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INVESTIGATIONS ON THE ANGLE OF DIRECTIONAL HEARING ACUITY

M. NIEWIAROWICZ[1], J. CZAJKA[1,2]
E. HOJAN[2]

[1)] Poznań University of Medical Sciences
Department of Otolaryngology
Przybyszewskiego 49, 60-355 Poznań, Poland
e-mail: niewiaro@amp.edu.pl

[2)] Adam Mickiewicz University
Institute of Acoustics
Umultowska 85, 61-614 Poznań, Poland
e-mail: hojanaku@amu.edu.pl

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This article presents results of investigations of the angle of directional hearing acuity (ADHA) as a measure of the spatial hearing ability. A modified method proposed by Zakrzewski has been used – ADHA values have been determined for azimuths in the horizontal plane at the height of the listener's head. Application of different acoustic signals – sinusoidal signals (pure tones), 1/3 octave noise, and amplitude modulated 1/3 octave noise, helped to reveal significant differences in ADHA values for individual signal types. A better localization of the sound source for noise type signals than those for sinusoidal signals has been found. Furthermore, smaller differences in the perception of noise signals compared with differences in the perception of sinusoidal signals were recorded for individual listeners. The best localization was stated for the azimuth 0° and the worst for the azimuth 90° and 270°.

Key words: sound source localization, angle of directional hearing acuity, amplitude-modulated 1/3 octave band noise.

1. Introduction

Directional hearing is philogenetically older than other functions of the ear, such as perception of tone, speech, music or different environmental sounds and has been of interest to neurologists, physiologists and otologists for a long time. The problem becomes more and more important today when humans are continuously subjected to different acoustic stimuli, different with respect to both their quality and intensity.

The angle of directional hearing acuity (ADHA) is a quantity, which partly provides information about the ability of spatial hearing. In an environment in which sounds can be generated and propagated, every human being is under their influence. Human senses help him to perceive the sounds. Since, unlike the eyes, the ears are always "open" and we can say that a human being constantly hears the environment that surrounds him to a lesser or greater extent and is also able to locate a given sound in the space. It is the hearing analyser that plays a significant role in spatial orientation while other senses make important contribution to the perception [12]. What should be emphasized is the ability to evaluate the position of the source in the space by means of hearing under restricted conditions, i.e. in darkness or in the fog, which could be helpful in the case of an object which we want to find or avoid. The problem of localization also arises in the case of urban noises, especially traffic noises (when sound sources represent mostly moving objects) and is of a great importance for our safety.

The localization ability is one of the higher activities of the hearing organ in the ganglion cells of the brain stem [10]. MILLS [8] was the first to attempt solving the problem of spatial resolution of the hearing organ for the tone pulses of the frequency between 250 and 10000 Hz. He determined a quantity, which helps us to evaluate whether and how the listeners perceive the change of the direction – the minimum audible angle (MAA), in the horizontal plane around the head of the subject. His investigations revealed that the differential azimuth discrimination varies with the azimuth and frequency of the stimulus signal. The value of MAA is about 1° for a source emitting a frequency of 500 Hz, located straight ahead of the subject. As the azimuth of the source approaches 90°, the value of MAA increases and at 90° the threshold becomes indeterminate. The smallest values of MAA are found in the frequency range between 250 and 1000 Hz. As the frequency is increased from 1000 to 1500 Hz, MAA grows toward a maximum. The frequency at which this maximum is reached varies with the azimuth, but at all azimuths MAA drops to another minimum between 3000 and 6000 Hz. In 1960 ZAKRZEWSKI developed a method, which helps to determine the angles of sound source localization [13]. A listener received two consecutive signals from different locations within a circle, while the loudspeaker was moving around that circle and the listener was in the centre. The smallest angle between the positions of the loudspeaker, when the listener was able to recognize theese both signals coming from two places in the space, was called the angle of directional hearing acuity (ADHA). The method was used, for example, in clinical studies on the localization of sound sources [11].

Many studies have proved that the best localization for a sound source in the horizontal plane is obtained when the sound source is located opposite the listener. If the azimuth of the sound source is increased, localization is deteriorated, particularly in case of signals with a frequency above 1000 Hz [5]. The localization ability deteriorates when the location of the sound source is changed in the vertical plane [9, 2]. However, as the azimuth increases, the difference gets smaller and for approx. 90° the precision of localization in the vertical and horizontal planes is almost identical [6].

