of recording from primary afferent fibres (Kiang, 1965).

Such technical variables as the above inevitably make impossible the *complete* reconciliation of the findings by different researchers; nevertheless, there are sufficient parallels that a synthesis is possible and useful. While response types cannot be correlated *exclusively* with regions, they can be related at least to subdivision and may turn out to be related to cell type (see, *e.g.* Kiang *et al.*, 1973). A general survey of single unit behaviour in relation to the organization of the cochlear nucleus will therefore be attempted, before proceeding with a more detailed account which will seek to emphasise the major differences in unit properties between the cochlear nucleus and cochlear nerve.

B. Organization

The fibres of the cochlear nerve divide within the VCN into an anterior "ascending" branch which innervates the AVN, and a posterior or "descending" branch which innervates the PVN. The innervation of the DCN is less clear, but appears to arise from a continuation of the posterior branch (Sando, 1965; Osen, 1970; Cohen *et al.*, 1972). In addition, the DCN receives a large projection of "association fibres" from the AVN (Lorente de Nó, 1933b; Harrison and Warr, 1962; Osen, 1970), and the DCN and VCN terminals from the descending, efferent system (Rasmussen, 1960, 1964, 1967).

1. Tonotopic Organization

Rose *et al.* (1959, 1960) were the first to show that there was a triple representation of the cochlea in the cat CN, namely in each of the three major subdivisions. Within each subdivision the CFs of the cells are arranged in strict sequence from high to low frequency in the dorsal to ventral, posterior to anterior, and medial to lateral directions (Fig. 28). This means that as a microelectrode traverses the boundary between two divisions, a discontinuity in CFs will be observed (*e.g.*

between DCN and AVN in Fig. 28). In the granular cell region between the DCN and AVN, the frequency representation is haphazard or reversed.

This strict, thrice-repeated tonotopic organization results from the orderly branching and distribution of the cochlear fibres (Lorente de Nó, 1933a; Sando, 1965). It has been confirmed by other workers and in other species: cat (Pfeiffer and Kiang, 1965; Evans and Nelson, 1973a), chinchilla (Mast, 1970a), gerbil (Smith and Zwislocki, 1971), bird (Konishi, 1970), crocodile (Caiman: Manley, 1970a).

2. Functional Organization

a) **VCN.** To a first approximation, the responses to clicks and tones of neurones in VCN resemble those of the cochlear nerve, and are relatively unaffected by anaesthesia (Evans and Nelson, 1973a). The latencies of the responses to suprathreshold click and tone stimuli are about 1 msec longer than those of cochlear fibres of comparable CF, *i.e.* range from 2—5 msec (Radionova and Popov, 1965; Evans and Nelson, 1973b). Their FTCs closely resemble those of primary fibres, as in Fig. 9 (Kiang *et al.*, 1965b). The predominant response to steady tones is excitation, and the discharge rate is a monotonic function of intensity. In the majority of units, the time course of the response resembles that of primary neurones (Fig. 29F, G, K, L), but, in a small number, the rate of adaptation is very rapid (Fig. 29I, N). In less than 10% of the neurones in the survey of Evans and Nelson (1973a) were inhibitory responses to pure tones observed (as in Fig. 30).

By the criteria of Pfeiffer and Kiang and their colleagues (Kiang *et al.*, 1965b; Pfeiffer, 1966b), neurones located in the anterodorsal region of the AVN can be distinguished from those in the remainder of the AVN and in the PVN. The cells of the *anterodorsal region of AVN* are the large spherical cells of Osen (1970) which receive only a few (three or so) very large terminals, the so-called calyces (bulbs) of Held. Characteristic prepotentials are observed in extracellular recordings from these neurones (Fig. 29P; Pfeiffer, 1966a). These appear to relate to discharges in the cochlear fibre terminals, and their constant relation to the cell discharges suggests that each input spike in any one afferent terminal generates an output spike in the CN cell providing that the input spike does not fall within the refractory period of spikes generated by the other terminals (Molnar and Pfeiffer, 1968; see (3) below). The spontaneous discharges are irregular, the interspike

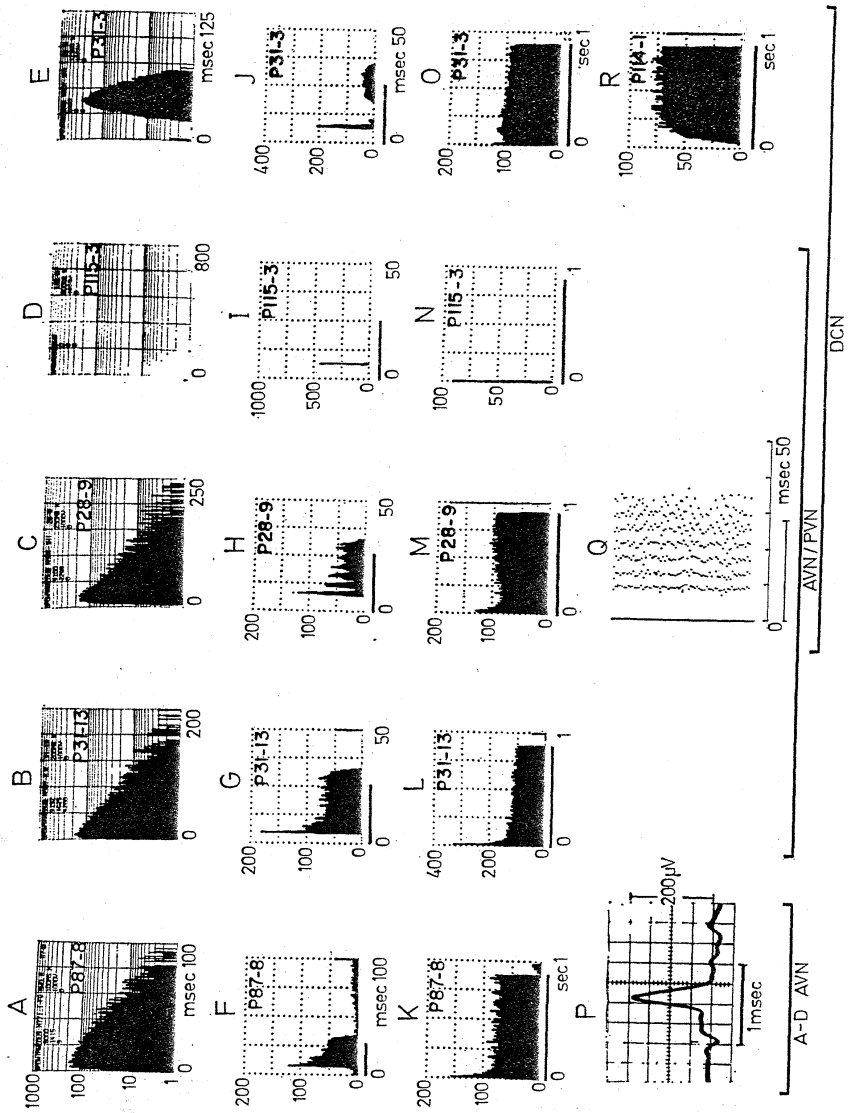

Fig. 29A—R. Categorization of CN units on basis of time course of response. In each column, the first three rows represent the same unit whose responses are typical of the location indicated below plots. A—E: interspike interval histograms of spontaneous activity. F—J: High resolution PST histograms of response to 25 msec tone burst at CF of unit. K—O: PST histograms of response to long duration tone (0.9 sec) at CF. P: waveform of extracellularly recorded potential from unit in anterodorsal cochlear nucleus (A—D AVN). Note positive pre-synaptic potential at beginning of time bar preceding the negative post-synaptic unit spike by about 0.5 msec. Q: "dot display" of individual responses of a "chopper type" unit. Each dot represents one spike, and adjacent horizontal rows response to successive tone bursts commencing at time zero. R: PST histogram to 0.9 sec tone of a different unit in DCN from O, with "build-up" time course. Ordinates: numbers of intervals (A—E) and spikes (F—R) per bin. Abscissae indicate linear time in msec (A—J, Q) and sec (K—O, R); tone bursts indicated by bars. (After Kiang *et al.*, 1965b; Pfeiffer, 1966)

Fig. 29A—R (Legend see p. 46)

interval statistics resembling those of cochlear fibres, with the exception that the rate of decay of the histogram function is somewhat greater than exponential (Fig. 29A; see (3) below). In all other respects the responses are "primary-like" (Fig. 29F, K).

The cells of the *remainder of the AVN, PVN* and the interstitial nucleus (in the root of the cochlear nerve) have similar latencies to the anterodorsal AVN units but can be divided into 3 categories on the basis of the interval statistics of the spontaneous activity and high resolution PST histograms of the responses to brief tone bursts (Fig. 29B–D, G–I). The first category, termed "primary-like", is characterised by an exponential decay of the interval histogram analysis of spontaneous activity (Fig. 29B) and a tone response pattern resembling that of primary

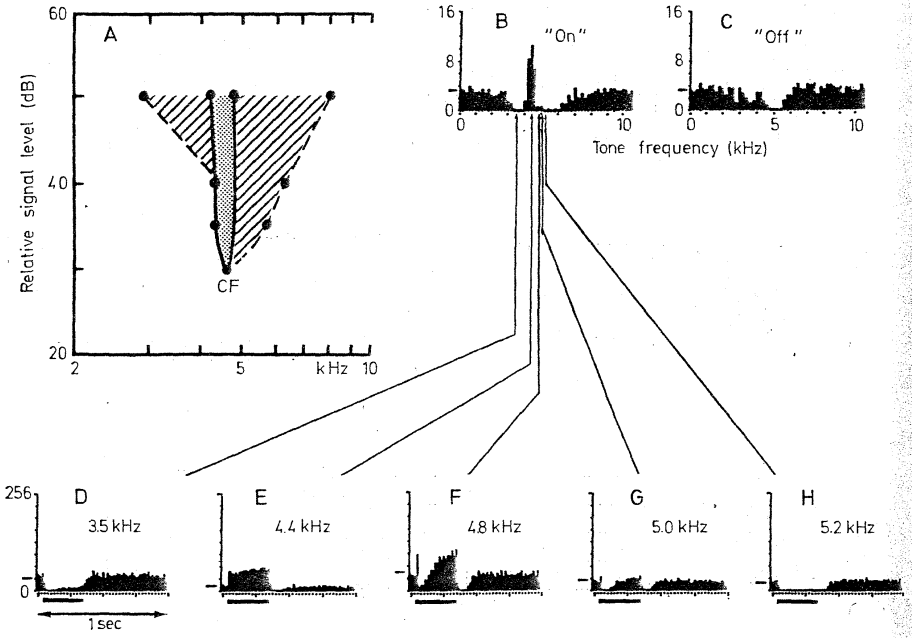

Fig. 30A—H. Frequency response area, frequency responses, and time courses of unit in DCN. A: Excitatory (stippled) and inhibitory (cross-hatched) response areas. Threshold expressed in terms of relative signal level to transducer. The values given represent dB SPL at the CF. The SPLs at other frequencies are within 5 dB of these values. B and C: frequency response histograms of mean response in a 100 msec period during (B) and immediately following (C) 100 msec tone bursts of randomly presented frequency at 20 dB above threshold. Spontaneous discharge rate indicated by bars against ordinate. Note upper and lower frequency inhibitory side-bands, and off-inhibition occurring over similar band as the on-inhibition. D—H: PST histograms of response to 0.3 sec tone burst (bar) at the frequencies indicated (in kHz), at same stimulus level as Band C. Ordinates: total number of spikes per bin, as a result of 53, 22, 79, 41, and 36 tone presentations respectively. Note "primary-like", "pauser", and "build-up" time courses in E, F, and G respectively, and inhibition of spontaneous activity during and following the tone in D and H. (From Evans and Nelson, 1973a)

fibres (Fig. 29G, L). Units of the second category have a variety of interval statistics (including modes longer than 12 msec and slower than exponential histogram decays, *e.g.* Fig. 29C). They are, however, characterised by a regularity of discharge to tones (Fig. 29Q) which produces a periodic "ripple" in the PST histogram pattern to brief tones (Fig. 29H) – hence the descriptive term "chopper-type"

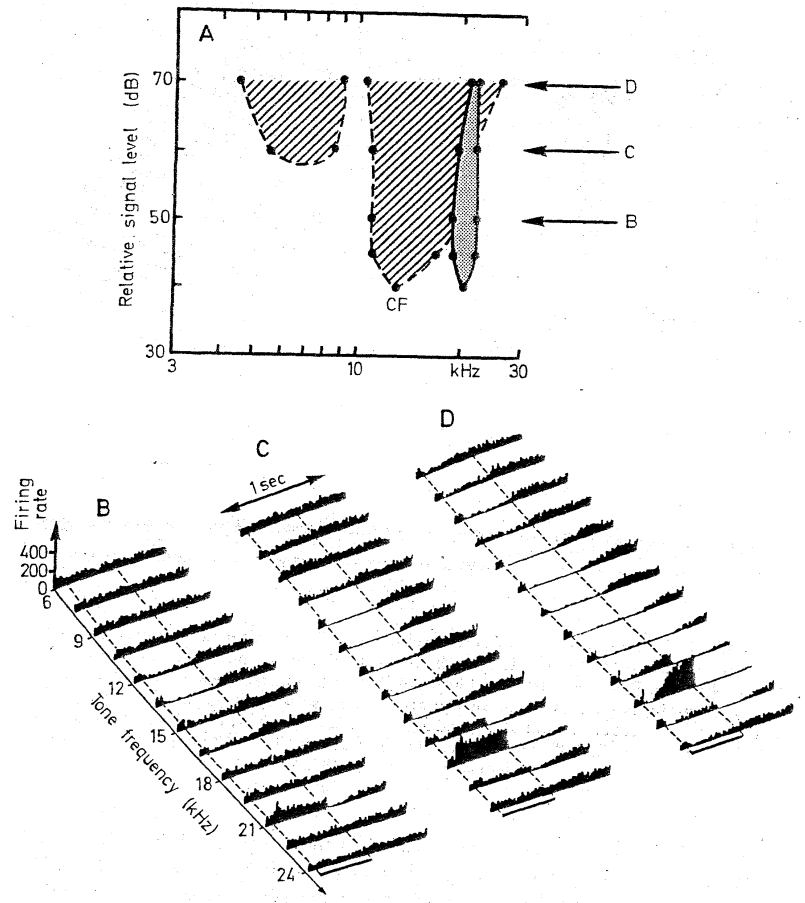

Fig. 31A—D. Frequency response and time courses of predominantly inhibitory DCN unit (cat under chloralose). A: Excitatory (stippled) and inhibitory (cross-hatched) response areas. Relative signal level equals dB SPL at CF (see Fig. 30). B—D: three-dimensional arrays of PST histograms ordered in frequency (6—24 kHz) and intensity (10, 20, and 30 dB above threshold respectively as indicated in A). Tone burst (0.4 sec) indicated by bar and interrupted lines. Ordinate: firing rate in spikes/sec. Note extensive "sea" of inhibition in D with narrow band "island" of delayed ("build-up") excitation at 21 kHz. (From Evans and Nelson, 1973a)

neurones. Units of the third category have little or no spontaneous activity and exhibit a transient response to tones (Fig. 29D, I, N). These are termed "on" units. They are particularly found in the "octopus cell" region of the PVN (Kiang *et al.*, 1973).

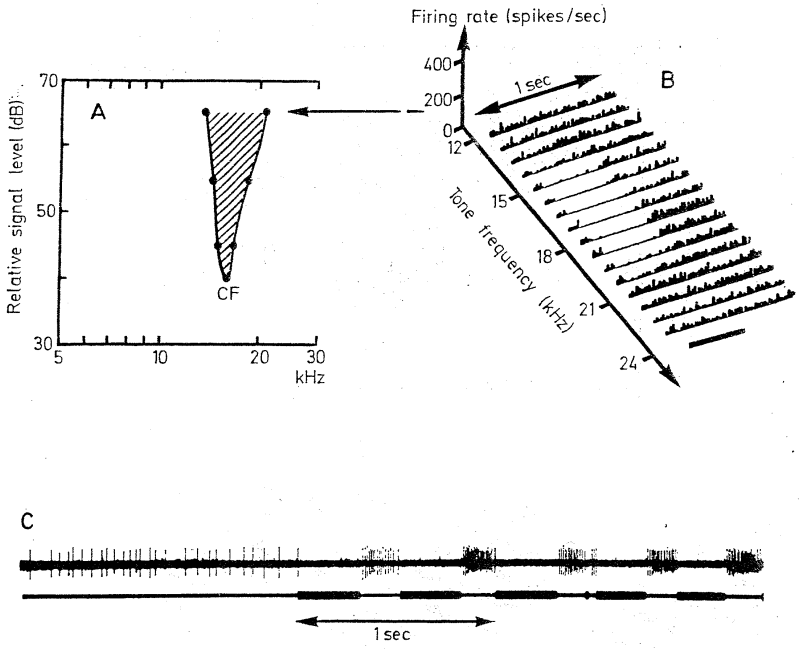

Fig. 32A—C. Frequency response and time course of wholly inhibitory DCN unit (unanaesthetized decerebrate cat). A: Inhibitory response area. Relative signal level equals dB SPL at CF (see Fig. 30). B: three-dimensional array of PST histograms of response to 0.4 sec tone at 25 dB above threshold. Note inhibition of spontaneous activity during, and following, tone. C: Different unit from A, B, but also found in unanaesthetized DCN. Inhibition of spontaneous activity during tone with off or rebound excitation. Tones at CF, 15 dB above threshold. (From Evans and Nelson, 1973a)

b) DCN. In the unanaesthetized cat, less than 10% of DCN units exhibit behaviour resembling that of primary fibres (Evans and Nelson, 1973a). The responses of the remainder arise from greater or lesser admixtures of inhibitory and excitatory influences, as indicated by inhibition of spontaneous activity and non-monotonic response relationships with stimulus level. The latency of the responses to click and tone stimuli are generally longer than those in the VCN, and range from 4—12 msec (Radionova and Popov, 1965; Evans and Nelson, 1973b). The frequency response areas range from central excitation with inhibition over one or more adjacent frequency side-bands (Fig. 30), through predominant inhibitory response bands associated with a narrow excitatory response band (Fig. 31), to inhibition only (Fig. 32). The complex time-courses of the responses associated with apparently contiguous inhibitory and excitatory bands indicate that the response regions in fact overlap (Figs. 30F, G and 31C, D). The proportions of DCN units exhibiting side-band, predominant, or total inhibition were about 20, 20, and 50% respectively in the unanaesthetized cat, compared with 40, 0, and 10% in pentobarbitone or halothane anaesthetized cats (Evans and Nelson, 1973a). These anaesthetic agents thus exert a profound effect on the DCN in reducing the predominance of inhibition.

