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INVESTIGATION OF DIRECTIONAL HEARING

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This paper presents the results of experimental investigations of the localization of the direction of sound signals. These investigations were performed in a purpose-built laboratory system equipped with 24 loudspeakers disposed in a horizontal plane around the person examined.

The results show that the external auditory canal has dominating influence on the efficiency of localizing signals at low frequencies, while the pinna has a prevailing effect at high frequencies. Application of ear plugs or ear muffs worsens the accuracy of the localization of sound sources in the frequency ranges mentioned above.

The optimum localization was obtained when the source of signals was in front of the person examined, the values of the sound pressure level were from 55 to 80 dB, and their frequency between 250-750 and 1500-3000 Hz. Since least errors in direction localization were committed for signals with large information content, i.e. natural signals, particularly an utterance, on this basis a general statement can be made, that the arrangement and structure of the human hearing organ is from the present point of view best adopted to human oral intercommunication.

1. Introduction

Localization of the sources of acoustic signals results from human ability of determining the distance and direction of the sources of these signals. Particularly, when there is a limited visibility in the place where the information is received, or the listeners are blind, the correct localization of the position of the acoustic sources is particularly important.

For those who can see the correct localization of acoustic signals is equally important, particularly under the industrial conditions, e.g. when the warning signal is emitted by a crane under load moving across the hall, the correct estimation of the direction of the signal may affect the safety of a worker, or in general case when —because of the desired quick reaction of the receiver — the distinguishing and identification of the signal against the background of other acoustic signals is not sufficient, but it is very often necessary to localize its position in the environment.

2. Theoretical relations

Man is able to localize the direction of a source of acoustic signals because of his binaural hearing. It should be added here that the zygomatic width of the face which roughly corresponds to the distance D between both ears, is for the Polish adult population [3] on average 14.2 cm for men and 13.4 cm for women (the width of the head is 15.7 cm and 15.1 cm, respectively).

As regards relatively long sound waves, i.e. at a frequency f for which the half wavelength emitted by a sound source is much greater than the width (diameter) of the head, $\lambda/2 = c/2f = 17\,000/f \gg D$, the determination of the direction is based on the difference between the arrival times of the sound wave for two ears. It can be assumed as an approximation for given values of D that these waves have a frequency $f \ll 1100$ Hz. This case is shown schematically in Fig. 1a.

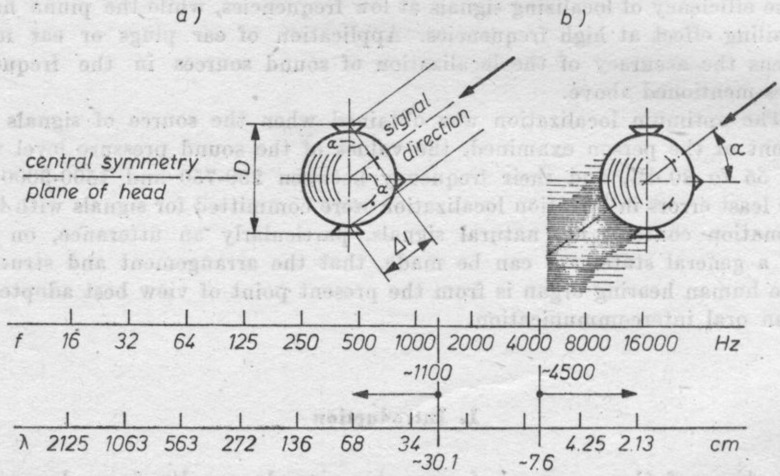

Fig. 1. A schematic diagram of the principle of human perception of acoustic signals at low and high frequencies

Since the human ear is sensitive to differences of the order $1\text{-}3\cdot10^{-5}$ s [7], and it can be seen from Fig. 1 that the arrival paths of the sound waves for two ears are proportional to $\sin\alpha$, the location of a sound signal in front or at the back of the head can accordingly be determined theoretically with an accuracy of 2-3°, and for sources on both sides with an accuracy of 10-15° [7].

For relatively short sound waves for which the ratio $D/\lambda \gg 2$, i.e. whose refraction around the barier is low (for the present head sizes these are the waves at a frequency $f \gg 4500$ Hz, approximately), the head constitutes a barrier behind which (cf. Fig. 1b) the "acoustic shade" occurs, and each ear receives the waves falling at some angle as an information signal of a different level [11]. The difference between these levels depends on the angle at which the wave falls, reaching its maximum value for $\alpha = 90°$.

For the sound waves of medium frequency ($1100 < f < 4500$ Hz), i.e. of a length that is approximately double the distance and half the distance between the ears, the determination of the direction of a source should therefore be more difficult from the theoretical point of view.

On the basis of the foregoing argument it can be predicted that the directional hearing characteristics of persons with normal hearing (particularly as far as equal hearing sensitivity of ears is concerned) will be symmetrical with respect

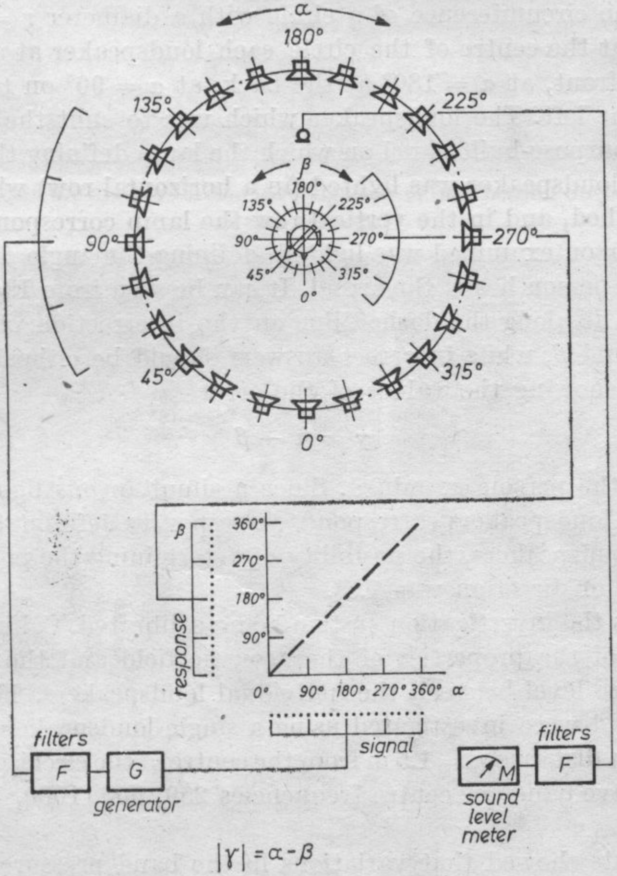

Fig. 2. A schematic diagram of the performance principle of the laboratory system used in the localization of acoustic signals

to the central plane of symmetry of the head, while the determination of the direction of sources of acoustic signals in this plane should be most difficult. Distinguishing between the positions of these sources, i.e. distinguishing between the positions at an angle in front and at the back upwards, will be facilitated by the pinna whose shape favours signals from the front.