The main aim of the investigations was to determine the ADHA values in the horizontal plane for a group of people with normal hearing, using different types of acoustical signals. Sinusoidal signals, 1/3 octave band noise and amplitude modulated 1/3 octave band noise signals were used. It was assumed that noise signals much better represent the conditions of the surrounding environment than sinusoidal signals. An attempt was made to compare localization abilities in ADHA studies for these signal types.

2. Experimental investigations

2.1. Measurement set-up and calibration

The measurement set-up included:
- Macintosh HD computer with Synthesiser 0.83 software;
- Optonica SM-1616 (Sharp) amplifier;
- Excellence EX-1S (Tonsil) loudspeaker;
- a unit used to move the loudspeaker.

Measurements were made in an anechoic chamber at the Institute of Acoustics, A. Mickiewicz University in Poznań, which meets the requirements of ISO 3745-1977.

In order to determine the level of acoustic pressure at the place where the listener's head was located during the measurement, the values of sound equivalent level were measured using Svan 945 Sound Analyser at respective positions of the amplifier digital potentiometer. The calibration method consisted in the measurement of a 10-second sound equivalent level with a constant "fast" time averaging (in dB SPL). A constant SPL of 80 dB was determined for all signals (the value corresponding to loud speech). Such a relatively high acoustic signal level was adopted because at that level, an increased number of correct answers are observed (particularly for signals coming from sources localized in the front part of the sphere) [3].

2.2. Acoustic signals

Synthesiser 0.83 software on Macintosh HD computer was used to generate the signals used in the experiment. The signals were:
- sinusoidal,
- 1/3 octave band noise,
- 1/3 octave band noise with amplitude modulation,
- *modulation frequency 4 Hz*,
- *modulation depth 100%*.

The frequencies were 500, 1000 and 4000 Hz (for sinusoidal signals and as mid-frequencies of the noise bands). Furthermore, attack and decay times of 50 ms were used in the signals. These values were selected on the basis of the results of the investigations conducted by FLORKOWSKI [1] on the effect of sound attack time on the accuracy of localization. The duration of the signal was 1s and the interval between the signals equalled 2.5 s.

Signal frequencies were chosen based on the localization abilities of our auditory system [7]. For the subrange of low frequencies, effective physical factors that permit precise localization of the source include interaural phase differences for tones, interaural time differences for complex signals and the correlation between the signals reaching the right and left ears in the case of noises. In the the case of high frequencies for a tone signal of a frequency of 4000 Hz there is a considerable interaural difference in intensity and, additionally, a difference in the spectrum in the case of complex signals. The frequency of 1000 Hz is the accepted limit for the two basic factors mentioned above, affecting the spatial hearing ability, i.e. the interaural time difference, which to a certain degree continues to help to localize the sound and the interaural intensity difference, which becomes significant for this frequency. The present investigations of ADHA were based first on sinusoidal signals and the results were compared with those previously published [8]. Selection of noise signals, i.e. 1/3 octave band noise and 1/3 octave band noise with amplitude modulation, was motivated by the fact that noise sounds are close to natural sounds, characteristic for the surrounding environment.

Same 1/3 octave band noise signals were amplitude-modulated with a frequency 4 Hz (this value is significant in the speech perception process by different set-ups, e.g. hearing aids).

2.3. Classification criteria for listeners participating in ADHA investigation

In the literature no single classification criteria for listeners taking part in ADHA investigations are defined. What is undisputed is the possibility of making ADHA measurements of both women and men treated as one group [4]. Most often the listeners are selected on the basis of measurement of the auditory threshold since the spatial hearing process is determined by the general hearing ability. Listeners were further selected on the basis of the correct results of tonal audiometry and acumetric tests.

2.3.1. Tonal audiometry

Investigations of tonal audiometry of ten listeners (6 women and 4 men, aged 18–28 years) were made in an audiometric chamber, using Interacoustic AD 229b audiometer with THD 39 headphones to allow air conduction by the ascending method, for frequencies 250, 500, 1000, 2000, 4000 and 8000 Hz.