On the basis of their PST histogram analyses of tone evoked activity, Kiang *et al.* (1965b) and Pfeiffer (1966b) observed in the anaesthetized cat a category of unit not found in the VCN, which they termed a "pauser type" (Fig. 29J). This type of PST histogram was also common in the DCN data of Evans and Nelson (1973a), but, as Figs. 30 and 31 indicate, it is not invariant of stimulus frequency or level. Figure 29R and Fig. 30G illustrate another type of time-course that is characteristic of some units in the DCN, namely, where the discharge rate increases (instead of adapting) with time. This pattern of behaviour was termed "build-up" by Rose *et al.* (1959); it is dependent upon the repetition rate as shown in Fig. 34 (also see Pfeiffer, 1966b). Units of the "chopper" and "on" categories were also found in the DCN. Analyses of the interval statistics of the spontaneous activity revealed almost symmetrical distributions in some DCN units (Fig. 29E) and that the majority of the DCN interspike interval histograms had modal values over 10—20 msec, in contrast to the situation in the VCN (Pfeiffer and Kiang, 1965).

3. Nature of Sensory Input to Neurones of CN

With its diversity of response, related to the morphology, the cochlear nucleus is ideally suited to studies of the functional significance of different patterns of innervation.

Pfeiffer and Molnar (1968) have been able to fit to the observed interspike interval statistics of primary and VCN neurones, input-output models with assumptions which correlate well with the anatomy. In the anterodorsal AVN, the statistics are consistent with a superposition of 3—4 input renewal processes, where (apart from its refractory period) the cell discharges each time a discharge appears on one of the 3—4 input fibres. These cells are innervated via the large calyces of Held by 3 or so cochlear fibres (Cajal, 1909). Certain cells in the PVN have discharge patterns consistent with a model where each output discharge requires the accumulation of a number of discharges from a large number of input fibres, a situation consistent with the morphology of the region.

In a remarkable series of experiments, Koerber *et al.* (1966) have demonstrated that the spontaneous discharge of units in the VCN is dependent upon the activity of the cochlear nerve input. Acute (and chronic) interruption of the nerve eliminated the spontaneous activity of all units in the AVN and of almost all in the PVN. In contrast, the spontaneous rates and interval statistics of units in the DCN were unaffected. This finding correlates with the conclusion, on anatomical grounds (Stotler, 1949; Rasmussen, 1957; Powell and Cowan, 1962; Harrison and Warr, 1962; Osen, 1970; Cohen *et al.*, 1972), that the cells of the DCN

receive at most only a small proportion of the total number of their afferents from the cochlear nerve. In a series of experiments, Evans and Nelson (1968, 1973b) have implicated the intranuclear fibre pathway running between the AVN and the DCN (Lorente de Nó, 1933b; see Fig. 49) as the mediator of the predominant inhibitory sensory input to the DCN, seen particularly in the unanaesthetized preparation. This inhibition has too short a latency (4–6 msec) for it to be mediated by the efferent auditory system, and it can be evoked by tones after interruption of descending pathways. Furthermore, it can be evoked by direct electrical stimulation of the cells of the AVN or the fibres of the intranuclear pathway itself. These data give further grounds for the conclusion, from the greater complexity of response, the longer latency, and susceptability to anaesthetic agents of cells in the DCN compared with those of the VCN, that the DCN is a higher than second-order nucleus.

C. Spontaneous Activity

The range of spontaneous rates from cell to cell in the CN is at least as great as that in the cochlear nerve, from 0–150 spikes/sec (Pfeiffer and Molnar, 1968; Evans and Nelson, 1973a). The latter authors found a slightly higher mean rate in cells of the VCN (29/sec) compared with those of the DCN (20/sec) in the anaesthetized cat, consistent with the former authors' report of a relative dearth of units in the AVN with rates below 10/sec.

Mention has already been made (Section III.B.2,3) of the finding and possible significance of the variety of interspike interval distributions in the CN. In addition to distributions identical or similar to those obtained in the cochlear nerve, *i.e.* quasi-Poisson (Fig. 29A–C; Viernstein and Grossman, 1961; Rodieck *et al.*, 1962; Pfeiffer and Kiang, 1965), more symmetrical and restricted distributions are encountered, particularly in the DCN (Fig. 29E; Pfeiffer and Kiang, 1965). This means that some units in the DCN have a comparatively regular spontaneous activity, and adds further weight to the argument that the activity of DCN cells is less dependent than that of the VCN on input from the cochlear nerve (Section III.B.3 above). This argument is based partly on the finding of Koerber *et al.* (1966) that the spontaneous activity of cells in the VCN is abolished by section of the cochlear nerve, while that of the DCN is unaffected.

D. Response to Click Stimuli

Not all units in the DCN are driven by click stimuli (Rose *et al.*, 1959); others are very sensitive. In the sample of Rose *et al.* (1959), thresholds of response to click stimuli ranged from 10–75 dB above those to CF tones. (The click stimuli had approximately the same threshold for normal human hearing as 2 kHz tones). Some of their units in the DCN were exquisitely sensitive to the click level, and required only a 4 dB increase to raise the probability of a response from zero to 100%.

The ability of CN units to "follow" repetitive clicks has received a good deal of attention. At least two types of behaviour have been found. In the first, resembling

that of the cochlear nerve, the discharge rate increases monotonically with click rate, while the probability of discharge per click decreases with click rates in excess of 10–100/sec. The second group of units, which exhibit transient responses to tones, generate one spike for every click at click rates of up to 100–800/sec (Kiang *et al.*, 1962 a in the cat; Møller, 1969b in the rat). Thereafter, the probability of discharge and the mean discharge rate, drop off abruptly towards zero. Konishi (1969a) has pointed out that this 1 : 1 response can be maintained in some units in the bird up to click rates in excess of 1000/sec.

The PST histograms of responses to clicks of "primary-like" cells with CFs below 4 kHz in the AVN exhibit the multiple peaks characteristic of cochlear fibres. On the other hand, cells of the "chopper", "on" and "pauser" types had histograms with single peaks only, irrespective of their CF (Kiang *et al.*, 1965b).

The latencies of response to click stimuli have already been mentioned (III.B.2).

E. Response to Single Tonal Stimuli

The varieties of response and their relative preponderance in the different divisions of the CN have already been outlined (III.B.2; Figs. 29–32). It will be necessary, however, to add a qualification in respect of the group of units exhibiting transient ("on") responses to tones. The proportion of these units found ranged from 1–20% as follows: 1% Evans and Nelson (1973a); 8% Pfeiffer (1966b); 20% Radionova (1965, 1971), Møller (1969b). In the latter studies, where these units accounted for one fifth of the total encountered, the possibility exists that some at least of these responses represent those of high CF units stimulated by the energy dispersion associated with the very short tone onset times used in the studies. This could account for the finding by Møller (1969b) and Radionova (1971) that the units had very high threshold, broadly tuned FTCs, and for the otherwise surprising independence found by Radionova (1971) of the threshold upon tone duration (for durations as short as 1 msec) compared with that of units where the response to tones was sustained. Furthermore, the thresholds of Radionova's transient units were sensitive to the rise time of the tonal stimuli, and transient responses were often present at the abrupt termination of the tones. The transiently responding units in the surveys by Pfeiffer (1966b) and Evans and Nelson (1973a), on the other hand, had relatively normal thresholds.

1. Threshold and Response as a Function of Frequency

With the possible exception of the "transient units" mentioned above, there is no evidence to suggest that the range of minimum thresholds of CN cells is any less restricted than in the cochlear nerve (Mast, 1970a). Similarly, the minimum unit thresholds approach the threshold of behavioural response ("audiogram") of the animal as in Fig. 8 (cat: Galambos and Davis, 1943; rat: Møller, 1969a; chinchilla: Mast, 1970a; bird: Konishi, 1969b, 1970). Konishi (1970) has shown that a striking correlation exists between the range of unit CFs in different birds with the frequency components of their song. Manley (*e.g.* 1970b) has demonstrated a relationship between the range of CFs and basilar membrane measurements in different species of reptile.

Under anaesthesia, the excitatory FTCs of CN cells are not substantially different from those of cochlear fibres (Kiang, 1965) nor are marked differences observed between divisions of the nucleus (Kiang *et al.*, 1965b). Unfortunately, there are insufficient data available obtained under identical and calibrated conditions to allow a quantitative comparison of excitatory bandwidths between cells of the cochlear nerve and nucleus, but if anything, the CN bandwidths at 10 dB above threshold are on average larger than those of the cochlear nerve (*e.g.* data of Kiang, 1965). The variation in bandwidth on the other hand may be much greater in the CN than in the cochlear nerve. Rose *et al.* (1959) and Møller (1969a) reported the finding of wide and narrow bandwidths in their data from the cat CN. Taking all the available data, it is clear that, at one extreme, one can find some FTCs which are substantially broader (especially on the low-frequency side) than those of cochlear fibres of corresponding CF, and, at the other extreme, some excitatory FTCs (particularly in the DCN) which do not increase in bandwidth with increase in stimulus level or which actually decrease (*e.g.* Fig 31 A; Katsuki *et al.*, 1958; Kiang *et al.*, 1965b). In other words, the latter FTCs are narrower (for higher stimulus levels) than those of corresponding cochlear fibres.

The FTCs of a few CN cells are multiple, *i.e.*, they have two or more definite peaks (Rose *et al.*, 1959; Moushegian *et al.*, 1962; Manley, 1970; Evans and Nelson, 1973a).

The major innovation in frequency response characteristics is the presence, in certain cells of the CN, of response regions where the spontaneous activity is inhibited by single tones, as has been outlined above (III.B.2). Cells with entirely inhibitory response areas (as in Fig. 32) have been found in 20% of cells of the N. magnocellularis of the anaesthetized pigeon (Stopp and Whitfield, 1961), in occasional cells of the unanaesthetized cat VCN (Moushegian *et al.*, 1962; Evans and Nelson, 1973a) and in cells of the DCN of cat (Gerstein *et al.*, 1968; Evans and Nelson, 1973a) and chinchilla (Mast, 1970a). In other cells, extensive (Fig. 31) or relatively restricted (Fig. 30) "side-bands" of inhibition are associated with and are usually contiguous with excitatory response regions (cat: Galambos, 1944; Katsuki *et al.*, 1958; Moushegian *et al.*, 1962; Greenwood and Maruyama, 1965; Gerstein *et al.*, 1968; Evans and Nelson, 1973a; chinchilla: Mast, 1970a). In some cells, frequencies, which near threshold are excitatory, become inhibitory at higher levels (*e.g.* 20 kHz in Fig. 31; Rose *et al.*, 1959; Greenwood and Maruyama, 1965). Reports on these inhibitory regions are almost entirely confined to findings in the DCN (see also Tasaki, 1957). Where they have been systematically looked for, inhibitory response regions were found in less than 10% of cells in the VCN but in over 90% of DCN cells in the *unanaesthetized* cat (Evans and Nelson, 1973a). About half of the DCN cells in the latter study had entirely inhibitory response regions.

2. Response as a Function of Intensity

From the fore-going, it will be apparent that the spike rate versus intensity functions differ from cell to cell and at different frequencies. While VCN units generally have monotonic rate functions resembling those of primary fibres (Fig. 14; Galambos and Davis, 1943; Rose *et al.*, 1959; Greenwood and Maruyama, 1965; Møller, 1969a), non-monotonic functions are found in the DCN (Fig. 33; Rose *et al.*, 1959; Greenwood and Maruyama, 1965; Goldberg and Greenwood, 1966). In the latter case, the ultimate reduction in firing rate with increase in intensity can occur at quite low stimulus levels (*e.g.* 30 dB SPL as in Fig. 33) and can be associated with inhibition of spontaneous discharges at higher stimulus levels still (as in Fig. 31). The converse occurs in other cases, *i.e.* inhibition at low stimulus levels is superseded by excitation at higher levels (Galambos, 1944).

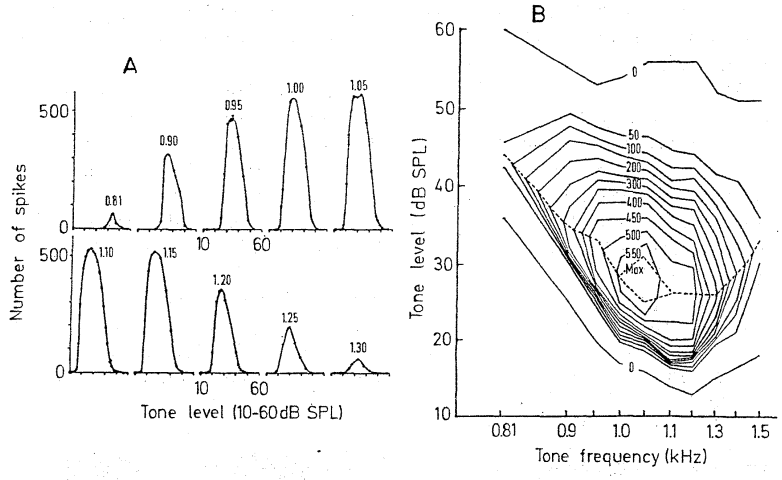

Fig. 33 A, B. Non-monotonic intensity functions of unit in anaesthetized DCN. A: spike discharge versus tone intensity functions at each of the frequencies indicated (in kHz). Number of spikes counted over 20 trials during initial 0.2 sec of tone presentation. Each plot relates to its own abscissa marked off in 10 dB steps, from 10—60 dB SPL. B: Iso-rate contours derived from A. Numbers on contours correspond to counts in A. The lowest curve (0 spikes) represents the FTC for excitation. (From Greenwood and Maruyama, 1965)

Smith and Zwislocki (1971) have addressed themselves to the interesting question whether the rate functions for the initial onset burst of primary-like monotonic cell discharges differ from those for the later, adapted portion of the response to tones. Comparing the firing rates at the tone onset and after 200 msec of adaptation, they concluded that the adapted response saturated at a lower discharge rate. Unfortunately, their experiments were conducted only over a range of intensities restricted to 10 dB, an insufficient range to demonstrate that the unit illustrated had actually reached saturation. On the contrary, in additional experiments, by superimposing short increments in intensity upon the adapting tone "pedestal", they demonstrated that the rate limited at essentially the same saturation rate as for the onset response, irrespective of the length of adaptation.

3. Response as a Function of Time

In Section III.B.2, and Figs. 29–31, the different time courses of responses to steady tones ("primary-like", "chopper", "on", and "pauser" types) and their relationship to location within the CN have been outlined according to the classification of Kiang *et al.* (1965); Pfeiffer (1966b). With the exception of the chopper-type time-courses, the different types have been noted by other workers (*e.g.* Rose *et al.*, 1959; Moushegian *et al.*, 1962; Greenwood and Maruyama, 1965; Evans and Nelson, 1973a). In addition, as noted, purely inhibitory responses with time courses the inverse of those of primary-like excitation (Fig. 32) and with (Fig. 32C) and without (Fig. 32B) an "off" response have been found in the DCN (Galambos, 1944; Moushegian *et al.*, 1962; Greenwood and Maruyama, 1965; Mast, 1970; Evans and Nelson, 1973a).

The "chopper" type of PST histogram is produced by a discharge pattern which is relatively regular in time (*i.e.* the intervals between successive spike discharges are approximately constant) and which is synchronized to the onset of the tone (Fig. 29Q). Since the preferred interspike interval is of the order of 3 msec, high resolution histograms are required to demonstrate the "chopper" appearance (compare Fig. 29H with M). This preferred interval is unrelated to the tone frequency, phase of tone inset, and the CF of the cell, and is relatively invariant of tone level (Pfeiffer, 1966b).

The "primary-like", "chopper" and "on" time-courses are maintained over a wide range of effective stimulus frequencies and levels (Pfeiffer, 1966b; Evans and Nelson, 1973a). This is not, however, the case for the DCN units where excitatory-inhibitory admixtures are evident in their responses (Figs. 30, 31; Rose

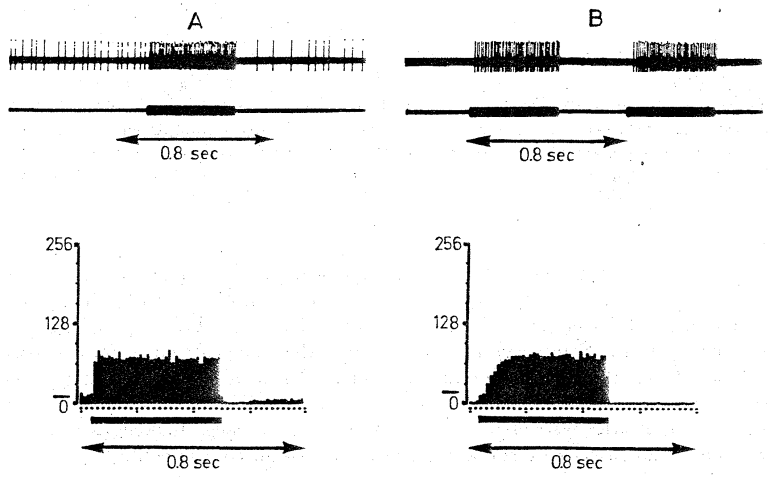

Fig. 34A, B. Effect of repetition rate on time course of response. Unit in DCN (anaesthetized cat). 0.5 sec tone at CF, 20 dB above threshold. Repetition rate: 1 per 3 sec in A; 1 per 0.8 sec in B. Above are shown continuous film records taken during PST histograms (below) of 32 and 43 tone presentations respectively

et al., 1959; Greenwood and Maruyama, 1965; Pfeiffer, 1966b; Evans and Nelson, 1973a). Pre-exposure to stimuli can modify the rate of adaptation of response (Rose *et al.*, 1959) or convert a "primary-like" time course into one characteristic of "build-up" units (Fig. 29R). The latter effect appears to result from a more powerful and long-lasting off-suppression seen in the responses of many CN cells (particularly in those in the DCN) compared with those of cochlear fibres (Fig. 34; Evans, 1971; Evans and Nelson, 1973a). From the relation observed between the duration of off-suppression and the duration and level of the stimulus tone, Starr (1965) concluded that the off suppression was a form of post-excitatory depression representing some metabolic effect of activity. However, this cannot be so for many units, particularly those in the DCN. Here, the frequency range over which the off-suppression is observed is not identical with that which evokes the preceding excitation (*e.g.*, Fig. 30C) and, in many cases, the off-suppression follows a response which is inhibitory (*e.g.*, Fig. 30C, G, H; Fig. 31D: responses between 16.5 and 22.5 kHz). Furthermore, in some units the duration of off-suppression is relatively invariant of tone duration. These observations strongly suggest that the powerful off-suppression seen in many CN units results from active inhibitory mechanisms, and Starr and Britt (1970) have succeeded in demonstrating, by intracellular recording, hyperpolarizing potentials during the post-stimulus period and inhibition, during these periods, of discharges evoked by intracellular current injection.

