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SAMENVATTING

Het experimentele gedeelte van dit onderzoek was hoofdzakelijk gewijd aan de toonhoogte van de enkele en de dubbele intertonen, welke gehoord kunnen worden als twee zuivere tonen, waartussen een klein frequentie verschil bestaat, dichotisch worden aangeboden.

Ter voorbereiding hiervan was het nodig dat allereerst de simultaan dichotische frequentieverschildrempel werd bepaald.

De luisteropgaven waren gestandariseerd en op magnetische band vastgelegd; de experimenten zijn in een stille en geluid-dode kamer gedaan; overspraak tussen de oren werd uitgesloten. Bij alle experimenten werd de methode van een gedwongen keuze uit twee alternatieven gebruikt. De inleidende proeven omvatten het frequentiegebied tussen 200 en 10 000 Hz, onderverdeeld in stappen van 100 Hz voor het gebied van 200 tot 3000 Hz; van 3000 tot 10 000 Hz bedroegen de stappen 1000 Hz.

In het frequentiegebied onder 1000 Hz blijkt er een nagenoeg constant frequentieverschil van 11 tot 14 Hz nodig te zijn voor een juist waarneembaar interauraal toonhoogteverschil; tussen 1000 en 1500 Hz neemt deze drempel snel toe tot 60 à 75 Hz, d.i. ongeveer 4 tot 5 % van de laatstgenoemde frequentie. Deze *procentuele* gevoeligheid blijft dan constant tot ongeveer 2400 Hz, waarna een tweede drempelstijging optreedt; de drempel bereikt dan bij 3000 Hz een waarde van 300 Hz; boven deze frequentie verandert de procentuele gevoeligheid niet meer en blijft op ongeveer 10 % staan.

Bij de bepaling van de toonhoogte der enkele en dubbele intertonen komt er een verschil tot uiting tussen het „gedrag" van de intertonen indien frequenties onder 1000 Hz en indien frequenties boven 1000 Hz worden aangeboden. In het gebied der lage tonen is de toonhoogte van de — zwevende — enkele intertoon gelijk aan die van een diotisch gehoorde toon, waarvan de frequentie het rekenkundige gemiddelde is van de frequenties der dichotisch aangeboden tonen. Boven ongeveer 1000 Hz worden geen zwevingen meer gehoord en de toonhoogte van de intertoon ligt lager dan die behorende bij het rekenkundige gemiddelde van de frequenties der dichotisch aangeboden tonen.

In het gehele onderzochte frequentiegebied verschuift de toonhoogte der dubbele intertonen, bij toename van het interaurale frequentieverschil, in de richting van de toonhoogten welke corresponderen met de frequenties der aangeboden tonen.

In het frequentiegebied onder 1000 Hz is deze verschuiving symmetrisch ten opzichte van de toonhoogte van een frequentie gelijk aan het rekenkundige gemiddelde van de frequenties der aangeboden tonen.

In het hoge frequentiegebied is het frequentieverschil waarbij de laagste intertoon gelijk van toonhoogte wordt aan die van de laagste der aangeboden tonen kleiner, dan het verschil waarbij de toonhoogte van de hoogste intertoon gelijk wordt aan die van de hoogste der aangeboden tonen.

Onder de 1000 Hz wordt noch de toonhoogte van de enkele, noch die van de dubbele intertoon beïnvloed door interauraal intensiteitsverschil; de intertonen worden gelocaliseerd aan de zijde waar de intensiteit van het aangeboden signaal het hoogst is.

Boven 1000 Hz wordt de enkele intertoon in geringe mate door interauraal intensiteitsverschil beïnvloed. Bij progressief afnemende intensiteit van de hoogste frequentie wordt de toonhoogte van de dubbele intertonen aanvankelijk hoger, waarna ze daalt. Progressieve intensiteitsdaling van de laagste frequentie doet de toonhoogte van beide intertonen aanvankelijk dalen, waarna een stijging van de toonhoogte optreedt.

In het theoretische gedeelte van dit onderzoek wordt aangetoond dat het „gedrag" van de toonhoogte van intertonen verklaard kan worden als de volgende veronderstellingen worden gemaakt:

(1) ieder oor is bilateraal gerepresenteerd in het centrale gehoorssysteem, waarbij de heterolaterale representatie sterker is dan de homolaterale;
(2) de „frequency response area" in het gebied onder 1000 Hz is symmetrisch t.o.v. de karakteristieke frequentie; in het gebied boven 1000 Hz is het basale been van het V-vormige gebied veel steiler dan het apicale.
(3) de ruimtelijke begrenzing van het geactiveerde gebied aan de „uitgang" van de nucleus cochlearis gelijkt op dat aan de „ingang", hoewel de „dynamic range" aan de uitgang veel kleiner is.

Deze veronderstellingen zijn gebaseerd op experimentele gegevens welke verkregen zijn bij proeven op katten, marmotten en apen.

Op basis van deze veronderstellingen kan ook de beweging van de draaitoon, welke sneller schijnt te verlopen van de zijde waar de laagste frequentie wordt aangeboden naar de zijde waar de hoogste wordt gegeven, dan in de tegenovergestelde richting, worden verklaard.

Geconcludeerd wordt, dat bij de mens, op wie direkt electrophysiologisch experimenteren onmogelijk is, de centrale representatie van zuivere tonen overeenkomt met die welke gevonden zijn bij de kat, de marmot en de aap.

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BY

D. W. ODENTHAL

CONTENTS

1. INTRODUCTION

The sensation perceived when two pure tones of slightly different frequencies, f and $(f-\Delta f)$ respectively, are simultaneously, and separately, presented to both ears, depends on f as well as on Δf.

For $f < 1000$ cps, the sensation passes from a "rotating tone", through one, beating, sound image in the sagittal plane, to two images, upon increase of the interaural frequency difference.

For f values in excess of about 1000 cps neither the rotating tone nor the binaural beats are heard. At small interaural frequency difference there is a single, midline image without beats, at larger differences the image splits and a bitonal sensation is heard.

In the whole audible frequency range the separating components are distinguished by increasing divergence in pitch as well as in phenomenal space, that is, the images migrate from the centre of the head or the midline position to the two ears at increasing difference in frequency.

The term "rotating tone" is used in the sense of v. HORNBOSTEL (Drehton) and v. BEKESY, for a continuous rotating or pendulum-like shift in subjective location of the sound image with a period equal to the frequency difference offered. The term "binaural beats" applies to the fluctuations in loudness of the tone and the roughness of the tonal sensation which may be considered, according to v. BEKESY (1935), as rapid fluctuations of loudness.

LICKLIDER (1950) assigns the term "binaural beats" to the whole continuum of subjective effects described as shifts, fluctuations and roughness, but since there is an absence of loudness fluctuations in the "rotating tone" and an absence of periodical shifts in subjective location in beating tones, separation of the continuum in rotating and beating tones is justified. The transition zone between rotating and beating tones is rather wide and covers some to 2 to 4 cps interaural frequency difference, independent of frequency.

Of the above mentioned phenomena, the "binaural beats" are important in auditory theory because they constitute a clear demonstration of binaural interaction in the central auditory system, and indicate that the discharges of the neurons of the auditory nerve in some way preserve information about the phase of the acoustic stimulus.

Therefore this phenomenon is relevant to two theoretical issues: (1) Volley vs. place as the basis for pitch perception and (2) phase relations vs. intensity relations as the basis of sound localization. (WEVER (1949), JEFFRESS (1948), LICKLIDER (1951).)

Little attention, however, has as yet been given to the fact that with increasing interaural frequency difference the central fusion mechanism breaks down; at the same time the pitches of the images are changing.

Investigation of these phenomena provides a new experimental approach to explore the mechanism of binaural interaction and offers the opportunity to study the relation between the mechanism of binaural fusion and the central mechanism involved in pitch perception.

Thus a better insight in the central evaluation of auditory information may be obtained.

The general purpose of the present study is to gather psychophysiological data on simultaneous dichotic pure tone stimulation and to compare them with existing electrophysiological data in order to investigate the neural representation of simultaneous dichotic stimuli.

First, some general considerations in regard to dichotic stimulation will be presented (section 2).

The main subject to be considered is the pitch of the single sound image and the pitches of the double images, and the influence of interaural intensity difference on the pitches named (section 4). As a preliminary to this, it is necessary to determine the simultaneous dichotic frequency difference limen (section 3).

In section 5, it will be shown that a model of neural activity in the central auditory system, based on experimental data by WHITFIELD (1957) and his associates, fully accounts for the behaviour of sound image pitches and the way in which they change upon changes in interaural frequency difference, as well as upon presentation of an intensity difference between the two pure tone stimuli. In section 6 it is shown that the model in question also accounts for the behaviour of rotating tones. Conclusions will be briefly presented in section 7.

2. GENERAL CONSIDERATIONS IN DICHOTIC SOUND STIMULATION

In dichotic sound stimulation experiments interaural insulation and thus intensity levels of the signals to be presented are of crucial importance. Furthermore establishment of reference levels for the signals, standardization of the listening task and proper selection of observers are necessary.

2.1. Interaural insulation

The possibility of overhearing the signals of the opposite ear must be excluded. Acoustical leakage between the ears may be due to air conduction, to bone conduction or to both.

From their experiments on masking, Wegel and Lane (1924) concluded that when earphones are used, acoustical leakage between the ears is mainly due to bone conduction, and that the maximal interaural insulation amounts on the average to about 50 dB. In experiments on binaural beats, Lane (1925) came to the same conclusion.

Sparrevohn (1946) measured the interaural insulation for earphone listening in unilaterally deaf subjects and also found values of about 50 dB. Zwislocki (1953) came to the same conclusions for telephone listening, but found that when the sounds are introduced to the ears through perforated earplugs instead of telephones, the interaural insulation could be increased considerably, mainly as a result of absence of bone conduction.

2.2. Establishment of reference levels for the signals to be presented

Although there is no *a priori* ground why the reference should be in terms of sensation level or of loudness, sound pressure levels (re 0.0002 μbar) have been used in the present investigation.

In this way all subjects are presented with the same signal levels. Also, this procedure opens the opportunity to study neuronal activity patterns under similar stimulus conditions in electrophysiological experiments. Even more important is the possibility of comparison of experimentally gathered psychophysiological findings with existing electrophysiological data, since in the latter intensities are expressed in dB. S.P.L.

From the data of Zwislocki (1953) it can be concluded that in the present experiments sound pressure levels up to 80–90 dB might be used if the earplug method is employed. However, according to Wegel and Lane (1924), Fletcher (1929), Egan and Hake (1950), Lawrence and Yantis (1956), and Bryan and Parbrook (1960), at about 50 dB sound pressure levels, harmonic distortion may be just audible. Therefore in the present study a sound level of 45 dB S.P.L. or less is used.

2.3. Standardization of the listening task

In order to obtain comparable results when a series of discriminatory tasks is presented to a group of observers, it is essential that all subjects are confronted with exactly the same task. The easiest way to meet this requirement is to make a recording of the desired listening task and present the stored program to the subjects.

This procedure also opens the opportunity to present the same task at any desired intensity level and as many times as necessary to obtain sufficiently reliable data.

In the present study the listening tasks were recorded on magnetic tape.

2.4. Selection of subjects

According to Seashore (1919), any group of observers may be divided, in respect to their listening abilities, into two main classes, i.e. those having a "musical ear" and those who have not. It was found in a pilot study that of a group of about 40 potential observers, (students who claimed to be interested in music and to possess a musical ear), the majority (32) made reproducible judgments whatever the listening task but the remaining eight could not tell one tone from the other.

The group that indeed could be regarded as possessing a "musical ear" could be divided into two sub-classes. In 22 of these subjects judgments were reproducible, but showed a rather large variability.

The other 10 observers were superior in that they showed a very small variability in their judgments. The last named subjects participated in the present study. All possessed normal hearing as measured by routine audiometric procedure (sweep frequency and octave audiometry), external auditory canals and eardrums where normal at inspection, diplacusis was not measurable and no subject suffered from tinnitus.

