Phantom source experiments in auditory localization

P. H. SCHMIDT

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PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE GENEESKUNDE AAN DE RIJKSUNIVERSITEIT TE LEIDEN OP GEZAG VAN DE RECTOR MAGNIFICUS Dr J. N. BAKHUIZEN VAN DEN BRINK, HOOGLERAAR IN DE FACULTEIT DER GODGELEERDHEID, TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER GENEESKUNDE TE VERDEDIGEN OP DONDERDAG 7 JULI 1955 TE 15 UUR

door

PIETER HERBERTUS SCHMIDT

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PROMOTOR: J. W. DUYFF

AAN MIJN OUDERS
AAN MIJN VERLOOFDE

CONTENTS

SAMENVATTING

1. De juist waarneembare interaurale verschillen in intensiteit en in tijd van aankomst werden, voor frequenties van 250 tot 5000 trillingen per seconde bij een intensiteit van 45 db boven de drempelwaarde, bepaald met behulp van phantoombronnen.
2. Het juist waarneembare intensiteitsverschil bedraagt voor frequenties boven 2000 trillingen per seconde 0,2 db. Voor lagere frequenties wordt de verschildrempel snel groter; bij 250 trillingen per seconde bedraagt zij 0,8 db. Het juist waarneembare tijdsverschil bedraagt 10 μsec voor frequenties lager dan 1000 trillingen per seconde, bij verhoging van de frequentie boven deze waarde wordt de gevoeligheid voor tijdsverschillen zeer snel minder.
3. De juist waarneembare azimuthverplaatsing van een reële geluidsbron uit het mediane vlak is in goede quantitatieve overeenstemming met de gevoeligheid voor tijdsverschillen in het frequentiegebied beneden, en met die voor intensiteitsverschillen in het frequentiegebied boven 1500 trillingen per seconde.
4. De gevoeligheid voor interaurale tijds- en intensiteitsverschillen vertoont een opmerkelijke overeenstemming met de grootte van de duidbare verschillen die door een reële bron kunnen worden aangeboden.

I. INTRODUCTION

The phenomenal location of a point source situate in the horizontal plane through the external auditory canals, involves a judgment as to its azimuth (ϑ) and its distance (ρ) in regard to a point midway between the ears. Except in those cases where the source is at zero or 180^{0} azimuth, there will be a difference in physical pattern between the stimuli presented to the ears. This difference, on which the lateralization of the source is based, is in its turn primarily dependent on the difference in path length between the source and the eardrums. The difference in path length - which can never exceed the effective distance between the drums - results in a difference in intensity of the signals received and in a difference in arrival time of the wave fronts.

Even in the case where the source and the observer are placed in an anechoic room, there will, however, be many complications, due mainly to the fact that the head is interposed between the ears, and that the eardrums do not lie at the surface, but at the end of the external auditory canals, whose entrances are adorned with the earflaps. Thus, the tympanic membranes are reached only after the signals have been strongly modified by reflection, refraction and scatter and by the resulting superposition phenomena. The influence of these factors is not the same for the various frequencies present in the signals emitted; they can be eliminated by removing the head from between the ears, i.e. by connecting the ears, by means of equal, suitable tubes, to a pair of equal non-directional receivers at a fixed distance from each other, and lying in a plane with the source, the head being well outside of that plane. In this simplified case, the signals received will show a difference in intensity and in arrival time dependent only on the position of the source with regard to the receivers. If, moreover, the source emits a continuous pure tone of constant intensity, the time difference gives rise to a constant phase difference which can, in principle, be considered as a phase lead at the ipsilateral ear.

The main problems regarding the mechanism of binaural auditory localization are those concerning the relative importance of temporal and intensive cues, and, for the case of a pure tone wave, the question of whether arrival time difference as such or phase difference is involved.

As to intensity relations, it can easily be shown (cf. SCHMIDT et al., 1953) that the ratio between the energies delivered to the receivers is the reciprocal of that between the corresponding path lengths squared; the intensity ratio is independent of the intensity at the source, and frequency does, in general, not enter into the case if the overall frequency characteristic of the receiving system is flat. For any given azimuth value, the ratio between the energy densities at the receivers is proportional to the sine of azimuth, the proportionality factor depending on distance. It follows that sensitivity to azimuth changes, as judged by changes in intensity ratio will, by close approximation, be a cosine function of azimuth.

Except for very small β values, the path difference - and thus the arrival time difference - will also be proportional to the sine of azimuth; it follows that, if arrival time difference serves as a cue, the sensitivity to azimuth changes will also be a cosine function of azimuth.

Thus, the fact that, in experiments on directional localization of actual point sources (SCHMIDT et al., l.c) the sensitivity to azimuth changes is indeed found to be directly proportional to the cosine of azimuth does not, in itself, allow of a decision as to the relative importance of intensitive and temporal cues. In practice, however, the influence exerted by the interposition of the head is strongly dependent on frequency, an effective shadow being cast by the head for wave lengths which are small in comparison to its circumference; this tends to magnify the importance of intensity difference as a cue to directional localization in the case of high frequencies.

As to the nature of the temporal cue, and the possible significance of phase relations as an index, it should be remembered that the phase difference corresponding to a given time difference depends on frequency; the phase lead at the ipsilateral ear is equal to the product of the residual path difference (i.e. the total difference in path length minus the combined length of the whole waves contained in it) and the wavelength constant $2\pi/\lambda$, and a phase lead exceeding π will be perceived as a lag equal to the supplement of that lead; in other words, the ear which leads will be the ear for which the residual path difference is the smaller only if the lead is less than 180°. For high frequencies in particular, phase relations as such could, in practice, hardly serve as a dependable cue, even if we leave the phase jumps caused by reflection out of consideration; for any given frequency, there will be no phase difference if the difference in path length equals a whole number of wavelengths, while the phase cue would break down in those cases where it equals an odd number of half wavelengths. In connection herewith, the fact that no apparent shift in position is exhibited by a source when its frequency is - slowly - changed is of importance.

The significance of attempts further to analyze the contributions of changes in intensity ratio, and in time relations, both of which are, by themselves, able to cause lateralization, to the perception of changes in position of an actual pure tone source lies less in their importance for an understanding of the mechanism of auditory localization in daily life than in the opportunity they offer of studying some aspects of the auditory mechanism as such.

pect to unity, it follows that, in the course of every full period, there are two moments, separated by a 3½ sec interval (at 1,75 and 5,25 sec, respectively) at which signal intensities are equal. These moments are indicated to the observer by an additional signal. Similarly, a signal is offered at the corresponding moments when, in the experiments on time difference thresholds, the time difference is zero. These additional signals punctuating the experiment serve the observer as reference points in time, from which to judge the direction of the change offered, i.e. the direction of the apparent shift of the source from the sagittal plane. As in the actual source experiments referred to earlier, there was no limit to the observation time allowed; on the other hand, the observer had to make a choice in every single observation. He indicated the nature of his choice (either an apparent shift to the left or one to the right) by pushing one of two buttons, each of which activated a lever writing on a drum which was invisible to him, and on which the movement of the rotor was also recorded.

The results to be described in the following are those obtained with one trained observer, whose threshold audiograms were normal and virtually equal, and who had obtained consistent results in actual-source experiments. The results obtained in the various experimental series are thus comparable inter se and can be considered in conjunction with those found earlier with actual sources.