3. Procedure

3.1. *Investigation system*

In order to check the validity of the relations discussed above, a series of experimental investigations were performed on a group of 6 persons with normal sight, in whom on the basis of audiometrical tests deviations in hearing from norm were found. These investigations were performed in a special laboratory room [9], well insulated with curtains (for 1000 Hz $a_{QV} = 0.7$), in which (see the diagram in Fig. 2) 24 identical loudspeakers with a power of 0.8 W were placed along the circumference of a circle with a diameter $r = 1.5$ m, so that for the person at the centre of the circle each loudspeaker at an angle $\alpha = 0° = 360°$ was in front, at $\alpha = 180°$ at the back, at $\alpha = 90°$ on the right, and at $\alpha = 270°$ on the left. The loudspeaker which was to emit the signal was controlled from a purpose-built panel on which the lamp defining the angle α of the position of the loudspeaker was lighted (in a horizontal row) when the relevant button was pushed, and in the vertical row the lamp corresponding to the response of the person examined was lighted, defining the angle β of the direction from which the person heard the signal. It can be seen from Fig. 2 that correct answers should lie along the dashed line on the intersection of the corresponding angles α and β, while incorrect answers should be either above or below this line, thus showing the values of the error

$$\gamma = \alpha - \beta$$

committed by the person examined. Since a simultaneous lighting of the two lamps from the loudspeakers corresponds to responses defining the position between the two loudspeakers, the posibility of determining the position of a given signal in terms of direction was 7.5°.

Fig. 3 shows the investigation system being calibrated. Calibration consisted in verification of the properties of the acoustic field and the equality of the acoustic pressure level between the individual loudspeakers. The properties of the acoustic field were investigated using a single loudspeaker which was turned around at a distance $r = 1.5$ m from the centre of the circle, generating a noise signal in octave bands of centre frequencies 250, 500, 1000, 2000, 4000 and 8000 Hz.

Measurements showed that variations in the band pressure level measured at the centre of the circle were ± 3 dB for 250 Hz and ± 1.5 dB for 500 Hz, and were negligible for the other bands. This is related to the magnitude of the

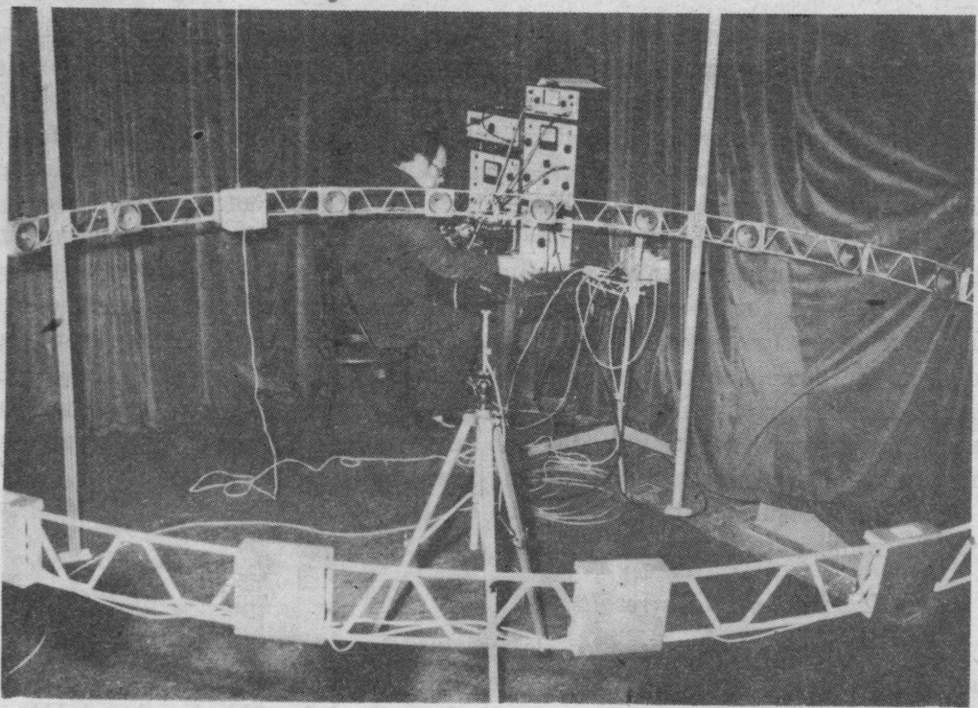

Fig. 3. The view of the system for the investigation of localization during calibration of this system