Based on ISO/TR 4870:1991(E) standard on the construction and calibration of speech intelligibility tests, when listeners whose auditory threshold is lower than 10 dB HL are selected, all the listeners were found to have normal hearing.

2.3.2. Acumetric investigations

Weber's test, using a vibrating tuning-fork of a frequency 512 Hz was used. The listeners felt the sound in the middle of their heads, which confirmed the fact that their auditory conditions for localization investigations were correct.

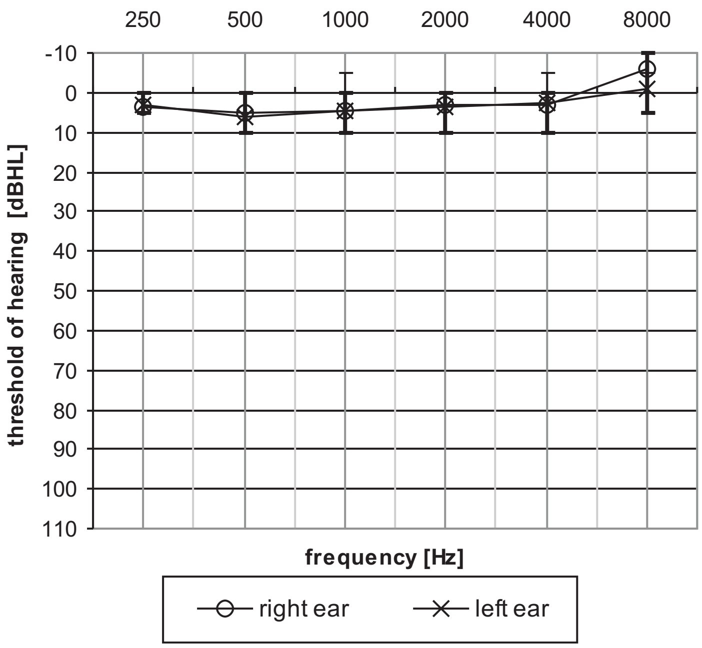

Fig. 1. Averaged values of the auditory thresholds for 10 listeners, including maximum and minimum values for all frequencies.

2.4. Measurement method

ADHA measurements were conducted for 8 azimuths in the horizontal plane at the height of the listener's head in the range of 0°–360°, every 45°. The listener sat in a special chair with a head support to prevent head movements. The experimenter moved the loudspeaker in sequences – the first signal was always given when the loudspeaker was at 0°, the next one was given for a defined, decreasing angle. The intrinsic difference of the ADHA method compared with the method proposed by MILLS [8] consists in the manner in which loudspeaker is moved: in ADHA method only to the right when in Mill's method to the right as well as to the left from the 0° position.

The listener's task was to say "yes" when s/he thought that two consecutive signals came from different points in the space and "no", when s/he did not perceive any localization difference (the signals were heard coming from one point). The listening session was stopped when the listener confirmed the value set for three times. The result was read from a calibration unit with an accuracy of 1° and it was the ADHA value that was looked for.

The measurement was repeated with the listener's position changing clockwise. At angles of 45°, 90° and 135° the loudspeaker was positioned opposite the listener's left ear, at angles 225°, 270° and 315° – opposite the listener's right ear. At angle 0° the listener sat exactly opposite the loudspeaker and at angle angle 180° – with his back to the loudspeaker. The distance from the loudspeaker was constant – 1.5 m.