It may be added that, though, of course, numerical values show rather large individual differences, the general picture is the same for a variety of trained obeservers.

The time taken by the observer to arrive at a judgement varied between 30 and 60 sec. After each single observation, the rubber tubes were removed and a rest period of a few minutes was allowed before the next observation.

Observations were, as a rule, made in series of about three quarters of an hour each, run with 30-minute intervals between successive series. By offering the various frequencies and intensity or time differences in random succession, a systematic influence of fatigue was excluded.

B. INTERPRETATION OF DATA

The way in which the data obtained are interpreted is analogous to that described in the report on actual source experiments. If the deviations from unity of the intensity ratio, or, as the case may be, the deviations from zero of the time difference, are so small as to be imperceptible, the 'judgment' made by the observer is a matter of pure chance, and, given a sufficient number of individual observations, it will be correct in 50 per cent of the cases.

respectively, and for continuous pure tones of a variety of frequencies at an intensity level of + 45 db re the ASA standard MAF level (2.10^{-4} dynes.cm^{-2} at 1000 cps). The setup of the experiments was partly based on that of the actual-source experiments referred to earlier.

II. L I T E R A T U R E

A. GENERAL CONSIDERATIONS

Though, at first sight, it appears to be a simple matter to study the threshold for isolated differences in arrival time, or changes in intensity ratio, for continuous pure tones by means of phantom sources, a careful design of the experiments, and of the apparatus used in particular, is necessary in order to avoid the many pitfalls which may cause faulty results, and to be certain that no cues but those intended are offered to the observer. Such additional cues are introduced in all cases where there is a abrupt change in either phase or intensity and where, as a consequence, new frequency bands of perceptible intensity might be produced. The changes in either intensity ratio or time relations offered should thus be gradual and, by preference, linear. The apparatus should be such that, when the threshold for intensity ratio changes is studied, no appreciable time- (or phase-) shift occurs, nor should there be a change in intensity when the time relations are modified.

In experiments on the threshold for changes in interaural intensity ratio, the fact should also be taken into consideration that such changes always involve a change in intensity at at least one of the ears.

According to RIESZ (1928), who studied the sensitivity of one ear to a change in intensity as a function of both intensity level and frequency, a change of less than 1 db is perceptible at an intensity level of 40 db in the frequency range of 100 - 8000 cps. As will be shown later, the monaural intensity difference limen is, at approximately this sound level, as low as 0,15 db at frequencies over 2000 cps.

Phantom experiments more or less closely related to those to be described in the present report, have been made by various authors. In part of the cases it is, from the data published, impossible to judge whether the experiments were correctly designed, while in others, the experimental procedure is certainly open to criticism.

B. INTENSITY RELATIONS

Thus UPTON (1936) determined the threshold for interaural intensity difference at 800 cps and at a variety of intensity levels. Initially, the intensity was the same at both ears; the intensity of the signal at one ear was kept constant, while it was slowly increased at the other. For initial total intensity levels of 60 - 100 db re the normal audibility threshold for the frequency used the just noticeable increase was about 1 db; at higher (!) or lower sound levels it increased to 2-3 db. UPTON's experiments cannot serve to determine the just noticeable interaural intensity difference, since the increase in intensity at one ear (which is of an order comparable to that which, even according to RIESZ, would in itself, already be perceptible) results in an increase in total (binaural) intensity. It must be admitted, however, that, as is apparent from UPTON's own results, such a small change in overall intensity would, at least in the 40 - 60 db region, hardly seem sufficient to cause a sizable change in sensitivity to interaural intensity difference. As a description of his apparatus is lacking, however, the possibility that changes in time relations occurred cannot be excluded.

An elegant method was used by FORD (1942) who based himself on earlier experiments by FIRESTONE (1930), in which this investigator determined with the aid of a wax dummy, the ratio between the intensity at the ears for various positions of the source, and for a number of frequencies. In FORD's experiments, the intensity ratio between the signals offered to the ears by means of a pair of telephones, could be varied by the subject turning his head in the horizontal plane, the circuit being such that the intensity ratio then varied according to the data collected by FIRESTONE at 256 cps. The subject had to find the position of the head in which the apparent source was at zero azimuth, i.e. where the intensity ratio was equal to unity.

As is apparent from the data published by FIRESTONE, his results at 256 cps differed greatly from those at 1944 cps, as is hardly surprising in view of the fact that the head casts a deep shadow at the last-named frequency; even so, FORD used FIRESTONE's 256 cps data for measurements at 2000 as well as at 200 cps. Still, the intensity ratio threshold was found to be substantially lower at 2000 cps than at 200 cps (0,3 db as against 0,9 db); from this, it can be concluded that the sensitivity to interaural intensity difference is less at low frequency. According to FORD the absence of time difference was proved by checking the LISSAJOUS patterns obtained by feeding the individual signals to the x- and y-deflection plates of an oscilloscope. If we take the just noticeable time difference to be of the order of 10 μsec (see III D, 4) however, it appears that, at 200 cps, a just noticeable difference in arrival time would give an ellipse pattern with a 1:100 axis ratio, which would probably escape detection on the oscilloscopes in use at the time; from the data on the circuit the possibility of time changes brought about by the head movements can certainly not be excluded. Quite apart from this, it should be remarked that the fact that if a phase difference between the electric signals fed into the telephones is absent this does not necessarily mean that the same is true for the acoustic signals emitted by the latter.

A somewhat similar objection applies to the method used by BOLLE, LO SURDO, and ZANOTELLI (1947a, b). In their experiments, the audio-frequency voltage delivered by a frequency-beat oscillator is amplified and fed into two parallel amplitude- and phase variators consisting of a R-C bridge of high input impedance and a potentiometer, each of the output signals being fed, via a final amplifying stage, into one of a pair of electrodynamic telephones. Though measures were taken to ensure equality of the sound levels when feeding voltages were equal, the possibility remains that, even when the voltages were isophasic, a phase difference, dependent on frequency, between the acoustic signals delivered was present; the fact that, according to these investigators, a frequency change gives rise to an apparent shift in position of the phantom source, suggests that such was the case.

At sensation levels of 45-70 db, the just noticeable intensity difference was found to be 1-2 db at 256 cps, sensitivity increasing somewhat with frequency.

C. TIME (PHASE) RELATIONS

Data on the threshold value of interaural time (or phase) difference are rather inconsistent. As a rule, the values are found to be rather high for pure tones, and markedly lower for complex sounds (VON BEKESY, 1930; WALLACH, NEWMAN and ROSENZWEIG, 1949; KLUMPP, 1953).

HUGHES (1940) started from the observation made by several authors, that at frequencies over soem 800 cps, an isolated difference in arrival time (which results, for pure tones, in an interaural phase difference), is comparatively ineffective in producing the sensation of a directional shift of the apparent source, and set himself the task of determining the upper frequency limit for the binaural localization of a pure tone by phase difference. The oscillator fed a quadrature circuit giving two equal EMF's differing 90^{0} in phase; each of these EMF's energized a phase-shifting transformer. The EMF delivered by each of the secondary coils was applied to a variable amplifier, the output of which activated a telephone. According to the author, the intensity variations of each signal, occasioned by the rotation of the coil did not exceed $\pm$ 0,2 db. His results would seem to show that, for trained observers, there is, at frequencies from 600 - 1200 cps, an approximately constant phase difference threshold of about 20 degrees; from these data it can be concluded that the threshold time difference would be about 120 µsec at 600 cps, as against some 60 µsec at 1200 cps. Beyond 1200 cps, the threshold shows an increase. Irregular results were obtained with untrained observers. In regard to HUGHES' experiments it must be remarked that the variations in intensity accompanying the variations in arrival time offered are such as to be noticeable in themselves. Though HUGHES' experiments are thus certainly open to criticism, the fact that when the frequency is increased to over 1200 cps there is an abrupt decrease in sensitivity to the time differences offered is of significance.