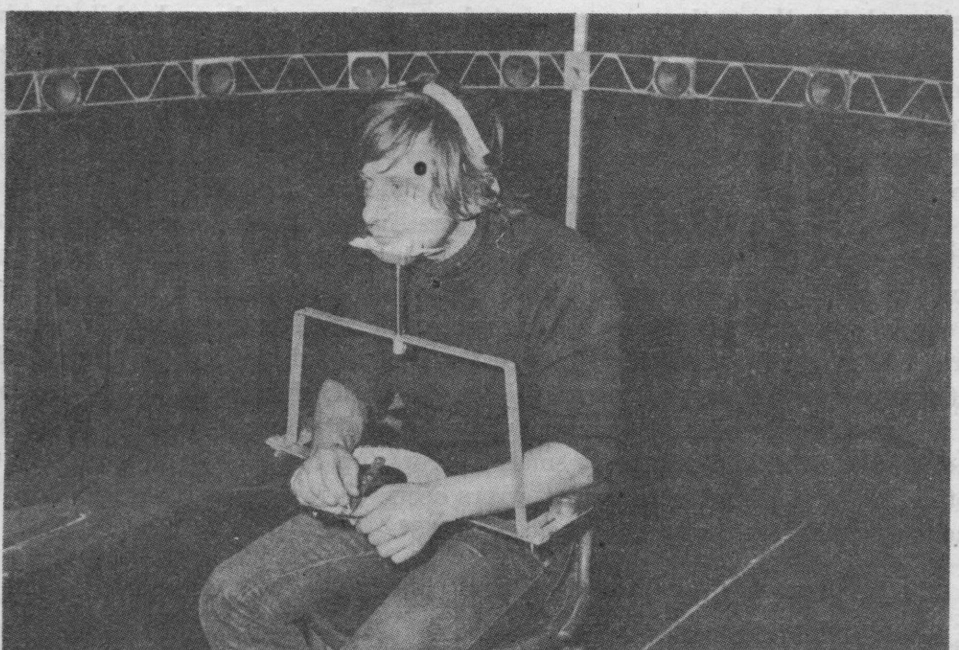

Fig. 4. The investigation of the directional hearing with ear muffs

boundary distance r_g which is 0.87 at a frequency of 2500 Hz and more than 1.5 at the other frequencies, which suggests that for signals at higher frequencies than 500 Hz the examined person at the centre of the circle is in free field of direct sound waves.

Verification of the band pressure level of the individual loudspeakers showed some differences in the value of the level to exist at the centre of the circle. These differences were reduced, however, by replacing the loudspeakers with greatest deviations, to a value of about ± 2 dB.

Fig. 4 shows the person examined wearing ear protectors. It can be seen that in front of the person there is a shield with an arrow which the person can point in the direction (corresponding to the angle β) from which he hears the signal. The chin rest whose elevation can be adjusted serves to keep the head in position over the rotation axis of the arrow and at the same time to prevent the head — often reflexively — turning towards the source of the signal.

In most measurements the duration of the signal which was to be localized was 3 s while its level was 60 dB (A).

3.2. *Elaboration of the results*

Fig. 5a shows the manner of elaborating the results of the measurements taken in the case when noise in an octave band with a centre frequency od 1000 Hz was being localized. The person examined was wearing the Auralgard III ear protectors on both ears. The curve in the upper part of Fig. 5a shows the results registered directly on the measurement sheet on the control panel, while the circles represent the responses of the person examined obtained for different directions. It can be seen from Fig. 5a that in the present case the sign changed for two angles, i.e. $\alpha' \cong 60°$ and $\alpha'' \cong 33°$, which signifies that with respect to the real location of the sound sources being localized the direction of errors committed moved from right to left and from left to right in terms of this location.

The curve at the centre of Fig. 5a shows the absolute values of errors committed, depending on the direction from which the signal was emitted, while the lower curve shows the directional characteristic of the localization of this signal. It can be seen from this figure that in agreement with expectations this characteristic is symmetrical with respect to the central axis (and, as is known, also with respect to the central plane [4]) of the head, showing for the conditions of the measurements large values of errors committed (up to $\gamma = 135°$) at the back of the head and relatively smaller errors (up to $\gamma = 45°$) in front and on both sides of the head. The lowest errors occurred for a location angle $\alpha = 60°$ and a symmetrically opposite angle $\alpha = 330°$.

3.3 *An example of application of the assumed procedure*

Similarly, Fig. 5b shows the results of measurements in which the shell of the ear protector was removed from the left ear of the person examined, while the right ear was covered. A comparison of the characteristics of directional localization for both ears covered (Fig. 5a) and for one ear covered (Fig. 5b) shows that baring one ear does not improve the efficiency of the localization at this side of the head, but also makes it worse at the back and at the opposite side. It can be seen from the curve in the upper part of Fig. 5b that in most cases the signal was estimated to be to the right of the real location, and it can be seen from the central curve that for the whole right side of the head (from $= 0°$ to $\alpha = 240°$) the values of error varied from 60° to 140°. The lowest error was also committed only at the left side of the head at an angle

