HUMAN RESPONSE TO INTENSE INFRASOUND

Thesis submitted in accordance with the requirements of the University of Salford for the degree of Doctor of Philosophy

by

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CONTENTS

CHAPTER 1

INTRODUCTION

1.1. Definition

(a) "Infrasound is a mechanical disturbance, propagated on an elastic medium, of frequency too low to be capable of exciting the sensation of hearing". (British Standard 661)

(b) In this work the upper limit of the infrasonic region will generally be taken as 20Hz. Propagation is in air unless otherwise stated.

1.2.

The literature on the effects of infrasound on both man and animals is reviewed in Chapter 2. In Chapter 3 the general requirements and possible sources of infrasound are discussed, the final apparatus is described together with its calibration and performance.

Chapters 4 and 5 deal with the methods used to detect both subjective and objective effects evoked by the stimulus and the preliminary experiments performed to test the feasibility of the project.

The experiments performed with the system in examining the physiological effects of monaural, binaural and whole body stimulation are discussed in detail in Chapters 6 and 7.

The physiological background to the experiments is discussed in Chapter 8.

Finally in chapters 9 and 10 the results are discussed and possible mechanisms for the production of the effects postulated.

CHAPTER 2

HISTORICAL REVIEW OF LOW FREQUENCY FIELD

2.1 General

Until recently examination of human reaction to low frequency acoustic stimulation was confined to determining the threshold of hearing at these low levels and it has been shown that contrary to the definition of infrasound given in the introduction frequencies below 20Hz do excite a sensation akin to hearing and quite reliable hearing thresholds from 1.5Hz upwards have now been established. In the past decade the low frequency acoustic output from rockets has increased and interest has been promoted on the physiological and psychological effects of intense pure tone and low frequency noise on man.

2.2 Subjective Effects

2.2.1. Threshold Work

The first true determination of the low frequency threshold of hearing was performed by Wien (1) (1883). Using earphones with progressively higher resonant frequencies he obtained threshold data from 50Hz to 8KHz. He assumed that the ratio of the diaphragm displacement to the input current was constant below the resonant frequency of the earphone. Elaborate precautions were taken to avoid air leaks and thus knowing the enclosed volume of the system the minimum audible pressure was assumed to be in constant relation with the diaphragm displacement and the input current. The results he obtained are generally more sensitive than those of later workers but it is possible that this was due to signal distortion.

At the beginning of the century several attempts were made to determine the lower limit of human hearing. Imai (2) (1907) used electrically driven tuning forks and frequencies in the range 12Hz to 35Hz were obtained by attaching weights. Overtones present in the signal caused some difficulty but it was reported that a vibration fundamental of 12Hz could be heard.

These experiments were repeated by Vance (3) (1914). More attention was given to subject training and improvement of the acoustic environment. He also reported that a fundamental of 12Hz could be detected but again took no steps to reduce the harmonics relying solely on the experience of the listeners.

Fletcher and Wegel (4) (1922) measured the monaural M.A.P. threshold of 82 ears down to 60 Hz using a specially calibrated air damped earphone. The effect of higher harmonics was reduced by filtering the electrical input signal. The calibration of the headphone involved a thermophone and this type of indirect calibration method is often unreliable as the ear is assumed to have approximately the same impedance as a rigid walled enclosure. Also according to Atherley (5) (1953) the refit variability of any normal type of headphone can lead to uncertainties of up to 20dB.

The same technique was used over the same frequency range by Munson (6) (1932).

Wegel, Riez and Blackman (7) (1932) removed subjective variability from the calibration by directly coupling the earphone to a condenser microphone by a volume of the order of the enclosed ear canal but the impedance assumption of the previous work was still made. Thresholds were reported down to 35Hz and in the 35Hz-500Hz range the threshold level was found to vary as the inverse cube of the frequency. This was taken to indicate that the vibration of the basilar membrane did not appreciably change in this range.

Brecher (8) (1934) performed the first really systematic work below 35Hz. He overcame the problems of obtaining a distortion free high sound pressure level by completely redesigning the apparatus. A membrane, forming one wall of a chamber, was oscillated by a motor driven arm. Large pressure fluctuations, thus set up by compression in the chamber were led to the observer's ear via a small opening in another wall of the chamber. The signal produced was very impure as it contained many distortion products and mechanical noise, nevertheless Brecher was the first to report an apparent change in the response of the hearing mechanism to tones below 20Hz. He reported that the stimulus only became tonal above 18.5Hz this was denoted as the 'fusion frequency'.

This system was developed by several workers. Wever and Bray (9) (1936) used a piston phone working into an enclosed volume, to provide the low frequency pressure variations, which passed two acoustic filters before reaching the observer's ear canal. The roll-off frequencies of the two filters were 100Hz and 3KHz and their combined response removed all motor noise but the harmonic distortion was still present. The maximum S.P.L. in these experiments was limited to 104dB (re 0.0002 μB). Subjective descriptions of the stimulus at various frequencies were recorded:-

5 Hz was described as 'pumping'

17 Hz as 'flutter with roughness'

The stimulus only became tonal in character above 30Hz. Subjects were still reporting roughness at frequencies as high as 60Hz but this was probably due to harmonic distortion.

The most careful examination of low frequency phenomena in this period was made by Bekesy (10) (1936). For the first time the problem of harmonic distortion was recognised and studied in detail. Both a thermophone and a piston phone were used as sound sources to enable cross-checking of results and calibration. The thermophone was directly mounted in the subject's meatus with an airtight seal. A sensitive manometer incorporating a rubber membrane was sealed into the cavity. A beam of light was deflected from this diaphragm thus enabling amplitude displacement to be measured in this way it was possible to calculate the S.P.L's below 50Hz. The piston phone could also be used with the manometer. Several mechanical filters were incorporated into the system which meant that, when presented to the subject, the tone was very pure. Thresholds were measured down to 1Hz and the effects of masking investigated. The only source of error was possibly that the small volume of air enclosed in the ear canal would accentuate the physiological noise (estimated by Shaw and Piercy (11) (1962) to be as high as 26dB in the mid frequency range). When working in the region below 5Hz factors such as heartbeat would be a significant source of interference and reduce the sensitivity of the ear.

No attempt was made to verify Bekesy's work in detail for many years. Corso (12) (1958) attempted to determine the M.A.P. threshold for low frequency tones using a specially designed earphone calibrated as an artificial ear, sealed into the observer's meatus . Only one threshold measurement below 25Hz was reported but this was in poor agreement with Bekesy's work. Very little analysis of the harmonic content of the signal was reported except that at a level of 120dB the total harmonic distortion was highest -3%- at 5Hz.

Fink (13) (1961) reported thresholds at 25Hz, 30Hz and 50Hz during a series of experiments on low frequency masking. A maximum level of 140dB was produced by using a 12" loudspeaker, mounted on a prismatic cabinet, as the source. The harmonic distortion was analysed fully and reported as being too low to disturb the fundamental threshold. The data given shows a small change in sensitivity over an octave.

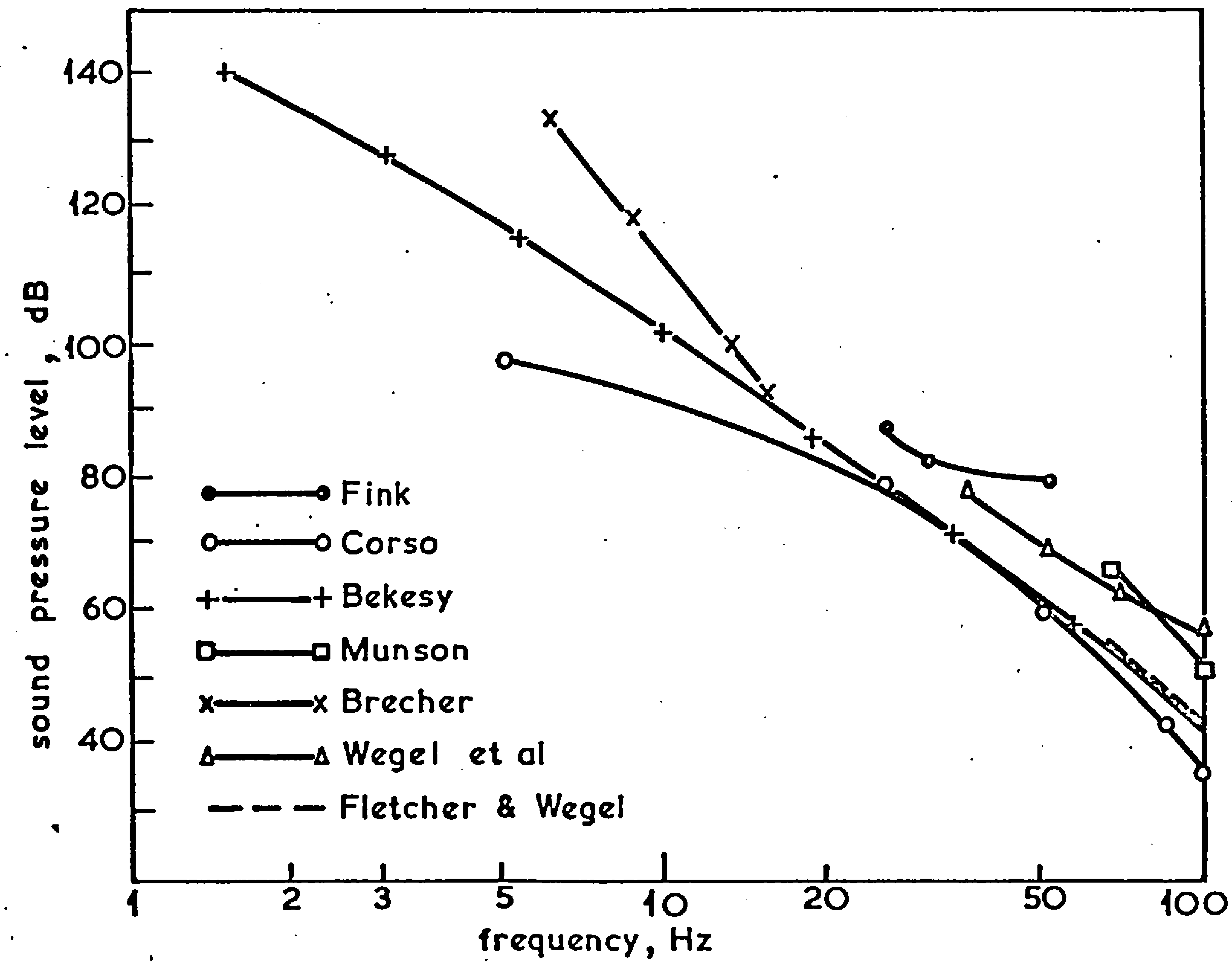

Fig. 1.1 Low frequency M.A.P. thresholds. (early work)

The first thorough attempt to verify Bekesy's data was by Yeowart, Bryan and Tempest (14) (1967). A detailed study of low frequency M.A.P. thresholds was performed. The apparatus used consisted of 12" loudspeakers mounted on an aluminium sealing plate with an ear defender cap mounted into the centre. Two of these were pressed firmly against the observer's head and an airtight seal was obtained by using soft rubber collars between the head and the eardefender. The effects of bad seal, harmonic distortion, hum and noise were all investigated in detail and a complete frequency analysis was performed. Monaural noise thresholds (15) and both monaural and binaural tone thresholds were measured at frequencies down to 1.5Hz. The monaural tone data generally agreed with Bekesy. A discontinuity in the threshold curve around 18Hz was noted which corresponded with a change in the subjective description of the stimulus as tonal only above this region. Below 18Hz the response fell by 12dB/octave and above 18Hz by 16dB/octave. This is in good agreement with Brecher's reported 'fusion frequency'.

The binaural advantage over monaural listening was found to be about 3dB (16). The noise thresholds were more sensitive than the tone thresholds below 32Hz. This separation at lower frequencies was attributed to the subject detecting peak frequencies.

Yeowart suggested that further experiments should be performed extending the work to all body exposure thus enabling the effects of body resonance and tactile sensations

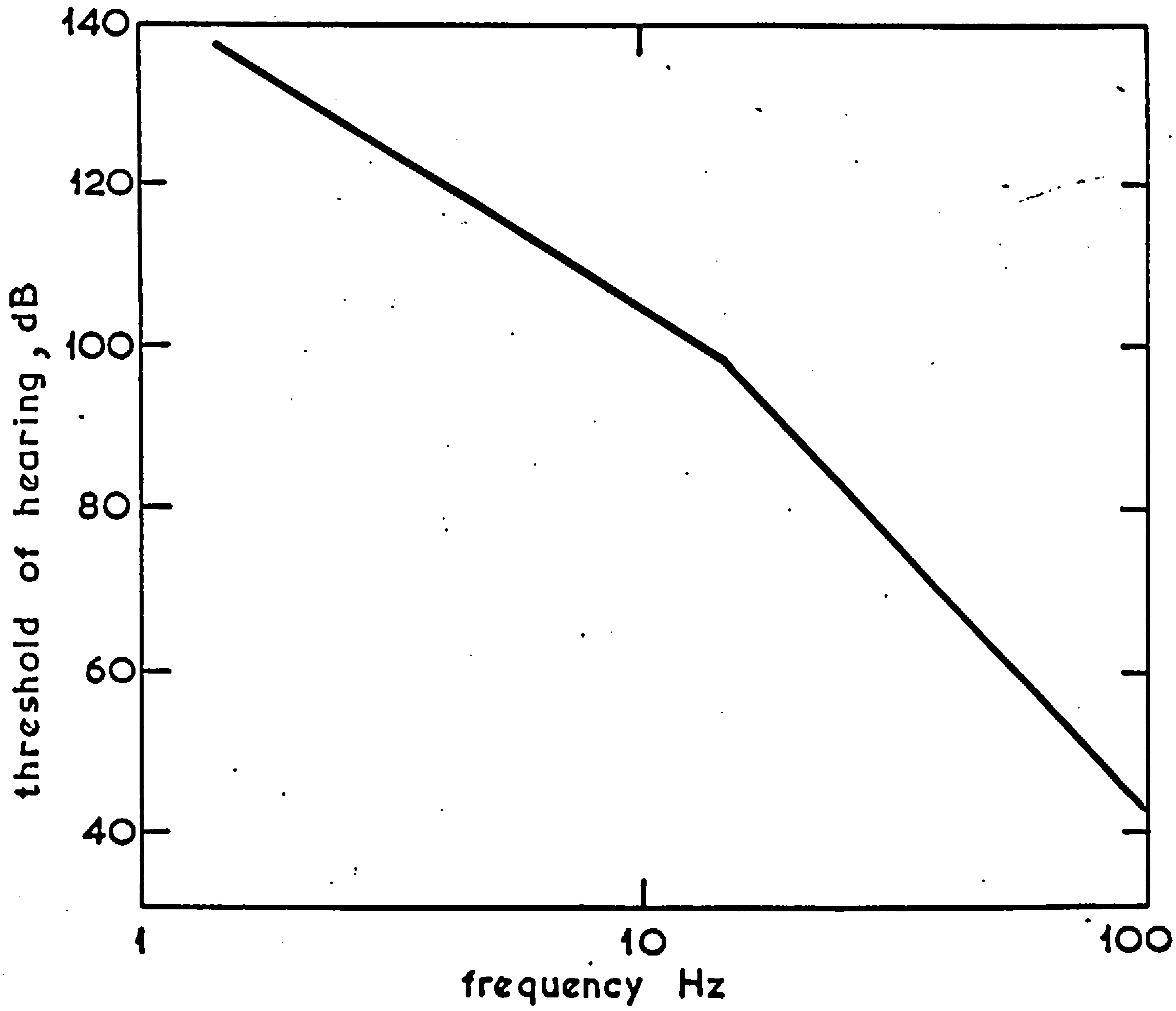

Fig.2.1 Monaural threshold of hearing — pure tone.

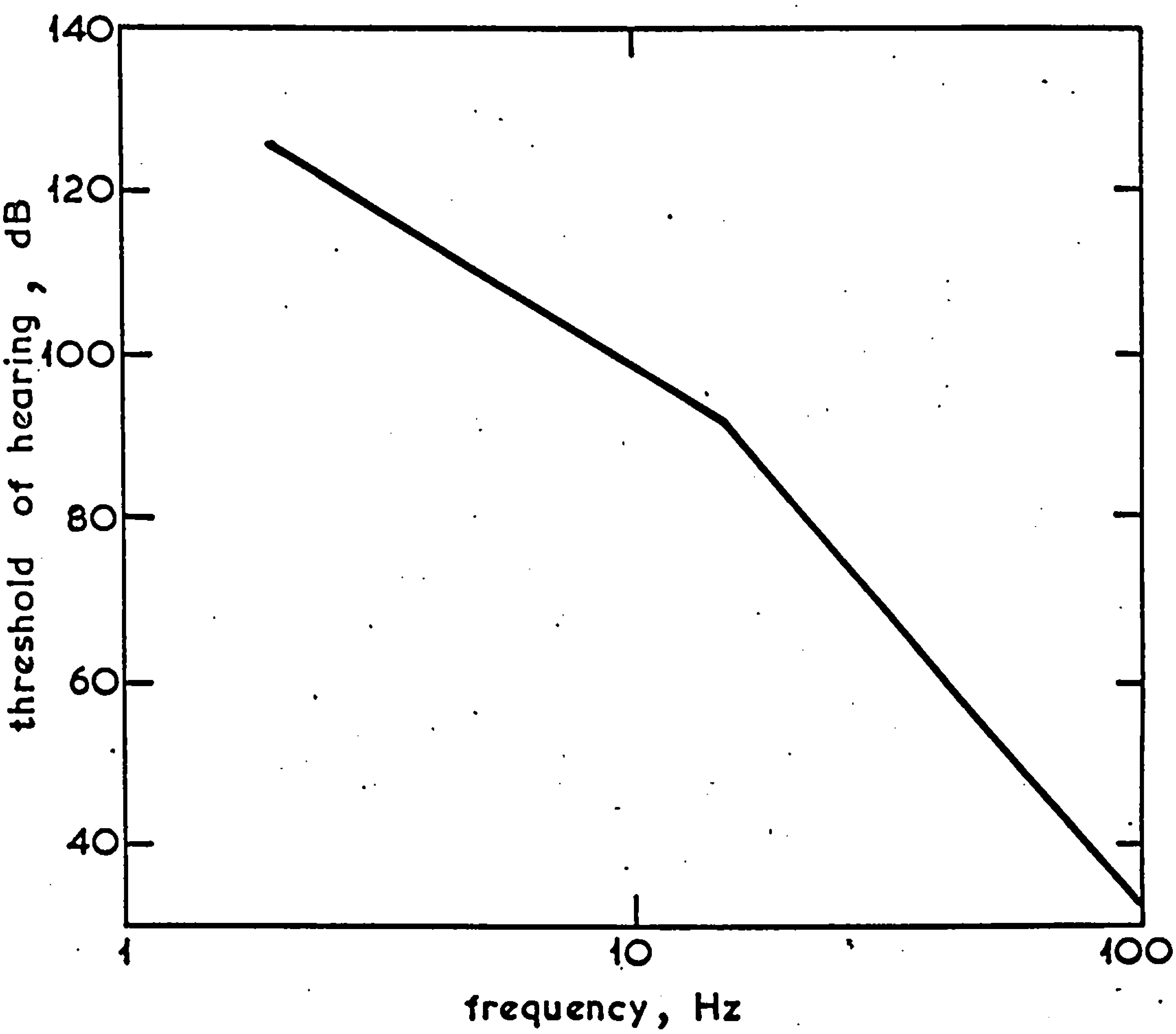

Fig. 2.2 Binaural threshold of hearing – pure tone, earphones.

on threshold to be examined. Whittle (17) (1971) performed similar experiments to the ones suggested. The observer was positioned on a sound proof prismatic chamber. Various combinations of direct radiator loudspeakers were used as sources. A mechanical filter was used to reduce the harmonic distortion. The results reported are in general agreement with Yeowart's binaural data and the discontinuity in the threshold curve was again established. No record was made of any subjective tactile effects of whole body stimulation.

2.2.2 Other Effects

Extremely low frequency signals have been reported from winds. Hot desert winds in California produced signals of 3.3×10^{-3}Hz when measured in 1964, (18) and upper air turbulence has been reported in the band 0.5Hz to 1.5Hz at pressures of 10 to 300 mN/m^2 (19). Signals of 0.6Hz have been recorded near Marseilles from the Mistral (20). A study of the effects of the Föhn winds on the population of Liechtenstein by Moos 1963 showed a statistically significant increase in deaths from cardiac failure, all deaths and also in the birth rate on days when the Föhn winds were blowing. The sample was only taken from the indigenous population of Liechtenstein and was rather limited in size hence the conclusions drawn can only be taken as general indications. Another study of the Föhn in Switzerland (Moos 1964) (22) showed an increase in the rate of traffic accidents and as this type of weather is typified by warm dry days with clear visibility the data would seem to support the general belief that Föhn and Pre-Föhn weather conditions have biological effects. Comparison of the

Föhn with the Mistral suggests that the typical frequency involved of 0.6Hz may be a significant factor.

In the summer of 1969 (23) few widely spaced stations in U.S.A. studied infrasound from hail producing thunderstorms. A positive correlation was found between the size of the hailstones and the frequency of infrasonic signals present in the storm. Generally the lower the frequency the more violent the storm. In a study in Chicago made by Green and Dunn the rate of absenteeism in primary school children and the incidence of traffic accidents was correlated against the occurence of infrasonic signals due to thunder which was not audible in Chicago and typically occured in storms at ranges of 2400Km. The correlation coefficient for absenteeism was 0.50 and for traffic accidents 0.49. During the period studied there were no major road hazards or traffic pattern changes that would have had a significant effect on traffic accident rates and there were no extremes of rain, fog or other adverse weather conditions. The absence rate among school children appeared to depend on the particular day of the week being higher on Mondays and Fridays. While this in an intuitively reasonable absence pattern, it is difficult to determine if this was a normal pattern or due to the presence of infrasonic waves as suggested as the occurence of infrasonic disturbances had on almost identical distribution pattern for the period studied and no statistics concerning daily absence rates among school children were reported.

2.2.3 Therapeutic Uses

Several workers (20, 25, 26, 27) have suggested that infrasonic signals may interact with the workings of the human brain. Their arguement is based on the fact that 7Hz is the median frequency of the alpha rhythm of the brain and that exposure to a 7Hz signal might prove extremely hazardous but there is no experimental evidence at all to support this hypothesis. It has also been suggested that infrasound at a much lower intensity but synchronised with the subject's alpha waves might enhance intellectual capacity. At least one attempt has been made to 'drive' the brain in this way but results are not available (27).

Blasts of high intensity sound of an unstated frequency have been used to help produce ovulation in women with sex gland deficiencies although the exact mechanism of the effect is rather unclear, but the author seems to suggest that stimulation of the womb would have the desired beneficial results (28).

Two cases of using slightly higher frequency stimulation for therapeutic use are in print. Electrical stimulation of the brain at 42.5Hz has been shown to rectify colour blindness (29, 30) and a research worker exposed to 155dB of 340Hz is reported to have regained a sense of smell he had lost some years previously (26). It was suggested that this was due to intense vibration of the nasal cavities.

2.2.4 Infrasound As A Weapon

There is a limited amount of non-classified material reporting tests carried out during the 2nd World War on the possibilities of using infrasound as a weapon.

A small British group in the Western Desert were studying the uses of extremes of light and sound as weapons (31). It was claimed that a British scientist had killed a rabbit at 90m with a 'sound gun' (32).

A 'sound gun' was developed by Wallauschek at Lofer in Austria at about the same time, a double shock wave tube using an explosive mixture of Methane and oxygen fed into a parabolic reflector 3.2m in diameter. It was reported to produce 100 N/m^2 at 60m in one report[33] and 100 KN/m^2 at 45m in another (34). No physiological experiments were conducted but it was estimated that 100 N/m^2 at 60m would kill a man in 30 to 40 seconds although how was left to the reader's imagination.

It is also understood that the Japanese and Americans were working on similar projects but no information is available.

Reports of work in this field, carried out since 1945 are nearly all classified and except for the writings of Gavreau the Press is the only source of information on the use of infrasound as a weapon. As newspaper reports tend to be rather flamboyant much of the material presented probably has its roots more in fantasy than in fact.

Aviation Week 14th July 1947 (32)

A United States general was reported to have said "What about the use of sound as a weapon?... An airplane equipped with a sort of super dog whistle conceivably could fly around a city for a while and upset the nervous systems of the whole population"

Miami Herald 27th April 1967 (35)

A popular article on the work of Gavreau was entitled "Sound Ray Developed as Killer - French Working on War Machine". The 'machine' was described as "an entirely novel method of human destruction ...... In developing a military weapon the scientists intend to revert to the policeman's whistle form, perhaps as big as 18ft across, mount it on a truck and blow it with a fan turned by a small airplane engine. It could kill a man 5 miles away."

The Observer 7th January 1968 (36)

This report in a British newspaper of the same work by Gavreau was considerably more subdued and more critical. "Infrasounds - might lead to a family of exceedingly unpleasant new weapons" but concluded that "a military infrasound gun would probably be much too cumbersome".

The only scientific reports on the uses of infrasound as a weapon generally available are those of Gavreau. The essentially military applications of infrasound are described in a French patent (37) using large pistonphones as sources and in a later publication (35) large whistles are advocated. The focussing of infrasound by the selective phasing of multiple sources and the suppression of rear emissions are described. A similar source placed $\lambda/4$ distant from the 'gun' with a $\lambda/2$ phase difference is proposed as protection for the operator.

Fortunately these rather disturbing propositions are rather impracticable. Recent work (reported later) indicates that the limit of voluntary tolerance of infrasonic stimulation is around 155dB. It is known that lung rupture occurs at $10KW/m^2$ for ramp type compressive changes (39), about 174dB, so even assuming that artificial infrasound could produce the same effect at least 174dB S.P.L. would be required. Now any weapon needs a minimum range of say 1000m at least and from the inverse square law a doubling of distance produces a 6dB drop in power and even assuming a focussing device which would reduce this drop to 3dB., there would still be a 30dB loss over 1000m. Thus to produce the theoretical levels for lung rupture a 204dB i.e. $320KW/m^2$ source would be required. As well as the difficulty of producing such a powerful source it is doubtful as to whether it is possible for such pressure to be transmitted by air.

There have been no experimental reports on the cases of infrasound as a non-lethal weapon. Although Captain J.F.J. Johnston in a Royal Military College of Science report (40) suggested that it could have possible uses for interrogation and riot control. His highly speculative conclusions are based on the subjective reports of anxiety from other workers but no work has been performed on the effects of long duration exposure. Although there are reports (41) of allegations of similar methods being used during the interrogation of internees in Ulster.

2.3 Experiments on Man

The effects of intense infrasound were first observed and studied during the two world wars. Surgeons serving on German submarines observed middle ear changes amongst diesel room personnel. After some medical investigations these changes were attributed to the infrasound produced by the suction strokes of the diesel cylinders. World War II 'snorkels' superimposed rhythmic pressure changes of about 1Hz which appeared to add to the frequency and severity of middle ear pathology.

Interest was again stimulated in 1964 by Gavreau after he and his colleagues were exposed to very intense infrasound emitted by a defective ventilator (20, 26) which caused painful periodic compression of their eardrums. A model was made of this device which incorporated an organ pipe of rectangular cross-section and a large Levavasseur whistle embedded in a block of concrete. The fundamental frequency of this device was 196Hz emitted at an S.P.L. of 160dB. This is reported to have caused severe body resonances after a five minute exposure and the author feared that internal heamorrage would have occured if the exposure had been longer. It should be noted at this point that the designer of the Levavasseur whistle R. Levavasseur severely and permanently injured himself with such a whistle emitting 2600Hz at 1KW which would suggest that the power of emission, rather than the frequency is the dangerous factor.

Equally exotic and more powerful low frequency emitters were developed by Gavreau as he concentrated his work into developing a 'focussed' beam of infrasound obviously for military purposes. These included a 1.5 metre diameter whistle which emitted 37Hz when indoors and 7Hz outside, (this change in frequency was probably due to the room acting as a resonance box) a large organ pipe 24 metres long 30cm diameter with a loudspeaker fitted into the end, this produced 7Hz and 3.5Hz. Gavreau hoped to design an 'acoustic laser' to emit a coherent beam of sound. This consisted of a network of tubes, all of the same length, these transmitted the sound of one emitter such as an organ pipe or whistle with the aim of producing a very directive beam of sound. As yet I have not come across any reports of the outcome of this idea. Gavreau noted various physiological phenomena including digestive disturbances at 16Hz and visual blurring at 7Hz. Gavreau reported that while being subjected to stimulation of 7Hz intellectual tasks were impossible and suggested that this was due to some form of interaction with the alpha waves. He also reported that ear protection or audible masking removed these unpleasant effects. The accuracy of this work is debatable as very little was given of the sound pressure levels involved and it would appear that no attempt was made to remove harmonics and noise from the signal.

In recent years interest in the various phenomena associated with infrasonic acoustic stimuli has rapidly increased, as high energy low frequency pressure oscillations have become common in the development of aircraft and spacecraft propulsion units. As the thrust at lift-off of projected space rockets is estimated to be in the multi-million pound thrust range, so the turbulent mixing of the exhaust gases with the surrounding atmosphere and the aerodynamic noise are expected to have peak acoustic outputs in the frequency range below 20Hz (42). Consequently problems concerning the physical and mental wellbeing of astronauts have arisen.

G.C. Mohr et al (43) used various existing facilities to examine human reaction when subjected to noise approximating to the noise profile expected in Saturn boosted spacecraft. The sources used were as follows:-

1. A 14 Kilowatt electrodynamic speaker located in a 5000 cu.ft. reverberation chamber. The arrangement was programmed to provide octave band noise levels ranging from 100dB at 10Hz to 120dB at 100Hz.

2. A turbo-jet with afterburner. Here the subject was placed in the jet stream 50ft. downstream from the outlet and 25ft. off the centre line. Protection was provided against heat and flying objects. Octave band levels of 110dB at 5Hz to 135dB at 100Hz were available.

3. The N.A.S.A. - Langley Thermal Structures Tunnel. Hot pressurised air produced broad-band noise, with levels of upto 120dB at 2.5Hz for 60 seconds, when expanding through a throttle.

4. The N.A.S.A. - Langley Research Centre Low Frequency Noise Facility (44) (1965). This system was specially designed to produce high level sinusoidal and noise fluctuations down to 1Hz. The cylindrical chamber 24ft long by 21ft diameter, was closed at one end by a 26 ton door and at the other by a sealing ring in which a 14ft diameter piston moved. Levels of up to 17dB at 1Hz were expected when the facility was fully operational.

In order to investigate human tolerance in the 1-100Hz range five noise experienced subjects were exposed for 2 minute periods to high intensity broad band, narrow band and pure tone low frequency stimulation. Some startling responses were elicited but in general the effects were nowhere near as dramatic or lethal as those suggested by Gavreau.

Six biological parameters were studied:

(a) Voluntary tolerance

(b) Visual acuity

(c) Spacial orientation

(d) Fine finger dexterity

(e) Speech intelligibility

(f) Stress responses - Body vibration, Pain respiratory changes, Nausea, Vertigo etc.

For frequencies from 1Hz-50Hz chest wall vibration, gagging sensations and respiratory rhythm changes were reported. From 50-100Hz visual blurring, transient headaches, choking and coughing were observed. The severity of these effects depended greatly on the noise facility used. The 14KW electrodynamic speaker which produced octave bands of white noise with a maximum level of 120dB at 100Hz and the turbo-jet which also produced octave band noise levels up to 135dB at 100Hz produced little change in any of the six parameters measured, except for some mild chest wall vibration and, as one would expect, speech was almost entirely masked by the higher frequency portion of the spectrum.

The Thermal Structures Tunnel which produced broad band noise up to 120dB was considered by the subjects to be more disturbing, producing pulse-rate change, body vibration and choking as well as speech masking but all the subjects had observed similar effects when exposed to higher frequency noise fields and this particular facility contained very high levels of energy throughout the audible spectrum.

The Low Frequency Noise Facility which was used to produce narrow band noise fields and pure tones caused considerably more discomfort especially when the subjects used no ear protection. Narrow band noise environments produced middle ear pressure changes, abdominal vibration and tympanic membrane irritation. Pure tone environments caused middle ear pain, modulation of speech sounds, chest wall vibration, gagging sensations and post exposure fatigue. Sound Pressure levels above 145dB exceeded the voluntary tolerance of the subjects and the intensity of the subjective sensations rapidly increased. The subjects experienced nausea, cutaneous flushing, coughing, choking, pain on swallowing, mild vertigo and all complained of considerable post exposure fatigue. However the authors concluded that man could tolerate levels as high as 150dB for short periods without undue discomfort so long as ear plugs were worn.

B.R. Alford et al (1966) (45) confined their interest to the effects of pure tone infrasound on man hoping to remove any uncertainty due to the presence of higher frequencies. A 13cu.ft. sound proof chamber was used as the test module. Sinusoidal pressure fluctuations were provided by a piston and crank assembly which varied the volume of the test chamber. The intensity of the pure tones produced were in the 119-144dB S.P.L. range at frequencies from 2-12Hz and harmonic distortion was reported as being less than 2%. The subject was exposed to a given stimulus for 3 minutes during which one ear was uncovered and the other used for auditory tracking. Cardiac activity, respiration and eye movements were continuously monitored. Five selected subjects were set various performance tasks to measure reaction time and reasoning.

The only alteration of function noted in any of the subjects was a temporary auditory threshold shift of up to 10dB and a feeling of pressure in the ears. There were no changes in heart function or respiration and nystagmus, indicating vestibular disturbance, did not occur although one subject did experience slight vertigo and no changes in the subject's reaction time or ability to reason occured. The authors seemed somewhat surprised if not disturbed by the absence of effects.

The most recent work brought to the author's attention is by Hood, Leventhall and Kyriakides (46) (1971) which is a report of some preliminary work investigating the subjective effects of prolonged exposure to infrasound. The subject was placed in a 72cu.ft. chamber and the stimulus was provided by four 15" loudspeakers mounted in the walls. A turnable neck was let into the side of the chamber and together they acted as a helmholtz resonator tunable in the 3-18Hz range. Maximum sound pressure levels obtained were 126dB for random noise and 145dB for pure tones. Seven subjects were subjected to various levels and frequencies of stimulation and 5 parameters were studied:-

(a) Balance - subjects were required to balance on a 1" wide rail

(b) Visual Acuity

(c) Reation time

(d) Coordination - subjects were required to follow a moving line with a mechanical pointer

Fig. 2.3 Effects on man of airborne infrasound, sound and ultrasound.

——— established – – – –indicated

(e) Temporary threshold shift

In the balance experiments only two of the subjects were significantly affected by infrasound. There was no decrement in visual acuity or the ability of the subject to store information. Reaction time was increased by as much as 30% for some subjects when exposed to infrasound at a level of 120dB for a prolonged period and the coordination of the subjects was similarly affected. Two out of the seven subjects suffered a temporary threshold shift of 10dB and one complained of tinnitus.

2.4 Animal Experiments

Parker, von Gierke and Reschke (47) (1968) undertook a series of experiments on guinea pigs in order to establish a clear relationship between infrasonic acoustical stimulation and the sensory receptors of the vestibular apparatus. Their initial hypothesis was that acoustical vestibular stimulation is the result of a d.c. displacement of the stapes footplate. The stimulus source used was a hypodermic syringe or an animal respirator supplying static or low frequency pressure changes which were applied to the animal via ear bars. Stimulus frequencies between 0.1 and 10Hz at intensities up to 5inHg (178.5dB) were presented to the subject while eye movements were observed and recorded. The form of the signal varied from approximately sinusoidal to trapezoidal. Various other parameters were introduced.

(a) Subjects were placed in a dark box to eliminate visual clues

(b) Two animals were deafened to reduce probability of stimulation of the auditory labyrinth

(c) The possibility that the responses were associated with displacement of the statoconia was examined by exposure of 3 animals to linear acceleration

(d) Streptomycin Sulphate injections were given to few animals to destroy the sensory cells of the vestibular receptors.

Three general classes of eye movement were produced:-

oscillatory eye movements - 165dB

counterrolling
 - 170dB
nystagmus

(a) No difference in the eye movements was observed when the experimental animals were placed in a light tight box

(b) Counterrolling and nystagmus were elicited from the deafened animals at approximately the same stimulus intensities as with normal animals

(c) The animals exposed to linear acceleration produced counterrolling and nystagmus at the same levels of stimulation as the normal animals but the authors reported that these movements differed somewhat in character.

(d) The results with the Streptomycin treated animals were rather ambiguous. Some animals exhibited no response at all, others slight responses usually counterrolling and one animal exhibited nystagmus at normal stimulus levels.

Reschke, Parker and von Gierke (48) (1970) continued this work by investigating vestibular stimulation of Guinea Pigs by static pressure changes only and considered both head and eye movements.

Static pressure changes of up to 1 minute duration were applied to 25 male Albino Guinea Pigs using a hypodermic syringe. The subjects' head and eye movements were recorded. Observations were made of response latencies, durations and amplitudes as a function of stimulus duration, intensity and onset rate. Head and eye movements in response to pressure changes in the external auditory meatus were observed in all 25 subjects. Eye movements included counterrolling and nystagmus. Head movements were complex and consisted of rotation about both cephalocaudal and dorsal-ventral body axes. The pattern of head and eye movements depended on which ear was stimulated and the onset threshold depended on the stimulus intensity and duration. Fairly long latencies between the onset of the response and the onset of the stimulus were noted but the authors could find no clear correlation between this latency time and any on the variable parameters.

It was suggested that overdriving of the ossicular chain might be responsible for causing the vestibular responses by producing a non-linear fluid flow.

In order to understand more clearly their previous results Parker and von Gierke (49) (1971) undertook experiments to obtain direct neurophysiological evidence of vestibular stimulation. Responses from primary vestibular afferent nerve cells of Guinea Pigs undergoing pressure change stimulation, were recorded. Increases and decreases of action potential rate were observed in some single vestibular ganglion nerve cells in response to pressure changes in the external auditory meatus. These neural responses were evoked by the same range of stimulus intensities as the head and eye movements in the previous experiments (48), but the long response latencies, which led the authors to postulate a high impedance mechanism for stimulation, were not exhibited in the neuronal activity. The neurons observed in this study exhibited response latencies of less than 1 second which would suggest a relatively low impedance fluid displacement pathway. It must also be noted that a large proportion of the nerve cells studied could not be activated by either sound or pressure and hence the experiments are rather inconclusive.

2.5 High Intensity Audio Frequency Experiments

In any study of the effects of intense very low frequency sound on the vestibular system it is necessary to consider the effects of intense audio frequency sounds on the same system.

The fact that prolonged exposure to loud sound has a deleterious effect upon the cochlea has been well documented in both human and experimental animals since the turn of the century, but in the past 20 years workers have begun to speculate on the action of loud sounds on the equilibritory labyrinth. Dickson and Chadwick (50) (1951) reported the occurence of momentary dizziness, unsteadiness and mental aberration in jet-engine workers subjected to 125-133dB of noise. No nystagmus was elicited and so it was suggested that the locus of the stimulation might be the utricle.

In the Benox Report (51) (1953) both nausea and vertigo are stated to have occured as effects of intense noise on aircraft carriers but the sensation on humans is apparently different from pure vertigo.

In 1958 McCabe and Lawrence (52) performed a series of experiments on Guinea Pigs in order to establish the site of disturbance in the non-auditory labyrinth due to intense sound. Two groups of animals were stimulated by noise at levels of 136dB and 150dB for 20 minutes and were then examined histologically for disturbance of the vestibular labyrinth. The saccule was found to be the locus of predilection for acoustic damage. Other parts of the vestibular system were untouched by the high level sound even in the most sensitive ears, and there was no significant degree of consistently greater damage to the saccules of those animals receiving 150dB than those receiving 136dB. When this work is considered together with that of Ashcroft and Hallpike (53) (1934) where the saccule of the frog was found to record and transmit pitches of 64, 256 and 512Hz but not higher it seems possible that the saccule has a dual function with a functional relationship to both the vestibular and the cochlea apparatus, and that symptoms reported by individuals placed in intense sound fields are mediated through the saccule. The distinct sensations of exaggeration of turning movements might further suggest some type of regulatory action of the saccule over the remainder of the vestibular labyrinth.

Albernaz, Covell and Eldredge (54) (1959) repeated this work using pure tone exposure from 170 to 50,000Hz. The whole of the vestibular system was examined for damage after post-stimulus periods of 0 to 133 days. The results were far from conclusive. As well as traumatic injury to the organ of Corti, which one would expect, the most common alteration in the vestibular labyrinth was rupture of the membrane separating the inferior and superior parts. Other findings included rupture of the saccule, rupture of the utricle, and collapse of the saccule, but little correlation was found between any of the effects and the frequency or intensity of stimulation. Collapse of the saccule was more common in animals with a long post-exposure life, but rupture of the utricle decreased in animals with a long post-exposure life, presumably because of the tendency for repair. This possibly explains the difference between the results of this work and that of McCabe and Lawrence, who only found saccular damage, as all their test animals had a 56 day post-exposure life, in which time any utricular damage would, according to the results of Albernaz et al, have been reported.

The non-auditory effects of high intensity sound on humans were investigated by Ades, Graybiel, Morrill, Tolhurst and Niven (55) (1958) and (56) (1959) on a more subjective level. A group of totally deaf observers who had retained some degree of vestibular function were exposed, monaurally, to a series of pure tone and wide band noise stimuli from 115dB to 170dB in 5dB steps for 5 seconds. During and after stimulation the subject's eye movements were observed and he was questioned as to his subjective experiences. Subjective responses reported included:- vibration, tickle, pain and dizziness with a large factor of individual difference, but the most sensitive frequency range for all subjects was 200-1000Hz. Noise, at intensities above 130dB, induced nystagmus in some observers and the lowest thresholds for this effect, 120-130dB, were found at the lowest frequencies used 200-500Hz. Although these results give rise to a great deal of speculation they are far from indicative of any general trend. Due to the requirement that the subject should be totally deaf but have no labyrinthine impairment only six subjects were used, of these only three exhibited any signs of balance disturbance. Due to the difficulties of communication between the experimenters and the subjects (frequency alluded to in the text) the subjective descriptions of balance disturbance must be regarded with caution, and hence give no indication of the site of the disturbance.

2.6 Summary of Current Knowledge

Monaural and binaural noise and pure tone thresholds have now been established down to 4Hz and 1.5Hz respectively. The binaural detection advantage over monaural listening is about the same as for higher frequencies, 3dB. A discontinuity in the threshold curve appears around 16Hz, at frequencies above this point the threshold falls by about 12dB/octave and below at 18dB/octave. This would perhaps indicate some change in the detection mechanism at this point.

Although there has been a great deal of speculation very little is known about the effects of infrasound on human observers. The statistical work from Europe and U.S.A. which has correlated to occurrence of high levels of infrasound in the atmosphere with various indescribable responses in humans such as road accident and illness would appear to suggest that frequencies in the 0-20Hz range do have a profound effect on human well being.

The actual experimental work on this problem is contradictory. With Gavreu (25, 26, 37, 38) postulating severe injury or even fatality due to exposure to infrasound and Alford et al (45) reporting that quite high levels of infrasound have no effect whatsoever on the stability or performance of humans.

Mohr et al (43) determined that the level of human voluntary tolerance to infrasound was around 155dB and that levels in the 145-155dB range caused various body vibrations, respiratory difficulties, middle ear pain and fatigue. Recent work by Hood et al (46) indicates that prolonged exposure to levels of infrasound just above the hearing threshold cause an increase in reaction time and a decrease in the ability to concentrate.

The work performed on Guinea Pigs by Parker et al (47, 48, 49) shows more clearly the effects of infrasonic and static pressure changes on equilibrium, counterrolling, head movements and nystagmus were all elicited responses. Thus indicating quite clearly that there is some form of vestibular response to this type of stimulus. Although the actual mechanism of stimulation is still unclear.

2.7 Proposed Research

When previous work is studied the sparse nature of our present knowledge of the effects of sounds below 20Hz is immediately obvious. Although the detection thresholds for these frequencies are fairly well determined the discontinuity in the threshold curve at 16Hz has not been explained, and no information exists on the effect of total body exposure, as opposed to aural exposure, on the detection threshold.

The organs of the inner ear, comprising the cochlea, the otolith system, and the semi-circular canals, respond in normal use to different frequency ranges. The cochlea is usually regarded as responding to pressure changes in the form of acoustic waves from 20Hz upwards, the otolith system will respond at rest to the force of gravity, which implies that it has a d.c. response, while the semi-circular canals have a response region between these two extremes. The 0-20Hz frequency range covers the sensitive range of the semi-circular canals and the upper range of the otolith system, it therefore seems possible that infrasound may affect the static and dynamic labyrinths.

A systematic study of the effects of monaural, binaural and whole body exposure to high levels of infrasound would clarify significantly to our knowledge of low frequency phenomena.

CHAPTER 3

INFRASONIC STIMULI

3.1 General Requirements

The main requirements for the infrasonic source are:-

(a) From a study of the previous work in this field it is indicated that infrasonic stimulation does not induce measurable responses from normal subjects until the auditory threshold is exceded by about 40dB. Hence it is necessary to be able to generate at least 140dB SPL. According to Mohr et al (43) the voluntary human tolerance level is about 150dB SPL therefore it is not desirable to exceed this level. The infrasonic source therefore must be able to generate at least 140dB but not greater than 150dB.