In contradiction to HUGHES, whose results would suggest that the temporal cue is furnished by phase difference, and not by arrival time difference as such, BOLLE, LO SURDO, and ZANOTELLI (1947a, c) found that, at a sensation level of 40-70 db, there is an approximately constant threshold time difference of some 100 μsec for the frequency range of 128-1024 cps.

GARNER and WERTHEIMER (1951) asked 54 naive observers, ranging in age from 7 to 45 years, whether they could hear a difference between two successive tones differing only in respect to which ear was leading in phase. Use was made of a continuous phase shifter and a reversing switch by means of which a phase lead at one of the ears in the first of the tones offered was abruptly changed into a lag of the same magnitude in the second. Frequencies ranged from 200-2000 cps; the intensity level was 90 db re 10^{-16} W/cm^2. The group data indicated that, at frequencies between 200 and 1000 cps, the interaural time difference threshold is approximately constant at 170 μsec; beyond the latter-named frequency, it strongly increases.

III. EXPERIMENTAL

A. GENERAL

As will be seen in the following paragraphes, the conditions named earlier were fulfilled in the experiments on which the present report is based.

For both series of experiments, the general setup was the same; it was in part based on that of the pendulum experiments described earlier (SCHMIDT et al. 1953). Experiments were made in a quiet, though not completely silent, and hypechoic room. The signals offered were emitted by a pair of virtually equal telephones fed by a low-distortion oscillator, and connected to the observer's ears by equal lenths of rubber tubing. Periodic, linear, and symmetrical changes in either arrival time difference or intensity ratio were produced by a rotating capacitor, or a rotating pair of sliding contacts on a potentiometer system, built into the circuit. In both cases, the period of rotation was 7 seconds; taken in conjunction with the fact that the retention period of the ear approximates one quarter of a second, this means, as has been argued earlier (loc. cit.), that the threshold values found can serve as a reliable index to the best of which the auditory apparatus is capable.

From the fact that the changes in intensity ratio are symmetrical in respect to unity, it follows that, in the course of every full period, there are two moments, separated by a 3½ sec interval (at 1,75 and 5,25 sec, respectively) at which signal intensities are equal. These moments are indicated to the observer by an additional signal. Similarly, a signal is offered at the corresponding moments when, in the experiments on time difference thresholds, the time difference is zero. These additional signals punctuating the experiment serve the observer as reference points in time, from which to judge the direction of the change offered, i.e. the direction of the apparent shift of the source from the sagittal plane. As in the actual source experiments referred to earlier, there was no limit to the observation time allowed; on the other hand, the observer had to make a choice in every single observation. He indicated the nature of his choice (either an apparent shift to the left or one to the right) by pushing one of two buttons, each of which activated a lever writing on a drum which was invisible to him, and on which the movement of the rotor was also recorded.

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If, on the other hand, they are large, a correct judgment will be made in all cases. In between, the percentage of correct judgments will increase with the extend of the variations offered, and the threshold of the variation range will be given by its value at the point corresponding with that at which the psychometric curve intersects the 75 per cent. line.

C. THE INTENSITY CUE; THRESHOLD VALUE OF INTERAURAL INTENSITY DIFFERENCES

1. Description of apparatus

The apparatus used in this series of experiments (Fig.1) was designed to produce continuous, isophasic pure tone signals at the telephones; the intensity of each of the signals shows a periodic, linear change from a maximum value to a minimum, and back; at the moment when the signal at one of the telephones reaches the maximum, that at the other is at its minimum. As a result of this, the intensity ratio changes periodically, and symmetrically in respect to unity. The circuit is fed by a low-distortion oscillator (GR 1301-A) furnishing an audio-frequency signal E_i (r.m.s. Volts) which is fed into a potentiometer system P consisting of a circular, linear continuous-winding resistor ($R = 400\,\Omega$) connected to the oscillator binding posts at two diametrically opposite points. Each of the, parallel, 200 Ω resistors to which the signal is thus applied serves as a linear potentiometer thanks to the presence of a pair of moving arms (sliding contacts) mounted in opposition on a common spindle, which rotates at constant velocity, the duration of one complete turn being equal to 7 sec.

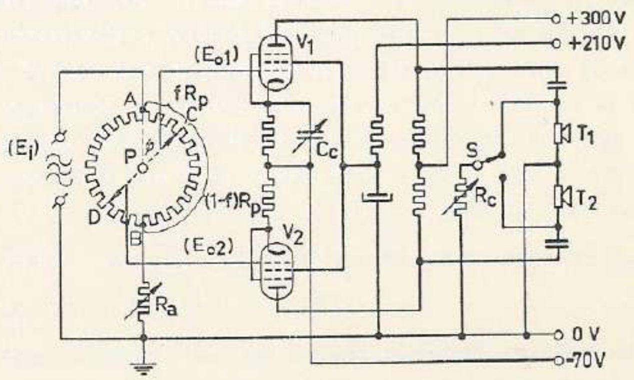

Fig. 1 Diagram of intensity ratio variator

As a result of this, each of the voltages E_{o1} and E_{o2} will show a periodic linear increase from a minimum value to a maximum, followed by a similar decrease back to the minimum, and, as far as these changes, the magnitude of which can be changed with the aid of the variable resistor R_a, are concerned, these voltages will be in counterphase.

E_{o_1} and E_{o_2} are fed to the grids of the amplifying tubes V_1 and V_2 (6AQ5), respectively, the anodes of which are capacitively coupled to the corresponding telephones T_1 and T_2; the acoustic signals emitted by the telephones are directed to the ears of the observer by means of a pair of rubber tubes of a length of about 30 cm and an inner diameter of 7 mm.

Provision for the fact that no two telephones with an absolutely identical characteristic can be found is made by the introduction in the circuit of the variable capacitor C_c, the variable resistor R_c, and the switch S. With the aid of the latter, R_c and C_c can be set in such a way that the acoustic signals emitted by the telephones are equalized as to intensity and phase. To this end, equal signals ($E_{o_1} = E_{o_2}$) are fed to the grids of the tubes, and a Y-shaped brass tube is connected to the free ends of the rubber tubes. C_c and R_c are then set to such values that no sound is delivered through the open end of the brass tube; the acoustic signals delivered at the free ends of the rubber tubes must then be of equal intensity, and in opposite phase. By commutating one of the telephones, its signal is then shifted 180 degrees; since the telephones are capacitively coupled to the corresponding anodes, commutation does not occasion any change in intensity nor any additional phase shift.