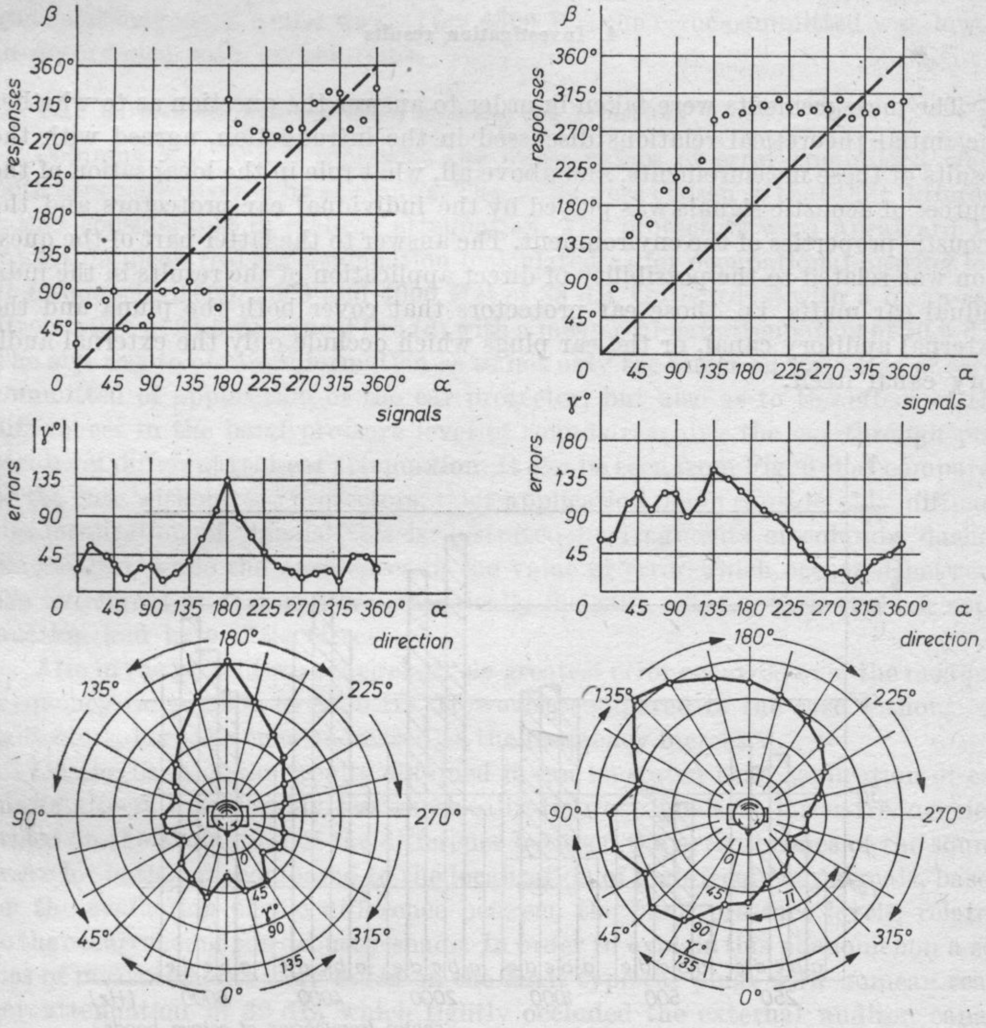

Fig. 5. The successive stages of elaboration of the measurement results; a) a symmetrical directional characteristic of error (both ears covered); b) nonsymmetrical (only the right ear covered)

$a = 300°$; this angle also involved a change in the relative value of the committed errors, i.e. for a small section of the circle in front to the left side the sound source was estimated to be to the left of the real location.

Since the real-ear attenuation of most ear protectors used is similar in its nature to the audiograms of persons with occupational hearing impairment, the characteristics of directional localization in Fig. 5a, b show the difficulty of these persons in correct localization of the sources of acoustic signals, particularly in the case of one-ear defects.

4. Investigation results

The measurements were taken in order to answer the question as to whether the initial theoretical relations discussed in the introduction, agreed with the results of these measurements, and above all, what role in the localization of the sources of acoustic signals was played by the individual ear protectors and the acoustic properties of the environment. The answer to the latter part of the question was related to the possibility of direct application of the results in the individual ear muffs, i.e. those ear protectors that cover both the pinna and the external auditory canal, or the ear plugs which occlude only the external auditory canal itself.

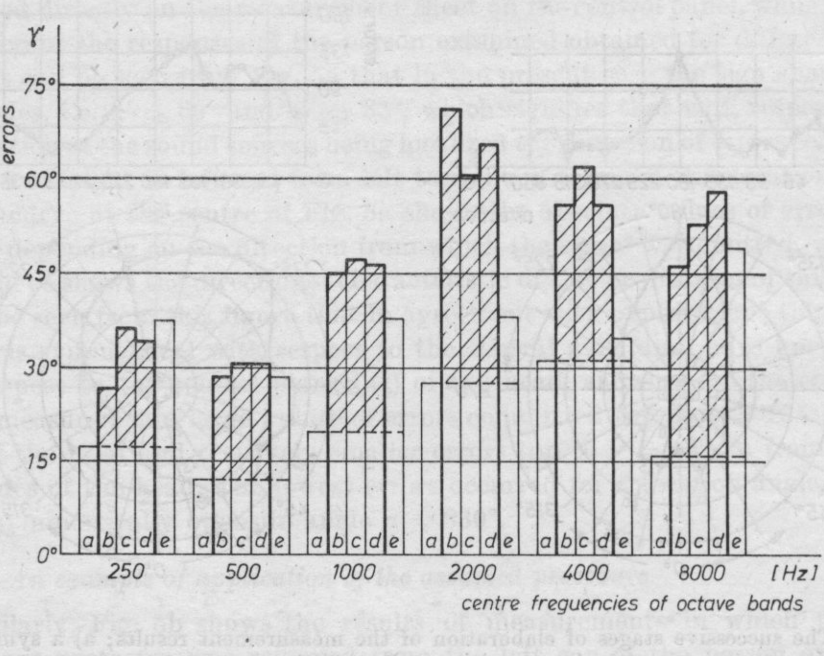

Fig. 6. The averaged values of error in the localization of sound signals at different frequency
a – without ear protectors, *b*, *c*, *d*, – with ear muffs of different real-ear attenuation, *e* – with ear plugs

Fig. 6 shows the results obtained in the form of columns whose height corresponds to the mean values of errors committed in the six groups corresponding to the individual frequencies of the signals used, calculated for 24 directions, i.e. in the course of 144 measurements.

Columns *a* correspond to the case when no protectors were used. It can be seen from Fig. 6 that in this case the relatively greatest error was committed for signals with centre frequencies of 2000 and 4000 Hz, i.e. over the medium frequency range ($1100 < f < 4500$ Hz) for which, in accordance with the theoretical relations discussed above, the localization of direction of the sound sources should be most difficult. For relatively long sound waves ($f < 1100$ Hz) and relatively short sound waves ($f > 4500$ Hz) the error committed was lower, in accordance with expectations.

4.1. *Directional hearing when wearing ear protectors*

Columns *b*, *c*, and *d* represent the mean values of error committed when both ears were covered by ear muffs. The muffs were chosen so that they different rather considerably in real-ear attenuation. The protectors were Auralgard III (*b*) with a mean real-ear attenuation (calculated as for occupational hearing loss at frequencies 1000, 2000 and 4000 Hz) of 38 dB, Optigard (*c*) with a mean-real attenuation of 24.5 dB, and TD-5 (*d*) with a mean real-ear attenuation of 30.5 dB. The aim was to obtain information as to not only the effect on the value of error committed of application of the ear protector, but also as to the effect of the differences in the band pressure level of sounds reaching the ear through protectors of different real-ear attenuation. It can be seen from Fig. 6 that compared to the case without ear protectors, their application made considerably difficult the localization of signals (this is ilustrated by fragments of columns dashed diagonally), while the differences in the value of error which occurred between the individual protectors were statistically insignificant, i.e. their real-ear attenuation had here little effect.

Also in the present case the relatively greatest error occurred over the medium frequency range 2000 to 4000 Hz. However, compared to the case without ear protectors, here the error increased as the frequency increased.