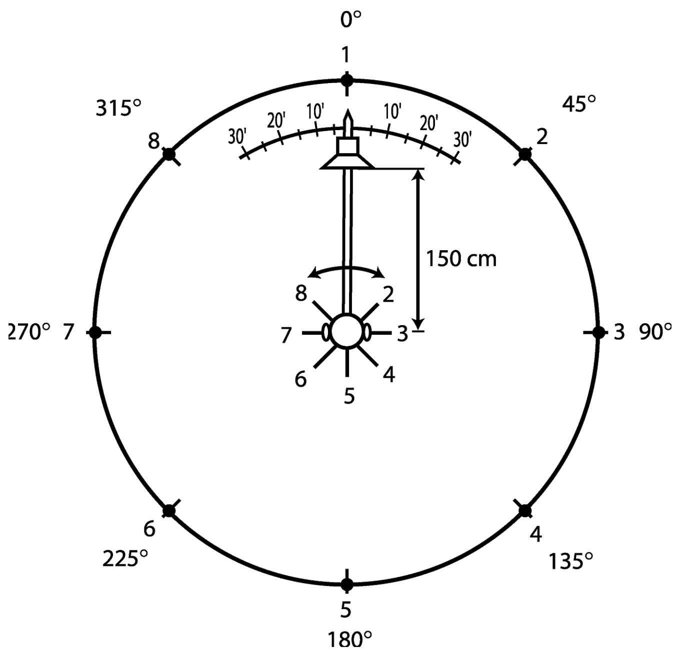

Fig. 2. The listener's position with respect to the loudspeaker.

The procedure was repeated for nine test signals used in the experiment.

3. Measurement results

At the first stage an analysis of the distribution of ADHA values was made. It was found that the distribution of ADHA values for different azimuths is asymmetric. For this reason, in the analysis of ADHA values a positional measure in the form of median was adopted. The median for an n element sample was determined as follows: from x_i elements of the sample a non-decreasing sequence was made and in case when the number of n elements in the sequence was odd, the central element was assumed to be the median. It was calculated from the formula:

$$Q_2 = X_{n+1}/2,$$

whereas an even number of n-elements of the sequence was calculated from the formula:

$$Q_2 = (X_{n/2} + X_{n/2+1})/2.$$

The lower quartile (first) – Q_1 and the upper quartile (third) – Q_3 were also determined.

3.1. Comparison of ADHA values for sinusoidal signals and noise bands of the same mid-frequencies

The figures below present ADHA values for sinusoidal signals and 1/3 octave noise bands of the same mid-frequencies 500, 1000 and 4000 Hz :

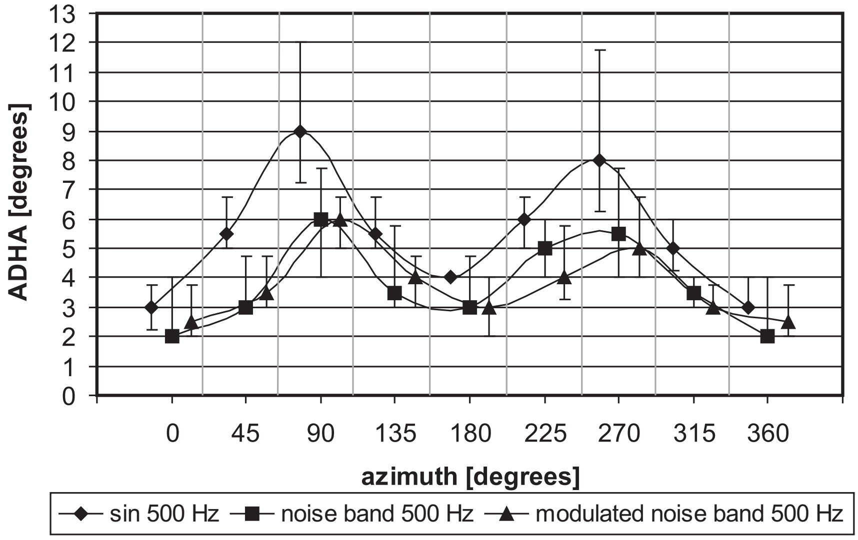

Fig. 3. Values of the median, lower and upper quartile of ADHA for sinusoidal signals and 1/3 octave band noise signals for mid-frequency of 500 Hz.