With these "super subjects", the duration of the series of experiments could be drastically shortened because only a few experimental runs were necessary to obtain sufficient accuracy of the results. At the start of the main series of experiments 8 of them were available. The number of subjects decreased in the course of the investigation, one of them was called into military service, a second suffered from an acute tubotympanitis and a third left Leiden and was no longer available. Thus only 5 subjects completed the whole program. Specially selected subjects were not used in the experiments on rotating tones.

3. SIMULTANEOUS DICHOTIC FREQUENCY DIFFERENCE LIMEN

3.1. INTRODUCTION

Reliable data on the dichotic difference limen for frequency are scarce. STUMPH (1883), BALEY (1915) and v. HORNBOSTEL (1923a), using tuning forks as sound sources, measured it at 500 cps. Later, v. HORNBOSTEL (1923b) determined the limen at 800 cps. At both frequencies the limen was found to amount to some 10–20 cps.

More recently THURLOW *et al.* (1957) determined the liminal frequency difference at 200, 1000, 4000, 6000, and 10 000 cps; after loudness matches. The way in which the interaural frequency difference was checked is not clearly indicated. A progressive increase in just noticeable frequency difference with frequency is reported.

In the present study the range from 200 to 10 000 cps is covered. In the subrange 200–3000 cps frequency steps are 100 cps; the subrange 3000–10 000 cps is covered in 1000 cps steps, as a pilot study had shown that at frequencies exceeding some 3500 cps the listening task became too monotonous to ensure consistent responses if smaller steps were taken.

3.2. APPARATUS

Experiments are performed in an anechoic and soundproof room. Fig. 3.2.–1 gives a block diagram of the setup. The program is prepared by means of two identical RC oscillators (General Radio audiofrequency oscillators 1302A; harmonic content less than 0.1 %), a symmetrical switch and a Telefunken M5 double-track tape recorder. Specially selected tape showing minimal amplitude fluctuation (BASF.–LGR) is used; tape speed is 38 cm/sec. Cross talk attenuation is better than 45 dB; S/N ratio is better than 40 dB; wow is 0.06 %. Tape speed is checked by a stroboscope device; in addition a reference signal is recorded on the first few meters of the sound track, and again somewhere in the second half of the tape length. The standard frequency, which is delivered by one of the oscillators is fed into one of the recorder channels and the variable into the other, care being taken that signal intensities are equal. The switch is commanded by hand and turns the signals on and off simultaneously. Signal duration and inter-stimulus interval are controlled by stopwatch reading.

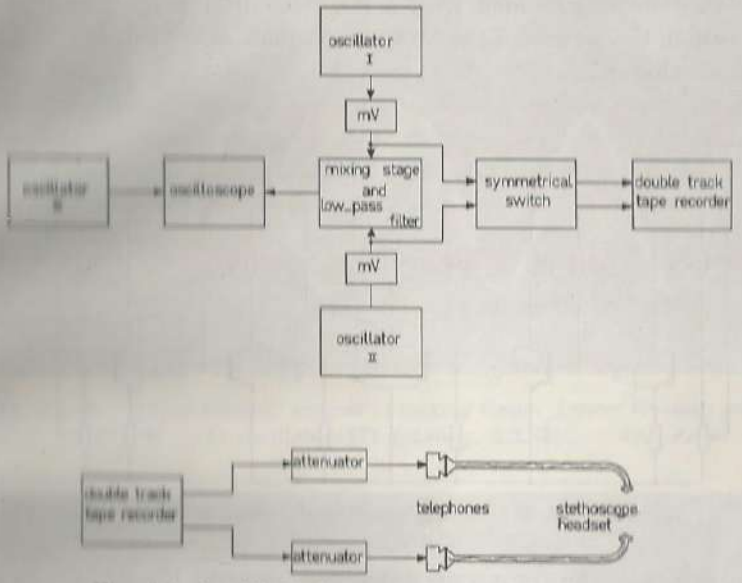

Fig. 3.2.–1. Block diagram of experimental setup.

The desired frequency difference between the tones of the paired signal is set on a third oscillator (Hewlett–Packard Low-frequency function generator) the dial of which had been calibrated for low frequencies against an electronic counter (Berkeley EPUT meter).

The signal of the third oscillator is fed to one pair of deflection plates of an oscilloscope (Philips type GM 5666); the output of a mixing stage, provided with a low-pass filter (Fig. 3.2.–2), and into which the signals of the first two oscillators are fed, is delivered to the other pair.

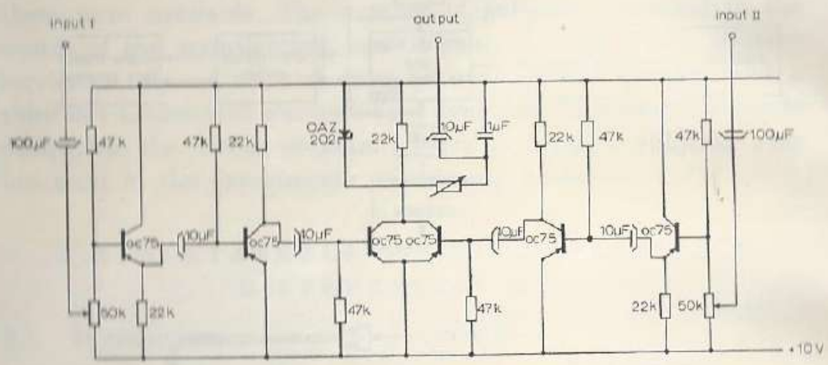

Fig. 3.2.–2. Mixing stage and low-pass filter.

In this way the frequency difference between the signals to be recorded is equated to the set frequency of the third oscillator with the aid of the Lissajous curves thus obtained (cf. Figs. 3.2.–3 and 3.2.–4).

The program is offered dichotically via a pair of attenuators and a matched pair of high quality moving coil earphones (Standard Telephones serial nos. 2305 and 2306; frequency response flat to within 4 dB up to 10 000 cps). To meet the requirements of inter-aural sound insulation, acoustical leakage between the ears due to air conduction and to bone conduction is minimized by the use of a "differential stethophone", as first described by Alison (1858). For this purpose, the earphones are connected to a stethoscope by plastic tubing. A length of woollen yarn is led through the whole length of the tubing in order to dampen unwanted resonance peaks (v. Bekesy 1960). The axial pressure exerted by the two parts of the stethoscope on the ears can be regulated so as to obtain a

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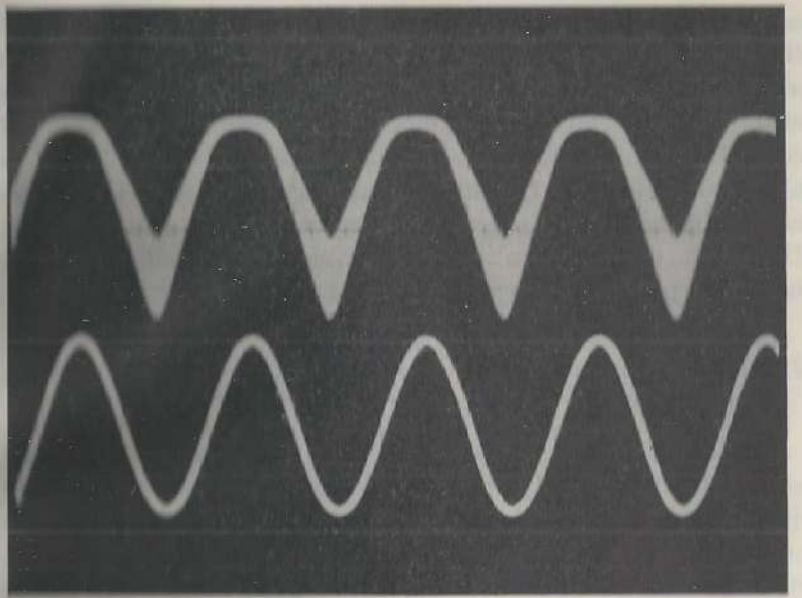

Fig. 3.2.–3. Upper tracing: output of mixing stage. Lower tracing: output of oscillator III (cf. Fig. 3.2.–1).

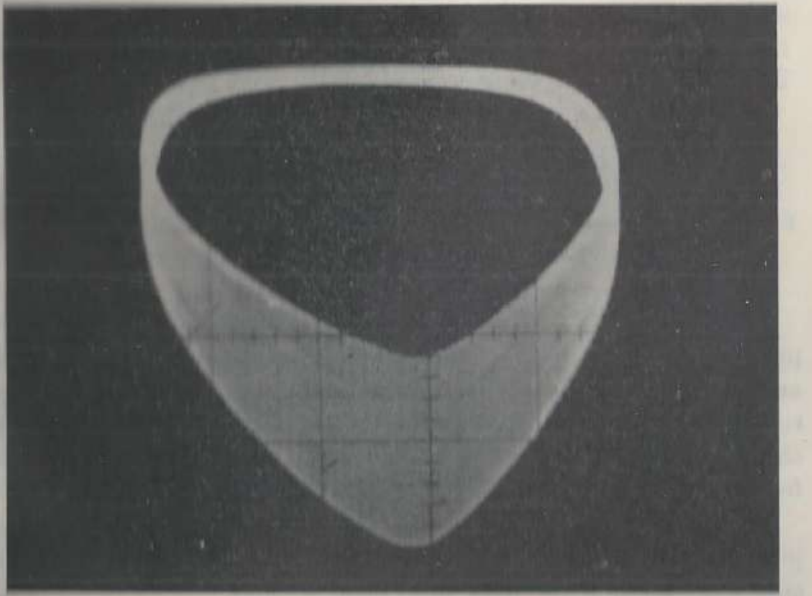

Fig. 3.2.–4. Lissajous figure on C.R.O. screen (cf. Fig. 3.2.–1).

comfortable, firm fit in the external auditory meatus. The use of this apparatus has the advantage that the earpieces give a good airborne sound insulation, and in addition the smallest possible effective surface for bone conduction is obtained. Furthermore, in contrast with earphone listening, the opening of the tubing is always in the axis of the external auditory canal and the location of this opening does not change between experimental sessions. During the experiments, the signal levels are checked at the coils of the earphones by means of a μVolt meter.

3.3. PSYCHOPHYSIOLOGICAL PROCEDURE AND STATISTICAL DATA PROCESSING

Two signals of frequencies f and $(f-\Delta f)$ of equal intensity and equal duration are produced simultaneously and presented dichotically. The duration of the signals is 5 seconds in order to enable the subject to arrive at a decision before the signals are turned off. Rise and decay times of the signals are about 125 msec so as to avoid audible transients. Interstimulus interval is 5 seconds in order to minimize the influence of a previous listening task upon the next one (cf. diagram in Fig. 3.3.–1).

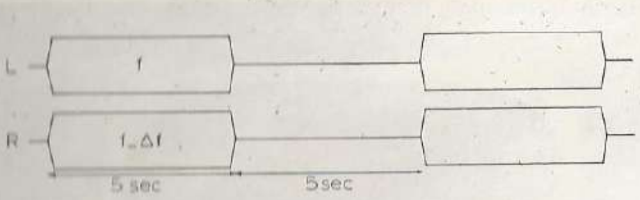

Fig. 3.3.–1. Diagrammatic representation of discriminatory task for determination of simultaneous dichotic frequency difference limen.

The "YES–NO" type of the two alternative forced choice procedure is used (HIRSH 1951), that is, the subject is regarded as reacting positively (YES) if he is certain that he has heard two tones simultaneously, differing in pitch, by marking a + on a sheet of paper that served as a matrix to read back the performance. "NO" is marked as a point on the matrix.

In this situation there is no way of determining whether a judgment is a "correct" or a "wrong" one. Therefore a special statistical method for data processing is used.

The difference Δf that the subject can just distinguish is somewhat variable.

If we write $p(\Delta f)$ for the probability that Δf is heard (i.e. in a large number N of tests the subject reacts positively pN times), the psychometric function, $p(\Delta f)/\Delta f$ takes roughly the form shown in Fig. 3.3.–2.

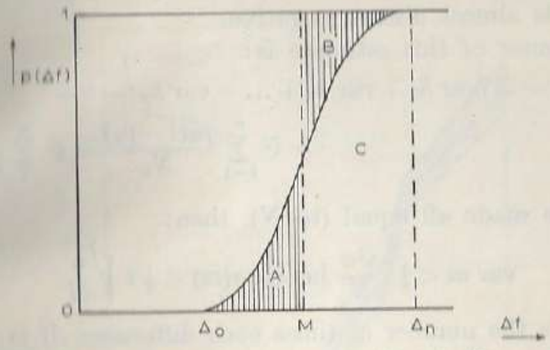

Fig. 3.3.–2. Determination of just noticeable simultaneous dichotic frequency difference.