On the basis of the results obtained it can be stated that application of ear muffs affects considerably less the localization of signals at lower frequencies, based on the evaluation of the difference between the arrival times of the sound wave for both ears, compared to the localization of high-frequency signals, based on the evaluation of the difference between the band pressure levels, related to the occurrence of the acoustic shade. In order to explain this phenomenon a series of measurements were taken on the EAR type ear plugs with a mean real-ear attenuation of 32 dB, which tightly occluded the external auditor canal. Columns *e* in Fig. 6 represent the mean values of error committed when the above ear protectors were used. It can be seen from Fig. 6 that at low frequencies (250 and 500 Hz) the error committed is in terms of value close to the error occurring when the ear muffs are used, while at medium frequencies (1000, 2000 and 4000 Hz) the value of error is lower and closer to that of the error for the uncovered ears. The result obtained permits the statement that occluding the external auditory canal makes difficult the localization based above all on the difference between the arrival times of sound waves for both ears, while it affects to a considerably lesser extent the estimation based on the difference between the band pressure levels.

The effect of high frequencies remains now to be explained. Is the difficulty in accurate localization of signals at high frequencies affected by covering the ear by the bowls of the ear muffs? In order to answer this question measurements were taken, during which the natural irregularities and cavities of the pinna in persons examined were filled with a special Stopper mass of properties close to those of smooth skin surface. In addition, in order to prevent the pinna sticking away from the head, it was pressed to the head by a special thin ring, thus leaving the external auditory canal open.

The results of the measurements taken in this manner and the results of the previous measurements are shown in Fig. 7 where the values of error committed are shown as a function of the frequency of a signal for eight selected characteristic directions of localization. In Fig. 7 the continuous lines represent the case

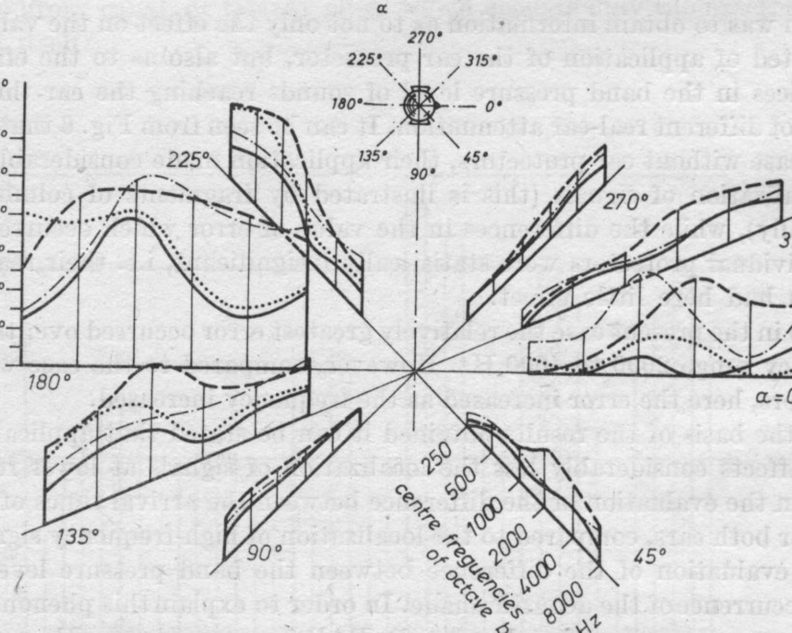

Fig. 7. The values of the error γ determined in a horizontal plane, depending on the frequency of sound signals and on the direction of their localization in the case without ear protectors ————, with ear muffs — — —, with ear plugs —.—.—, with the pinna covered ....

without ear protectors, the dashed lines, the case with ear muffs, the point and dash lines the case when both external auditory canals were covered by ear plugs and the point lines the case when the pinna was covered. It can be seen from this figure that localization of signals at the back of the head ($\alpha = 180°$) is relatively most difficult, and easiest in front ($\alpha = 45$-$315°$); that application of ear muffs increases the error in all the presented directions to a relatively greatest extent in front of the head, and to the least extent on both sides ($\alpha = 90$ and $270°$); and that in most cases the localization of the sources of signals (both with and without ear protectors) is most difficult over the frequency range $1100 < f < 4500$ Hz. The difficulty in the localization of signals at lower and medium frequencies ($f < 1100$ Hz), which causes a considerable increase in error committed, results from limited reception of signals of that frequency in the external auditory canal, while the difficulty in the localization of signals at higher frequencies ($f > 4500$ Hz) – which is particularly conspicuous at the back of the head ($\alpha = 225$-$135°$) – results from the covering of the pinna. Since it is confirmed by the results of the measurements that the determination of the direction of signals in the central plane of the head (back-front) is most difficult, the pinna facilitates this localization by concentrating the sound waves reaching it from the environment and directing them in the form of reflections modelled by itself to the external auditory canal. It can be seen from Fig. 7 that this is the case at medium and high frequencies and above all in the space corresponding to the values of the angle α in the limits 90-$270°$, in front of the person examined.

The present results confirm the results of the investigations of the GARDNERS [4] who in order to explain the localizing effect of the pinna used a similar device made of identical loudspeakers placed in the central plane at a constant distance from the head of the person examined, but, contrary to the measurements described here (Figs. 2, 3 and 4), in a semicircle from the front upwards to the back of the head. By successively covering the individual cavities and irregularities of the pinna they showed that the pinna facilitates the localization of sound signals in front of the head, particularly over the high frequency range. According to these scientists the dashed columns in Fig. 8 represent the values of the index of error committed in reference to the group of small loudspeakers situated from the front upwards, while the columns not dashed refer to the loudspeakers placed downwards and backwards for the pinna with a different degree of covering. The index of 100% applies to the case when the greatest error is committed in the determination of direction. It can be seen from Fig. 8 that largest differences in the value of this index occurred when the whole pinna was covered, and not covered in the case when high-frequency signals were used, i.e. in bands of 8 and 10 kHz. This result suggests that the pinna facilitates the localization of signals in the central plane of symmetry of the head, i.e. when it is most difficult from the theoretical point of view to determine the location of these signals, particularly over the high frequency range.