4. Response to Low-frequency Tones

"Phase-locked" responses (*cf.* II.D.4) in the cat CN were first reported by Galambos and Davis (1943) and were consistent with an upper limit of neural following of about 4 kHz. Unlike the situation in the cochlear nerve, however, not all CN units of low CF exhibit phase locking to the cycles of low frequency tones within their response areas (Rupert and Moushegian, 1970: kangaroo rat VCN; Lavine, 1971: cat). Rupert and Moushegian (1970) described a group of units in the VCN which appeared to give phase-locked responses only over a narrow range of low frequencies (*e.g.* less than 0.5 kHz). (It is not clear, however, whether in some of their cases phase-locked responses were being confused with or were receiving interference from chopper types of response.) On the basis of these studies, Rupert and Moushegian (1970) have suggested that this response diversity may correlate with the heterogeneous morphology of the kangaroo rat VCN.

In the cat, on the other hand, Lavine (1971) found the heterogeneity of phase-locking properties to occur only in the DCN. Those units which showed phase-locking exhibited a variation in the preferred phase of discharge with stimulus frequency, which was relatively unaffected by changes in stimulus levels, as found in the cochlear nerve (II.D.4).

Large electrodes have been used to record gross potentials which correspond to the cycles of stimuli up to frequencies of 2 to 3 kHz – the so-called "frequency following response" of Marsh and Worden (1968; see also Marsh *et al.*, 1970). Starr and Hellerstein (1971) have mapped out these responses in the cat CN and found them to have larger amplitudes in the VCN than in the DCN. This may relate to the narrower distribution of response latencies in the VCN.

F. Response to Complex Sounds

1. Two-tone Stimuli

Suppression of the excitation due to one tone, by tones at other frequencies has been observed in many studies of the CN in the cat (Galambos, 1944; Katsuki *et al.*, 1959; Moushegian *et al.*, 1962) and in the pigeon (Stopp and Whitfield, 1961). The characteristics of this two-tone suppression are identical in many respects (particularly for cells in the VCN) with those already described for the cochlear nerve (Section II.E.1.a). Thus, the frequencies of suppressing tones adjoin and overlap the upper and lower frequency borders of the excitatory response area. Such properties are presumably handed on to the CN neurones by the primary fibres.

In addition, there is considerable evidence to indicate that neural inhibition is involved in the two-tone suppression of some cells at least. As originally described by Galambos (1944), the inhibition in some cases extended well below the spontaneous discharge rate, even for tones of long (20 sec) duration; the two-tone inhibitory frequency bands were often associated with the frequency bands in which inhibition of the spontaneous discharge could be evoked by single tones.

Greenwood and Maruyama (1965) have demonstrated that a narrow band of noise can be as effective as a second tone in suppressing tone evoked activity. Again, the results obtained under these conditions can be interpreted in terms of two stimulus interaction effects in the primary afferents to the CN cells, with the addition of local inhibitory influences (Greenwood and Goldberg, 1970).

2. Noise Stimuli

As might be expected, the responses of neurones in the CN to noise stimuli depend upon the type of neurone and upon the frequencies covered by the noise spectrum.

Møller (1970a) has carried out a comparison of noise and tone thresholds in the rat CN, analogous to that described for the cochlear nerve in Section II.E.2 (Fig. 35M, solid points). In addition, he has made a similar comparison between *suprathreshold* noise and tone intensities, *i.e.*, those required to evoke the same firing rate as a tone at 10 dB above threshold (Fig. 35M, circles). The data have been replotted in Fig. 35 for convenient comparison with the analogous cochlear nerve data in Fig. 26. It will be seen that the cochlear nerve and nucleus measurements *at threshold* are very comparable (in spite of the species difference). This is also the case for most of the suprathreshold data. Some of the latter, however, appear to form a separate population (circles above main body of data) with behaviour substantially different from the remainder. This is what would be expected if the separate population was drawn from DCN cells, where lateral inhibitory processes could be expected to produce the effect of raising the noise threshold relative to that of a tone at the CF. In the lower panel (C) of Fig. 35 are shown the corresponding values derived, as indicated in Fig. 26, from the FTCs of the units represented in M. The effective bandwidths of the FTCs were not computed directly by Møller but were estimated by taking half the value of the bandwidths measured at 10 dB above minimum threshold. A comparison of

Fig. 35M with C indicates that, apart from the "separate population" referred to above, there is good agreement between the noise thresholds actually measured and those derived on the basis that the FTC represents a linear filter function. Pooling and averaging his data, Møller himself concluded that the suprathreshold spectral resolution of CN units was higher than would be indicated by the FTC

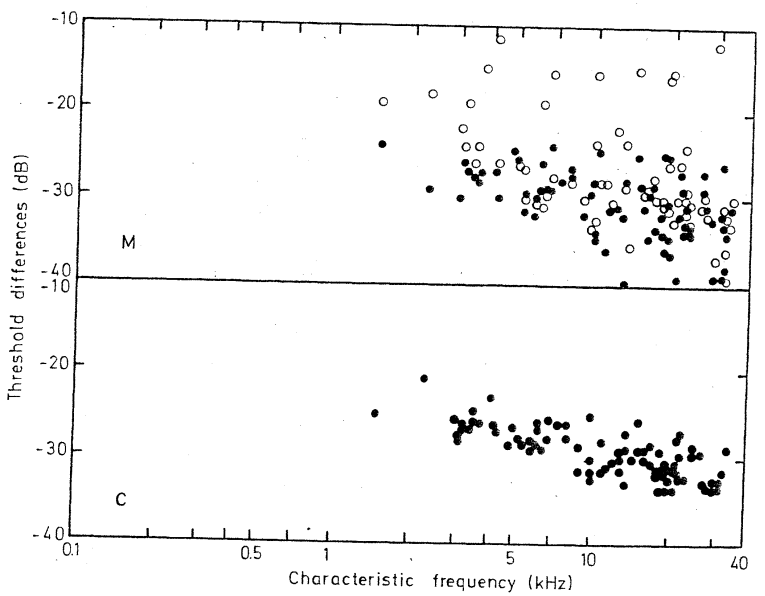

Fig. 35. Difference between noise and tone thresholds for CN units in anaesthetized rat, plotted against CF for each unit. See legend of Fig. 26 and text. Filled circles: determinations at threshold; open circles: determinations of signal levels for equal response at 10 dB above threshold. (Data from Møller, 1970a)

and by the near threshold noise: tone comparisons. The point being made here is that Møller's conclusion only holds for *part* of his data, namely, from a population of cells which might be drawn from the DCN. In contrast, the majority of his units behaved as did the cochlear fibres, *i.e.* their spectral resolution was consistent with that predicted from the pure tone FTC. The CN cannot be treated as if it were a homogeneous nucleus.

Goldberg and Greenwood (1966, 1970) found that the responses of CN neurones to narrow bands (100–200 Hz wide) of noise centred at the CF were generally similar to the response to CF tones, but differed slightly in some details (Fig. 36A). The thresholds for the noise stimuli (open circles) were slightly lower than for the CF tones (open squares); the rate of increase of response with increase in intensity was not as rapid with the noise as with the tones; and the maximum,

saturated, discharge rates in some cases was lower with noise compared with tones. These effects are presumably related to the considerable fluctuations in amplitude, characteristic of such narrow noise bands.

In many units, widening the bandwidth of the noise stimuli about the CF produced summation effects as would be expected from the considerations of Section II.E.2. That is, doubling the bandwidth (at constant spectrum level) had

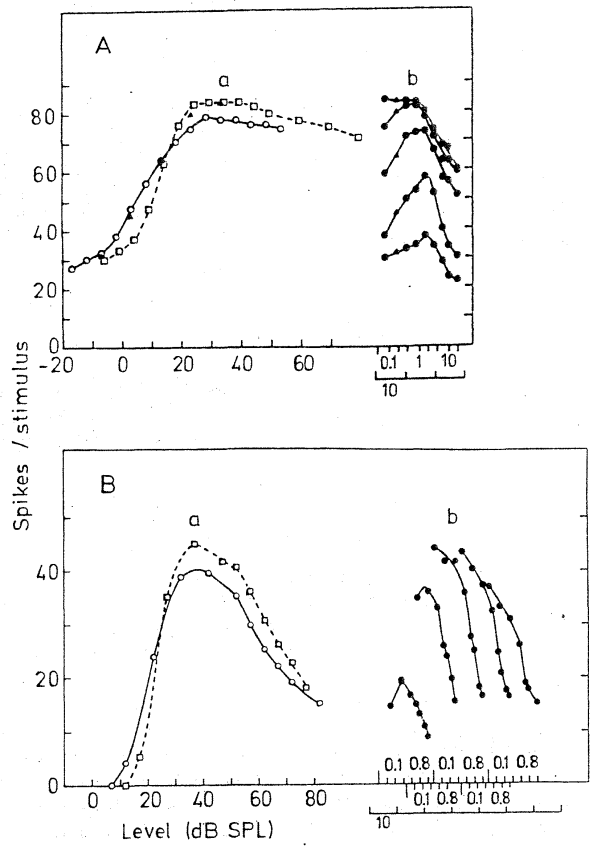

Fig. 36A, B. Effect of widening noise bandwidth on two units in the cat CN with A, monotonic and B, nonmonotonic intensity functions. A in PVN; B in DCN. Left-hand plots (a): Number of spikes per 200 msec stimulus, square symbols: tones at CF, open circles: narrow band (A: 200 Hz; B: 60 Hz) noise centred on CF (13.4 kHz in A; 0.8 kHz in B). Righthand plots (b: solid circles): number of spikes per 200 msec stimulus of band-limited noise (centred on the CF) of increasing bandwidth at constant spectrum level (left to right: expressed in kHz in upper abscissae and as relative intensity in 10 dB steps in the lower abscissae) and increasing spectrum level (lower to upper plots). (From Greenwood and Goldberg, 1970)

the same effect on the response as increasing the spectrum level by 3 dB, until the noise bandwidth approached the effective bandwidth of the FTC. Thereafter, widening the noise band had progressively less effect on the response (as the increments in bandwidth and, therefore, power lay outside the FTC bandwidth). This was not the case however in all units: in some, summation occurred only up to a certain bandwidth beyond which the neurone's discharge rate actually *decreased* towards, and in some cases below, the spontaneous level. For the latter units which had monotonic rate-intensity functions (drawn from DCN and PVN), the bandwidths at which suppression began to appear ranged from about 1—4 kHz, tending towards the lower values at higher spectrum levels (Fig. 36A). For non-monotonic units (found in the DCN), on the other hand, these bandwidths were below 0.4 kHz (Fig. 36B). In these cases, presumably, the widening noise bands are encroaching on lateral inhibitory side-bands (Section III.B.2.b). It is doubtful whether a substantial reduction in the input from primary fibres is involved by a mechanism analogous to that of two-tone suppression, in view of the fact many CN neurones do not show this suppression with increase in bandwidth, and in view of the findings discussed in Section II.E.2.

The narrower bandwidths of summation found in nonmonotonic DCN cells presumably reflect the greater incursions of the inhibitory sidebands in these units.

3. Stimuli with Multicomponent Spectra

Møller (1970b) has carried out an ingenious experiment in which the responses to paired click stimuli of units in the rat CN were measured over a wide range of separation of the clicks. He interpreted his results in temporal terms (*i.e.* interference between two damped oscillatory responses of the peripheral auditory analyser), but they could equally be looked at in spectral terms, for paired click stimuli generate short term comb-filtered spectra where the spacing of the spectral peaks and valleys is related to the click pair separation (vd. Section II.E.3). Figure 37A shows the responses of a unit to paired click stimulation, where the interval is varied from about 50—1000 μsec. After converting the response (number of discharges per click pair) into terms of the equivalent stimulus level, an autocorrelation function was computed of the system's impulse response (Fig. 37B, interrupted line). The thin continuous line in Fig. 37B represents the autocorrelation function computed, by inverse Fourier transform, of a near threshold isorate function for the unit (analogous to the FTC). Møller found that a better fit could be obtained between observed and computed autocorrelation functions if the response area used for the computed continuous line in Fig. 37B was halved in bandwidth. From this he suggested that the peripheral analyser had a higher spectral resolution with regard to double click stimulation than it had for tones. Such a conclusion conflicts with findings in the cochlear nerve (discussed in II.E.3), where the results of comb-filtered noise stimulation were consistent with the cochlea acting as a simple linear filter of *equal* bandwidth to tones and multicomponent spectral stimuli. However, it is clear from Fig. 7 of Møller (1969a) that the isorate contour chosen from the data on that unit by Møller (1970b) was somewhat anomalous and was wider in bandwidth than the suprathreshold isorate contours obtained for the same unit and than the average for the rat CN (Møller, 1972b: Fig. 20). If he had used one of the suprathreshold isorate contours (which

in fact would seem to be a more appropriate choice in view of the click results being obtained at suprathreshold levels), it appears likely that a more satisfactory fit still would have been obtained with the observed data in Fig. 37 B, in terms of both amplitude and phase. This, then would be consistent with cochlear nerve findings. Møller's demonstration that the frequency selectivity represented by his results was available immediately and persisted unchanged over a click intensity range of 30 dB is also consistent with the cochlear nerve data and affords

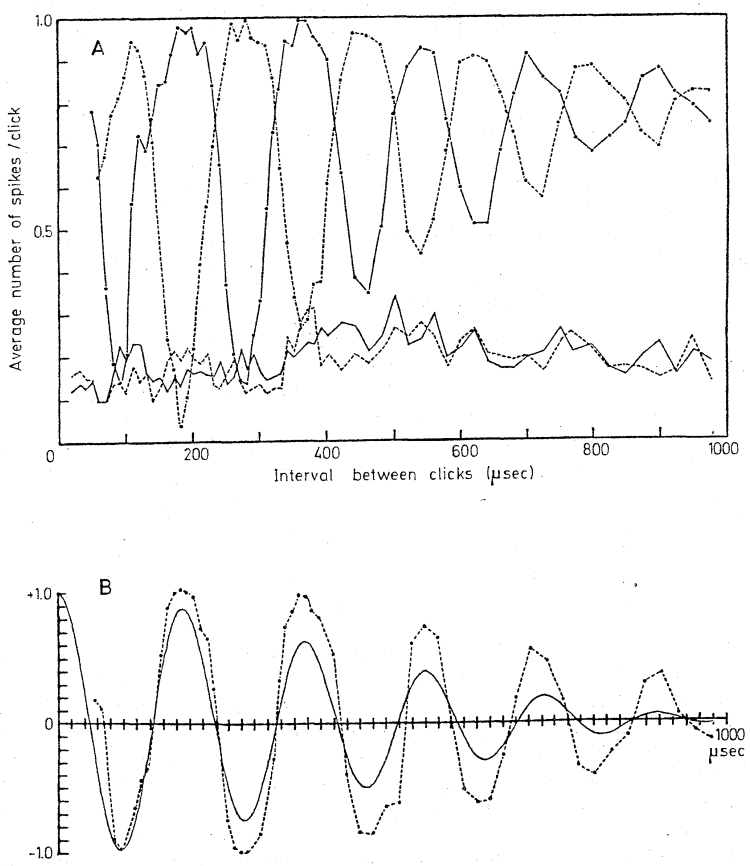

Fig. 37 A, B. Response of unit in rat CN to stimulation with paired clicks. A: Average number of spikes evoked by a click pair at the interclick intervals indicated. Solid lines: response to one polarity of clicks; interrupted lines: response to opposite polarity. Lower curves: index of spontaneous activity. B: Interrupted lines: Autocorrelation function of the system impulse response computed from A. Continuous lines: autocorrelation function computed by inverse Fourier transform of the unit's FTC. Abscissa: Linear delay. See text. (From Møller, 1970b)

further evidence that the frequency selectivity is not accomplished by sharpening mechanisms (such as lateral inhibition) which take a significant amount of time to operate (see Section VI.A.1).

4. Frequency and Amplitude Modulated Tones

Since the finding, in the upper levels of the auditory system, of units selectively sensitive to frequency-modulated sounds (Bogdanski and Galambos, 1960; Evans and Whitfield, 1964; Suga, 1964, 1965b; Watenabe and Ohgushi, 1968), there have been many studies of the responses to modulated tones in the cochlear nucleus. In contrast to the former data, there is little evidence for *specific* sensitivities for modulation in the CN. In fact, little difference exists in the thresholds of CN cells for both steady and modulated stimuli (Suga, 1965a: bat; Evans and Nelson, 1966a, b: cat; Møller, 1971: rat).

To a first approximation, the responses of most CN cells to modulated tones can be predicted from the response, as a function of frequency and time, to steady tones (Fig. 38). Thus, sinusoidal modulation of frequency from the high frequency border into the excitatory response area (bar C under frequency response histogram A and modulation histograms C, G, I) produces a roughly sinusoidal distribution of unit discharge density, the maximum of which corresponds with minimum tone frequency. In fact, the phase of maximum firing density "leads" the modulation waveform slightly, as would be expected on the basis of the adaptation with time shown to a steady tone (B). Modulation at the low frequency border (bar D and histogram D) evokes a similar pattern but with inverted relationship to the modulation. Modulation of frequency across the bandwidth of response (bar E and histogram E) evokes a symmetrical bimodal distribution, as expected. Amplitude modulation (at the CF marked by the arrow, and histograms F, H, J) likewise evokes a nearly sinusoidal distribution. These correspondences between firing density and modulation are maintained over a wide range of modulation rates (C, G, I; F, H, J). The main divergences occur at higher modulation rates (G, I; H, J) where the flanks of the histograms (corresponding to minimum excitation) drop *below* the spontaneous discharge level (horizontal bars). This is a common feature and appears to result from the cumulative off-inhibition characteristic of many cells in the CN (see Fig. 34 for another example of this effect). In a few cells (particularly in the DCN), however, the sensitivities to upward and downward frequency sweeps are not symmetrical (see Fig. 39 for an extreme example: Evans and Nelson, unpublished data). Lesser degrees of asymmetry have been reported by Erulkar *et al.* (1968) and Møller (1971) using linearly frequency-modulated tones. This asymmetry was often related to asymmetrical disposition of inhibitory side-bands about the central excitatory response area in the data of Evans and Nelson (Nelson and Evans, 1971). Thus, explanatory models based on asymmetrical inhibition (analogous to that of Barlow and Levick (1965) for the sensitivity of units in the retina to direction of movement) may be more appropriate than ones based on a tonotopic organization of synapses on the dendrites of single cells (Fernald, 1971).