At $\Delta f=\Delta_0$, p is very nearly zero, and for $\Delta f=\Delta_n$, p is very nearly unity. The middle value of the just perceptible difference, M, say, is defined to be such that the two shaded areas, A and B, are equal. (If the distribution of Δf is uniform, M is actually the mean threshold and the curve gives the accumulated distribution of thresholds.)

The area under the curve equals $\int_0^{\Delta_n} p(\Delta)\cdot i\Delta$, where i stands for the width of the – equal – intervals in which the range of interaural frequency differences, $\Delta_0-\Delta_n$, is devided, the area of the rectangle, C, is equal to $\Delta_n - M$, so $M=\Delta_n-\int_0^{\Delta_n} p(\Delta)\cdot i\Delta$.

An approximation to the area under the curve is obtained from the trapezoidal rule.

According to the trapezoidal rule we have:

$$i\left(\frac{p_0+p_1}{2}+\frac{p_1+p_2}{2}+\ldots+\frac{p_{n-1}+p_n}{2}\right)=$$

$$=i\left(\frac{p_0}{2}+p_1+p_2+\ldots+p_{n-1}+\frac{p_n}{2}\right),$$

so $M = \Delta_n - i\,(\tfrac{1}{2}p_0 + p_1 + p_2 \ldots + p_{n-1} + \tfrac{1}{2}p_n)$, where p_k is the probability of a positive reaction to a difference Δ_k.

Suppose now that N_k observations are made at a difference Δ_k, of which a portion h_k are positive. Then, as an estimate of M, we have, $m = \Delta_n - i\,(h_1 + h_2 + h_3 + \ldots + h_n + \tfrac{1}{2})$, provided that Δ_n is chosen such that the reaction is almost always positive, and Δ_0 so that it is almost always negative.

The variance of this estimate is:

$$\operatorname{var} m = i^2 (\operatorname{var} h_1 + \operatorname{var} h_2 + \ldots + \operatorname{var} h_n) =$$

$$= i^2 \sum_{k=1}^{n} \frac{p_k(1-p_k)}{N_k} < i^2 \sum_{1}^{n} \frac{1}{4N_k}.$$

If N_k are made all equal (to N), then:

$$\operatorname{var} m < \tfrac{1}{4} \cdot \frac{i^2 n}{N} \text{ hence } \sigma(m) < \tfrac{1}{2}\, i \sqrt{\frac{n}{N}}.$$

Thus N is the number of times each difference Δf is presented to the subject, and n is the number of steps on which he does not always give the same judgment.

As a 95 % confidence interval for M we can give $m \pm 2\sigma$.

Thus if $n \div N = 4$, $\sigma = \tfrac{1}{2}i$.

For example: if $i = 2$ cps, $2\sigma < 2$ cps.

3.4. THE CHOICE OF Δf FOR VARIOUS f VALUES

In a pilot study Δf had been observed to be such that the ratio $\Delta f/f$ changes suddenly between 800 and 1000 cps, and again between 2400 and 3000 cps. Roughly the curve, which is a log/log plot of Δf vs. f, was found to fall within the shaded area of Fig. 3.4.–1.

Above and to the left of the shaded area the reactions were always positive and below and to the right of it the reactions were always negative. Observations need only be made in the shaded region, since outside it the results are almost certain.

The steps (i) for Δf are chosen so as to increase with f. Table 3.4.–I gives the values of i in the whole frequency range investigated.

Tone pairs are presented in double random order, that is, both the fixed frequencies and the i values are randomized. Numbers are assigned to the various f–$(f - \Delta f)$ combinations, and the sequence in which they are to be presented is determined with the aid of a table of random numbers. Thus a two-dimensional random order of stimulus presentation is obtained. This procedure helps to meet the objection that a small difference is less likely to be noticed when it follows a large difference.

The individual series are run two or more times, depending upon the accuracy required.

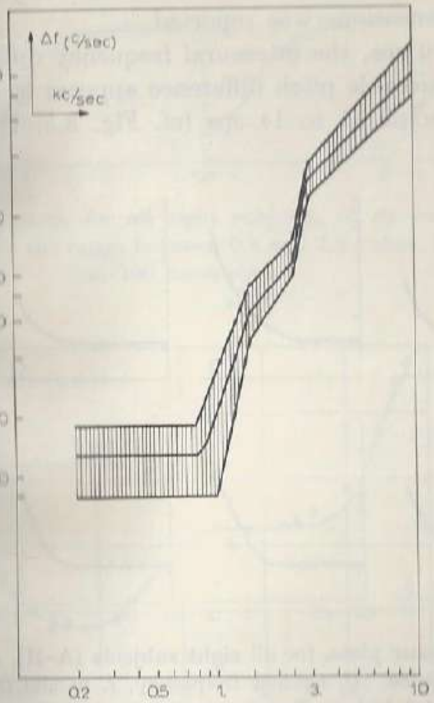

Fig. 3.4.–1. The function $\Delta f/f$ (log-log plot).

TABLE 3.4. – I

Frequency range (kc/sec)	i Value (c/sec)
0.2–0.9	2
1.0–1.5	5
1.6–2.0	10
2.1–3.0	10
3. – 8.	50
9. –10.	100

3.5. RESULTS

In the frequency range below some 1000 cps, and at 45 dB re 0.0002 μbar, all 8 observers reported to hear, at low Δf values, one beating tone; upon increase of Δf, two beating sound images are perceived; a further increase of Δf leads to the perception of two non-beating, smooth tones simultaneously. Above 1000 cps no beating sensations was reported.

For $f < 1000$ cps, the interaural frequency difference Δf, needed for a just noticeable pitch difference appears to be approximately constant at some 11 to 14 cps (cf. Fig. 3.5.–1).

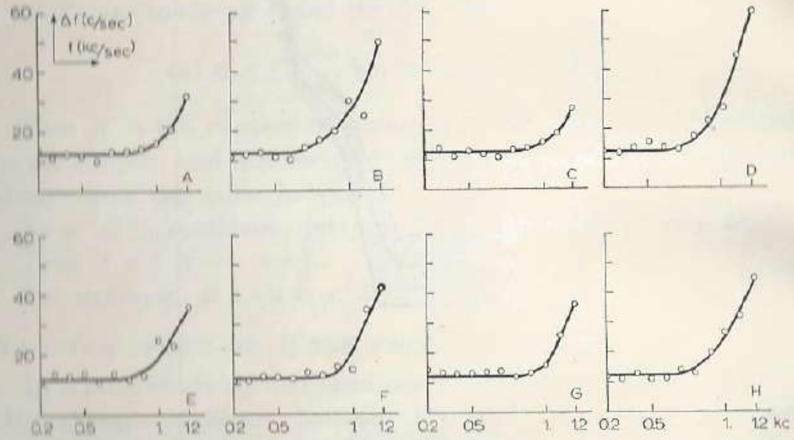

Fig. 3.5.–1. Linear plots, for all eight subjects (A–H), of liminal absolute frequency difference, Δf, against frequency, f, in the frequency range up to 1.2 kc/sec. Range covered in 100 c/sec steps.

Between 1000 and 1500 cps there is a transition zone where the difference limen rapidly increases with frequency, so that, at the latter frequency, it amounts to some 60–75 cps, i.e. to about 4–5 % of the fixed frequency (cf. Fig. 3.5.–2). Up to about 2400 cps, the percentage sensitivity remains at the same level, i.e., $\Delta f/f$ is approximately constant. The limen then exhibits a second sharp rise in the region between 2400 and 3000 cps (cf. Fig. 3.5.–3) at which frequency it is in the order of 300 cps, or 10 % of the fixed frequency. This percentage sensitivity is maintained up to 10 000 cps (cf. 3.5.–4).

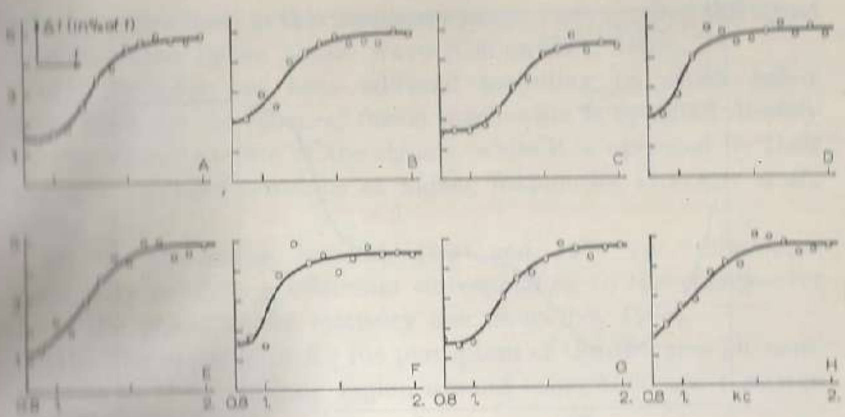

Fig. 3.5.–2. Linear plots, for all eight subjects, of Δf, in percent of f, against frequency, for the range between 0.8 and 2.0 kc/sec. Range covered in 100 c/sec steps.

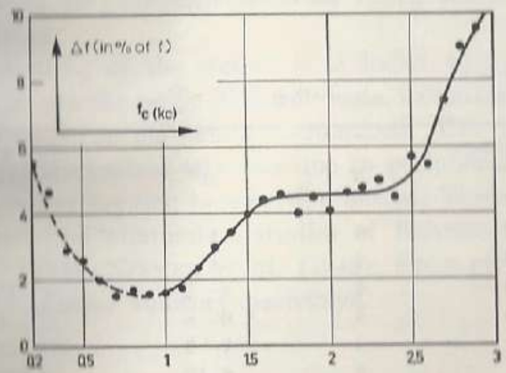

Fig. 3.5.–3. Subject C. As Fig. 3.5.–2, for the range up to 3.0 kc/sec. Range covered in 100 c/sec steps.

For the higher frequency ranges there is appreciable scatter between results obtained on one and the same subject in successive tests.

The number of test sessions therefore was augmented in order to obtain sufficiently reliable data. Table 3.5.–I gives the number of trials N, the number of differences n for which the subject did not always give the same judgment, and the 95 % confidence interval 2σ expressed in cps.

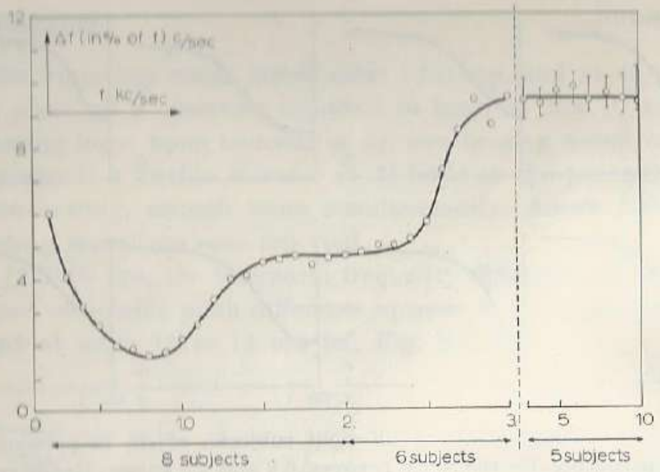

Fig. 3.5.–4. As Fig. 3.5.–2, for the whole range covered. Note the change of frequency scale at 3.0 kc/sec: above this frequency, range covered in 1.0 kc/sec steps.

TABLE 3.5. – I

Frequency range (kc/sec)	N	n	$2\ \sigma$ (c/sec)
0.2– 0.9	4	4	< 2
1. – 1.5	4	4	< 5
1.6– 2.0	4	4– 5	< 10 – 11.2
2.1– 3.0	8	6– 8	< 8.7– 10
3. – 8.	8	7– 9	< 45 – 50
9. –10.	8	8–10	< 100 –112

3.6. DISCUSSION

The discontinuity of the response curve in the region from 1000 to 1500 cps, which was found to be present in all of the subjects tested (i.e. 32 subjects including those who participated in the pilot study), is of particular interest, as other features of auditory perception have also been found to exhibit a sudden change in about the same region.