2. The intensity of each of the acoustic signals offered as a function of time

At the moment when one of the sliding contacts is at A, and when, in consequence, the corresponding output voltage, say E_{o_1}, is at its maximum E_i, the other will be at B, and the corresponding voltage E_{o2} will be at its minimum. Let the total resistance of each of the potentiometer-wires be R_p, then, at the moment when, starting from this position, an angle φ has been traversed, and when the sliding contact has thus moved from A to C, where $\frac{AC}{AB} = f = \frac{\varphi}{\pi}$, then the value of E_{o1} will be given by the r.m.s. voltage at C re earth, viz. $E_i(1-f.\frac{\Delta}{1+\Delta})$, where $\Delta = \frac{R_p}{2R_a}$; at this moment, the value of E_{o2} will obviously be $E_i\left[1-(1-f)\frac{\Delta}{1+\Delta}\right] = E_i.\frac{1+\Delta.f}{1+\Delta}$.

Now let the maximum intensity of the acoustic signal emitted by one telephone be I_{max}, then it follows that, when I_1, the sound intensity at T_1, is equal to $(1-f\frac{\Delta}{1+\Delta})^2.I_{max}$, that at the other, ($I_2$) will be $\left(\frac{1+\Delta.f}{1+\Delta}\right)^2.I_{max}$, and the intensity at each individual telephone will periodically vary between I_{max} and I_{min}, which latter equals $\left(\frac{1}{1+\Delta}\right)^2.I_{max}$.

Thus, at time $t_{(f)}$ the sound intensity at T_1 will differ from I_{max} by $20 \log (1-f\frac{\Delta}{1+\Delta})$db, or since $\Delta \ll 1$,

$I_{1(t)}$ (db) $= I_{max}-20 \times 0,4343 f \frac{\Delta}{1+\Delta}$ (db) $\approx I_{max}-8,7 f . \Delta$ (db) $=$ $I_{max}-8,7 f . \frac{R_p}{2R_a}$ (db)

Similarly $I_{2(t)}$ (db) $= I_{max}-8,7(1-f)\Delta$ (db) $= I_{max}-8,7(1-f)\frac{R_p}{2R_a}$ (db)

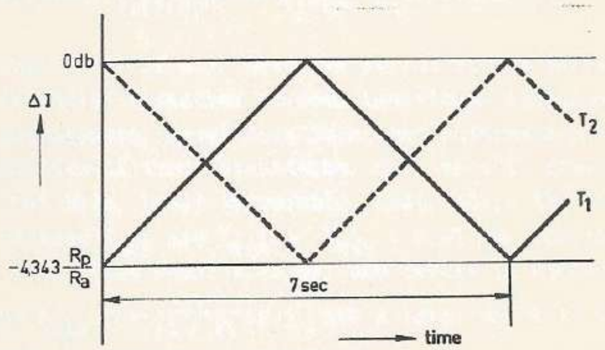

Fig. 2 Intensity of sound signals emitted by each of the telephones, with reference to I_{max}, as a function of time

The range, r, of intensity variation of the signal emitted by each telephone I_{max}(db)$-I_{min}$(db) is given by $8,7\frac{R_p}{2R_a}$ (Fig. 2); since $R_p = 200\,\Omega$ we have: r(db) $= \frac{870}{R_a}$

and the maximum change in interaural intensity difference will be twice this amount.

With the aid of this relation R_a could be preset in such a way as to vary r in 0,025 db steps; for r $=$ n. 0,025 (db), $R_a = \frac{34800}{n}(\Omega)$

3. Combined sound intensity as a function of time

At any given moment, the combined intensity $I_{tot} = I_1 + I_2$ will be equal to $\left[1+\frac{1}{(1+\Delta)^2} - 2f(1-f)\frac{\Delta^2}{(1+\Delta)^2}\right] . I_{max}$

I_{tot} thus shows a maximum for f $=$ 0 and f $=$ 1, and a minimum at f $=$ ½.

The value of I_{tot} at time $t_{(f)}$ will be

$$I_{tot\ max} - 10 \log \frac{1 + \frac{1}{(1+\Delta)^2} - 2f(1-f)\frac{\Delta^2}{(1+\Delta)^2}}{1+\frac{1}{(1+\Delta)^2}} =$$

$$= I_{tot\ max} - 10 \log \left[1 - \frac{2f(1-f)\Delta^2}{1+(1+\Delta)^2} \right] \quad \text{(db)}$$

Now since $\Delta \ll 1$, Δ^2 will be $\lll 1$, so by close approximation $I_{tot(t)} =$

$$I_{tot\ max} - 10 \times 0{,}4343 . \frac{2f(1-f)\Delta^2}{1+(1+\Delta)^2} = I_{tot\ max} - 8{,}7 f(1-f)\Delta^2 \text{(db)}$$

It follows, first of all, that the period of the variation of I_{tot} is half that of the intensity variation at each individual telephone; variations of I_{tot} can, in consequence, never have furnished reference points in time. As regards the magnitude of these variations, Δ , as will presently be shown, never exceeds 0,1. For this, least favourable, case, where the intensity at each ear thus varies between I_{max} and $I_{min} = I_{max} - 0{,}87$ db, and the interaural changes in intensity ratio thus equal 1,74 db, the change in combined intensity only varies between $I_{max} . (1 + \frac{1}{(1+\Delta)^2})$ and a level which is lower by 0,022 db; a variation which is completely negligible.

4. The maximum phase shift caused by the variations in f

The question remains whether the phase shift occasioned by the periodic changes in f might have a disturbing influence. Let the responsible stray capacity equal 100_pF (a value which is certainly much too high), then the equivalent circuit will be as in Fig.3, and the resulting phase shift will equal

$$\varphi \approx \text{tg}\,\varphi = 2\pi\nu RC = 2\pi\nu . 10^{-8}$$

As will be shown later, the just perceptible arrival time difference corresponds, at the low-frequency end of the range where the sensitivity to time difference is highest, to a phase difference of $2\pi\nu . 5 . 10^{-6}$; i.e. to a phase shift which is 500 times larger than that which might have occurred even with this stray capacity

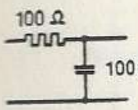

Fig. 3

5. Results

The results obtained are pictured in the graphs of Fig.4, where the percentage of correct judgments is plotted against the width of the interaural intensity variation range for a number of frequencies ranging from 250 - 5000 cps,