Møller (1969c, 1971, 1972a) has made a detailed quantitative study of the characteristics exhibited by CN cells in the rat to linear and sinusoidal FM and AM

at higher rates of frequency change than so far discussed. Under these conditions, two main departures occur from a discharge pattern which simply corresponds to the modulation. Firstly, the bandwidth of the units' response area appears to become narrower at intermediate modulation rates (Fig. 40A: 12.8 and 25 sweeps/

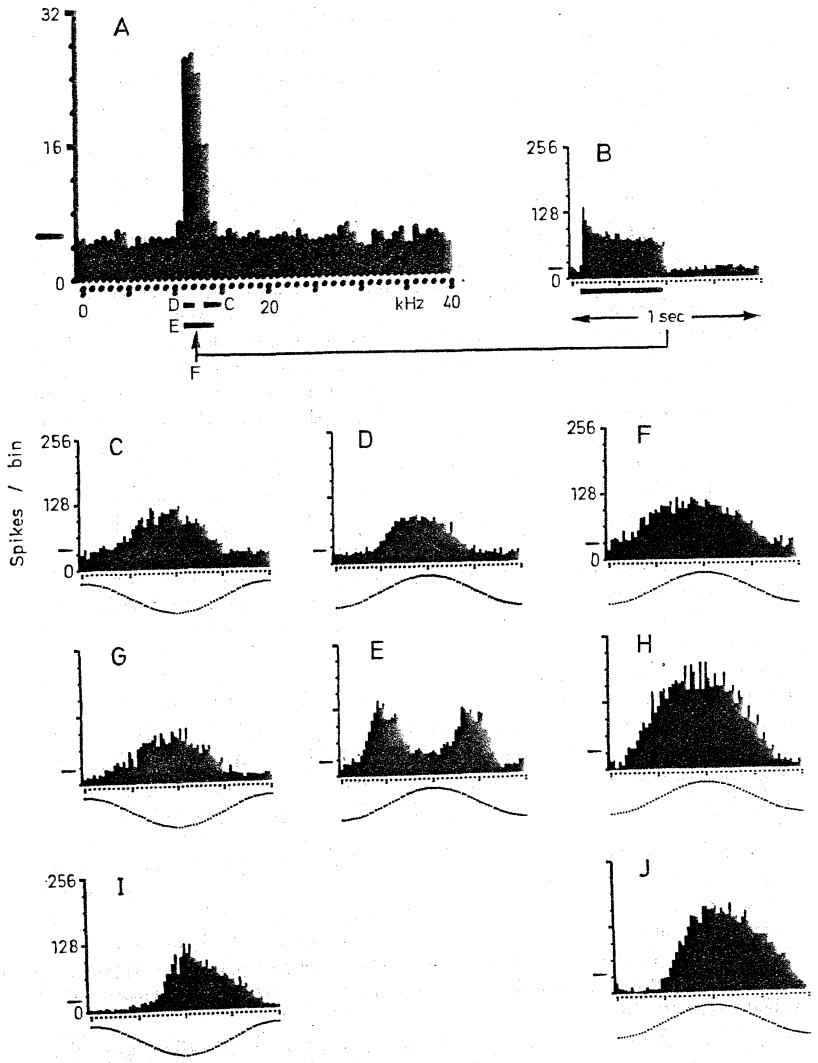

Fig. 38A—J. (Legend see p. 65)

sec). This is probably a result of cumulative off-inhibition preferentially diminishing the responses to the less effective (flanking) frequencies. Secondly, at intermediate modulation rates (50–300 c/s for sinusoidal modulation) the modulation of the response discharge density reaches a maximum, for both FM and AM

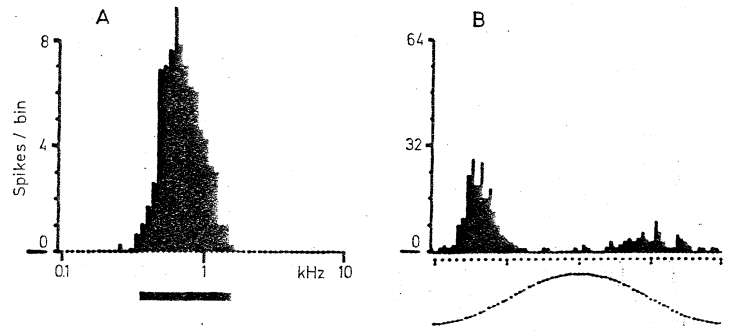

Fig. 39A, B. Uncommon type of response of CN unit to frequency modulation. Cat AVN. A: Frequency response histogram of response to 100 msec tones at 30 dB above threshold. B: Asymmetrical response distribution to frequency modulation positioned across response area (bar below A). Modulation rate: 1 c/s. Optimum response to upward frequency changes. Data collected for 30 sec

(Fig. 40B), and, for AM, exceeds the stimulus modulation depth by factors of 2–15 dB, as in Fig. 40B (Møller, 1972a). Sinusoidally amplitude-modulated noise had similar effects. Fig. 40B, C indicates that, for many units, amplitude and phase characteristic of the response to FM and AM are very similar, at least when the FM is not such as to produce an inverted or bimodal relationship between response firing density and the modulation waveform (as in Fig. 38C and E respectively).

Glattke (1969) has looked at the responses of CN units to square wave modulated AM tones of high frequency for evidence of "de-modulation" of the signal, *i.e.* responses to the modulation in units of CF corresponding to the modu-

Fig. 38A—J. Common types of response of CN unit to frequency and amplitude modulated tones. Cat PVN. All analyses at 20 dB above threshold. A: Frequency response histogram (see Fig. 30) of response to 100 msec tones as a function of frequency. B: PST histogram at CF. C, G, I: Modulation histograms of averaged firing density in response to sinusoidal frequency modulation over band of frequencies indicated by bar C under A. Waveform of modulation indicated under modulation histogram. Modulation rate: 1, 10, 40 c/s in C, G, I respectively. D: Frequency modulation over band of frequencies D; Modulation rate: 1 c/s. E: Frequency modulation symmetrically across excitatory response area (E). Note symmetrical double peaked distribution of discharge, corresponding to modulated frequency crossing CF twice per modulation cycle, F, H, J: Amplitude modulation (depth 80%) at CF (F) at modulation rates of 1, 10, and 40 c/s respectively. At the higher rates of modulation (G, I, H, J) note depression of "tails" of distributions below spontaneous level (indicated by bars against ordinates). Data collected for about 30 sec in each analysis

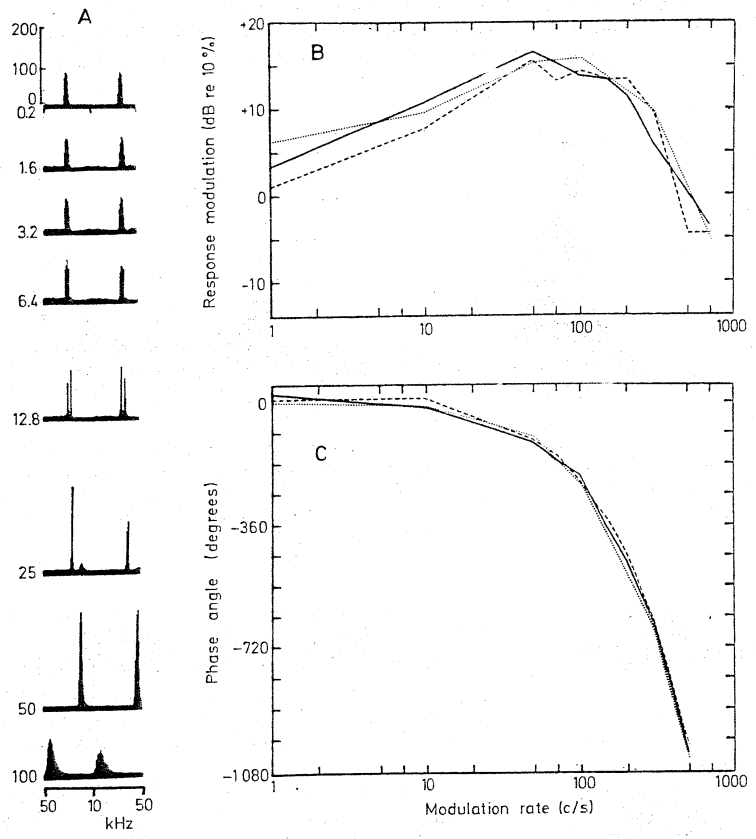

Fig. 40A—C. Effect of rapid rates of frequency and amplitude modulation on response of CN units. Rat. A: linear (triangular) frequency modulation between 10 and 50 kHz across CF of unit (29.3 kHz), at 20 dB above threshold. Note narrowing of firing distributions at sweep rates of 12.8 and 25 c/s (rates in c/s indicated to left of modulation histograms). The progressive shift of histogram peaks to the right with increasing modulation rate (which causes the right-hand peak at 50 c/s to appear as the left one at 100 c/s results from the latency of response. B: Modulation of discharge rate in response to sinusoidal frequency-modulation (dotted line) and amplitude modulation of tone at CF (solid line) and of broad-band noise (dashed line) as a function of the rate of modulation. Response modulation expressed in terms of ratio of observed modulation of response relative to 10%, which in the case of amplitude modulation equals the depth of stimulus modulation. (100% response modulation is represented by +20 dB.) Measurements obtained from the sinusoids which best fit the modulation histograms. Frequency modulation: ± 45 Hz at CF of 1.5 Hz. C: Phase of discharge modulation relative to that of stimulus modulation. (From Møller, 1969c, 1972a)

lation frequency. No such responses were found[3]. Glattke claimed to have found two classes of CN units: one class where the modulation of activity became negligible with modulation rates in excess of about 200 Hz; another where the response and stimulus modulations corresponded to rates in excess of 500—800 Hz. It appears, however, from the published data, that the latter class of units are of the "chopper" type where the regular interspike repetition period of 3—4 msec can be confused for "following" of the modulation by the unit. With the latter qualification, however, Glattke's results are consistent with those of Møller (1972a).

5. Effect of Noise on Responses to Click and Tone Stimuli

The presentation of wide band noise reduces the responses of CN units to click and tone stimuli (Galambos, 1944; Møller, 1969b; Marsh *et al.*, 1972). To what extent this effect differs from that found at the level of the cochlear nerve (Section II.E.4) is not known, in the absence of quantitative comparisons. Certainly, the desynchronization by noise stimuli of unit activity in response to low frequency tones (Marsh *et al.*, 1972) is not unexpected. On the other hand, the results of Greenwood and Goldberg (1970) where progressive inhibition was found in certain units with widening bands of noise, suggest that the inhibitory response regions characteristic of many CN units must contribute to the reduction in response found under conditions of broadband noise stimulation.

Goldberg and Greenwood (1966) and Greenwood and Goldberg (1970) have made a careful study of the responses of CN units to combinations of tones and narrow (ca. 0.1 kHz) bands of noise centred (a) at the CF and (b) off the CF of the units. In the former case, where the two stimuli were excitatory the *intensities of the stimuli* (rather than the responses) appeared to sum. Thus, the discharge rate and certain statistics of the discharge to the stimulus combination were determined by the more intense of the two stimuli. The addition or subtraction of the less intense stimulus had little effect (see Section VI. C.2). In the second case, where the narrow noise band was displaced from the CF and centred over an inhibitory sideband, the response to the tone at the CF was *reduced* (Fig. 41). The degree of reduction increased with increase in intensity of the noise band, although the relationship was not always monotonic (Fig. 41B). In addition, the response pattern (*i.e.* statistics) could shift from one corresponding to response to the tone alone, to that corresponding to the inhibiting noise signal alone.

It appears that in many respects, the behaviour of the CN neurones described by Greenwood and Goldberg (1970) to combinations of tone and noise bands, resembles that of the cochlear nerve to two-tone combinations (as discussed in II.E.1c). In particular, the response discharge rate, and the pattern of response were generally dominated by the more effective component of the two stimuli, whether the latter produced a lesser (or in the case of the CN an inhibitory) response than of tone alone (as in Fig. 41A, a—d; 41B, a—c), or whether it produced a greater response (Fig. 41Ac; 41Ba). In some cases, however, the situation was less straightforward, in that a narrow band of noise in an inhibitory side band could augment or suppress the response to a tone at the CF depending upon the level of

[3] Incidentally, this result appears to conflict with that of Boerger and Gruber (1970) obtained in the cochlear nerve and discussed in Section II.E.1.b.

the latter. (Response to tone in combination with noise at 60 dB SPL in Fig. 41 B; compare with response to tone alone at each tone level.)

In summary, therefore, the addition of a band of noise to a tone stimulus at the CN level may render the tone without effect upon the unit either by inhibiting or interfering with the response to the tone or by activating the unit itself. "In either case, the effect of the noise is to mask the tone as far as this unit is concerned" (Greenwood and Maruyama, 1965).

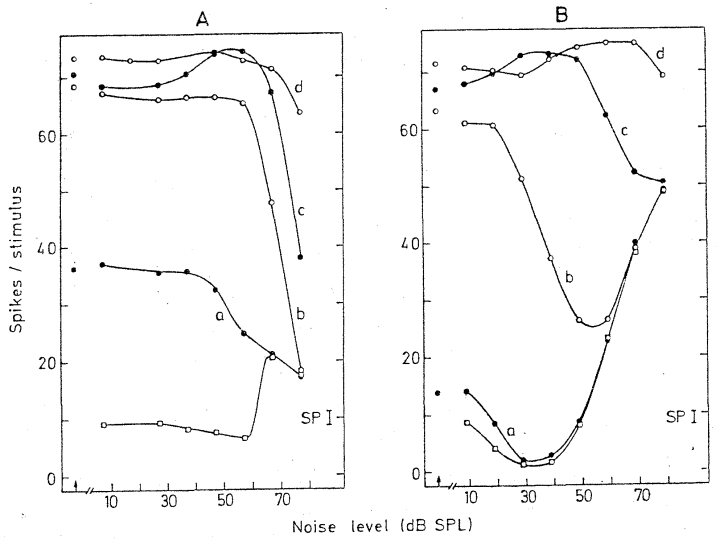

Fig. 41 A, B. Response of CN unit to noise bands placed at frequencies (A) below and (B) above CF and to combinations of noise bands and CF tone. Cat PVN. CF of unit: 11.6 kHz. Noise bandwidth: 200 Hz, centred at 6 kHz and 13.5 kHz in A and B respectively. Square symbols: noise alone; a—d: noise, plus tone at CF of intensity 4, 24, 44, and 64 dB respectively. Ordinates: spikes per 200 msec stimulus. Responses to tone alone indicated by arrow. SP indicates level of spontaneous activity. (From Greenwood and Goldberg, 1970)

In a study directed at the question of the neural mechanisms underlying non-simultaneous psychophysical masking, Watenabe and Simada (1971) have demonstrated some correlation between the time course of psychophysical forward masking and that of off-inhibition in CN cells. Forward masking occurs when a preceding noise ("masking") stimulus interferes with the response to a succeeding ("test") tone stimulus. Figure 42 indicates the elevation of threshold for a 10 msec tone burst at the CF, produced by the off-inhibition (Section III.E.3.), and the time course of its recovery. This magnitude and time course of the threshold elevation resembles that which can be obtained psychophysically in forward masking paradigms (*e.g.* Plomp, 1964a). Watenabe and Simada did not find any correlates of backward masking in the CN.

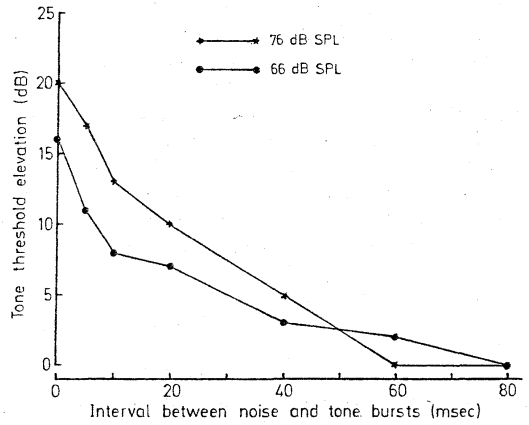

Fig. 42. "Forward masking" of unit in CN of cat. Elevation in threshold of a 10 msec test tone at CF by 40 msec broadband noise bursts at 66 or 76 dB SPL preceding the test tone by the interval indicated on the abscissa. (From Watenabe and Simada, 1971)

IV. Gross Nerve Action Potential Responses

It has long been known (Derbyshire and Davis, 1935) that an electrode in the region of the cochlea can record a succession of potential waves in response to acoustic clicks or tone bursts. The close relation of the waves to gross potentials recorded directly from the cochlear nerve and their lack of similarity with the cochlear microphonic potentials (*e.g.* Derbyshire and Davis, 1935; Peake and Kiang, 1962) have led to their being termed the gross nerve action potential or AP. Most, but not all, of the data pertaining to the AP response have been superseded and made clear by studies at the single fibre level in the cochlear nerve. However, it has recently been shown that these APs can be reliably recorded in normal and deaf human subjects from an electrode in the outer or middle ear and be related to normal and pathological subjective thresholds (Yoshie *et al.*, 1967; Yoshie, 1968, 1971; Portmann *et al.*, 1967; Sohmer and Feinmesser, 1967; Spreng and Keidel, 1967; Coats and Dickey, 1970; Aran, 1971; Cullen *et al.*, 1972). Hence, their study and interpretation has taken on a new lease of life. The present account will be limited to the question of the origin of the components of the AP and the effects of stimulus intensity.

At suprathreshold stimulus levels, the AP response consists of two or occasionally three negative waves, the N_1, N_2, and N_3 waves (Fig. 3 C—F shows the N_1 and N_2 waves). The N_1 response appears to originate predominantly from the basal turn of the cochlea (Tasaki, 1954; Deatherage *et al.*, 1959; Peake and Kiang, 1962; Kiang *et al.*, 1965a). Its latency corresponds, with allowance of approximately 0.2 msec (presumably representing conduction from a more peripheral location to the internal auditory meatus) with that of single cochlear fibres of high CF (Fig. 3 E, F). It does, however, receive some contribution from the second turn

of the cochlea in the guinea pig at least (Teas *et al.*, 1962). There is less unanimity for the origin of the later AP waves. The N_2 wave has been considered to arise in part from the cochlear nucleus (Kiang *et al.*, 1962a) or from repetitive activity in the cochlear nerve (Tasaki, 1954; Teas *et al.*, 1962). Against the former suggestion is the demonstration that the N_2 component can still be recorded after section of the cochlear nerve (Daigneault *et al.*, 1968). Against the second suggestion (repetitive activity in cochlear nerve), PST histograms of the activity of cochlear fibres of high CF do not show an appropriate second peak (Fig. 3E, F; Kiang *et al.*, 1965a). In fact, there is positive evidence that the later waves originate in the upper turns of the cochlea (Pugh *et al.*, 1973).

To broad-band signals such as clicks, the cochlea acts as a delay line. Hence, the AP recorded by a gross electrode must represent the spatially weighted sum over time of the progressive activation of endocochlear or modiolar all-or-none synaptic or nerve potentials which may be diphasic in nature (Teas *et al.*, 1962). Inasmuch as the thresholds of these individual component potentials are a function of frequency (*e.g.*, Fig. 8) and therefore delay along the cochlea (Fig. 21), and the time of initiation is dependent to a greater or lesser extent upon the level and phase (Fig. 6) of the stimulus, the form and latency of the AP will depend in a complex manner upon the level and phase of a broadband stimulus and also to a certain extent on the frequency response of the transducer used.

