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CHARACTERISTICS OF NEURAL TRANSMISSION FROM THE SEMICIRCULAR CANAL TO THE VESTIBULAR NUCLEI OF CATS

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SUMMARY

1. The characteristics of the dynamic response of specifically canal-dependent neural units in cat vestibular nuclei have been examined during sinusoidal rotation of the head in decerebrate cats over the narrow frequency range 0·25–1·7 Hz.

2. Unit action potential frequencies were averaged on line from extracellular steel micro-electrodes stereotaxically located in the vestibular nuclei through the intact cerebellum.

3. Action potential frequency was approximately in phase with stimulus angular velocity, the mean phase for forty-six units being $+11{\cdot}4°$ (S.E. of the mean $\pm 2{\cdot}2°$). Correction for a form of dynamic asymmetry reduced this value almost to zero.

4. The mean gain of thirty-nine single unit responses was 0·76 (S.E. $\pm 0{\cdot}08$) AP/sec per °/sec. The gain varied as the $(-0{\cdot}28)$ power of stimulus angular velocity, for the five cells appropriately tested.

5. A method was evolved for computing the spontaneous condition of cells, in terms of an equivalent spontaneous firing frequency, f_{sp}, irrespective of whether they were spontaneously active or silent. This f_{sp} value was normally distributed about a mean value of 11·2 AP/sec (range $+70$ to -40 AP/sec).

6. Directionality was examined in 116 units, of which 62 % were ipsilateral (e.g. cells on left side excited by left-going rotational velocity) and 38 % contralateral. Ipsilateral units proved easier to isolate and retain than contralateral ones.

7. No significant differences in mean phase or gain were found in the sub-sets of spontaneously active/inactive cells and ipsilateral/contralateral cells.

8. It is inferred that the cell population examined was a functionally homogeneous one in which the neural signal was closely tied to the angular velocity of canal rotation for the narrow band of sinusoidal rotational stimuli here employed. It is suggested that this signal is probably retained essentially intact in the ensemble neural message fed forwards from this region.

INTRODUCTION

It has been shown by several authors that the mechanical response of a semicircular canal to rotational stimulation is such that within a limited range of stimulus conditions the angular displacement of endolymph in the canal circuit is directly related to the angular velocity of rotation (Schmaltz, 1931; Steinhausen, 1933; van Egmond, Groen & Jongkees, 1949; Mayne, 1950). In particular, Jones & Milsum (1965) have suggested this angular velocity transducing characteristic would be manifest in man during sinusoidal rotation over the frequency range 0·1–5·0 Hz.

Jones & Spells (1963) investigated the variations of the relevant physical constants as functions of canal dimensions in a wide range of animal species using the method of dimensional analysis. They found changes between species which have since been shown by Mayne (1965) and Jones (1969) to be appropriate for maintaining angular velocity transduction over the likely frequency range of natural head movement predicted by dimensional analysis of animal size. These latter observations seem to imply that there has been strong evolutionary pressure for selection of canal parameters specifically yielding an angular velocity signal over the frequency range appropriate to each species. A natural corollary would be that integrity of the angular velocity signal should be maintained in the neural signal transmitted to the brain.

Accordingly the present study examines the dynamic response of neurones in the vestibular nuclei of cats exposed to sinusoidal rotational stimulation over a range of frequencies (0·25–1·7 Hz), presumed to lie within the domain of angular velocity transduction by the end-organ hydrodynamics (Jones & Milsum, 1965). Preliminary results have been previously reported (Melvill Jones & Milsum, 1969).

METHODS

Decerebrate, or occasionally ether anaesthetized, cats were held in a conventional stereotaxic device located on a movement platform illustrated diagrammatically in Fig. 1. The lateral canals were aligned in a horizontal plane by tilting the head downwards 30°, with the mid-point between the canals on the axis of turntable rotation. The whole platform assembly was first suspended from the ceiling by parallel springs after the method of Adrian (1943) so that the animal could be exposed to all six

degrees of freedom of movement (three rotational and three translational). This slung system was poised over a servo-controlled turntable as indicated in Fig. 1 so that it could be attached thereto after location of horizontal canal-dependent cells as described below.

Long and rigid steel micro-electrodes were introduced through a small trephined opening in the occipital skull and advanced through the intact cerebellum, to a point estimated to be approximately 1 mm above the floor of the fourth ventricle, 9 mm posterior to the Horsley Clark zero and 2 mm lateral to the mid line. The electrode

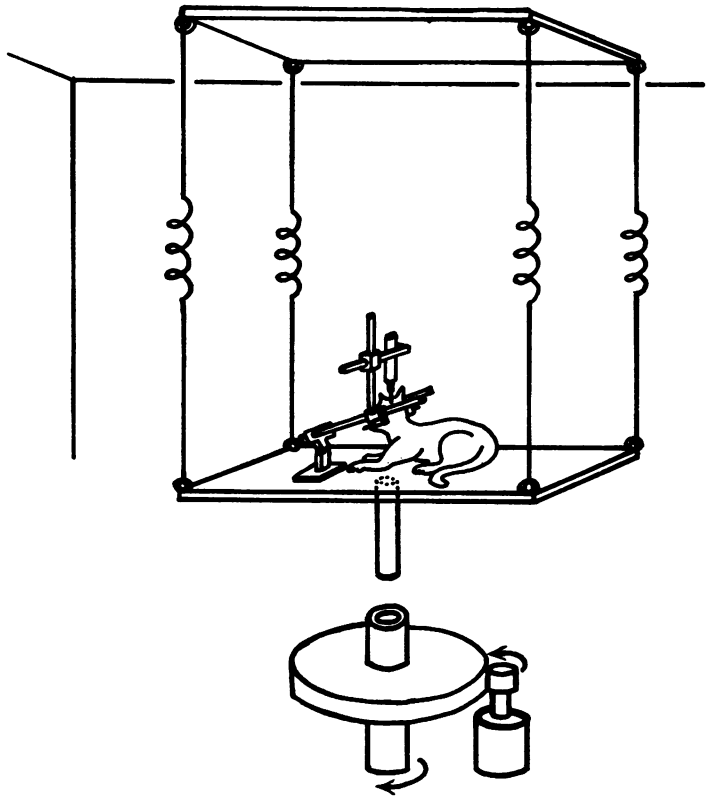

Fig. 1. Diagram of essential components in the movement platform assembly.

advancement was 30° downwards and forwards relative to the stereotaxic vertical in order to avoid contact with the bony tentorium cerebelli. This location was chosen as the one most likely to yield specifically horizontal canal-dependent units.