(1) Up to 1000 cps, the phase difference between stimuli is transmitted to the level where the auditory pathways converge, which implies that, in this frequency range, each cycle of the signal is represented by an action wave (CHOCHOLLE, 1959).

(2) Evidence has been adduced according to which below 1000–1500 cps the binaural fusion mechanism is operated directly by the microstructure of the signals, while it is operated by their running averaged envelope at higher frequencies (LEAKEY *et al.*, 1958).

(3) In the range between 1000 and 1500 cps, directional sensitivity exhibits a minimum corresponding to the change-over from the phase to the intensity cue (SCHMIDT, 1954).

(4) The upper limit for the perception of the Huggins phenomenon is in the frequency region around some 1000 cps (CRAMER and HUGGINS, 1958).

(5) At frequencies in excess of some 1000 cps, the binaural beats can no longer be perceived (STEVENS and DAVIS, 1938, LICKLIDER, 1950, and the present investigation).

The fact that two beating tones are heard simultaneously is rather surprising.

Since overhearing of the signals is excluded, this phenomenon must be due, as are the single binaural beats, to central interaction between two neighbouring neural populations. This leads to the conclusion that the central activities due to peripheral stimulation of both ears is overlapping to a certain extent. This conclusion is in accord with the anatomical studies of BARNES *et al.* (1943), RASMUSSEN (1946), NIEMER *et al.* (1949), STOTLER (1953), and others on the central auditory pathways.

4. THE PITCH OF THE SINGLE SOUND IMAGE AND THE PITCHES OF THE DOUBLE SOUND IMAGES, AND THE INFLUENCE OF INTERAURAL INTENSITY DIFFERENCE ON THE PITCHES NAMED

4.1. INTRODUCTION

A new approach is used in the investigation of the binaural interaction and integration mechanism, by measuring the subjective pitches of the perceived tone or tones when simultaneous dichotic pure tones are offered.

4.2. DETERMINATION OF PITCH OF SINGLE SOUND IMAGE

4.2.1. *Procedure*

In determining the pitch of the single sound image, the task consists in matching the pitch of the dichotically offered pair of frequencies f_1 and f_2, where $f_2 = f_1 - \Delta f$, Δf being constant, with that of a diotically offered pure tone of a variable frequency f_x, where $f_1 > f_x > f_2$.

Duration of stimuli is 1.4 sec; rise and decay times are both 100 msec; interval between dichotic and diotic stimulus is 0.6 sec. (cf. Fig. 4.2.1.–1).

According to KÖNIG (1957), pitch discriminability reaches its maximum at this interval.

After an interval of 5 sec, to minimize fatigue, a second task is set, for a different value of f_x, and so on. Here again the two alternative forced choice method is used (HARRIS, 1948): the subject has to decide which of the two, the dichotic or the diotic stimulus, possesses the highest pitch.

If the pitch of the second tone stimulus is perceived as being the higher, he marks "H" on a sheet of paper due to serve as a matrix to read back the performance; in the opposite case, an "L" mark is made.

In a session, each combination of dichotic and diotic stimulus, is presented ten times, the different f_x values being offered in random order.

Psychophysiological procedure and statistical data processing are the same as used in determining the simultaneous dichotic frequency difference limen.

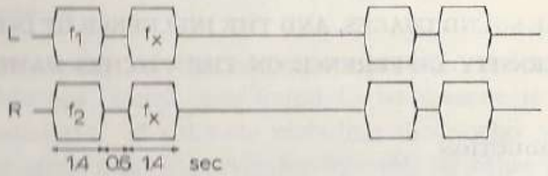

Fig. 4.2.1.–1. Diagrammatic representation of listening task for determination of single intertone pitch.

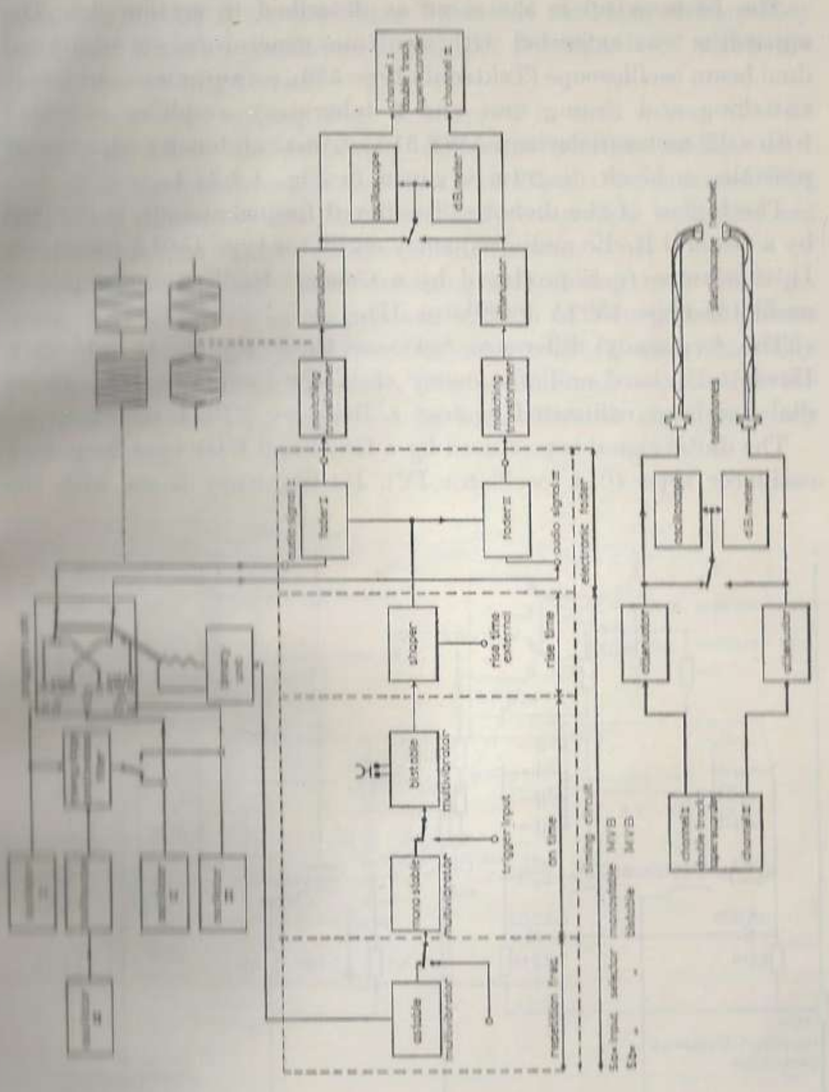

Fig. 4.2.2.–1. Block diagram of apparatus used for determination of intertone pitches. Fader according to DE BOER (1957).

4.2.2. *Apparatus*

The basic setup is the same as described in section 3.2. The apparatus was extended with two tone generators, an additional dual beam oscilloscope (Tektronix type 536), an automatic electronic switching and timing unit and a laboratory amplifier provided with a dB meter (Solartron AWS 51A), to make intensity adjustment possible. A block diagram is given in Fig. 4.2.2.–1.

The higher of the dichotically offered frequencies, f_1, is emitted by a General Radio audiofrequency oscillator type 1301A (oscillator I), the lower, f_2, is produced by a General Radio audiofrequency oscillator type 1302A (oscillator II).

The frequency difference between these signals is set on a Hewlett Packard audiofrequency oscillator (oscillator III), whose dial has been calibrated against a Berkeley EPUT meter.

The diotic signal is produced by a Bruel and Kjär beat frequency oscillator type 1014 (oscillator IV). Its frequency is set with the aid of oscillator I and a Hewlett Packard low frequency function generator model 202A (oscillator V), set at the desired frequency difference between oscillators I and IV, the signals of which are led to the mixing device.

The frequency mixing stage is changed in such a way that at its output either the frequency difference between oscillators I and II or that between oscillators I and IV can be obtained. The frequency difference can thus be easily controlled with the aid of the Lissajous figures on the C.R.O. screen.

The automatic electronic switching and timing unit (cf. Figs. 4.2.2.–2,3) is set so as to produce a train of two paired pulses. The first consists of the frequencies f_1 and f_2, simultaneously produced on separate channels. The second pair consists of the variable frequency f_e, produced on both channels simultaneously and in phase.

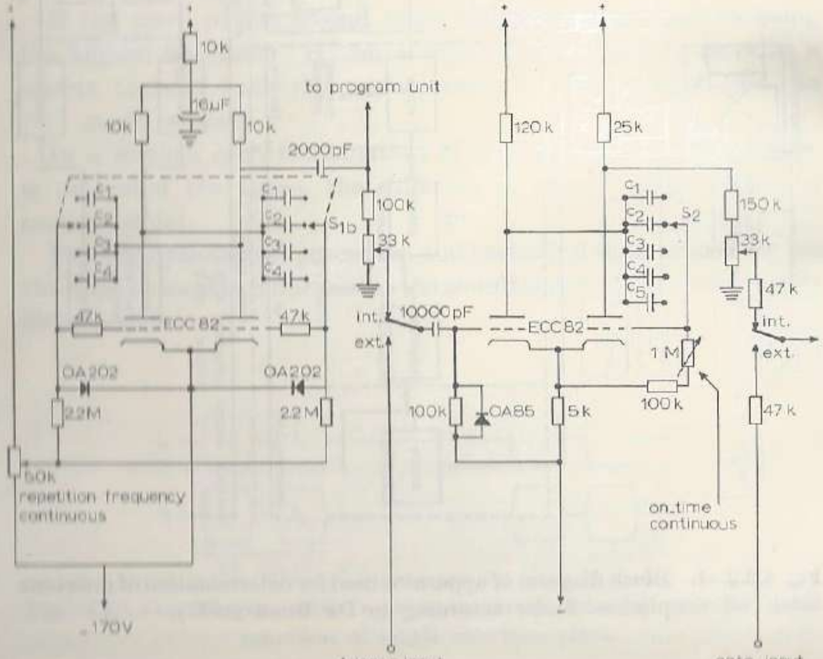

Fig. 4.2.2.–2. Timing circuit.

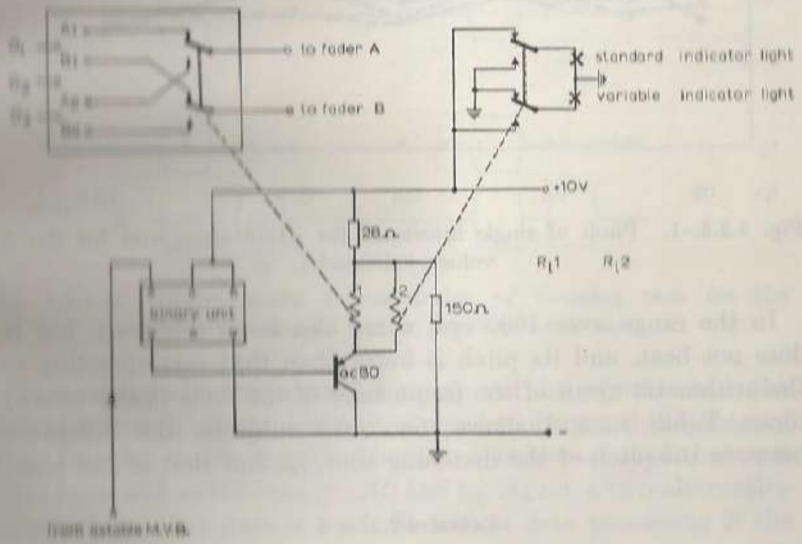

Fig. 4.2.2.–3. Binary switch and program unit.

Timing and pulse shape are checked with the aid of a dual beam oscilloscope. A program is prepared and noted on a matrix to read back the subject's performance.

4.2.3. *Results*

In the frequency range below 1000 cps, at an intensity level of 45 dB S.P.L., without interaural intensity difference and at an interaural frequency difference of 6 cps, the pitch of the single, beating, sound image corresponds with that of a diotically heard pure tone of the same intensity, the frequency of which is equal to the arithmetic mean, m, of the two frequencies offered dichotically. In fact an intertone is heard (cf. Fig. 4.2.3.–1).