Some of these features are illustrated in Fig. 43. Almost all investigations of the relation between the amplitude of the N_1 response (measured as peak-to-peak amplitude of first negative and positive waves or as baseline to N_1 peak) and the intensity of click stimuli in cat (Derbyshire and Davis, 1935; Rosenblith, 1954; Kiang *et al.*, 1962a; Peake and Kiang, 1962; Radionova, 1963; Wiederhold and Kiang, 1970), guinea pig (Teas *et al.*, 1962; Taub and Raab, 1969; Nieder and Nieder, 1970; Spoor and Eggermont, 1971) and normal man (Yoshie *et al.*, 1967, 1971; Eberling and Solomon, 1971) have found the function to have an inflexion or even a dip at about 50–60 dB above the threshold for visual detection of the AP, in conjunction with a discontinuity in the latency function, as in Fig. 43. This finding has almost invariably been interpreted in terms of the participation of two populations of receptor elements or neural units, a small low threshold set responsible for the low threshold segment of Fig. 43 (continuous curve) and a larger high threshold set responsible for the remainder (Rosenblith, 1954; Davis *et al.*, 1958; Keidel, 1965, 1970; Radionova, 1963, Yoshie, 1968; Aran, 1971). With the demonstration that in the cat the number of cochlear fibres innervating the inner hair cells exceeds those for the outer hair cells by a factor as much as 20 : 1 (Spoendlin, 1966, 1970, 1971, 1972), it has appeared more reasonable to relate the low and high threshold populations with the two populations of cochlear fibres innervating the outer and inner hair cells respectively than to the receptors themselves, where the numerical relations are reversed (Spoendlin, 1971). Attempts to produce differential damage to the outer hair cells by exposure to noise or ototoxic agents in animals (*e.g.* Davis *et al.*, 1958; Keidel, 1965) also support this notion. Against this interpretation, it must be emphasised (a) that two populations of cochlear fibres distinguishable by their thresholds have not been found in the

normal cochlear nerve (see Section II.D.1); (b) that the AP is a compound potential and its amplitude a complex sum of potentials differing in time, space, and possibly polarity. That a drastic change is introduced in the intensity and latency function by merely a change in phase of the click (Fig. 43 interrupted line) illustrates the latter point, and consequently many workers are reluctant to press an anatomical interpretation (*e.g.* Aran and Delaunay, 1969; Yoshie, 1971). It is also possible that the inflexion present in almost all AP intensity functions is

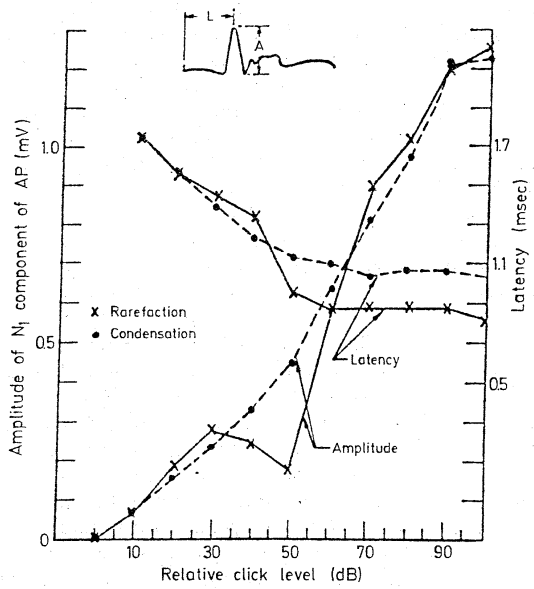

Fig. 43. Amplitude and latency of gross AP response (recorded by concentric electrodes in the cochlear nerve) as a function of relative click intensity. Cat. Latency corrected for acoustic delay. Solid curves: rarefaction clicks; interrupted lines: condensation clicks. Measurements of amplitude and latency made as indicated in inset. (From Peake and Kiang, 1962)

related to the sudden change in bandwidth of cochlear fibre FTCs about 50 dB above their minimum threshold (Fig. 9), and that the loss of the low threshold segment in cochlear pathology is related to the uniformly high threshold, broadly tuned, FTCs obtained in such preparations (Kiang *et al.*, 1970; Evans, 1972b). Clearly more correlative studies are required between single fibre and gross AP recordings.

Most recently it has been claimed that potentials reflecting activity in the cochlear nucleus and higher auditory centres as well as the cochlear nerve can be recorded from the region of the pinna in man and animals (Lev and Sohmer, 1972).

V. Effects of Activity in Efferent Pathways

As the anatomy and functional properties of the recurrent, efferent, auditory system are fully discussed in Chapters 8 and 11 of Vol. V/1 of the Handbook, only a brief account of the direct effects on the cochlear nerve and nucleus will be given here.

A. Cochlear Nerve

The efferent fibres which project to the cochlea originate in the superior olivary nucleus (SON) of the same and contralateral sides, forming the uncrossed and crossed olivocochlear bundles (OCB) (Rasmussen, 1960, 1964). The effects of electrical stimulation of the OCB on the cochlear nerve were first noted by Galambos (1956) with gross nerve AP recordings. Subsequent studies of the AP response (Desmedt and Monaco, 1962; Wiederhold and Peake, 1966; Dewson, 1967; Nieder and Nieder, 1970; Galley *et al.*, 1971) and of single cochlear fibres (Fex, 1962; Wiederhold and Kiang, 1970; Wiederhold, 1970; Teas *et al.*, 1972) have established a consensus of opinion in regard to the effect of artificial stimulation of the efferent system at this level, while paradoxically its action in the behaving animal remains obscure (Galambos, 1960; Irvine *et al.*, 1972). Because of its accessibility, the crossed OCB has been the component studied most thoroughly.

Electrical stimulation of the crossed OCB results in an inhibition (never an increase) in the activity of most, but not all cochlear fibres. Individual fibres show considerable differences in sensitivity. It takes 40–110 msec for the maximum effect to occur, while fibres take 100–400 msec to recover after the termination of electrical stimulation, fibres with higher CF having a longer latency of effect yet taking a shorter time to recover. The inhibition involves activity evoked by acoustic stimuli, but there is some uncertainty whether the spontaneous activity can be so affected. In a careful study on this point, Wiederhold and Kiang (1970) found definite *maintained* reductions in the spontaneous activity of a small proportion of their fibres (*e.g.*, Fig. 44A), but these were restricted to the lowest threshold fibres, and the question remains whether, in spite of precautions, these fibres were being subjected to low level background acoustic stimulation such as may arise from the respiration and circulation. The time course of the inhibition and recovery is illustrated in Fig. 44A.

The magnitude of the suppression by stimulation of OCB depends on many factors, including the parameters of acoustic and electrical stimulation (Wiederhold and Kiang, 1970). In a systematic study, where the latter parameters were optimized, Wiederhold (1970) examined the effects of prior electrical stimulation of the crossed OCB on the responses of cochlear fibres to tones. In nearly all cases, the effects could be summarised as a greater or lesser degree of shift of a fibre's discharge rate versus intensity function to higher sound levels (Fig. 44B). In other words, the suppression was maximal (and nearly constant) over an intermediate range of tone intensities, and minimal at subthreshold and supra-saturation intensities. The magnitude of the shift is maximal when the fibre is being stimulated at its CF. Thus, OCB stimulation reduces the sharpness of the FTC (Fig. 45A), by a factor of 7–31% expressed in terms of Q_{10dB}. In addition, the

magnitude of the shift differs from fibre to fibre over a range of 1–25 dB, maximum values being obtained for fibres in the intermediate range of CFs (Fig. 45B). Similar results were obtained in the guinea pig by Teas *et al.* (1972). These findings are consistent with those from studies of the gross AP response to acoustic transients, where the degree of suppression observed differs from animal to

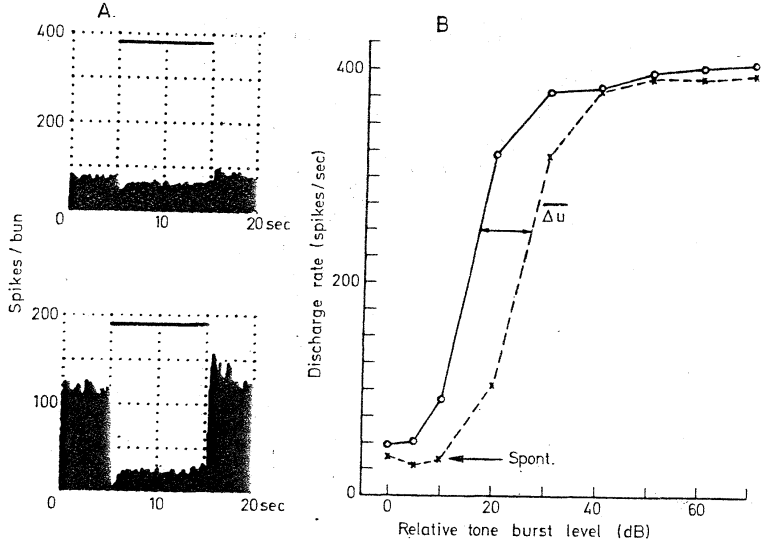

Fig. 44A, B. Effect of crossed OCB stimulation on spontaneous and tone evoked activity of cochlear fibres. Cat. A: PST histograms of effect of electrical stimulation of the crossed OCB (during bar) on spontaneous activity (above) and on activity evoked by a continuous tone at the fibre's CF (11.58 kHz), 10 dB above threshold (below). Ordinate scale (spikes per bin) and number of presentations represented by the two histograms arranged so that equal bar heights represent equal discharge rates. (From Wiederhold and Kiang, 1970.) B: Mean discharge rate (spikes/sec) evoked by 40 msec tone bursts at the CF of a cochlear fibre at the relative stimulus levels indicated, without (continuous line) and immediately preceded by electrical stimulation of the crossed OCB (interrupted line). Spont. indicates spontaneous discharge rate. Upper arrow indicates one determination for estimate of mean shift of the rate-intensity function, $\overline{\Delta u}$ used in Fig. 45B. (From Wiederhold, 1970)

animal over a range of 13–23 dB, is minimal at high click levels, and is maximal for high frequency acoustic transients (Wiederhold and Peake, 1966). The dependence of the magnitude of the inhibition upon the CF of the fibres may correlate with the finding that the density of the efferent innervation of the outer hair cells is maximal in the basal turn of the cochlea and decreases towards the apex and in the extreme basal end (Ishii and Balogh, 1968). This point will be further discussed in relation to the question of the cochlear innervation in general in Section VI.B.

Whereas histochemical findings suggest strongly that the efferent endings are cholinergic, pharmacological evidence is incomplete (for reviews see Whitfield, 1967; Klinke and Galley, 1974).

The functional role of the cochlear efferent system is surprisingly unclear, in spite of the above data. No effects of section of the crossed OCB have been observed on absolute behavioural threshold (Dewson, 1968; Igarashi *et al.*, 1972). Of considerable interest has been the question whether efferent activity can increase the detection of acoustic signals in the presence of background noise. Such an effect was inferred by Dewson (1967) and apparently demonstrated by Nieder and Nieder (1970) from the effect of electrical stimulation of the OCB on the gross AP

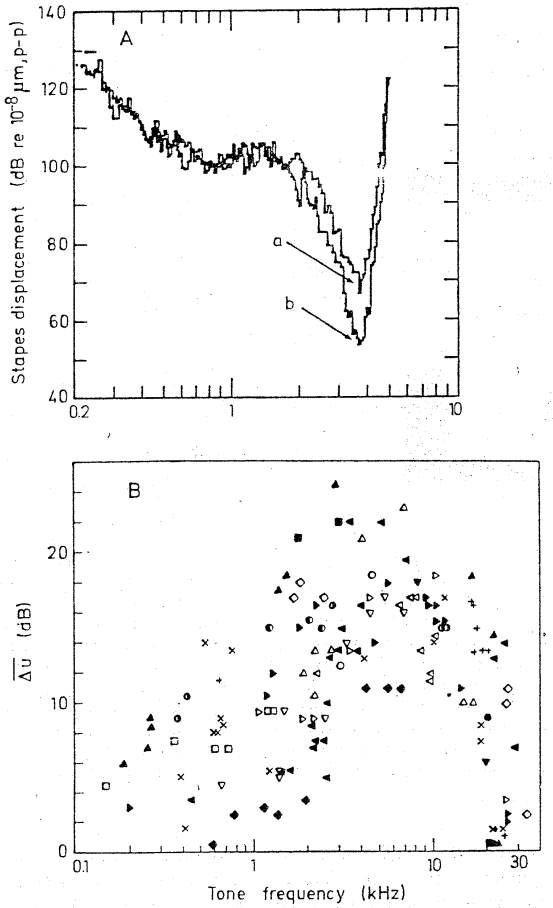

Fig. 45A, B. Effect of crossed OCB stimulation on cochlear fibres as a function of stimulus frequency (A) and fibre CF (B). Cat. A: FTCs (where tone threshold level is expressed in terms of stapes displacement) of single cochlear fibre with (a) and without (b) electrical stimulation of crossed OCB. (From Kiang *et al.*, 1970.) B: Plot of mean shift of rate intensity function, $\overline{\Delta u}$ (see Fig. 44B) for 141 cochlear fibres against their CF. Different symbols represent different animals. (From Wiederhold, 1970)

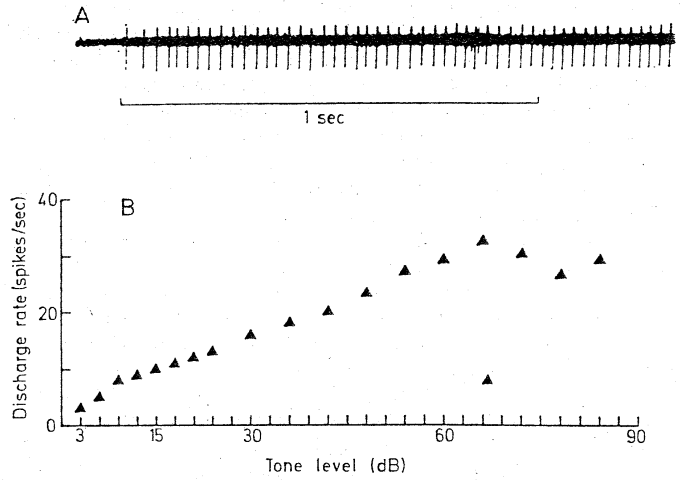

Fig. 46A, B. Response of cochlear efferent fibres to tones. Cat. A: Response to tone at 66 dB above threshold. Note regular discharge and absence of adaptation. Tone commences at time marker. B: Rate: intensity function for the fibre shown in A. (From Fex, 1962)

responses to clicks in background noise. Behavioural evidence, however, is conflicting (compare Dewson, 1968, and Comis and Pickles, 1972; with Trahiotis and Elliott, 1970, and Igarashi *et al.*, 1972). In fact, apart from the inexplicable finding of Capps and Ades (1968) that the frequency discrimination of squirrel monkeys deteriorated after crossed OCB section (contrary to what would be expected from the effect of the OCB on cochlear tuning, Fig. 45A), investigations looking for systematic effects of the OCB at the cochlear level related to attention, conditioning etc. in behaving animals (with their middle ear muscles cut) have proved negative (Galambos, 1960; Irvine *et al.*, 1972).

Fex (1962, 1965) has recorded the activity of the crossed and uncrossed efferent fibres themselves in the vestibulo-cochlear anastomosis in unanaesthetized decerebrate cats with the ipsilateral ear destroyed. Most of the fibres were silent in the absence of acoustic stimulation to the contralateral ear, but when activated by tones gave a low, regular, discharge with little adaptation, after a latency of 5–40 msec (Fig. 46A). The FTCs of the crossed fibres resembled those of VCN cells, whereas those of most of the uncrossed fibres had both excitatory and inhibitory response bands (Fex, 1965). Interestingly, the discharge rate versus tone

intensity functions, for some of these units at least, have dynamic ranges in excess of 60 dB (Fig. 46B). In other experiments, Fex (1963) found that the crossed efferents were best activated from the ipsilateral ear.

B. Cochlear Nucleus

At least four efferent pathways to the CN have been described (*e.g.* Rasmussen, 1960). The first takes origin from the OCB. The second enters the DCN via the dorsal acoustic stria and takes part origin from the ventral nucleus of the contralateral lateral lemniscus. The third enters via the intermediate stria, originates in the *S* segment of the ipsilateral SON, and terminates chiefly in the VCN. The fourth takes origin in the ipsilateral inferior colliculus and dorsal nucleus of the lateral lemniscus and enters the DCN via the trapezoid body. Investigations of the actions of these pathways, with the exception of the last, have been made by electrical stimulation of the nuclei of origin.

Desmedt (1960) was the first to describe an inhibitory efferent effect on gross potentials recorded in the CN of the unanaesthetized decerebrate cat after electrical stimulation near the ventral nucleus of the lateral lemniscus. Recording from single units in the anaesthetized cat, Comis and Whitfield (1968) found that electrical stimulation of the ventral nucleus of the contralateral lateral lemniscus evoked inhibition of spontaneous and tone evoked activity in the DCN. Stimulation of the *dorsal* nucleus of the contralateral lemniscus, on the other hand, generally evoked inhibition in the DCN and excitation in the VCN.

Comis and Whitfield (1968) and Comis (1970) have studied the effects of electrical stimulation of the SON on the responses of cells in the ipsilateral CN. They used direct-current stimulation to minimise the effects on afferent and efferent fibres of passage. Stimulation of the medial portion of the *S* segment produced an increase in spontaneous and tone evoked activity in AVN cells with, in some cases, a reduction in threshold of up to 15 dB. The minimum latency of the effects was 25–50 msec. There is a considerable body of evidence suggesting that this pathway is cholinergic (Rasmussen, 1964; Comis and Whitfield, 1966, 1968; Comis and Davies, 1969). Stimulation of the *lateral* portion of the *S*-segment, in contrast, evoked inhibition in cells of the DCN and in some cells of the VCN (Comis, 1970).

Starr and Wernick (1968) also found excitatory and inhibitory effects on single units of the CN, but resulting from stimulation of the crossed OCB in decerebrate cats. Both the spontaneous and tone evoked activity were affected. Inhibitory effects were the most commonly encountered, and the effects on the spontaneous activity persisted after destruction of the ipsilateral cochlea. Nevertheless, the question remains how far the effects on tone evoked activity were mediated via the cochlea.

Inhibition of cells in the CN can be obtained by acoustic stimulation of the contralateral ear (Pfalz, 1962; Dunker, Grubel, and Pfalz, 1964; Klinke *et al.*, 1969; Mast, 1970b). The effect is not mediated by the crossed OCB, but disappears when lesions are made in the trapezoid body (Grubel *et al.*, 1964). Pfalz and his co-workers demonstrated the inhibition on the spontaneous activity after destruction of the ipsilateral cochlea, a finding that suggests that it was the DCN

that was being recorded from (see Section III.B.3), in keeping with the findings of Mast (1970b). The effect can be obtained with contralateral tones within 40 dB of the animals' behavioural threshold, where interaural cross-talk can be excluded (Boerger *et al.*, 1968), thus enabling a study of contralateral inhibition with both cochleas intact (Klinke *et al.*, 1969). While the effect on the responses to ipsilateral acoustic stimulation was small at these levels, it was frequency dependent: frequencies immediately on either side of the unit's CF were most effective in depressing the response to ipsilateral tones at the CF. Again, the latency of inhibition was relatively long: from 30–50 msec (Klinke *et al.*, 1969).