After locating a cell, shown on the slung platform to respond *specifically* to rotational stimulation of the horizontal canals, the platform was carefully lowered on to the turntable, and the spring suspension removed. The whole system was then exposed to a wide range of sinusoidal and transient rotational stimuli. Only the responses to sinusoidal rotation within the range 0·25–1·7 Hz are described in this article since this is presumed to lie within the velocity transducing range of the end-organ. Cells responding specifically to rotational stimulation in the plane of one pair of vertical canals could only be tested at the natural frequency of the slung platform.

Usually the angular velocity amplitude of the sinusoidal stimulus was chosen to generate an easily audible modulation of the cell's firing frequency during the sinusoidal stimulus, without incurring saturation of the cell's response at maximum stimulus angular velocity.

The frequency of action potentials (AP) throughout a sine wave of stimulation was averaged using a Burns neurophysiological computer (Burns, Ferch & Mandl, 1965), the original APs and their triggered replica being simultaneously displayed by means of an ultra-violet galvanometer recorder having suitable frequency response (5% attenuation at 5000 Hz). This latter procedure permitted immediate and continuous visual monitoring of the reliability with which the triggered signal (fed into the computer) corresponded with the original AP (Fig. 2).

By splitting the computer operation between stimulus (obtained from a suitable tachometer) and response, the corresponding AP frequency and stimulus angular velocity could be averaged simultaneously until sufficient data had been accumulated to permit numerical analysis. At this point, the final averaged stimulus–response curves were photographed on polaroid film directly from an oscilloscope display as illustrated in Figs. 3, 4 and 10.

Electrode tip location was marked by electrolytic deposition of iron from the steel electrode tip either at points of special interest or in a set of eight stereotaxically located co-ordinates at the end of an experiment. The iron deposition was developed by perfusion with a ferro-ferri cyanide mixture in 10% formal-saline solution at the end of an experiment. The anatomical location of such spots was determined by conventional histological sectioning at 25 μ throughout the relevant part of the brain stem and subsequently stained with cresyl violet for cell structure. Usually alternate slides were stained in addition by the luxol blue method to display myelin sheathed tracts, particularly to aid distinction between medial and inferior (descending) vestibular nuclei (Brodal, Pompeiano & Walberg, 1962). Knowing the stereotaxic co-ordinate settings associated with anatomically defined blue spots, it was then possible to make suitable computations for actual tip locations which had not been 'spotted'.

RESULTS

The numerical results were obtained from 170 averaged recordings of action potential frequency originating from sixty-one single units and groups of units in nineteen cats. The unprocessed audible responses of an additional fifty-five units or groups of units were noted both for their directionality of sensitivity to rotation and anatomical location. The majority of cells were assessed to be located in the medial nucleus and rostral part of the inferior nucleus, but 13% were in the superior and 9% in the lateral nuclei. From the results of Shimazu & Precht (1965) it seems safe to assume that all responses here recorded were post-synaptic to the primary vestibular neurones. In all instances the responses described were obtained from controlled adequate (rotational) stimulation of the canal end-organ.

Fig. 2 shows two extracts from original and triggered records of AP obtained from single cells in the left medial vestibular nucleus during sinusoidal rotation in the plane of the horizontal canals at periodic times and angular velocity amplitudes of (*a*) 1·4 sec and 30°/sec and (*b*) 4 sec

and 35°/sec. The top and bottom records in each part of the figure give respectively the stimulus angular velocity (down = left-going) and the original train of spikes. The middle record displays the train of artificial stereotyped spikes. Direct inspection of records such as these is informative. For example, the spike train frequency is obviously modulated in a systematic way by the stimulus, with the particular feature that at these frequencies of sinusoidal rotation the maximum firing frequency was

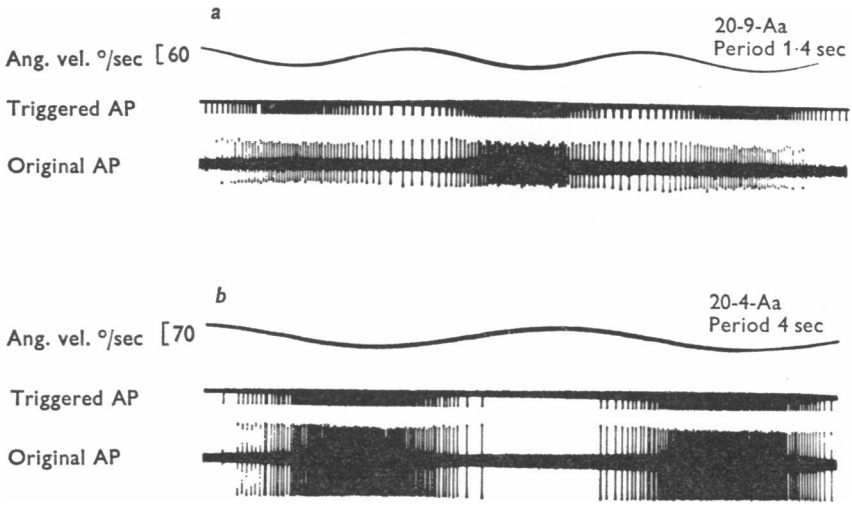

Fig. 2. Extracts from original records of turntable (head) angular velocity, triggered action potentials (AP) and original AP train. In both sets of records downward displacement of the angular velocity trace indicates left-going angular velocity. The records were obtained from units in the left medial vestibular nuclei of different cats.

approximately in phase with the angular velocity of left-going rotational stimulation. During right-going rotation, cells were inhibited below their spontaneous levels, either firing throughout the cycle at reduced frequency (*a*), or being cut-off at threshold of firing (*b*), according to the particular combination of spontaneous level, cell gain and stimulus amplitude. Incidentally, the periodic modulation of AP size is not an artifact of the instrumentation.

For systematic investigation of numerical relations between stimulus and response, these raw data were processed as described in Methods to yield results such as illustrated in Fig. 3*a* and *b*, which were obtained from single cells in different cats. These figures display curves of averaged spike frequency throughout a sinusoidal cycle of stimulation, with both phase and amplitude of response numerically related to the stimulus (upper traces). The lowest trace in Fig. 3*a* shows zero firing frequency. For

comparison with the raw records note that Figs. 2*a* and 3*a* were obtained from the same unit.