(b) The frequency response of the system must be stable if an accurate assessment of the degree of stimulation the observer is subjected to is to be made. If any non-sinusoidal stimulation is to be used the frequency response of the system must be flat within the range of interest.

(c) The sound pressure level produced must, for ease of operation, be easily variable.

(d) Before any work on the effects of various intensities of infrasound on observers can be assessed it is useful to know the auditory threshold levels of the subjects involved at the frequencies used. For this reason it is important to have a low harmonic content in the signal. From Bekesy's work (10), the shape of the threshold curve suggests that the harmonics must fall of at a rate greater than 20dB/octave to avoid any significant lowering of the thresholds obtained.

3.2 Possible Sources

3.2.1. The Pistonphone

Although the pistonphone can produce intense infrasonic presures by compression of a small enclosed volume of air, and there is no lower-limit to its frequency response, it is difficult to drive the piston in a true sinusoidal manner and noise is generated by the piston mechanism. This noise would have to be removed by filters which become inconveniently large when the roll-off frequency is only several hertz. It is also difficult to produce smooth variations in pressure.

3.2.2. The Thermophone

As mentioned above the main disadvantage of producing sinusoidal changes of air pressure by mechanical means is the problem of noise and the difficulty of changing frequency and amplitude. The thermophone is free from such difficulties and as a method of sound generation is relatively free from overtones and is reliably stable.

The thermophone produces fluctuations in pressure by imposing a varying temperature on an enclosed volume of air, by means of a current heated wire. For high sound pressure levels the enclosed volume must be small and the heat capacity of the current heated wire must be low.

Low frequency signals free from harmonic content can be produced by heating the wire with two high frequency currents. The sound pressure level produced is easily variable and by careful choice of the input frequencies the harmonics will be inaudible and only the beat frequency will be heard. Although there is a danger of physiological noise being accentuated by the small volume, the overriding disadvantage of using a thermophone is that the air inside the ear canal is heated and could possibly produce caloric type vestibular disturbance. As one of the objectives of this work is to study the vestibular effects of infrasound this thermally produced vestibular disturbance could be confusing.

Heating Effect

This method of low frequency sound generation was used extensively by Bekesy. A typical Bekesy thermophone incorporated a 5mm wide 4cm long gold foil in a 7mm cavity and produced maximum sound pressure levels of about 143dB at 50Hz. From reference 64 the temperature of the thermophone walls in this case would be 77°C which would result in considerable heating of the air in the meatus and thermally induced vestibular effects would be highly probable as well as considerable subject discomfort.

3.2.3. Electroacoustic driving sources

Suitably chosen loudspeakers are an obvious source for an easily controllable pressure fluctuation but a loudspeaker in a baffle is a poor radiator of low frequencies or infrasonics unless the baffle is large compared with the wavelength and as the wavelength at 1Hz is over 300m the baffle would be impracticably large. It is possible to improve the low frequency performance of a loudspeaker with a low resonant frequency by using various coupling arrangements.

3.2.4. Coupling Arrangements

(a) Resonant Cavities

Isolation of the two faces of a loudspeaker can be effected by allowing one face of the cone to work into an enclosed resonant cavity which can be tuned to the desired frequency. This approach was used by Gavreau (20). The main disadvantages of this type of system are that:

i. Random noise production is impossible

and ii. Many such units would be required to cover the frequency range.

(b) Headphones

Commercial headphones are not designed for use in the desired frequency region. Two specially designed headsets have been reported ((106), 1963 (14) 1967) both have a flat response down to 1Hz.

(c) Pressure Chamber-Non resonant

A chamber has the attractive facility of whole body stimulation. Several pressure chambers operating on the principle of the pistonphone have been constructed (12, 43, 45, 46). The large volume of the chamber requires a large piston amplitude to produce the required stimulus levels, this increases the harmonic content of the signal and stresses imposed on the driving mechanism necessitate limits of velocity and acceleration as the frequency increases from zero, hence it is difficult to obtain a flat frequency response.

The problems can be overcome by using loudspeakers for the driving source into the chamber. Several speakers working in-phase into a sealable chamber would act as a stable and variable source of both pure tone infrasonic and low frequency noise.

(d) Resonant Pressure Chamber

The output of the latter type of pressure chamber can be increased by making the chamber tunable over the desired frequency range. An adjustable opening in one wall of the chamber would mean that the system could operate as a Helmholtz resonator, and improve the maximum output from the chamber for pure-tones.

3.2.5. Free field Systems

Specially designed low frequency sound sources emitting discreet frequencies were used by Gavreau (20) in some of the earlier work in this field. The general operating principle of these devices is an edge effect, similar to that of an ordinary whistle or organ pipe. The flow of air across a knife edge causes eddies in the air stream and resonant vibrations are set up in an air column enclosed in a sound box.

The obvious disadvantages of this type of system are:-

i. A different unit is needed for each frequency

ii. The output level is not easily measurable or controllable.

iii. Generation of overtones and noise is inevitable

iv. For very low frequencies the order of a few hertz the physical size of the system is impracticable.

3.3. Methods of Pressure Measurement

There are several highly specialised microphone systems which have been developed to detect very low frequency infrasound typically occuring during atmospheric disturbances (e.g. hot wire, electrolytic and thermistor). The detection and measurement of infrasound in the frequency range under consideration requires basically the same apparatus as at audio frequencies. After suitable modification condenser and piezo-

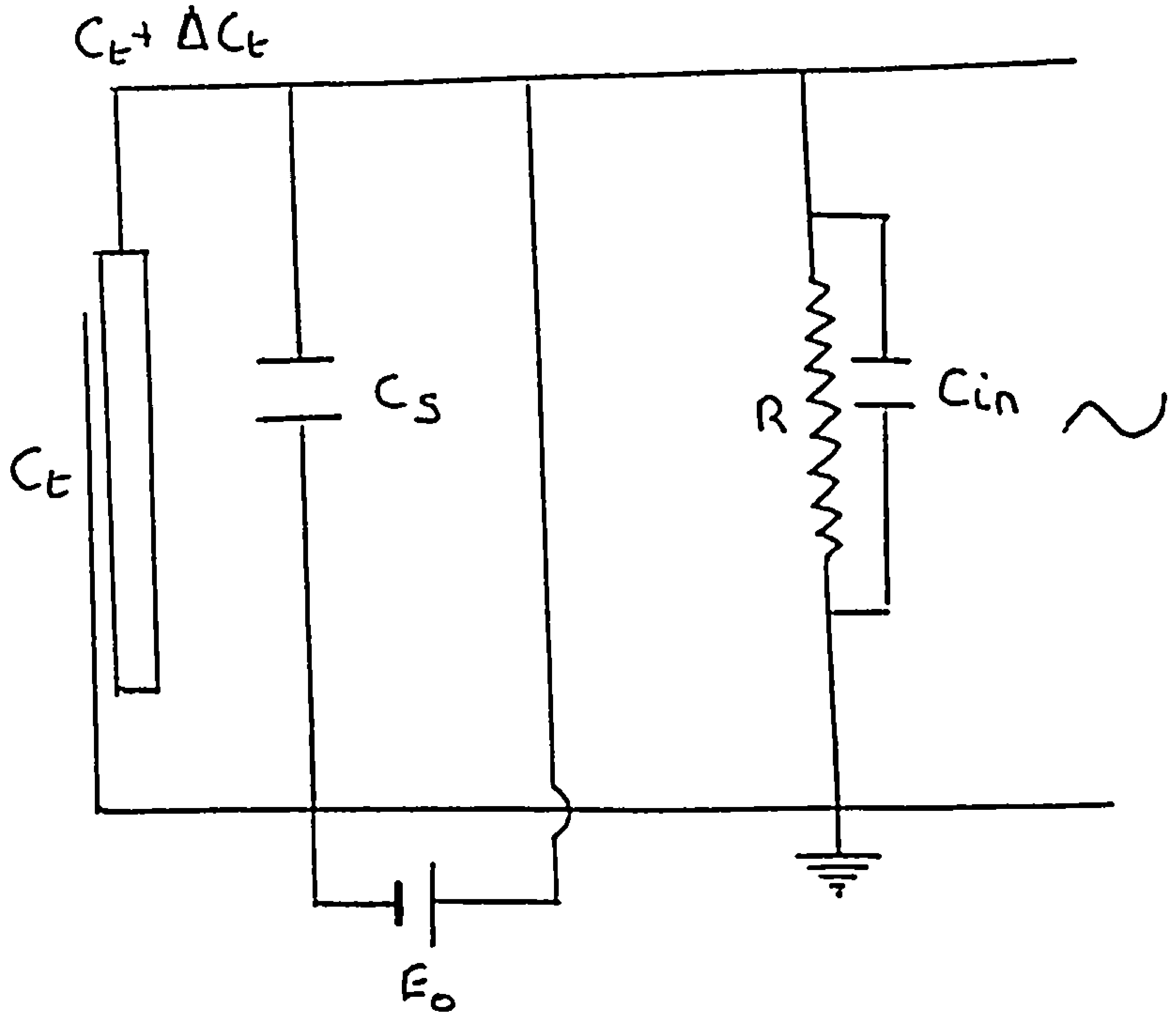

Fig 3·1a Simplified equivalent circuit for condenser microphone electric microphones may be used.

Blocking the pressure equalization hole, which controls the low frequency limit of such diaphragm microphones, can theoretically extend its response down to zero frequency. This method of extending the low frequency response is used in the B + K condenser microphones types 4144/5/6.

Charge leakage through external resistance from the sensing element, (capacitor or piezoelectric crystal) which transmits the diaphragm's deflection usually means that a microphone cannot maintain a low frequency response. High impedance pre-amplifiers can be used to reduce this charge leakage and hence extend the frequency response. This method of extension is used in the F.E.T. input type condenser microphone Fig.3.1a

The output voltage Vo is determined from:-

$$Vo = \frac{\Delta c(t).E_o}{C_t} \cdot \frac{R.C_t}{R.(C_t+C_s+C_{in})-j\frac{1}{2\pi f}}$$

From this the lower limiting frequency f_n is determined by:-

$$f_n = \frac{1}{2\pi R.(C_t + C_s + C_{in})}$$

Therefore if a linear frequency response in the low frequency region is required R must be large.

The input stage is fully transistorised and is built around a low noise silicon field effect transistor. This gives

Fig. 3.1 Cross-sectional sketch of headset.

an input impedance of about $20\,G\Omega$ parallel by < 0.5pF.

The insensitivity of the ear to low frequencies makes direct measurement relatively simple as low self-noise or high sensitivity is not required in the monitoring device to record sound pressure levels.

At these very low frequencies the wavelengths involved are much greater than the dimensions of the apparatus and hence a reliable determination of the sound pressure level can be obtained by using a microphone mounted in such a way as to measure the SPL directly in the region of the ear, and this can be regarded as the same as that found at the ear. Precautions must be taken to ensure that the microphone calibration is valid under the conditions experienced in the cavity surrounding the ear.

3.4 Conclusions

Of the possible sources discussed only a specially designed headset of the type used by N. S. Yeowart et al (14) or an electro-acoustically driven pressure chamber meet the necessary requirements.

A directly mounted condenser microphone of a suitable type is the most promising method of monitoring the infrasonic sound pressure levels provided that the frequency response and sensitivity of the microphone are accurately known. In order to use a microphone in this way the dimensions of the apparatus must be small compared with the wavelengths involved and this limits the physical dimensions of the source. The enclosed volume must be of suitable size to allow a microphone to monitor the pressure fluctuations and also ensure that these are uniform throughout the cavity.

3.5. Final Apparatus - Headset

A modified headphone of the type used by Yeowart et al (14) was used as the basis of a binaural headset. A 12" loudspeaker was clamped onto a 14" diameter ¼" thick aluminium plate. A 1" dia. hole, ¾" along a diameter connected the internal volume to an earpiece, the eardefender from a Denis Ferranti noise excluding headset. This type of ear defender has a glycerine filled pad covering the edges to be applied to the ear, this provides an adequate and comfortable airtight seal under the pressures required to seal the headset to the subject's head.

The ear defender cap was relatively large hence the problem of monitoring the pressure fluctuations set up in the total enclosed volume of 1 litre was simplified. There was sufficient space to allow a B + K microphone cartridge No.4132 to be mounted in the cup in such a way that its diaphragm was exposed to the pressure fluctuations in the cavity. The microphone was mounted into the cup using a B + K adaptor ring push fitted into an aluminium collar. Four bolts located the collar onto the cup so as to allow the adaptor ring to fit into a 1" dia. hole in the side of the cup. An airtight fit was obtained by using a sealing compound on all the surfaces. The protective guard was removed from the microphone which was screwed into the adaptor ring. The front face of the microphone diaphragm looked directly into the enclosed cavity and was isolated from the backface of the diaphragm by a sealing ring in the guardring. This blocked the pressure equalization path and so the frequency response of the microphone cartridge was extended. The complete earphone is shown in Fig.3.1.

Two such speaker systems were mounted on a support which allowed variation of separation and height to accommodate various subjects. The apparatus was used in a room isolated from structural vibration by a glass fibre carpet and from airborne noise by foam damped walls, floor and ceiling (Fig.3.2).

3.6 Calibration

A condenser microphone was used as the basic measuring transducer. As was described in section 3.3 the low frequency response falls off due to air leaks and loading of the cartridge by the cathode follower. The microphone mount was designed to block-off the air leak through the pressure

Fig 3.2 The Headset

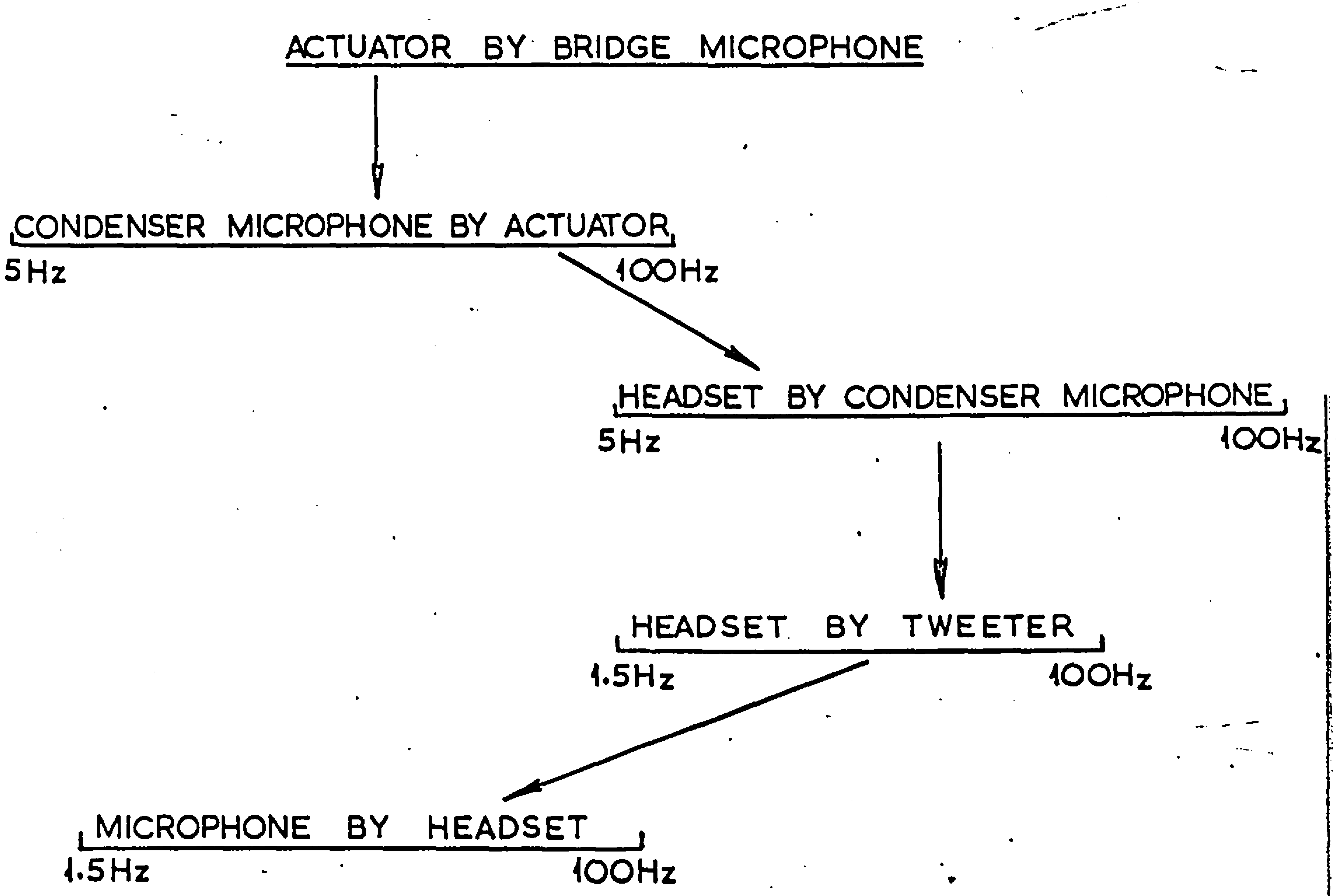

Fig. 3.3 Calibration routine

equalization hole so that as little loss as possible would be experienced in the low frequency region. The fall-off in response due to the cathode follower loading can be easily compensated for in ~~sonic~~ sine wave experiments.

3.6.1. Condenser microphone by actuator

An electrostatic actuator (type UA0023) which had been previously calibrated;using a bridge microphone (107) was used to determine the frequency response of the selected microphone cartridge and cathode follower, (B + K mic. cart. type 4132 and cath. foll. type 2613) in the 5Hz to 100Hz range.

With the microphone's protective grid removed the actuator was mounted close to the diaphragm of the condenser microphone. The input to the actuator was maintained at a constant level and the output from the microphone was examined over the frequency range using a microphone amplifier. Fig.3.4 shows the frequency response of the microphone cartridge and cathode follower down to 5Hz. The fall in response at the lower frequencies is due to loading of the microphone by the cathode follower as described in section 3.3.

The cut-off frequency is given by:-

$$f_n = \frac{1}{2\pi} \quad \frac{1}{(C + C_s + C_i)\ (R_i)}$$

C = polarized microphone capacity

C_s = stray capacity

$R_i C_i$ = input impedance to cathode follower

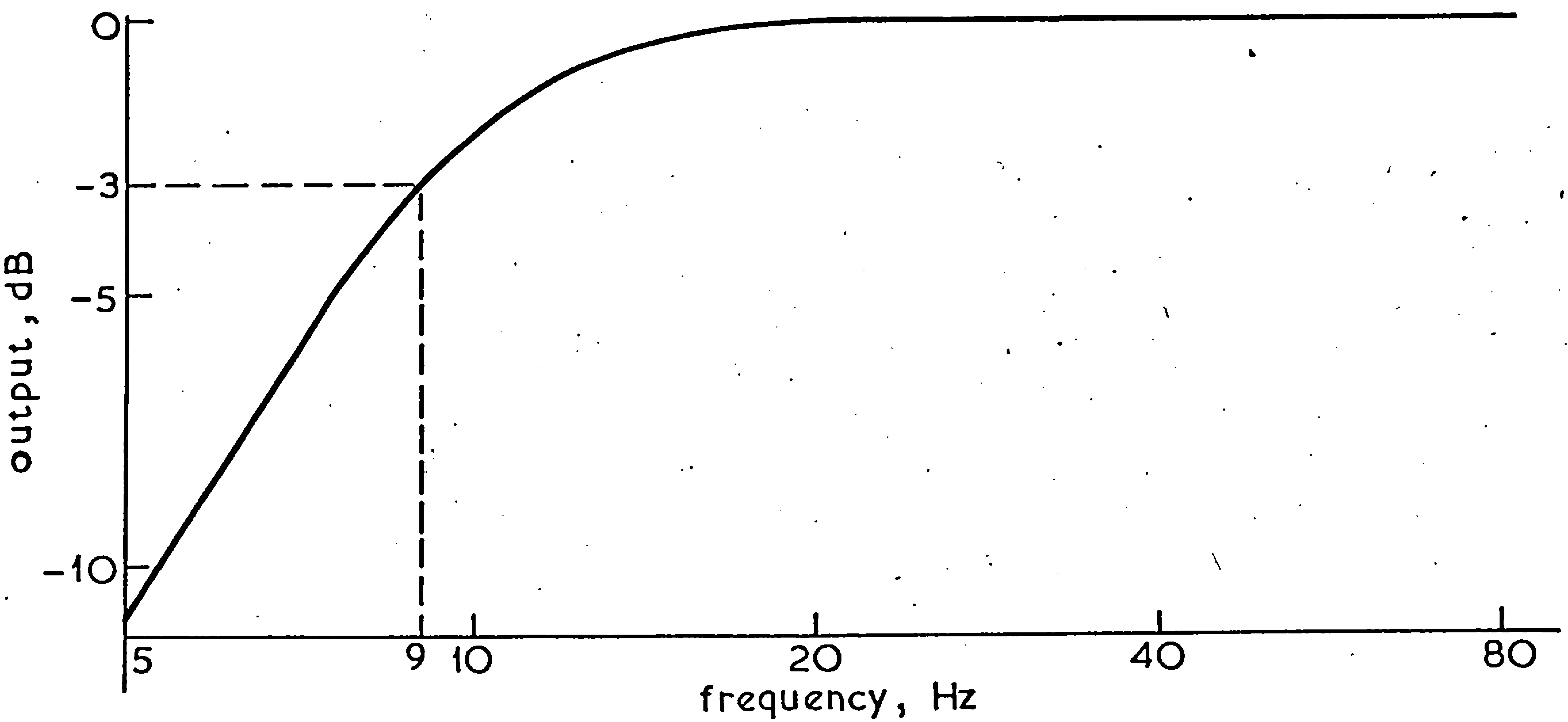

Fig. 3.4 Microphone response down to 5Hz

For the units used

$$C = 60pF$$

$$R_i = 270M\Omega$$

$$C_i = 3pF$$

and allowing 2pF stray capacitance

$$f_n = \frac{1}{2\pi} \frac{10^6}{65 \times 270 \times 10^6} \sim 10Hz$$

Theoretically this combination should be 3dB down at 10Hz. From Fig.3.4 it is seen that the true combination is 3dB down at about 9Hz. This change in sensitivity does not prohibit the use of the microphone as a measuring device provided that the deviation is stable and accurately known.

3.6.2. Headset by Condenser Microphone

The calibrated microphone was used to measure the frequency response of the headset.

A 'dummy head' was used to close the openings for the subject's pinna in the headset. A constant electrical input was maintained at the terminals of the headset as the input frequency was varied in the range 5-100Hz. A correction for the microphone roll-off was applied to the sound pressure level indicated. The frequency response of the headset was found to be flat in the 5-100Hz region. Fig.3.5.

3.6.3. Headset by Tweeter

The extended calibration of the headset down to 1.5Hz is based on the following theoretical considerations.

For a loudspeaker let M = mass of cone and coil

K = stiffness of the cone suspension + enc. volume

F = electromagnetic force on the coil

R = electromagnetic damping and frictional losses in the suspension

Then assuming the cone is leak free the equation of motion of the loudspeaker working into an enclosed volume is:-

$$M\ddot{x} + R\dot{x} + Kx = Fe^{j\omega t}$$

Assuming the solution is in the form

$$X(x)\, e^{j\omega t} = x$$

then

$$X(x) = \mathrm{Re}\left[\frac{F}{-M\omega^2 + j\omega R + K}\right]$$

The fundamental resonance of the system is given by

$$K - M\omega^2 = 0$$

and if the frequency is such that

$$\omega << \frac{K}{M}$$

i.e. much lower than the resonant frequency then the displacement $X(x) \longrightarrow \frac{F}{K}$

i.e. THE DISPLACEMENT AMPLITUDE IS PROPORTIONAL TO THE IMPRESSED FORCE AND IS INDEPENDENT OF FREQUENCY.

Now if

B - flux density of the magnetic field

l - length of wire in the coil

i - current in the coil

Then

$F = B \times l \times i$

and the equation of motion reduces to:-

$X(x) \propto i$

i.e. THE DISPLACEMENT OF THE CONE IS DIRECTLY PROPORTIONAL TO THE INPUT COIL CURRENT.

The motion of the coil wire produces a change in volume ΔV which will result in a pressure change ΔP.

If P_o is the ambient pressure of the system

$$\frac{\Delta P}{P_o} = -\gamma \frac{\Delta V}{V} \propto \frac{X(x)}{V}$$

$$\therefore \quad \frac{\Delta P}{P} \propto i$$

We may therefore conclude that for a loudspeaker whose front face works into an enclosed volume at frequencies well below the resonant frequency of the system, the change in pressure in the enclosed volume depends only on the input current to the loudspeaker coil and is independent of the frequency.

i.e. THE SYSTEM HAS A CONSTANT FREQUENCY RESPONSE.

Consider the cone being driven by a constant amplitude sinusoidal pressure

$emf = B \times l \times v$ v = velocity of the cone,

the motion of the cone will be

$x = X(x) \sin\omega t$

and the cone velocity

$v = \omega X(x) \cos\omega t$

the ratio of the r.m.s. induced voltage measured in the coil of the driven loudspeaker for the same pressure amplitude but different frequencies is

$$\frac{e_1}{e_2} = \frac{\omega_1}{\omega_2} \qquad f = \frac{\omega}{2\pi}$$

for $f_1 = 2f_2$

ratio = 2

the induced voltage will fall by 6dB/octave for decreasing frequency.

Hence by using the relationship between sound pressure level and the voltage on the coil it was possible to measure the frequency response of the headset down to 1.5Hz.

A small loudspeaker, a 'tweeter' with an airtight plastic cone, was sealed into the opening for the subject's pinna. The pressure changes set up in the enclosed cone of the headset cone drove the cone of the 'tweeter'. The voltage thus induced in the coil of the tweeter was measured by a calibrated meter for various frequencies with a constant voltage input to the headset.

The induced e.m.f. at the coil should fall by 6dB/octave with decreasing frequency for a constant peak to peak displacement of the 'tweeter' cone if the system is operating as described above. Readings were taken in the 10 to 1.5Hz range and this was found to

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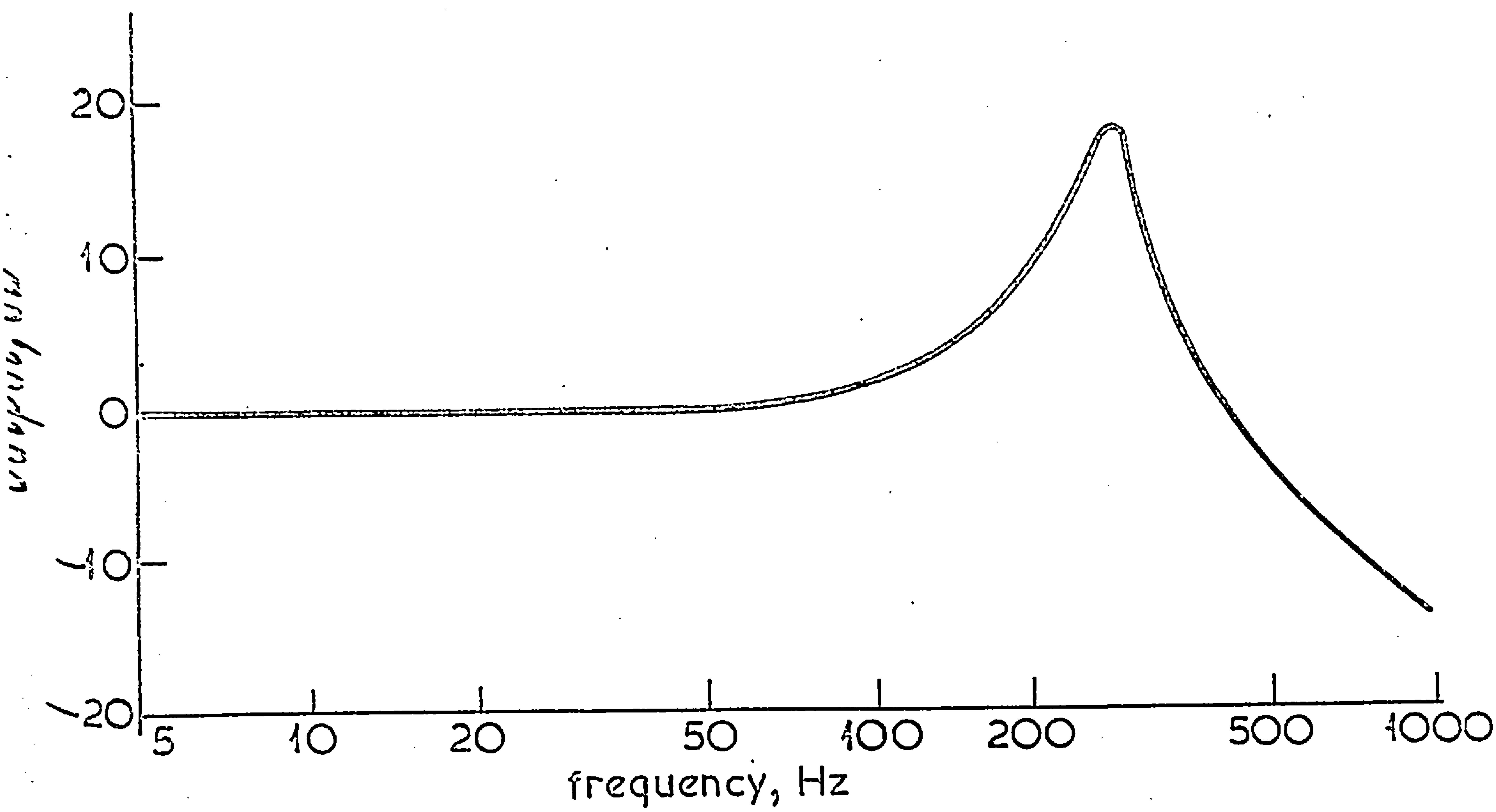

Fig. 3.5 Headset response without filter.

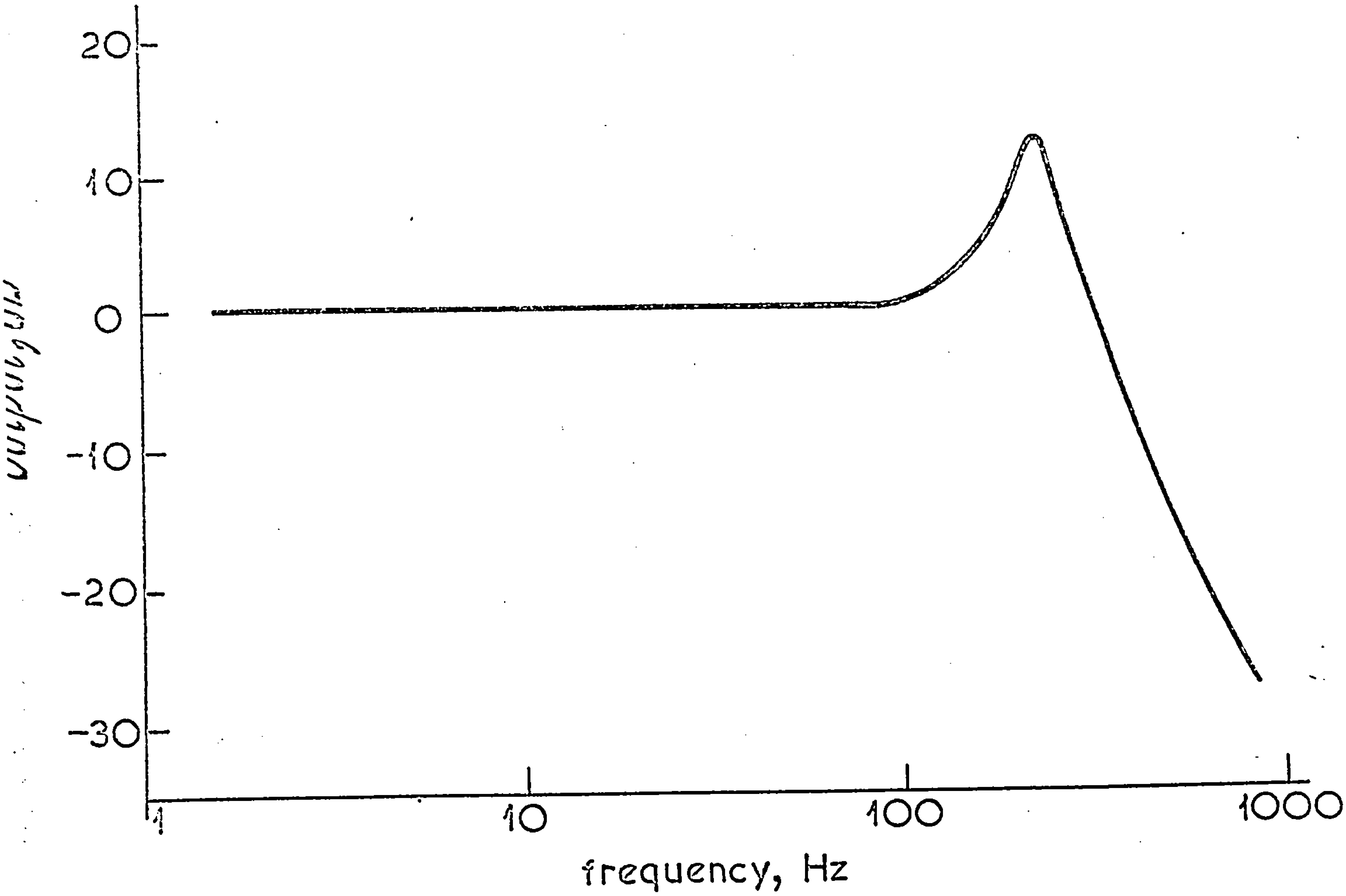

Fig. 3.6 Frequency response of headset + amplifier with filter.

hold true. Hence it can be deduced that for a constant input to the headset terminals a constant peak amplitude pressure variation was set up in the cavity. Hence it was possible to measure the response of the headset down to 1.5Hz. Fig.3.6.

3.6.4. Microphone by Headset

With the response of the headset determined down to 1.5Hz it was possible to extend the frequency response calibration of the microphone from 5Hz to 1.5Hz.

The microphone, calibrated to 5Hz, was mounted in the headset and the cavity sealed with the dummy head. The output from the microphone was monitored in the 1.5 to 10Hz range for a constant sound pressure level in the headset. The final calibration curve is shown in Fig.3.7.

3.7 Filtering

High frequency noise in the power amplifier was removed by a simple roll-off filter, Fig.3.8. The roll-off frequency of the filter was chosen to extend the constant frequency response of the loudspeaker unit. The filter had a low frequency input impedance of 15Ω, a 6dB d.c. loss and was 3dB down at 110Hz. The falling filter balanced the rise in the headset response resulting in a constant frequency response up to 120Hz. The mechanical resonance peak was reduced to about 10dB. The frequency response of the headset with and without the filter is shown in figs. 3.6 and 3.5 respectively.

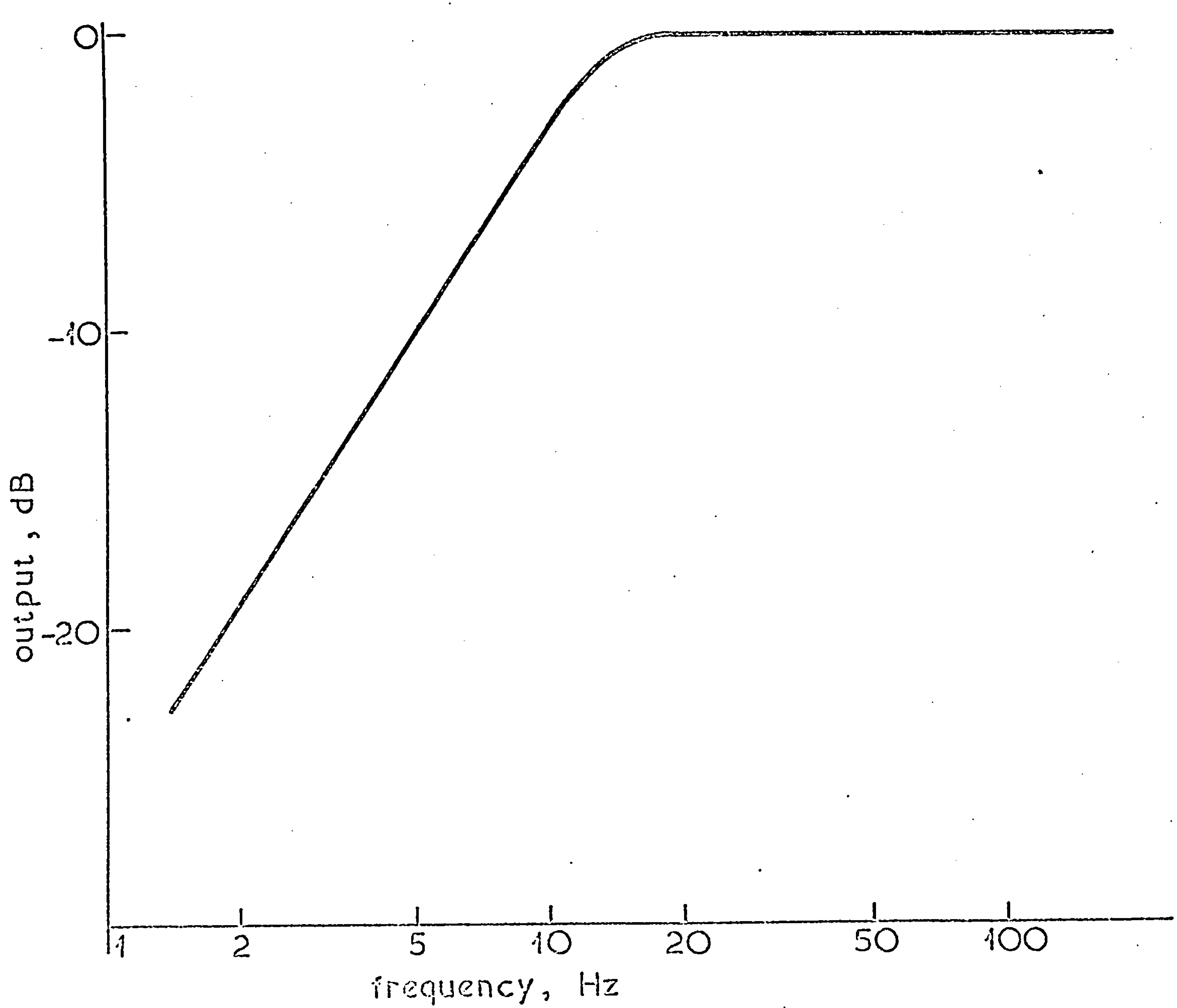

Fig. 3.7 Microphone response down to 1.5Hz.

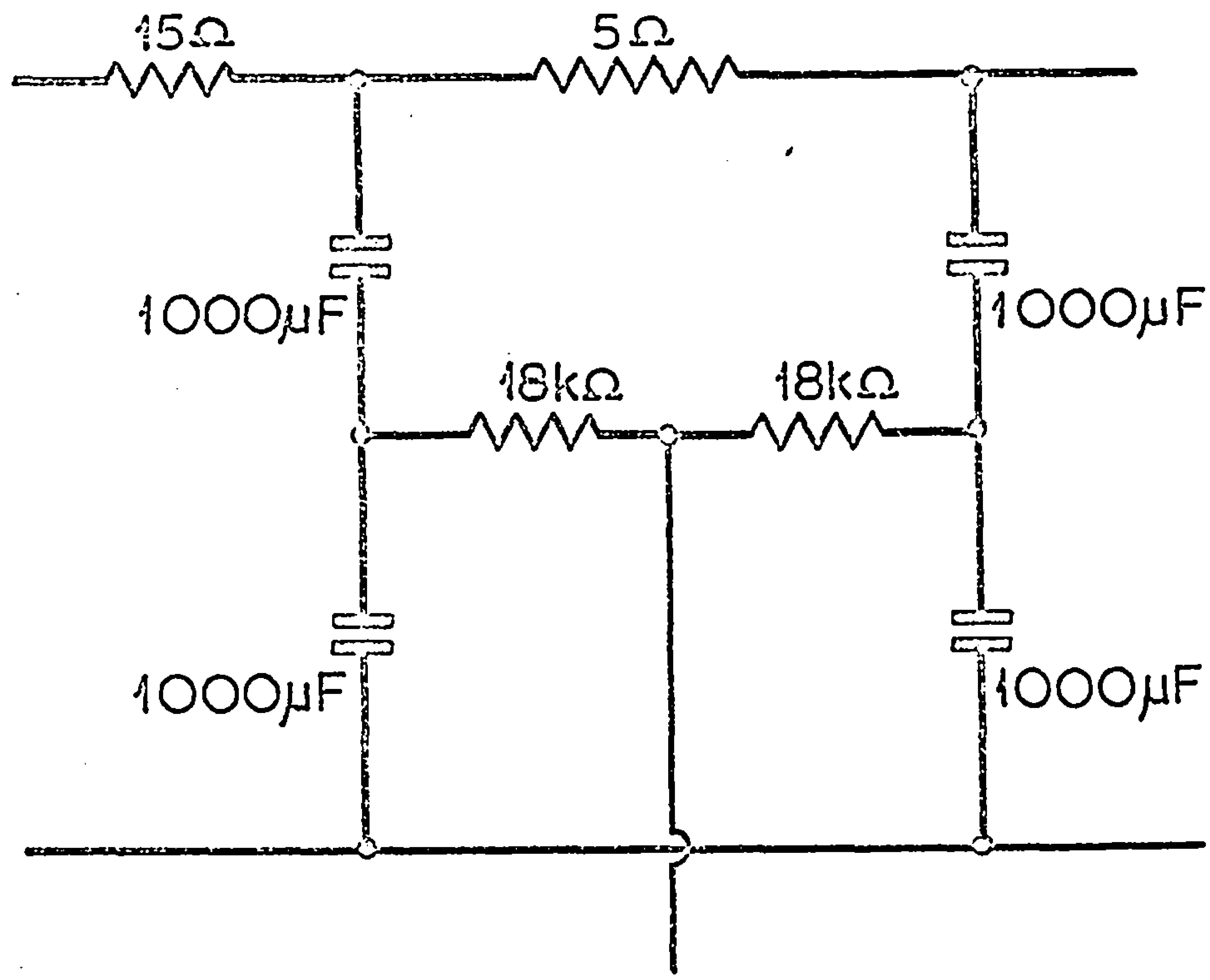

Fig. 3.8 Headset filter

3.8. Distortion

Because of the decreasing sensitivity of the ear with decreasing frequency the harmonics in the infrasonic signal will be more readily audible than the fundamental, hence it is important to know the harmonic content of the stimulus, Fig.3.9 shows a schematic diagram of the apparatus used.

3.8.1. Rejection Bridge

The rejection bridge was specially designed for harmonic analysis at various octave intervals from 16Hz to 1Hz.

The bridge was designed to be loaded by the input impedance of a B + K wave analyser, about 2.2MΩ, and to be driven by ~~a 15Ω loudspeaker coil~~ an amplifier with a 50Ω output resistance. It was of a parallel T type and based on the B + K distortion bridge type.

The characteristic broad skirt of a parallel T network is not suitable for harmonic analysis, a much flatter frequency response is required for the second harmonic and above. The parallel T characteristic was shaped by following the network with an R.C. roll-off filter whose falling response balanced the rising skirt of the 'T' over a restricted frequency range.

Component Values

The null point of a balanced network is given by

$$f_{\infty} = \frac{1}{2\pi\sqrt{RC}}$$

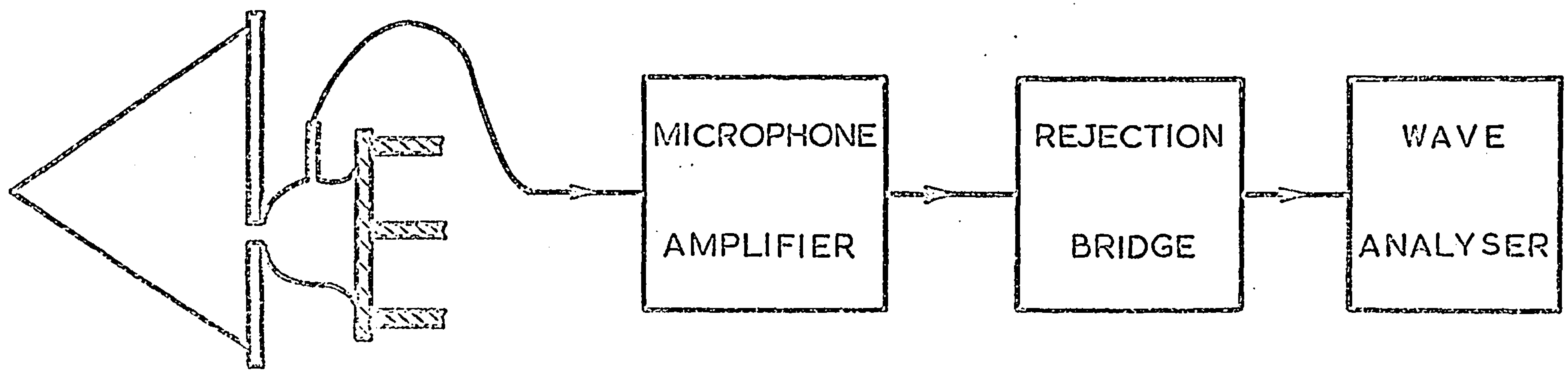

Fig. 3.9 Schematic apparatus for distortion measurement.

and the optimum values of R are determined by the condition

$$\sqrt{1.5\ R_o R_i} \quad < \quad 2\sqrt{R_o R_i}$$

where R_o and R_i are the output and input resistances loading the circuit.