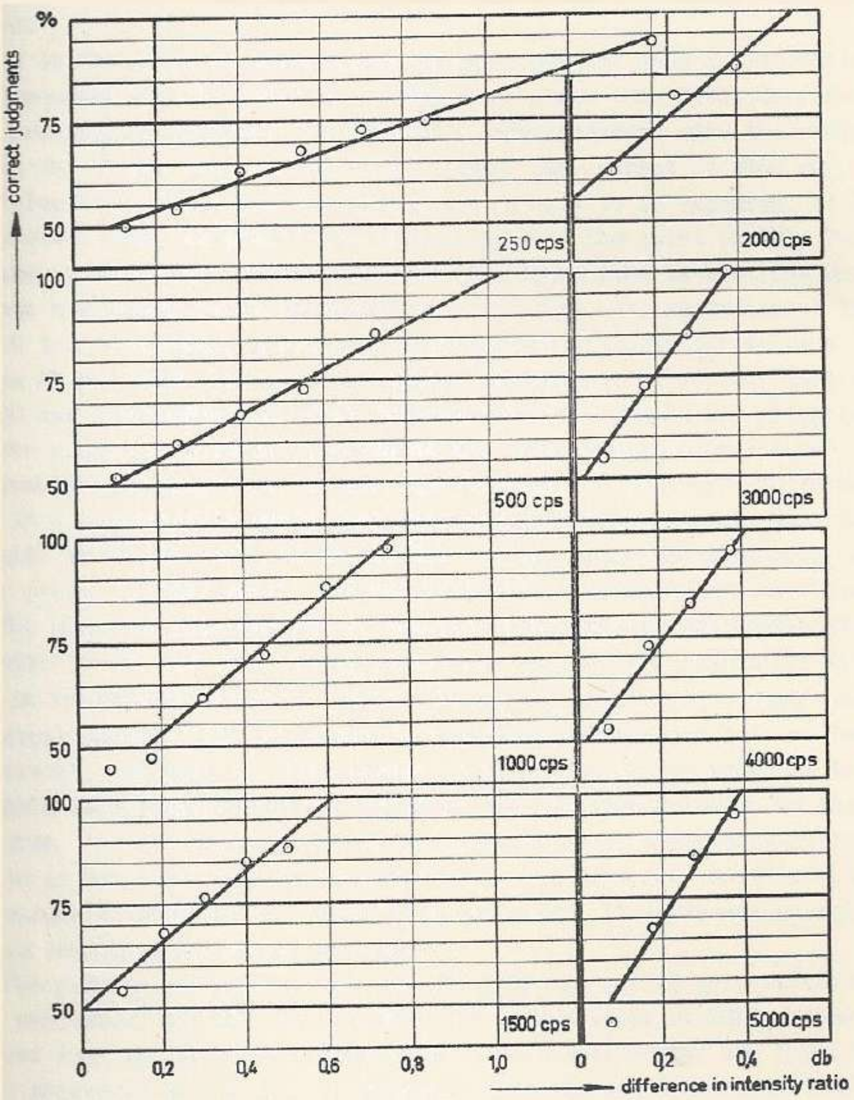

Fig. 4 The psychometric function for changes in intensity ratio at various frequencies

and at an I_{max} of 45db re the ASA standard MAP level. Each point represents the results obtained in at least 75 observations.

As is apparent from these graphs, the psychometric function can, by close approximation, be represented by a straight line ($y = \underline{a}x + \underline{b}$), at all frequencies investigated. The straight lines drawn in the graphs are those which - assuming the function to be linear - give the best fit by the method of least squares.

As to the slope of these lines, a would seem to show a systematic increase with frequency for the range up to 3000 cps; above this frequency, the slope remains practically constant. As regards b, the intercept with the ordinate lies near to the 50 per cent. level in all cases, and, except at 2000 cps, the point of intersection lies below this level, as is only to be expected; at 1500 cps, on the other hand, it practically coincides with the point (0,50). Though, in the case of 2000 cps, as in the others, the drawn line is the line best fitting the data collected, it is certainly not a correct representation of the situation at this frequency, a point of intersection with the Y-axis at a level exceeding 50 per cent. being theoretically impossible. It may be, that the result at 1500 cps approaches the ideal representation of the actual situation, and that the slightly different results at the other frequencies are due to small experimental imperfections; it may also be that, in reality, the threshold value is not infinitely small, and that the fact that, at 1500 cps, the intercept lies at 50 per cent. is accidental. In any case, the threshold, should it really exist, is very small, and not systematically dependent on frequency.

The point of intersection of the line representing the psychometric function with the 75 per cent. level is defined as the just noticeable difference (jnd) in interaural intensity ratio. It may be added that, in this connexion, the actual shape of the psychometric function is not essential, as long as it is symmetrical, and that a slight change in slope, or in the value of the apparent threshold hardly influences the value of the jnd thus defined; in the 2000 cps case also, the jnd value found can be considered as very nearly correct.

As is apparent, the jnd is practically constant at less than 0,25 db for frequencies of 2000 and up; below this frequency, it increases sharply, to reach a value exceeding 0,8 db at 250 cps.

The results obtained at 250 cps and 2000 cps are in good agreement with those published, for 200 cps and 2000 cps respectively, by FORD, whose method presents some analogies with that used in our experiments; the approximate value of the threshold at 800 cps, as computed from the results obtained at 500 cps and 1000 cps is about half that found by UPTON; that at 250 cps (about 0,8 db) is noticeably lower than that found by BOLLE, LO SURDO, and ZANOTELLI at 256 cps, viz. 1-2 db.

D. THE TEMPORAL CUE; THRESHOLD VALUE OF DEVIATION FROM ZERO TIME DIFFERENCE

1. Description of apparatus. The apparatus used in this series of experiments is largely analogous to that described in the preceding section.

In this case (Fig. 5), the low-distortion oscillator delivers an audio-frequency voltage which is, by means of the potentiometer P_g, made exactly symmetrical re ground; it thus varies between $+E_i$ and $-E_i$.

C_f is a fixed capacitor of 1200 pF, while C_v is a variable capacitor, the capacity of which shows a periodical linear variation between 325 pF (= $C_f - C_o$) and 2075 pF (= $C_f + C_o$)

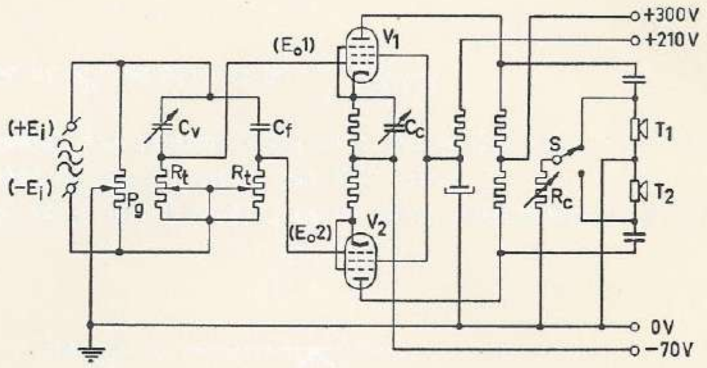

Fig. 5 Diagram of phase shift variator

as a result of continuous rotation of one set of plates, the rotation period again being 7 seconds. As a result of the changes in C_v, E_{o_1} will alternately lead E_{o_2} and lag behind it; the extent of the phase shift can be set by means of the tandem potentiometer R_t.

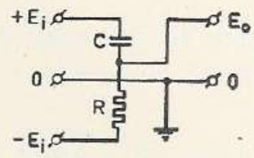

Fig. 6

E_{o_1} and E_{o_2} are again fed to the grids of V_1 and V_2 and the anodes of the tubes are again capacitively coupled to the telephones.

2. <u>Phase relations between E_{o_1} and E_{o_2} as a function of time</u>

Each of the channels pictured in Fig. 5 can, in principle, be represented by Fig. 6, where E_o equals the voltage over R, minus E_i.

Thus $E_o = \frac{R}{R+\frac{1}{j\omega C}} \cdot 2E_i - E_i = E_i \frac{j\omega RC-1}{j\omega RC+1}$, so $|E_o| = E_i$

It follows that the amplitude of E_o is independent of C and R (cf., however, section 3).