The two responses in Fig. 3 seem at first glance to show markedly different characteristics. However, such differences can arise simply from different combinations of the cell's spontaneous condition, its sensitivity to input stimuli and the amplitude of the particular sinusoidal stimulus. For example, Fig. 4 illustrates a sequence of responses from a *single cell* in which transition occurred from 'all-round' firing to a 'cut-off' pattern, as the stimulus amplitude progressively increased. At a stimulus amplitude

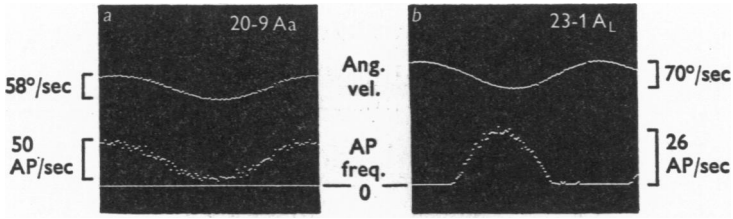

Fig. 3. Averaged stimulus (angular velocity) and response (AP frequency) obtained from two canal-dependent units in the vestibular nuclei of decerebrate cats during sinusoidal rotation in the plane of the lateral canals. (*a*) Stimulus amp. = 29°/sec, period = 1·4 sec; maximum response 52 AP/sec; average of 76 cycles. (*b*) Stimulus amp. = 35°/sec; period = 4 sec; maximum response 26 AP/sec; average of 68 cycles. Left-going angular velocity registered up in (*a*) and down in (*b*). Both units assessed as located in the left medial vestibular nucleus.

of 17°/sec, the firing frequency of this cell was continuously modulated above and below a mean frequency of approximately 36 AP/sec. This mean value corresponds well with the observed spontaneous firing frequency of 34 AP/sec in the absence of rotational stimulus. A stimulus amplitude of 61°/sec increased the range of the cell's response sufficiently that over part of the inhibitory half of the cycle it was suppressed below its threshold of firing. This pattern was progressively accentuated with increasing amplitude of stimulus.

It is of interest that despite the transition from an all-round to a cut-off pattern of firing, an 'equivalent mean firing frequency' (f_{sp}, eqn. 3 and Fig. 7) computed on the basis of completion of the response curve in sinusoidal fashion through the silent part of the cycle, remained essentially unchanged from the observed spontaneous firing frequency for all records in the series presented in Fig. 4. Table 1 presents these data from seven runs of progressively increasing stimulus amplitude. Evidently the equivalent mean values derived in this way did not differ significantly from the measured mean spontaneous firing frequency throughout either this large dynamic range of stimulus or the transition from all-round to cut-off response.

Thus although the all-round and cut-off patterns of response look quite different, it seems that they both manifest the output of a system whose characteristics are reasonably well predicted from the resulting AP train independently of whether or not that train is arbitrarily cut-off by the cell's threshold of firing during part of the cycle.

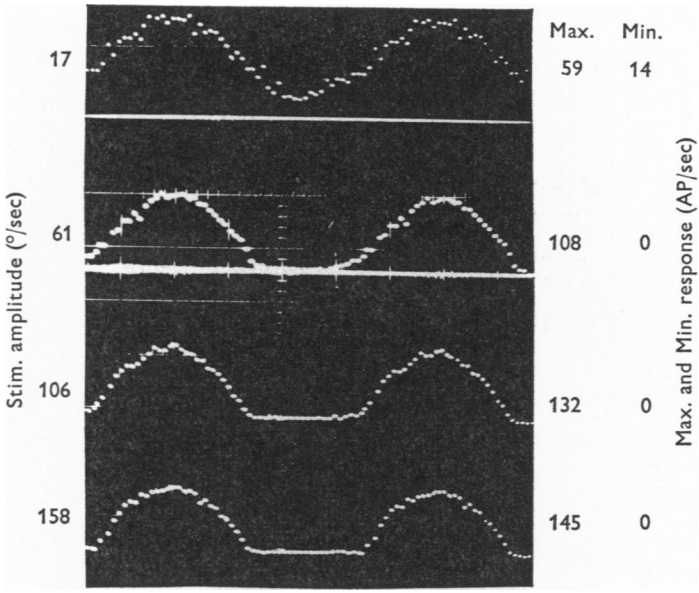

Fig. 4. Transition from 'all-round' to 'cut-off' patterns of firing as stimulus amplitude increases. All records were obtained from the same single cell. The spotted curves show averaged firing frequency throughout a cycle of sinusoidal rotation at 0·25 Hz. The displays are each written out twice to aid their visual interpretation.

TABLE 1. Mean firing frequency (f_{sp}) calculated according to eqn. (3) from the complete series of records of which those in Fig. 4 are samples (stimulus frequency 0·25 Hz)

Stimulus amplitude (°/sec)	Mean or equivalent mean firing frequency (f_{sp}, AP/sec)
17	36
35	32
61	38
88	35
105	31
123	38
158	30
Measured spontaneous firing frequency	34

On the basis of this assumption, values for phase, gain, and spontaneous level have been computed from all averaged records, irrespective of whether or not they were cut-off. In addition, the distribution of a form of dynamic asymmetry described previously (Milsum & Melvill Jones, 1969) is examined in the cut-off responses.

Phase

In the all-round response curve of Fig. 3*a*, the maximum and minimum firing frequencies are seen to be approximately in phase with maximum stimulus angular velocities to left and right respectively, the measured phase being approximately + 12°. In the cut-off response of Fig. 3*b*, it is of course only possible to estimate phase from the maximum firing frequency. Again the phase of response was tied closely to stimulus angular velocity.

TABLE 2. Phase advancement (degrees) of firing frequency relative to rotational velocity, obtained from forty-six cells in the vestibular nuclei

	No. of units	Mean phase	S.E.	Significance of difference
All units	46	11·4	2·2	
Single units	35	12·3	2·5	$P > 0{\cdot}2$
Multiple units	11	8·5	4·4	
Spontaneously active	34	13·2	2·6	$P > 0{\cdot}2$
Spontaneously inactive	12	6·3	3·6	
Contralateral	7	6·6	3·8	$P > 0{\cdot}2$
Ipsilateral	39	12·3	2·5	
Horizontal	39	13·7	2·3	$P < 0{\cdot}01$
Vertical	7	(−) 1·7	3·7	

Table 2 summarizes the phase data for the forty-six cells from which reliable averaged results could be obtained. Where more than one result was available from an individual cell a mean value was used to avoid undue weighting.