R was fixed at 20KΩ which led to convenient values of C = 0.5, 1, 2, 4, and 8μF for the capacitors for rejection frequencies of 16, 8, 4, 2 and 1Hz respectively.

The component values in the roll-off filter to give satisfactory output characteristics were R/2 and 2C in relation to the parallel T network components. The complete circuit diagram is shown in Fig.3.10.

Operation

The bridge had three modes of operation:-

i. Frequency - parallel T network alone

ii. Distortion - shaped parallel T network

iii. Linear.

Fig.3.11 shows the generalised frequency characteristics for the FREQUENCY and DISTORTION modes.

The optimum setting on the pre-set potentiometer was determined empirically.

The upper skirt of the bridge was made flat to within

Fig. 3.10 Circuit diagram for parallel T distortion bridge.

Fig. 3.11 Frequency characteristics of rejection bridge as a function of rejection frequency f_o H

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$\pm$ 1dB over the frequency range 1.87 f_∞ to 8.75f_∞ where f_∞ is the rejection frequency. This flat portion is centred at 20dB below the input signal.

This circuit can be used to examine the harmonic content of an input signal up to the 7th harmonic providing the harmonics measured at the output are referred to the fundamental 20dB below its measured value on the linear setting.

Components of 1% tolerance were used and the variable potentiometer in the leg of the T network enabled the effect of these component tolerances on rejection to be removed resulting in maximum attenuation of the fundamental. The circuit was carefully screened to reduce pick-up.

3.8.2. Procedure

The entire harmonic content of the 16Hz signal fell within the range of the wave analyzer, so after rejecting the fundamental with the low frequency bridge it was possible to use normal distortion measurement techniques.

With the fundamental frequency of 8Hz only the third and higher harmonics fell within the range of the wave analyzer, these were measured directly. The second harmonic fell on the flat part of the microphone response, so from the measured total harmonic distortion and the higher harmonic results it was possible to calculate the second harmonic content of the signal.

Measurements below 8Hz were complicted by the falling response of the microphone. The signals here could only be measured for total harmonic distortion. This was calculated from the measured voltages and the frequency response of the microphone. It was assumed that the total harmonic voltage could be treated as being second harmonic distortion.

3.8.3. Measured Distortion

Table 3.1. shows the total harmonic distortion measured at various frequencies up to 100Hz. The sound pressure level was 120dB.

TABLE 3.1. TOTAL HARMONIC DISTORTION UP TO 100Hz

FREQ.	100	50	40	30	20	16	8	4	2
% AGE DISTORT.	0.80	0.65	0.60	0.75	0.85	0.70	0.75	1.3	2.1

Table 3.2 shows the harmonic analysis of an 8Hz signal.

TABLE 3.2. VARIATION OF HARMONIC CONTENT WITH SIGNAL LEVEL

	dB LEVEL OF HARMONICS BELOW THE FUNDAMENTAL				
S.P.L.	2nd	3rd	4th	5th	6th
140	25	42	62	70	>80
135	27	44	60	76	-
130	33	43	70	>80	-
120	40	50	71	-	-
100	46.5	51	>70	-	-

No evidence of any frequency dependent distortion was found and so these results were considered typical of the distortion at all frequencies.

3.9. Final Apparatus Chamber

The low frequency pressure chamber was constructed of ¼" aluminium plate mounted on a frame of 1" square section steel, and with a capacity of 43½ cu.ft. it could accommodate a subject with a sufficient margin of comfort. Six 18" diameter loudspeakers (Celestion G18C) were bolted, using airtight seals, over 10¾" diameter holes in three upright faces of the chamber. The fourth upright face formed the door, again constructed in such a way that it was airtight when closed. Two heavy duty perspex windows were let into the door for subject observation or illumination as required.

The loudspeaker cones were of the normal construction and hence porous. In order to obtain the maximum sound pressure levels it was necessary to seal the cone surface thus rendering them impervious to air leaks. This was achieved by painting the inside surface of the cones with alternate layers of apiezon vacuum paint and a non-stiffening rubber solution of low viscosity until air leaks were no longer detectable. Fig.3.12 shows the external view of the chamber.

3.9.1. Theoretical sound pressure levels available

Assuming Boyles Law applies to the loudspeaker system

$$PV = RT \qquad \ldots(1)$$

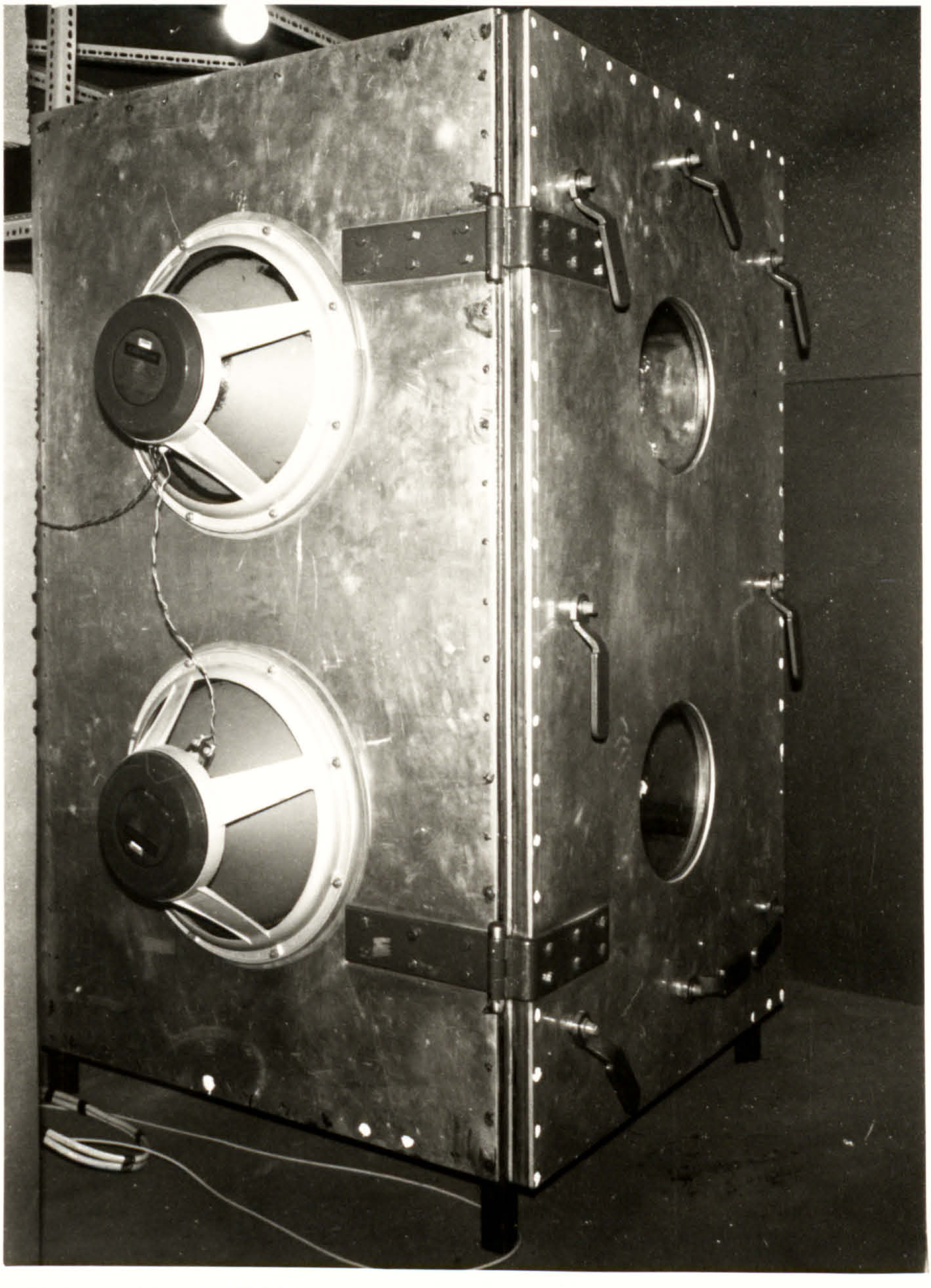


Fig. 3.12 The Chamber

∴ for a volume change ΔV resulting in a pressure change ΔP and a temperature change ΔT

$$(P + \Delta P)(V + \Delta V) = R(T + \Delta T) \qquad \ldots(2)$$

neglecting the products of the small quantities ΔP and ΔV

$$P\Delta V + V\Delta P = R\Delta T \qquad \ldots(3)$$

The change in internal energy ΔU is given by

$$\Delta U = -P\Delta V \qquad \text{assuming adiabatic conditions} \qquad \ldots(4)$$

or

$$\Delta U = C_v \Delta T \qquad C_v = \text{specific heat at constant volume} \qquad \ldots(5)$$

$$C_v \Delta T = -P\Delta V \qquad \ldots(6)$$

eliminating ΔT between (5) and (6)

$$\frac{\Delta P}{P} = -\frac{C_p}{C_v}\frac{\Delta v}{v} \qquad \text{where } C_p - C_v = R$$

C_p = specific heat at const. pressure ...(7)

$$\frac{\Delta p}{P} = -\gamma \frac{\Delta v}{v} \qquad \ldots(8)$$

(This is the expression for an ideal gas for a real gas the expression becomes

$$\frac{\Delta P}{P} = -\gamma \frac{\Delta v}{V-B}$$

where B is the 2nd Virial coefficient but for air at room temperature $B = -50 \times 10^{-5}$ and can therefore be neglected).

In the case of the pressure chamber

P = atmospheric pressure = 76cm hg.

γ = 1.40 for air

V_o = 1295.9 litres

TEXT BOUND INTO

THE SPINE

The maximum displacement of the cones was found empirically to be 3cm.

$$\Delta V = \frac{1}{3}\pi r^2 .3 \qquad r = \text{radius of the cone}$$

$$\Delta V = 1.6625 \text{ litres}$$

$$\Delta P = \frac{1.6625 \times 1.4 \times 76}{1295.9} \text{ cm hg}$$

$$\Delta P = 0.1361 \text{ cm. hg.}$$

and 1cmhg = 13332.2 μB

$$\therefore \text{dB SPL re } 0.0002 \text{ dynes} = 20\log. \frac{13332.2 \times 1.361 \times 10^{-1}}{2 \times 10^{-4}}$$

$$= 139.16\text{dB.}$$

The theoretical maximum sound pressure level available

$$= \sim 139\text{dB re } 0.002 \text{ dynes/cm}^2$$

In practice it was found that the maximum undistorted sound pressure level was 137.5 dB.

3.9.2 Electrical driving system

The electrical signal was derived from a commercial function generator with a continuous frequency range from 0.01-100KHz (Hewlett and Packard 3300A function generator). This was used in conjunction with a Crown 170w/channel dual channel amplifier and simple roll-off filters to remove any high frequency components or noise.

With six loudspeakers and two amplifier channels several loudspeaker configurations were possible. The most efficient configuration was found to be two sets of three in parallel each driven by one amplifier channel. The resistance of each loudspeaker set was measured at 3.5Ω. Without any form of filtering and with the speakers working at their maximum displacement without overloading 139dB SPL was obtained from the chamber in the frequency range 2Hz -15Hz but there was considerable high frequency noise on the speakers and so some form of filtering was necessary. When R.C. filters with a roll-off frequency of 40Hz were incorporated the maximum output from the chamber was 137.5dB SPL in the same frequency range. The chamber was working at a rate of 57.3 watts/speaker. Fig.3.13.

Sound pressure level measurements were made directly using a B + K condenser microphone which has its low frequency response extended by means of blocking the pressure equalisation hole as described in section 3.3. It had a 3dB lower limiting frequency of 1.5Hz.

3.9.3. Distortion

The same measurement technique was used to measure distortion of the infrasonic signal in the pressure chamber as was used for the headset. The response of the microphone was such that distortion measurements down to 2Hz could be made by this method.

The levels of the measurable total harmonic distortion at frequencies of 16Hz 7.5Hz 3.7Hz and 1.9Hz, and the variation of total harmonic distortion with sound pressure level are shown in table 3.3.


OSCILLATOR
ATTENUATOR
AMPLIFIER CHANNEL1
AMPLIFIER CHANNEL2
FILTER 1
FILTER 2
LOUD-SPEAKERS
LOUD-SPEAKERS

Fig. 3.13

The harmonic content of the 16Hz and 7.5Hz signals at a sound pressure level of 130dB is shown in Table 3.4 and is typical of the frequency range examined. The rate of fall of harmonics with increasing frequency was greater than the rate of fall of the threshold of hearing and so reliable threshold measurements could be made.

TABLE 3.3. VARIATION OF TOTAL HARMONIC DISTORTION WITH S.P.L.

Fundamental freq. Hz	percentage total harmonic distortion				
	137.5db	135dB	130dB	125dB	120dB
16	2.46	2.42	2.27	1.86	1.86
7.6	2.97	2.85	2.44	2.12	1.94
3.7	2.96	2.95	2.44	2.54	2.44
1.9	3.02	2.95	2.79	2.54	2.50

TABLE 3.4. HARMONIC CONTENT AT 130dB

Fundamental freq. f_oHz	distortion products: dB below fundamental				
	f_1	f_2	f_3	f_4	f_5
16	34	45	63	69	>77
7.5	38	46	58	61	>70

3.9.4 Frequency Response of the Chamber

A B + K condenser microphone type 4145 which has a 3dB lower limiting frequency of 1.5Hz was used to measure the frequency response of the chamber. The six 18" loudspeakers were connected in two sets of parallel threes, each set was driven by one channel of the power amplifier. A constant voltage input was maintained at the loudspeaker terminals as the input frequency was varied in the 0-100Hz range. The frequency response was measured under three conditions:

i. Chamber empty } No Filters

ii. Containing 2 cu.ft. of foam to represent the absorption of a subject } No Filters

iii. With 40Hz roll-off filters to remove high frequency noise and 2 cu.ft. of foam.

Fig.3.14 shows the three frequency responses.

Fig. 3.14 Frequency response of pressure chamber.

CHAPTER 4

DETECTION OF EFFECTS.

4.1. Objective Effects

4.1.1. Nystagmus

The basic premise of this work was that infrasonic stimulation could possibly disturb the organs of equilibrium in normal human subjects.

When an animal or human subject experiences motion, real or apparent, each eye ball rotates in the opposite direction to the perceived motion. This action is clearly directed towards maintaining a steady image on the retina. If the motion persists, the eyes, upon nearing the limit of their travel will rapidly flick in the direction of motion and then resume their compensatory motion in the direction opposite to that of the imposed motion. This periodic eye movement is typical of a condition where the control can no longer govern eye motion and this periodic eye movement, which continues for as long as the subject experiences motion, is termed NYSTAGMUS. It occurs in both the vertical and horizontal planes.

Nystagmus always occurs when a subject experiences a disturbance of balance and hence is a reliable indication of balance disturbance.

Nystagmus can be either observed visually or recorded electrically.

4.1.2. Electronystagmography

The extra ocular, or extrinsic, eye muscles control the position of the eye in its socket. For each eye there are three pairs of antagonistic muscles: fig.4.1 and 4.2.

Muscle Pair	Function
1. Superior and inferior rectus	Elevation and depression
2. Lateral and medial rectus	side to side (abduction and adduction)
3. Superior and inferior oblique	Intorsion and extorsion (rotation about optic axis)

Movement of muscle pairs 1 or 2 produce corneo-retinal potential changes. The corneo-retinal potential depends on the distance between the cornea - the electropositive pole and the retina - the electronegative pole, of the eye. These distances change with movement of the eyes up, down or from side to side thus producing a corneo-retinal potential change, which can be easily detected using skin electrodes.

The corneo-retinal potential change, like that of all other d.c. bipotentials, is a change without a true threshold and without any quantal character. Yet such changes must reach a certain quantity to become registerable. This is not a true threshold, because it depends only on the efficiency of selective amplification, almost infinitesimal potential changes can be detected if the disturbing internal or external influences can be minimized. These artifacts can be divided into three groups:

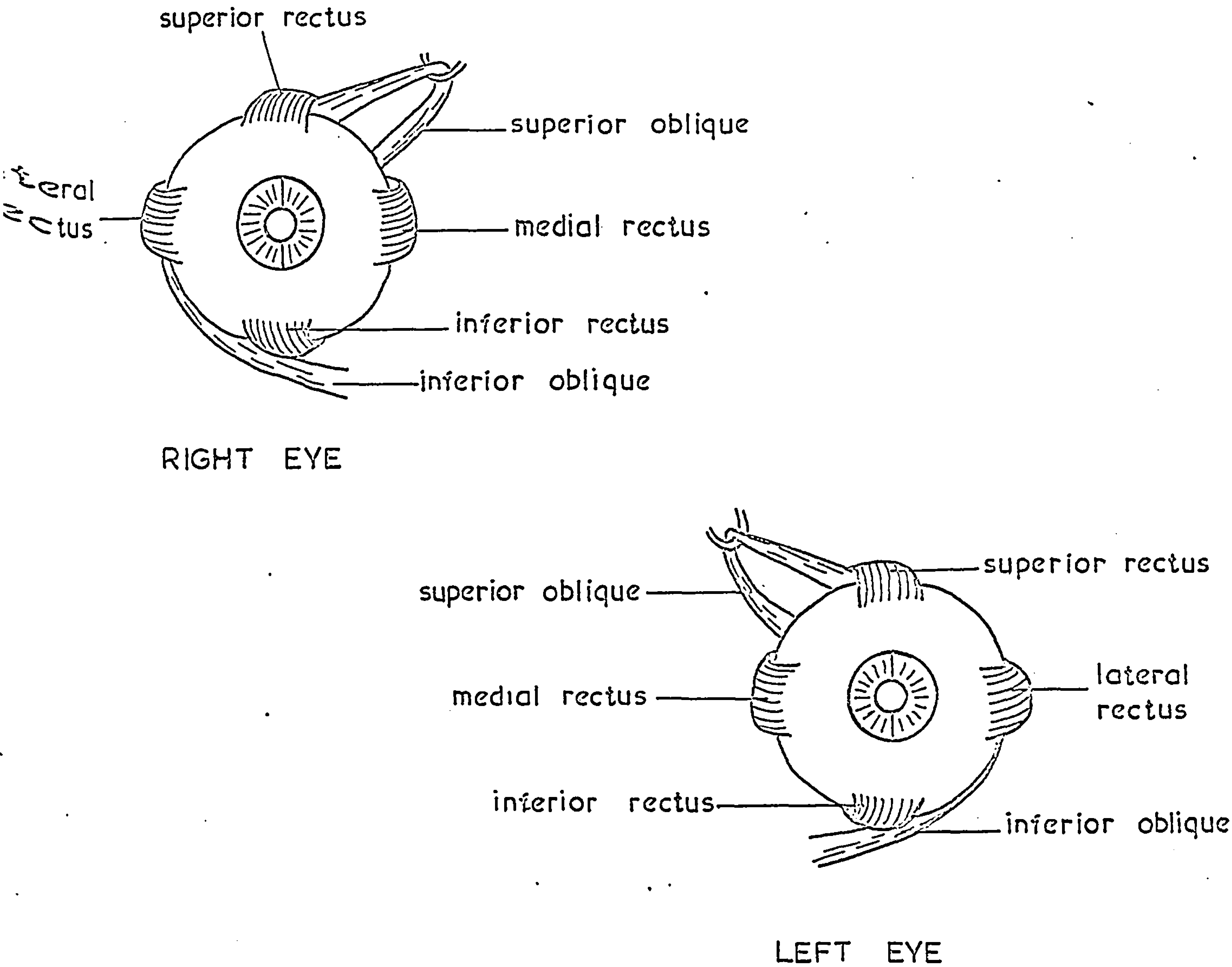


Fig. 4.1 The Extrinsic Ocular Muscles

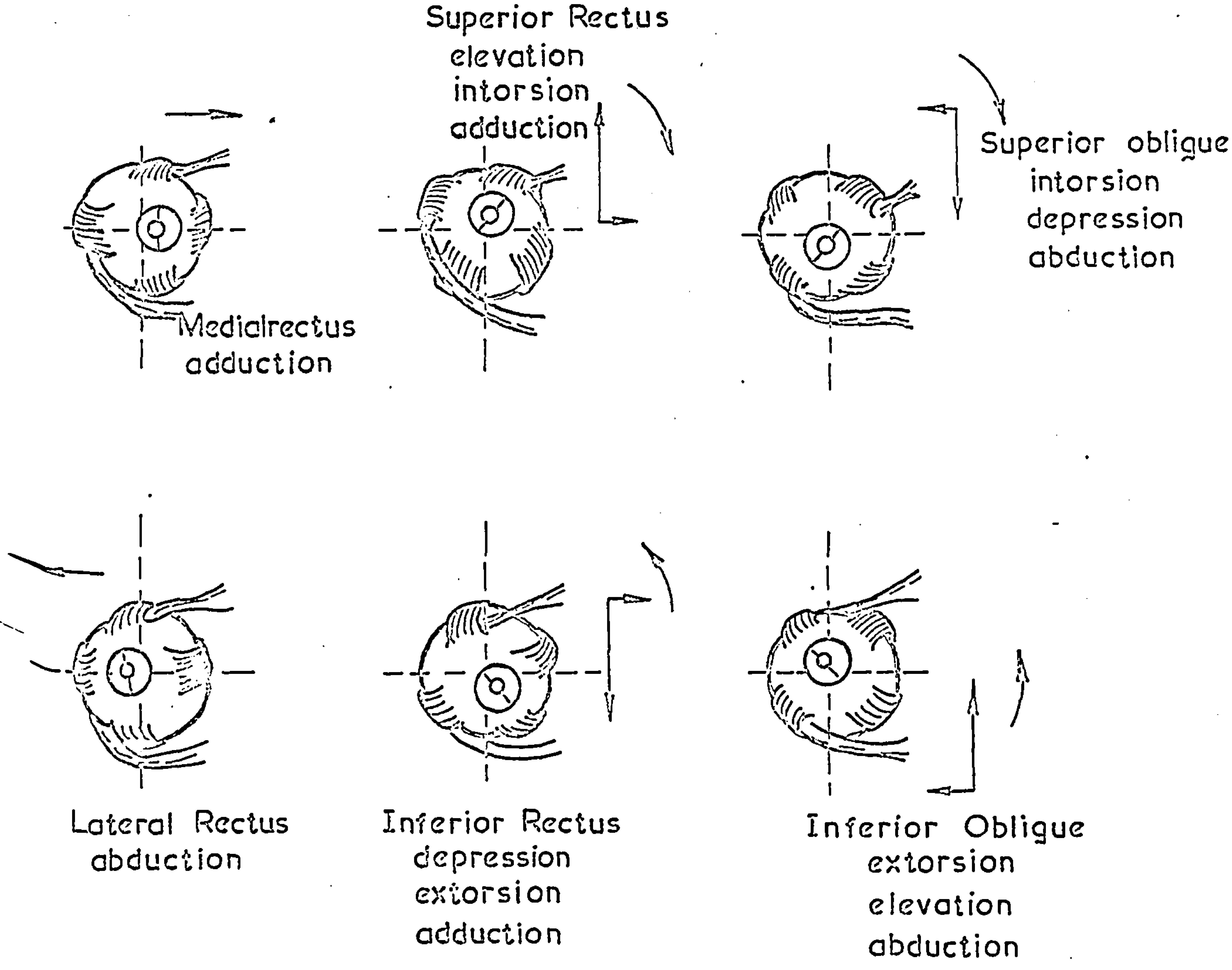


Fig.4.2 Action of three pairs of antagonistic eye muscels.

i. Internal artifacts such as hum and noise are generated in the amplifying system

ii. External artifacts consisting mostly of mains supply disturbance, efficient electrical screening will minimize this.

iii. Bioelectrical potentials arising elsewhere within the body of the test subject: these include brainwaves, muscle potentials, cardiac potential changes etc.

The corneo-retinal potential changes can be measured only if they produce pen excursions with an amplitude which is sufficiently larger than that of the base line oscillation. Overall amplification will not help in this case as it amplifies without discrimination both the artifacts and the potential changes under observation. Suitable filters and careful electrode placement are the only ways of making electronystagmography more sensitive by resulting in selective amplification of the corneo-retinal potential changes.

4.2. Amplification

4.2.1. Possible Methods

D.C. and R.C. amplifiers with relatively long time constant produce a direct record of the bioelectrical potential. The graphic curve is in linear relation with the angular deviation of the eye. Unfortunately the base line of these registrations is rather unstable.

A.C. amplifiers, using time constants shorter than the periodicity of the recorded potentials, register only the changes of bio-electrical potential and not the magnitude of the potential itself.

Mathematically this means that the expression of the entire nystagmic movement is a differential of time. Hence there cannot be a linear relationship between the angular deviation of the eye and the amplitude of the graphic spikes. Instead the spike amplitude indicates the velocity of the eye movement. For the same reason the graphic curve returns to the base line after each eye movement, no matter in what position the eye actually comes to rest. This type of amplification does provide a stable base line but is really of more use when the occurence of nystagmus is well established.

4.2.2. Methods Used

None of the above methods are wholly satisfactory. The two following methods of amplification were found to give the best approximation to the ideal conditions.

a. Chopper Amplifier (57)

The difficulties encountered in the assessment of a.c. traces and the stability of d.c. traces can be overcome by chopping the signal on a 400Hz square waveform by means of a chopper hence converting the standing potential difference between the electrodes into an alternating waveform; this can then be easily amplified by using a two section a.c. amplifier with gains of 10 and 100; the signal is then returned to a d.c. level by using a second chopper exactly synchronised with the first.

50 and 400Hz components are filtered out and the impedances matched using an emitter follower.

b. Differential Amplifier

To avoid many of the problems inherent in d.c. amplification and at the same time use time constants of a suitable length an a.c. derived d.c. amplifier with a differential input may be used. Ideally a differential amplifier will amplify only the instantaneous difference between two input signals.

The signal is fed through a large capacitor into a differential pair with a transistor tail for stability. The out of balance signal from this pair is fed into a second differential pair and the amplified signal taken off one side into a final stage amplifier with a switched gain control. The circuit is shown in fig.4.3.

High frequency hum and noise components were removed by an L.C. low pass filter with a nominal cut-off at 50Hz fig.4.4. The frequency response of the system, amplifier and filter, is shown in Fig.4.5. This is flat in the 0.5 to 1.5Hz range and 0.25dB down to 3Hz. As any nystagmus is expected to occur in this range the amplifier response is satisfactory.

The output signal was recorded on an ultra-violet recorder (S.E. 2005).

Fig. 4.3 Differential amplifier

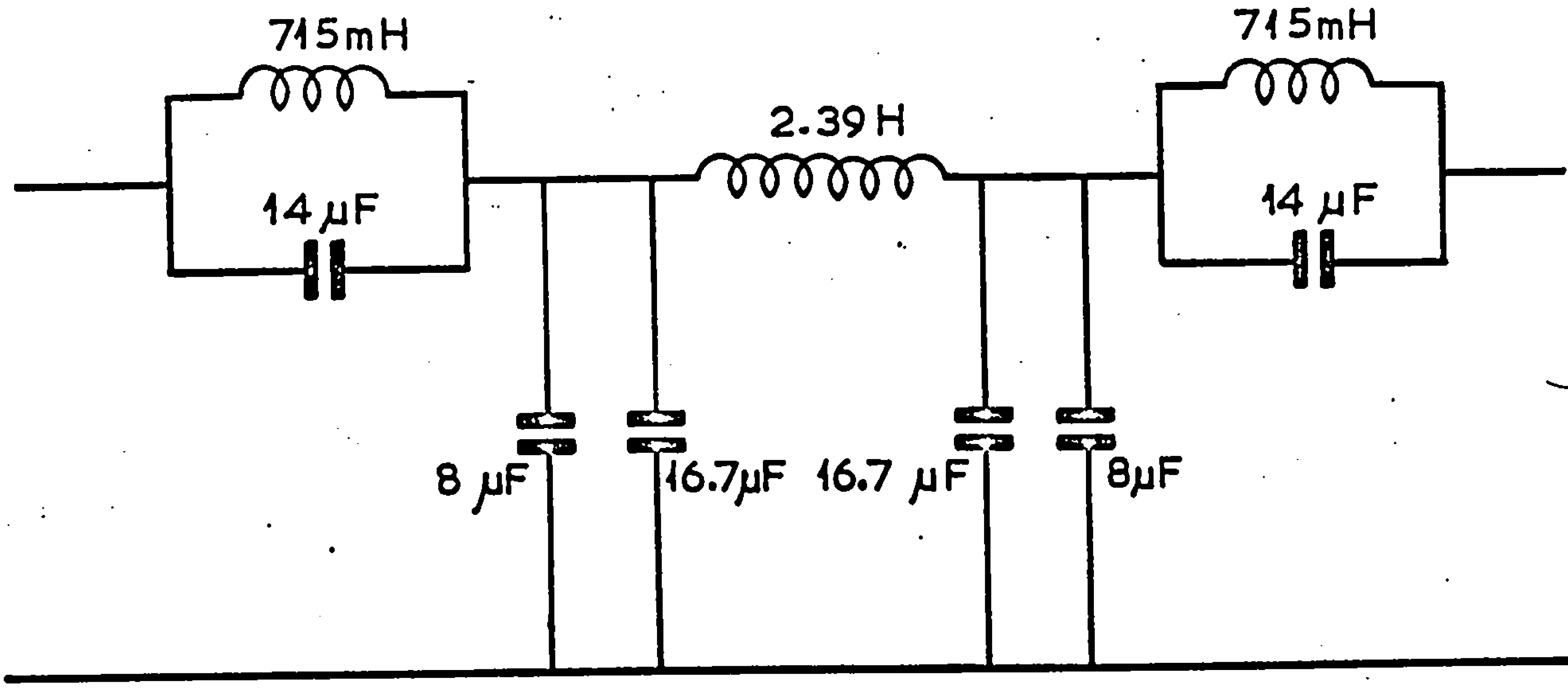


Fig. 4.4 Low pass filter.

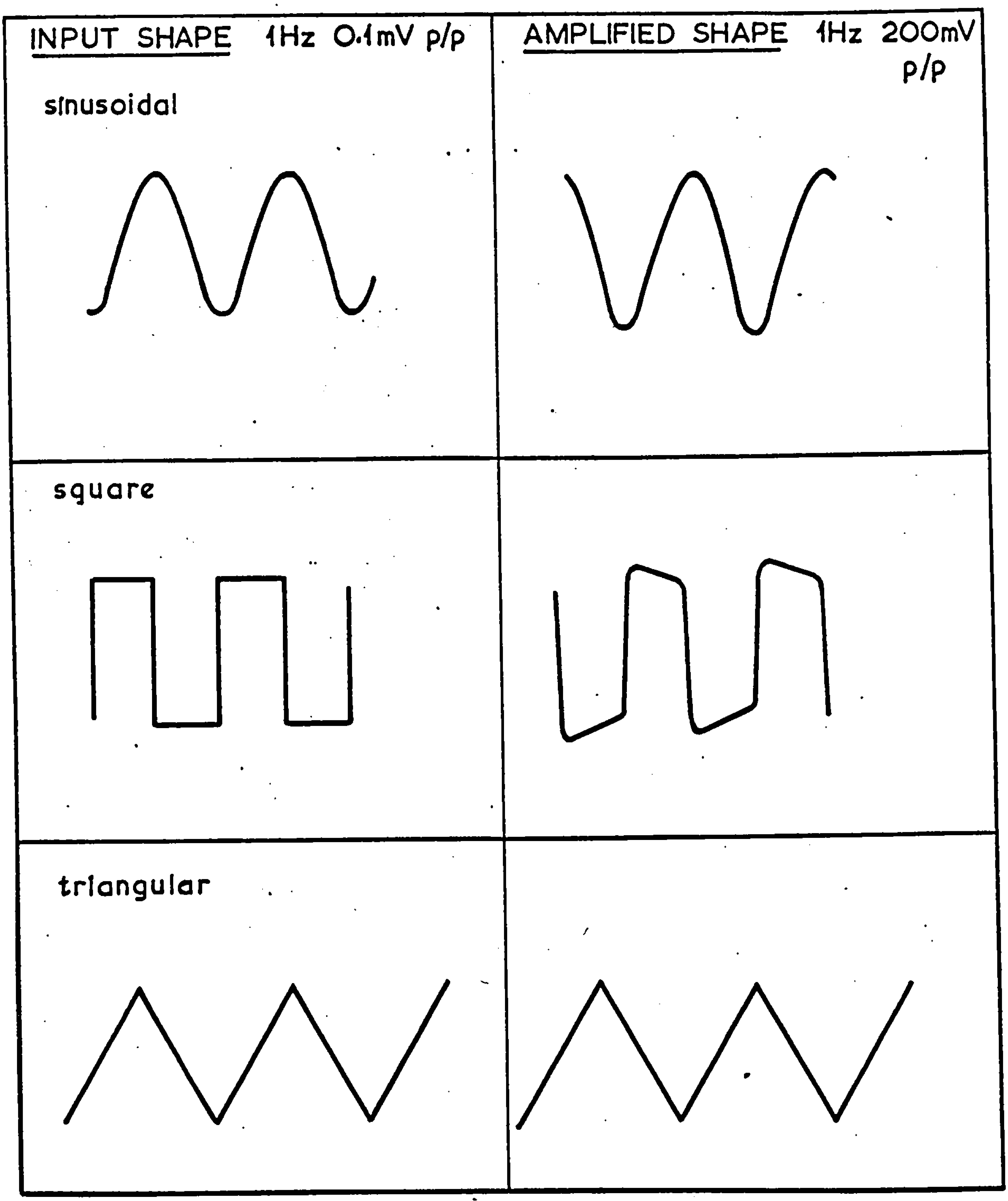


Fig. 4.5 Shape reproduction of the amplifier – filter system.

Fig. 4.6 Frequency response of differential amplifier and filter.

Both of these amplification techniques were used. The differential amplifier was found to be the most satisfactory from aspects of noise, amplification and shape reproduction, Fig.4.5.

4.2.3. Calibration

The differential amplifier and filter system were calibrated for each subject tested. The subject was seated at a fixed distance from a series of pairs of illuminated points. Moving the eyes from one point to the other for any pair gave an eye deviation of 5^{o} 10^{o} 15^{o} 25^{o} or 30^{o}. The amplitude of the resultant eye movement trace for each pair of points was recorded. Hence it was possible to assess the amplitude of any subsequent nystagmus.

4.3 Electrode Placement

Selective amplification of corneo-retinal potential changes, hence making electronystagmography more sensitive, is achieved by careful arrangement of the electrodes. The efficiency of any arrangement depends on three factors:

i. Firm electrode attachment:- An efficient electrode attachment requires firm and stable contact electrodes and skin. This was achieved by using dome shaped silver/silver chloride electrodes with screened leads attached to the skin by means of plastic adhesive tap, Fig.4.7. The skin-electrode gap was filled with a saline based electrode jelly to minimize the electrical resistance. The skin area was previously cleaned using surgical spirit.

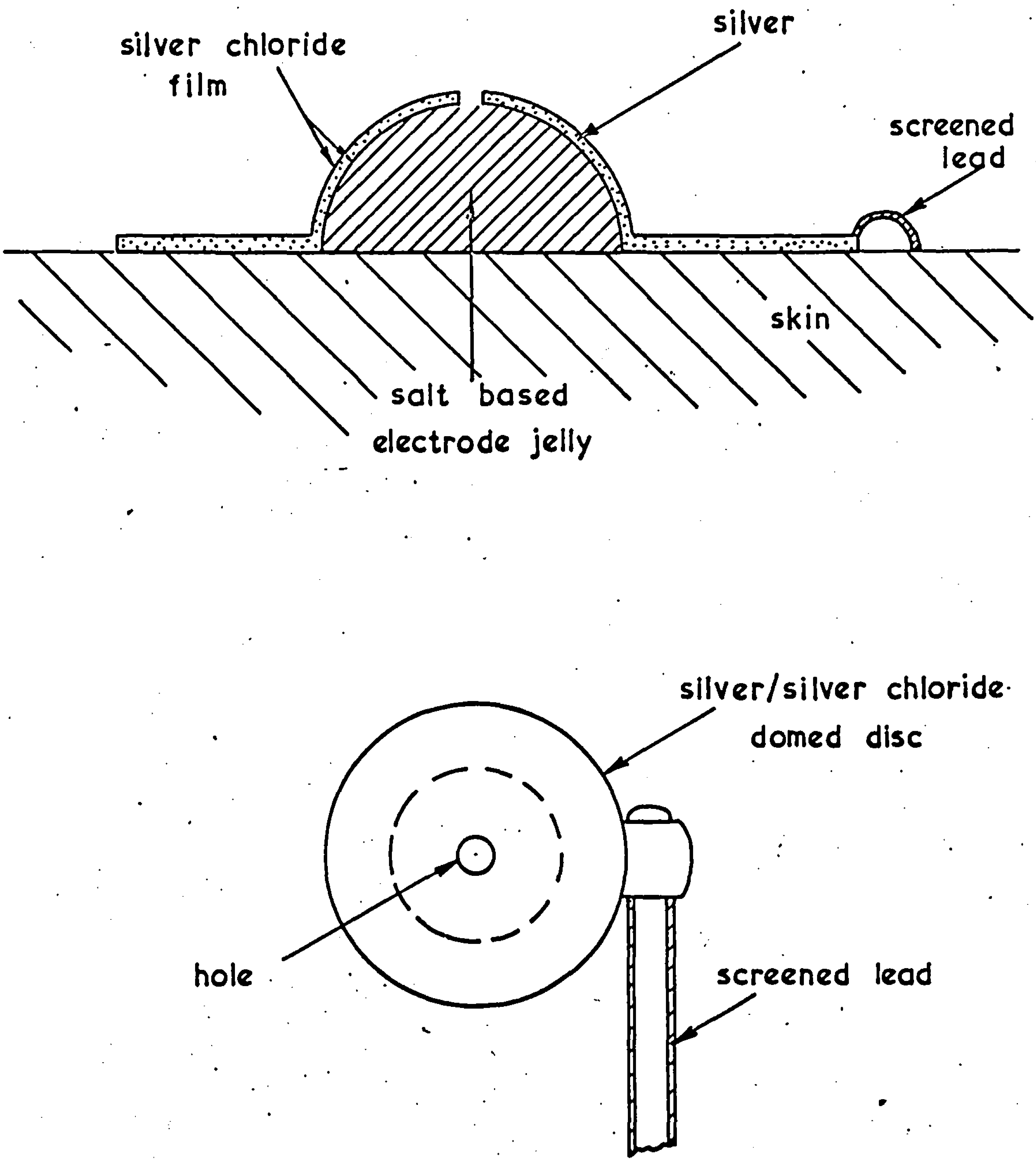


Fig. 4.7 E.N.G. electrode.

ii. Distance between the electrode and the eye:-
The nearer the electrode is placed to the source of the potential (corneal and retinal eye pole), the stronger is the recorded potential. An electrode attachment within the orbital margin, or by means of a contact eye-glass, seems to be more effective than attachment outside the orbital margin, where a bony layer increases the resistance between the electrodes and the electrical eye poles. The minimal possible distances for such an arrangement depend on the individual anatomical conditions: if the electrodes are attached too near to the eyelids they irritate the subject and stimulate undesirable blinking reflexes. Contact eye-glasses were not considered as it was thought that they may possibly alter the nystagmic movement.

iii. Optimal electrode position:- The basic working principle of E.N.G. is the amplification of the potential changes between two electrodes. In the course of eye-movements one electrode picks-up increasingly positive potentials, and the other increasingly negative potentials. The greater the difference between the recorded potentials the stronger is the response. Again, the potential difference depends on the placement of the electrodes. It follows that the best position is near the electrically neutral equatorial parts of the eye bulb (108).

4.3.1. Experiments with Electrode Arrangements

(a) Horizontal

Various types of electrode arrangement for the registration of horizontal eye movements were compared. Each comparison was made using the same degree of amplification and the same subject.

Arrangement 1 as shown in Fig.4.8 was used as the basis for these comparitive tests. This arrangement is suitable for the separate registration of the horizontal movement of each eye.

Arrangement 2 (109) as shown in Fig.4.9 produced spikes which were about 1.3 times smaller than those obtained from arrangement 1.

Similar findings were made with electrode arrangement 3 (110) as shown in Fig.4.10. It proved less effective than the reference arrangement by a ratio varying from 1.04 to 1.30.

Electrode arrangements 2 and 3 were also less satisfactory than arrangement 1 from the aspect of reproducibility. Table 4.1 shows the variation in spike size with each arrangement for a constant input signal.

For the registration of horizontal eye-movement electrode arrangement 1 produced the best response/artifact ratio and the best reproducibility. It is most appropriate when the response of each eye individually is required. However in some cases the efficiency of all three arrangements was not satisfactory, when the eye deviation was small, about 2.5°, the spikes were hardly distinguishable from the baseline oscillations.

As a rule both eyes perform associated movements during nystagmus, it is therefore sufficient to record the movement of

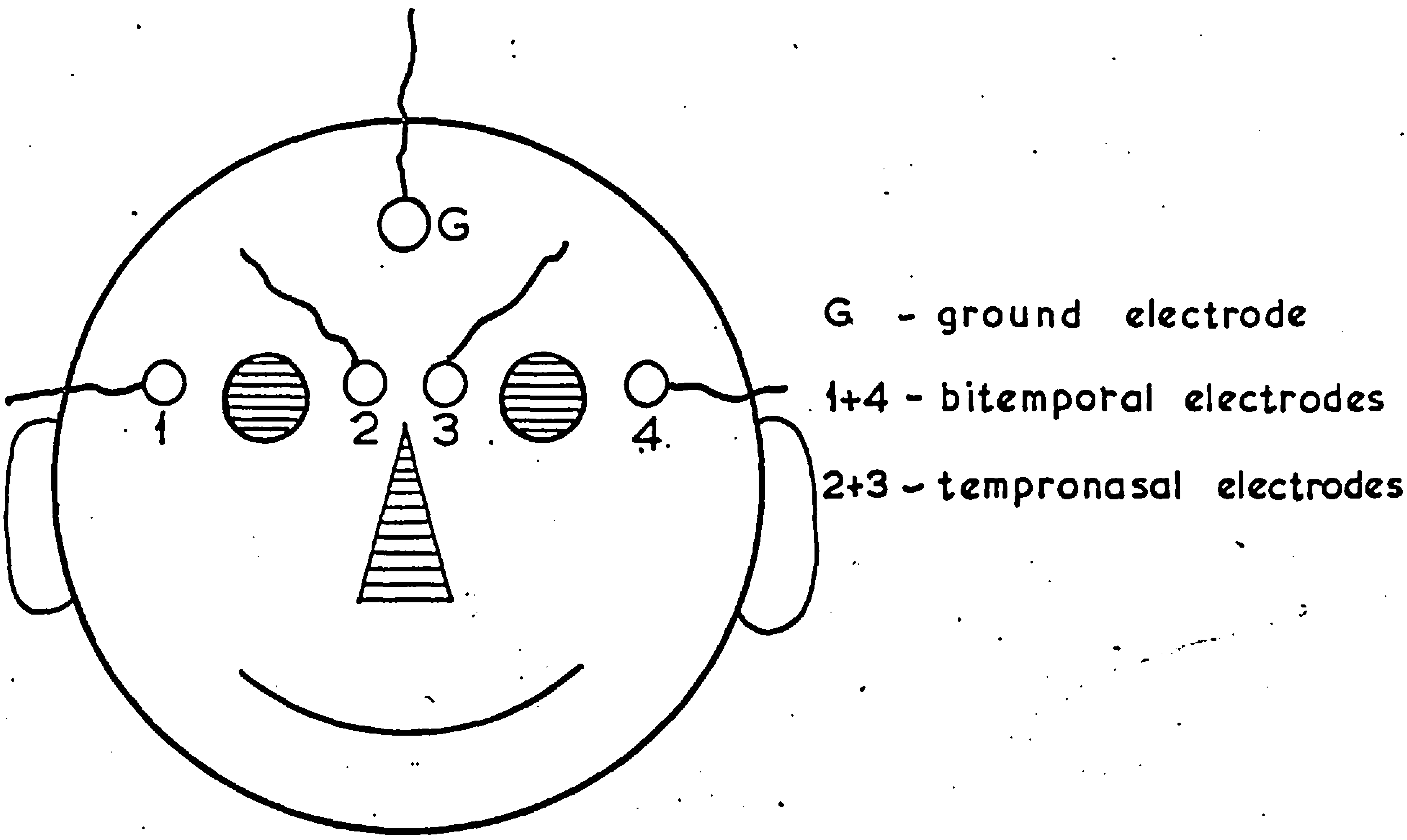


Fig. 4.8 Arrangement 1

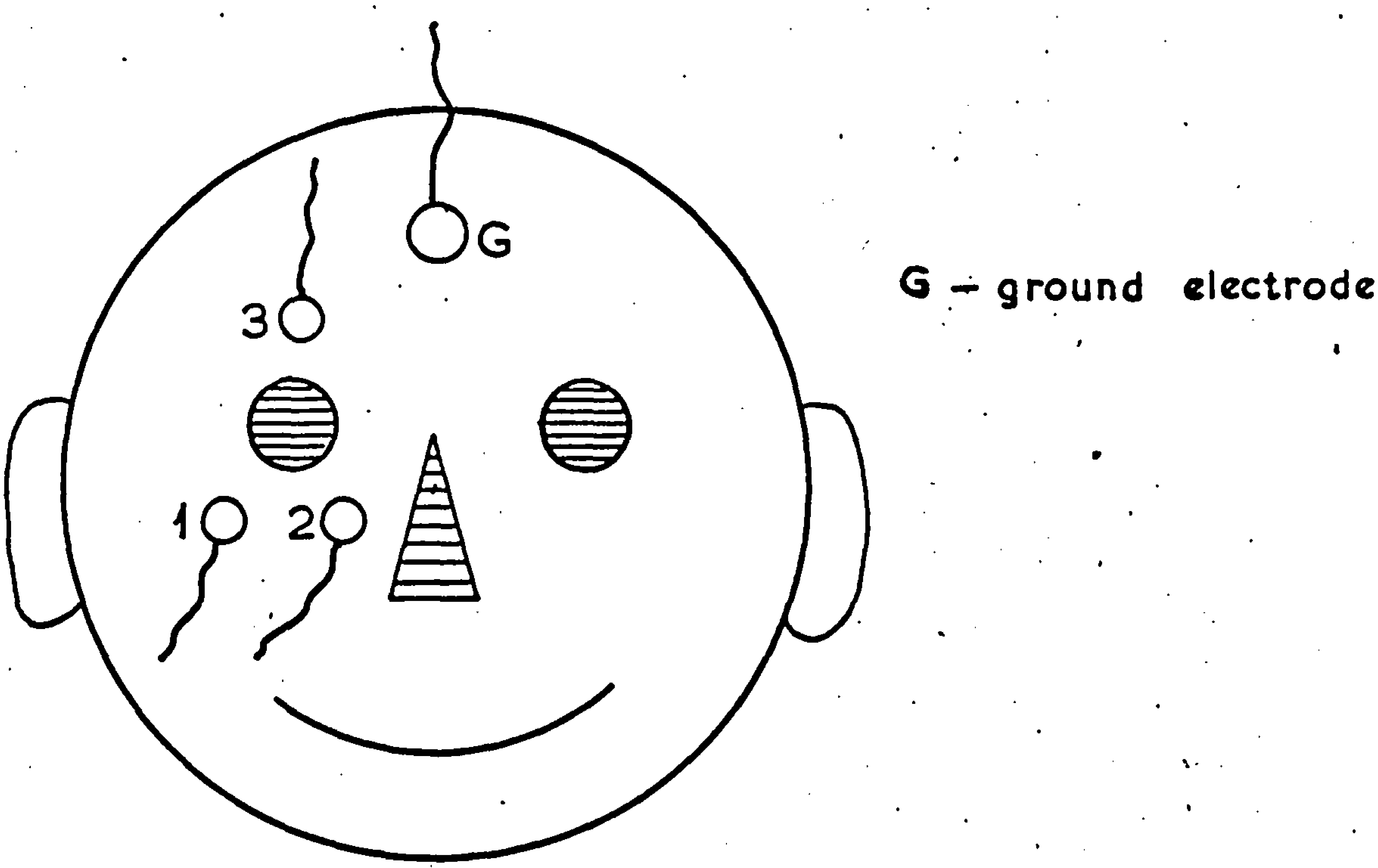


Fig. 4.9 Arrangement 2.