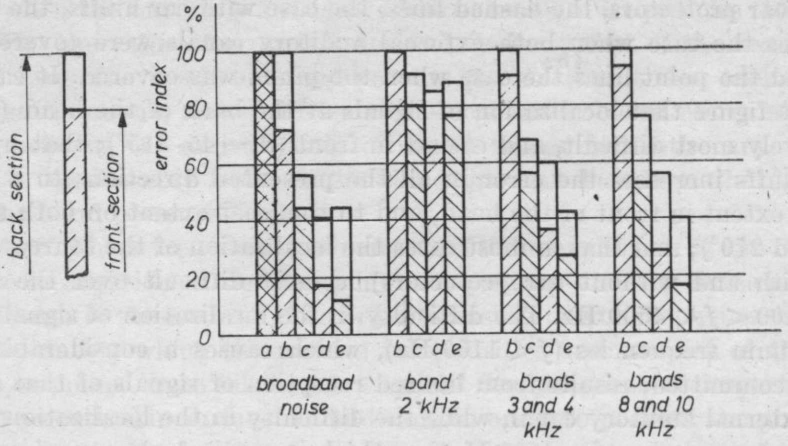

Fig. 8. The values of the index of the error committed in the central plane of the head, after the Gardners, depending on the degree of covering the pinna

with: *a* – the whole pinna covered, *b* – the navicular fossa, cavity and earlap covered, *c* – the navicular fossa and cavity covered, *d* – the cavity covered, *e* – uncovered

In conclusion, it can be stated that application of ear plugs can worsen the localization of sound signals at relatively low frequencies, while application of ear muffs (and also kerchiefs, caps and hairdoes which cover the ears) can worsen this localization in the case of sound signals at relatively high frequencies. For both cases this worsening also occurs over the medium frequency range ($1100 < f < 4500$ Hz) for ear muffs, irrespective of their real-ear attenuation. Therefore in the planning of warning signals these circumstances must be considered.

4.2. *The effect of the acoustic properties of the environment*

4.2.1. *The acoustic conditions* of the room. The measurements whose results were discussed above were taken in a damped laboratory room ($r_g > 1.5$ m), i.e. (for $f > 250$ Hz) under the conditions of the acoustic field close to free space. Under these conditions the values of error committed, calculated for 24 directions of observation, varied in the limits of $\gamma = 10\text{-}20°$. It can be seen from Fig. 9 (columns *a*) that the value of the error was $\gamma = 12.5°$ for the localization of tones at a frequency of 1000 Hz.

In order to examine the masking effect of the reflected sounds, a series of measurements were taken (in the manner discussed above) under the conditions of the acoustic field with greater diffusion, i.e. in a room of average acoustic properties ($r_g < 1$ m) – columns *b* and in a reverberation chamber ($r_g < 0.4$ m) – column *c*. It can be seen from Fig. 9 (columns not dashed *a*, *b* and *c*), that as a result of masking the information about the presence of a signal by reflected sounds the value of the error γ committed increases considerably with increasing diffusivity of the acoustic field, i.e. with decreasing boundary distance r_g.

Since, particularly in these cases, a prevailing role in the determination of the direction of a signal should be played by the beam of direct sound waves, i.e. the beam reaching the ears directly after a given signal has been switched in, a series of measurements were taken in order to confirm this relation. Columns *a* and *b* dashed diagonally in Fig. 9 define the value of the error γ committed when the moment of switching in a signal being localized was masked by another much louder signal. It can be seen from Fig. 9 that in a semi-anechoic laboratory room (columns *a*), i.e. when the person examined is continuously in the field of direct sound waves, no significant increase in the error γ can be noticed. In a room of average acoustic properties (columns *b*), however, when the sound waves which are not disturbed with reach a given person only at the moment of switching in a signal, a considerable increase in the error occurs. This increase is close in its value to that of the error committed (without masking) in a reverberation chamber.

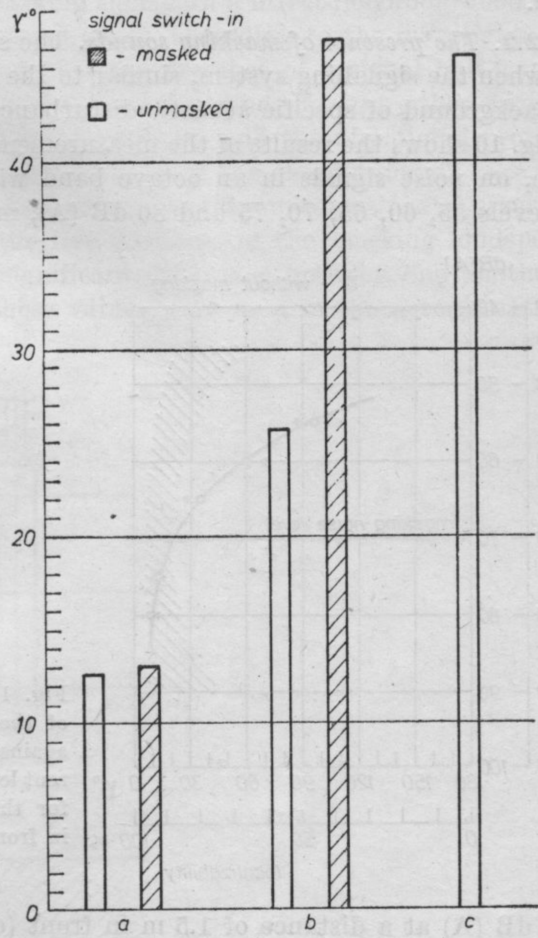

Fig. 9. The effect of the acoustic properties of the room and the contribution of direct waves from the sound wave localized on the value of the error γ

a – semi-anechoic laboratory room, *b* – room of average acoustic properties, *c* – reverberation chamber

The acoustic properties of a room also affect the directional characteristic of signal localization. When the position of the person examined in a damped laboratory room with respect to the walls of the room had little effect on the above characteristic (irrespective of its position it was symmetrical to the central plane of the head), the diagonal position, with respect to the walls, of the person examined in a room of smaller absorption caused a fairly distinct rotation of the axis of symmetry of this characteristic with respect to the above plane.

4.2.2. *The presence of masking sounds.* The situation changes in a significant way when the signalling system, similar to the real conditions, operates against the background of specific acoustic disturbances.

Fig. 10 shows the results of the measurements taken in the manner described above, on noise signals in an octave band with a mid-frequency of 2000 Hz and levels 55, 60, 65, 70, 75 and 80 dB (A), masked by white noise at a level of 70 dB (A) at a distance of 1.5 m in front (circles) and at the side (crosses) of the person examined. The curve in this figure was plotted against the area (dashed diagonally) corresponding to the case without masking. When it is assumed that an error of less than about 30° (corresponding to the localizability of more than about 85 %) can be admitted, in the present case an error of greater value was committed for signals of a level that was equal to or lower than the masking one. However, in the case without masking less error was committed at a level in the range 55 - 80 dB, i.e. for the range of human oral intercommunication.