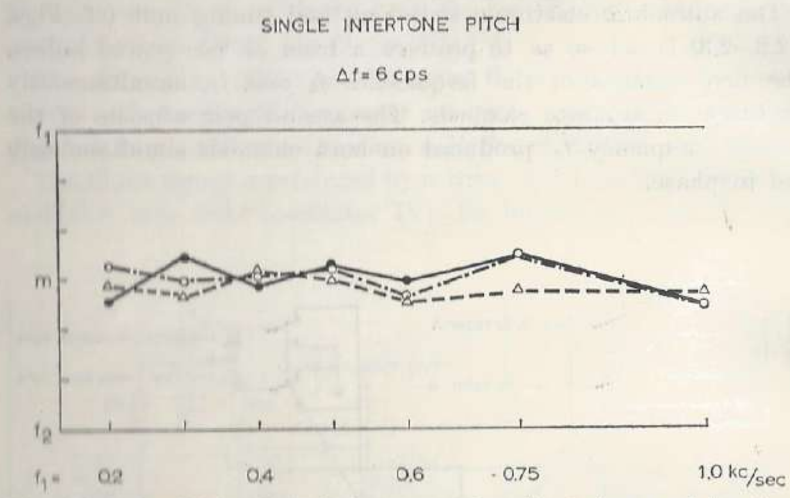

Fig. 4.2.3.–1. Pitch of single intertone, for $\Delta f = 6$ c/sec, and for the f_1 values indicated.

In the range over 1000 cps, there also is an intertone, but it does not beat, and its pitch is lower than that corresponding to the arithmetic mean of the frequencies of the dichotically offered tones. Table 4.2.3.–I shows, for three subjects, the difference between the pitch of the matching tone, f_x, and that of the tone, m, of a frequency which equals the arithmetic mean of the frequencies, f_1, f_2, offered dichotically.

TABLE 4.2.3. – I

Subjects	f (cps) Δf (cps)	1000 8	1500 45	2000 60	2400 75	3000 180	4000 240	5000 300	6000 360
I	$m - f_x$	0.5	3.0	2.0	5.0	19	36	50	39
II	$m - f_x$	0.6	2.0	5.0	13.0	22	39	42	45
III	$m - f_x$	0.2	2.0	2.5	4.5	29	45	41	40

Values for Δf are chosen so as to remain well below the shaded area in Fig. 3.4.–1.

4.3. DETERMINATION OF THE PITCHES OF DOUBLE SOUND IMAGES

At large interaural frequency differences, when two tonal images of different pitch are heard simultaneously, the same apparatus is used; the matching procedure, however, is slightly different.

4.3.1. *Apparatus and procedure*

The automatic electronic switching and timing unit is set such that the matching frequency, f_x, is offered monotically either to the right or to the left ear instead of diotically (cf. Fig. 4.3.1.–1).

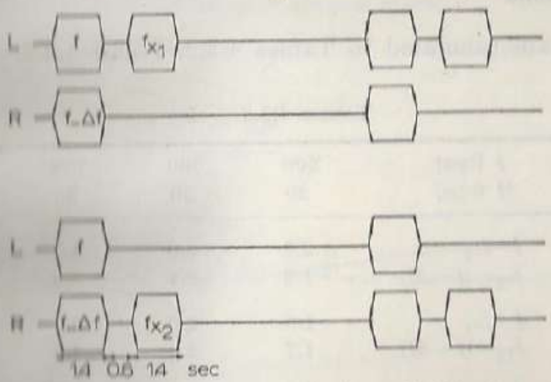

Fig. 4.3.1.–1. Diagrammatic representation of listening task for the determination of double intertone pitches.

The subject knows which channel will be silent when the matching tone is offered, and is instructed to disregard this channel when listening to the dichotic stimulus. Matches are made between f and f_{x_1} as well as between $(f - \Delta f)$ and f_{x_2}. Again, a two-alternative forced choice procedure is used. Statistical data processing is the same as used in the preceding experiments.

In a pilot study it had been observed that, in matching f_{x_1} to f, after disregarding the $(f - \Delta f)$ component of the dichotic stimulus, the frequency of the matching tone is found to be less then f; if f_{x_2} is matched to $(f - \Delta f)$, it is found to be higher than the last named frequency.

Consequently two intertones instead of the primaries are heard.

Over the whole frequency range, increase of frequency difference Δf causes both intertone pitches to shift towards the corresponding stimulus pitch. In the range below 1000 cps, the course of the pitch change of the intertones upon increase of Δf is symmetrical with regard to the pitch corresponding to the arithmetic mean of the pitches of the dichotically offered frequencies; at a given value of Δf, the pitch of each of the intertones becomes equal to that of the corresponding primary. In the range over 1000 cps, and upon increase of Δf, the Δf value at which the pitch of the lower of the intertones becomes equal to that of $(f-\Delta f)$ is less than that at which the pitch of the higher intertone is equalized with that of f.

In the main series of experiments, Δf was 20 cps for f values below 1000 cps; a value well above those in the shaded area of Fig. 3.4.-1; for f values in excess of 1000 cps, Δf amounted to 10–15 % of f.

4.3.2. *Results*

Results are tabulated in Tables 4.3.2.–I and 4.3.2.–II.

TABLE 4.3.2. – I

Subjects	f (cps)	200	500	750	1000
	Δf (cps)	20	20	20	20
I	$f-f_{x_1}$	2.2	2.0	4.2	4.3
	$f_{x_2}-(f-\Delta f)$	1.9	2.4	3.8	3.9
II	$f-f_{x_1}$	1.5	2.0	3.7	3.8
	$f_{x_2}-(f-\Delta f)$	1.7	2.0	4.3	3.5
III	$f-f_{x_1}$	3.0	2.3	3.1	3.9
	$f_{x_2}-(f-\Delta f)$	2.6	2.5	2.8	3.7

TABLE 4.3.2. – II

Subjects	f (cps)	1500	2000	4000
	Δf (cps)	150	200	600
I	$f-f_{x_1}$	27	36	81
	$f_{x_2}-(f-\Delta f)$	20	21	40
II	$f-f_{x_1}$	28	26	117
	$f_{x_2}-(f-\Delta f)$	20	18	70
III	$f-f_{x_1}$	30	46	90
	$f_{x_2}-(f-\Delta f)$	23	29	49

4.4. INFLUENCE OF INTERAURAL INTENSITY DIFFERENCE UPON THE PITCH OF SINGLE AND DOUBLE SOUND IMAGES

4.4.1. *Apparatus and procedure*

The apparatus used and the procedure are the same as mentioned previously. The same taped program is used as in the iso-intensity experiments. The signal in one channel is attenuated by either 6, 12, or 18 dB.

4.4.2. *Results*

In the range below 1000 cps, neither the pitch of the single intertone, nor those of the double intertones are influenced by interaural intensity difference (cf. Fig. 4.4.2–1 and Fig. 4.4.2.–2).

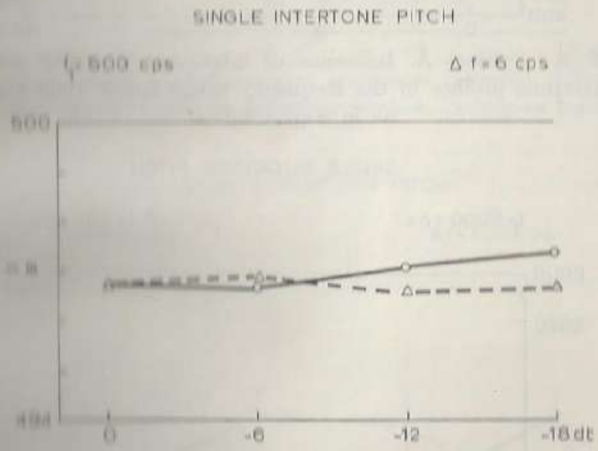

Fig. 4.4.2.–1. Subject A. Influence of interaural intensity difference on single intertone pitch in the frequency range below 1000 c/sec. △: intensity decrease of higher frequency; ○: intensity decrease of lower frequency.

The unitary sound image as well as the double sound images appear to be displaced towards the side at which intensity is greatest. In the frequency range over 1000 cps, the pitch of the single intertone is slightly influenced by interaural intensity differences (cf. Fig. 4.4.2.–3).

Upon decrease of intensity of the higher frequency stimulus, the pitch of the double intertones first rises, to fall when intensity

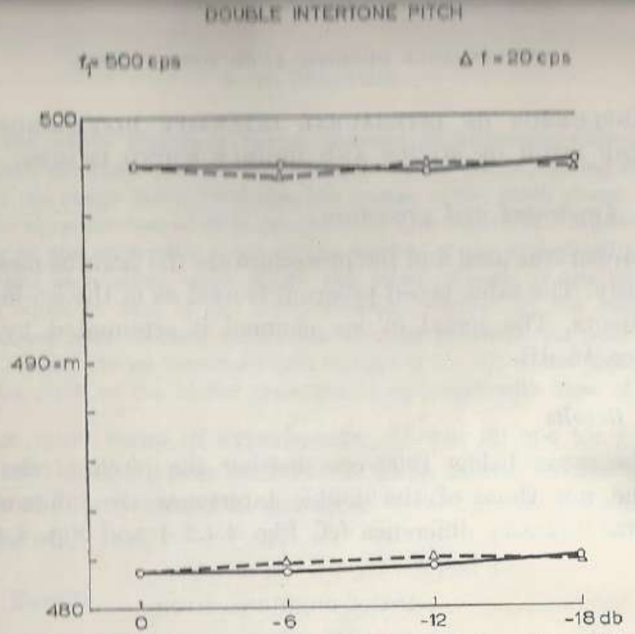

Fig. 4.4.2.–2. Subject A. Influence of interaural intensity difference on double intertone pitches in the frequency range below 1000 c/sec. Coding as in Fig. 4.4.2.–1.

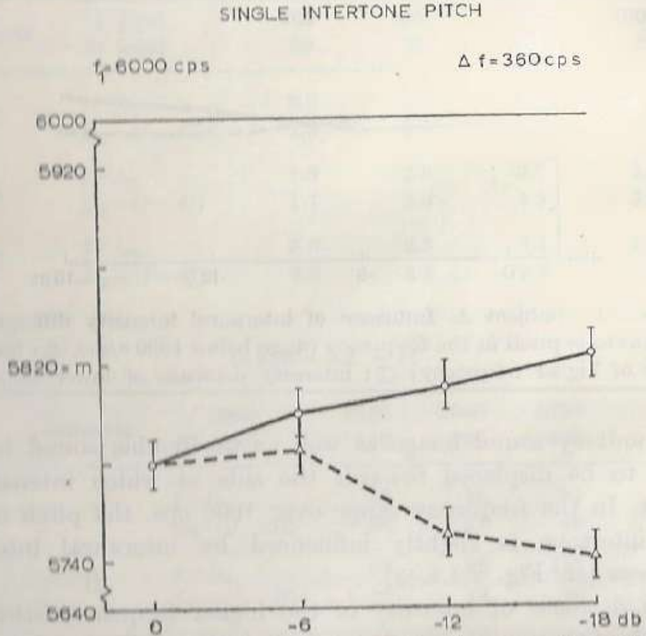

Fig. 4.4.2.–3. Subject C. As Fig. 4.4.2.–1, for the range from 1000 c/sec upwards.

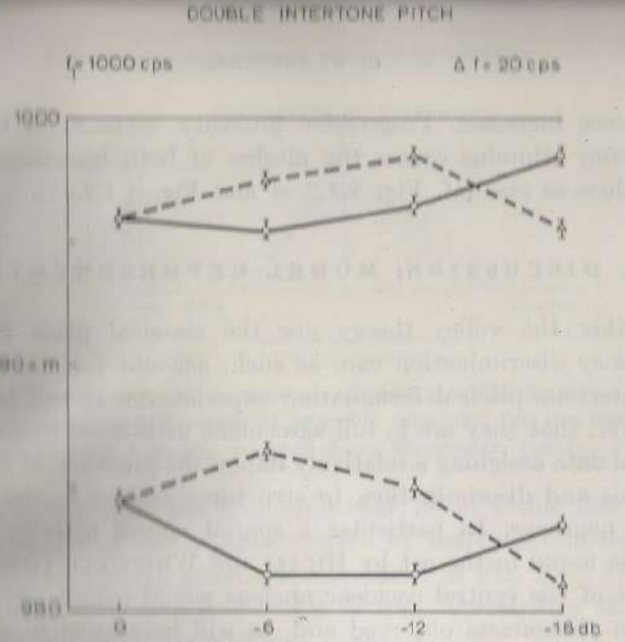

Fig. 4.4.2.–4. Subject C. Influence of interaural intensity difference, for $f_1 = 1000$ c/sec, $\Delta f = 20$ c/sec, on intertone pitches. Coding as before.