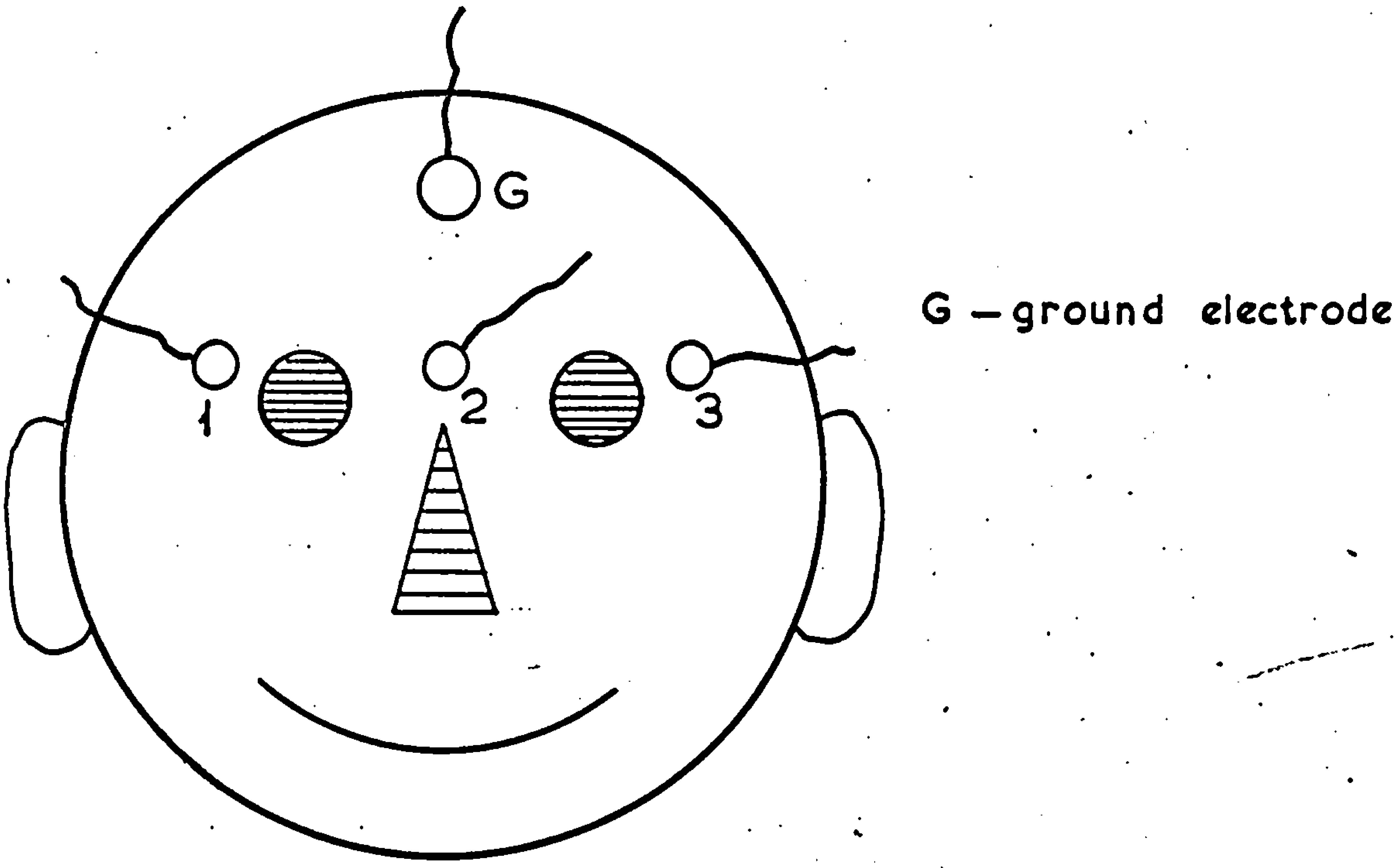


Fig. 4.10 Arrangement 3

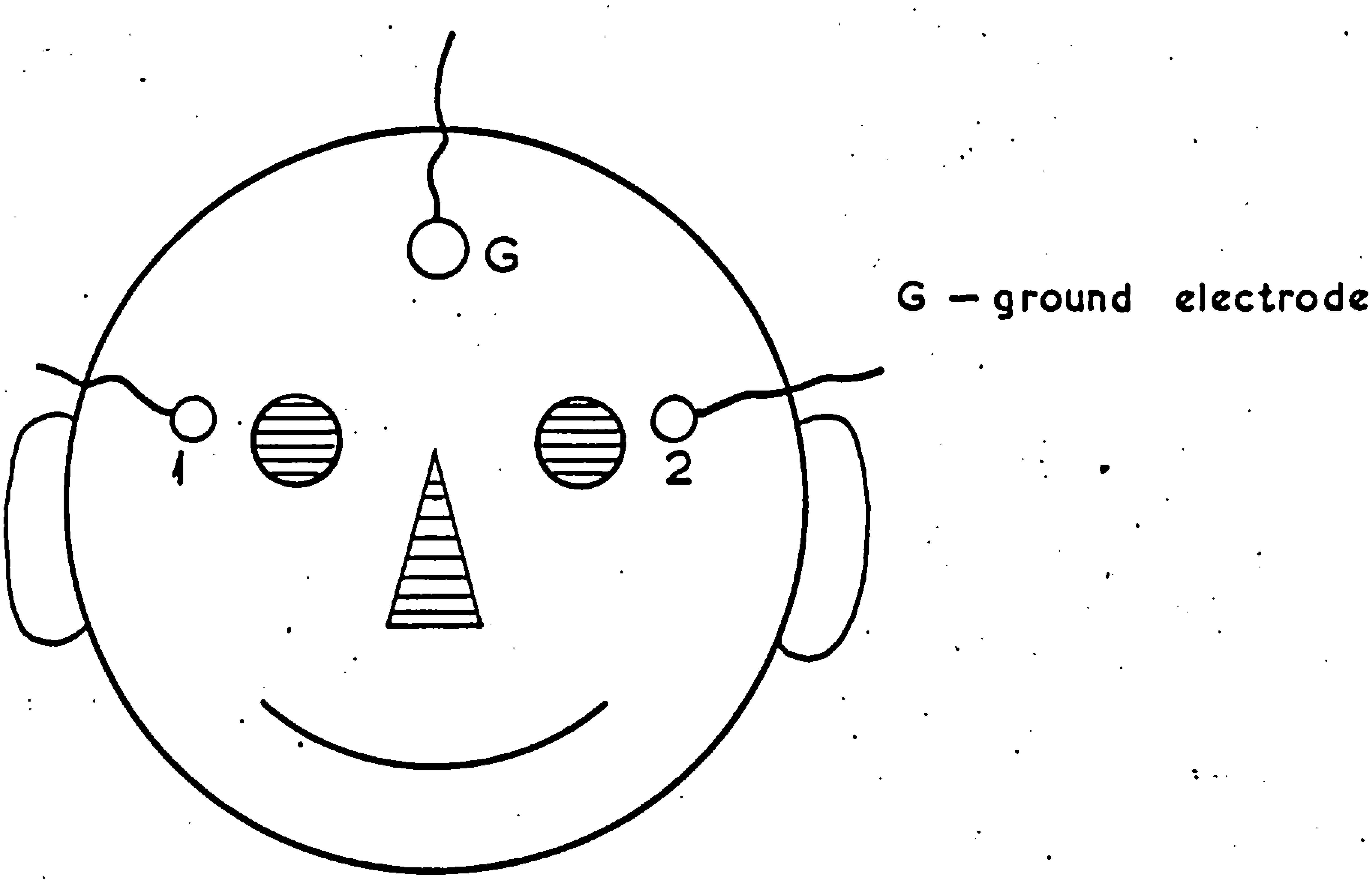


Fig. 4.11 Arrangement 4

TABLE 4.1

VARIABILITY OF SINGLE SPIKE AMPLITUDES IN ENG TRACINGS ACCORDING TO DIFFERENT VOLUNTARY EYE MOVEMENTS AND DIFFERENT ELECTRODE ARRANGEMENTS

Electrode Arrangement		AMPLITUDE VARIATION AT DIFFERENT DEGREES OF MOVEMENT					
		5°	7.5°	10°	15°	20°	32.5°
Bitemporal Leads	st.d. st.e.m.	0.32 0.06	0.63 0.14	0.58 0.12	0.65 0.15	0.61 0.14	0.97 0.22
Binocular Leads	st.d. st.e.m.	0.66 0.15	0.69 0.15	0.71 0.16	0.80 0.24	0.97 0.22	0.88 0.19
Arr. 3 Fig.4.5	st.d. st.e.m.	0.64 0.15	1.05 0.24	0.97 0.21	1.32 0.39	0.87 0.19	1.07 0.20
Arr. 2 Fig.4.4	st.d. st.e.m.	1.8 0.39		1.55 0.34			

st.d. = standard deviation

st.e.m. = standard error of the mean

The results represent ± values in degree of eye movement.

both eyes together using arrangement 4 as shown in fig.4.11. The signals from both eyes should appear summarized between the bitemporal electrodes (110, 111). This arrangement produced spikes which were 1.75 times higher than those recorded by arrangement 1 and 4 times higher than arrangement 2.

Using this electrode arrangement with bitemporal leads it was possible to record eye movements of less than 2.5^{o}. As a result of the increased response/artifact ratio the overall amplification could be reduced and consequently all artifacts were also reduced. The removal of the tempronasal electrodes decreased the possibility of blink reflex action (The placement of electrodes too near the inner canthus irritates the sensitive subject and increases the blink reflex).

Arrangement 4 was used throughout the later experiments.

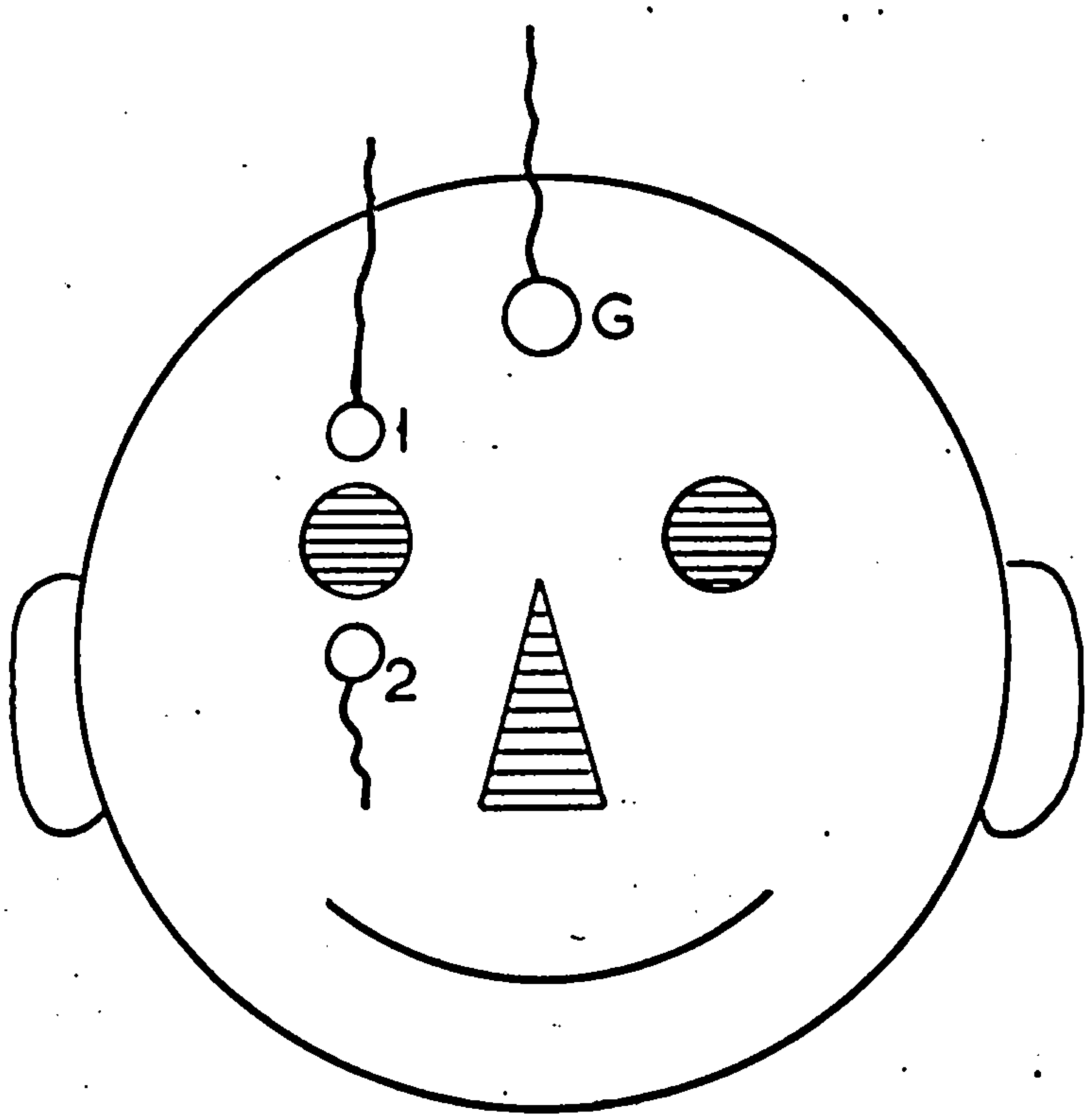
b. Vertical

The vertical placement of electrodes did not present as many problems or possibilities as horizontal placement.

Both arrangements as shown in fig.4.12 and 4.13 produced satisfactory response/artifact ratios. In both cases it was possible to record eye movements of less than 2.5^{o}. Arrangement 1 as shown in fig.4.7. produced the most easily reproducible spikes, and was used throughout the experiments.

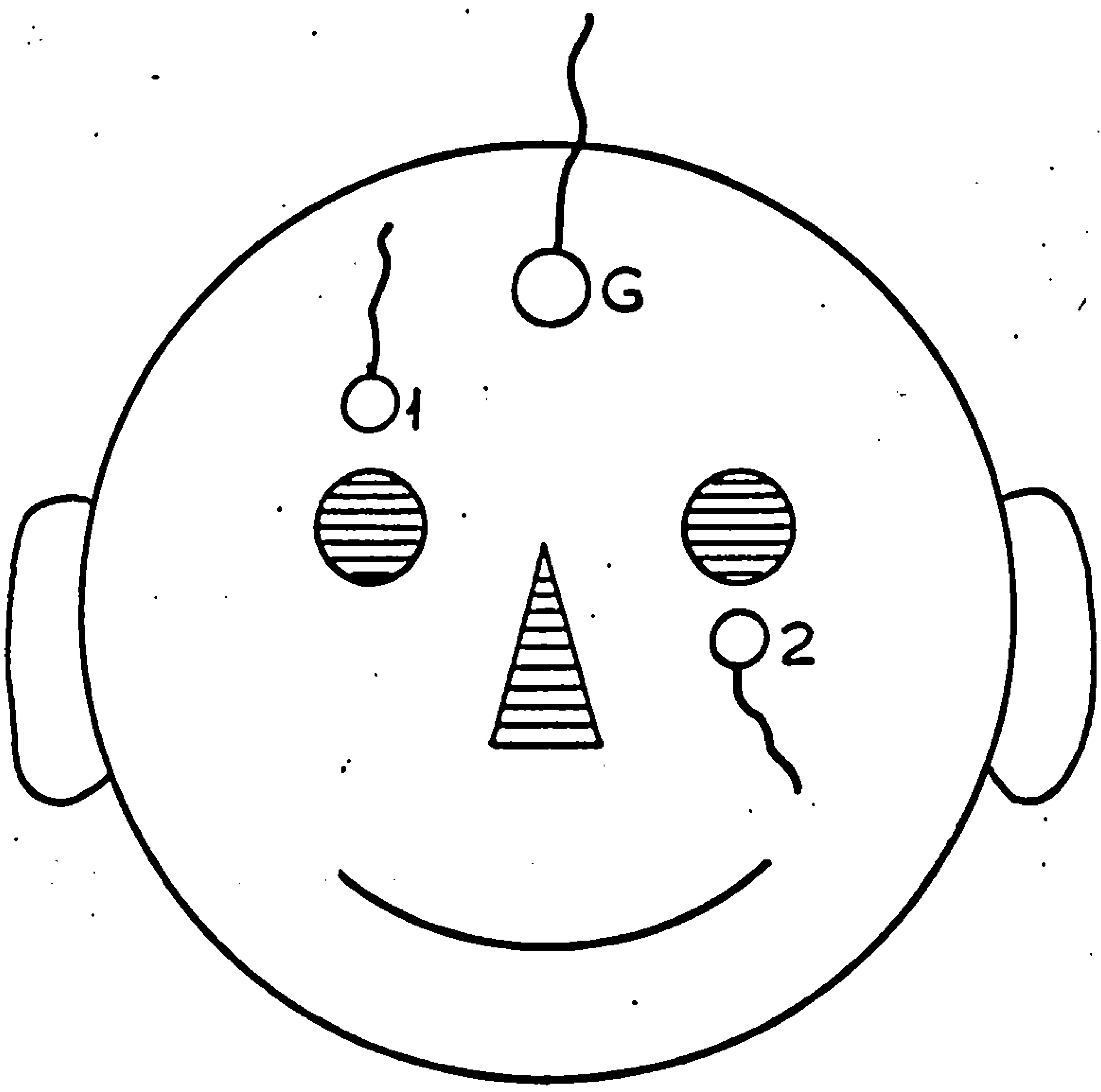
4.4. Effects of Eye Closure

It is the normal procedure when recording horizontal eye movements electronically for the subject's eyes to be closed. It is known that upon eye closure in darkness the eye ball rotates, usually upwards (112). During the course of this work vertical eye movement was to be monitored and so it was necessary to investigate the effects of eye closure on the



G - ground electrode

Fig. 4.12 Arrangement 1



G - ground electrode

Fig. 4.13 Arrangement 2.

vertical movement of the eyes.

25 subjects with normal eye movements and no history of vestibular disturbance were selected for the test. The vertical electrode arrangement 1 was used. The test subject was initially asked to look at a point marked on the wall whilst the position and movement of the eyes was recorded, the subject was requested to close the eyes after 30 seconds and to reopen them after a further 60 seconds. To ascertain whether any resulting eye movement might be due to a fortuitous position of the bulb above or below the horizontal plane, the subject was asked to elevate and depress the eyes behind closed lids for some seconds.

4.4.1. Results

When looking at the fixed point none of the test subjects exhibited any signs of spontaneous vertical nystagmus. After closure of the lids all initially showed an upward deviation of the eyes. After about 5 seconds the eyes were depressed below the zero line. Simultaneously or shortly after ocular reflex activity, of varying appearance commenced. In 20 cases there was a distinct vertical nystagmus upwards of varying amplitude and frequency. Vertical nystagmus downwards was obtained in one case only. In the other four cases, rather than nystagmoid eye movements, large amplitude undulations were observed. Figs. 4.14 and 4.15.

The nystagmic activity commenced after eye closure and

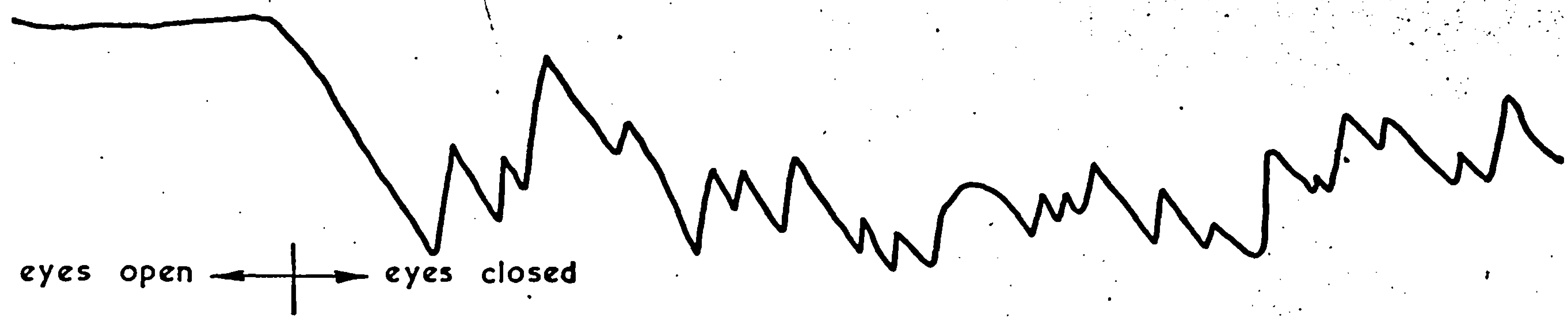


Fig. 4.14 Spontaneous upwards vertical nystagmus behind closed eye-lids

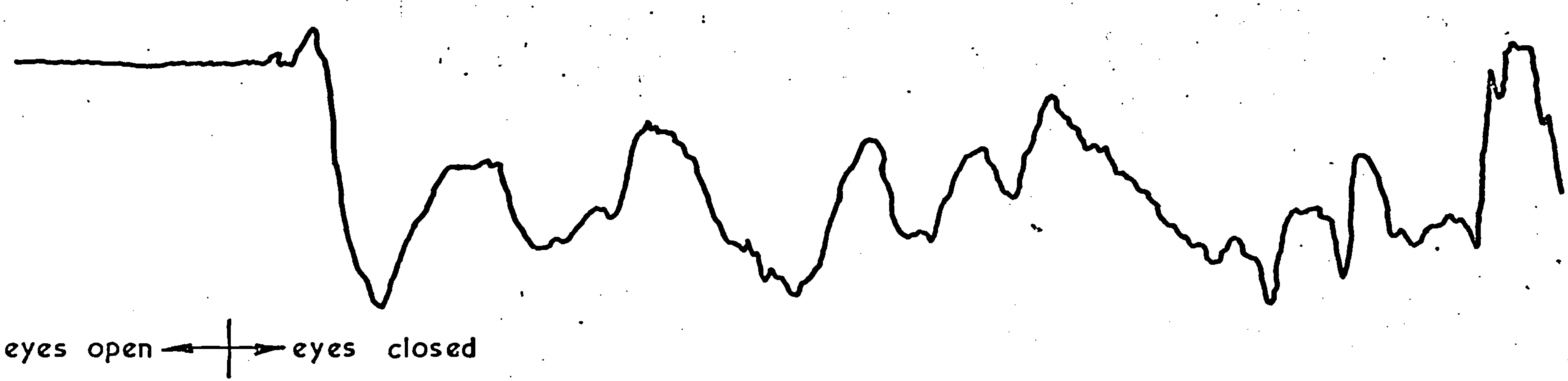


Fig. 4.15 Undulating eye movements behind closed eye-lids.

continued for the 60 seconds that the eyes remained closed in all but 2 cases where the nystagmus gradually diminished and was replaced by undulating motion.

When the subjects were asked to elevate and depress the eyes behind closed lids no qualitative effect on the nystagmus was noted but occasional quantitative changes in the form of reduced amplitude and/or frequency variation.

4.4.2. Conclusions

This examination revealed that the eyes were elevated after closure in all the test subjects, but contrary to the results reported in earlier investigations (112) the eyes did not remain stationary in this position but after a few seconds descended below the medium and produced vertical nystagmus, a result supported by the work of Fluur and Eriksson (113).

This phenomena did not depend on voluntary activation or inhibition as elevation and depression of the eyes did not appreciably affect the appearance of the nystagmus. Since 84% of the subjects examined exhibited some kind of vertical nystagmus electronystagmographic recording behind closed lids must be deemed unsuitable for studying vestibularly induced vertical nystagmus and all subsequent experiments must be performed with the subject's eyes open.

CHAPTER 5

PRELIMINARY EXPERIMENTS

PART A - LOW FREQUENCY AUDITORY THRESHOLDS

5.1. Subjects

All the subjects employed were drawn from the University population. All were in the 18-45 years age group, of both sexes, and each had an audiogram within 10dB of the British Standard for earphone listening.

5.2. Binaural Pure Tone Thresholds

5.2.1. Procedure and Monitoring

The experimental configuration is shown in Fig.5.1, this is essentially a dual channel configuration driven by a common oscillator. Identical sound pressure levels could be set up in the two headphones at all frequencies. The headset was mounted onto a chair with provision for height adjustment, the whole apparatus was located in a quiet room.

A light signalling system was set up such that a green light showed to both the operator and the subject when the test was in progress, and a red light was controlled by the subject with a hand operated switch. This was seen only by the operator outside the room.

The subject sat in the chair in a comfortable position and the headset was adjusted to the correct height. This ensured

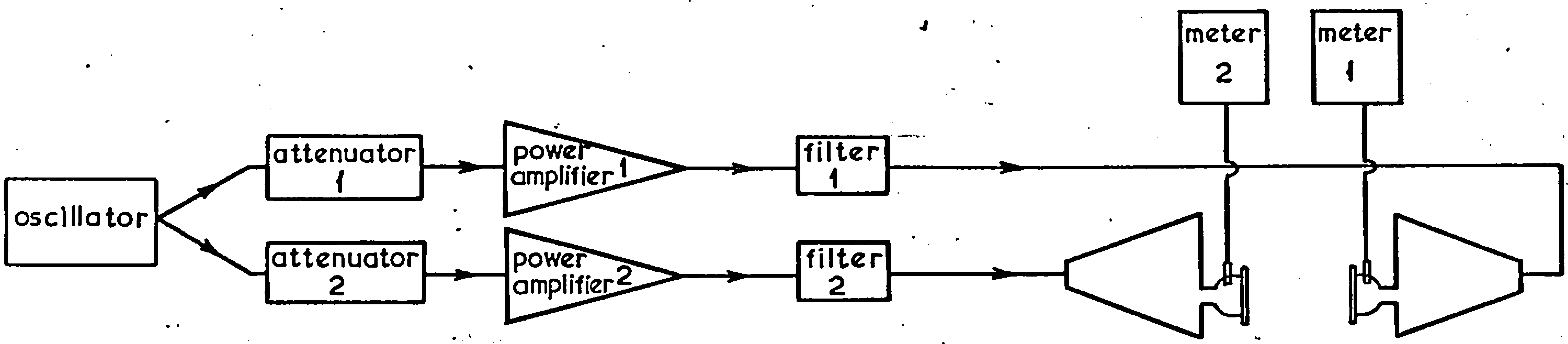


Fig. 5.1 Schematic diagram of binaural pure tone threshold apparatus.

that the whole of the subject's pinna entered the cavity and was not crushed by the sealing cushions. The headset was tightened onto the subject's head until a good seal was achieved.

The subject was instructed to depress the hand switch (controlling the external red light) when the signal became audible and to release the switch when the signal became inaudible. This informed the operator of the subject's upper and lower decision levels.

The sound pressure levels required to reach the threshold region for the frequency range considered, 0-20Hz, are high enough to allow the sound pressure level to be measured directly. The output from the condenser microphone could be read directly without interference from external noise or subject movement.

Once the threshold region was established the level was slowly raised and lowered manually by the output potentiometer of the oscillator. It was necessary to use this method of continuously varying the level as the clicks made by a step attenuator were clearly audible to the subject. After several excursions 6 upper and lower threshold limits were noted.

It was found that in this region the threshold was very sharp, in many cases the difference between the signal being audible and inaudible was only 1dB. Therefore it was necessary to vary the sound pressure level very slowly.

The low frequency hearing thresholds of 25 subjects were examined at frequencies of 2Hz, 4Hz, 5Hz, 8Hz, 10Hz, 12Hz, 15Hz and 20Hz. Finally the sensitivity of the microphone was checked using a pistonphone.

5.2.2. Results

The resulting mean threshold data of the 25 subjects, with standard deviations, is given in table 5.1 and graphically in Fig.5.2.

TABLE 5.1

FREQUENCY Hz	THRESHOLD dB SPL	STANDARD DEVIATION
2	122.45	1.95
4	112.41	2.10
5	111.25	1.69
8	103.00	2.01
10	100.05	1.89
12	97.70	1.71
15	92.15	1.45
20	85.50	1.75

The subjects reported a decrease in tonality with decreasing frequency. It was also reported that in the lower frequency region, below about 10Hz, the stimulus gave a tactile sensation as well as an auditory sensation.

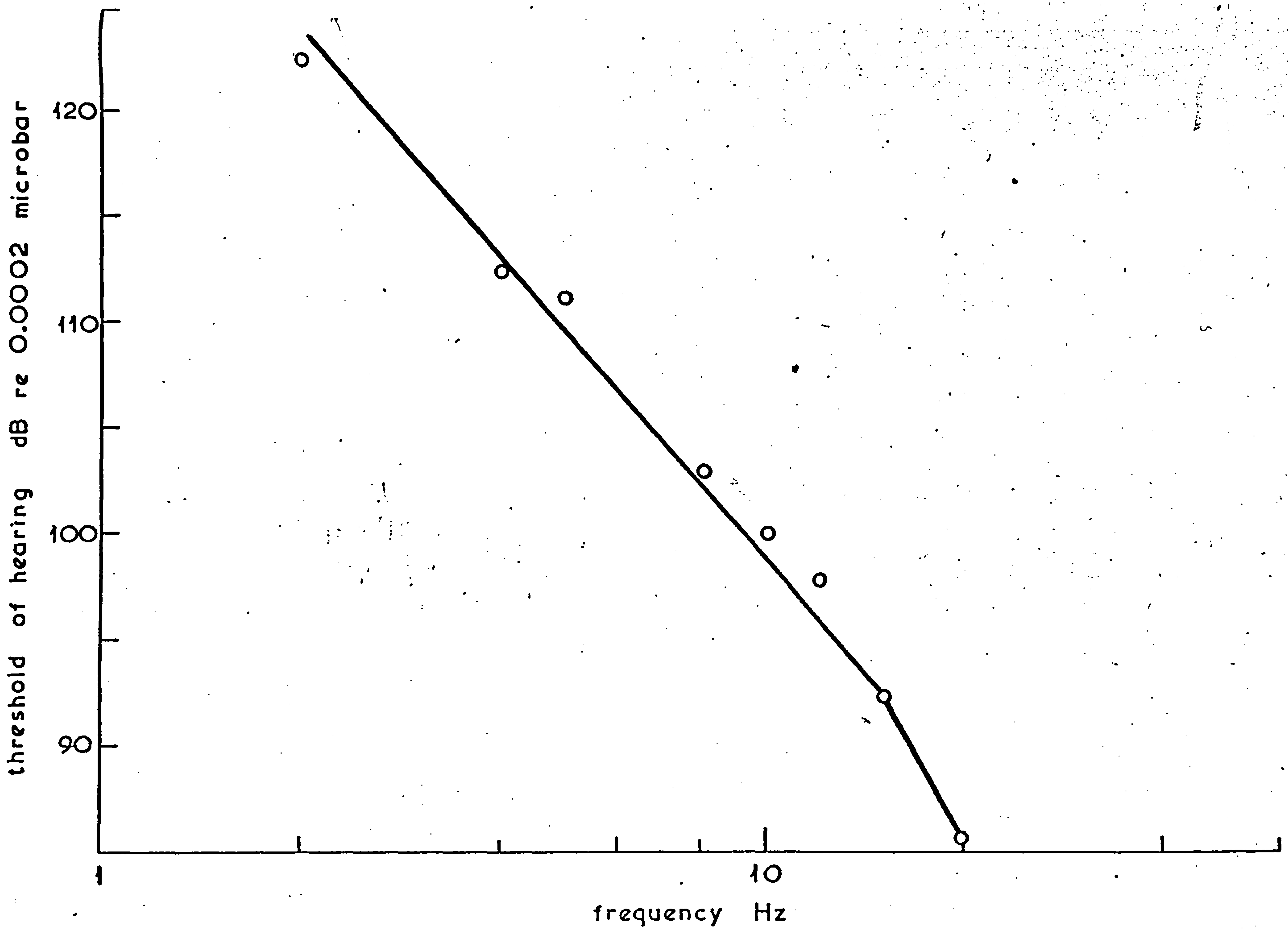


Fig. 5.2 Binaural low frequency hearing threshold — headset.

5.3. Pure Tone Chamber Thresholds

5.3.1. Procedure and Monitoring

The experimental configuration is shown in Fig.5.3. The chamber was located in a free-field listening room which has been described elsewhere (Marsh, Bryan and Tempest 1967) (58). The same light signalling system was used as for the binaural thresholds. The subject was seated on a chair at the centre of the chamber. The same experimental technique was used to determine the thresholds for 12 subjects at frequencies of 2Hz, 4Hz, 5Hz, 8Hz, 10Hz, 12Hz, 15Hz and 20Hz. Finally the sensitivity of the microphone was checked using a pistonphone.

5.3.2. Results

The resulting mean threshold data of the 12 subjects with standard deviations is given in Table 5.2 and graphically in Fig.5.4.

TABLE 5.2

FREQUENCY Hz	THRESHOLD dB SPL	STANDARD DEVIATION
20	85.20	2.13
15	92.06	1.29
12	97.00	2.06
10	99.50	1.95
8	102.40	2.39
5	111.05	2.10
4	112.39	2.51
2	121.40	1.67

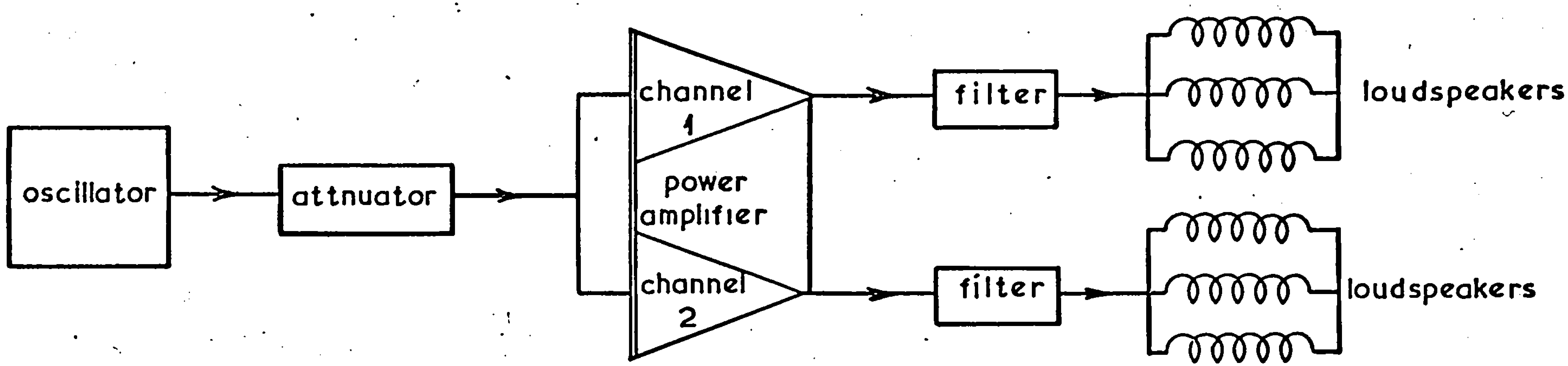


Fig. 5.3 Schematic diagram of pure tone chamber threshold apparatus.

Fig. 5·4 Pure Tone Chamber Threshold.

The subjects again reported a decrease in tonality with decreasing frequency and stronger tactile sensations.

5.4. Comparison of Headset and Chamber Thresholds

The binaural earphone data can be compared directly with the chamber data in the frequency range below 20Hz. With normal headphones at higher frequencies there is a 6dB or more difference between field and pressure thresholds. This difference can be explained as due to masking of the earphone threshold by physiological noise in the enclosed volume around the ear (Anderson and Whittle 1971 (59)). The low frequency headphone had a volume of about 1 litre and so was large enough to avoid noise from vascular origins. Broadband noise in the headphone was less than 30dB SPL and was therefore unlikely to mask a tone threshold some 60dB higher in level. Fig.5.5. shows the combined threshold data from the two sets of experiments.

Visual inspection of the data suggests that there are two distinct frequency regions on each side of 15Hz. The least square regression lines of this data has slopes of:-

22.2 ± 3.5 dB/octave above 15Hz

12.3 ± 0.9 dB/octave below 15Hz

The cross over point between the two regions is 92dB SPL at 15.5Hz.

This discontinuity in the threshold curve suggests some change in the mechanism of the detection process.

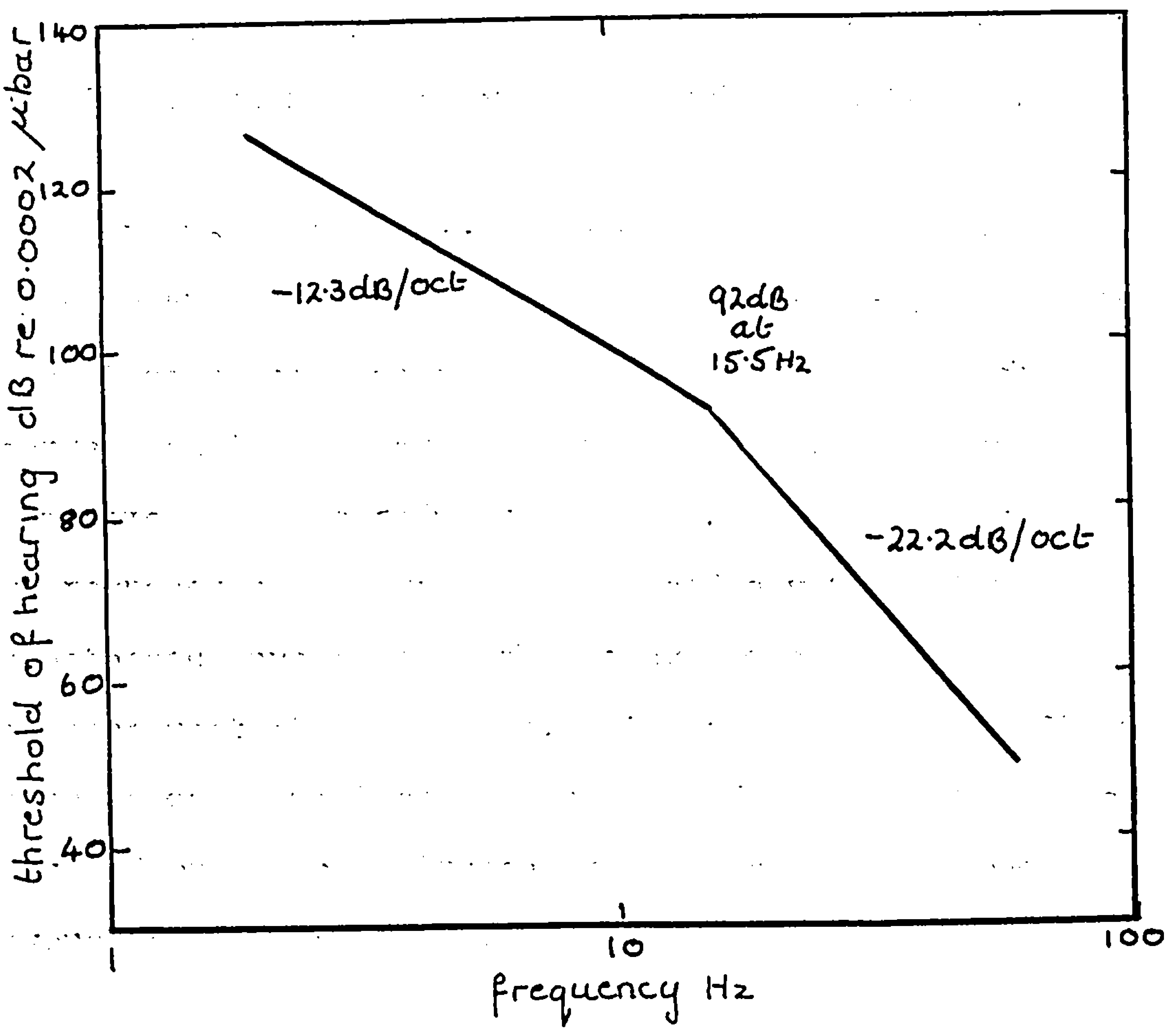


Fig. 5·5 Combined Chamber and Binaural Headphone Threshold Data.

PART B: BALANCE DISTURBANCE

5.5 Subjects

The group of 25 subjects whose binaural auditory thresholds had been accurately assessed were used for the preliminary experiments on balance disturbance. All were in the 18-45 years age group of both sexes and their audiograms were within 10dB of the British Standard for earphone listening.

All the preliminary experiments were performed in the headset with the subject in a sitting position. The first stage of each test was a five minute period in which the observer sat in the darkened test room while the pattern of eye movements was carefully examined. During this stage no low frequency signal was applied, and any subject who exhibited a spontaneous nystagmus with the eyes open was asked to terminate the experiment at this point. It was necessary to discontinue the tests on a small proportion of individuals who seemed disturbed by the experimental conditions, or who became nervous or claustrophobic.

5.6. Monaural Infrasonic Stimulation

5.6.1. Procedure

When the initial five minute period had been completed a series of infrasonic tones was applied monaurally (to the subject's left ear) and the effects on eye movement were recorded. The tests included a range stimulus frequencies and intensities, all the stimuli had a duration of 60 seconds. Separate experiments were performed to measure both horizontal and vertical eye movement using the electrode positions described in Chapter 4. The horizontal measurements were made with the subject's eyes both open and closed, the vertical measurements with the eyes open.

5.6.2. Results

(a) Horizontal eye movement

The test variables were as follows:-

Sound Pressure Level	100-146dB
Frequencies	2,6,7,10 and 15Hz
Duration	60 seconds.

The subjects were not given any form of mental task during the test but were advised to relax.

This series of experiments did not reveal any well defined pattern of nystagmic response to the infrasonic stimuli although random eye movements became stronger during the stimulus periods.

At the highest levels attainable, 140-146dB, all the subjects reported feelings of unease.

(b) Vertical eye movement

Approximately equal numbers of tests were performed using left and right eyes for monitoring. The test variables were as follows:-

Sound Pressure Level	130-146dB
Frequencies	2,5,7,10 and 15Hz
Duration	60 seconds
Subject's attention	relaxed or performing simple arithmetical tasks.

In this series of tests a number of nystagmic effects were recorded. For some subjects these effects were enhanced by mental activity, but in the majority of cases this was counterproductive as it also led to an increase in the random eye movements which formed a 'noise' background.

The overall pattern of response from the 25 subjects can be summarized as follows:-

No response	1
Spontaneous nystagmus	2
Excessive blinking	5
Indistinct nystagmic response	10
Clear nystagmic response	7

Fig.5.6 shows a typical nystagmic response to monaural infrasonic stimulation. It takes the form of two periods of nystagmus with a few seconds interval between them. Nystagmic responses were only obtained at stimulus levels above 140dB.