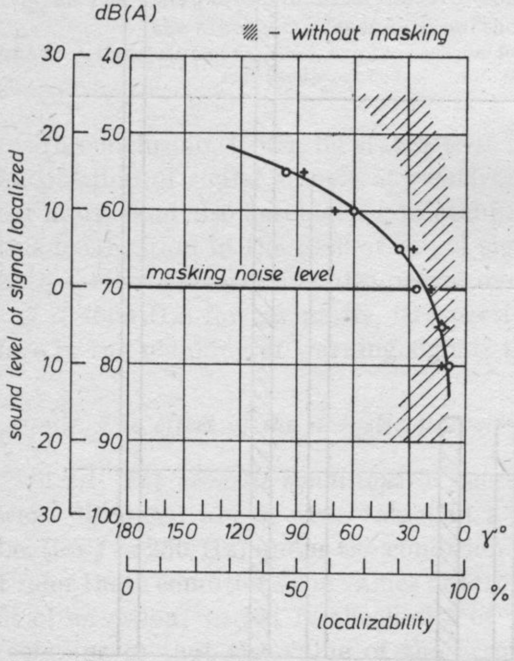

Fig. 10. The effect of masking on the value of the error committed in the localization against the noise of acoustic signals of different level. Circles denote the results obtained for the source of the masking signals placed in front, crosses for the case at the side of the person examined

In order to determine the effect of the direction of the source of a masking signal, the position of the loudspeaker generating these signals was changed from successively $\alpha = 0°$ (in front) to 45, 90° (on the right), 135 and 180° (at the back) of the examined person. The characteristic of the error in the localization of the masked signal was determined for each of the above positions in the case with masking and that without masking. It follows from the measurements taken that a distinct decrease in the error committed occurs for the direction corresponding to the position of the masking signal. In a direct neighbourhood of the masking direction the error increases, since, according to the investigations of **Haas** [8], the persons examined indicate the presence of a signal half-way between the masking loudspeaker and the masked one. For the other directions the effect of the masking signal is less distinct, and the directional properties of hearing determine the resultant behaviour of the characteristic.

Since for both the described and other cases the mean values of error committed, calculated for each of the five positions of the masking loudspeaker, did not show any statistically significant difference between one another (at a significance level $\alpha = 0.01$), these values were used in the determination of

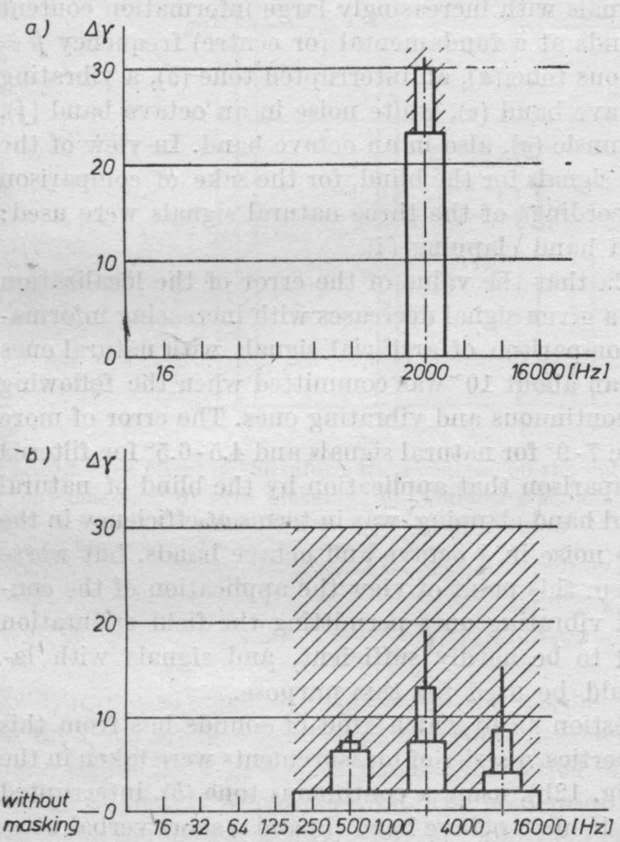

Fig. 11. The dependence of the increase in the mean error with masking and without masking on the bandwidth (the information content) of the masked signal
a) with masking by octave noise, b) with masking by broadband noise

the error committed in the localization of signals with bandwidth equal or narrower than the bandwidth of the masking signal. Fig. 11a shows the results of measurements in the case when the noise of octave width with a midfrequency of 2000 Hz (the area dashed diagonally) masked noise signals at the same frequency and the widths of octave, $\frac{1}{3}$ octave, and tone; Fig. 11b refers to a similar case when broadband noise masked (the area dashed diagonally) the broadband noise and for the noise of the widths of octave, $\frac{1}{3}$ octave and tone at frequencies 500, 2000 and 8000 Hz. It can be seen from Fig. 11 that the increase in the mean value of the error committed $\Delta\gamma$ (defined as the difference in the error between the case with masking and that without) are the greater the lower the information content of the masked signal.

4.2.3 *The effect of the information content of a signal.* The previous experiments used sound signals in the form of continuous tones or noise in $\frac{1}{3}$ octave bands or octave bands, i.e. signals with relatively low information content, which occur rather rarely in practice. In order to define the effect of the content in terms of a warning signal in the successive experiments (whose results are shown in Fig. 12), artificial signals with increasingly large information content were used. These were the sounds at a fundamental (or centre) frequency $f = 1000$ Hz; namely: a continuous tone (*a*), an interrupted tone (*b*), a vibrating tone (*c*), white noise in a $\frac{1}{3}$ octave band (*e*), white noise in an octave band (*f*), and a fragment of symphonic music (*g*), also in an octave band. In view of the possibility of using information signals for the blind, for the sake of comparison with the above sounds, the recordings of the three natural signals were used: stick tapping (*h*), steps (*i*) and hand clapping (*j*).

It can be seen from Fig. 12a that the value of the error of the localization of the position of the source of a given signal decreases with increasing information content of this signal. A comparison of artificial signals with natural ones shows that the error greater than about 10° was committed when the following tones were used: interrupted, continuous and vibrating ones. The error of more than 7° was committed for noise 7-9° for natural signals and 4.5-6.5° for filtered music. It follows from this comparison that application by the blind of natural signals; stick tapping, steps, and hand clapping, was in terms of efficiency in the orientation in space, similar to noise in $\frac{1}{3}$ octave and octave bands, but worse than that of filtered music. From this point of view the application of the continuous, interrupted tones and vibrating ones permitting the field orientation in space should be considered to be hardly sufficient, and signals with larger information content should be used for this purpose.