The Table shows that the mean phase for all forty-six cells or cell groups measured was 11·4° ± 2·2° (S.E. of mean), implying that the response was closely in phase with the stimulus angular velocity in this range of stimulus frequency. Fig. 5 shows the histogram of phase distribution and indicates that the above mean is derived from a relatively homogeneous data set. However, a number of subsets exist in these data, and Table 2 shows the results of testing whether the means between the groupings within any subset differ significantly. Thus there are no significant differences ($P > 0{\cdot}2$) between the responses, first of single and multiple cells, secondly of spontaneously active and spontaneously silent cells, and thirdly of ipsilateral and contralateral cells. The latter terms are chosen

to conform with the definitions employed by Shimazu & Precht (1965), i.e. cells on the left (right) side of the brain excited by left-going (right-going) rotational velocity are termed ipsilateral, while cells excited in the opposite sense are termed contralateral.

There is a small but significant difference at the 1 % level, between the mean phase of the 'horizontal' and 'vertical' cells. Probably this small difference arises because the few vertical cells tested could only be stimulated at a single frequency which was in fact the highest used in these experiments. This difference is consistent with the trend to be expected from end-organ mechanics (Jones & Milsum, 1965).

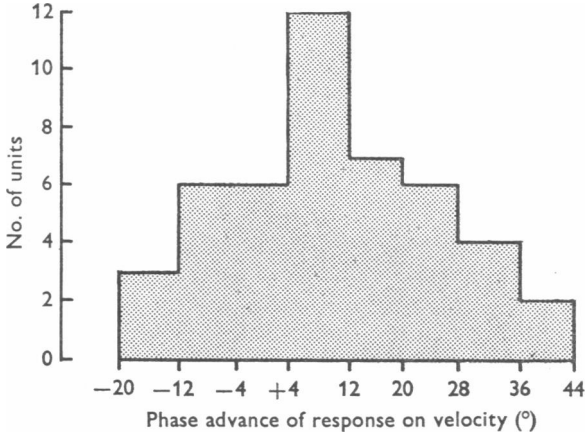

Fig. 5. Histogram of phase distribution.

Dynamic asymmetry

The value of the mean phase is sensitive to any deviation of the response pattern from the symmetric sinusoidal shape of the input stimulus. In this connexion a consistent feature of the present results, reported in detail elsewhere (Milsum & Melvill Jones, 1969), was the tendency for a form of dynamic asymmetry to develop in cut-off patterns of response to sinusoidal stimulation. This feature was characterized numerically, for cells firing through less than half the cycle, as the ratio of the time from commencement of firing to maximum firing frequency, and the time from maximum frequency to cessation of firing; it was termed the 'skew ratio' of the response (Sk). In Fig. 3*b*, for example, Sk = 0·87 and in Fig. 10, Sk = 0·85. The records in Fig. 4 are atypical in showing virtually no dynamic asymmetry. The mean skew value obtained from forty-four cells exhibiting *cut-off* responses in the present experiments was 0·81 ± 0·02 (S.E. of mean), which differs from a symmetrical response (Sk = 1·0), highly significantly. In contrast to this the mean skew value obtained from seventeen cells

exhibiting *all-round* responses in the present experiments was $0{\cdot}99 \pm 0{\cdot}04$ (S.E. of mean), which does not differ significantly from the value 1 for the symmetric response. The distributions of Sk values are shown in the histograms of Fig. 6*a* and *b* for cut-off and all-round firing respectively. These figures show clearly the shift from a mean Sk of 0·81 for the cut-off responses to a mean of 0·99 for the all-round firing.

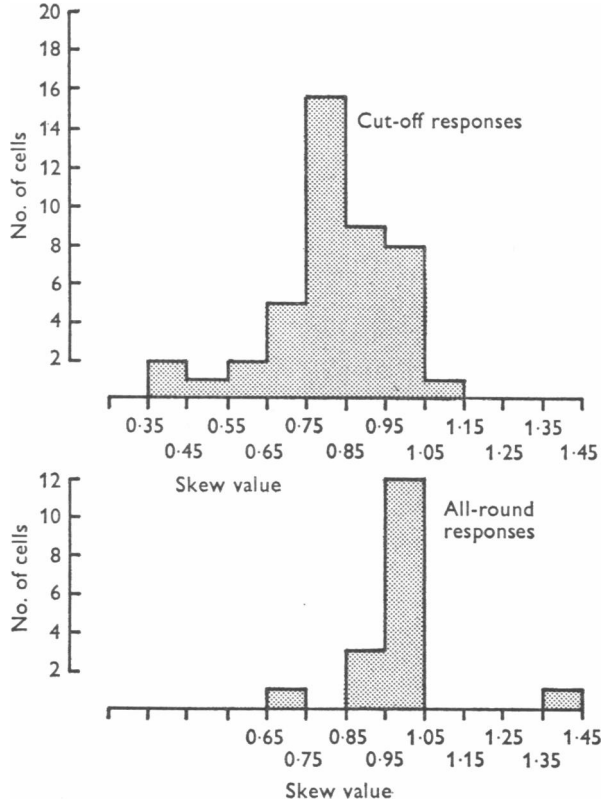

Fig. 6. Histograms of skew distribution.

It should be noted that dynamic asymmetry advances the phase of the response peak, relative to that of a symmetric response, by an amount

$$\theta = \left(\frac{1-\mathrm{Sk}}{1+\mathrm{Sk}}\right) 90°.$$

The mean skew of 0·81 for the cut-off responses therefore advances their mean phase by about 9°, which in turn represents approximately three quarters of the measured mean phase advancement in the present results.

Gain

In an all-round response such as that of Fig. 3*a*, the gain is directly measurable as the ratio of amplitude of the cell's response in AP/sec and the amplitude of stimulus in °/sec. Thus for the result in Fig. 3*a*, the gain was 25/29 = 0·86 AP/sec per °/sec.