During this series of tests considerable difficulty was experienced due to the occurence of excessive blinking and

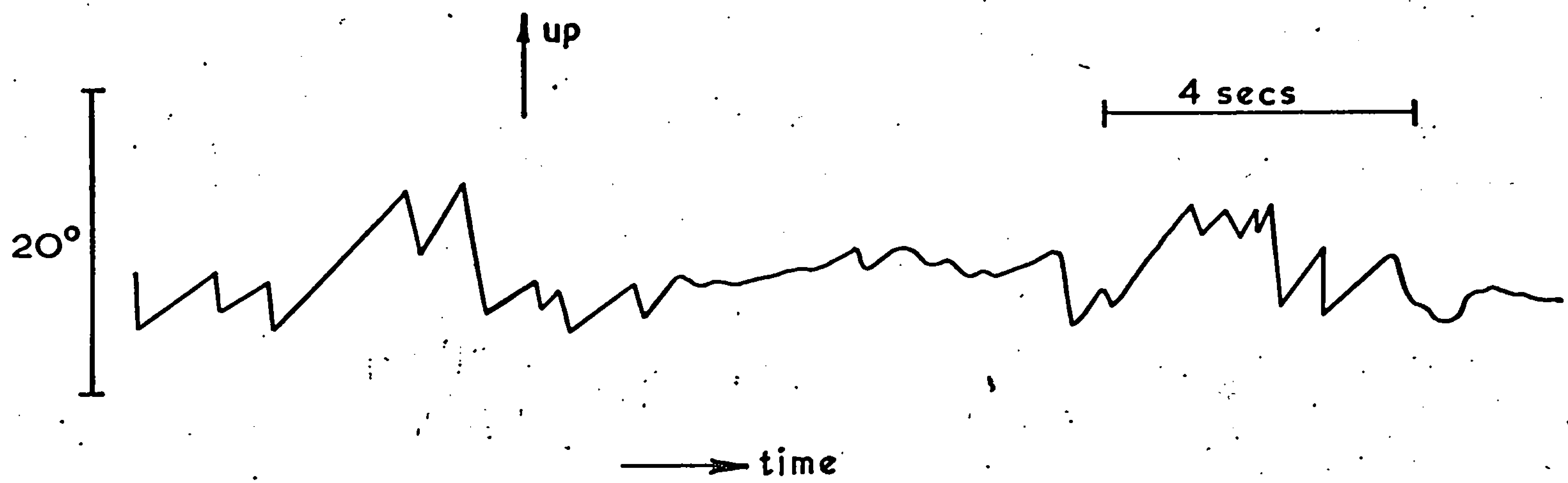


Fig. 5.6 Nystagmic response to monaural infrasonic stimulation.

large random eye movements in many of the subjects.

5.7. Binaural 'In Phase' Stimulation

5.7.1. Procedure

The same procedure was followed as for monaural stimulation. The subject was advised to relax and after the initial conditioning period a series of infrasonic tones was applied binaurally to the subject. The apparatus was designed so that the same SPL was presented in phase to both ears.

Both horizontal and vertical eye movements were recorded with the subject's eyes open in all cases.

5.7.2. Results

(a) Horizontal eye movement

The test variables were as follows:-

Sound Pressure Level	130-146dB
Frequencies	2,5,7,10 and 15Hz
Duration	60 seconds
Subject attention	Relaxed

No clear pattern of horizontal eye movement was established although one subject repeatedly produced a slow undulating eye movement with a period of about 2 seconds, Fig.5.7.

(b) Vertical eye movement

The recording of vertical eye movement under binaural stimulation was far more productive.

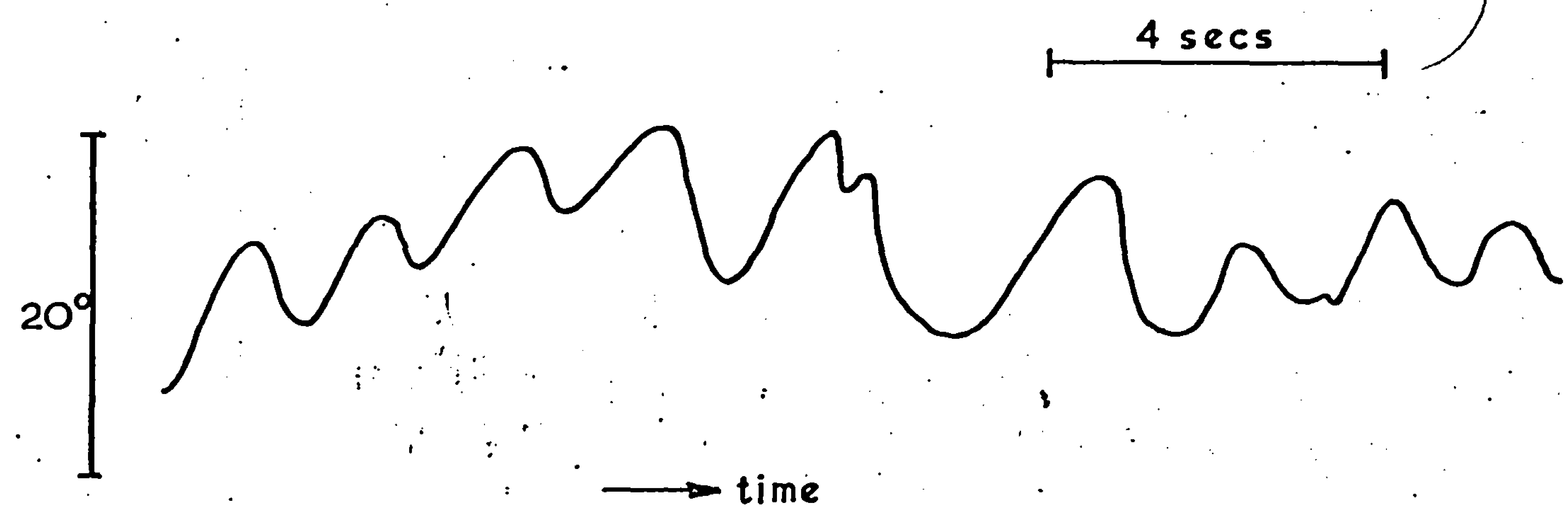


Fig. 5.7 Undulating horizontal eye movements in response to binaural stimulation.

The test variables were as follows:-

Sound Pressure Level	130-146dB
Frequencies	2,5,7 and 10Hz
Duration	60 secs.
Subject attention	Relaxed.

Again excessive blinking and random eye movements created considerable difficulties during the interpretation of the eye movement traces but the responses can be summarized as follows:-

No response	1	
Spontaneous nystagmus	2	
Indistinct nystagmic response	8	SPL $\gg$ 137.5dB
Clear nystagmic response	10	
Excessive blinking	4	

Fig.5.8 shows a typical nystagmic response to binaural infrasonic stimulation and fig.5.9 shows how excessive blinking masks any other vertical eye movement induced by the stimulus.

5.8. Binaural Antiphase Stimulation

5.8.1. Procedure

In this case the headphone loudspeakers were arranged to deliver identical sound pressure levels to both ears but in antiphase. This antiphasic binaural signal was applied to the relaxed subject after the initial conditioning period of 5 minutes. Both horizontal and vertical eye movements were

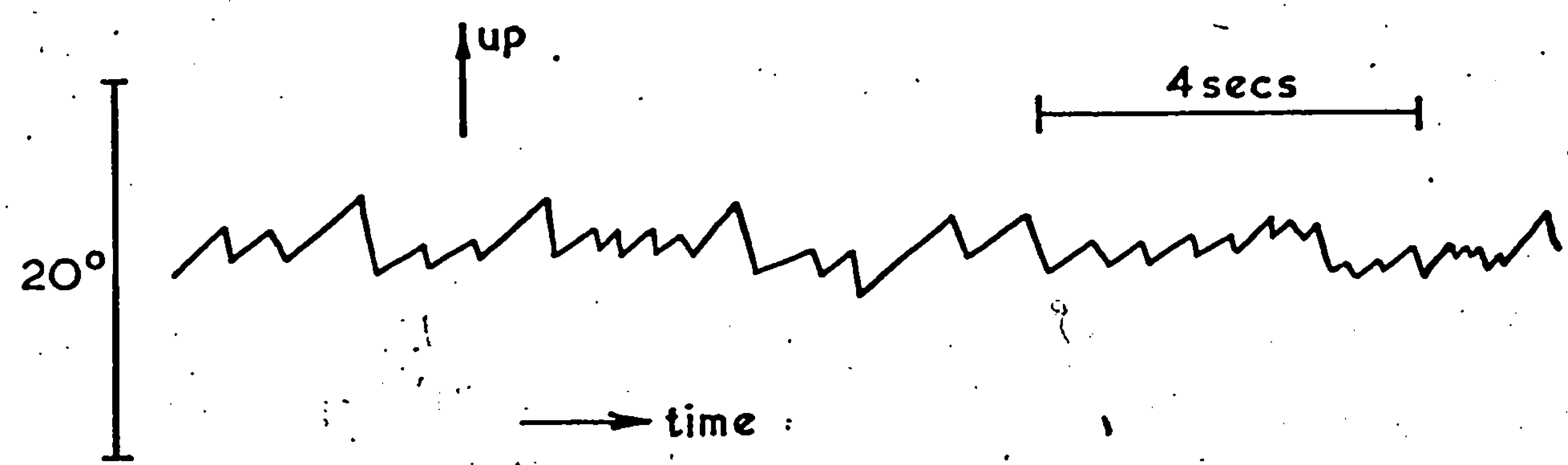


Fig. 5.8 Typical vertical nystagmic response to binaural inphase infrasonic stimulation.

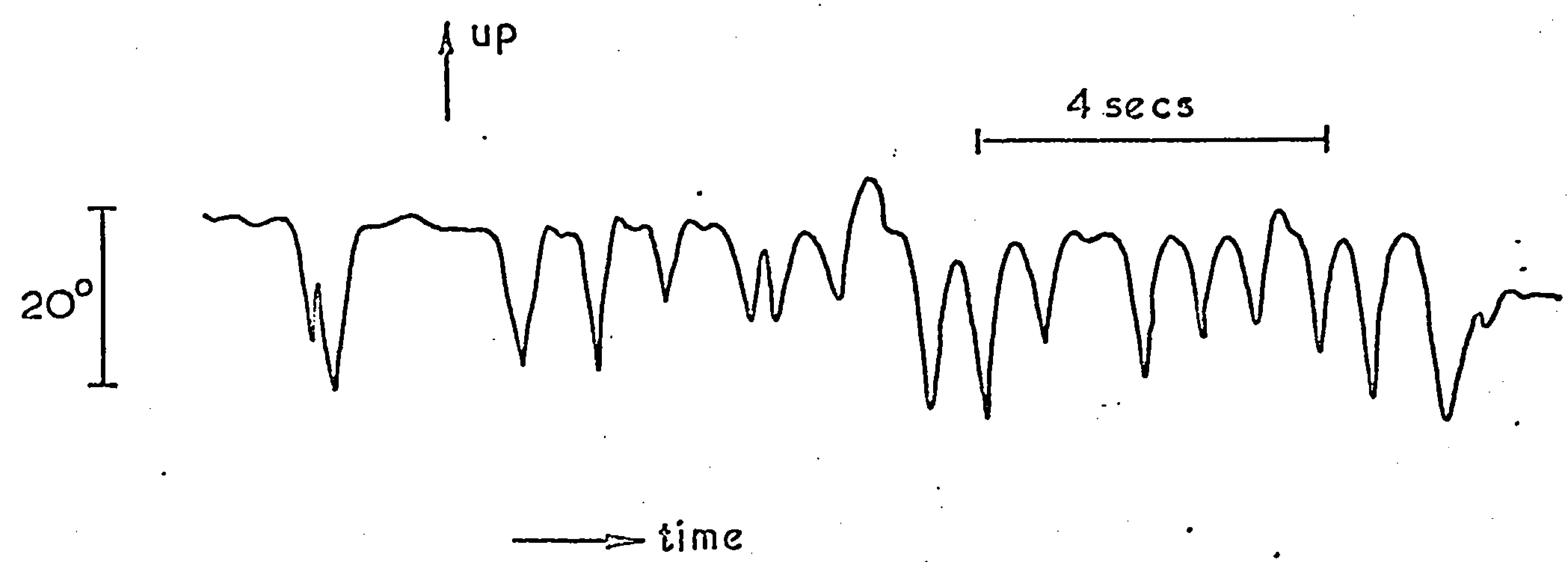


Fig. 5.9 Excessive blinking.

recorded with the subject's eyes open in all cases.

5.8.2. Results

(a) Horizontal eye movement

The test variables were as follows:-

Sound Pressure Level	130-146dB
Frequency	2,5,7 and 10Hz
Duration	60 secs.
Subject attention	relaxed.

No horizontal nystagmus was induced in any of the 25 subjects but 7 subjects (28%) showed a clear pattern of eye movement in the form of slow undulations. The periodicity of these undulations varied from subject to subject but was relatively stable for each subject. Fig.5.10 shows a typical horizontal eye movement pattern.

(b) Vertical eye movement

The test variables were as follows:-

Sound Pressure Level	130-146dB
Frequency	2,5,7 and 10Hz
Duration	60 seconds
Subject attention	Relaxed.

88% of the subject sample showed a clear vertical nystagmus under antiphasic binaural stimulation at sound pressure levels above 135dB. Fig.5.11 shows a typical vertical nystagmus trace recorded under these conditions.

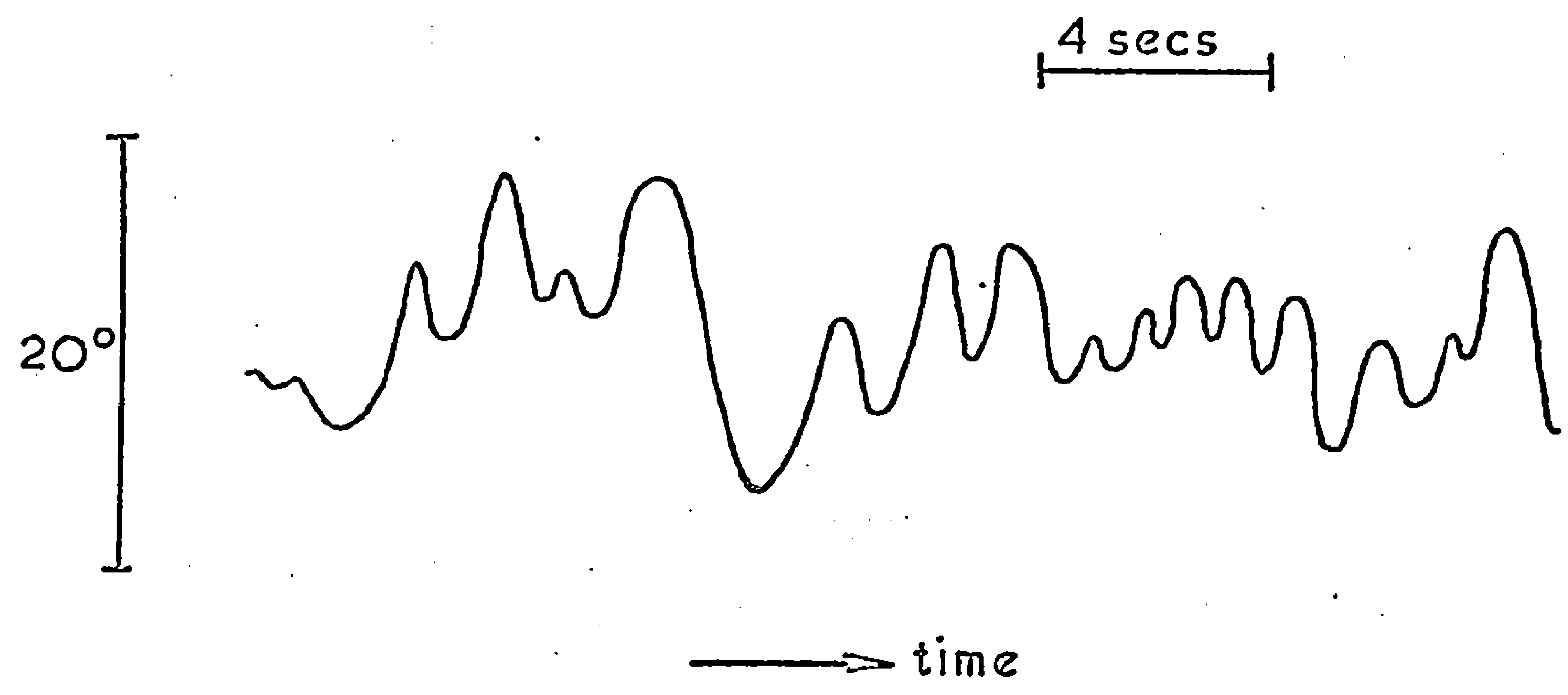


Fig. 5.10 Horizontal eye movement pattern.

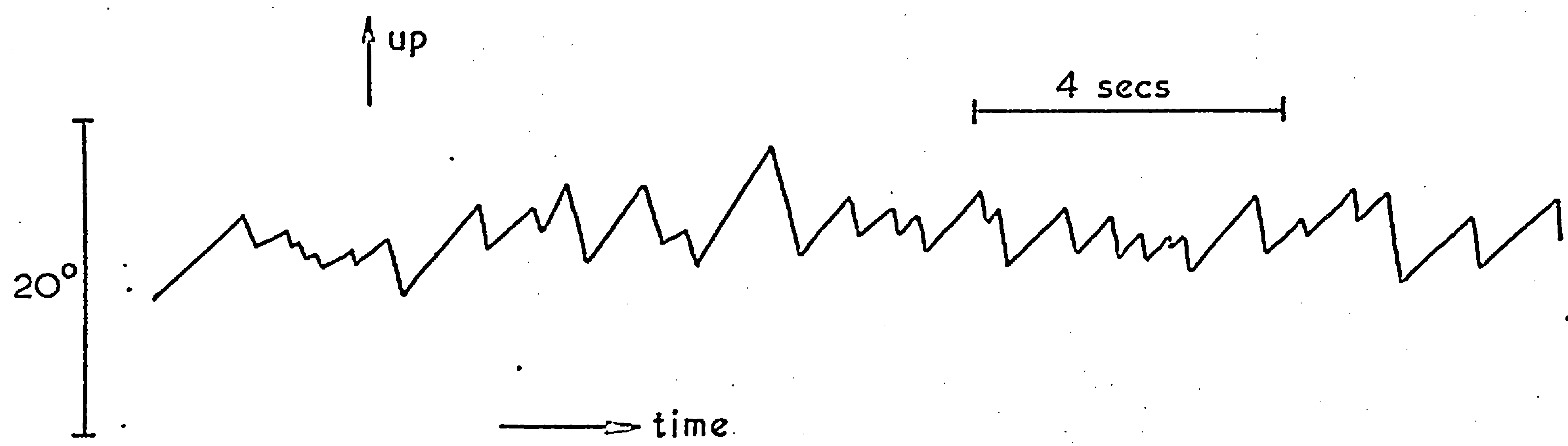


Fig. 5.11 Typical vertical nystagmic response to binaural 'antiphasic' infrasonic stimulation.

5.9. Abnormal Subjects

During the course of these preliminary experiments two subjects became available for test who had histories of sensitivity to balance disturbance.

The first was a pathological case who had anchylosing spondylitis, and hence his sense of balance was almost totally dependent on his eyes and inner ear. This subject had hypersensitive inner ear mechanisms and mild semi-circular canal stimulation such as an isolated head swing produced sensations of extreme dizziness.

As with all the other subjects attempts were made to measure the subject's infrasonic hearing threshold starting monaurally at 2Hz. At a sound pressure level of 104dB, which was below the subject's threshold of hearing, the subject became nauseated and complained of 'falling sensations'. The symptoms were so severe that no further tests were made on this individual and hence no nystagmic record is available.

The second abnormal subject was not pathological but had a history of balance sensitivity. An infrasonic hearing threshold was successfully determined and fell within the 'normal' range. When a 7Hz stimulus was applied for 20 secs. at levels ranging from 120dB upwards in 5dB steps the subject complained severely of balance disturbance and refused to continue with the tests.

It will be noticed from the previous results of the 25 'normal' subjects that one subject repeatedly gave no response to any of the stimuli. Unlike all the other subjects giving negative results this was not due to possible nystagmus being masked by blinking or random eye movement. Both the vertical and horizontal traces were straight and showed no indication of eye movement of any type. The subject was then tested by the standard method for vestibular testing using a rotating chair and again produced no nystagmus. This subject did not have any medical history which would explain this apparent total insensitivity but it later transpired that he had practised yoga from childhood and it can only be assumed that he had some form of control over his eye movements.

5.10 Effects of Body Position

This series of experiments in which the subjects were exposed to monaural, binaural and binaural antiphasic stimulation at sound pressure levels of above 130dB at frequencies of 2,5,7 and 10Hz was repeated with the subject lying horizontally face upwards with the head slightly raised, ~~Fig. 5.12~~. In all cases the subject was relaxed with the eyes open. No reliable pattern of eye movement was induced in any of the test conditions.

5.11. Conclusions

These preliminary experiments were concentrated on establishing if any effects occured under laboratory conditions, and if so, under which conditions the effects were maximised.

The most productive test situation was found to be that in which the subject sat upright while vertical eye movements were recorded. In this situation it was found that monaural stimulation could produce a well defined vertical nystagmic response in 25% of the sample tested and a slight nystagmus in a further 40% of the sample. The same experiments were then repeated on the same group of observers using binaural stimulation with the signals presented to each ear in phase. In this case 40% of the sample gave a clear vertical nystagmic response and a further 32% showed a slight nystagmic response which was difficult to distinguish from the background noise.

The most effective form of stimulation was with the signal presented binaurally with the two ears in antiphase. A clear vertical nystagmus was induced in 88% of the sample, and except for the one subject described in section 5.9 who showed no eye movement at all, the subjects in whom vertical nystagmus was not detectable responded with excessive blinking or large random eye movements, which would mask any nystagmus presented, being of a much greater amplitude.

In the course of these experiments high sound pressure levels were used, greater than 130dB, and all the stimuli were of a 60 second duration.

These preliminary experiments have established that infrasonic stimulation will induce vertical nystagmus, thus indicating balance disturbance, in normal observers, in a sitting position, and that binaural antiphasic stimulation is the most disturbing. These symptoms of balance disturbance are not present when the subject is in a prone position.

Two of the abnormal subjects tested showed that infrasonic stimulation causes extreme symptoms of balance disturbance in hypersensitive cases and it was assumed that the third abnormal subject who appeared to have some degree of control over his involuntary eye movements, was a special case.

The greatest problem encountered in the interpretation of the eye movement traces was that of excessive blinking or large random eye movements. This was common to all subjects initially but some subjects improved as the test series progressed, and so it was assumed that this was due to too short a conditioning period. The performance of all subjects would be improved by a longer period in the test environment or several 'dummy' runs on the test series.

CHAPTER 6

OBJECTIVE AND SUBJECTIVE RESPONSES INDUCED BY INFRASOUND

6.1 Subjects

The results of the preliminary experiments suggested that a longer period of time should be spent on subject training, consequently a smaller group of subjects was used for the main series of experiments.

Six subjects were chosen from the original group of 25. They were chosen on the basis of availability for testing and not on the results of the preliminary experiments. The subjects were:-

1 University Lecturer ,	Male ,	age 30
1 Senior Technician ,	Male ,	age 34
2 Research Students ,	Male ,	age 21 and 24
1 Research Student ,	Female ,	age 24
1 Research Assistant ,	Female ,	age 25

The subjects underwent clinical vestibular testing at the Manchester Audiology clinic, and gave normal vestibular responses by both the Caloric and Rotating Chair Methods.

Each subject sat in the test apparatus for 5 periods of 15 minutes, no measurements were made during these periods and the subjects were allowed to read. In this way the subjects became accustomed to the experimental environment and nervous responses such as blinking and excessive random eye movement were eliminated.

The recording electrodes were then attached to each subject in turn and the unstimulated eye movements were recorded for 15 minutes. All six subjects were able to maintain a steady trace without excessive blinking or random movement for at least 5 minutes.

Before each subsequent experiment was carried out the electronystagmographic apparatus was calibrated for each subject by having the subject move the eyes between pairs of illuminated points which caused eye deviations of 5° to 30° in 5° steps.

6.2 Stimulus

The preliminary experiments showed that binaural antiphasic stimulation was the most disturbing of the stimuli used. The nystagmic responses obtained from this type of stimulus were easily detectable and stable hence this type of stimulus was used for the subsequent experiments.

Sound pressure levels in the range 110 to 145dB re 0.0002 dynes were used at frequencies of 2, 4, 5, 7, 12, 15 and 20Hz. The observers were subjected to stimulus durations of 5 to 85 seconds and all were tested in the sitting position.

6.3 Nystagmus Thresholds

Basically the same experimental techniques were used to measure the thresholds for the onset of nystagmus as were used previously. As well as sound pressure level there are two other parameters which could possibly affect the nystagmus threshold, these are the duration and the frequency of the stimulus.

6.3.1. Stimulus Duration

After the periods of conditioning to the experimental environment each of the six subjects was exposed to a series of infrasonic pure tones at a fixed frequency from 100dB SPL to 145dB SPL in 5dB steps for durations of 5 to 85 seconds. 7Hz was chosen for this full investigation as Gavreau (20) and other workers had suggested that this was possibly the most disturbing frequency, being close to the natural resonance frequency of many internal body organs and having the same frequency as the alpha brain waves. All the subjects were tested with their eyes open in the darkened test room and were asked to relax. Vertical eye movements were recorded.

Only one stimulus was used at each sitting to avoid any possibility of overlap of effects. Hence each subject experienced a maximum of 170 discreet exposures at 7Hz on different days.

Because of the time involved it was not possible to completely repeat the whole experiment but the test was repeated for each subject using the stimulus durations and intensities in the region of their individual thresholds to ensure that the results were reproducible.

Fig.6.1 shows the average results of the six subjects at 7Hz. If the combination of a particular stimulus duration and intensity did not induce a nystagmic response in the subject this pair of coordinates is marked with an open circle. When the combination of a duration/intensity pair did produce a nystagmic response the coordinate is marked with a cross. Hence the graph does not represent an absolutely determined threshold curve but the interface between coordinates giving and not giving a nystagmic response. The hatched area represents the region of uncertainty where some subjects responded positively and some negatively.

This shows that the minimum infrasonic stimulus necessary to induce a vertical nystagmus in normal subjects is a function of both the intensity and the duration of the stimulus and that for durations shorter than about 15 secs. some form of stimulus integration is involved.

6.3.2. Stimulus Frequency

The series of experiments was repeated for all six subjects at frequencies of 2, 4, 5, 12, 15 and 20Hz. Figs. 6.2 to 6.7 show the threshold curves obtained these were plotted in the same manner as the 7Hz curve described in section 6.3.1. Fig.6.8 shows the combined set of curves for

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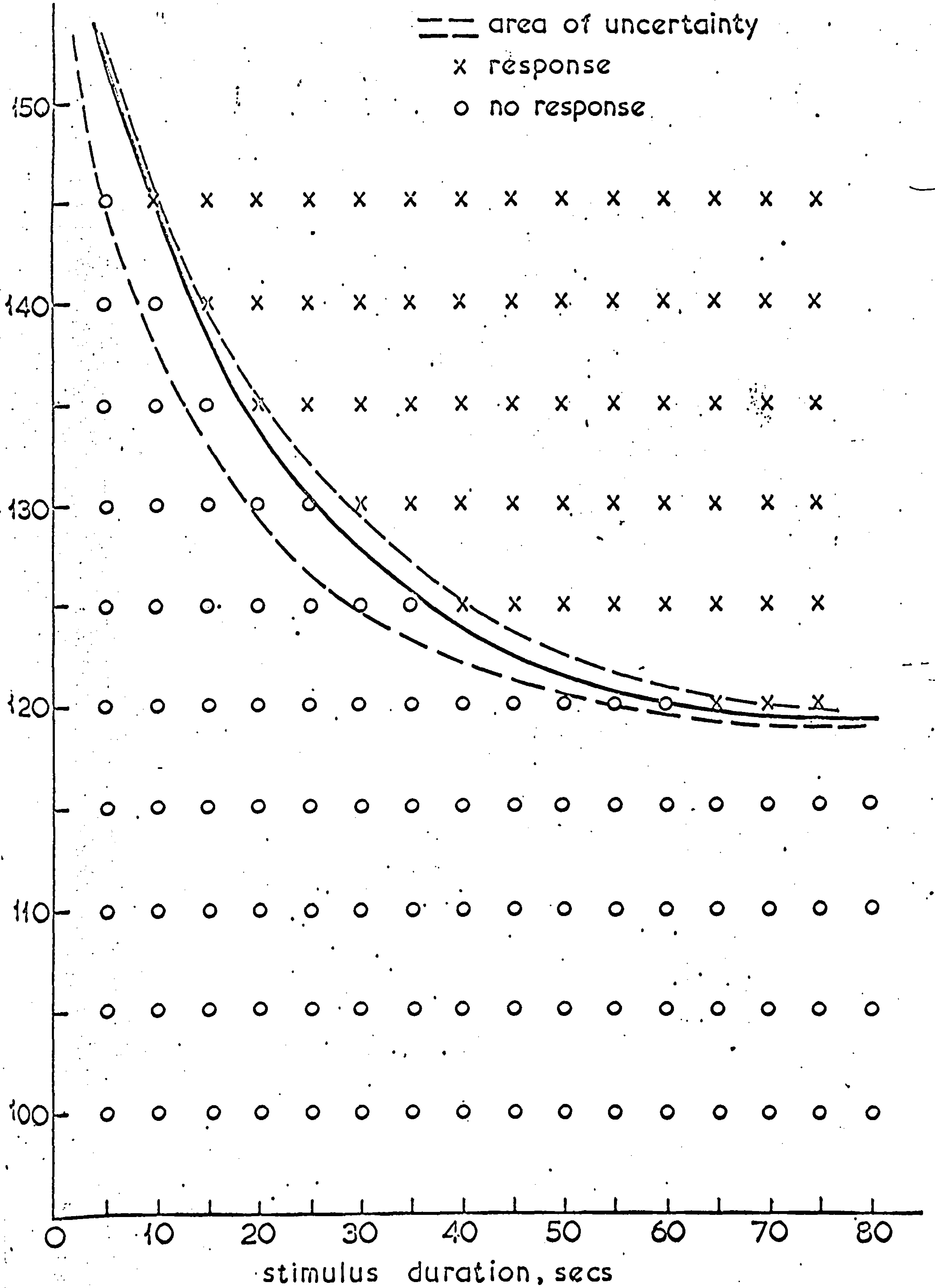

Threshold curve for Vertical Nystagmus induced by a 7Hz Binaural signal.

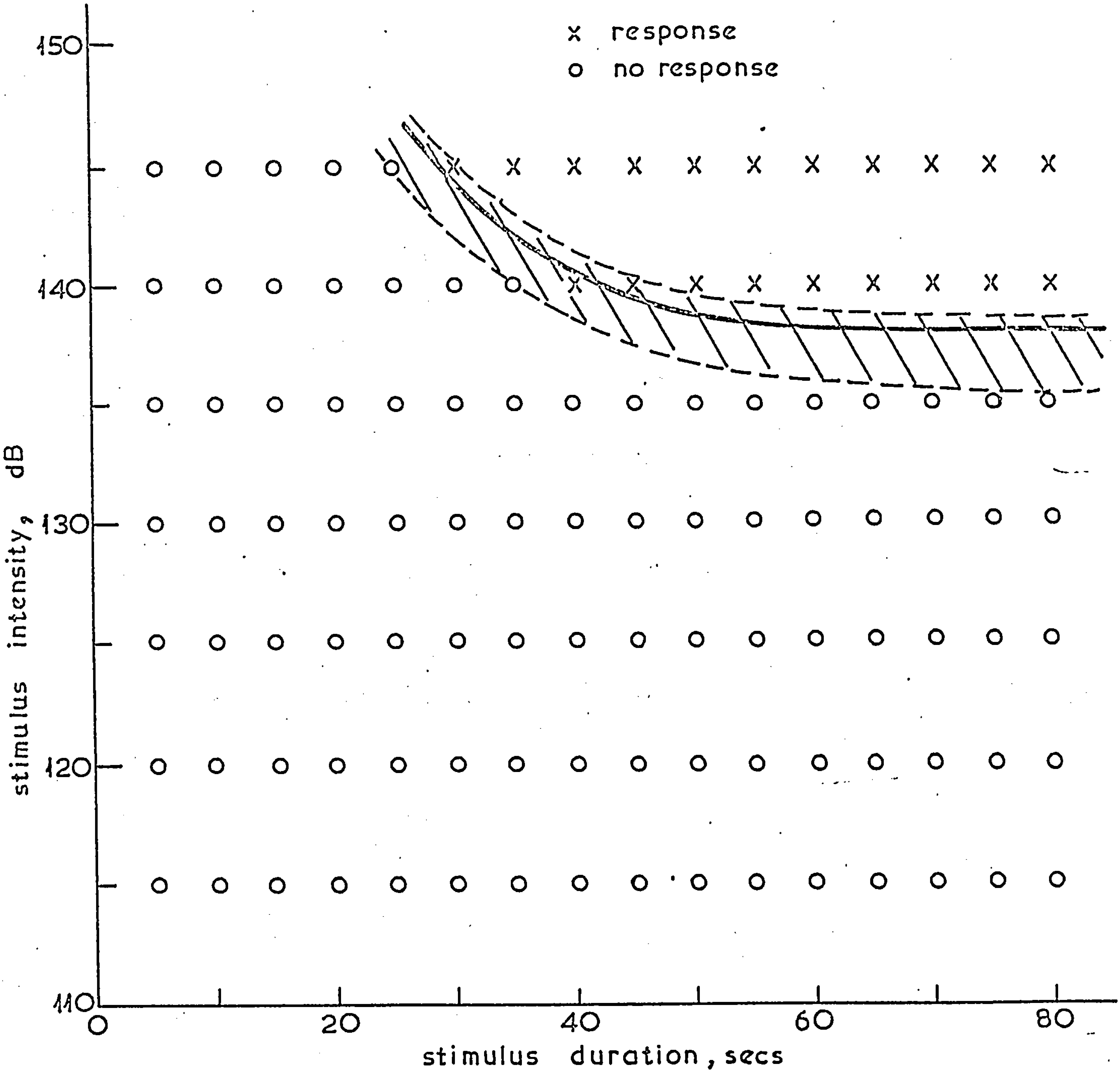

Fig. 6.2 Threshold curve for a vertical nystagmus induced by a 2Hz binaural signal.

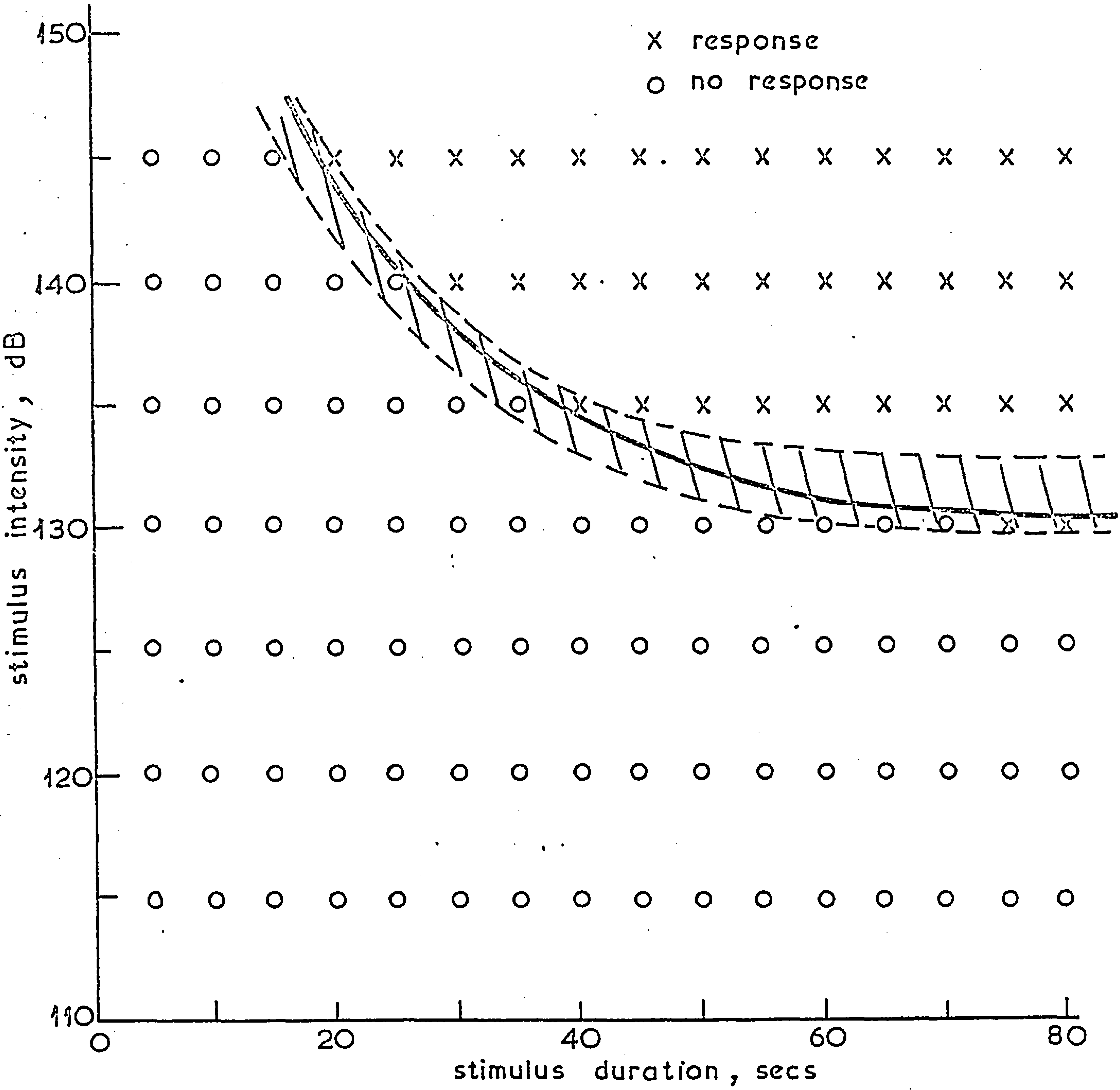

Fig. 6.3 Threshold curve for a vertical nystagmus induced by a 4Hz binaural signal.

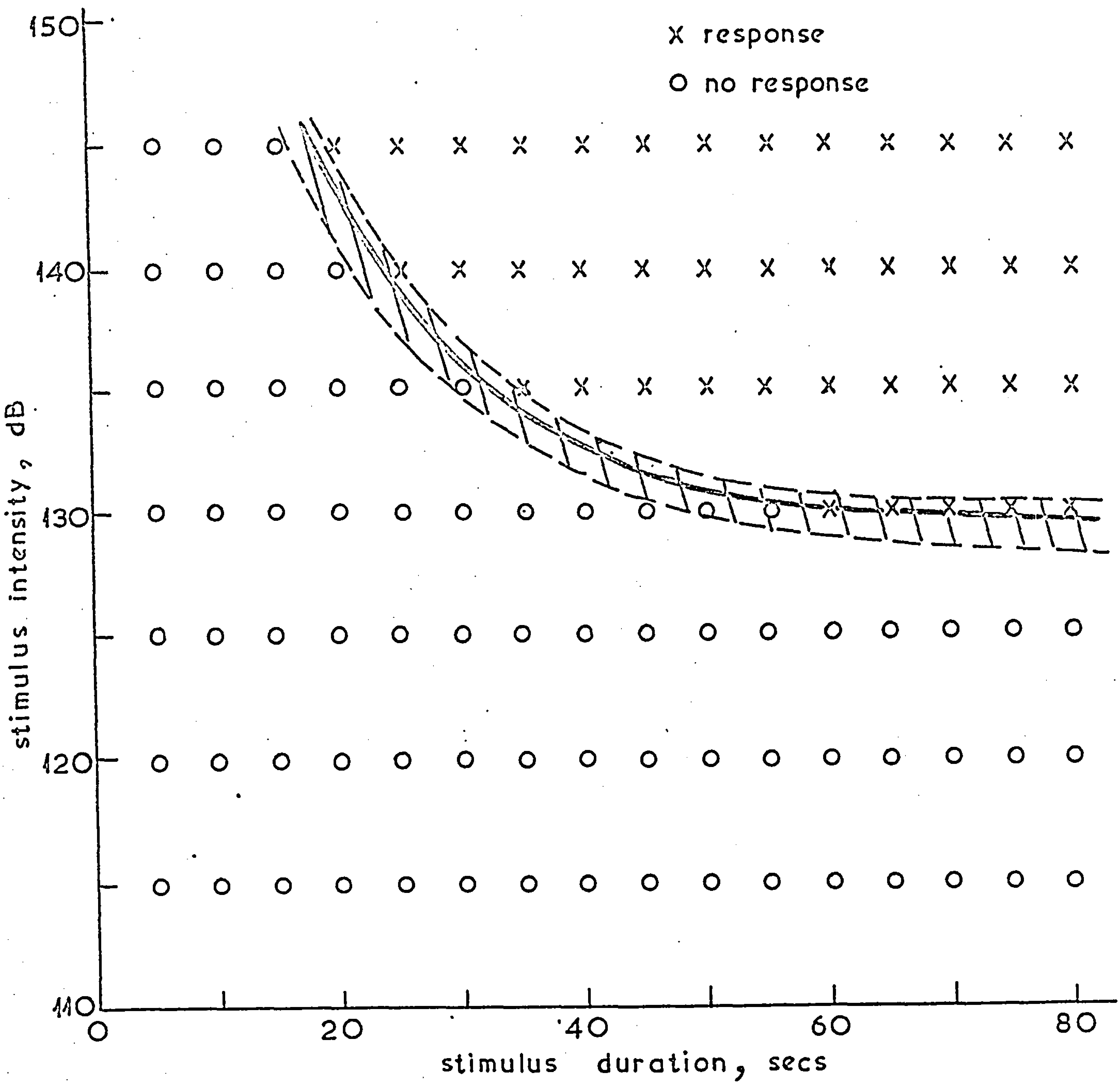

Fig. 6.4 Threshold curve for a vertical nystagmus induced by a 5Hz binaural signal.

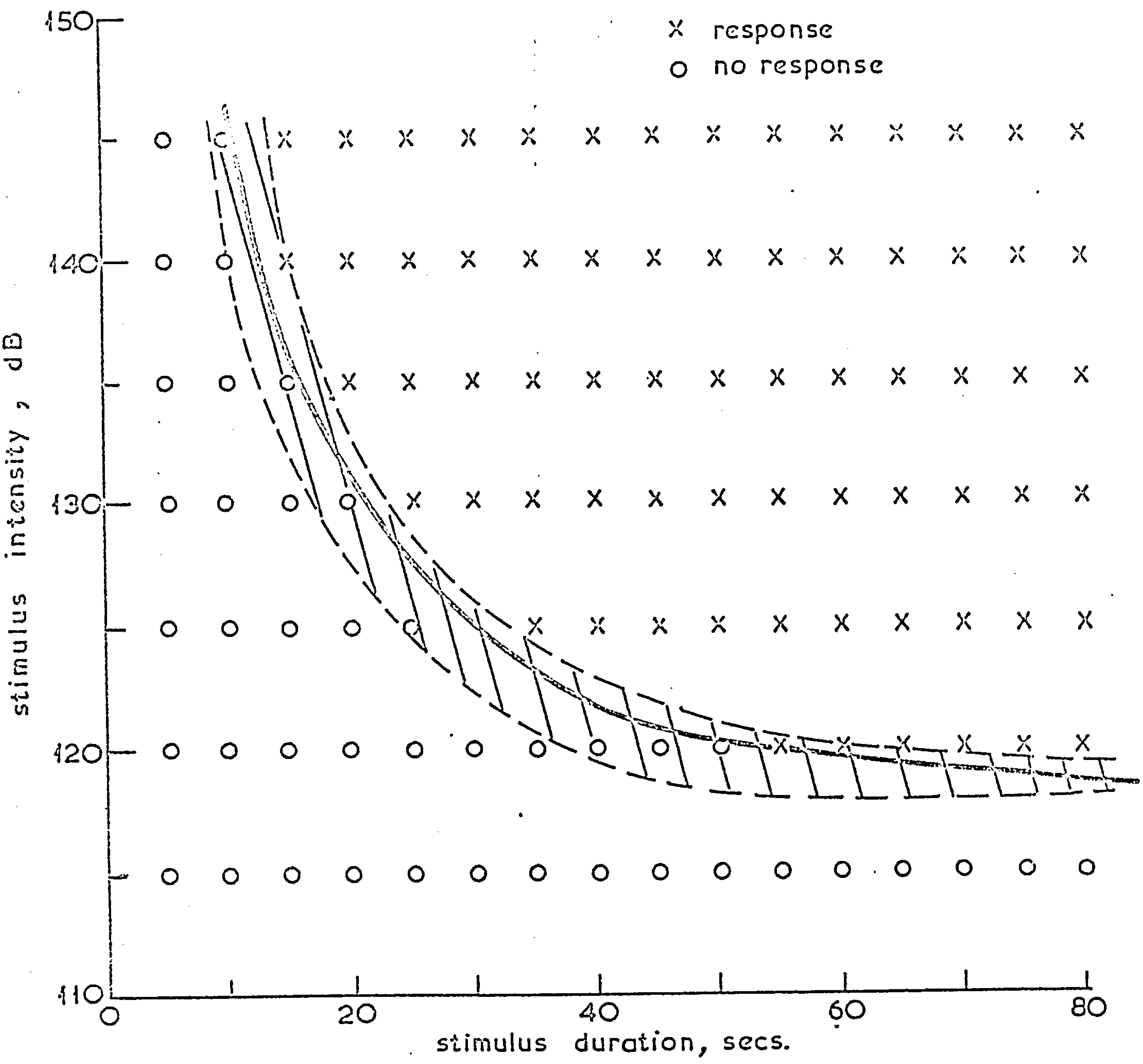

Fig. 6.5 Threshold curve for a vertical nystagmus induced by a 12Hz binaural signal.