As to the phase of E_o, we have $\operatorname{tg} \varphi = \frac{2\omega RC}{1-\omega^2R^2C^2}$

In our experiments, the maximum value of R was 10.000 (Ω), that of ν was 2.000 (cps), while that of C, as stated, was 2075 (pF).
In consequence, RC always $\leqslant 4.10^{-2}$, so by close approximation, $\varphi \approx \operatorname{tg}\varphi = 2\omega RC$.

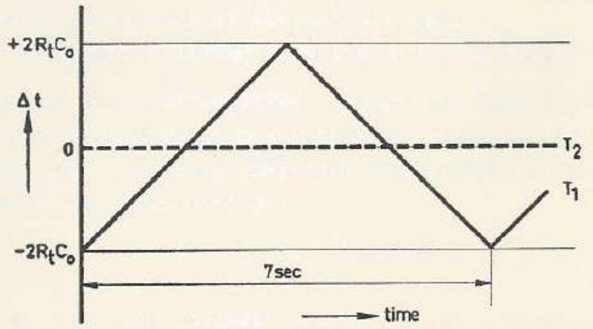

Fig. 7 Time course of the phase relation between the signals emitted by the telephones

Now let the phase of E_{o_1} and E_{o_2} be φ_1 and φ_2, respectively, then the phase difference $\varphi_0 = \varphi_1 - \varphi_2 = -2\omega R_t(C_v-C_f)$.
As (C_v-C_f) varies from $-C_o$ to $+C_o$ and back, φ will vary from $+2\omega R_tC_o$ to $-2\omega R_tC_o$ (Fig. 7), and back, so the total variation of the phase is $4\omega R_tC_o$.

Now if the frequency be ν (cps), then the total range of arrival time variation will equal $\frac{4\omega R_t C_o}{2\pi} \cdot \frac{1}{\nu} = 4R_t C_o$ (sec); and since C_o is a constant, the extend of this range is determined by R_t alone.

Since R_t can be set to any value between 0 and 10.000 Ω, while C_o = 875 pF, the total extent of the arrival time differences caused by the variations of C_v can thus be set to any value up to 35 μsec, that is, the signal at one telephone alternates between leading that at the other by a time of maximally 17,5 μsec and lagging behind it by the same amount.

3. Changes in E_o resulting from the periodic changes of C_v

Though, as stated above, the amplitude of E_o is, in principle, independent of both C and R, there still are two possible causes of intensity variations which might influence the results.

Firstly, current uptake will vary slightly as a result of the variations in C_v; since the equivalent output impedance of the oscillator is not infinitely small, they will cause slight variations in E_1 and thus in E_o. These variations can be made negligibly small by choosing a very low value (50 Ω) for P_g, and thus making the equivalent oscillator output impedance less than 50 Ω.

Also, slight leaks of the condensers, and stray capacities might occasion very small intensity variations of the output signals.

E_{o_1} and E_{o_2} were continually tested with the aid of a vacuum tube voltmeter. No voltage variations could be observed, though the sensitivity was such that voltage variations corresponding to a change in intensity by 0.01 db could easily be detected. Any intensity variation which might have occurred must then certainly have been less than 0,01 db.

4. Results

Fig. 8 shows the correct judgment percentage as a function of time difference for the frequencies investigated and at the intensity level of 45 db re the ASA standard MAF level.

In the 500 and 1000 cps series, each point represents at least 80 observations; in the others, at least 50.

It will be seen that the lines best fitting the experimental points obtained at 500 and 1000 cps on the assumption that the psychometric function is indeed linear, are coincident, and that their common intercept with the Y-axis lies very near to the 50 per cent. level; i.e. if there should be a real threshold, it must be extremely small. (In a way, this might be considered as an argument by analogy for the view that, in the experiments on intensity differences, the line found at 1500 cps is the nearest to a correct representation of

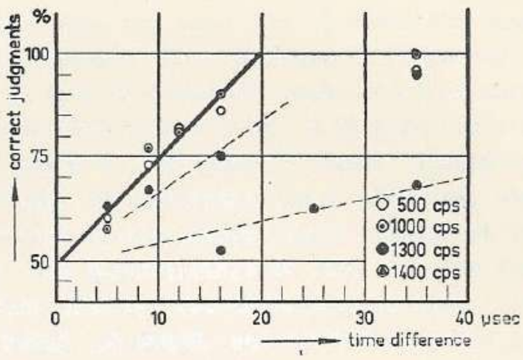

Fig. 8 The psychometric function for changes in arrival time difference at various frequencies

the actual situation). For these frequencies, the jnd for time difference is found to be 10 µsec. Though the exact course of the psychometric function for the remaining frequencies cannot be determined on the basis of the results collected - the thin, interrupted lines drawn in the graph are only intended to show its general character - it is clear that, as frequency increases from 1000 cps to 1400 cps, the value of the jnd shows a very marked increase; for the latter frequency it can be computed at some 50 µsec.

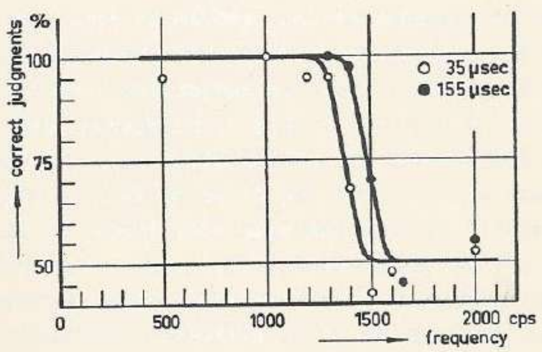

Fig. 9 The breakdown of the temporal cue between 1200 and 1600 cps

In an additional series of experiments, the virtual breakdown of the time cue in the frequency region over 1000 cps was further investigated by offering, besides a 35 µsec time difference (the maximum value used in the main series), a difference of no less than 155 µsec. Fig. 9 gives the number of correct judgments at both time differences, as a function of frequency. The precipitous drop in sensitivity to time differences, occurring in a narrow frequency range, in immediately apparent (see also Fig. 10); a 35 µsec difference, with is perceived in nearly all cases at 1300 cps, is rightly judged in only 68 per cent. of the cases at 1400 cps, and imperceptible at 1500 cps; similarly a 155 µsec difference, which is very nearly always judged rightly at 1400 cps, is down to 70 per cent. at 1500, and imperceptible at 1650 cps. The fact that the temporal cue is found to be furnished by time difference as such, (in agreement with the results obtained by BOLLE, LO SURDO, and ZANOTELLI, (1947 a, c), and GARNER and WERTHEIMER (1951) is hardly a matter for surprise. (Of course, it should be understood that the perception of time difference rests, in the case of a pure sine wave, on the combined indications furnished by the perception of phase and of frequency). As to the magnitude of the time difference threshold, the value found in the present investigation (10 µsec) is noticeably lower than that obtained by BOLLE et al. loc. cit., and GARNER et al. loc. cit.).

IV. C O M M E N T

A. APPLICATION TO ACTUAL SOURCE LOCALIZATION

It is of some interest to see in how far the results obtained in the present investigation contribute to an understanding of the mechanism of localization of actual sources, and to compare them with those on the sensitivity to azimuth changes found earlier.