It is not at all clear what the functional relevance of the efferent pathways actually is. In spite of encouraging early reports, later studies of the grossly recorded CN activity in behaving animals under conditions of directed attention and conditioning have not found consistent effects attributable to a descending control system (see Whitfield, 1967 for review), with the exception of the series of experiments by Piddington (*e.g.* 1971) in the fish.

VI. Discussion

The large body of data which has been collected at this peripheral level of the auditory system, and particularly those quantitative studies conducted under controlled conditions, have given rise to considerable efforts to relate them to cochlear mechanisms on the one hand, and psychophysics, including disorders of hearing, on the other. This section will be limited to these topics, and to a brief account of their relevance to the problem of coding of frequency and intensity information.

A. In Relation to Cochlear Mechanisms

In the wake of the quantitative studies, summarised in earlier sections, particularly those of the cochlear nerve, a number of "blackbox" models of the inner ear mechanisms have been developed (*e.g.* Siebert, 1965, 1968, 1970; Weiss, 1966; Geisler, 1968; De Boer, 1969; Duifhuis, 1970, 1972; models restricted to cochlear mechanics are dealt with in Chapter Mathematical Models in Vol. V/3 of this Handbook). While it is evident that many of the components of these models cannot be identified with presently available physiological and anatomical data nor presented with the same degree of confidence, nevertheless the models continue to serve useful explanatory and heuristic purposes. One of the earliest and probably the most comprehensive of these models, that of Weiss (1966) will serve as a useful point of departure (Fig. 47).

1. Cochlear Filtering

The first compartment of the model accounts for the mechanical properties of the outer, middle and inner ears. In Weiss's model, these were considered to be linear over a large intensity range (80 dB), and the frequency response characteristics of the outer and middle ears were neglected. For the purpose of accounting for the dependence of threshold on frequency represented by the audiogram, it is clear now that the effect of the outer and middle ear response can be quite significant

(Price, 1971; Dallos, 1971; Johnstone and Sellick, 1972). There is, however, still uncertainty on whether the audiogram can be entirely accounted for in this manner, or whether inner ear mechanisms are also to be implicated, as Weiss assumed (Manley, 1970b, 1971; Evans, 1972b; Evans and Wilson, 1973).

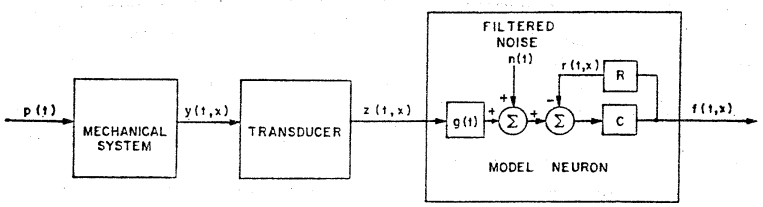

Fig. 47. Compartmental outline of model of Weiss (1966) relating the discharge of cochlear nerve fibres to acoustic stimuli. $p(t)$: pressure at ear; $y(t, x)$: displacement of cochlear partition; $z(t, x)$: output of transducer; $f(t, x)$: sequence of discharges; $r(t, x)$ threshold potential; $g(t)$: linear filter; t: time; x: distance along cochlear partition

The major component of the first compartment is the band-pass filtering characteristic existing at any point along the cochlear partition. The nature of this filter function, and its relation to the form of the neural FTCs continues to be the subject of much experiment and discussion. The similarity between the first successfully measured cochlear fibre FTC (Tasaki, 1954 in the guinea pig) and the so-called resonance curves of the cochlear partition (*e.g.* Békésy, 1944) has prompted the conclusion that the relatively broadly tuned characteristics of the basilar membrane were handed on to the auditory nervous system relatively unchanged (*e.g.* Békésy, 1969, 1970; Whitfield, 1967, 1968). However, the more recent FTC measurements in cat (Kiang *et al.*, 1965a, 1967) indicated that its cochlear nerve frequency responses were substantially sharper than Békésy's curves. It has now been shown (Evans, 1970a, 1972b) that this is in fact true for the guinea pig, so that comparisons can be made (Fig. 9B) between the neural and mechanical tuning in the same species, but more importantly at the same frequencies. For the latter purpose we now have measurements of the frequency response at the basal end of the guinea pig basilar membrane by Johnstone *et al.* (1970) using the Mössbauer technique and by Wilson and Johnstone (1972) using a capacitive probe. Both mechanical and neural functions show an increase in sharpness with frequency, but at all frequencies the two sets of data are substantially different. These differences can be examined quantitatively in Fig. 10 (filled circles versus star symbols). The most conspicuous difference is in the slopes of the low frequency cut-off of the cochlear nerve FTCs, which are steeper than the analogous mechanical values by factors of between 2 and 12 for fibres with CF below 2 kHz, and between 6 and 36 for those above 2 kHz. Above 2 kHz the neural high-frequency cut-offs are 1–7 times as steep as the mechanical. (Slopes here measured are of the cut-off segment between 5 and 25 dB above the tip of the curves). In terms of 10 dB bandwidth (Fig. 10C), the neural FTCs were narrower than the mechanical functions by a factor approaching an order of magnitude at intermediate CFs (3–10 kHz).

Unfortunately, no actual measurements of the guinea pig basilar membrane motion exist at these intermediate regions.

The question arises whether one is justified in making these comparisons between the neural frequency response functions determined at threshold and the mechanical functions determined at much higher sound levels (above, and in most cases well above, 70 dB SPL). This question has received added force from the recent Mössbauer measurements of Rhode (1971, 1973) in the squirrel monkey. While his published slope values for the basilar membrane frequency response of a region subserving frequencies of 6–8 kHz are in substantial agreement with the guinea pig data (large open star in Fig. 10A–C), Rhode found substantial non-linearities in the response at frequencies near the peak of vibration. These were such that, if a constant low amplitude criterion (*e.g.* 0.003 μm, Fig. 7; Rhode, 1971) is used for constructing a frequency response function, then the frequency response function has cut-offs and bandwidth approaching those of cochlear fibres of comparable CF. However, the fact that this derivation depends upon a level dependent non-linearity which was specifically *not* found by Békésy, Johnstone *et al.*, and Wilson and Johnstone (the latter over SPLs from 40–120 dB at the peak) makes it difficult to interpret. More mechanical data are evidently required in this intermediate frequency region to resolve this discrepancy between the data of Rhode and the other investigations. In this connection, it is appropriate to note that the frequency response inferred from the differential cochlear microphonic study of the guinea pig by Dallos (1973), is in close agreement with that of Wilson and Johnstone in both relative amplitude and phase. The correspondence between the neural data of Figs. 9 and 10 make a substantial species difference seem unlikely. As far as the question of using threshold criteria for estimating neural tuning is concerned, there is no evidence that isorate contours constructed for cochlear fibres become less sharp as higher rate criteria are used (Fig. 13) at least over the 30–40 dB range available before saturation of the discharge rate is reached (above these levels, there is evidence of a decrease in sharpness of the cochlear filter: see later in this section). Furthermore, the slopes of the high frequency cut-offs of the neural FTCs become steeper at higher levels, whereas the measurements of Rhode, Wilson and Johnstone, and Johnstone (personal communication) have in common an as yet unexplained plateau of the vibration amplitude at about 30–40 dB from the tip on the high frequency side.

Huxley (1969) raised the question whether the discrepancy between neural and mechanical measurements could arise as a result of the surgical opening of the cochlea necessary to make the mechanical measurements thus disturbing a mechanical resonant system. However, Evans (1970b) has shown that normally sharp FTCs can be recorded from cochlear fibres emanating from the region of the guinea pig basilar membrane exposed as in the experiments of Johnstone *et al.* and Wilson and Johnstone.

To reconcile the sharp neural tuning with the relatively broadly tuned properties of the basilar membrane, Weiss inserted a second linear filter into his model, but in the neurone compartment. He used a filter which was essentially low-pass, but with a constant slope of decrease in sensitivity with increasing frequency which effected some improvement in the slope of the low frequency cut-offs. It is clear, however, from the data of Fig. 10, that such a second filter needs

to be *band-pass* in its characteristics. This notion of a second, more sharply tuned, filter succeeding a relatively broad basilar membrane filter has received support from a number of sources. Firstly, a feature of the neural FTCs is the considerable variation which exists in the cut-off slope, and bandwidth values, from fibre to fibre even at similar CFs and in the same animal (Evans, 1972a, b; Evans and Wilson, 1973). This variation may amount to differences in bandwidth up to a ratio of 4 : 1. Secondly, in the guinea pig (Evans, 1972a, b) fibres recorded under conditions of cochlear circulatory insufficiency have high threshold, broadly tuned characteristics resembling those of the basilar membrane (small open circles in Fig. 10). In addition, such fibres are occasionally found apparently adjacent to and sharing a common CF (above 12 kHz) with fibres of normal threshold and tuning. These findings led us to propose the existence of a second filter "private" to each cochlear fibre, whose normally sharply tuned properties were thereby physiologically vulnerable and the differences between which could account for the lack of homogeneity observed in the tuning properties of cochlear fibres. It is difficult to reconcile such properties with any filtering properties of the basilar membrane, which would be expected to the *evenly distributed*. Direct evidence for such a physiologically vulnerable second filter is in fact provided by the demonstration that the sharply tuned segment of the FTC can be eliminated and restored within a few minutes by the action of hypoxia and certain agents (cyanide, Frusemide) on the cochlea *without substantial effects on the cochlear microphonic* (Evans, 1974b, c, d; Evans and Klinke, 1974; vd. p. 18). The time scale of these effects is much shorter, and their magnitude much larger than those that have been observed in Mössbauer measurements of the squirrel monkey basilar membrane vibration *after death* by Rhode (1973), where all normal cochlear potentials would have been eliminated (*e.g.* Butler *et al.*, 1962). The third line of support for the notion of a second sharply tuned filter comes from studies of two phenomena which are related to cochlear non-linearities, *i.e.* the combination tone $2f_1 - f_2$ and two-tone suppression. Psychophysical (Goldstein, 1967, 1970; Smoorenburg, 1972b) and neurophysiological (Goldstein and Kiang, 1968) investigations of the $2f_1 - f_2$ cubic difference tone (CDT) indicate that the "essential" non-linearity must be preceded by a frequency selective process (which accounts for the dependence of the level of the CDT on the frequency separation of the primary tones) and also followed by a frequency selective process (to account for the frequency analysis of the CDT to separate it from the primaries). Two possible ways by which this double filtering process may be accomplished have been proposed by the above authors. In the first, the coupling hypothesis, the nonlinear process is tightly coupled to a sharply tuned distributed mechanical frequency analyser (the basilar membrane), so that the CDT generated at the region of overlap of the primaries is fed back to the basilar membrane and analysed at the place appropriate to its frequency. In the second (two-filter) hypothesis, the non-linearity follows a broadly tuned basilar membrane filter, and the CDT it generates is not coupled back to the basilar membrane but is analysed by a separate, more sharply tuned filter. The ingenious study by Smoorenburg (1972b) of a subject with a sharply defined hearing defect (likely to be of hair cell origin) excludes a third possibility, perhaps implicated in the results of Rhode (1971), in which the non-linearity resides in a sharply tuned basilar membrane. The two filter hypothesis is in fact favoured by the demonstration that no $2f_1 - f_2$ component of the magnitude predicted by the coupling hypothesis is present in the basilar membrane vibration pattern, according to the differential cochlear microphonic data of Dallos (1969) and the direct measurements of basilar membrane vibration by Wilson and Johnstone (1972, 1973), using a capacitance probe technique. Lastly, Pfeiffer (1970) has demonstrated that such a two filter model can also account, qualitatively at least, for the characteristics of the two tone suppression encountered in the cochlear nerve (Section II.E.1.a).

In spite of the presence of these cochlear non-linearities, there is now a good deal of evidence that, for a wide variety of stimuli, the sharply tuned cochlear filtering process(es) act as if they were linear, at least over a 30–60 dB range above threshold. This holds for wideband noise assessed by two different methods (Section II.E.2), for click stimuli (Section III.F.3), and for comb-filtered noise (multicomponent spectra: Section II.E.3), and in each case the effective bandwidth of the filtering approximates to that of the pure tone FTC. As will be noted later (Fig. 48; Section VI.C.1) the magnitude of the effective bandwidth of the cochlear filter corresponds to the analogous psychophysical measure, the critical band. Goldstein *et al.* (1971) have made an interesting comparison of cochlear nerve response times estimated from click responses and pure tone data with those computed on the basis that the cochlear filter responsible for the FTC was a minimum phase linear filter. The tolerable degree of agreement led them to conclude that the cochlear nerve FTC, phase and click data were interrelated in a manner similar to that which would be predicted for a linear filter system. The important point that they make is that the response time (which is approximately the delay to maximum response of the system) of any *linear* filter system *cannot be less* than that for the equivalent minimum phase filter. In the case of their own (cat) data it appears that the agreement was obtained only by neglecting the finite synaptic delay and neural conduction time. The former could be about 0.5 msec, and the latter, from the latency of direct electrical stimulation of the cochlea (Kiang and Moxon, 1972) 0.5 msec also. Taken at face value, this then suggests that the response of the cochlear filter is faster than that of a minimum phase network by approximately 1 msec. If this is the case, it is serious evidence against the sharply tuned second filter being linear. On the other hand, the comparison of Goldstein *et al.* (1971) may be rendered inaccurate if, as appears to have been the case, the tone phase and click data from which the estimates of response time were derived, were obtained at high stimulus levels. As Fig. 6 demonstrates, the response time indicated by the click PST histogram becomes substantially shorter at higher levels. In other words, comparisons of response times computed from the frequency threshold curves should be made with estimates derived from click and tone phase data within 20–30 dB of threshold.

The sharp filtering characteristics of cochlear fibres appear to remain relatively unchanged over at least an intensity range of 30–60 dB above threshold (see Section II.D.1; II.E.2; III.F.3; see also Evans and Wilson, 1973). At higher levels, however, there is some indication that the cochlear filter becomes nonlinear, or less sharply tuned, or both. The increasingly nonlinear behaviour with stimulus level of cochlear fibres in respect of two tone interactions has already been noted (Section II.E.1.c). In addition, the investigation by Goblick and Pfeiffer (1969) of the extent of cochlear linearity (by an ingenious method involving the nulling of

individual peaks of the cochlear nerve PST histogram in response to a click by a second click stimulus) has demonstrated the existence of an amplitude non-linearity increasing from zero to about 6 dB over the upper 20 dB of the 40 dB dynamic range tested (probably representing levels of 40–60 dB above threshold). Furthermore, the fact that fewer than expected later peaks appear in the click PST histogram with increase in stimulus levels (*e.g.* 30–70 dB in Fig. 6, where the scale is constant) has been interpreted as an indication of a decrease in the system's "Q" at higher levels (Pfeiffer and Kim, 1972; compare response of Weiss' (1966) model). The progressive shift of the mode of the PST histogram to the left with increase in stimulus level (from ca. 8 msec at +10 dB to ca. 3 msec at +70 dB above "threshold" in Fig. 6), implying a decrease in the "response time" of the filter, would also appear to support this conclusion. An increase in damping of the cochlear filter with stimulus level has also been proposed by Anderson *et al.* (1971) as a possible explanation of the changes in phase of cochlear fibre discharge with level of low frequency tone stimulation (Section II.D.4). All of these findings may, of course, be consistent with the basilar membrane vibration patterns observed by Rhode (1971; see discussion by Pfeiffer and Kim, 1973), but, as discussed above, the interpretation of his data remains a difficult question.

Many mechanisms have been proposed to account for the sharpening of the basilar membrane frequency response discussed above. These range from mechanical processes (*e.g.* "beam" hypothesis of Huggins and Licklider, 1951; longitudinal shear model of Tonndorf, 1962, Khanna *et al.*. 1968; fluid-hair cell coupling, Steele, 1973), through innervation pattern models (*e.g.* Nieder, 1971), positive feedback models (Gold, 1948), to lateral inhibition (*e.g.* Békésy, 1960, 1970; Furman and Frishkopf, 1964). Unfortunately, none of these models appears to account quantitatively for the extent of sharpening required and at the same time is consistent with the available physiological and anatomical data. Evidence against lateral inhibition as a mechanism in the cochlea has been presented above (Section II.D., II.E.1.a, II.E.3, III.F.3). Gold's model, involving a positive feedback mechanism, has some attractions in relation to the physiologically vulnerable second filter hypothesis and the mechanisms underlying tone-like tinnitus, in spite of it being based on estimates of cochlear "Q" which were incorrect by over an order of magnitude and which were derived from incorrectly interpreted data (vd. Hiesey and Schubert, 1972). Another class of second filter type mechanism, as yet not explicitly treated, involves some form of active "resonance" of electrochemical nature within the hair cells themselves. Such a mechanism, however, would appear to have too high a noise limitation set by Brownian motion for a system loosely coupled to the basilar membrane or other structures, if the arguments of Harris (1968) can be applied to this situation.

Clearly, further experimental data on the properties of the basilar membrane and of the hypothetical frequency sharpening process are required before further assessment of these and other models is appropriate.

2. Transducer Nonlinearity

The second compartment of Weiss' model incorporated a non-linear no-memory transducer. The non-linearity was invoked to account for the greater

number of peaks encountered in the cochlear nerve PST histogram in response to a click, compared with that computed from a model based on Békésy's basilar membrane data. (In fact, data from recent measurements of basilar membrane motion (Robles *et al.*, 1973; Wilson and Johnstone, 1972) indicate that the (more basal) cochlear partition is less damped than was thought by Békésy.) De Boer (1969) first suggested that such a nonlinearity could be dispensed with if the linear cochlear filter was made as sharp as that required to account for the FTC. The finite "response time" (see Goldstein *et al.*, 1971; above) of such a filter could also account for the appearance of earlier peaks in the PST histogram on raising click levels above threshold, which were inexplicable on Weiss' model.

Two types of cochlear non-linearity, both of which have received some attention above, may well, however, reside in the transducer stage. The first is the so-called "essential" nonlinearity (Zwicker, 1955; Goldstein, 1967, 1970) responsible for generation of the $2f_1 - f_2$ combination tone (CDT). Psychophysical measurements of this CDT indicate that it is generated at stimulus levels close to threshold, and that its level is proportional to the level of the primaries (Goldstein, 1967; Smoorenburg, 1972a; see Section II.E.1b). This nonlinearity is therefore not a level-dependent saturating type of non-linearity (such as that responsible for the difference tone, $f_2 - f_1$, heard only at much higher stimulus levels, Goldstein, 1967). It could also be responsible for the generation of the two-tone suppression phenomenon observed in the cochlear nerve, the effects of which are also observable close to threshold (Fig. 22; Section II.E.1.a).