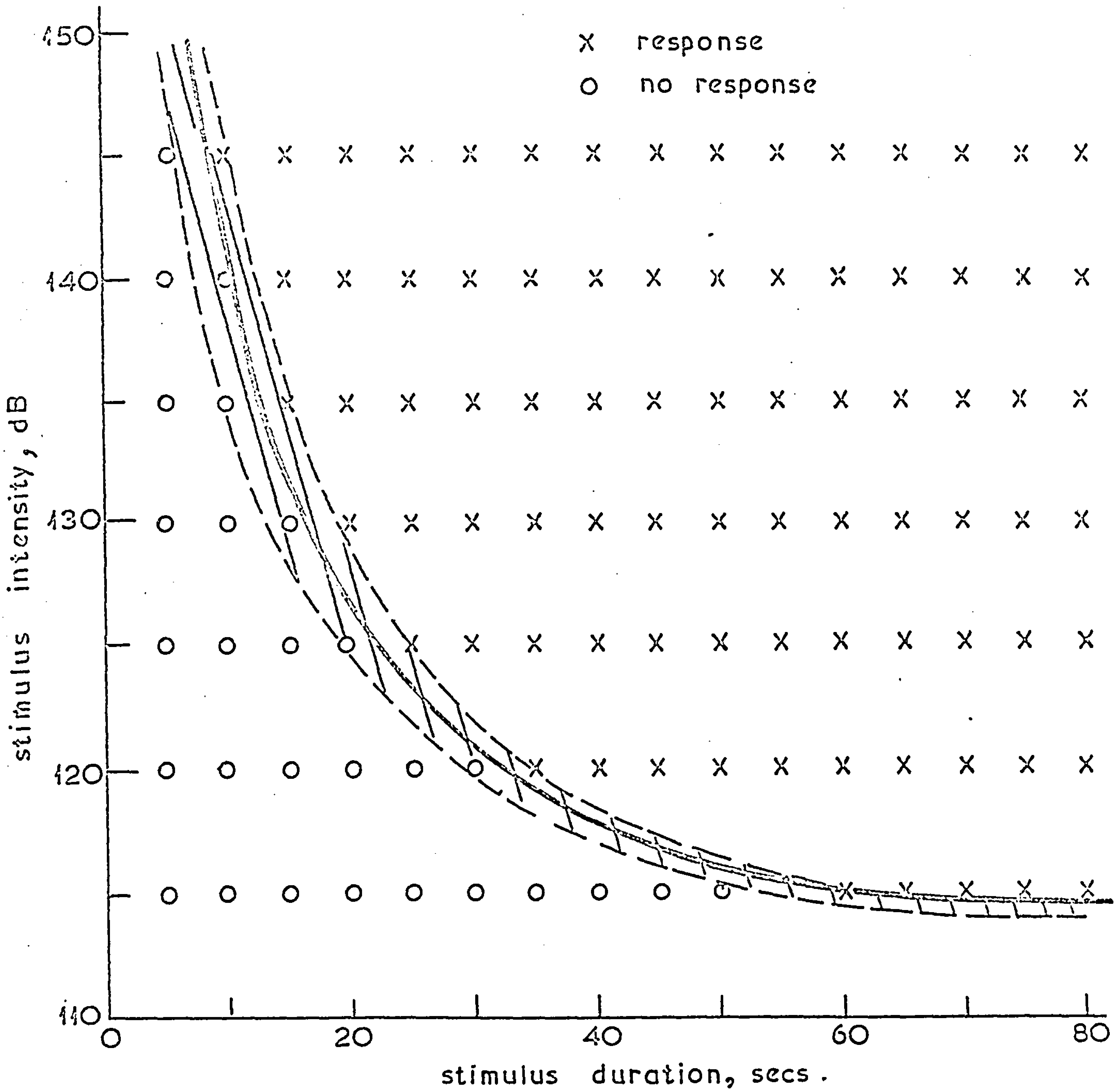

Fig. 6.6 Threshold curve for a vertical nystagmus induced by a 15Hz binaural signal.

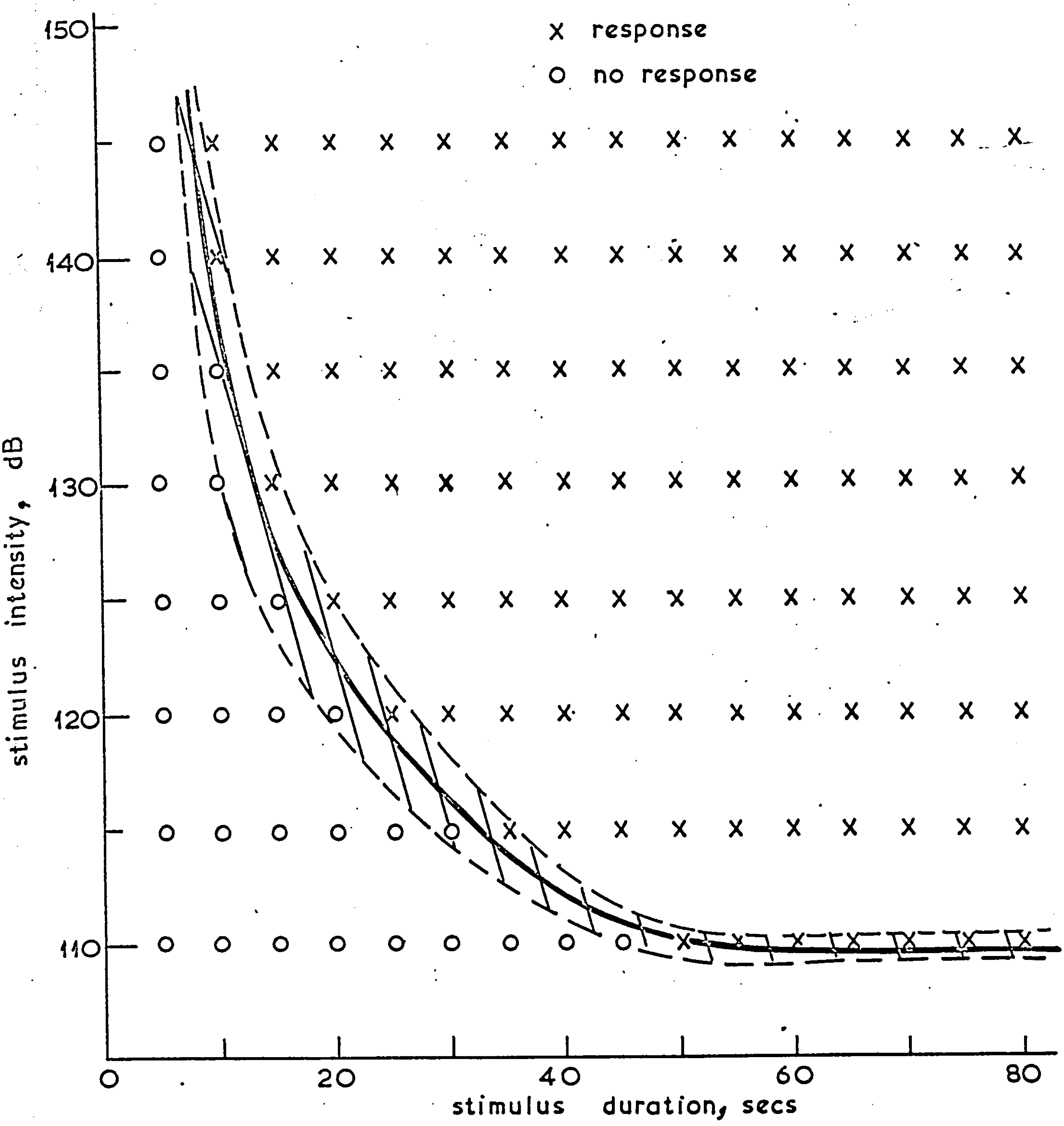

Fig. 6.7 Threshold curve for a vertical nystagmus induced by a 20Hz binaural signal.

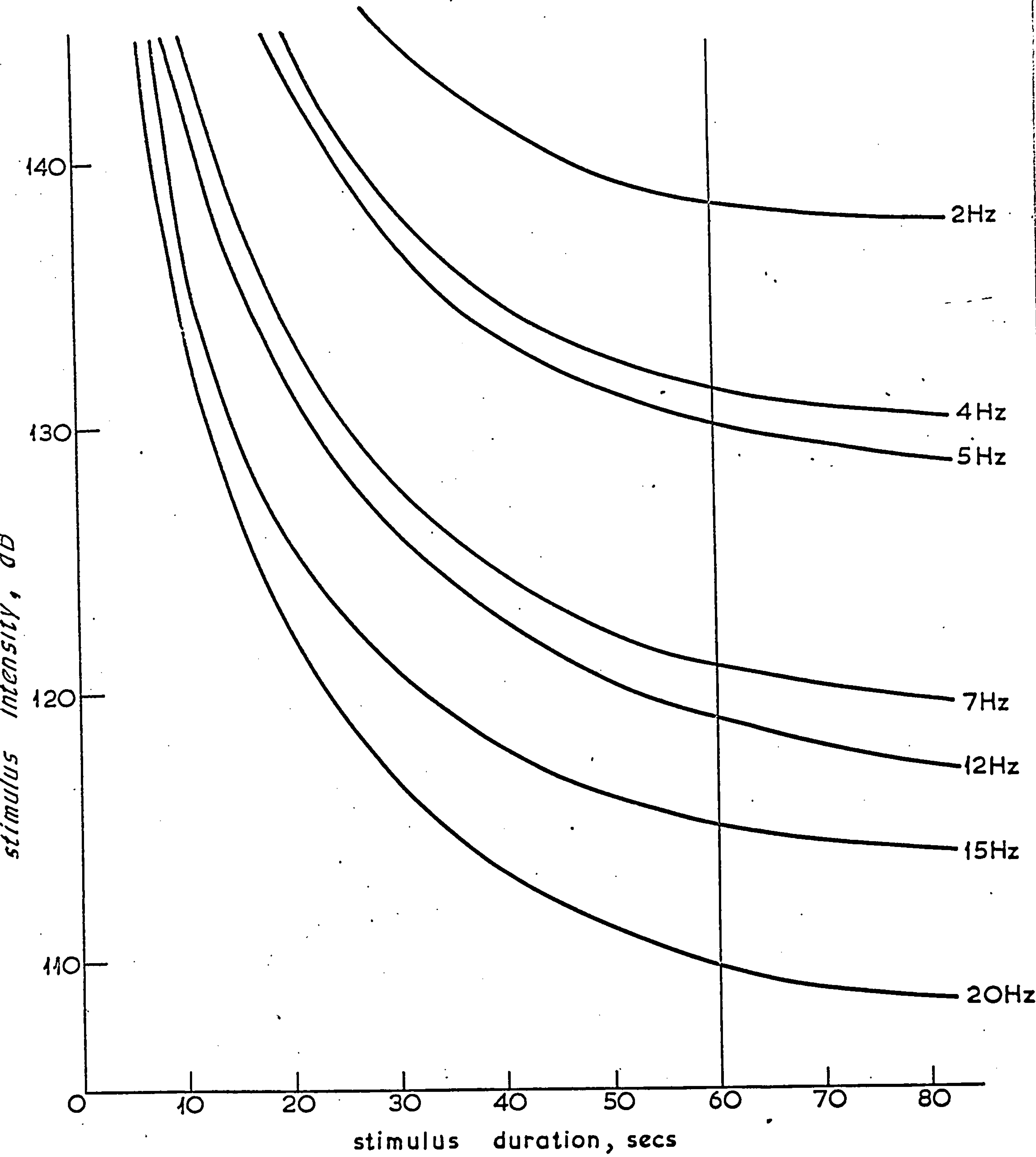

Fig. 6.8 Thresholds of vertical nystagmus induced by pure infrasonic tones.

the 7 frequencies used.

The actual variation of nystagmus threshold with frequency is shown in figs. 6.9. The mean threshold level for the six subjects at each frequency for a 60 second duration was obtained from the above curves and hence the sound pressure levels are subject to a 5dB uncertainty.

In Fig.6.9a the threshold for the onset of nystagmus is expressed in terms of the actual intensity of stimulation. In Fig.6.9b it is expressed in terms of sensation level, that is the level of the stimulus above the auditory threshold level at that frequency.

6.4. Duration of Nystagmic Response

The duration of the nystagmic response for each exposure was taken from the nystagmic trace recording. The duration was taken as the time from when the nystagmus was clearly present until it was not easily recognised. Fig.6.10 shows the relationship between the duration of the stimulus and duration of the recorded nystagmic response. This figure represents the total data obtained from the six subjects and shows a significant correlation between the duration of the stimulus and the duration of the recorded nystagmus. No relationship was found between the duration of the nystagmus and the intensity or frequency of the stimulus. Hence it would appear that the duration of the nystagmic response is dependent solely on the duration of the stimulus, although the amplitude of the nystagmic beats depended on the intensity and frequency also.

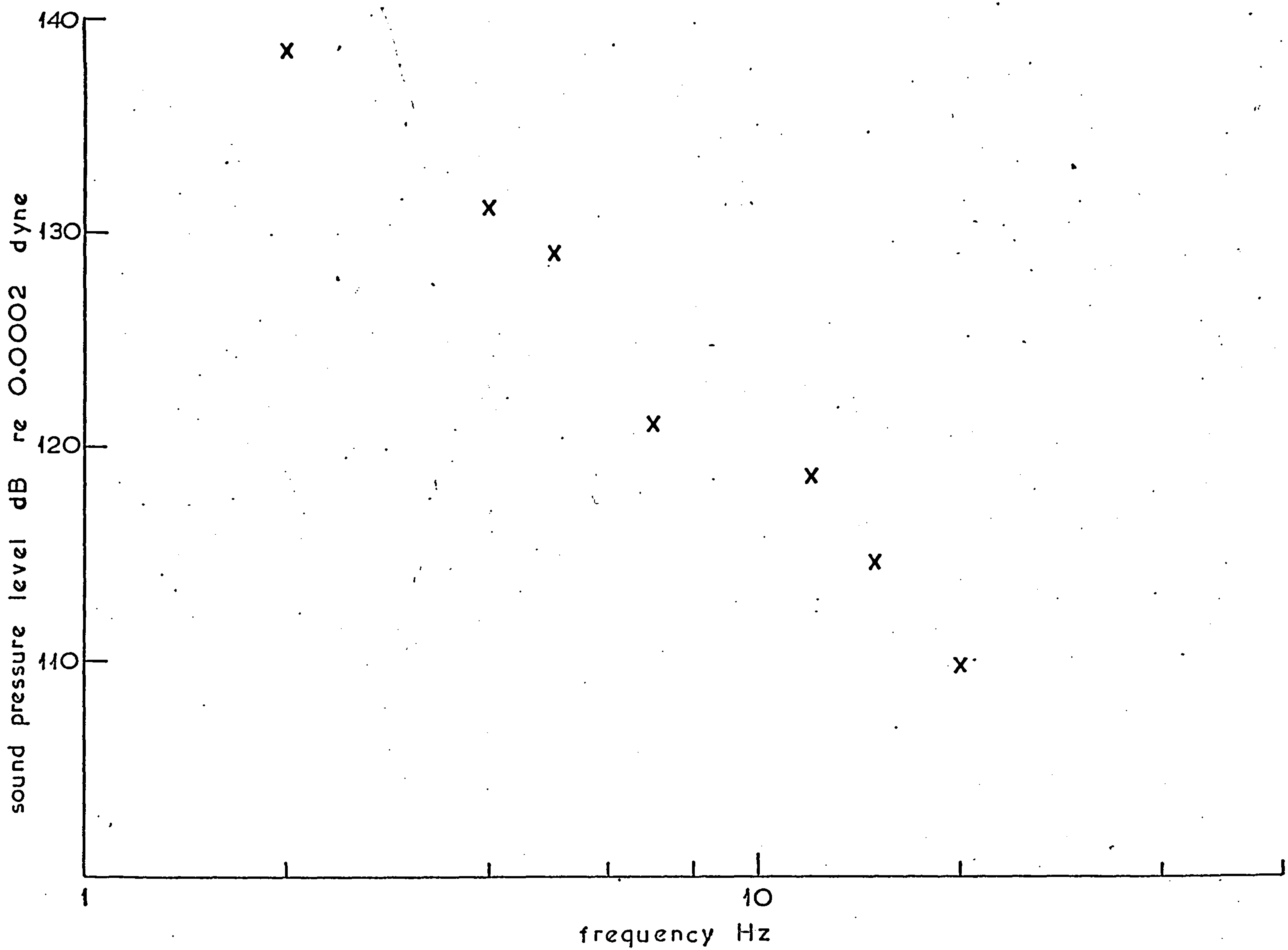

Fig. 6.9a Variation of nystagmus threshold with frequency 60sec stimulus duration.

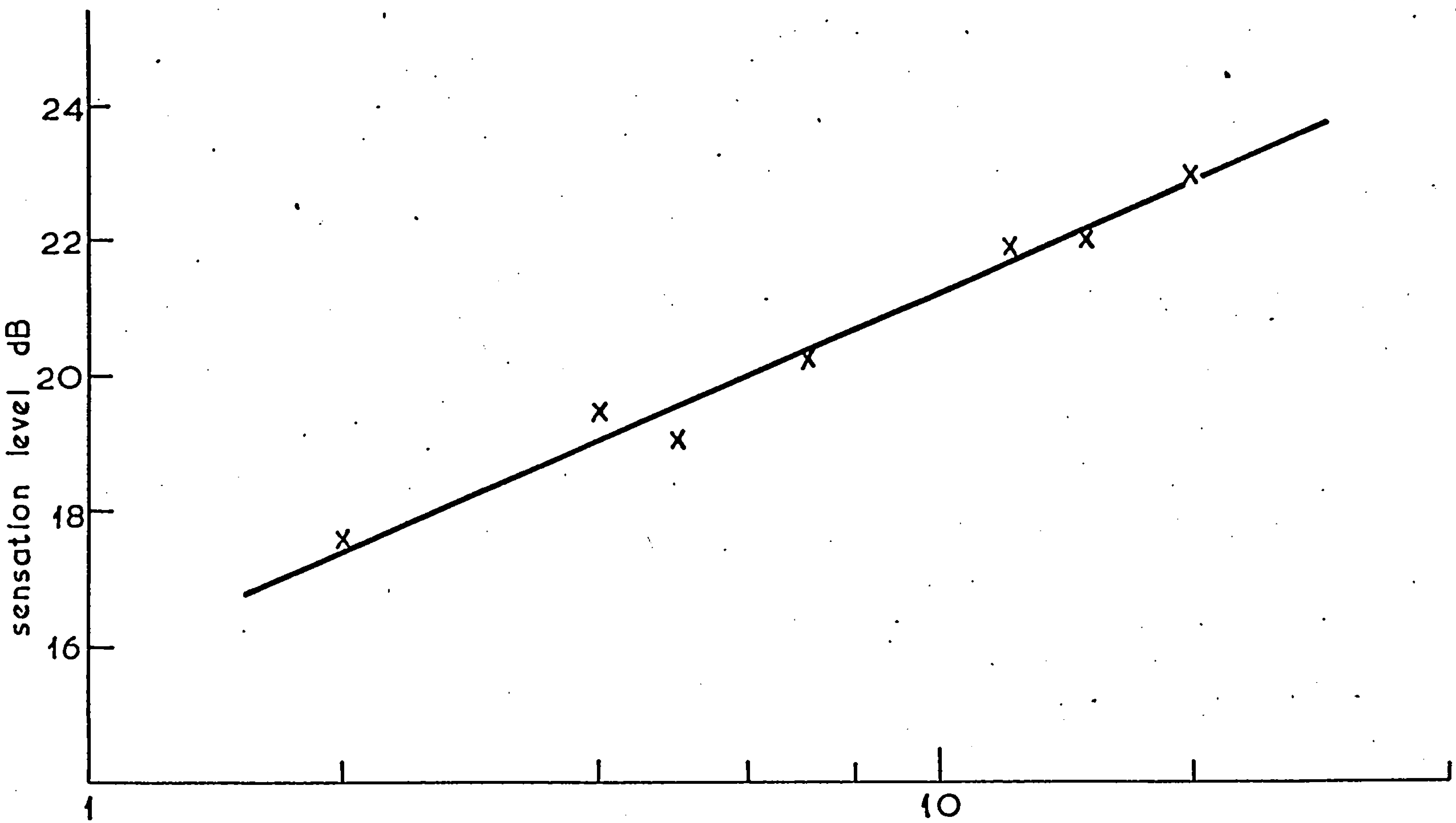

Fig. 6.9b Variation of nystagmus threshold with. frequency. 60sec stimulus duration.

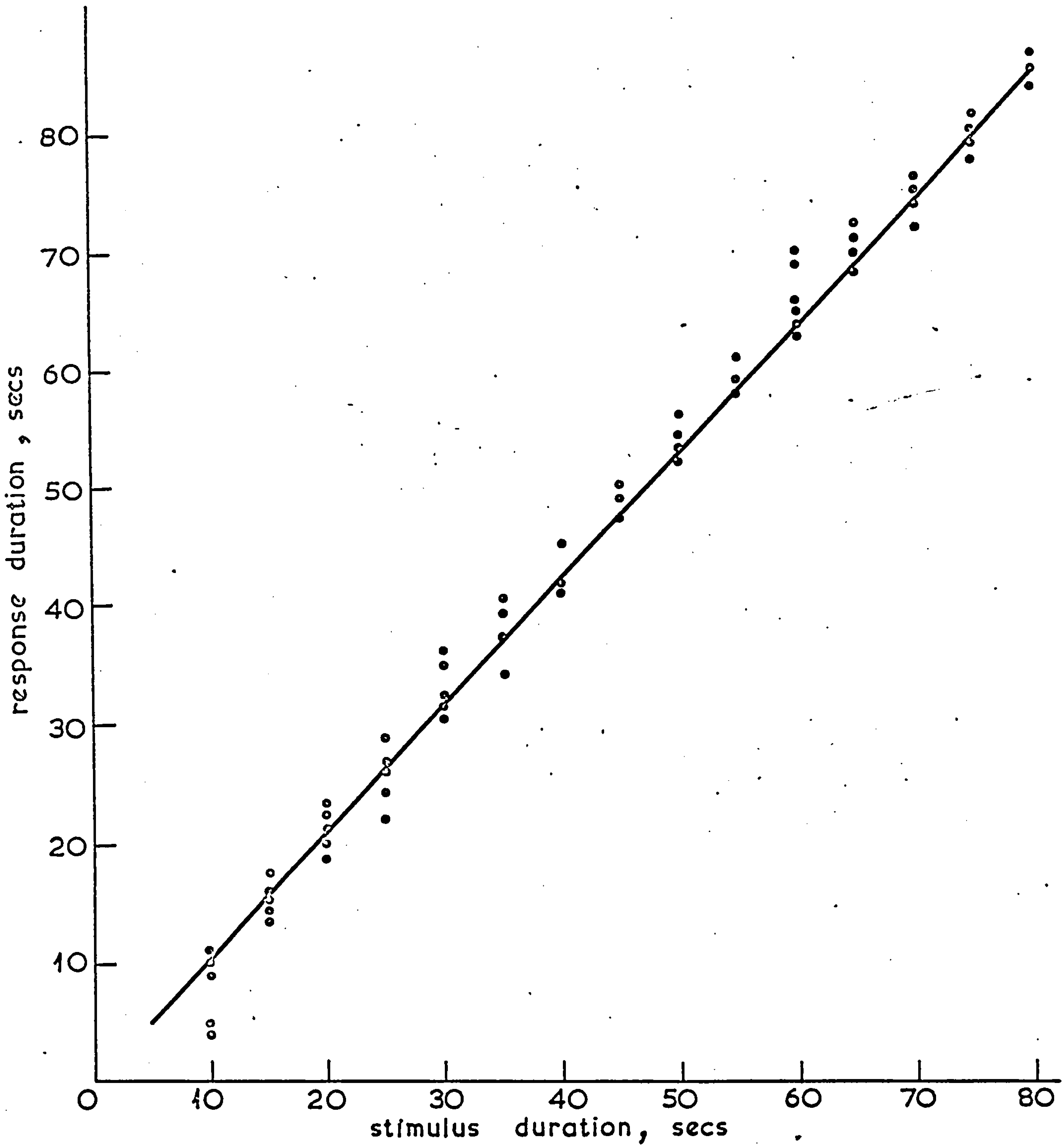

Fig. 6.10 Stimulus duration / response duration relationship.

6.5 Type of Nystagmus Induced

In all cases the nystagmus induced by infrasonic stimulation was of the slow face first type, with the slow component representing the upward movement of the eyes and the fast face the rapid downward return to the normal position. The frequency of the nystagmic beats was independent of the frequency of the stimulus and the sound pressure levels used and was of the order of 1 beat/second. This was not entirely stable, a typical trace contained nystagmic beats varying from 1.5 beats/sec. to 0.7 beats/sec.

6.5.1. Latency

Unlike most other forms of vestibular stimulation it was noticed that, although the nystagmic response was closely correlated in duration to the duration of the stimulus, the two did not appear to be synchronised. There was a variable latency period between the onset of the stimulus and the onset of the nystagmic response. This latency period varied from stimulus to stimulus and slightly from subject to subject, although it was constant for each subject for each particular stimulus of a given frequency and intensity. Generally the higher the intensity the greater the amplitude of the nystagmus, and the mid frequencies of 5 and 7Hz tended to induce nystagmus of a slightly greater amplitude than the lower or higher frequencies. For a given intensity the amplitude was about 2^{o}-3^{o} greater at 7Hz than at 2Hz or 20Hz.

6.5.3. Fixation Effects

In order to induce nystagmus in normal subjects it was necessary to isolate them from all stimuli and visual clues other than the selected infrasonic stimulus. This, together with the low amplitude nystagmic trace suggest that the effect is only marginal and that if the subject had other information about his body position the nystagmic response would possibly be eliminated although the more severe subjective responses, described in section 6.6, would still be present.

This situation was examined by introducing a small, dim light into the test room directly in front of the subject at a distance of about six feet. The subjects underwent infrasonic stimulation in the same manner as previously using 80 second exposures at intensities in the 130-145dB range for the full frequency range. Although the test room was darkened the subject could see the small light which supplied visual information about the subject's position. Vertical eye movements were recorded.

A clear nystagmus was not obtained from any of the subject's under any of the test conditions, although in two cases it was possible to detect a slight nystagmus with about a 2^{o} amplitude, at the highest stimulus levels.

The subjects reported the same subjective sensations as previously (see section 6.6). Hence it is possible to conclude that visual fixation almost eliminates the occurence of nystagmus although the unpleasant subjective sensations are just as intense.

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6.5.4. Habituation

During the course of the experiments it was noticed that the two subjects who had considerable experience of exposure to infrasound became temporarily habituated to the stimulus. If these two subjects underwent several periods of stimulation at the same frequency on one day their nystagmic response decreased. The duration of the response was shortened, the frequency of the beats decreased, and occasionally the beat amplitude also decreased. If these subjects were again exposed to the same stimulus on the following day, after about 18 hours stimulus relief, vertical nystagmus, without an habituation decrement, was again induced.

Reduced vestibular response can be produced by any one of at least three factors:-

i. Visual Suppression

Visual suppression or fixation was described in section 6.5.3. and clearly was not the cause of habituation in this case.

ii. Arousal Decrement

Nystagmic output is very dependent on the level of arousal or alertness of the subject. A high stage of arousal occasions a high nystagmic output, and a monotonous repetitive stimulus does cause a decrease in the state of arousal of the subject.

In this case the exposure periods had a maximum duration of

85 seconds and hence it is improbable that there was any appreciable change in the subject's arousal level. Also if arousal decrement had been the cause of the stimulus habituation one would have expected all the subjects to become habituated to some extent, although this would have varied from subject to subject, and not just the two most experienced subjects.

iii. Sensory Adaption

Sensory adaption refers to the decrement in supra organ sensitivity during the extended application of a sapra-threshold stimulus, the mechanism for which is undecided. This is a short term change, the sense organ returns to its initial sensitivity after stimulus relief.

As the habituation experienced in this case was only temporary and dependent of the subject's experience it would appear to be mainly due to sensory adaption.

6.6 Subjective Responses

After each exposure the observers were asked to record any subjective effects they had experienced and their descriptions of the stimulus. The subjective descriptions of the stimuli varied with frequency, but generally fell into three categories:-

a. Frequencies above 20Hz were described as smooth and tonal.
b. Frequencies in the 5-15Hz range were described as sounding

like 'a rapid series of pops'. The signal was far less tonal and much 'rougher'.

c. Frequencies below 5Hz were described mainly as 'chugging' or 'whooshing' sounds, each cycle could be heard. In this lower frequency range subjects reported that they could feel as well as hear the stimulus, and that this tactile sensation was unpleasant and that they felt apprehensive.

The subjective effects reported may be divided into five basic categories depending on both the frequency and intensity of the stimulus, these are presented in tabular form below.

Voluntary tolerance was not exceeded in any of the cases although at the higher frequencies and intensities, i.e. at the higher sensation levels, the subjects were approaching this point, and were reluctant to continue with the longer duration exposures.

6.6.1. Frequency Range 2-5Hz: SPL Range 100-135dB

a. Movement of the eardrum in response to the pressure changes.
b. Pressure build-up in the middle ear.
c. Difficulty in swallowing, all subjects were persistently trying to swallow as a mechanism for pressure release.
d. Slight post exposure headaches which were not persistent.

6.6.2. Frequency Range 2-5Hz: SPL Range 135-145dB

a. Movement of the eardrum

b. Middle ear pressure build-up with associated middle-ear pain.

c. Difficulty in swallowing.

d. Sensations of "fullness in the throat".

e. Difficulty in speaking and voice modulation

f. Abdomen vibration } mild and not unpleasant.

g. Thorax vibration } mild and not unpleasant.

h. Post exposure headaches which were more persistent than in case 1.

6.6.3. Frequency Range 5-20Hz: SPL Range 100-130dB

a. Movement of the eardrum

b. Difficulty in speaking and voice modulation

c. Chest wall vibration

d. Swaying sensations as if falling backwards

e. Lethargy and drowsiness

f. Slight tinnitus at frequencies above 10Hz

g. Post exposure headaches and fatigue

6.6.4. Frequency Range 5-15Hz: SPL Range 130-145dB

a. Movement of the eardrum

b. Middle ear pain

c. Difficulty in speaking and voice modulation

d. Severe chest wall vibration

e. Severe abdomen vibration and associated feelings of nausea

f. Sensations of falling backwards

g. Lack of concentration and drowsiness

h. Tinnitus

i. Severe post exposure fatigue and throbbing headaches.

6.6.5. Frequency Range 15-20Hz: SPL Range 130-145dB

a. Severe middle ear pain

b. Respiratory difficulties - gagging sensations. In one case spasms of uncontrollable coughing developed.

c. Nasal cavity vibration

d. Persistent eye watering

e. Tinnitus

f. All the subjects experienced sensations of fear including excessive perspiration and shivering these symptoms decreased with successive exposures.

g. Severe post exposure fatigue and headaches.

h. In two cases (both female) cutaneous flushing.

CHAPTER 7

THE ORGANS OF EQUILIBRIUM AND THEIR FUNCTION

7.1. Description

The vertebrates, fishes, reptiles, birds, amphibians and mammals all have organs of equilibrium of the same fundamental construction, although the final shape varies from species to species, Fig.7.1.

The organs are arranged in two symmetrical groups, situated in the left and right side of the skull. In humans each group consists of:-

a. Utricular otolith and macula fig.7.2
b. Saccular otolith and macula
c. Semi-circular canal system with its cupulae and cristae, Fig.7.3

The otoliths are jelly like substances saturated with calcium carbonate crystals (aragonite). The important feature of the otolith is that it is of a greater density, 2.95 gm/ml, than the surrounding fluid, 1.02 gm/ml. It is situated on or against a layer of sensory cells which have hair like extensions, cilia. Between the otolith and this cell bedding, the macula, there is a jelly-filled narrow space which enables the otolith to move lightly over the macula. This fundamental construction of a base of sensory cells with cilia, held rigidly together by supporting cells, and an

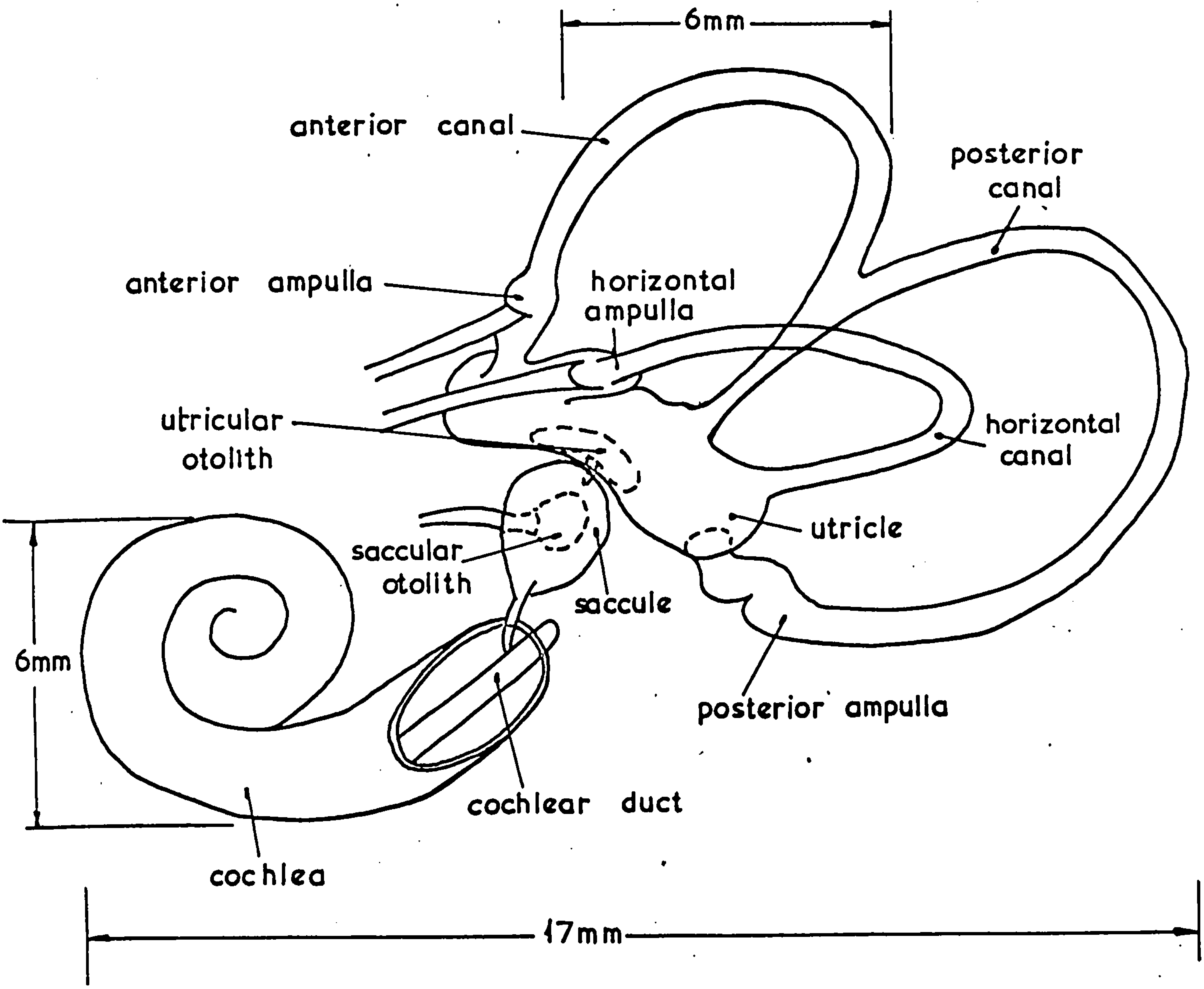


Fig. 7.1 Ventro-lateral view of the left human labyrinth.

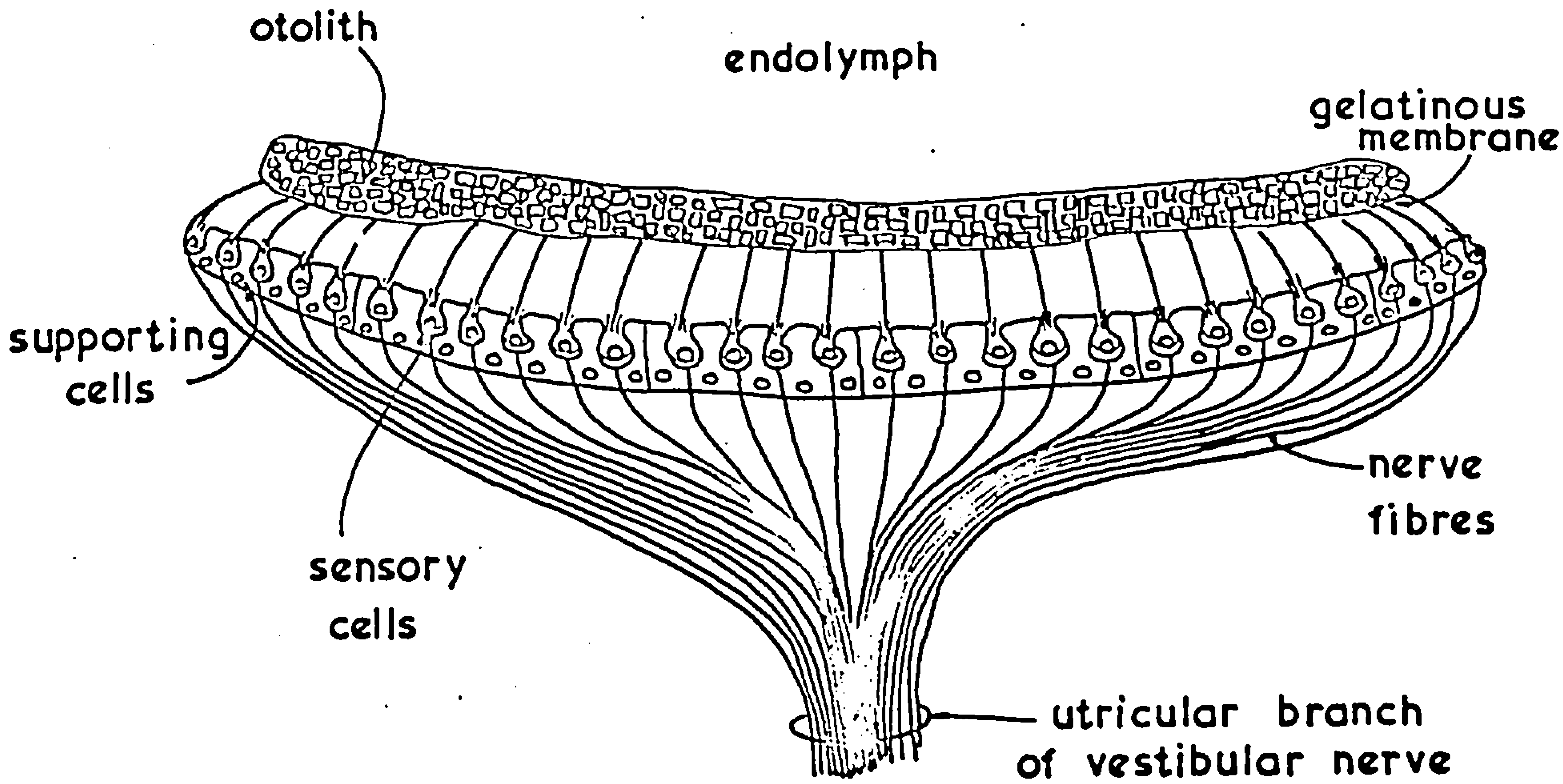


Fig. 7.2 Schematic diagram of a cross section of an otolith and its macula.

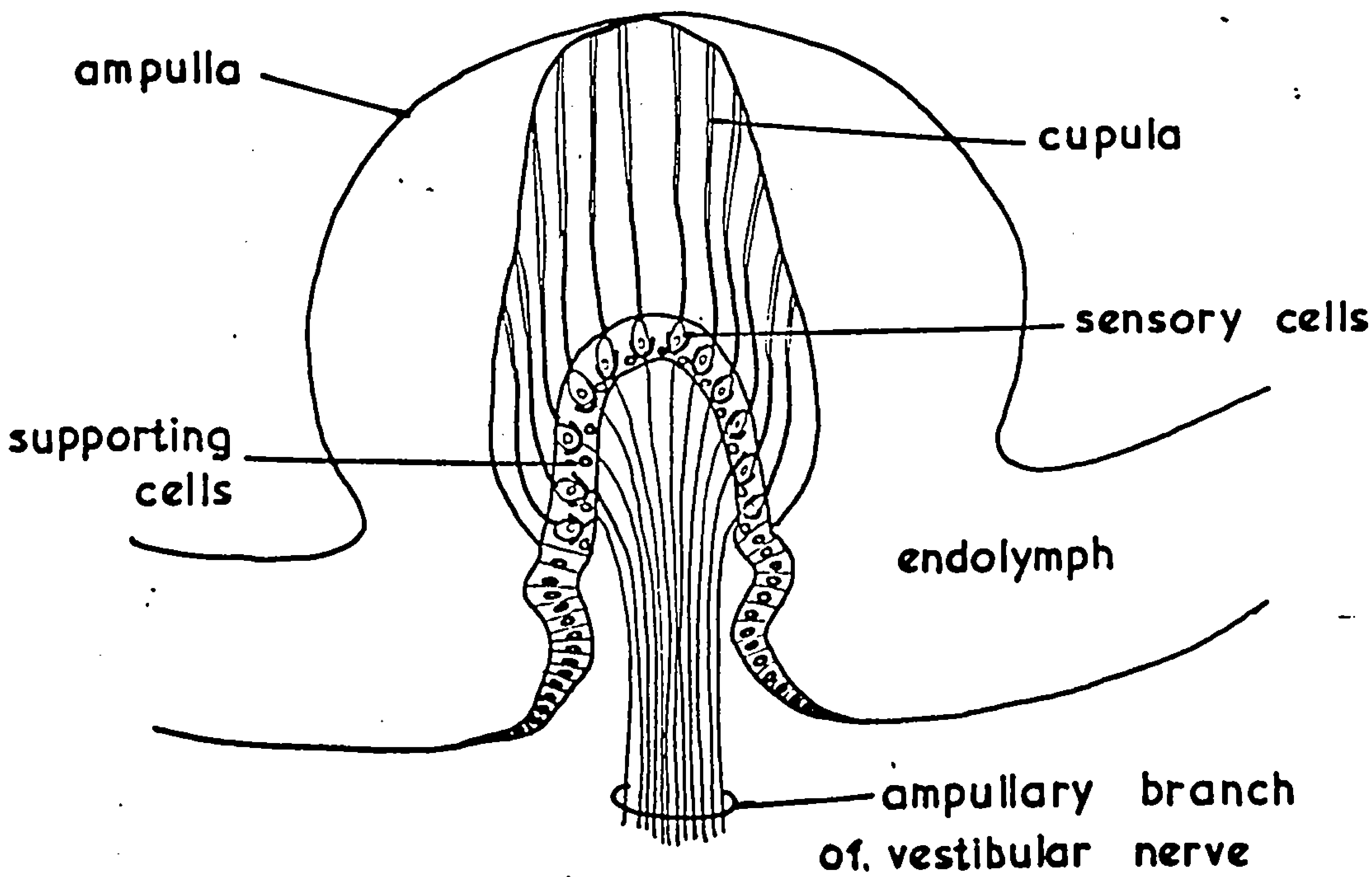


Fig. 7.3 Schematic diagram of a cross section of a semicircular canal + ampulla.