This direct measurement of gain cannot be made when the cell is 'cut-off' at its threshold of firing, as in Fig. 3*b* and the lower three curves of

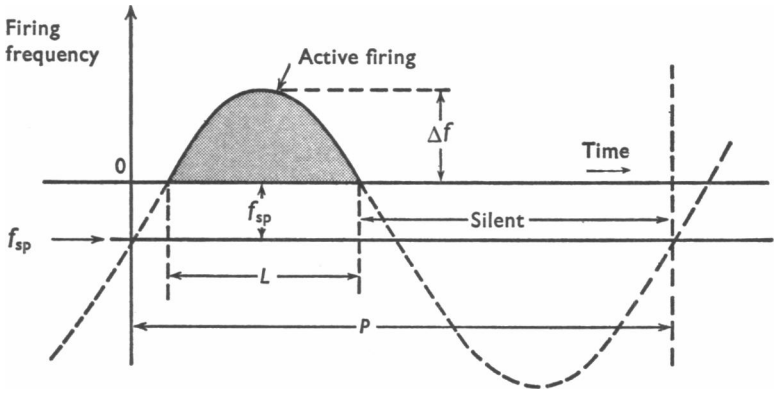

Fig. 7. Basis for calculations of 'gain' G and 'spontaneous firing frequency' f_{sp} from 'cut-off' responses.

Fig. 4, or when the cell 'saturates' at some upper level of firing frequency. The former situation applied in about three quarters of the reported cases, but the latter was never permitted in these experiments.

In this cut-off condition, it seems appropriate to define the gain, G, as the ratio of maximum change of AP frequency (Δf, Fig. 7) to the change in stimulus angular velocity ($\Delta\Omega$) occurring over the same proportion of the sinusoid as there is active firing, namely L/P in Fig. 7. This is consistent with an underlying assumption that some cellular phenomenon such as membrane potential undergoes a smoothly graded continuation of the response throughout the whole cycle.

Then,

$$G = \frac{\Delta f}{\Delta\Omega} = \frac{\Delta f}{\Omega\text{amp}\{1-\cos\pi(L/P)\}}, \tag{1}$$

where

Ω_{amp} = amplitude of sinusoidal stimulus (angular velocity) (°/sec),
P = period of stimulus (sec),
L = duration of cell firing (sec).

For example, in Fig. 3*b*, where the cell fired over 194° of the cycle,

$$G = \frac{26}{35\{1-\cos\frac{1}{2}(194°)\}} = 0{\cdot}66 \text{ AP/sec per °/sec.}$$

Table 3 gives the gains obtained for thirty-nine single units and nine multiple unit recordings, and Fig. 8 presents the histogram of the gain distribution for the single cells. The histogram is skewed toward low gain. The value for mean gain of multiple units was 2·85, compared with 0·76 for the single units, presumably indicating that about four cells were contributing on the average to multiple unit recordings. As with the phase

TABLE 3. Gain data (AP/sec per °/sec) obtained from thirty-nine single and nine multiple units

	No. of units	Mean gain	S.E.	Significance of difference
All single units	39	0·76	0·08	
Spontaneously active	28	0·81	0·08	$P > 0·2$
Spontaneously silent	11	0·64	0·18	
Contralateral	5	0·91	0·26	$P > 0·2$
Ipsilateral	34	0·74	0·08	
Multiple units	9	2·85	1·2	

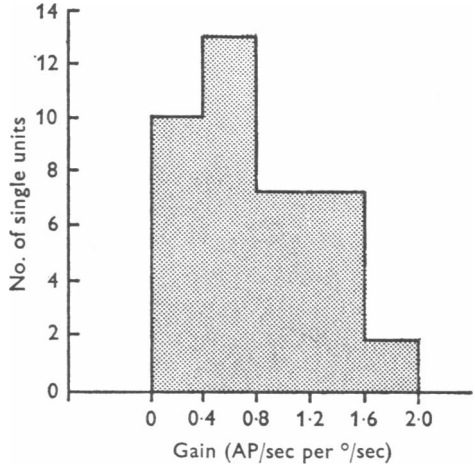

Fig. 8. Histogram of gain distribution.

data, the gain data do not show significant differences between the means of subsets of spontaneously active and silent single cells, nor of ipsilateral and contralateral single cells. There was no significant difference between the gains of cells driven by horizontal and vertical canals and consequently results from these two subsets have been pooled in Table 3.

Non-linear dependence of gain on stimulus amplitude

Tests were made on four single and one double unit, recording over wide ranges of stimulus amplitude to investigate whether the gain showed an

amplitude-dependence. In some cases such testing involved taking a cell through the transition from all-round to cut-off firing, taking care always to avoid upper firing frequency saturation. Each unit was tested at some single frequency, while the stimulus amplitude range was from 6·6 to 158°/sec.

The original data are shown on log.–log. scales in Fig. 9*a*, from which it is clear that the gain bears a generally monotonically decreasing dependence

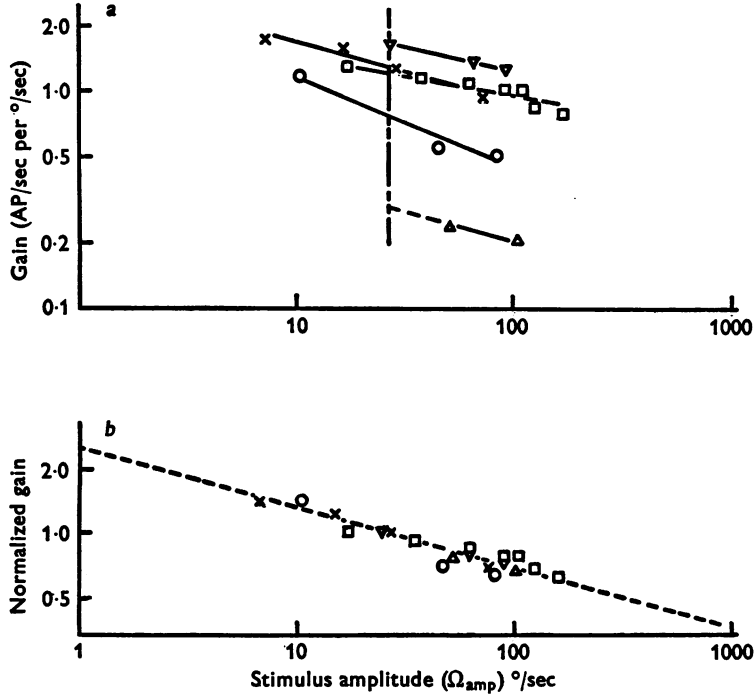

Fig. 9. Gain dependence upon amplitude of stimulation at a fixed frequency. × (P = 1); ○ (P = 1·5); □ (P = 4); △ (P = 4); ▽ (P = 4). P gives stimulus period, sec.

upon stimulus amplitude. Fig. 9*b* shows the same data after normalizing with respect to each unit's gain at an arbitrarily chosen stimulus amplitude of 25°/sec, G_{25}.