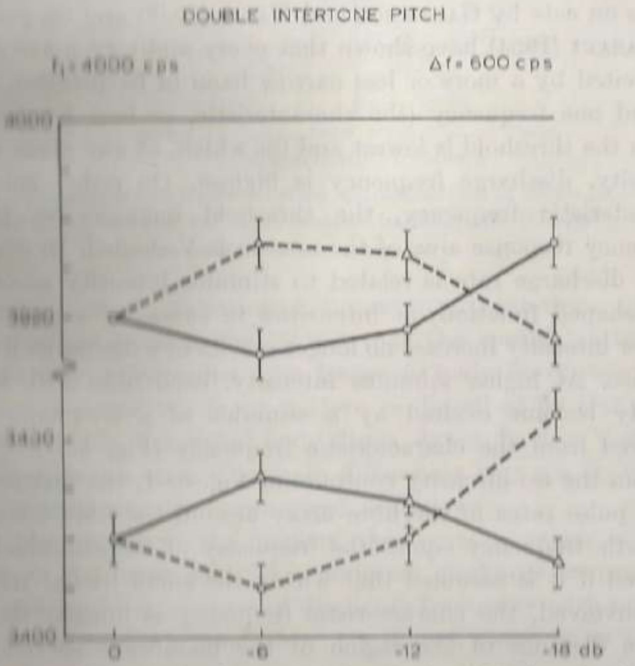

Fig. 4.4.2.–5. Subject C. As Fig. 4.4.2.–4, but for $f_1 = 4000$ c/sec; $f = 600$c/sec.

difference increases. Progressive intensity decrease of the lower frequency stimulus causes the pitches of both intertones first to fall, then to rise (cf. Fig. 4.4.2.–4 and Fig. 4.4.2.–5).

5. DISCUSSION; MODEL REPRESENTATION

Neither the volley theory nor the classical place theory of frequency discrimination can, as such, account for the results of the intertone pitch determination experiments. It can be shown, however, that they are in full agreement with more recent experimental data assigning a relatively important function, in frequency analysis and discrimination, to structures central to the cochlear nerve neurones. In particular a spatial neural activity pattern, such as found in the cat by HILALI and WHITFIELD (1953) at the output of the ventral cochlear nucleus would completely account for the phenomena observed and, as will be argued in section 6, furnish an explanation for a relatively unknown, and hitherto unexplained, property of rotating tones.

WHITFIELD's (1957) reasoning starts from the fact that experiments on cats by GALAMBOS and DAVIS (1943) and on guinea pigs by TASAKI (1954) have shown that every auditory nerve fibre can be excited by a more or less narrow band of frequencies, grouped around one frequency (the characteristic, or best frequency) for which the threshold is lowest and for which, at any given stimulus intensity, discharge frequency is highest. On either side of the characteristic frequency, the threshold increases so that the frequency response area of the neuron is V-shaped. In every fibre mean discharge rate is related to stimulus intensity according to an S-shaped function; at intensities in excess of a given level a further intensity increase no longer results in a discharge frequency increase. At higher stimulus intensity, each fibre will, however, already become excited by a stimulus of a frequency farther removed from the characteristic frequency (Fig. 5.–1).

From the iso-intensity contours of Fig. 5.–1, the distribution of mean pulse rates in the fibre array around the fibre whose characteristic frequency equals the frequency of the stimulus, can be deduced if it is assumed that within the small basilar membrane area involved, the characteristic frequency is linearly dependent on the distance of the region of the membrane served by the fibre in question from the apex, and that, again within this small area, the shape of the response curves of individual neurons is the same. The pattern obtained is pictured in Fig. 5.–2. It is to be noted that it is a mirror image to that representing the corresponding family of iso-intensity contours.

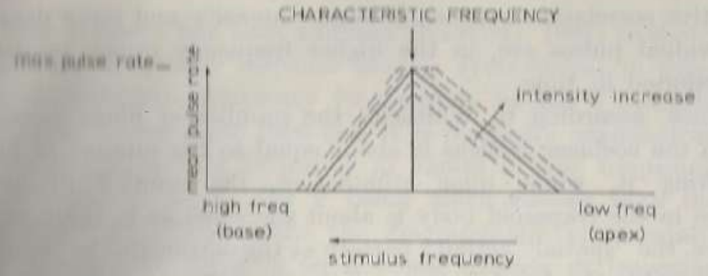

Fig. 5.–1. Diagrammatic representation of pulse rate distribution in fibres of activated area, as a function of stimulus intensity, for the frequency range over 1 kc/sec, adapted from WHITFIELD (1957).

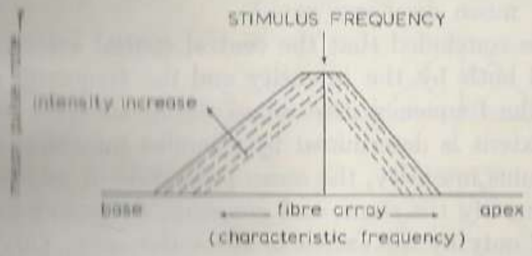

Fig. 5.–2. Diagrammatic representation of distribution of mean pulse rates in the fibre array around the fibre whose characteristic frequency equals stimulus frequency.

WHITFIELD *et al.* determined input-output relations of the ventral cochlear nucleus, and found that the spatial pattern of output activity, as recorded from trapezoid body fibres resembles, in its main features, the input pattern as described by GALAMBOS and DAVIS (1943). Trapezoid body fibres, again, have a V-shaped frequency response area. The main differences between input and output patterns can be summarized as follows:

(1) at the output of the nucleus, the dynamic range is much less than at the input side; i.e. maximum discharge frequency is much lower, and the increase of discharge frequency with increase of stimulus intensity is much less; (2) though there is an overall

positive correlation between stimulus intensity and pulse density, individual pulses are, in the higher frequency range, randomly distributed in time.

Since, according to Whitfield, the number of fibres emerging from the cochlear nucleus is about equal to the number of fibres entering it, while, upon stimulation, the number of active fibres in the trapezoid body is about the same as in the cochlear nerve, the "spatial" activity pattern at the output can be supposed to resemble the input pattern, if the term "spatial" is used in a "connective" sense. The main difference between the input and output patterns of the cochlear nucleus can be summarized as follows:

As follows from (1) and 2, activity within the active fibre array will, at frequencies over some 1000 cps, be randomly distributed in time;

As a result of (2), the "shape" of the active fibre array will be different; beyond a given intensity, an increase of stimulus intensity will result in activation of more fibres rather than in an increase in mean discharge rate.

It can be concluded that the central spatial activity pattern is determined both by the intensity and the frequency of the tonal stimulus: the frequency determines the localization of the active area; its extent is determined by stimulus intensity. Since, for a given stimulus intensity, the mean pulse rate of adjacent neurons is approximately the same, and constant, frequency and intensity are defined only by the extent of the active area. This means that the information content of the activity is concentrated in the delimitation of the active area.

The behaviour of intertone pitches can be explained if we assume that the central representation of the tonal stimulus in man resembles that in the cat, the guinea pig, and the monkey and if we make use of the fact that, as is apparent from anatomical (cf. section 3.5) as well as neurophysiological (KEMP *et al.* (1937), ADES (1944), KATSUKI *et al.* (1958) and (1962), FEX (1962), MOUSHEGIAN (1962), RUPERT *et al.* (1963)) evidence, each of the ears is represented bilaterally in the central auditory system, and that the heterolateral representation is stronger than the homolateral one. As mentioned earlier, the diagram representing the active fibre array is a mirror image of that consisting of the corresponding iso-intensity curves.

Now evidence has been adduced (KATSUKI, 1962) to show that, while the frequency response area is symmetrical in regard to the characteristic frequency for neurons having a characteristic frequency below some 1000 cps, it is markedly asymmetrical for fibres having a best frequency in excess of this frequency, the high frequency leg of the V being much steeper than the low frequency leg. Thus, while the diagrammatic representation of the active fibre array is an isosceles triangle or trapezium for characteristic frequencies below some 1000 cps, it is asymmetrical for fibres with a best frequency over 1000 cps, where the leg representing the equivalent of the apical end of the cochlea is steeper than the other.

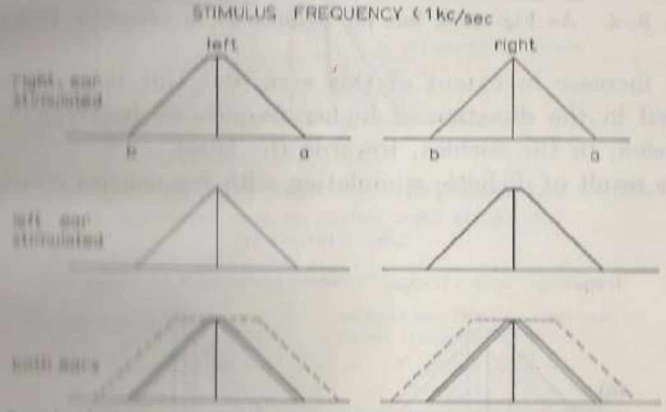

Fig. 5.–3. Activity patterns in the central auditory system upon stimulation of the right ear, the left ear, and both ears, with a frequency below 1000 c/sec. Heavy contour line indicates contribution from heterolateral ear; the thin line that of ipsilateral ear; dashed line indicates total activity due to stimulation of both ears.

Fig. 5.–3 shows, for the frequency range below 1000 cps, the activity in the central auditory system upon stimulation of the right ear, stimulation of the left ear and simultaneous stimulation of the ears with the same frequency. It will be seen that simultaneous stimulation of both ears does not change the location of the maximum activity, but extends the activated area; this represents the binaural supplementation of loudness.

The corresponding diagrams for frequencies in excess of 1000 cps are given in Fig. 5.–4. Here again, the location of the activated area does not change when both ears are stimulated; again, there

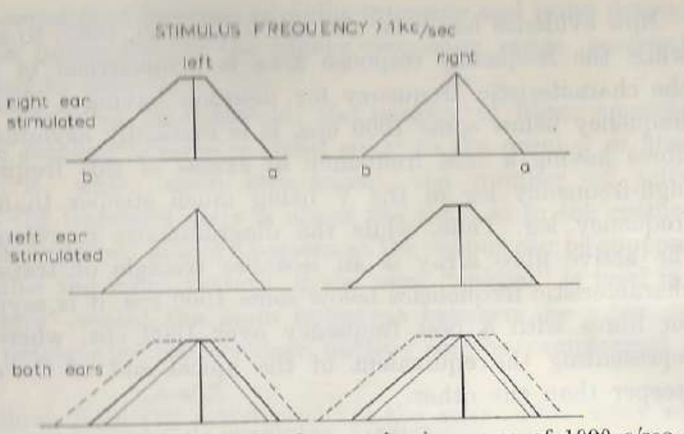

Fig. 5.–4. As Fig. 5.–3, but for frequencies in excess of 1000 c/sec.

is an increase in extent of this area, but this increase is more marked in the direction of higher frequencies (equivalent to an extension, in the cochlea, towards the base).