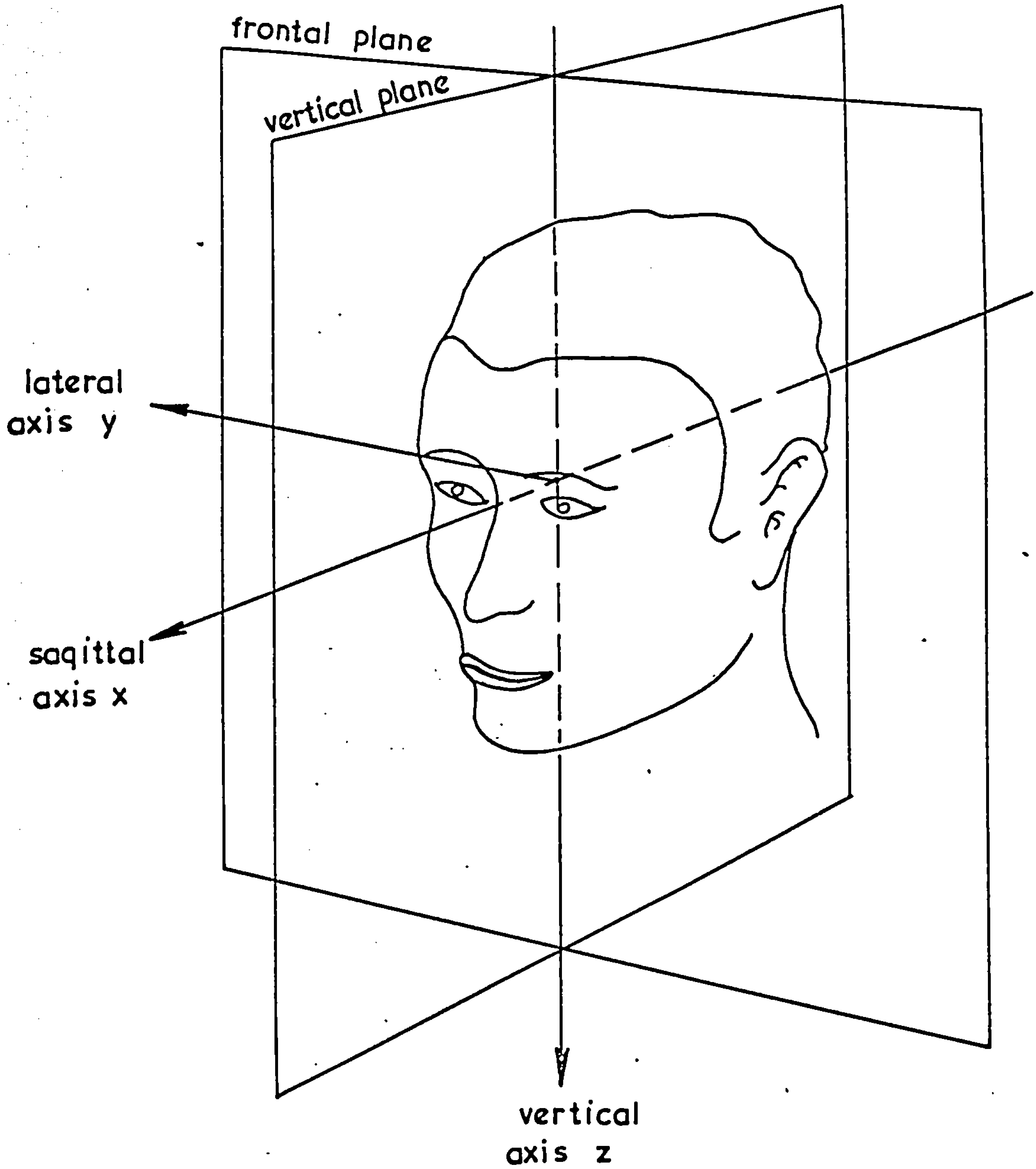
intermediate layer to allow some excursion of an upper structure (here the otolith) is also found in the sensory elements of the semi-circular canals, and in highly evolved species such as humans, in the cochlea also.

The three semi-circular canals lie in planes which form roughly an orthogonal system. Fig.7.4.

Each canal starts from a common vesicle, the utricle, and comes back into it at the other end. In the region of the utricle the canal expands forming the ampulla, thereafter it narrows to its former diameter and opens into the utricle. Fig.7.5. The sensory structure is found in the ampulla. It consists of a rigid sensory cell formation, the crista, from which the cilia penetrate into the fine tubes of the jelly-like formation, the cupula, which is the moving element. Between the crista and the cupula there is again a thin fluid layer which enables the cupula to move bodily over the crista thereby pulling the cilia. The cupula hermetically seals the ampulla.

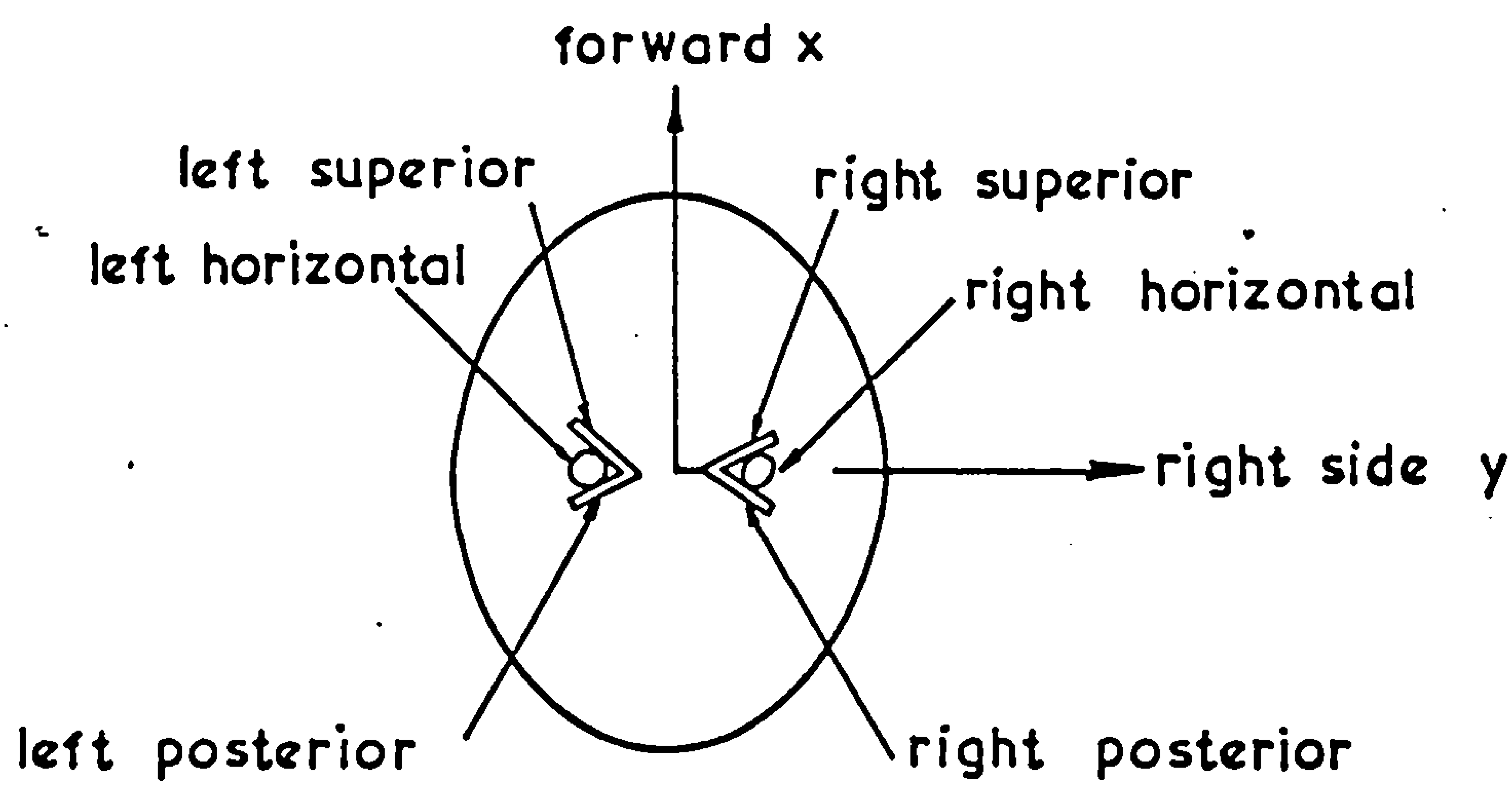
As the whole of the vestibular system is filled with endolymph, the fluid in the canals will cause the cupula to bend sideways as soon as the fluid starts to move under the influence of inertial forces. The density of the cupula is the same as that of the endolymph and is completely controlled by it.

All the organs described above are situated in membraneous sacs filled with endolymph while outside there is another fluid,



Head planes and axis system

Fig. 7.4a



Top view of head showing the orientation of semi-circular canals.

Fig. 7.4b

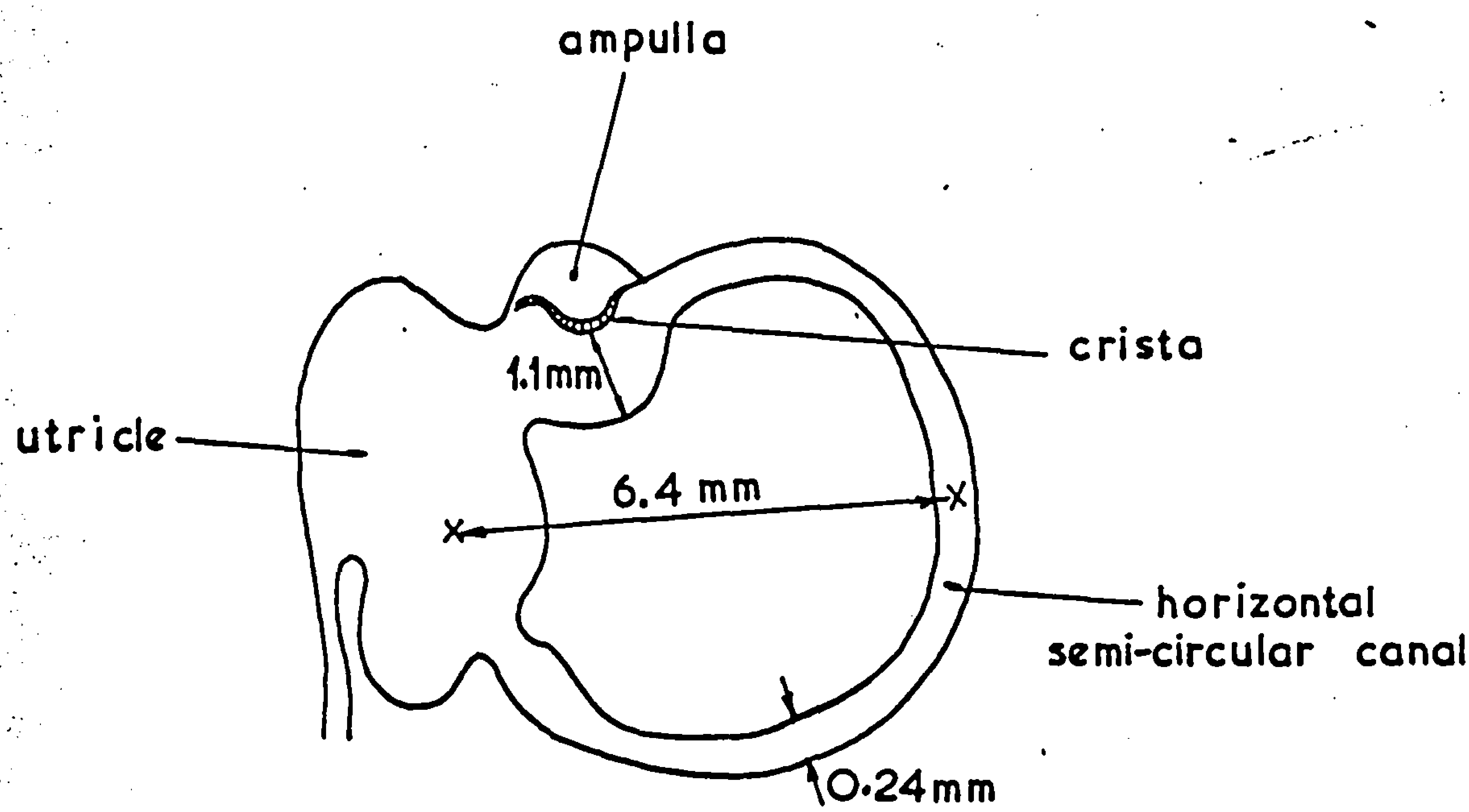


Fig. 7.5 Average dimensions of membraneous horizontal semi-circular canal.

perilymph, enclosed by the surrounding bony walls, connected to the sacs by fine ligaments. In some places the endolymphatic sac is connected to the bony wall directly. The nerve fibres, coming from the sensory cells, penetrate the bone.

It is assumed that all the organs are kept in place by their ligaments during normal physiological movement. Only the upper structures, the otolith and the cupula, are allowed their virtual movement.

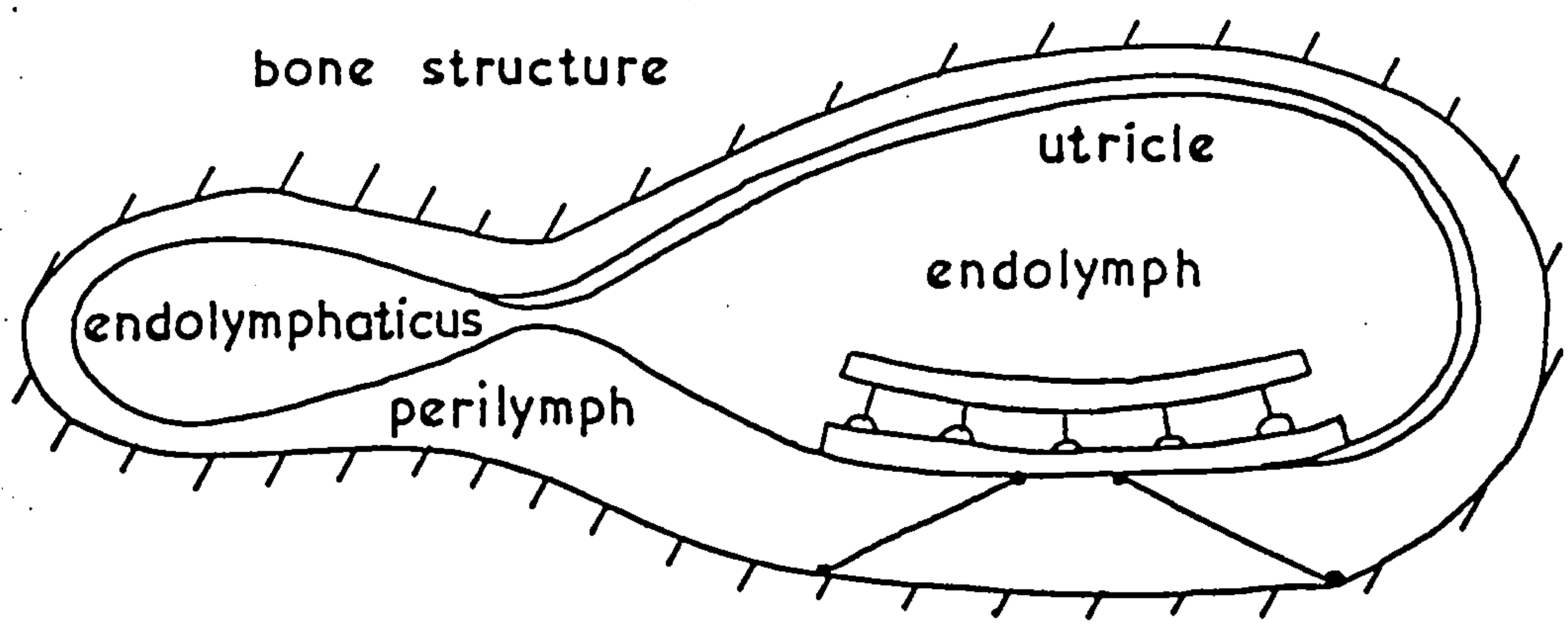
The nerves form a basket-like structure surrounding the sensory cells and go via the ganglion of scarpa to the brainstem ending there in the vestibular nuclei.

7.2. Function

The otoliths with their associated macula and higher connections are the receptors of linear acceleration giving information of direction as well as magnitude and position.

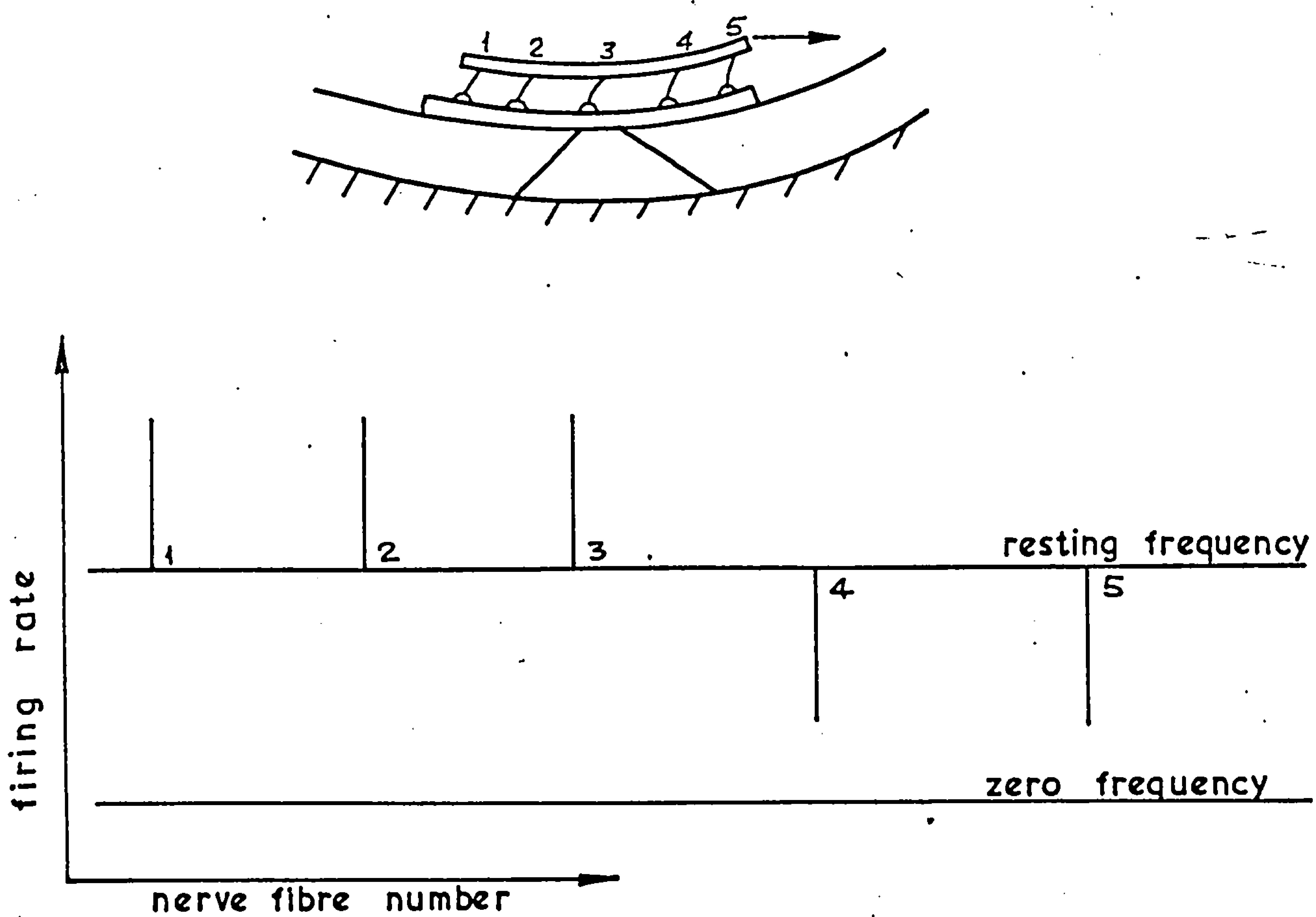
The 'heavy' otolith resting on or against its macula will shift its position as soon as the skull is moved. In one position the cilia of one section of the sensory cells in the macula are continuously pulled resulting in the subject receiving information of his position with regard to the gravitational vertical. If the position is changed another group of sensory cells is engaged and part of the former tension is released, the subject then received information of the change in position. Changes in muscular tension, especially in the neck result, this causes the eyes to move in a compensatory manner preventing the subject from losing his orientation. This action is shown in fig.7.6. 7.6a represents the utricular otolith at rest, all the cells fire at the same frequency. If the organ is acted up by, for example, a linear acceleration there will be a nearly instantaneous shift of the otolith mass with respect to the macula. The hair cells respond increasing or decreasing their firing rate depending on their orientation. The possible responses of the five cells are shown in fig.7.6b. Three cells respond with increasing frequency and two with a decrease from the resting frequency. At the same time, the acceleration acting on the mass of the otolith causes another movement involving the entire organ as shown in fig.7.6c (Mayne 1950, (60)). This movement produces a change in volume of the utricular sac requiring a flow of endolymph from the endolymphaticus to the utricle and creating a damping force. The effect of this movement is to change the radius of curvature of the otolith membrane in such a way as to reduce the effect of the previous movement by a varying amount depending on the velocity of the stimulus. The firing rate of the cells is then a function of both acceleration and velocity. The response of the 5 cells is also shown in fig.7.6c.

The frequency of cell 1 is reduced to the resting frequency.
That of cell 2 to a static value depending on the acceleration.
That of cell 3 is not reduced at all
Cells 4 and 5 are opposite in response to cells 1 and 2 in that the signals correspond to a drop instead of an increase of frequency.



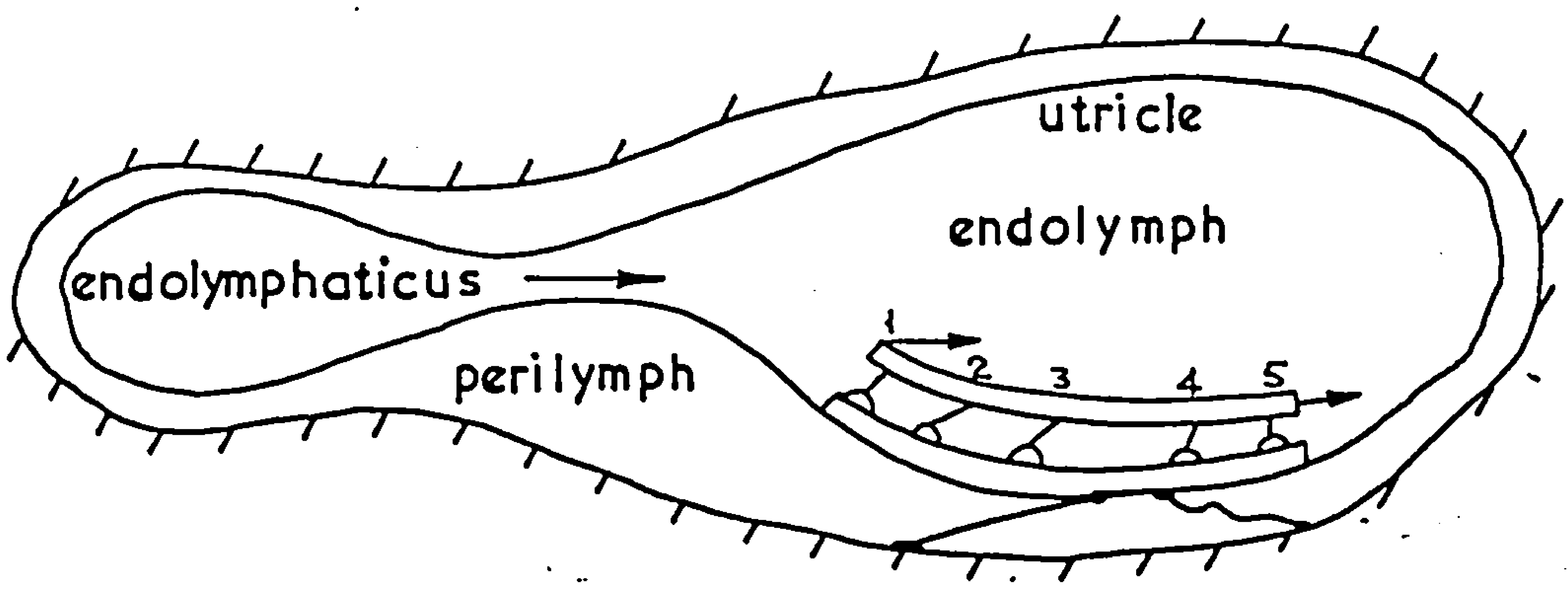
Diagrammatic representation of the utricular otolith at rest.

Fig. 7.6a

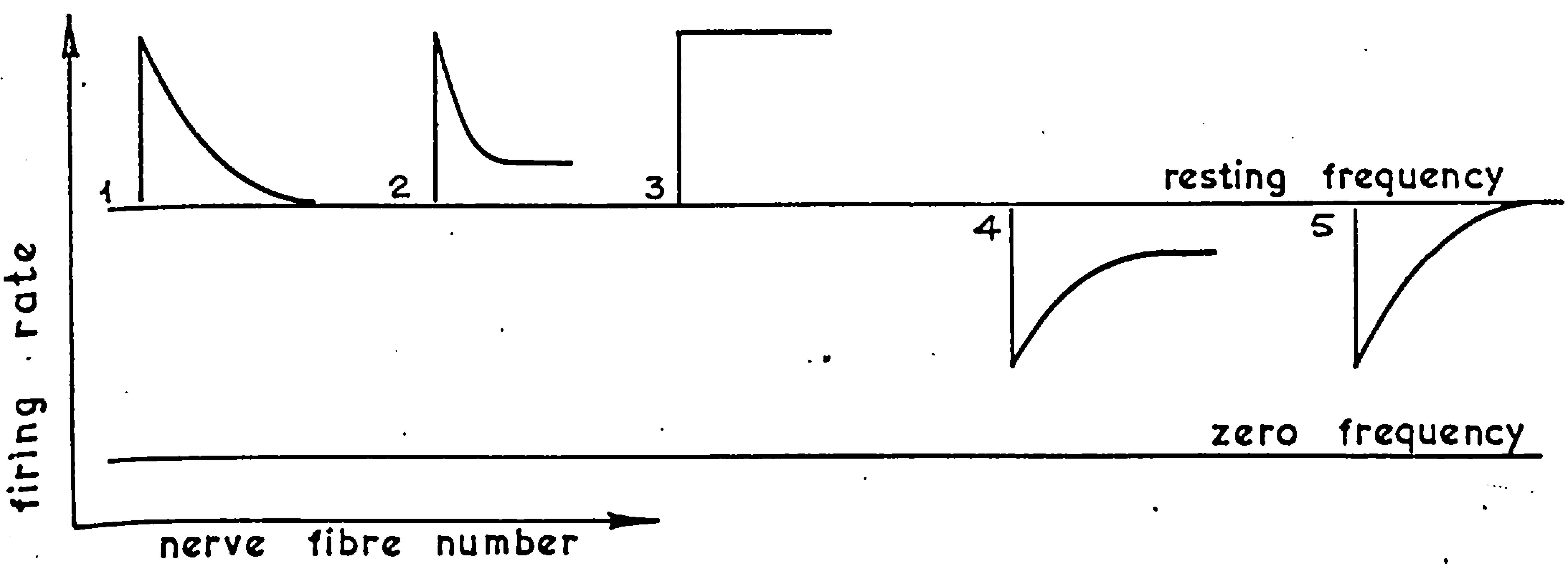


Initial response of the otolith to a step acceleration.

Fig. 7.6b



Utricular otolith



Ultimate response of the otolith fibres to step acceleration.

Fig. 7.6c

Each semi-circular canal responds to angular acceleration in its own plane, giving information of the angular rate and producing sensations of rotation.

Angular accelerations of the head in the plane of a particular canal cause the endolymph, due to its inertia, to flow through the canal deflecting the cupula from its rest position. This again results in a change in the frequency of the action potentials proportional to the angle of deflection of the cupula (Groen et al, 1952 (61)) and for small deflections around the rest position of the cupula there exists a strict proportionality.

The semi-circular canals are ideally adapted to sense the motions which are likely to be experienced under normal conditions. If, for example, the head is moved and then stopped, acceleration is followed almost immediately by deceleration and the inertia of the endolymph causes the cupula to be displaced only momentarily and the effects of its displacement are short-lived. If, however, the acceleration is followed by rotation at a constant rate, the endolymph catches up with the rotating canal, and the deflected cupula is restored to its rest position very slowly by virtue of its own elasticity. This gives rise to an erroneous perception of motion. On cessation of rotation the inertial reaction of the endolymph tends to keep it moving, thus deflecting the cupula in the opposite direction to its initial deflection. This gives rise to a sensation of rotation in a direction opposite to that of the physical rotation. The post-rotory sensation persists until the cupula is again restored to its rest position by its elasticity. (There is some debate as to whether the semi-circular canals are also stimulated by linear acclerations. This was suggested by Lansberg et al (62) but refuted by Johnson (63)).

7.3. Nervous Structure

The vestibular sensory cells are contained in five areas in each ear, the three cristae, one in each ampulla of the three canals, and the two macula, one each in the utricle and saccule, all are of basically the same structure. It is generally accepted that there are two basic types of sensory cells in the vestibular epithelia (Ades et al, 1965 (64)). The gross features of these cells are shown in fig.7.7. Each sensory cell is equipped with sensory hairs which project into either the cupula or the otolith. There are two types of sensory hairs as shown in fig.7.8, the sterocilia and the kinocilia, each cell has 30 to 100 hexagonally packed stereocilium and 1 kinocilium always situated on the periphery of the bundle.

When the surfaces of the sensory epithelium are examined a regular pattern of cell orientation is observed. (Wersall and Lundquist (65)). On the cristae of the horizontal semi-circular canals the kinocilium are on the sides of the cell nearest the utricle and in the vertical canals the kinocilia are on the sides of the cells farthest away from the utricle. The orientation on the macula is more complex. The direction of polarization varies gradually over the surface and a curving demarcation line divides the surface roughly in

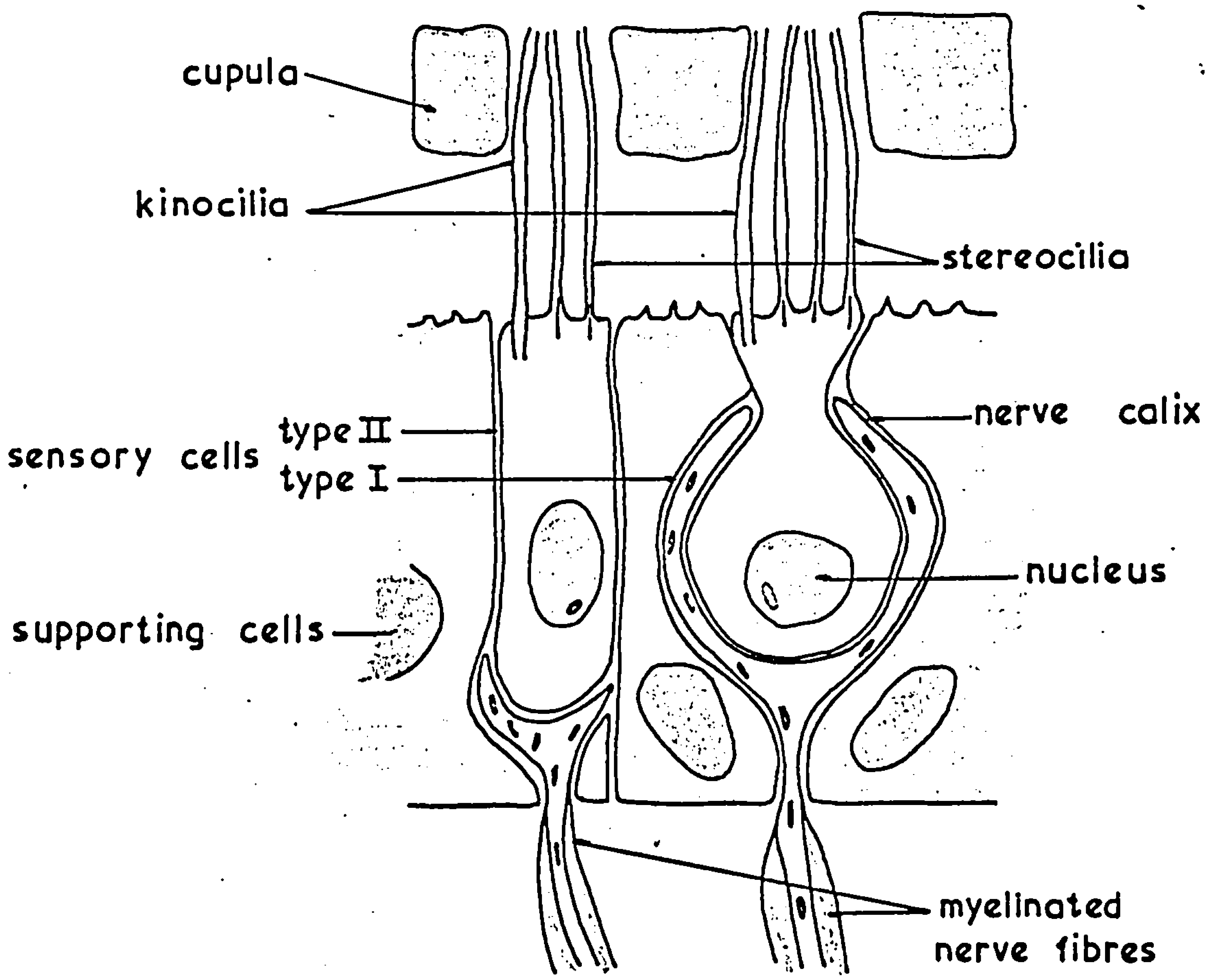


Fig. 7.7 Highly simplified diagram of the two types of sensory cells found in the crista. Type II cells are most frequent in the peripheral regions of the crista.

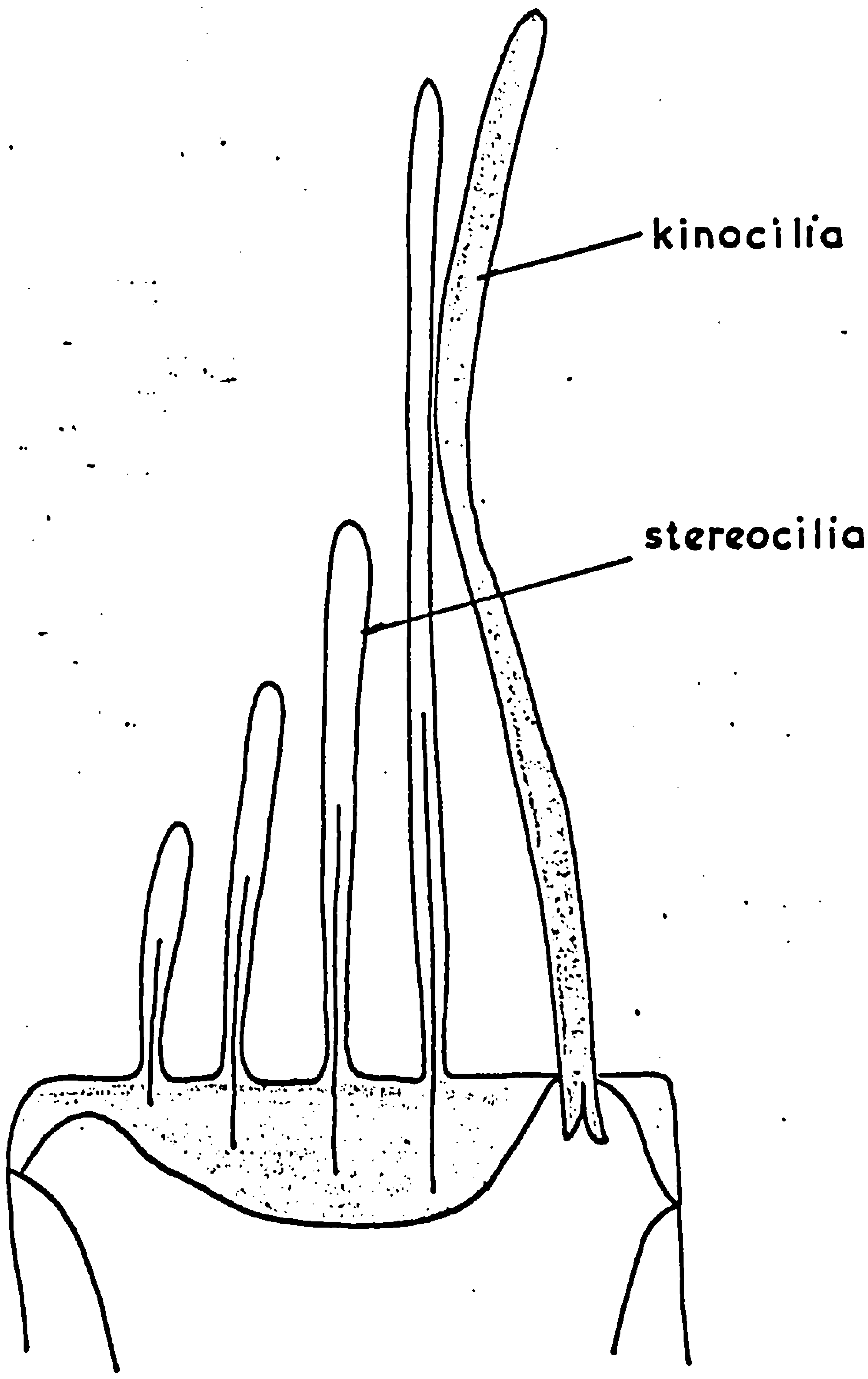


Fig. 7.8 Schematic diagram of a section through a vestibular sensory cell.

half. Across this line the sensory cells are oppositely polarized as shown in fig.7.9, all possible directions of polarization are represented according to Wersall and Lundquist (65) this polarization represents a directionally sensitive transducer mechanism. The main orientation of the sensory cells within a certain area of the sensory epithelium, reflects the directional sensitivity of that area. Although the importance of the kinocilium to the stimulation of the sensory cells has not been established, Lowenstein and Sand (66) showed that the deflection of the cupula towards the kinocilia increased the nerve discharge rate and that deflection in the opposite direction decreased the nerve discharge rate, Fig.7.10. Hence it is possible to hypothesise that the sensory cells are aligned in the direction of cupula displacement.

If the same correlation between morphological and functional polarization is assumed for the macula, then the macula should be sensitive to directional stimulation in all four quadrants of the macula plane. This assumption is supported by the findings of Lowenstein and Roberts (67) who obtained responses from a single utricular macula by tilting about all its horizontal axes.

In 1892 Ewald (68) observed that the endolymph flows through the horizontal canal towards the ampulla and utricle (ampullopetal or utriculopetal flow) elicited a stronger nystagmus reaction than did equal flow in the opposite direction (ampullofugal or utriculofugal). This effect was reversed in the vertical canal. These observations correspond with the alignment of the sensory cells, and form Ewald's Second

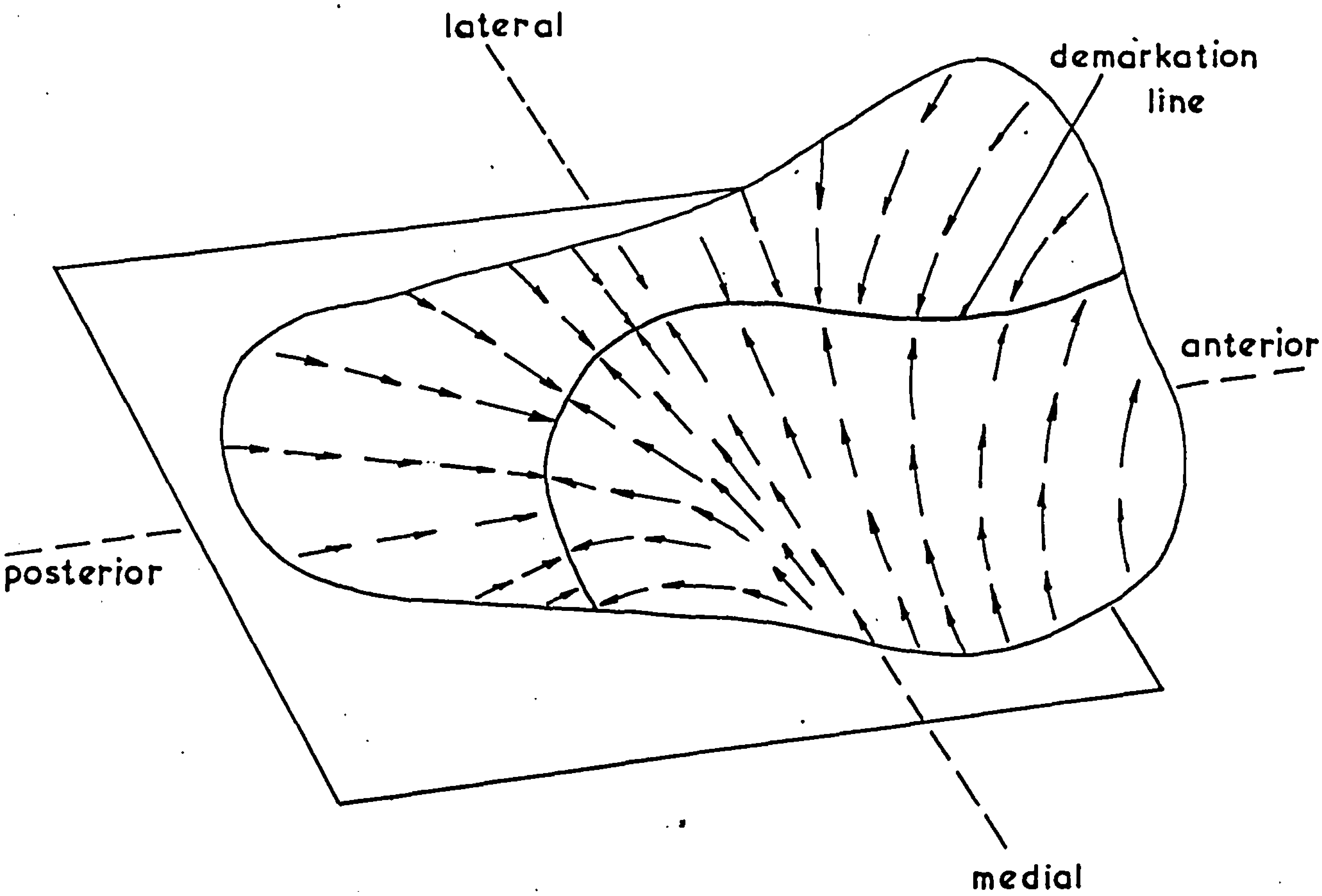


Fig. 7.9 Schematic representation of polarization pattern of sensory cells in utricular macula of a guinea pig. The kinocilia on either side of the demarkation line face each other.

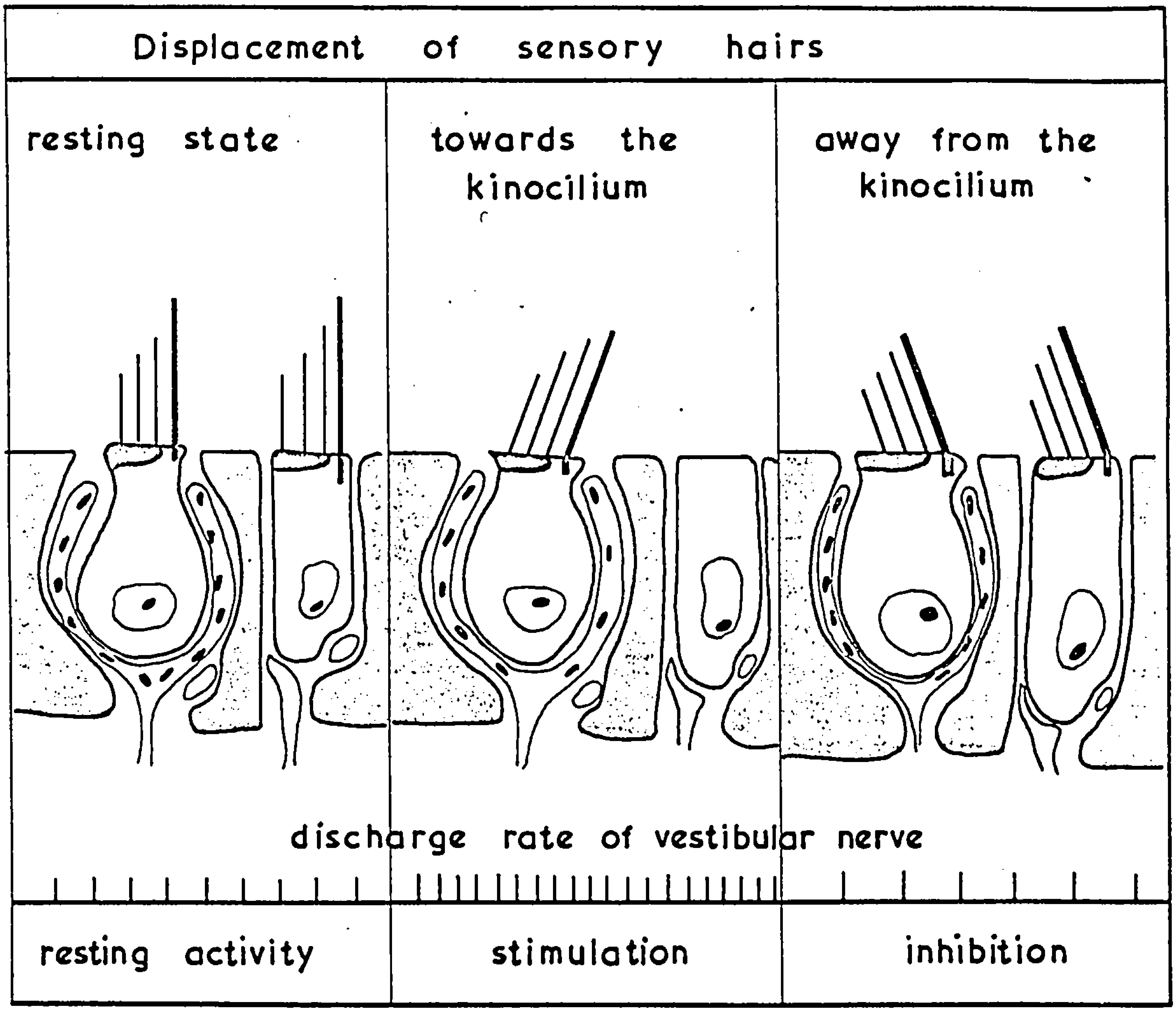


Fig. 7.10 Electrical discharge rate of the hair cells a function of the displacement of the sensory hairs.