As stated, a displacement of an actual source always results in a combined change of intensity and time relations, unless special measures are taken. The first question to arise regards the relative contribution of temporal and intensitive cues in actual sound localization at various source frequencies. To facilitate analysis, the data presented in Fig. 8 and Fig. 9 are collected in Fig. 10, where the just noticeable time difference (i.e. the arrival time difference at which a correct judgment is given in 75 per cent. of the cases) is plotted against frequency. It is immediately apparent that at frequencies over some 1500 cps the time cue breaks down; it follows, that, in the range beyond 1500 cps, changes in intensity ratio alone must be responsible for the detection of azimuth changes. In connection herewith it is of interest that, according to TASAKI (1954), who recorded single-fiber responses from first-order neurones of the guinea pig, there is, at frequencies up to some 2000 cps, some kind of phase representation, the responses tending to appear at approximately the same part

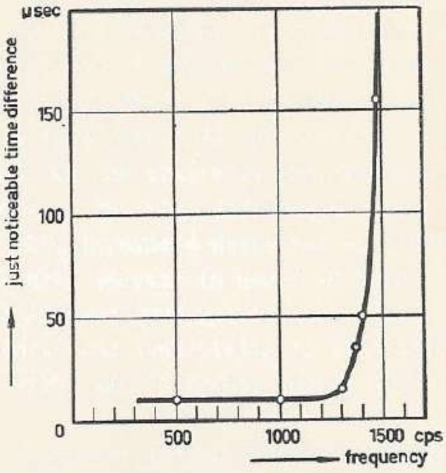

Fig. 10 Threshold value of interaural arrival time difference as a function of frequency

of the stimulating sound; at 2000 cps, this effect was no longer very clear, the duration of one sound cycle becoming too short in comparison with the variability in spike latency.

At frequencies between 500-5000 cps, and at a sensation level of 45 db, the just perceptible shift of an actual point source from zero azimuth was found to average 0,7 degrees. (SCHMIDT et al., 1953).

From the data given by FIRESTONE (1930) it follows that such a shift results in an interaural intensity difference of 0,27 db at 1944 cps, while according to those published by STEINBERG and SNOW (1934), the ensuing intensity difference is about 0,14 db at 2240 cps, and some 0,23 db at 4200 cps. It follows that the sensitivity to intensity ratio changes, as found in the present experiments, is indeed in accordance with the sensitivity to azimuth changes at frequencies over 1500 cps.

B. RELATION BETWEEN INTERPRETABLE DIFFERENCES IN PHYSICAL PATTERN OFFERED IN THE CASE OF AN ACTUAL SOURCE, AND FEATURES OF THE MECHANISM OF HEARING

The way in which the interaural intensity ratio threshold depends on frequency is pictured in Fig. 11, where the heavy line is drawn in accordance with the data presented in Fig. 4. It will be seen that at frequencies between 2000 and 5000 cps, the intensity ratio threshold is virtually constant at 0,22 db, independently of frequency, but that it rises sharply below 2000 cps, to attain a value of about 0,8 db at 250 cps. This signifies an absolute breakdown of the intensitive cue at low frequency, as is evident upon comparison of the threshold value of some 0,8 db at 250 cps with the change in intensity ratio occasioned by an actual source shift of 0,7 degrees from zero azimuth which, according to FIRESTONE, is less than 0,03 db. In the low-frequency region, therefore, the time cue alone must be active in the perception of deviation for zero azimuth of an actual source. The time difference engendered by a shift from zero azimuth of 0,7 degrees (the threshold deviation as found in the pendulum experiments referred to earlier). amounts to about 10 μsec, i.e. to the time difference threshold found at 500 and 1000 cps in the present experiments. In the low-frequency range, therefore, the sensitivity to time-differences is in excellent quantitative agreement with that to actual source displacements from zero azimuth.

The fact that the interposition of the head results in an exaggeration of the interaural intensity difference caused by deviation from zero azimuth in the case of high frequencies, while, on the other hand, the indications furnished by temporal cues become equivocal when wavelength is less than the maximally possible path difference, i.e. at about 1500 cps and up, has been known since the times of RAYLEIGH (1907). Now it appears that the sensitivity of the auditory apparatus is admirably adapted to the differences in sound pattern to which it may actually be subjected: the relation between the wavelengths of audible frequencies and the size of the head is such, that physically unequivocal phase cues, to be used, in combination with the perception of frequency, in order to arrive at a measurement of time difference, and thus, at a directional localization, cannot be offered by an actual source if the frequency is in excess of some 1500 cps; sensitivity of time difference sharply decreases at about this frequency; on the other hand, sensitivity to interaural intensity differences is high only in the frequency range where such differences are needed, and, thanks to the shadow cast by the head, able to take over from the failing time cues in directional localization; in this range, the interaural intensity difference threshold is such as to ensue that the sensitivity to displacements for zero azimuth is, within narrow limits, constant over the whole frequency range from 500-5000 cps. It remains a matter of speculation whether the functional development on which this adaptation to naturally reigning conditions is based, is, in its turn, consequent upon the fact that the system is never subjected to the influence of low-frequency signals of appreciable interaural differences in intensity, nor to that of high frequency signals exhibiting unequivocal temporal differences.

C. NEUROPHYSIOLOGICAL BASIS OF THE CHARACTERISTICS OF THE CENTRAL DIFERENTIATING MECHANISM

It remains to discuss the neurophysiological basis of the abrupt decrease in sensitivity to time differences at high frequencies, and of the breakdown of intensity ratio sensitivity at the low-frequency and of the scale.

It is often suggested, or at least implied, that the refractory period of the cochlear fibres would in some way be responsible for the insensitivity to interaural time difference at high frequencies (STEVENS and SOBEL, 1937; HUGHES, 1940; KIETZ, 1953; RANKE, 1953). Sofar, however, no valid argument has been brought forward in favour of such a concept. Possibly, the results obtained by TASAKI and referred to above might furnish an explanation, (this would mean that the physiological limitation of the accuracy of phase perception as given by spike latency variability would become effective exactly where phase would no longer furnish a useful indication in any case); but, pending the collection of more data on the way in which the information contained in the sound signal offered is coded, it is impossible to verify this.

As to the way in which sensitivity to interaural intensity differences depends on frequency, here, too, the sensitivity of the central differentiating mechanism must first of all be limited by the monaural sensitivity to intensity differences. From the data given by RIESZ (loc. cit.) it appears that, at the sensation level of 40 db, the monaural intensity difference limen is practically constant at somewhat less than 1 db in the frequency range of 200-10.000 cps. The decrease in sensitivity to interaural differences at low frequencies thus appears to be a peculiarity of the central differentiating system. The fact that the monaural threshold is constant over a wide frequency range could be confirmed in experiments made to obtain monaural data to be used in comparison with those on interaural sensitivity collected in our experiments; with our method, it was found to be approximately constant at 0, 15 db in the frequency range of 500-4000 cps.

Now the monaural sensitivity to intensity changes is equal to the maximal sensitivity which is physically possible (VAN GEMERT, 1955), which means that no information is lost in transmission.

As to the way in which the code signals from the two ears are centrally combined, it appears first of all that the binaural sensitivity to intensity changes is virtually twice that to intensity changes offered to one ear only, which means that the central mechanism serves as an additive mechanism for intensities, as was already shown to be the case for binaural summation at absolute threshold by CHOCHOLLE (1954).