These normalized data fit a statistically valid straight line defined by

$$G = (2{\cdot}6G_{25})(\Omega_{amp})^{-0{\cdot}28}. \qquad (2)$$

As a result of this power relationship, the distribution of gain in Fig. 8 is wider than it would be after correction for the various amplitudes of stimulation used. Numerically, the number of units in the first gain bracket of Fig. 8 (0–0·4) becomes 11 (instead of 10), and successive values are 13 (13), 9 (7), 5 (7) and 1 (2).

Spontaneous firing frequency, f_{sp}

The assessment of spontaneous condition throughout the population of cells here examined presents an additional difficulty arising from the fact, already noted, that about one quarter of them were spontaneously inactive and only made their presence known during part of the sinusoidal stimulation. Fig. 10 shows both the raw and averaged data for such a spontaneously inactive cell, which it should be noted was firing necessarily during less than half the stimulus period. Since the phase and gain of these spontaneously inactive cells did not appear to differ significantly as a group from the group of spontaneously active ones (Tables 2 and 3) it

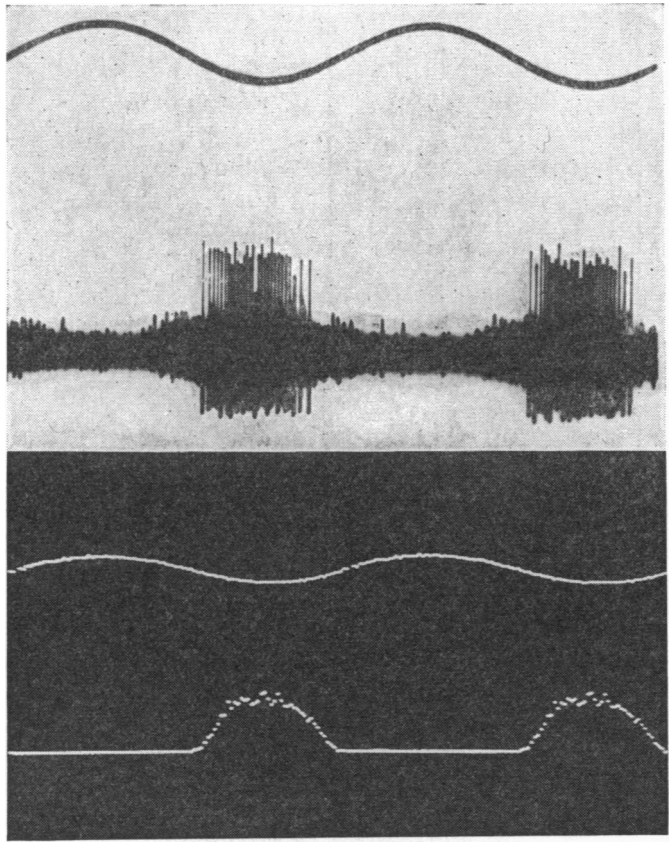

Fig. 10. Raw (black-on-white) and averaged (white-on-black) response records from a spontaneously inactive cell. Averaged data from ten cycles; stimulus amplitude 70°/sec; $f_{sp} = -16$ AP/sec; maximum AP frequency 76 AP/sec. Periodic time 4·0 sec.

seemed desirable to devise a quantitative measure of spontaneous condition suitable for both spontaneously active and inactive cells. The equivalent mean firing frequency (f_{sp} in Fig. 7), is a logical measure, which has been shown to provide a good estimate of the actual spontaneous firing frequency (Fig. 4 and Table 1). The advantage of this measure is that it is independent of whether or not the cell is spontaneously firing. It is thus

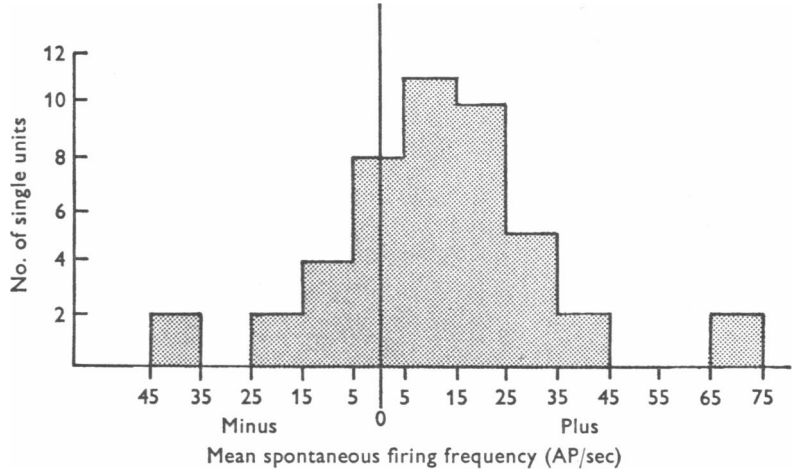

Fig. 11. Histogram of spontaneous firing frequency (f_{sp}) calculated from eqn. 3, which also defines significance of negative f_{sp} values.

possible to compute from experimental records, such as in Fig. 10, negative values for f_{sp} as quantifying the cell's subthreshold spontaneous condition.

It can be shown that

$$f_{sp} = \frac{-\Delta f \cos(\pi L/P)}{1-\cos(\pi L/P)}. \tag{3}$$

This relation is valid for all cases except those for which the cell never ceases firing; but then f_{sp} is simply defined as the mean of the maximum and minimum firing frequencies.

As examples, we may calculate f_{sp} for the responses shown in Fig. 3*b* and Fig. 10. Thus in the first instance f_{sp} = 3·6 AP/sec which agrees well with the cell's measured spontaneous firing frequency of 4·5 AP/sec. In the second instance the cell was only firing for 160° of the 360° stimulus cycle and hence the value of f_{sp} for this spontaneously inactive cell becomes *minus* 16 AP/sec.