The result of dichotic stimulation with frequencies which differ

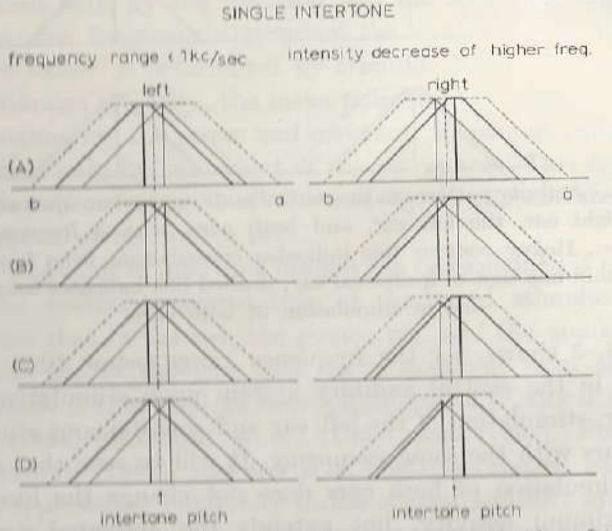

Fig. 5.–5. Activity patterns, in the left and right hand sides of the central auditory system, upon dichotic stimulation; lower frequency offered to the left ear; single intertone. A: intensity at both ears equal; B, C, D, progressive decrease in intensity of higher frequency stimulus. Frequencies below 1000 c/sec. Single intertone pitch remains unchanged.

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by a value such as to produce a single intertone is pictured, for the range below 1000 cps, in Fig. 5.–5, which also shows the effect of a decrease in intensity of one of the stimuli. Single intertone pitch is equal to the pitch corresponding to the arithmetic mean of stimulus frequencies; intensity decrease of one stimulus does not influence intertone pitch but narrows the activated area, which corresponds to a decrease in loudness.

Since, in this frequency range, a certain degree of isoperiodicity between pulse rate variation and stimulus frequency is retained, the activated area will slightly expand and contract in period with

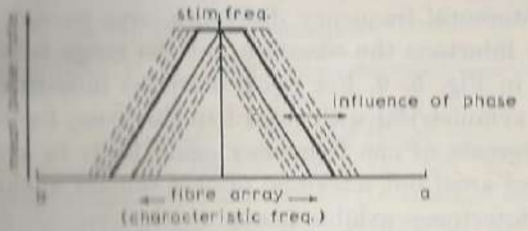

Fig. 5.–6. Frequencies below 1000 c/sec. Expansion and contraction of activated area in period with stimulus.

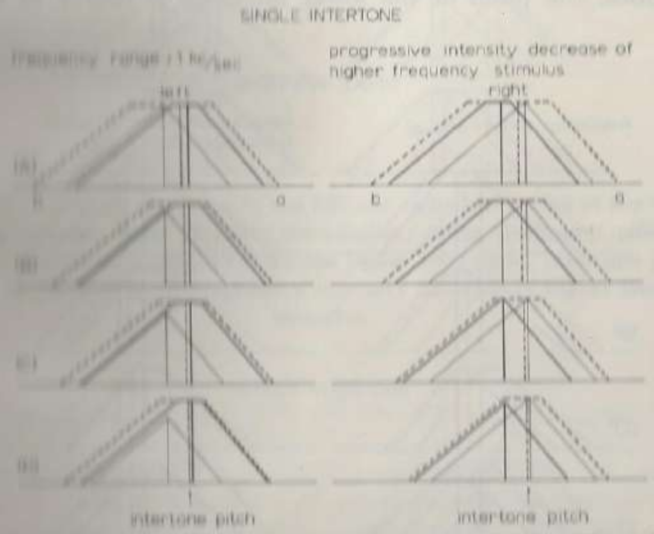

Fig. 5.–7. As Fig. 5.–5, but for frequencies over 1 kc/sec. Upon decrease of intensity of higher frequency stimulus, intertone pitch is displaced downward.

the stimulus. The single intertone then has a beating or rough character (cf. Fig. 5–6).

The corresponding diagrams for the range above 1000 cps are given in Figs. 5.–7 and 5.–8.

Owing to the asymmetry of the array, single intertone pitch is seen to correspond to the pitch of a tone of a frequency lower than the mean of the stimulus frequencies. Decrease of intensity of one of the stimuli results in a shift of intertone pitch towards that corresponding to the frequency of the other stimulus. As phase representation is lost in this frequency range, the intertone is smooth and exhibits no beats.

For an interaural frequency difference large enough to give rise to a double intertone the situation, for the range below 1000 cps, is pictured in Fig. 5.–9. For equal stimulus intensities, intertone pitches are symmetrical with regard to the mean frequency pitch; intensity decrease of one frequency again leads to a reduction of the activated area, but intertone pitches remain unchanged. Here again, the intertones exhibit beats.

The behaviour of double intertone pitches in the frequency range over 1 kc is pictured in Figs. 5.–10 and 5.–11. At equal stimulus intensities, the pitch of the lower intertone is nearer to that of

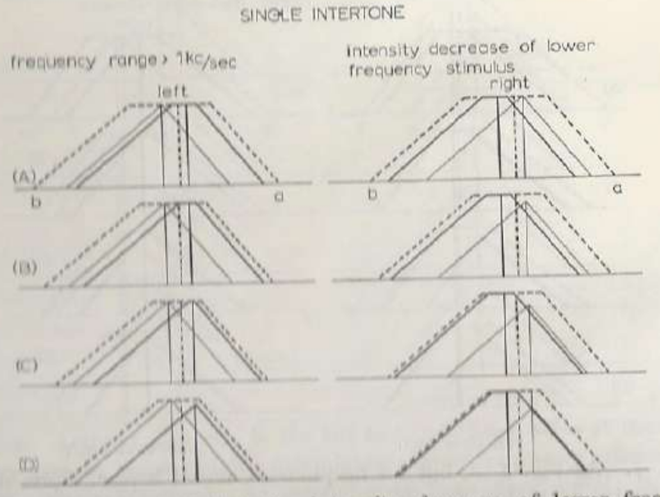

Fig. 5.–8. As Fig. 5.–7, but for intensity decrease of lower frequency. Intertone pitch is displaced upward.

the lower stimulus frequency, than that of the higher intertone is to that of the higher stimulus frequency. This phenomenon which is the expression of the diminishing degree of overlap between the homolaterally and heterolaterally activated areas is, in consequence, the more marked as the frequency difference between the stimulating tones is larger.

At a given interaural frequency difference, lower intertone pitch thus becomes equal to the pitch of the lower stimulating tone, while that of the higher intertone is still below that of the higher one.

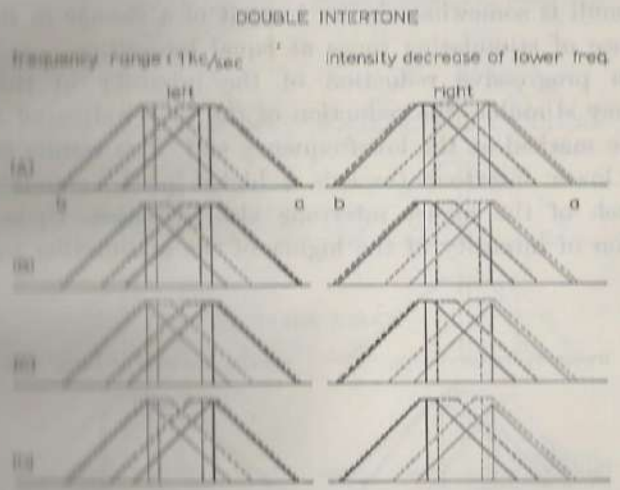

Fig. 5.–9. Activity patterns, in the left and right hand sides of the central auditory system, upon dichotic stimulation; lower frequency offered to left ear; double intertone. Frequencies below 1000 c/sec. Intertone pitches remain unchanged upon progressive intensity decrease of higher frequency stimulus.

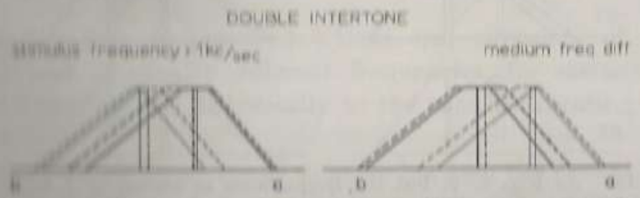

Fig. 5.–10. Double intertone pitches, for medium frequency difference, in the frequency range upward from 1 kc/sec.

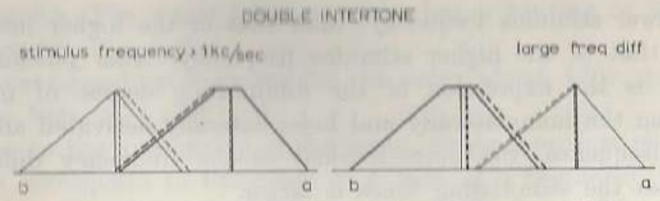

Fig. 5.-11. As Fig. 5.-10, but for large frequency difference.

Just as the single intertone, both intertones are smooth. Fig. 5.-12 shows the effect of interaural intensity difference on double intertone pitches. The effect of a decrease in intensity of one of the stimuli is somewhat similar to that of a change in frequency difference of stimulating tones at equal intensities.

Upon progressive reduction of the intensity of the higher frequency stimulus, the reduction of the total activated area will be more marked at the low-frequency end. This results in a shift of the lower intertone towards a higher pitch; simultaneously, the pitch of the higher intertone also increases. Upon further reduction of intensity of the higher of the stimulating tones, the low-frequency edge of the activated array will coincide with that of the array stimulated by the lower of the two frequencies offered. A further decrease in intensity of the higher stimulating tone will now only be able to reduce the activated array at its high-frequency edge. As a result of this, both intertones now shift to a lower pitch.

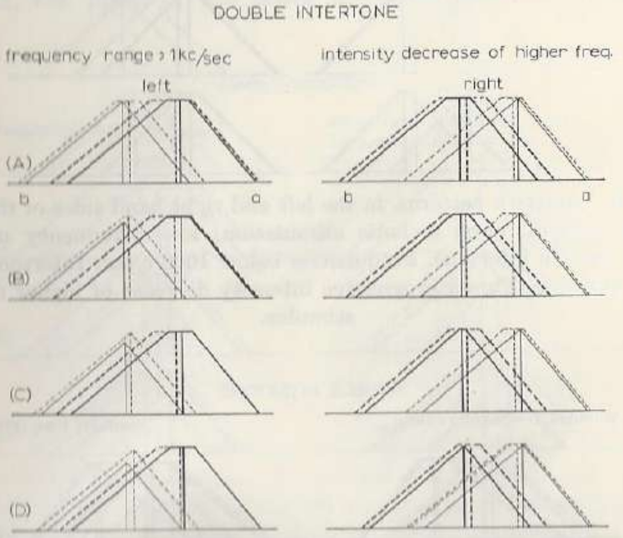

Fig. 5.-12. As Fig. 5.-9, but for frequencies in excess of 1 kc/sec. Note changes in intertone pitches as intensity of higher frequency signal is diminished.

Conversely, a reduction in intensity of the lower of the stimulating tones will cause both intertone pitches first to decrease, then to increase again (cf. Fig. 5.-13).

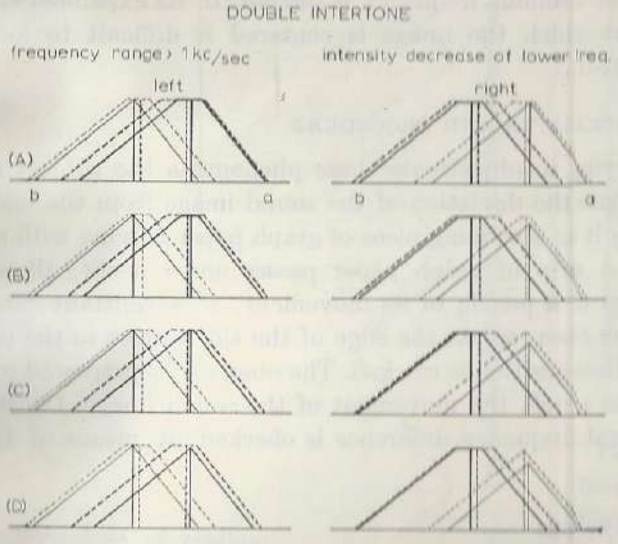

Fig. 5.-13. As Fig. 5.-12, but for decrease in intensity of lower frequency signal.

6. THE "ROTATING TONE"

6.1. INTRODUCTION

When two low frequency ($\nu < 1000$ cps) sinusoids of equal intensity and of slightly different frequencies, for instance 400 and 400,5 cps, are led dichotically to the ears, a "rotating tone" is heard.