The second type of non-linearity is that discussed in the section above, responsible for the deviation of certain cochlear nerve properties from linear behaviour at stimulus levels higher than 40–60 dB above threshold (*e.g.* Section II.E.1.c).

3. Generation of Cochlear Nerve Discharges

In the third compartment of Weiss' model, the transducer output was added to internally generated low-pass filtered noise to produce a noisy membrane potential which, whenever it exceeded a threshold, triggered a neuronal spike. Immediately after each spike, the threshold was reset to some higher value (by the component R in Fig. 47) from which it decayed to a resting value. These features were incorporated to account respectively for the spontaneous discharge and probabilistic suprathreshold behaviour, and the refractory period exhibited by cochlear fibres.

A threshold trigger mechanism was also incorporated in the models of Geisler (1968) and de Boer (1969) which modified the overall model of Weiss to account for cochlear nerve behaviour in response to low frequency tones and broadband noise. A problem with all these threshold trigger type models is that they fail to describe adequately the responses of cochlear fibres to high level click and low frequency tone stimulation (de Boer, 1969; Geisler, 1968; Duifhuis, 1972). In particular, at high stimulus amplitudes, the effects of the internal noise would be expected to become less significant, and the temporal "jitter" observed in the PST histograms of activity evoked by clicks (*e.g.*, Fig. 6) and tones (*e.g.*, Fig. 18) should show a tendency to disappear, which is manifestly not the case. Similarly the phase of discharge should correspond increasingly with the hypothetical zero crossing at

higher levels, which again does not occur with noise (Fig. 25) or with tones at the CF of a cochlear fibre (Fig. 18).

For these reasons, Siebert (*e.g.*, 1965, 1970) and Duifhuis (*e.g.*, 1972) have instead utilised in their models a stochastic spike generator where the probability of discharge at any instant is a *continuous* function of the unidirectional amplitude of the transducer output (*i.e.*: there is no threshold trigger level). The properties of adaptation and saturation of discharge can either be incorporated in the mathematical relation connecting the discharge probability to the transducer output waveform (Siebert), or, as in the case of refractoriness, as a multiplicative feedback from the spike generator output to the input to the Poisson probabilistic generator (Duifhuis, 1972).

An outcome of both classes of model is the effective rectification of the stimulating waveform, which is demonstrated most clearly in response to click, tone, and noise stimulation in Figs. 6, 16B, 17, 18, 24, 25, all of which show a discharge pattern more clearly correlated with the stimulus waveform (stochastic model) than a threshold crossing (threshold trigger) model.

Duifhuis' (1972) model incorporates a linear filter with a finite "response time" (consistent with the cochlear nerve FTC properties) to precede the Poisson process, and accounts satisfactorily for the statistics of cochlear fibre spontaneous and tone evoked discharges (*e.g.* Fig. 2), for interspike interval and period histograms of the response to low frequency tones (*e.g.* Figs. 19 and 18 respectively), and for PST histograms to click stimuli (including the shift of the centre of gravity to the left with level introduced in the model by a reduction of filter "Q" at higher stimulus levels).

The incorporation of a linear filter with finite "response time" in Duifhuis' model (as in Goldstein *et al.*, 1971) eliminates the need for some form of feedback control, as in the model of Lynn and Sayers (1970), to account for the apparent "suppression" of the early peaks of the click evoked PST histogram.

All of the models referred to above may have to be revised in the light of very recent findings which run counter to the generally accepted conclusion that the spike generator discharged only in response to "upward" movements of the basilar membrane, *i.e.* towards the scala vestibuli, (*e.g.* in response to the predominant component of a rarefaction click, Kiang *et al.*, 1965a). Thus, under low frequency tone (Kiang and Moxon, 1972) or noise (de Boer, 1969) stimulation, different cochlear fibres exhibit differing phases of discharge inspite of their having a similar CF. More strikingly still, Konishi and Nielsen (1973) claim to have found a majority of guinea pig cochlear fibres which were excited by static "*downwards*" displacement of the basilar membrane (*i.e.*: toward the *scala tympani*), a minority whose spontaneous discharge was inhibited by the same displacement, and a substantial proportion of fibres which were excited during dynamic changes of membrane position. It is unlikely that these differences can be accounted for by different hair cells having different "polarities" to movement of their hairs, in view of their basal bodies being oriented in the same direction (see Flock, 1971). Perhaps the differences may arise from different modes of bending of the hair cells, as suggested by the recent findings of Dallos *et al.* (1972), who infer that the outer hair cells (mainly responsible for generating the cochlear microphonic) are sensitive to displacement, while the inner hair cells are sensitive to the velocity of

endolymphatic flow (consistent with the anatomical evidence which suggests that, the inner hair cells, unlike the outer hair cells, are *not* attached to the tectorial membrane, *e.g.* Lim, 1972). At least, all of these findings underline our almost complete ignorance of the processes lying between the displacement of the basilar membrane and the generation of nerve impulses in the cochlear nerve (see also Fex, volume V/1).

B. In Relation to Cochlear Innervation

The question remains open as to what part the complex innervation patterns of the cochlea might take in the mechanisms discussed in the last section. There is good evidence that the probabilistic generator responsible for the "jitter" of discharge to low frequency tones (vd. Section II.D.4) and which is sensitive to non-excitatory outputs of the transducer, thus mediating static (vd. above) and dynamic (vd. Section II.C) depression of spontaneous activity, is located peripheral to the generation of action potentials, and, therefore, presumably in the hair cell-synapse area. Similarly, the process underlying the saturation of discharge rate is not likely to be in the nerve fibres, in view of Kiang and Moxon's (1972) observation that direct electrical stimulation of the cochlea (and therefore presumably of the cochlear fibre initial segment) could evoke higher rates of discharge than could be evoked by acoustic stimulation. In keeping with this, the passage of direct current through the cochlear partition augments the "spontaneous" and "evoked" activity without affecting the maximal (saturation) discharge rate (Konishi *et al.*, 1970). Perhaps the most economical hypotheses are to locate the transducer process inthe hair cell (as in the generally accepted hypothesis of Davis, 1965, for CM), and the probabilistic generator in a chemical transmission process in the synaptic junction. Refractory processes could be located in the nerve itself. Unfortunately, chemical transmission has been confirmed only in the fish sacculus, in an important series of experiments by Ishii *et al.* (1971) and by Furukawa *et al.* (1972).

One problem which has attracted considerable attention is the role played in cochlear nerve responses by the outer spiral fibres innervating the outer hair cells (OHC). The OHC have been held responsible for the low thresholds of cochlear fibres in contrast to the presumed higher thresholds of the inner hair cells (IHC), inferred from the assumed relative mechanical disadvantage of the latter. However, the detailed electron microscopic studies of Spoendlin (1966, 1968, 1970, 1971, 1972) in the cat indicate that no more than 5% of the the fibres leaving the cochlear partition originate in the OHC. In other words, the great majority of fibres recorded by microelectrodes in the cochlear nerve must innervate the IHC. Yet it is these fibres which have uniformly low thresholds approximating to behavioural threshold (Fig. 8). Apart from the very recent description by Pfeiffer and Kim (1972) of "anomalous" PST histograms to click stimuli in 7% of their cat cochlear fibre population (where the number of peaks increased dramatically up to 34 with increase in level), there is no real evidence for the separation of the cochlear nerve into two fibre populations, particularly on the basis of threshold and tuning properties (see discussion of cochlear nerve homogeneity in Section II.D). This is in spite of assertions to the contrary from observations on threshold tuning and rate-

intensity properties of cochlear fibres (see detailed discussion in Section II.D.1,2) and from studies of the gross cochlear AP (see detailed discussion in Section IV).

On the other hand, there is some evidence suggesting that the cochlear fibres innervating the IHC may receive interaction from outer spiral fibres or actually be dependent upon the latter for their normal function. Firstly, Kiang *et al.* (1970), recording from the cochlear nerve of cats poisoned with an ototoxic antibiotic, were unable to obtain normal threshold responses in regions of extensive OHC loss from fibres innervating IHC which were (to light microscopy at least) normal in appearance. Secondly, as has been pointed out in Section V.A, maximal crossed OCB inhibition of cochlear fibres occurs in fibres whose CFs correspond with the region of maximal density of efferent innervation of the *OHC*. In contrast, the density of efferent innervation of the IHC afferents appears to be more evenly distributed (Ishii and Balogh, 1968). Consequently, it has been concluded (Wiederhold, 1970; Teas *et al.*, 1972) that the effectiveness of crossed OCB stimulation corresponds more closely with the pattern of efferent innervation of the OHC than the IHC, (although it must be admitted that the data on the efferent distribution to the IHC afferents are far from complete). In fact, whereas the activity of nearly all cat cochlear fibres can be suppressed by crossed OCB stimulation (Fex, 1962; Wiederhold and Kiang, 1970), it has been reported that in the rat the whole crossed OCB innervation goes to the OHC (Iurato, 1964). Recent anatomical studies of the cat cochlea (Spoendlin, 1970), however, suggest that at least part of the IHC efferent innervation comes from the crossed OCB.

If the fibres innervating the IHC do depend upon the integrity of the OHC for their normal function, this could relate the finding of occasional high threshold high frequency cochlear fibres in otherwise normal cochleas (Section II.D.1; Evans, 1972b), to the presence of sporadic OHC loss in normal guinea pigs (Wersäll, personal communication).

In the absence of signs of synaptic contact or branching (*contra* Nieder and Nieder, 1970) between outer spiral and inner radial fibres, the above considerations lead to the speculation that interaction between one of the former and 20 of the latter takes place in each habenular opening, where they become intimately apposed (Smith and Dempsey, 1957; Spoendlin, 1970; Arthur *et al.*, 1971; Lynn and Sayers, 1970). Considerations of the length and diameter of the outer spiral fibres appear to rule out electrotonic conduction (*contra* Lynn and Sayers, 1970), and lead to the suggestion that action potentials propagated along them could produce sufficient local current to generate action potentials at the inner segment region of the inner radial fibres. On this basis, and considering for a moment that the OHC are sharply tuned, whereas the IHC mirror the basilar membrane motion, the low threshold sharply tuned properties of cochlear fibres would be accounted for by OHC activity, whereas the higher threshold, more broadly tuned, and non-linear neural properties would depend on IHC activity. Under conditions where OHC function was impaired, broadly tuned, high threshold FTCs would result (as in Section II.D.1 and from exposure to intense noise and ototoxic agents). Furthermore, the fact that each outer spiral fibre innervates OHC in a higher frequency region than that of the inner radial fibres with which it comes into contact could account for the asymmetry of the upper section of the normal FTC and for the relatively greater effectiveness of low frequency compared with high frequency

tones at high levels (see Section II.E.1.c). Similarly, it could account for the shift of the CF towards lower frequencies which accompanies the loss of the sharply tuned low threshold segment of the FTC during the action on the cochlea of hypoxia (Evans, 1974 b, c, d) and certain ototoxic agents (Evans and Klinke, 1974; Evans, 1974 c, d)

Unfortunately, this speculation is not supported by the close correspondence between CM and basilar membrane filtering properties (Section VI.A) if as Dallos (1973) suggests, the OHC are almost entirely responsible for the CM generation; and by the fact that the period of the click evoked PST histogram does not show signs of increasing with stimulus level (*e.g.* Fig. 6).

An alternative possibility is interaction, at the IHC level, of local currents generated by the OHC. These are not likely to be in phase with the IHC currents (Dallos *et al.*, 1972). If sufficient phase differences could exist between these IHC and OHC "currents", the otherwise curious abrupt reduction in cochlear nerve spike discharge (see Section II.D.2) and in cochlear microphonic (Karlan *et al.*, 1972) at high stimulus levels could be accounted for in terms of cancellation in the region of overlap of the lower threshold OHC and high threshold IHC "currents".

The participation, in cochlear nerve excitation, of two different excitatory processes (Kiang and Peake, 1960) or of the local efferent innervation (Nieder and Nieder, 1970) has also been suggested. Clearly the need is for more data, before the roles of the IHC, OHC, their innervations, and that of other structures such as the giant fibres linking 10 or so IHC (Spoendlin, 1971, 1972), can be established.

C. In Relation to Psychophysical and Behavioural Phenomena

1. Critical Band and Other Measures of Frequency Selectivity

Figure 48 plots a number of psychophysical and behavioral measures of frequency selectivity in comparison with the effective bandwidths of cat cochlear fibres (Evans and Wilson, 1973). "Effective bandwidth" is approximately the half-power bandwidth of the cochlear fibre filter function expressed by the FTC (and defined and measured exactly as in the legend of Fig. 26). It should be emphasised that by frequency selectivity we do not mean frequency discrimination – the ability to distinguish a change or difference in frequency. What is meant is the ability of the ear to select or separate information arriving at one frequency from that at another. This is expressed in the "critical band", which at any frequency is about 30 times wider than the difference limen for frequency discrimination (Zwicker, 1970). The critical band expresses the frequency band: within which simultaneously sounded tones cannot be separated (Plomp, 1964 b; McClelland and Brandt, 1969); within which power summation occurs for threshold measurements in the presence (Greenwood, 1961) and absence (Gässler, 1954) of masking noise; within which loudness is determined by the summed power of the components (Zwicker *et al.*, 1957); within which tones are effective in masking a narrow band of noise centred between them (Zwicker, 1954); within which the effects of the phase relations between components of modulated tones can be detected (Zwicker, 1952); and within which "roughness" arising from a complex of tones can be detected (Terhardt, 1968, 1970). The critical band can thus be

understood by analogy with the bandwidth of a linear filter (Greenwood, 1961; Zwicker, 1971). That this measure (the critical band) determined in man corresponds tolerably well over a wide frequency range with the analogous measure for individual cat cochlear fibres (Fig. 48) leads to the conclusion that the ear's critical band property derives directly from the filtering properties of cochlear

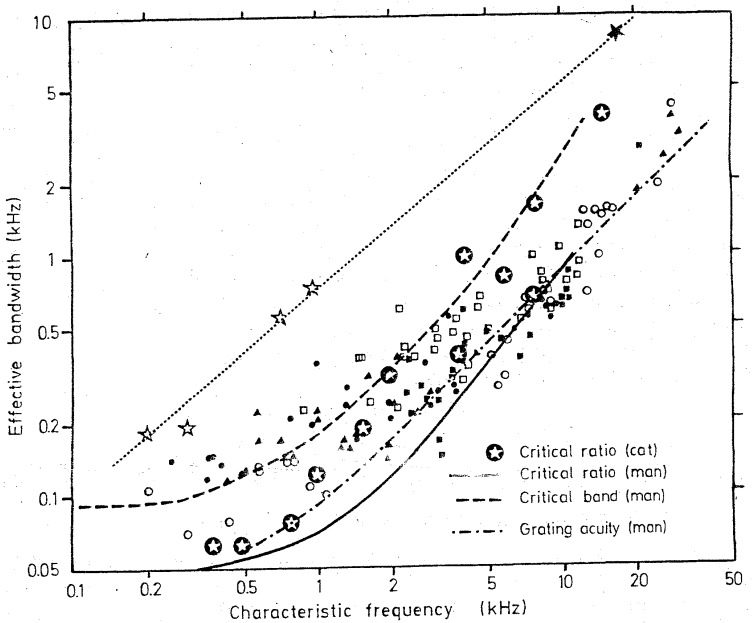

Fig. 48. Comparison of effective bandwidths of cat cochlear fibres with human psychophysical and cat behavioural measures of frequency selectivity. Circle, triangle, and square symbols: effective bandwidths computed for 140 cochlear fibres from 5 cats, plotted against their CFs. Dotted line: effective bandwidths computed for basilar membrane response curves of Békésy (1944; open stars) and Johnstone *et al.* (1970; solid star). Dashed line: critical band values for man (Zwicker *et al.*, 1957). Solid line: critical ratio values for man (Hawkins and Stevens, 1950). Dotted and dashed line: resolving power expressed as effective bandwidths for acoustic grating measurements (Wilson and Evans, 1971). Enclosed stars: behavioural measurements of critical ratio in cat (Watson, 1963). (From Evans and Wilson, 1973)

fibres and is therefore already determined at the cochlear level (Evans and Wilson, 1973). This conclusion is supported by the correspondence between direct measurements of the frequency resolving power of cat cochlear fibres (vd. Section II.E.3) and of human subjects for acoustic "gratings" *i.e.*: comb-filtered noise (Wilson and Evans, 1971; Evans and Wilson, 1973). These measurements determine the limit of the ability of single cat cochlear fibres and of human subjects (in psychophysical experiments) to resolve between peaks and valleys of the comb-

filtered noise spectrum at successively closer spacings (vd. Fig. 27 and text). The effective bandwidths derived from the psychophysical measurements are shown as the dot-dash curve in Fig. 48, although there are indications that the values below 2 kHz may be too low (Wilson and Seelman, data to be published), and therefore may agree better with the cat neural data.

The cochlear nerve effective bandwidths represent a filter "Q" (*i.e.*: CF/effective bandwidth) of about 10 from 1–10 kHz (Fig. 48). This figure agrees well with that derived by Duifhuis (1971) from measurements of the peripheral filtering characteristics of the human ear.

A possible objection to comparison between cat neurophysiological and human critical band data arises from the one existing series of behavioural measurements of an analogous function, the critical ratio (Watson, 1963; enclosed stars, Fig. 48). In man, this function is approximately 2.5 times smaller than the critical band (continuous versus dashed lines, Fig. 48; Zwicker *et al.*, 1957), hence the values of critical band for the cat might be expected to be well above the points representing the measured cochlear nerve effective bandwidth. However, Seaton and Trahiotis (1973) have recently suggested that such behavioural indications of poorer frequency resolving ability in animals may in fact not be the case, but may be related to the high criterion adopted in the training paradigms.

The correspondence proposed between the critical band measures and the effective bandwidth of cochlear fibre FTCs would appear to account for all of the characteristics of the critical band so far mentioned. In addition, it would account: for the findings which indicate that the critical band does not require any significant amount of time to be established apart from the "response time" of the cochlear filter (Zwicker and Fastl, 1972) because the cochlear filter characteristics hold for click stimuli also (Section III.F.3); for the increase in the critical band with stimulus level (corresponding to the inferred decrease in "Q" of the FTCs at levels 40 dB and above minimum threshold, vd. Section VI.A.1); and for the frequency asymmetry of masking (*e.g.* Small, 1959; Scharf, 1971).