It is clear that, when comparing the sensitivity to interaural differences on the one hand, and the monaural and binaural thresholds on the other, the intensity variations offered to each separate ear should be used. The differences in intensity offered to each separate ear at the threshold for interaural intensity difference are represented by the stippled line (Fig. 11), derived from the

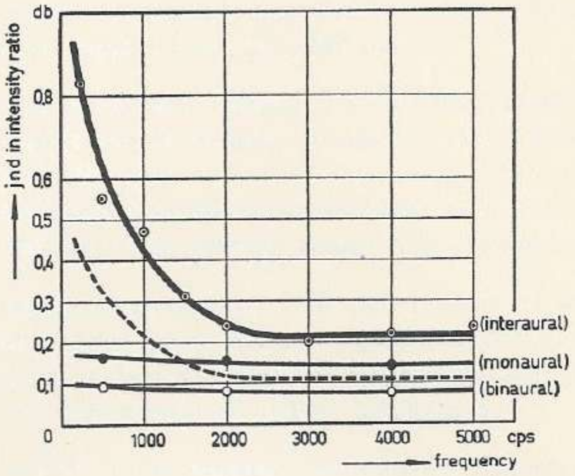

Fig. 11 The sensitivity to monaural, binaural, and interaural intensity changes as a function of frequency

interaural threshold line upon dividing the ordinate values by 2. At frequencies over 2000 cps, this line lies between the monaural and binaural intensity difference threshold lines. That it can never lie at a lower level than the binaural threshold line is self-evident; the fact that it lies at a higher level signifies that, besides a connecting mechanism, situated beyond the two unilateral intensity recorders, and which is responsible for the additive combination of their readings, there must be, apart from the predominant connection of each of those recorders with the corresponding ear, some degree of cross-connection since, if individual readings are different, the combined reading is less than their sum total. The importance of the last-named connection would seem to increase at the low-frequency end of the scale, where it must be present if the central auditory system is to serve as a differentiating mechanism in regard to arrival time. Such anatomical evidence as is available would indeed seem to point in this direction; from the data given by LEWY and KOBRAK (1936), it appears that, whereas fibers from the middle and apical end of the cochlea send a small number of branches out of the ventral nucleus to the trapezoid nucleus on the opposite side, no such connection was observed for the most basal cochlear fibers.

S U M M A R Y

1. With the aid of phantom sources, interaural intensity difference and arrival time difference thresholds were determined at a 45 db sensation level and at frequencies ranging from 250-5000 cps.

2. The intensity difference threshold is constant at 0,2 db at frequencies over 2000 cps; below this frequency, it shows a sharp increase to attain a value of 0,8 db at 250 cps.

   The time difference threshold is constant at 10 μsec at frequencies up to about 1000 cps and rises sharply beyond this frequency.

3. The sensitivity to deviations from zero azimuth of an actual source at the same intensity level is in excellent quantitative agreement with the sensitivity to arrival time differences at frequencies below 1500 cps, and with that to intensity differences at higher frequencies.

4. The sensitivity of the auditory mechanism to interaural differences in arrival time and in intensity exhibits a remarkable adaptation to the magnitude of the interpretable differences which can actually be offered.

RÉSUMÉ

1. La sensitivité aux différences interaurales d'intensité et de temps d'arrivée a été déterminée, à l'aide de sources sonores virtuelles, pour les fréquences de 250 - 5000 v.d. par seconde, au niveau d'intensité de 45 db.
2. Pour les fréquences élevées (c.à.d. de plus de 2000 vibrations doubles par seconde) la sensitivité aux différences d'intensité est constante a 0,2 db. Au-dessous de cette fréquence, la sensitivité diminue rapidement, le seuil atteignant la valeur de 0,8 db à 250 vibrations doubles par seconde.
   Le seuil pour les différences de temps d'arrivée, qui est à 10 µ secondes pour les fréquences inférieures à 1000 v.d. par seconde, s'élève rapidement pour les fréquences plus élevées.
3. La sensitivité aux changements d'azimuth d'une source réelle, en partant du plan sagittal, est en accord complet avec celle aux différences de temps pour les fréquences inférieures à 1500 v.d. par seconde et avec la sensitivité aux différences d'intensité pour les fréquences plus élevées.
4. Il existe une adaptation remarquable de la sensitivité aux différences interaurales de temps d'arrivée aussi bien que d'intensité à la magnitude des différences physiquement interpretables qui peuvent se présenter dans le cas d'une source réelle.

ZUSAMMENFASSUNG

1. Die eben wahrnehmbaren interauralen Intensitäts- und Zeitunterschiede wurden für den Frequenzbereich von 250 - 5000 Hz, bei einer Intensität von 45 db über die Hörschwelle, unter Zuhilfenahme virtueller Schallquellen bestimmt.

2. Die eben wahrnehmbaren Intensitätsunterschiede für Frequenzen über 2000 Hz entsprechten 0,2 db. Unter dieser Frequenz nimmt die Unterschiedsschwelle schnell zu; sie erreicht einen Wert von 0,8 db bei 250 Hz. Die eben wahrnehmbaren Zeitunterschiede für Frequenzen unter 1000 Hz entsprechen 10 µsec, bei Erhohung der Frequenz nimmt die Unterschiedsschwelle sehr schnell zu.

3. Die Empfindlichkeit für Azimuthveränderungen bei kleinem Ausgangswert des Azimuth einer reellen Schallquelle zeigt eine sehr gute quantitative Übereinstimmung mit der Empfindlichkeit für Zeitunterschiede bei Frequenzen unter 1500 Hz, und mit der Empfindlichkeit für Intensitätsunterschiede oberhalb dieser Frequenz.

4. Es zeigt sich eine bemerkenswerte Übereinstimmung zwischen der Empfindlichkeit des auditiven Systems für interaurale Zeit- und Intensitätsunterschiede einerseits und die Grösze der einer Deutung zugänglichen Unterschiede, die sich im Falle einer reellen Schallquelle darbieten, anderseits.

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S T E L L I N G E N

I

De methode van HALDANE-PRIESTLEY ter bepaling van de samenstelling van de alveolaire lucht is verwerpelijk.

II

Kunstmatige ademhaling waarbij niet afwisselend over- en onderdruk wordt gegeven dient te worden afgekeurd.

III

Gescandeerde spraak komt bij multipele sclerose zeer zelden voor.

IV

In de controverse tussen GOERTTLER en BEHRINGER enerzijds en WUSTROW anderzijds over vorm en functie van de musculus vocalis kieze men de zijde van laatstgenoemde auteur.

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V

Het verdient aanbeveling bij een patient met het syndroom van CUSHING met eenzijdige bijnierexploratie te beginnen; wordt de bijnier niet duidelijk atrophisch bevonden dan verrichte men een totale resectie van dit orgaan.

VI

De verbinding van de medulla spinalis met het cerebellum over de nucleus cervicalis lateralis wordt bij de kat voor een deel gevormd door collateralen van vezels die meelopen met de tractus spinocerebellaris dorsalis.

VII

Het is onjuist het woord *functioneel* als synoniem voor *psychogeen* te gebruiken.

VIII

Dat de drempelverhoging bij perceptiedoofheden bijna steeds overwegend de discantzijde betreft is te verklaren uit de *response area* van de afzonderlijke elementen in nervus en nucleus cochlearis.

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IX

De door RANKE gegeven verklaring voor het feit dat voor zuivere tonen van meer dan circa 1000 trillingen per seconde een interauraal phaseverschil niet meer kan worden waargenomen is onhoudbaar.

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