In order to answer the question as to which kind of sounds has from this point of view the optimum properties, a series of measurements were taken in the manner described above (cf. Fig. 12b), using a continuous tone (*b*), interrupted noise in an octave band (*i*), music in an octave band (*k*) and a short verbal utterance (*l*), masked by a signal of the same level as that of a given signal to be localized. It can be seen from Fig. 12b that the least error was committed in the localization of the verbal utterance.

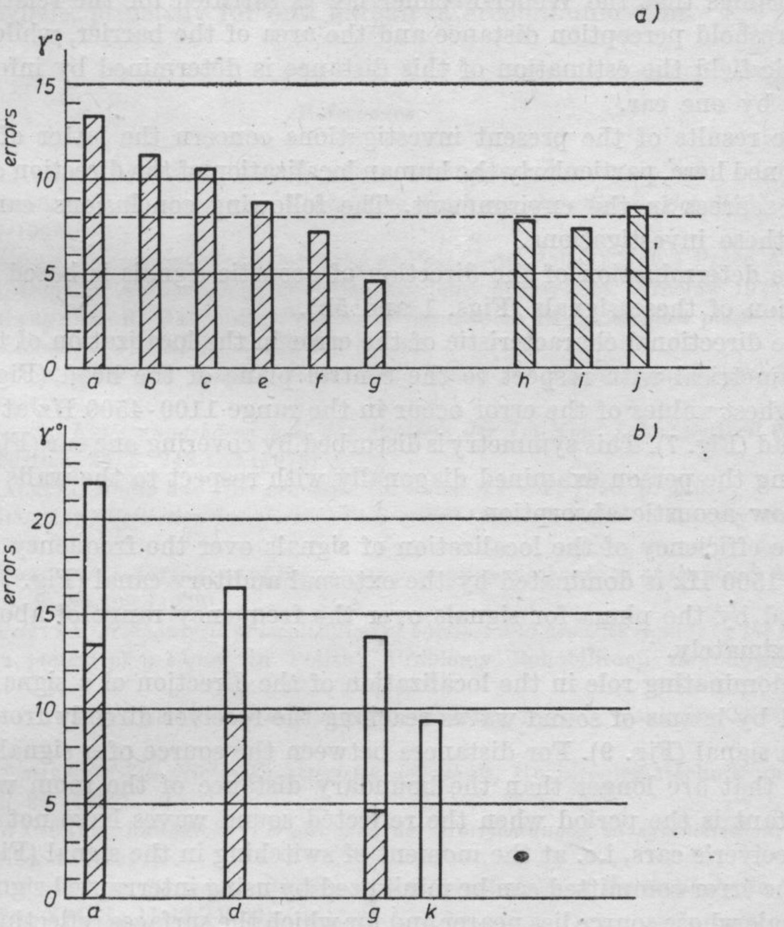

Fig. 12. The effect of the information content on the value of the error γ committed: a) without masking, b) with masking. The following signals were used in the investigations artificial signals: *a* – continuous tone, *b* – interrupted tone, *c* – vibrating tone, *d* – interrupted octave noise, *e* – 1/3 octave noise, *f* – octave noise, *g* – octave music; natural signals: *h* – stick tapping, *i* – steps, *j* – hand clapping, *k* – verbal utterance

5. Conclusions

In the case when it is difficult or impossible to use sight, a dominating role in the human orientation in the surrouding space is played by the audible acoustic signal. Two groups of phenomena based on slightly different mechanisms should be distinguished here, i.e., the perception and estimation of the distance from the sound source or the barrier, and the perception and localization of the direction of the sound source or barier in this space.

The results of the investigation of the former group of phenomena were discussed in reference [9]. On the basis of these investigations it was found among other things that the Weber-Fechner law is satisfied for the relation between the threshold perception distance and the area of the barrier, while in the free acoustic field the estimation of this distance is determined by information received by one ear.

The results of the present investigations concern the latter of the groups mentioned here, particularly the human localization of the direction of the sound signal·sources in the environment. The following conclusions can be drawn from these investigations.

The determination of the direction of acoustic signals is based on binaural reception of these signals (Figs. 1 and 5b).

The directional characteristic of the error in the localization of these signals is symmetrical with respect to the central plane of the head (Fig. 5a), while the highest values of the error occur in the range 1100-4500 Hz at the back of the head (Fig. 7). This symmetry is disturbed by covering one ear (Fig. 5b) or positioning the person examined diagonally with respect to the walls of the room with low acoustic absorption.

The efficiency of the localization of signals over the frequency range below about 1500 Hz is dominated by the external auditory canal (Fig. 7), while it is affected by the pinna for signals over the frequency range of above 2000 Hz, approximately.

A dominating role in the localization of the direction of a signal localized is played by beams of sound waves reaching the receiver directly from the source of this signal (Fig. 9). For distances between the source of a signal and the receiver that are longer than the boundary distance of the room what is most important is the period when the reflected sound waves have not yet reached the receiver's ears, i.e. at the moment of switching in the signal (Fig. 9). In the case the error committed can be minimized by using interrupted signals and those signals whose source lies nearer and for which the surfaces reflecting the sounds are further away from where they are received.

In the acoustic field conditions close to free space the localization of the source of the masking signal had little significant effect on the mean value of the error in the localization of the source of the signal masked. This effect is found, however, when the ratio between the information content of the signal masked and that of the masking signal was changed. The higher the ratio was in a given case the higher the error committed (Fig. 10).

Since the optimum conditions of localization of acoustic signals were achieved when the source of these signals was in front of the person examined (Fig. 7), the value of the level of these signals varied over the range 55-80 dB (Fig. 10), their frequency (for $\alpha = 45$-$315°$) over the ranges 250-750 and 1500-3000 Hz (Figs. 6 and 7), and the lowest error was commited in the localization of a verbal utterance (Fig. 12), therefore on this basis it can be generally stated that the arrangement and structure of the human hearing organ are well formed and fitted for the reception of information reaching the listener from the front in the form of natural signals, primarily for oral human intercommunication.

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