A unitary sound image seems to move between the ears at a rate equal to the difference between the frequencies offered. At careful listening a distinct difference between the experience of movement of the sound image from the left to the right versus that from right to left is observed. MOL (1949) remarks on an interesting property of the rotating tone. If the lower frequency stimulus is applied to the left ear, the image is reported to move rather fast from left to right, and moves slowly back from the right to the left.

This statement could be confirmed and extended to include an allied phenomenon; while during the fast phase the sound image remains well-defined, it appears to spread out in phenomenal space during the slow phase, i.e. in its course back to the side at which the lower stimulus frequency is offered. In its expanded state, the point at which the image is centered is difficult to locate (cf. Fig. 6.1.–1).

6.2. APPARATUS AND PROCEDURE

In trying to objectivate these phenomena the subject is asked to indicate the deviation of the sound image from the midline by plotting it on a running piece of graph paper moving with constant speed. A strip of graph paper passes under a slit, allowing the insertion of a pencil, in its movement, at a constant rate, away from the observer. At the edge of the slit nearest to the observer, the midline position is marked. The observer is instructed to follow, with the pencil, the movement of the sound image. Constancy of interaural frequency difference is checked by means of Lissajous figures.

6.3. RESULTS

A typical record is given in Fig. 6.3.–1.

All observers tested indicated the difference in speed between the shifting of the image from left to right and from right to left described above; also, there was a notable degree of uncertainty in the phenomenal location of the image in its passage from the side of the higher stimulating tone to that of the lower one. This area of uncertainty is indicated as a shaded area in Fig. 6.3.–2.

6.4. DISCUSSION

These phenomena are readily explained by the model described in section 5.

If we consider the fact that for frequencies below some 1000 cps the time pattern of nerve spikes shows a correlation between pulse density and phase of the signal (GALAMBOS and DAVIS, 1943), the fact that individual fibers fire at slightly different moments in respect to the phase of the signal (v. BEKESY, 1962, KIETZ, 1962), leads to the conclusion that pulse density is a measure of the

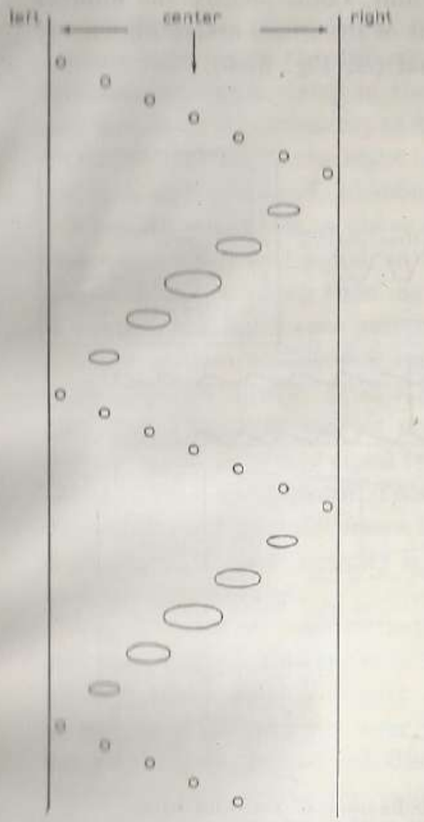

Fig. 6.1.–1. Behaviour of rotating tone. Image moves faster from side at which lower frequency is applied to that at which higher frequency is offered, than in the opposite sense; during the slow-moving phase, the image is expanded and blurred in space.

Fig. 6.3.–1. Typical tracking record of phenomenal location of rotating tone.

Fig. 6.3.–2. Diagrammatic representation of uncertainty area in phenomenal location of image on its course to the side at which lower frequency is offered.

number of active fibers per time-unit. Consequently the number of active fibers, and thus the extent of the whole active fibre array varies with the phase of the signal (cf. Fig. 5.–6).

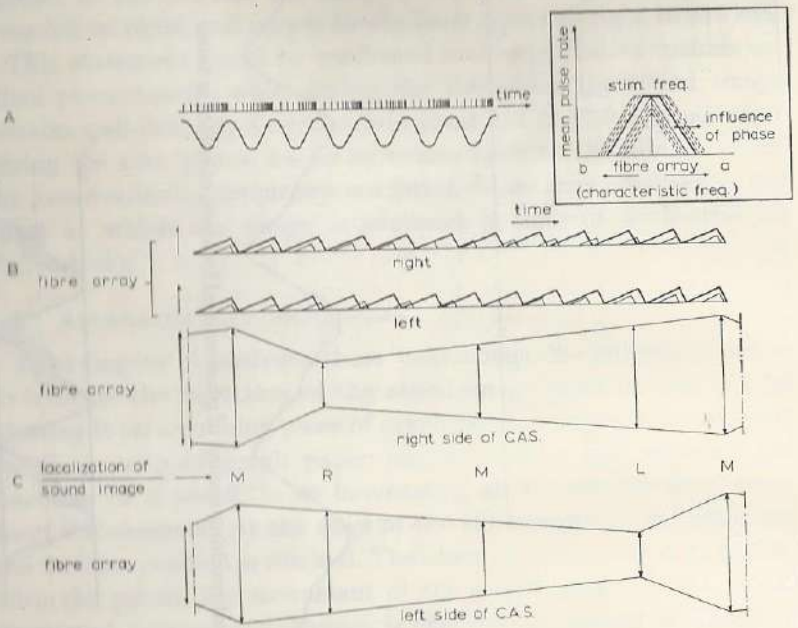

Fig. 6.4.–1. Explanation of behaviour of rotating tone.
A: spike density as a function of signal phase. B: shifts in extent of activity due to signal phase difference. (Inset upper right: cf. Fig. 5.–6). C: Location of sound image.

Fig. 6.4.–1 shows what happens if the lower of the stimulating frequencies is offered to the left ear.

There will be a continuous shift in phase between activation due to both of the stimuli, with a period equal to that corresponding to the frequency difference offered. This phase shift consists, in both sides of the central auditory system, in a progressive lag of that part of the activity due to stimulation of the left ear with regard to the other. In the whole period, the rotating tone comes full circle.

The image is phenomenally located in the sagittal plane when

activities are in phase or in counterphase; it is located at the extreme right when the difference in extent of the activated area, in favour of the activity in the left half of the central auditory pathway, is at a maximum; at the moment when the difference in favour of activity in the right half of the central auditory system is maximal, the image is phenomenally located at the extreme left.

When activities are in phase (first midline position) they are at their maximum, and equal, in both sides of the central auditory system. The increasing time lag of the activity due to stimulation of the left ear will cause activity in the right half of the central auditory system to decrease quickly, and that in the left half to diminish more slowly. After a short while however, that is, after much less than one quarter period, activity in the right half will increase again at a rate equal to that at which that in the left half still continues to diminish. This means that at the moment where the activity on the right passes through its minimum, the difference in favour of left side activity is maximal, and the image is located at the extreme right.

After exactly one half period, activities will again be equal, but less than when activities were in phase. Again, the image passes through the midline. Activity on the right side continues to increase, at constant rate, over the remaining half period; on the left side it first continues to diminish at the same rate, to increase sharply to its maximum value from a moment preceding the completion of the cycle by a time equal to that after which, on the right side, decrease of activity gave way to increase. At this moment, activity difference in favour of the right hand side of the central auditory system is at its maximum, and the image is located at the extreme left. It is evident that, since the time between in-phase activity and localization at the extreme right, and that between localization at the extreme left and renewed in-phase activity are, together, much shorter than that needed to pass from extreme right localization, via counterphase, to extreme left localization, the image appears to move more quickly from the left to the right (i.e. from the side at which the lower frequency is offered), than in the opposite direction. No explanation can be offered as to why counterphase activity should be associated with blurring of the image rather than with a diminished loudness compared to in-phase midline localization.

7. SUMMARY AND CONCLUSION

The experimental part of the present investigation was mainly concerned with the pitch of the single and double intertones which may be perceived when two pure tone stimuli of slightly different frequencies are offered dichotically to the ears.

As a preparation for this, it was necessary to determine the simultaneous dichotic frequency difference limen as a function of frequency.

Listening tasks were standardized and programs were stored on tape; experiments were made in an anechoic and soundproof room; acoustical leakage between the ears was excluded. The two-alternative forced choice procedure was used throughout.

In the introductory experiments the range from 200 to 10 000 cps was covered (subrange 300–3000 cps in 100 cps steps; subrange 3000–10 000 cps in 1000 cps steps.). It was found that, in the range below 100 cps, an approximately constant frequency *difference* of 11 to 14 cps is needed to obtain a just noticeable interaural pitch difference; between 100 and 1500 cps the limen rapidly increases to 60–75 cps, i.e. about 4–5 pct. *Percentage* sensitivity then remains constant up to some 2400 cps, when a second sharp rise occurs; the limen reaches a value of 300 cps (or 10 pct) at 3000 cps; beyond this frequency, percentage sensitivity remains constant.

Behaviour of single and double intertone pitches in the frequency range below 1000 cps is different from that in the higher frequency range.

In the lower range, the pitch of the—beating—single intertone is equal to that of a diotically heard pure tone of a frequency equal to the arithmetic mean of the frequencies offered. In the range over 1000 cps, the image does not beat and the pitch is lower than that corresponding to the arithmetic mean.

Over the whole range, double intertone pitches shift towards the corresponding stimulus pitches upon increase of interaural frequency difference.

In the range below 1000 cps the course of the pitch change of the intertones is symmetrical with regard to the pitch corresponding to the arithmetic mean of the frequencies offered. In the higher range, the frequency difference at which the pitch of the lower intertone becomes equal to that of the lower frequency offered is less than that at which the higher intertone is equalized with the higher frequency stimulus tone.

Below 1000 cps neither the pitch of the single intertone nor those of the double intertones are influenced by interaural intensity difference; images are displaced toward the side at which stimulus intensity is greatest.

Over 1000 cps, single intertone pitch is slightly influenced by interaural intensity difference; upon progressive decrease in intensity of the higher frequency stimulus, the pitch of the double intertones first rises, then falls. Progressive intensity decrease of the lower frequency stimulus causes the pitches of both intertones first to fall, then to rise.

In the theoretical section of the present paper it is shown that the behaviour of intertone pitches can be explained if the following assumptions are made:

(1) each ear is represented bilaterally in the central auditory system, the heterolateral representation being stronger than the homolateral one;

(2) the frequency response area is symmetrical with regard to the characteristic frequency in the range below 1 kc/sec; in the range over 1 kc/sec, the high-frequency leg of the V-shaped area is much steeper than the low-frequency leg;

(3) the spatial activity pattern at the output of the cochlear nucleus is similar to the input activity pattern, even though the dynamic range at the output is much less.

These assumptions are based on experimental evidence collected in cats, guinea pigs and monkeys. On the basis of these assumptions the behaviour of the rotating tone, (which appears to move more quickly from the side at which the lower frequency is offered to that at which the higher frequency is applied, than in the opposite direction), can also be explained.

It is concluded that, in man, where direct electrophysiological experimentation is impossible, the central representation of the pure tone stimulus is similar to that found in the cat, the guinea pig and the monkey.

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STELLINGEN

I

De beschrijving van lysosomen als „suicide bags" is misleidend.

II

Toediening van anticoagulantia aan comateuse patienten is een kunstfout.

III

In alle gevallen van chronische meningitis van onbekende aard moet men een kweek volgens Sabouraud inzetten.

IV

Bij anurie door barbituraatvergiftiging verdient longlavage overweging.

V

De demping van de trillingen bij produktie van vocalen wordt niet veroorzaakt door absorptie in de mond-keelholte.

VI

In geval van — van frontaal — op het oog inwerkend geweld dienen neusbijholte foto's gemaakt te worden.

VII

Nog steeds is niet bewezen dat radicale mastectomie de beste therapie is voor „curabel" carcinoma mammae.

VIII

Regelmatige audiologische contrôle van patienten, welke worden behandeld met chloroquine verbindingen, is noodzakelijk.

IX

Een intubatie-set dient op iedere ongevalspolikliniek aanwezig te zijn.

X

De benaming „Castratenstem" ter aanduiding van een manlijke alt (counter tenor) is onjuist.

D. W. ODENTHAL
LEIDEN