2. Masking

While the arguments of the previous section enable an understanding to be made of the energy and frequency relations which exist between masker and maskee signals, the mechanisms responsible for the actual elevation of maskee threshold are less clear. At least four mechanisms have been proposed to explain how peripheral auditory neurones are prevented from transmitting or processing information that would be adequately dealt with in the unmasked state. (That masking is not primarily a cochlear mechanical effect is suggested by its absence in the cochlear microphonic, *e.g.* Derbyshire and Davis, 1935.) On the other hand, it must be emphasised that explanations based on peripheral mechanisms may be inappropriate or at best incomplete for high levels of masking, in view of the phenomenon of binaural unmasking (first extensively described by Hirsh, 1948), where a monaural tone signal, masked completely by a noise signal in the same ear, can be rendered *audible* by the presentation of a correlated noise signal to the other ear. This reduction in masked threshold can amount to 10–20 dB under certain conditions of interaural phase of tone and masking noise signals.

The earliest explanation of masking was a *"line-busy"* effect (Derbyshire and Davis, 1935). Here, a neurone is prevented from responding to the maskee stimulus because its discharge rate has already saturated due the masker, or because of refractory effects from the latter stimulus. While there is no evidence for the latter, the "masking" of tone and click responses of the cochlear nerve by noise stimuli mentioned in Section II.E.4 does appear to represent the inability of the fibre to discharge at any greater rate.

The second, and most compelling explanation of masking, that of stimulus *dominance,* is able to deal with stimulus levels below those producing saturated discharge rates (Greenwood, 1961; Goldberg and Greenwood, 1966). In this case, the response of a neurone is dominated by the more effective stimulus, in the sense that the response to the two stimuli is virtually identical to that to the more effective (masking) stimulus alone. For stimuli of similar frequency, this effect will arise because the response of cochlear nerve and nucleus units (of appropriate CF) is related to the *logarithm* of the combined stimulus power (Section II.D.2, III.E.2), hence the addition of a second stimulus of equal power does not double the response but only increases it by the equivalent of an extra 3 dB of stimulus level; similarly, the addition of a second stimulus 10 dB below the first, however effective on its own, will have a negligible effect in combination, given a noisy system which has to detect increments in overall signal intensity. For masking stimuli displaced in frequency from the CF of a unit, the situation can be complicated by the two tone suppression phenomenon, but the net effect is the same as in the case above. Thus, the pattern of response (mean rate and temporal statistics) is dominated by the more effective component of the two stimuli whether the addition of the latter produces an increase, decrease, or no change in the discharge rate (vd. Section II.E.1.a, c; III.F.1, 2, 5).

Thirdly, at the cochlear nucleus level, a masking signal can inhibit the response to a test signal if it is situated in the inhibitory side bands (Section III.E.1, III.F.2, 5). The fact that the inhibitory side bands often extend over a wider frequency range compared to the excitatory band suggests that a wide range of masking frequencies could prevent any response to an exciting tone arising in the population of cells with such side-bands (Galambos, 1944; Greenwood and Maruyama, 1965).

Fourthly, evidence obtained from studies of the cochlear AP response, and the "frequency following" gross response of the CN, suggests that masking represents a disruption of the synchronization of individual neurone activity to the masked stimulus (Bone *et al.*, 1972; Marsh *et al.*, 1972). While it is the case that the statistics of the activity of individual neurones in the CN are dominated by the more effective stimulus of a stimulus pair, this cannot serve as an explanation for masking of responses with masker and maskee at frequencies higher than 4 kHz (observed even at the AP level Finck, 1966).

The fact that broadband noise masking is restricted by critical band considerations suggests that the second of the above mechanisms is the most likely one to be involved. There is evidence that lateral inhibition is not involved when broadband signals are used (vd. Rainbolt and Small, 1972). In the case of tone on tone masking however (*e.g.* Small, 1959), lateral inhibitory effects could well be involved, at the level of the CN and above.

The above considerations apply to simultaneous masking. A good deal of interest has been aroused by the non-simultaneous psychophysical masking procedures of Houtgast (1972) which appear to produce definite evidence for lateral inhibitory effects. These effects, however, are unlikely to be related to cochlear nerve activity but may represent temporal facilitation and inhibition due to the different latencies of responses at different frequencies at higher levels of the auditory system. Watenabe and Simada (1971) were able to find evidence of single unit behaviour corresponding to forward masking in the CN; whereas evidence of backward masking effects were only found in the inferior colliculus (vd. Section III.F.5).

Zwislocki (*e.g.* 1971) has shown that a number of aspects of central masking (*i.e.*: with binaural stimuli) can be related to the behaviour of CN neurones.

3. Combination Tones

The most prominent combination tone, particularly at low stimulus levels, is that corresponding in frequency to $2f_1 - f_2$. This has been discussed above in terms of cochlear nerve activity (Section II.E.1.b) and cochlear mechanisms (Section VI.A.1, 2). It is only necessary here to emphasise that, except in one respect, the psychophysical properties of this combination tone correspond to the behaviour of single cochlear fibres to the same stimulus combination. In terms of mean discharge rate and synchronization in relation to the level and frequency separation of the primaries, cochlear fibres of CF corresponding to the combination tone frequency respond as if there was a component of frequency $2f_1 - f_2$ actually present in the stimulus. The possible site of generation of the CT is discussed in Section VI.A.1, 2. Arguments against the suggestion that the effects are produced simply as a result of the rectifier action of the cochlear nerve spike generator are given in Section II.E.1.b. Further work is necessary to account for the significant contrast between the phase behaviour with level of the combination tone observed psychophysically and the absence of such effects at the cochlear nerve (Section II.E.1.b).

4. Sensorineural Deafness

The more recently obtained cochlear nerve fibre data have allowed a revision of hypotheses on the mechanisms underlying the perceptual deficits produced by pathological conditions of the inner ear (vd. Evans, 1972b; 1974c).

Formerly, it was held (and still is, from misinterpretations of AP data, *e.g.* Portmann *et al.*, 1973, *cf.* Section IV) that the phenomenon of *loudness recruitment* (which is associated with threshold elevation of cochlear origin, Dix *et al.*, 1948), arose because of a selective loss of activity in lower threshold cochlear fibres (assumed to originate in the outer hair cells) out of a population of fibres with widely differing thresholds (*e.g.* Kiang *et al.*, 1965a). The loss was related in turn to outer hair cell damage. On the contrary, it has now been established that most cochlear fibres innervate the inner hair cells (Section VI.B.), and, in the normal animal, all have uniformly low thresholds consistent with behavioural threshold (Fig. 8). Furthermore, the data from guinea pig cochleas with evidence of circulatory insufficiency (Section II.D.1) and from cats poisoned with ototoxic antibiotics (Kiang *et al.*, 1970) indicate that hair cell damage causes an elevation in

the threshold of the *same* fibres, and in addition, a substantial broadening of their FTCs. It is as if there was a selective loss of the more sharply tuned, lower threshold segment of the FTC to leave the high threshold wide-band segment (*cf.* Fig. 9). Under conditions where the FTCs of a fibre population are abnormally broad, a correspondingly greater proportion of fibres will be recruited for a given increase in suprathreshold tone level than when the fibres are normally sharply tuned. If the sensation of loudness is related (among other factors) to the proportion of fibres active, then loudness should grow at a greater rate under conditions where the fibres have abnormally broad frequency response properties than under normal conditions (Evans, 1972b). There is in fact evidence of abnormally broad critical bands in patients with cochlear deafness (*e.g.* de Boer, 1959; Scharf and Hellman, 1966). If, as appears to be the case from Fig. 10 of Kiang *et al.* (1970), the properties of the cochlear fibres innervating apparently normal inner hair cells are affected by loss of outer hair cells, the additional assumption of some form of interaction between inner and outer hair cells and/or their innervations is required (see Section VI.B.).

It is possible to speculate further that the impaired speech perception which patients with cochlear deafness possess even after correction for the elevated thresholds may reflect the inability of their abnormally broadly tuned cochlear fibres to resolve (separate) the formant frequencies of the speech signal (Evans and Wilson, 1973).

D. In Relation to the Coding of Acoustic Stimulus Parameters

1. Frequency

Abundant quantitative data are now available on the peripheral auditory nervous system to indicate that it carries information which could be analysed by either "place" or "periodicity" mechanisms for the coding of stimulus frequency. In order to discover the relative role of such putative codes, it is of course necessary to determine whether the information they carry can be utilized at higher levels of the auditory system (*e.g.* see Whitfield, 1970). On the other hand, it can be instructive to examine some of the possible obstacles to the acceptance of presently formulated "place" and "periodicity" coding theories set by the properties of the auditory periphery.

Naively, it may be throught implicit in the discussion above that if cochlear fibre FTCs can account quantitatively for frequency selectivity (critical band) they cannot, as filters, account for our acuity of frequency discrimination, which is some 30 times finer. The problem appears to be analogous to that between grating and vernier acuity in vision. However, slopes of the FTCs, and particularly the high frequency slopes are sufficiently steep that at least the low frequency border of the activity in a tonotopic array of cochlear fibres would be very sharp. Furthermore, this border should become sharper at higher tone levels (as the high frequency slopes become steeper: see Fig. 9) and could therefore account for the observed improvement in the difference limen. In fact, Siebert (1968, 1970) has estimated that an "ideal observer", having access to this sort of information from an array of fibres with the threshold, FTC, and rate-intensity properties measured

for cat cochlear nerve fibres, would have a difference limen for frequency approximating to that observed psychophysically. Zwicker (1970) has similarly obtained a correspondence between a difference limen estimated from the shape of the cochlear "excitation function" (inferred from psychophysical masking measurements) and that observed psychophysically.

Perhaps the greatest problem facing an exclusive place theory is the limited dynamic range implicit in the cochlear nerve and nucleus data. Not only is the increase in mean discharge rate of a single neurone limited to an intensity range of less than 50 dB (Section II.D.2, III.E.2), but the distribution of thresholds of different neurones at any one CF in an animal is less than 20 dB (Section II.D.1, III.E.1). While this is not necessarily a problem for pure tone discrimination (where the low frequency border of an active fibre array will remain sharp, and the high frequency border could still convey intensity information, as in the scheme of Allanson and Whitfield, 1956), it is not clear how the frequency components of complex waveforms such as speech could be separated. At average speech levels, the energy in a critical bandwidth is 50–60 dB above threshold for frequencies between 0.5–2 kHz. This means that most fibres will be saturated, and differences of energy between formants could not be signalled, nor presumably the formants themselves coded in separable groups of fibres (Kiang and Moxon, 1972). This problem of course rests on the contrast between human perceptual performance and that of anaesthetized cat cochlear fibres, where the activity of middle ear muscles and efferent nervous system are inoperative. However, the results described in Section V suggest that any effects of the latter would be to broaden rather than to sharpen the frequency selectivity of the cochlear fibres. The studies of Simmons and Linehan (1968) and of Rupert *et al.* (1963) of cochlear fibres in awake cats do not provide any further clues.

It is clear from the data described in Section II.D.4 that the phase-locking properties of cochlear fibres are not limited in this way. Phase-locking to tonal stimuli can be observed for 10 dB or so below the mean rate "threshold" and this is retained at levels in excess of 90 dB SPL (Fig. 18). On the other hand, Siebert (1968, 1970) has shown than "an ideal listener" who utilizes all the time clues transmitted in his cochlear nerve (inferred from the cat's nerve) would have a difference limen two orders of magnitude smaller than that actually observed. But as the relationship of the limen to many stimulus parameters would also be substantially different a complicated type of inefficiency would have to be involved. There are however, a number of more serious problems for an exclusive periodicity theory. Firstly, the ability of cochlear nerve and nucleus discharges to retain periodic information concerning tones appears to be lost above 4–5 kHz. Furthermore, while the degree of neural phase locking improves with *decrease* in frequency (see Fig. 19), there is no such improvement in the difference limen; on the contrary dF/F *increases* with frequency reduction below about 0.5 kHz (but this could be expected on considerations of the high frequency slopes of FTCs). Secondly, from the data of Rose and colleagues (vd. Section II.E.1.c), it does not look as if periodicity information in the discharge patterns will disappear for combinations of tones separated in frequency by less than the critical band; whereas the ability of the ear to "hear out" (Plomp, 1964b) or match in pitch (McClelland and Brandt, 1969) the individual frequency components is lost. Thirdly, as Rose *et al.*

(1969) point out, the time structure of cochlear fibre discharges does not correlate well with the perception of combination tones. In particular, apart from the fundamental of a harmonically related pair of tones, their data predicted the presence of combination tones of frequencies above the primaries, but none below. This conflicts with the psychophysical finding that the $2f_1 - f_2$ tone (see Section VI.C.3) is the most prominent combination tone heard (Goldstein, 1967). Furthermore, Goldstein and Kiang (1968) demonstrated that responses to the $2f_1 - f_2$ component were present in the appropriate place in the cochlear fibre spectrum at frequencies well above that at which phase locking becomes insignificant (Section II.E.1.b). Fourthly, Brugge *et al.* (1969), Goldstein (1970, p. 191), and Smoorenburg (1972b) have pointed out that there is a discrepancy between (a) the marked sensitivity of cochlear fibre temporal discharge patterns to the phase of interaction of the tone components of a combination, and (b) the lack of corresponding phase sensitivity of the ear. Fifthly, the transmission of periodic information in the discharge patterns of fibres, irrespective of their CF, makes it difficult to understand why a patient with a sharply defined tonal gap and focal cochlear lesion should have evidence of a diplacusis related to stimulus level (Smoorenburg, 1972b). Lastly, one classical argument for periodicity coding theory — residue pitch — has been called into question by the psychophysical investigations of Houtsma and Goldstein (1972), Goldstein (1972), and also by the data of Gruber and Boerger (1970; but see the reservations on these data in Section II.E.1.b). In contrast, an attractive theory of pitch perception is emerging which accounts for these and other data by proposing a peripheral spectral frequency analysis and a central pitch extraction mechanism (*e.g.* de Boer, 1956; Wilson, 1970, 1974; Whitfield, 1970; Wightman, 1972).

2. Intensity

The problem of the limited dynamic range demonstrated in the present data from cochlear nerve and nucleus neurones has been detailed in (1) above. For stimulus levels above those which saturate the neurones with corresponding CFs, it appears that we must conclude that the intensity information is carried by neurones of higher and lower frequencies, *i.e.*: on the outskirts of the active array as well as by the width of the array (Allanson and Whitfield, 1956), although the perception of multicomponent stimuli such as speech cannot be explained in this way (see above section).

3. Sound Complexes

The great majority of data on cochlear nerve and nucleus have been obtained with pure tones, clicks, and noise as stimuli. Experiments with more complex stimuli suggest that in contrast to the situation at higher levels of the auditory system (vd. Evans, 1968), the responses of neurones in the periphery to more complex and behaviourally meaningful sounds are relatively simply predicted in the spectral and temporal terms described above. Thus, no evidence of specific or even substantial sensitivity to the rate of change of frequency and amplitude of sounds has been obtained in cochlear nerve (data of Watenabe, 1972) or cochlear nucleus (see Section III.F.4). What evidence there is appears to be predominantly in the

dorsal cochlear nucleus, where much more complex excitatory-inhibitory interactions abound compared with the ventral division (Section III.B.2, 3, III.F.4). This latter dichotomy has led to the proposal that in the diversity of the CN we may have the earliest evidence of a "division of labour" within the auditory system into neural mechanisms responsible for complementary information processing tasks. Thus, in Fig. 49, the division of the cochlear nucleus and its ascending projections is crudely represented into functionally separable dorsal and ventral systems. The conjecture has been made elsewhere (Evans, 1971; Evans and Nelson, 1973b) that this subdivision may be analogous to that apparently present in the visual system: namely into (at least) two systems responsible for place and form information processing respectively (Held *et al.*, 1967, 1968). In the case of Fig. 49, the ventral pathway would be ideally suited, by its preservation of temporal information, for the transmission of information pertaining to sound localization, while the dorsal pathway with its more complex responses may represent the first stages in the neural processing of acoustic patterns (Evans, 1971, 1974a).

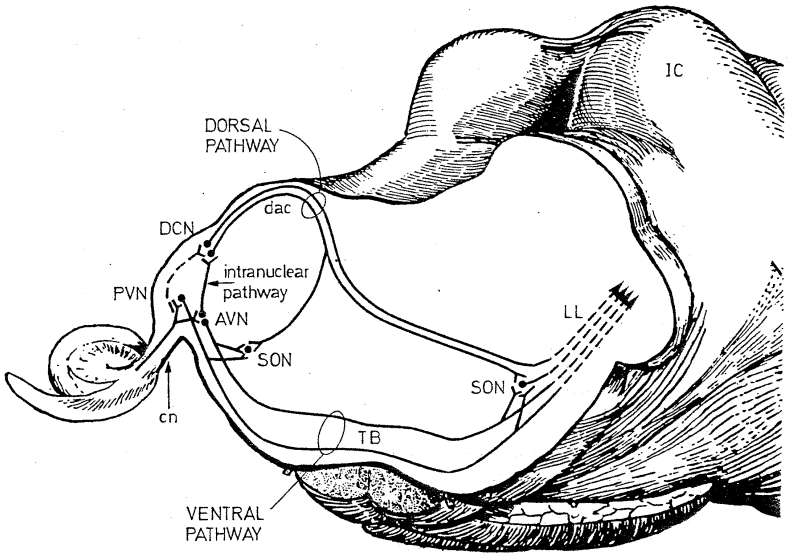

Fig. 49. Dorsal and ventral ascending acoustic pathways. Transverse section of brainstem at level of cochlear nuclei (after Papez, 1929). cn: cochlear nerve; DCN, AVN, PVN: dorsal, anteroventral and postero-ventral divisions of cochlear nucleus. dac: dorsal acoustic stria. SON: superior olivary complex (includes nuclei of trapezoid body). TB: Trapezoid body. LL: lateral lemniscus. IC: inferior colliculus. This diagram represents a gross simplification of the output fibre pathways of the cochlear nuclei, after Poljak (1926); Lorente de Nó (1933b), Warr (1966, 1967) and Jungert (1968). The dorsal pathway represents the classical dorsal acoustic stria of Monakow. The ventral pathway represents the intermediate acoustic stria of Held and the trapezoid body. The SON is not subdivided into the trapezoid nuclei and medial, lateral, peri- and pre-olivary nuclei of the superior olive proper. (From Evans and Nelson, 1973b)

Acknowledgements

I am indebted to Dr. J. P. Wilson for extensive discussion of many of the topics dealt with herein and for his helpful comments and those of Dr. R. Klinke on the manuscript. I also wish to thank Mr. J. S. Corbett, for photographic assistance, and Miss H. O. Henry and Mrs. J. E. Clarke for their patient typing of the manuscript.

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Chapter 2

Physiological Studies of Auditory Nuclei of the Pons*

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With 20 Figures

Contents

I. Introduction

The superior olivary complex and the nuclei of the lateral lemniscus are a group of more or less distinct nuclei, located in the pons and lying in close association with the major tracts interconnecting the cochlear nuclei with the inferior colliculus. The tracts, the acoustic striae and the lateral lemniscus, provide afferent

* Preparation of this chapter supported by Grant NS-05237, National Institutes of Health, and by a Sloan Foundation Grant.