Law of Directional Preponderance, describing the characteristics of the semi-circular canals.

i. The receptors of the semi-circular canals are direction specific.

ii. There is a quantitative difference in the response to equal ampullopetal and ampullofugal stimulation.

Lowenstein (69) found two types of sensory units, one having a steady state firing rate the other being quiescent at rest. Stimulation in the direction of the polarization of the sensory cells (positive stimulation) increases the firing rate of the spontaneously active cells and activates the quiescent cells. Negative stimulation, i.e. stimulation away from the direction of polarization, decreases the firing rate of the spontaneously active cells but does not activate the quiescent cells. Hence there is a greater overall change in firing rate for positive stimulation than for negative stimulation. This explains part ii of Ewald's Second Law. The two types of sensory cells, active and quiescent, cannot be correlated to the two structural types I and II, Fig.7.7. The structural features of the vestibular sensors may be summarized as follows:-

i. The polarization and orientation of the vestibular sensory cells, as indicated by the kinocilia, follows a definite pattern in each of the cristae and maculae and indicate directional sensitivity.

ii. The mammalian vestibular epithelia all contain two structural types of sensory cell which differ from each other in form and in the pattern of nerve endings.

iii. These sensory cells are further differentiated into spontaneously active and quiescent types. This possibly eplains the directional sensitivity of the vestibular sensors.

7.4. Interconnections with the Eyes

7.4.1. The Semi-circular Canals

The control of the eye muscles over various eye movements was described in section 4.1.

The work of various authors has suggested that stimulation of different parts of the vestibular system elicit different eye movements.

Szentágothai (70) stimulated the semi-circular canals of dogs individually and elicited contractions in pairs of muscles as follows:-

Canal stimulated	Muscle Contractions
Horizontal canal	homolateral medial rectus contralateral lateral rectus
Superior Canal	homolateral superior rectus contralateral inferior oblique
Posterior Canal	contralateral inferior rectus homolateral superior oblique

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Simultaneously, the antagonists of each of the muscles involved relaxes. This work was supported by that of Cohen et al (71) who found that stimulation of single nerves produced strong contractions in one pair of muscles and weak contractions in a second pair:-

Canal Stimulated	Strong Contractions	Weak Contractions
Horizontal Canal	homolateral medial rectus contralateral lateral rectus	None
Superior Canal	homolateral superior rectus contralateral inferior oblique	Contra. superior rectus homo. superior oblique
Posterior Canal	contralateral inferior rectus homolateral superior oblique	homolateral inferior rectus contralateral inferior oblique

The muscle contractions elicited by semi-circular canal stimulation produce eye movements as follows:-

Canal Stimulated	EYE MOVEMENT RESPONSES			
	Left Eye		Right Eye	
	Strong	Weak	Strong	Weak
left horiz. right horiz.	right left	none none	right left	none none
left superior right "	up left roll	right roll up	right roll up	up left roll
left posterior right posterior	right roll down	down left roll	down left roll	right roll down

Hence stimulation of the vertical canals singly produces disjugate eye movements. For example stimulation of the left superior canal causes the left eye to move up strongly with a weak rolling movement to the right, and the right eye to roll to the right with a weaker upward movement. Stimulation of either horizontal canal produces conjugate eye movements.

Cohen and his coworkers also stimulated the ampullary nerves in various combinations and observed eye movements as follows:-

SEMI-CIRCULAR CANAL PAIR STIMULATED.	LEFT EYE MOVEMENT	RIGHT EYE MOVEMENT
left and right horizontal	none	none
left and right superior	up	up
left superior and posterior	right roll	right roll
left superior and right posterior	none	none
right superior and posterior	left roll	left roll
right superior and left posterior	none	none
left posterior and right posterior	down	down

The disjugate eye movements elicited by stimulation of one vertical canal only are no longer seen, when pairs of canals are stimulated the eyes move conjugately or not at all. For example simultaneous stimulation of the superior canals produces activation of the left and right superior rectus muscles and inhibition of the oblique and inferior rectus muscles of both eyes thus producing a strong upward movement.

7.4.2. The Utricles

The classical otolith theory asserts that the effective stimulus of the utricle is a displacement of the otolith in the plane of the macula.

Szentágothai (72) studied the patterns of reflexes in the extraocular muscles of the dog to artificially induced movement of the utricular otolith, and the findings agreed with the classical theory. The eyes responded as would be expected if the head was tilted, that is, when the otolith was moved laterally the appropriate eye muscles tended to counterroll the eyes, and when the otolith was moved forward the eyes were elevated. These reflexes developed very slowly compared with those elicited by stimulation of the semi-circular canals, indicating more complex and devious pathways inter-connecting the utricular maculae and the ocular muscles.

It was also noted that the pattern of ocular muscle responses varied with the direction of the force applied to the otolith. From this Szentágothai developed a mosaic quadrant theory of macula function. According to this theory the sensory cells of each quadrant of the macula activate different pairs of ocular muscles as shown in fig.7.11. Whenever the otolith moves the bending of the hairs towards the centre or

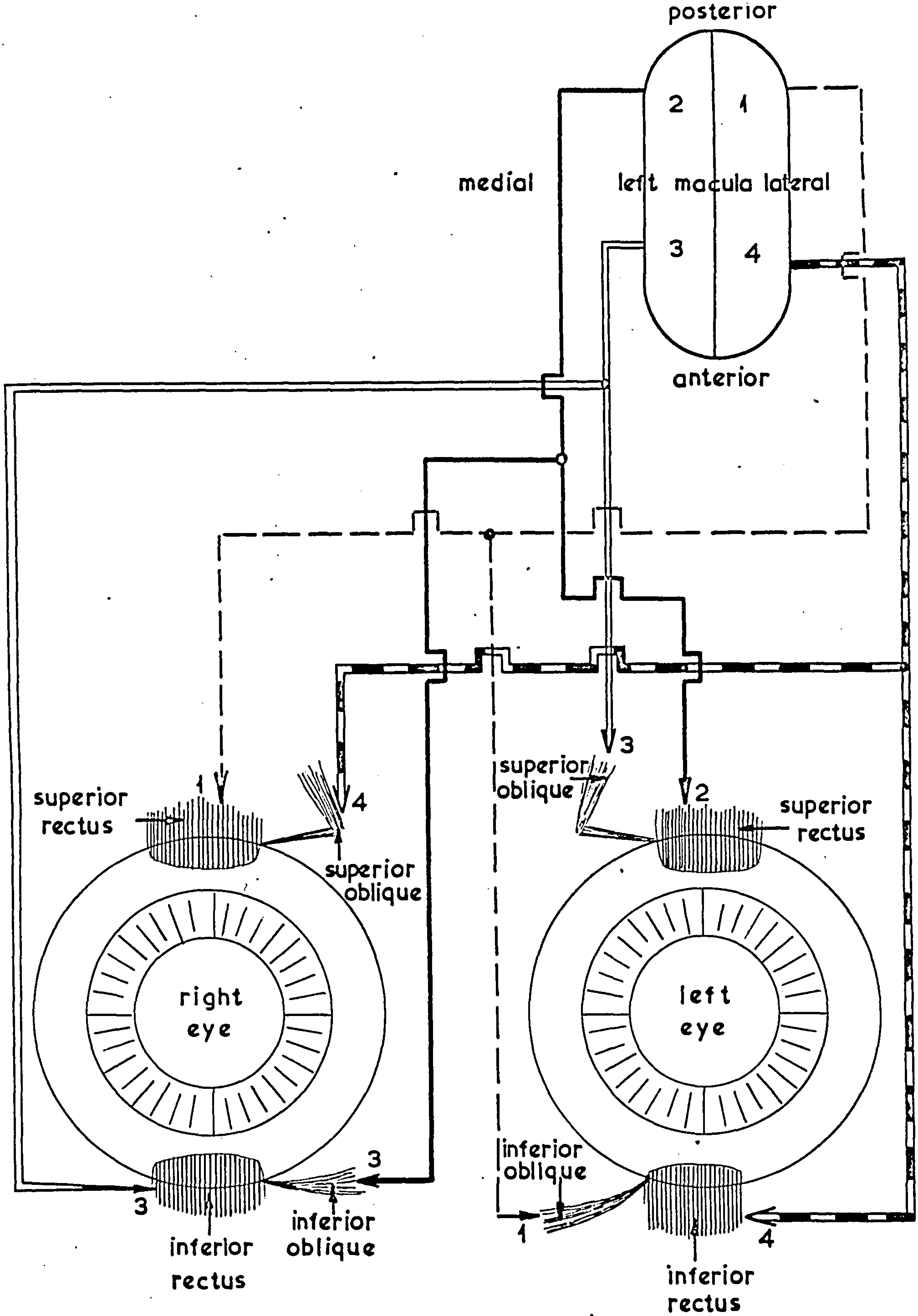

Fig. 7.11 Guaudrant theory of connections of the utricular sensory cells with the vertical recti and obliques. (after Szentágothai)

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opposite margin of the macula increases the discharge rate of their sensory cells, thus causing the muscles indicated in fig.7.11 to contract. Simultaneously, the antagonists of the contracting muscles relax or are inhibited. The pattern of excitation and inhibition of the ocular muscles is shown below.

Left Eye Muscles	QUADRANT STIMULATED			
	1	2	3	4
Superior rectus Inferior rectus Superior oblique Inferior oblique	 inhibition excitation	excitation inhibition	 excitation inhibition	inhibition excitation
Right Eye Muscles	**QUADRANT STIMULATED**			
	1	2	3	4.
Superior rectus Inferior rectus Superior oblique Inferior oblique	excitation inhibition	 inhibition excitation	inhibition excitation	 excitation inhibition

Responses to stimulation of the left and right utricles are the same.

If the head is tilted forward quadrants 1 and 2 of each macula are stimulated and the superior rectus and inferior oblique muscles of each eye contract, this causes both eyes to elevate with a rolling to the left of the left eye and to the right of the right eye. Elevation of the eyes is compensatory and the reflex to be expected, but disjugate rolling of the eyes is not. However, refering to section 4.1 where the action of the extraocular muscles was discussed, it is possible that the contractions of the inferior obliques are just sufficient to counteract the tendency of the superior recti to produce intorsion (see fig.4.2). If this were so a pure compensatory motion of the eyes would result. Similar but oppositely directed reflexes follow tilting the head backwards.

In the case of lateral tilting or rolling of the head, for example, to the left, quadrants 2 and 3 of the maculae are stimulated. This causes the superior rectus and superior oblique muscles of the left eye and the inferior rectus and inferior oblique muscles of the right eye to contract. These reflexes produce the desired compensatory counterrolling of both eyes to the right but also tends to produce elevation of the left eye and depression of the right eye. Again it may be that the contractions of the rectus muscles, which are non-compensatory, are just sufficient to counteract the tendency of; (i) the contracting superior oblique to depress the left eye and (ii) the contracting inferior oblique to elevate the right eye; thus resulting in pure compensatory eye movements. Since observations of normal animal and human subjects show that pure compensatory eye movements do take place it is likely that the proposed explanation is valid.

The work of Wersall and Lundquist (65) on sensory cell polarization in the macula supports the quadrant theory.

7.4.3. The Saccules

No work directly measuring the activation of the extraocular muscles by saccular stimulation has come to the author's attention but it is possible to deduce these activations by studying observations made of eye movements produced by saccular stimulation.

An investigation made by Lowenstein et al (69) showed that the saccular surface is divided into two areas according to the orientation of the stereocilia and kinocilia. In the superior part the kinocilia are directed upwards and in the inferior part, downwards (fig.7.12). Fluur and Mellstrom (95) studied the ocular responses produced in spinalized cats by direct stimulation of different parts of the two regions of the saccular macula in order to ascertain which eye movements could be released from the two regions, and if the reciprocal orientation of the hair cells corresponded to a similar reciprocity in their physiological influence on the oculomotor reaction.

When decerebrated cats were used uncoordinated eye movements were produced. During stimulation of the superior saccular area on the left side, the left eye was elevated and the right eye rotated clockwise. This corresponds to the activation of the left superior rectus and the right inferior oblique. Stimulation of the inferior area again of the left side produced anti-clockwise rotation of the left eye and depression of the right eye. This indicates that the main activation is of the left superior oblique and the right inferior rectus.

When alert cats were used only coordinated eye movements were produced. Stimulation of the superior saccular region produced an initial elevation followed by a nystagmus downwards. Thus indicating activation of both superior rectii. Stimulation of the inferior region produced coordinated depression of the

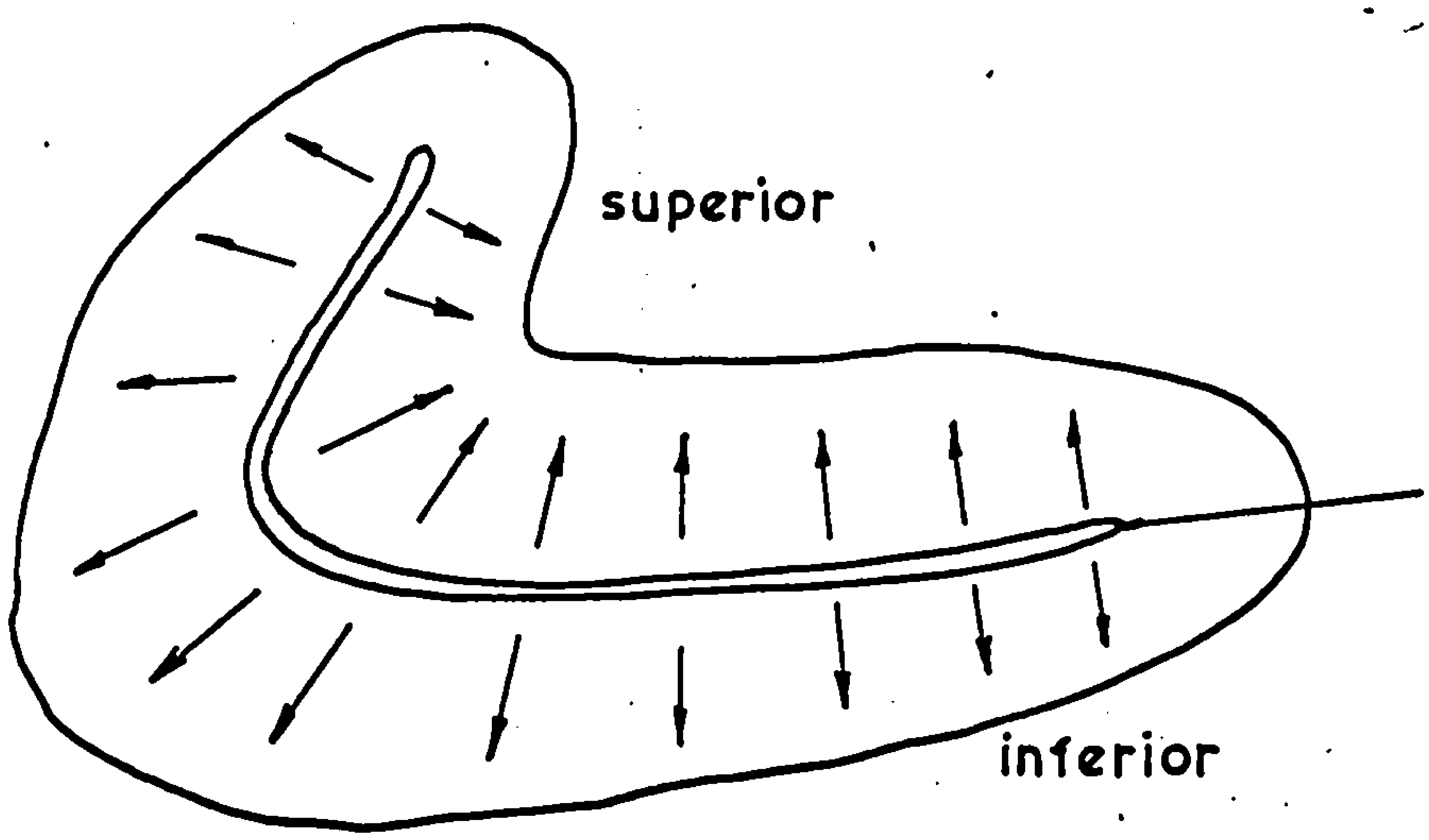

Fig. 7.12 Illustration of the anatomical orientation of the sensory cells of the two saccular areas on the left side.

eyes thus indicating activation of both inferior rectii. It is possible (referring to section 4.1) that in the alert animal the central coordinating mechanism overrules the activation of the obliques which produced the non-compensatory disjugate rolling.

Stimulation of the striola - the border between the two regions - produced clockwise rotatory eye movement indicating activation of the superior rectii and superior obliques of both eyes.

If each of the two areas was stimulated at successive points along an interior-posterior line the amplitude of the eye movement decreased.

CHAPTER 8

KNOWN CAUSES OF BALANCE DISTURBANCE

8.1 Semi-Circular Canal Disturbance

Semi-circular canal reflexes, which indicate disturbance of this part of the balance mechanism, are elicited by a stimulus which produces endolymph flow causing a deflection of the cupula. The normal stimulus is angular acceleration in the plane of one or more of the canals, but endolymph flow, and consequent cupular displacement, can be induced by temperature gradients in the endolymph brought about by irrigation of the ear with hot or cold fluids (caloric stimulation). The semi-circular canal reflexes can also be induced by electrical stimulation of the ampullary nerves, however these reflexes are not complete as it is not possible to duplicate electrically the nervous stimulation evoked by movements of the head.

8.1.1. Angular movement stimulation

Each semi-circular canal acts as a heavily damped angular accelerometer. (See Appendix 1).

If the head is moved and then stopped, a movement experienced by all animals under normal conditions, the endolymph causes the cupula to be displaced only momentarily, the subject received accurate information of his change in position, the response is immediate and the effects of the displacement are short-lived. If, however, the subject is rotated at a constant rate after the initial acceleratory movement, the endolymph catches up with the rotating canal and the cupula is restored to its rest position very slowly by means of its own elasticity. When the rotation stops the inertial reaction of the endolymph keeps it moving and the cupula is deflected in the opposite direction. This transmits false neural information of motion and the subject experiences a sense of rotation in the opposite direction to the initial movement. This post-rotatory sensation persists until the cupula is again restored to the rest position.

The general nature of the eye movement reflexes is as follows: When a subject, with head erect, is rotated about a vertical axis each eyeball will rotate in the opposite direction in order to maintain a steady image on the retina. If the rotation persists, nystagmus occurs, the eyes upon nearing the limit of their travel will rapidly flick in the direction of rotation and then resume their compensatory counterrotatory motion. When the rotation stops the reflex reverses and the nystagmus is in the opposite direction. The signal output of the semi-circular canals gradually declines, the sensation of rotation vanishes, and the compensatory eye movements stop. If the changes in rotation rate are large enough and sufficiently abrupt, disorientation results as the reactions evoked cannot be suppressed by other modalities such as vision.

8.1.2. Caloric Stimulation

The semi-circular canals may be stimulated by temperature changes introduced, usually, by irrigation of the auditory canal with either hot or cold water or air. The temperature change is conducted first to the lateral part of the horizontal canal and then to the lateral parts of the vertical canals. This causes temperature gradients and hence density gradients in the endolymph, convection currents are then produced in any canal not lying in the horizontal plane, and the associated cupula is deflected. Consequently neural information of a change in position is transmitted by the sensory nerves of the ampulla and the subject experiences a sense of rotation. This does not correspond to physical reality, and disorientation results. Reversing the temperature gradient, by using cold instead of hot water, reverses the direction of the convection currents and reverses the deflection of the cupula thus producing a rotatory sensation in the opposite direction.

Nystagmus accompanies deflection of the cupula. The canal stimulated and the direction of the nystagmus induced depends on the orientation of the subject's head during stimulation and whether or not hot or cold water was used.

The convection currents and hence the nystagmic reflexes are increased by increasing the gravitational field and eliminated by a zero-gravitational field this indicating that the neural responses are produced by convection currents moving the cupula and not by the thermic stimulus acting directly on the ampullary or oculomotor nerves.

8.2 Otolithic Disturbance

The theory of the otolith functions, their operating principles and causes of disturbance has not progressed to the same stage as that of the semi-circular canals. Although it is known that linear acceleration and changes in the gravitational vertical are the physiological stimuli of the otolith organs, the reflexes induced by such stimuli and the mechanism of disturbance have not been conclusively determined or other modes of stimulation considered.

8.2.1. Static disturbance-tilting

When the subject is in the supine position the plane of the utricular macula is almost vertical and the plane of the posterior part of the saccular macula is at an angle of 22^{o} to the sagittal plane behind the head. If the subject is tilted, keeping the relative position of the head and body constant, the positions of the otolithic organs with respect to the gravitational vertical is changed. The otoliths of the uptilted utricle glides parallel to the vertical plane of the utricle causing deflection of the sensory hairs of the antero-lateral part. When the angle of tilting is 22^{o} the plane of the saccule is almost vertical and the saccular otoliths glide across the macula causing deflection of the sensory hairs of the postero-medial part. The eye-movement reflexes induced are anti-compensatory. Stimulation of the right otoliths causes tonic eye deviations to the left, and stimulation of the left otoliths causes tonic eye deviations to the right.

8.2.2. Dynamic Disturbance-Linear Acceleration

The normal stimulus for the otolith organ is gravitational force - variation of the directional parameter was discussed above and constitutes a static disturbance. To vary the magnitude parameter of the gravitational force a linearly accelerating force must be applied, the resultant of these two acts on the otoliths essentially as a single force as it is impossible for any measuring instrument to distinguish between inertial and gravitational forces (Colenbrander 73). As described in section 7.1.2. this causes a nearly instantaneous shift of the otolith mass with respect to the macula and the hair cells respond by increasing or decreasing their firing rate depending on their orientation. This neurological signal is directly proportional to the applied force.

The linear acceleration can be applied in three ways i. by centrifuge ii. by vertical linear accelerator, iii. by parallel swing. Each method gives a different ocular response thus indicating stimulation of different quadrants of the macula (see fig.7.11).

When the linear acceleration is applied using a centrifuge the ocular response induced is counterrolling and Colenbrander (73) demonstrated a simple linear proportionality between the outward shearing force of the otoliths on the utricular maculae and the counterrolling response. This particular response indicates lateral movement of the otoliths across the maculae (see section 7.1.4b) causing stimulation of quadrants 2 and 3.

Using a vertical linear accelerator the applied force varies in direction and magnitude hence the effect on the otoliths is effectively that of a periodically changing gravitational field. The ocular response induced is a vertical nystagmus with the fast phase downwards. The slow component starts at the point of maximum gravitational force and the fast component appears during the time of greatest build-up of the gravitational force. The nystagmic beat has a characteristic notch in the slow component which disappears when the saccule of the test subject is destroyed thus suggesting that both the utricular and saccular otoliths contribute to the eye movement (McCabe 74). This type of ocular response indicates stimulation of quadrants 3 and 4 of the macula.

The parallel swing effectively applies a periodically changing linear acceleration in the horizontal plane. The ocular response is again a vertical nystagmus, but without the saccular notch and the direction is reversed (Jongkees and Philipozoon 75). This indicates that the shearing of the otolith across the macula stimulates quadrants 1 and 2.

8.3. Saccular Disturbance

Even less is known about the function of the saccular otoliths. It was suggested by Kubo (76); Magnus and deKleyn (77); Benjamins (78); Hasegawa (79); Perlman (80); Adrian (81); Lowenstein (82); Jongkees (83); Szentágothai (84) and others that the saccular otolith responds to linear acceleration and keeps the equilibrium posture. On the other hand Maxwell (85); Versteegh (86) and McNally (87) considered the saccular otoliths to play no role in the equilibrium function. From yet another standpoint Ashcroft and Hallpike (88); Zotterman (89) and Tait (90) induced responses from the saccular otolith and macula by stimulation with sound vibration. Although these reports were highly speculative they suggested that incident sound vibration stimulates the hair cells of the saccular macula directly by causing the nerve fibres to discharge. Tait (90) suggested that while the cochlea responds only to externally produced sound vibration the saccule responds to both externally and internally produced sound vibration and that it is probably involved in the emission and regulation of the voice.

This confusion was somewhat resolved by the work of Owada and Shiizu (91) in recent years who resected the upper saccular nerve of the rabbit at the exit of the labyrinthine bony capsule and by observing the eye movements produced by changing head positions investigated the relationship between these eye movements and the postural role of the saccule. No spontaneous nystagmus wasobserved after resection with the head in the normal upright position, thus indicating that the saccule does not control posture. When the operated ear was placed down the normal compensatory eye deviations did not occur, but when the operated ear was placed upwards normal compensatory deviation was observed. When both saccular nerves were resected compensatory deviation was not observed in any head position but there was a slight increase in nystagmic activity. The compensatory deviation of the eyeballs is, as stated previously, a reflex function to fix images on the retina and thus assist orientation. So it would appear from the work of Owada and Shiizu that the saccular otoliths have no function in equilibrium posture but play some role in re-orientation when this equilibrium is disturbed and that the saccular macula is stimulated by the hanging position of the otolith.

In a second series of experiments d.c. stimulation was applied to the saccular macula. When a positive current was applied to one labyrinth the homolateral eyeball deviated downwards and the ipsilateral eyeball upwards. By applying a negative current the deviations were reversed. Although the authors draw no conclusions from this result it would suggest that the stimulation causes the nerve fibres to discharge i.e. it is a saccular macula rather than saccular otolith effect.

8.4. Functional Relationships Between the Vestibular Organs

8.4.1. Interaction between the semi-circular canals and the otolith system

As was described previously the generally accepted theory of the function of the vestibular organs is that: i) the static group, consisting of the otolith organs, respond to gravity and gravity changes induced by linear accelerations but not to angular accelerations; and ii) the rotatory group, consisting of the six semi-circular canals respond to angular accelerations but not to linear accelerations or gravity. This distinction does not adequately explain many observed responses to vestibular stimulation. For example, a subject over exposed to angular acceleration becomes dizzy and falls down. The dizziness is a manifestation of semi-circular canal disturbance but the 'falling down' aspect is an otolithic reaction. This is usually explained as being due to slight head tilts after the angular acceleration has stopped. Alternatively it is possible that rotatory stimulation somehow affects the static organs directly, or the central nervous system associated with the utricles, implying that the utricles and the semi-circular canals have a combined function.

Apart from reports of subjective observations which support this theory (Gray 92 and Lansberg 93) the only corroborative work is that of Owada and Okubo (94). Two groups of rabbits, one with totally intact vestibular systems and the second with sectioned utricular or saccular nerves, were subjected to various vestibular investigations.

Spontaneous nystagmus was induced by sectioning the ampullar nerve. For animals with intact otolithic organs this spontaneous nystagmus is suppressed by cold caloric stimulation to the contralateral, normal ear. When the utricular nerve was also sectioned much stronger cold caloric stimulation was necessary to suppress to nystagmus. This phenomena was not observed in animals with sectioned saccular nerves.

When hot or cold caloric stimulation was applied to the operated ear changes in the spontaneous nystagmus were observed. When only the utricle was left intact cold caloric stimulation decreased the nystagmic activity, but the same stimulation when only the saccule was intact increased the nystagmus. When all three receptors were destroyed little or no change was observed.

From these observations it can be concluded that the utricle and the saccule respond to caloric stimulation, and have a controlling effect on nystagmus, the utricle being an inhibitor and the saccule an enhancer.

8.4.2. Interaction between the utricle and the saccule

There would appear to be no true interaction between the utricle and the saccule, in the sense that one modifies the action of the other, but according to Fluur (95, 96) certain types of linear acceleration activate the sensory cells of parts of both the utricular and saccular maculae producing a combined ocular response.

a. Utricular areas where the sensory cells are oriented backwards are stimulated during linear acceleration forwards producing a downward eye movement.

b. Utricular areas where the sensory cells are oriented forwards are stimulated during linear acceleration backwards producing upward eye movements.

c. Saccular areas where the sensory cells are oriented downwards and forwards respond to linear accelerations upwards and backwards producing vertical eye movements downwards.

d. Saccular areas where the sensory cells are oriented upwards and backwards respond to linear accelerations downwards and forwards producing vertical eye movements upwards.

Hence a. and d. and b. and c. are antagonistic and tend to decrease the ocular response.

e. Utricular areas where the sensory cells are oriented to the right are stimulated during linear acceleration in the frontal plane to the left causing horizontal eye movement to the right with a slight anti-clockwise rotation.

f. Utricular areas where the sensory cells are oriented to the left are stimulated by linear acceleration in the frontal plane to the right causing horizontal eye movement to the left with a slight clockwise rotation.

g. The saccules produce rotatory eye movements only if the stimulation is perpendicular to their surface.

When both sensory cell orientation areas are stimulated simultaneously. The left saccule then functions antagonistically to the left utricle (point E) and the right saccule functions antagonistically to the right utricle (Point F).

CHAPTER 9

DISCUSSION OF RESULTS

This work has shown that low frequency sound, when applied binaurally to normal observers can produce a disturbance of the balance organs, indicated by a clearly defined vertical nystagmus. Although vertical nystagmus is classically regarded as the ocular response induced by stimulation of the anterior vertical canal there is a body of work which indicates that it can also be induced by stimulation of the otolith system (63, 74, 98). Both the objective and subjective results of this series of experiments indicate otolithic stimulation.

9.1. Summary of observed low frequency effects

At all levels of stimulation subjects reported sensations associated with extreme pressure changes i.e. middle ear pain and difficulty in swallowing. During whole body stimulation sympathetic vibrations of various parts of the body were set up when the stimulus frequency was in the range of the natural resonance of these organs. For example the abdomen and thorax vibrated in the 10Hz region and spasmodic coughing and nasal vibrations occured in the 15-20 Hz range. Sensations of falling occured at all frequencies. In the 2-5Hz range these only occured above a sound pressure level of 140dB. In the mid-frequency range 5-10Hz these sensations were very strong at all levels. Above 10Hz this particular sensation was reported less frequently possibly due to the much more severe and fightening sensations of shivering, perspiration and uncontrollable coughing occupying the subject's attention.

Of the three methods of stimulation used a binaural antiphasic presentation induced a stronger nystagmic response than either binaural in phase or monaural presentation. Nystagmus was only induced when the subject's head was vertical, no response was obtained from prone subjects. In all cases the vertical nystagmus induced was of the type with the fast movement downward, it was completely removed by visual fixation and short term habituation occured.

The stimulus and nystagmic response were not synchronised and there was a variable latency period between the onset of the stimulus and the onset of nystagmus. This latency was subject dependent but no relationship with any of the other parameters could be found although generally the stronger the stimulus the shorter the latency period. That is the time lag between the onset of the stimulus and the onset of the response, for a specific stimulus varied from subject to subject, but for each subject a specific stimulus always resulted in the same latency period. For any given subject no relationship could be found between this latency period and any of the other parameters although it did vary from stimulus to stimulus. The stimulii which resulted in the stronger subjective effects generally produced shorter latencies.

NO relationship between the duration of the nystagmus and the intensity or frequency of the stimulus was found. The nystagmus duration was solely dependent on the duration of the stimulus in an approximately 1:1 ratio. For stimulus durations of less than 15 seconds the ear appears to behave as a simple stimulus integrator.

It was found that the minimum infrasonic stimulus necessary to induce a vertical nystagmus is a function of both the intensity and duration of the stimulus at any given frequency. This nystagmic threshold varies with frequency in the same manner as the auditory threshold varies with frequency, in the same frequency range.

9.2. Relationship of low frequency effects to other causes of balance disturbance

Over stimulation of the semi-circular canals is the most common cause of vestibular nystagmus and, as was stated above, stimulation of the anterior vertical canal is classically regarded as the cause of vertical nystagmus; but when the nature of the response is considered it is apparent that simple over-stimulation of the canals does not occur. The subjective response to be expected from canal stimulation is one of spinning and in this case the only subjective sensation of movement reported was that of swaying or falling which is the response to be expected only from otolithic activity.

When the semi-circular canals of normal subjects are stimulated in a manner which induces occular nystagmus, for example by the rotating chair method, the response is closely synchronised with the onset of the stimulus. Even when caloric stimulation is used, a method which employs the peripheral pathway of setting up convection currents, a similar response pattern is observed. These pathways, for stimulation of the semi-circular canals, can be said to be of 'low resistance' in that the organs being stimulated respond very easily in a straightforward manner.

The results obtained by infrasonic stimulation do not follow this pattern. There was considerable latency between the onset of the stimulus and the onset of nystagmus, these events were not synchronised and for stimulus durations of less than 15 seconds a degree of stimulus integration was involved. Hence it is unlikely that low frequency tones cause disturbance of the semi-circular canals, but the results do indicate disturbance of either the utricular or saccular otolithic systems.

That an otolith-occular reflex exists has been suggested for over 40 years. Sjoberg (97) 1931 demonstrated in rabbits, a vertical eye movement when subjected to horizontal linear acceleration. Jonkees (98) 1961 recorded rhythmic eye movements on humans subjected to regular oscillations on a parallel swing. Johnson (63) 1963 using a counterrotating chair, which produces otolithic stimulation rather than semi-circular canal stimulation, showed a regular eye movement in humans. In all cases the eye movement was rhythmic but without the quick-slow character typical of nystagmus. Relatively recent work by

McCabe (74) 1964 showed that vertical nystagmus can be induced by stimulation of the otolith system. Subjects both human and animal were accelerated vertically rather than horizontally and the accelerating forces varied sinusoidally in direction and intensity. A vertical nystagmus of small amplitude was induced, the direction of which depended on the direction of acceleration. It was ascertained that the nystagmus arose from the otoliths by using streptomycin to destroy the crista neuroepithelium and hence removing the possibility of canal response. This did not appreciably affect the ocular response, thus indicating that it arose from either the utricles or saccules. The most interesting results were obtained after destruction of the saccules leaving only the utricles intact. With the subject's head upright no eye movements were recorded, with the head in the lateral position a nystagmus of much smaller amplitude was obtained. This would suggest that to a large extent the nystagmus arises from saccular disturbance.

Even stronger evidence of a saccular-ocular reflex was obtained by Owada and Shiizu (91). This work was discussed in detail in Chapter 8. When pressure changes were applied to the saccules by changing the head positions of the experimental animals, ocular reflexes, including vertical nystagmus were obtained. Owada and Shiizu suggested as a result of this work that the action of the saccules are mutually antagonistic. That is if only one saccule is stimulated the ocular response is in the opposite direction in each eye-ball. Hence if both saccules are stimulated simultaneously in the same direction the ocular response induced from the left saccule tends to counteract the ocular response induced from the right saccule, but if the two saccules are stimulated in opposing directions the two ocular responses are complementary. This could possibly explain why the low frequency stimulus presented binaurally in antiphase had a much stronger ocular effect than when presented in phase or monaurally, as for any given cycle one ear experiences an increase in pressure while the other experiences a decrease in pressure i.e. stimulii in 'opposing directions'

9.3. Comparison with other evidence of acoustical vestibular stimulation

Since the 19th century evidence has suggested that the vestibular apparatus can be activated by low frequency acoustical vestibular stimulation. In 1899 Deetjen (99) observed movement in the perilymph in the vertical canal of a calf's head following stimulation with a Klein's whistle. He suggested that movements of the perilymph could be transmitted to the cupula via the walls of the membraneous labyrinth and the endolymph. Richard 1916 (100) demonstrated that vestibular responses to acoustical stimuli could be obtained in guinea pigs following the destruction of both cochleae but not following bilateral destruction of the vestibular receptors.

Indications of vestibular excitation, including nystagmus, shifts of the visual field, and subjective sensations of motion have been associated with acoustical stimulation at intensities of 120-150 dB SPL in the 5-2500Hz range by von Bekesy 1935 (10);

Wever and Bray 1936 (9); Cawthorne 1949 (101); Dickson and Watson 1949 (102); Dickson and Chadwick 1951 (50); Harris and Sommer 1967 (103); Mohr and von Gierke 1965 (43) and Nixon, Harris and von Gierke 1966 (104). Histological studies by McCabe and Lawrence 1958 (52); Albernaz, Covell and Eldredge 1959 (54); Covell and von Gierke 1968 (105) provide further evidence that the vestibular apparatus can be stimulated acoustically and that exposure of guinea pigs to intense sound can produce damage to the vestibular labyrinth particularly the saccule.

Recent work by Reschke, Parker and von Gierke 1968-1970 (47, 48, 49) investigated the effects of very low frequency acoustical stimulation, in the form of static pressure changes, on guinea pigs. The results obtained closely correlate to the low frequency effects on humans presented in chapter 5. Nystagmus, counter-rolling, and head movements were induced. Stimulus integration occured for short duration exposures and there were variable latency preriods between the onset of the stimulus and the induced response.

9.4. Mechanisms of vestibular activation implied by the observations

9.4.1. Fluid Flow Theory

The results shown in chapter 6 support the hypothesis that one possible mechanism for the acoustical stimulation of the vestibular system is perilymph/endolymph displacement. Very low frequency sounds of the type used in these experiments may be regarded as low frequency periodic pressure changes, which could induce motion in the stapes footplate, thus displacing the inner ear fluids. As the vestibular receptors are suspended in a continuous fluid fitted system and are close to the perilymphatic volume under the stapes footplate it is reasonable to expect that large displacements of the stapes footplate could result in stimulation of these receptors.

When the stapes is displaced inward fluid flows round the cochlea and produces deformation of the elastic round window. Consider that parallel to this normal path for fluid flow and wave propagation there is a second high impedance path for fluid displacement as the results imply, then high pressure in the perilymph under the stapes footplate could produce a fluid flow through the vestibular portion of the membraneous labyrinth resulting in deformation of the hair cells.

If fluid is to be displaced through the vestibular labyrinth there must be some elastic structure allowing volume displacement or an outlet through which fluid could flow. It is possible to conjecture that such a pathway exists via the endolymphatic duct to the endolymphatic sac. (see figure 7.6c).

The speculation is that there are two pathways for fluid flow through the labyrinth when pressure is applied to the oval window; one through the cochlea and the other via the perilymph through the endolymphatic duct to the endolymphatic sac. The second pathway would have a much higher mechanical impedance and probably such a high resistive component as to limit any appreciable fluid displacement, and potential vestibular stimulation, to low frequency or static pressure changes. Therefore for audio frequency stimulation, this low pass characteristic of the second pathway would result in no effective fluid displacement through the vestibular apparatus.

Support for these speculations is as follows:-

1. The long response latencies which were observed suggest that there is a high resistance to fluid flow.

2. Differences in latency as a function of stimulus intensity suggests that fluid flow through the endolyphatic duct occurs more readily following intense stimulation than following moderate stimulation.

3. The observation that stimulus integration occurs for low intensity/duration stimulation suggests a complex high resistive pathway. The more intense physical stimulation produces a higher rate of fluid flow causing more intense physiological stimulation as well as a shorter latency.

4. The change in the shape of the auditory threshold at low frequencies indicated in chapter 4 suggests that some change in the detection process occurs at around 16 Hz it is possible that in this region the fluid flow ceases to be through the cochlea only.

The main contradiction to this theory is presented by the work of Ades et al (55) on the vestibular response to very high intensity audio frequencies in deaf human subjects, which does not support the theory of a low pass characteristic pathway. The only possible explanation of this phenomenon in terms of the above hypothesis is that irregularities or non-linearities in the ossicular chains of the subjects used changed the pathway characteristics. As these subjects all suffered from total deafness this possibility cannot be ruled out.

9.4.2. Fatigue Theory

In these experiments it is evident, from the subjective responses of the subjects to infrasound, that some part of the otolithic system is being stimulated, but the ocular response obtained, vertical nystagmus, can be attributed to either the saccules or the anterior vertical canals. The theory hypothesised in section 9.4.1. assumed that this nystagmus arose from the saccules but the possibility of it arising from the semi-circular canals cannot be overlooked.

The distinction drawn between the function of the static and dynamic vestibular organs is inadequate for the explanation of many observations concerning response to vestibular stimulation. For example if a person is subjected to sufficient angular acceleration he becomes dizzy and falls, these sensations indicate both canal and otolith disturbance. Jongkees 1950 (83) observed positional nystagmus after the destruction of the saccule in rabbits, and various papers by Owado et al (91, 94) reported changes in positional nystagmus due to changes of endolyphatic pressure on the otolithic maccula. All these observations indicate that the otolithic organs may have some influence on the occurence of nystagmus.

Hence it is suggested that the otolithic organs exercise some control over the semi-circular canals and act in an inhibitory fashion on the occurence of nystagmus under normal conditions. But when a normal subject is exposed to infrasound the otoliths (probably the saccules) are stimulated as described in section 9.4.1, this inhibition is removed and vertical nystagmus arising from the anterior vertical semi-circular canal occurs.

9.5. Conclusions

Infrasound does have some effect on the human vestibular system. It is evident from both the objective and subjective results that it is some part of the otolith system that primarily responds to the stimulus. When the results of this work are compared with other work (67, 88) indicating that the saccular maculae respond to sonic vibration, and the work of Owada and Shiizu (91) on stimulation of the saccules it would appear that it is this part of the otolith system which responds initially to infrasound. A possible mechanism for this stimulation is hypothesised in section 9.4.1. but the ocular response of vertical nystagmus could arise either directly from the saccules or from the anterior vertical canal due to the stimulus upsetting the controlling interaction between the otolith and canal systems.

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APPENDIX 1

TORSION PENDULUM ANALOGY FOR THE SEMI-CIRCULAR CANALS

Steinhausen (114) 1931, proposed that the function of the semi-circular canal/cupula/endolymph system could be represented analytically by that of a heavily damped torsion pendulum with the inertia, spring restoring torque and damping of the pendulum representing respectively the inertia of the endolymph ring, the elastic restoring force of the cupula and the viscous damping of the endolymph in the canal.

If θ = angular displacement of the fluid ring

$\dot{\theta}$ = its angular velocity

$\ddot{\theta}$ = its angular acceleration

I = moment of inertia

B = dynamic friction couple at unit angular velocity

K = stiffness couple at unit angular acceleration

Then when the system is in equilibrium and there are no external couples working

$$I\ddot{\theta} + B\theta + K\dot{\theta} = 0 \qquad \ldots 1$$

Substituting $\theta = A \exp(wt)$

$$Iw^2 + Bw + K = 0 \qquad \ldots 2$$

and

$$w_{1,2} = \frac{-B \pm \sqrt{B^2 - 4\,KI}}{2I}$$

In this case B is large compared with the other forces on the 'pendulum'

i.e. $B^2 \gg 4KI$

$\therefore$ only the real root is significant

With the initial conditions

$t = 0 \quad \theta = 0$ and $\theta = \gamma$

The solution of equation 1. is

$$\theta = \frac{\gamma}{w_1 - w_2}\left[\exp(w_1 t) - \exp(w_2 t)\right] \quad \ldots 3.$$

$$\theta = \gamma \frac{I}{B}\left[\exp\left(\frac{-K}{B} t\right) - \exp\left(-\frac{B}{I} t\right)\right] \quad \ldots 4.$$

where $w_1 \sim -\frac{K}{B}$ and $w_2 \sim -\frac{B}{I}$

As $\frac{K}{B} \ll \frac{B}{I}$ it is neglected.

This means that the endolymph is passing zero position with an angular velocity γ at $t = 0$, it will travel over an angle θ

$$\theta \sim \gamma \frac{I}{B} \quad \text{(approx)}$$

in the time interval $\frac{I}{B}$ seconds. Afterwards the endolymph will retreat slowly, controlled by the weak spring of the cupula and resisted by the high degree of friction.

This return is given by:-

$$\theta = \gamma \frac{I}{B} \exp\left[\frac{-K}{B} t\right]$$

which points to a strictly exponential reduction of θ with time.

At a time t_m an angle θ_{min} is reached which is the threshold of perception

$$t_m = \frac{B}{K} \ln \frac{\gamma I}{B\theta_{min}}$$

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on the 'pendulum'

i.e. $B^2 \gg 4KI$

$\therefore$ only the real root is significant

With the initial conditions

$t = 0 \quad \theta = 0$ and $\dot{\theta} = \gamma$

The solution of equation 1. is

$$\theta = \frac{\gamma}{w_1 - w_2} \left[\exp(w_1 t) - \exp(w_2 t) \right] \qquad ...3.$$

$$\theta = \gamma \frac{I}{B} \left[\exp\left(-\frac{K}{B} t\right) - \exp\left(-\frac{B}{I} t\right) \right] \qquad ...4.$$

where $w_1 \sim -\frac{K}{B}$ and $w_2 \sim -\frac{B}{I}$

As $\frac{K}{B} \ll \frac{B}{I}$ it is neglected.

This means that the endolymph is passing zero position with an angular velocity γ at $t = 0$, it will travel over an angle θ

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in the time interval $\frac{I}{B}$ seconds. Afterwards the endolymph will retreat slowly, controlled by the weak spring of the cupula and resisted by the high degree of friction.

This return is given by:-

$$\theta = \gamma \frac{I}{B} \exp \left[-\frac{K}{B} t \right]$$

which points to a strictly exponential reduction of θ with time.

At a time t_m an angle θ_{min} is reached which is the threshold of perception

$$t_m = \frac{B}{K} \ln \frac{\gamma I}{B\theta_{min}}$$

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