In this way it has been possible to present data on f_{sp} for thirty-three spontaneously active and twelve spontaneously inactive cells, in histogram form as shown in Fig. 11. The mean value is 11·2 AP/sec. It is seen that the distribution approximates a normal one, but that this would

certainly not be so had the spontaneously inactive cells been excluded. Therefore, it would seem unlikely that the spontaneously inactive cells belong to a functionally different population than that of the spontaneously active cells.

It is relevant to enquire whether there is any interaction between gain and spontaneous condition. Fig. 12 is the scatter plot between these

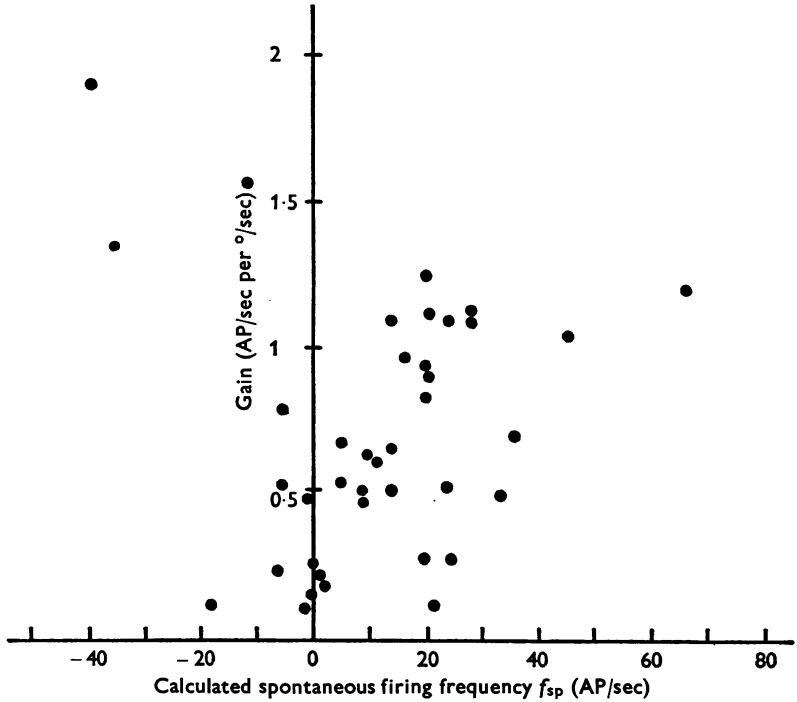

Fig. 12. Cross plot of corrected gain and spontaneous firing frequency to investigate their possible correlation.

measures for the thirty-nine single cells so measured. No strong correlation emerges, although there is a general trend, with three notable exceptions in cells having negative f_{sp} values, for higher gains to be correlated with higher spontaneous firing frequencies. It is noteworthy that confidence in the trend is strengthened when the gain data has been corrected for the power law effect, since the stimulus amplitudes utilized varied considerably; the data used in Fig. 12 are in fact corrected.

Ipsilateral and contralateral cells

As indicated earlier, responses were usually of the ipsilateral or contralateral type. Not infrequently bidirectional responses were observed; however, in all but one instance this pattern of response could not be

definitely attributed to a single cell and usually it was quite definitely associated with a mixed population, part of which fired during rotation in one direction and part in the other direction. Bidirectional responses were not therefore studied.

However, a number of clearly unidirectional responses were examined qualitatively only for directionality. Of the unidirectional units or populations of units examined for directional sensitivity, seven-two were ipsilateral and forty-four contralateral. In view of this approximately two-to-one proportion of directional responses, it is interesting to note that of the forty-six cells successfully examined for numerical response data, only seven fell into the contralateral category, a subject which will be discussed below.

DISCUSSION

Integrity of the neural message

The results in Fig. 5 and Table 2 show that, over the narrow frequency band of sinusoidal stimuli employed in these experiments, the neural signal received in the brain stem, expressed in terms of cell firing frequency, was approximately in phase with the angular velocity of rotational stimulus. It is important, however, to appreciate that the present experiments have not attempted to establish the full frequency response of the system. Rather the intention has been to obtain data in a narrow frequency band, the width of which was set here by the dynamic response of the servo-drive on the lower end and by the natural frequency of the slung table at the upper end. In practice this band was sufficiently narrow to represent essentially one frequency located in the predicted range of angular velocity transduction in the end-organ (Mayne, 1950; Jones & Milsum, 1965). Bearing this in mind, it may be inferred from these results that within this narrow band width, the phase of the message formulated in mechanical components of the end-organ appears to have been carried forward to the cell bodies in the cat brain stem with fair integrity. The results of Groen, Lowenstein & Vendrik (1952) obtained from primary afferent vestibular neurones in the ray fish may be interpreted in a similar way, as may the recently communicated findings of Goldberg & Fernández (1969) obtained from primary neurones of the monkey.

So far as the authors are aware, the actual range of frequencies necessary to characterize angular head movements of the cat in its natural life have not been defined. However, it is of interest that Taylor (1969) has measured regular oscillatory movements of cat lower jaw during natural lapping of fluids, when frequencies up to 3·5 Hz were observed, that is roughly twice the maximum frequency employed in our experiments. Possibly this mandibular activity might be expected to induce head move-

ments of similar frequency. But it seems unlikely that over-all response characteristics of the canal system would be significantly altered at this frequency since the upper break (or cut-off) frequency for the angular velocity transducing characteristics of the mechanical components of the cat's canal is defined by an inertial/viscous time constant which is very small. Thus Fernández & Valentinuzzi (1968) have calculated the relevant time constant for cat as 1/657 sec, which defines the upper limit of the band width of angular velocity transduction as about 100 Hz. This value implies that the hydrodynamic response at 3·5 Hz would still be in phase (i.e. within 2°) with head angular velocity. At sufficiently high frequencies the canal response would correspond progressively more to head angular displacement than velocity, but since the pertinent transition frequency is the 100 Hz already mentioned it seems unlikely that this transition would be approached during most naturally occurring events.

If the system under investigation proves to be sufficiently linear, then a knowledge of the response over a suitably extended range of sinusoidal frequencies should permit prediction of its response to a wider variety of movements, including such transients as may be associated with natural life. The results of current experiments along these lines, to be reported later, encourage this view; particularly in the light of experiments on man which have shown that complicated patterns of jolts applied to his body tend to be substantially filtered by body and neck dynamics to yield relatively simple, low frequency head movements (Begbie, Gainford, Mansfield, Stirling & Walsh, 1963; Walsh, 1966).

Of course, for prediction of transient responses from sinusodal analysis the dependence of gain, as well as phase, upon frequency becomes an essential component of the experimental data, whereas in the present context of an essentially single frequency of oscillation, knowledge of the mean value of the gain does not contribute towards recognizing the mode of the system's response in the same way as does that of phase. The present results therefore represent only the first step in this direction, by establishing the response characteristics, especially the phase, at a particularly pertinent frequency, i.e. one lying as already noted, well within the predicted 'flat' range of angular velocity transduction in the hydrodynamic and cupular components of the canal end-organ.

The power relationship derived from the data of Fig. 9*b* seems to reflect a reliable trend, although only five units were studied. In the present context the important conclusion is that the non-linear effect introduced is apparently very small since the exponent is only approximately minus one quarter. With regard to the asymmetric form of the gain distribution (Fig. 8), it is noteworthy that values have been specified without regard to sign. However, owing to the differential nature of the bilateral input, the

whole system would presumably include equal distributions of positive and negative gains. This would be shown in Fig. 8 by a reflected histogram of gain distribution to the left of the zero, so that a symmetric gain distribution would then result.

The method used here to describe the response of a cell to rotational stimulation of the canal employs only that portion of the cycle over which the cell was firing. However, the fact that the unit's gain calculation (Fig. 7) satisfactorily predicts the spontaneous level, f_{sp} (Table 1), and further that apparently the calculated values of f_{sp} are continuously distributed across the zero value (Fig. 11), strongly suggest that the signal characteristics derived in this way do indeed reflect a meaningful function of the signal *arriving* at the individual cells in the brain stem.

We could now well ask whether these results help suggest to what extent the *departing* neural message retains the information of this arriving signal? Of course, in practice the signal fed forward from this stage can only be carried in the actual AP sequences generated, since any silent periods can make no contribution. However, such cut-off responses comprise only a part of the ensemble of responses in this multipath neural tract. The ensemble includes, in addition, both the all-round pattern of firing and the cut-off pattern due to saturation (Milsum & Melvill Jones, 1969). In these experiments units have their thresholds spread over a wide range, with an approximately normal dstribution (Fig. 11), which conforms with observations of Groen *et al.* (1952) who drew the same general conclusion. This suggests that the ensemble effect should be to extend the range of the system's response beyond that of any single unit. Any such extension would presumably be further improved by the differential drive due to the bilateral crossed inhibition demonstrated in the vestibular nuclei of cats by Shimazu & Precht (1966). It should be noted that *temporal averaging* has been used in these experiments to improve the signal-noise ratio in individual cell responses, although clearly this cannot apply for the non-repetitive stimuli of natural life. However, it has been shown that *ensemble averaging* of multipath neural transmission can indeed improve the signal-noise ratio of the over-all signal (Lee, 1969; Poppele & Terzuolo, 1968; Maffei, 1968).

With regard to actual gain values from these experiments, the 'average' cell had a gain of 0·76 AP/sec per °/sec and a spontaneous frequency of 11·2 AP/sec. Consequently, a sinusoidal stimulus of 15°/sec amplitude in the angular-velocity-transducing range of the canal was sufficient to drive such a cell into threshold cut-off, with an associated maximum firing frequency of about 23 AP/sec. If these conditions are representative of those in the intact cat, then it might be inferred that an important component of naturally occurring stimuli would be in this order of magnitude.

Homogeneity of cell population

Shimazu & Precht (1965) have suggested that spontaneously active and inactive units in the vestibular nuclei of the cat constitute two functionally discrete groups. However, the data for phase and gain in Tables 2 and 3 respectively, do not show significant differences between mean values obtained from spontaneously active and inactive cell groups. Further, the distribution of spontaneous levels, f_{sp}, shown in Fig. 11, which includes all units observed irrespective of whether they were spontaneously active or silent, is approximately normal. Of course, our procedure has introduced the somewhat speculative idea of assigning a value to the spontaneous level of silent cells, dimensionally equivalent to a negative firing frequency. However, the fact that the inclusion of these negative values alters the distribution from one arbitrarily terminated at zero, to an essentially unimodal and normal one, seems to justify this procedure. Thus our results suggest rather that the cells studied belong to a homogeneous cell population. This argument does not, of course, have any necessary bearing on whether spontaneously active and silent cells represent anatomically discrete entities, and indeed other response features mentioned as supporting the contention of Shimazu & Precht might well define attributes which cannot be evaluated in the present experiments.

During the experiments, the impression was that cells with higher spontaneous firing frequency tended to exhibit higher gain. However, no very clear relation emerges from Fig. 12 although it does seem there was a tendency for the majority of cells to lie within parallel lines sloping upwards and to the right. It was interesting to find this general pattern was somewhat tightened after correcting the gain data for the power–law relationship described above. However, the level of confidence seemed too low to justify detailed statistical analysis, particularly in view of the three high gain units at large negative spontaneous levels. Possibly the latter might represent responses from functionally discrete cell types of the kind mentioned by Shimazu & Precht, although as already mentioned our failure to detect generally bimodal distributions do not particularly encourage this view.

Directionality of response was examined in 116 cells, of which 62 % were designated ipsilateral and 38 % contralateral. In view of the elegant demonstration of crossed inhibition pathways in the vestibular nuclei by Shimazu & Precht (1966), it seems probable that the ipsi- and contralateral cells represent anatomically discrete populations. Hence, it was interesting that in none of the characteristics measured in the present experiments were there significant differences between the responses of ipsi- and contralateral cells. This finding suggests that despite anatomical differences the

two populations respond dynamically to adequate canal stimulation in a similar manner.

In this context, it may also be noted that despite functional similarity of response, ipsi- and contralateral responding cell groups were frequently found to be organized in alternating layers along the line of electrode insertion throughout the depth of the vestibular nuclei, particularly in the medial and inferior nuclei. However, the majority of cells which could be retained sufficiently long for detailed experimental investigation were ipsilateral ones. It seems that single contralateral cells were more difficult both to isolate and to hold than ipsilateral ones, which possibly suggests that the contralateral cells tend to be of smaller size.

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