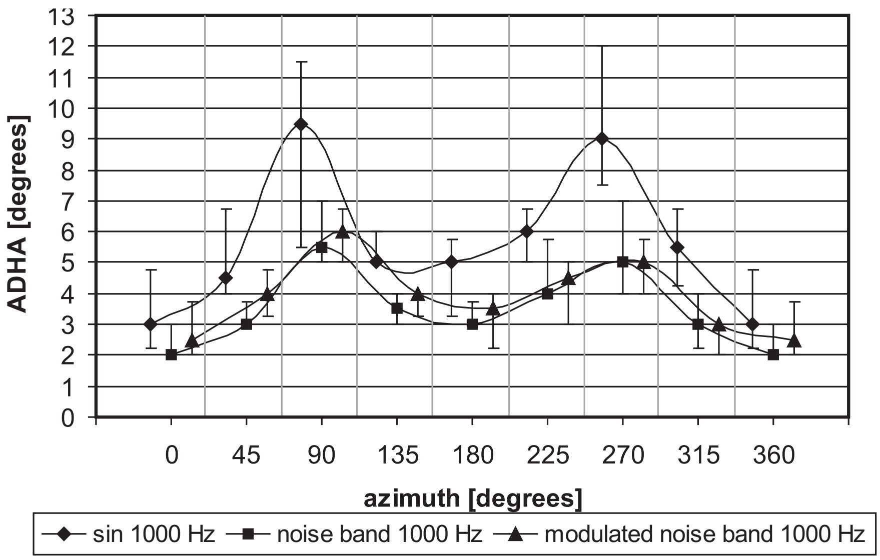

Fig. 4. Values of the median, lower and upper quartile of ADHA for sinusoidal signals and 1/3 octave band noise signals for mid-frequency of 1000 Hz.

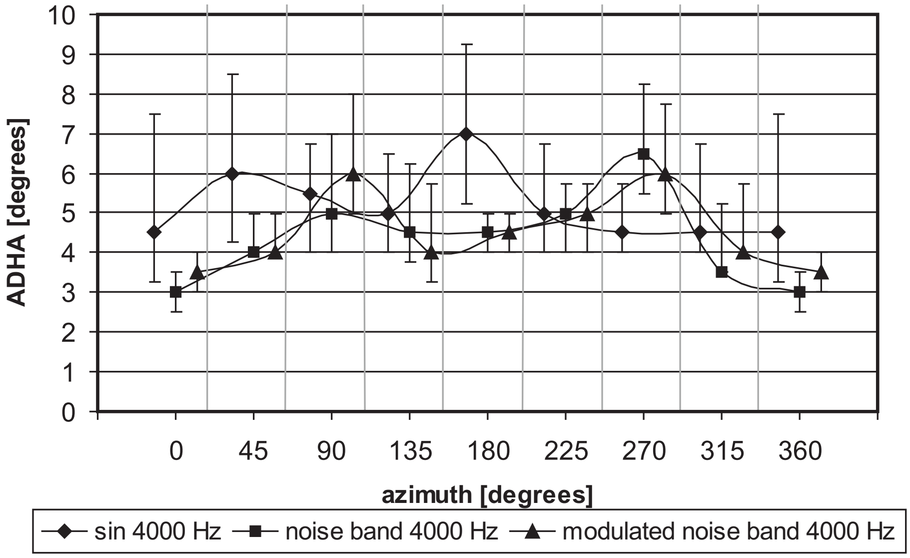

Fig. 5. Values of the median, lower and upper quartile of ADHA for sinusoidal signals and 1/3 octave band noise signals for mid-frequency of 4000 Hz.

The above figures reveal that ADHA values for individual azimuths are similar for the frequencies of 500 and 1000 Hz. The highest ADHA values (the worst localization ability) are in the case of sinusoidal signals for the lateral azimuths (90° and 270°) and the lowest ADHA values (the best localization ability) are for azimuth 0° (opposite the listener's head) and 180° (at the back of the listener's head). For the signals of a frequency 4000 Hz, ADHA values are more uniform (there are no significant maxima for the lateral azimuths) and the maximum value is reached in the case of azimuth 180°.

For sinusoidal signals of the frequencies 500 and 1000 Hz ADHA values are very similar; however they differ significantly when compared with the values for the frequency 4000 Hz, where the maximum value is recorded for azimuth 180°. In the case of noises and modulated noises there is a significant regularity, namely maximum ADHA values are recorded for azimuths 90° and 270° for all frequencies.

3.2. Comparison of ADHA values with respect to individual listeners

Results of the evaluation of ADHA values were compared with respect to all the listeners. Figure 6 shows examples of the results obtained for the sinusoidal signal and 1/3 octave band noise for mid-frequency 500 Hz.

The analysis of the diagrams in Fig. 6 indicates clearely that there are greater differences in the responses given by individual listeners in the case of the sinusoidal signal as compared with the 1/3 octave noise band signal. A similar tendency was also observed in the case of signals of the frequency 1000 Hz and 4000 Hz. Furthermore, no significant differences were found when comparing the results for the noise and modulated noise band signals.

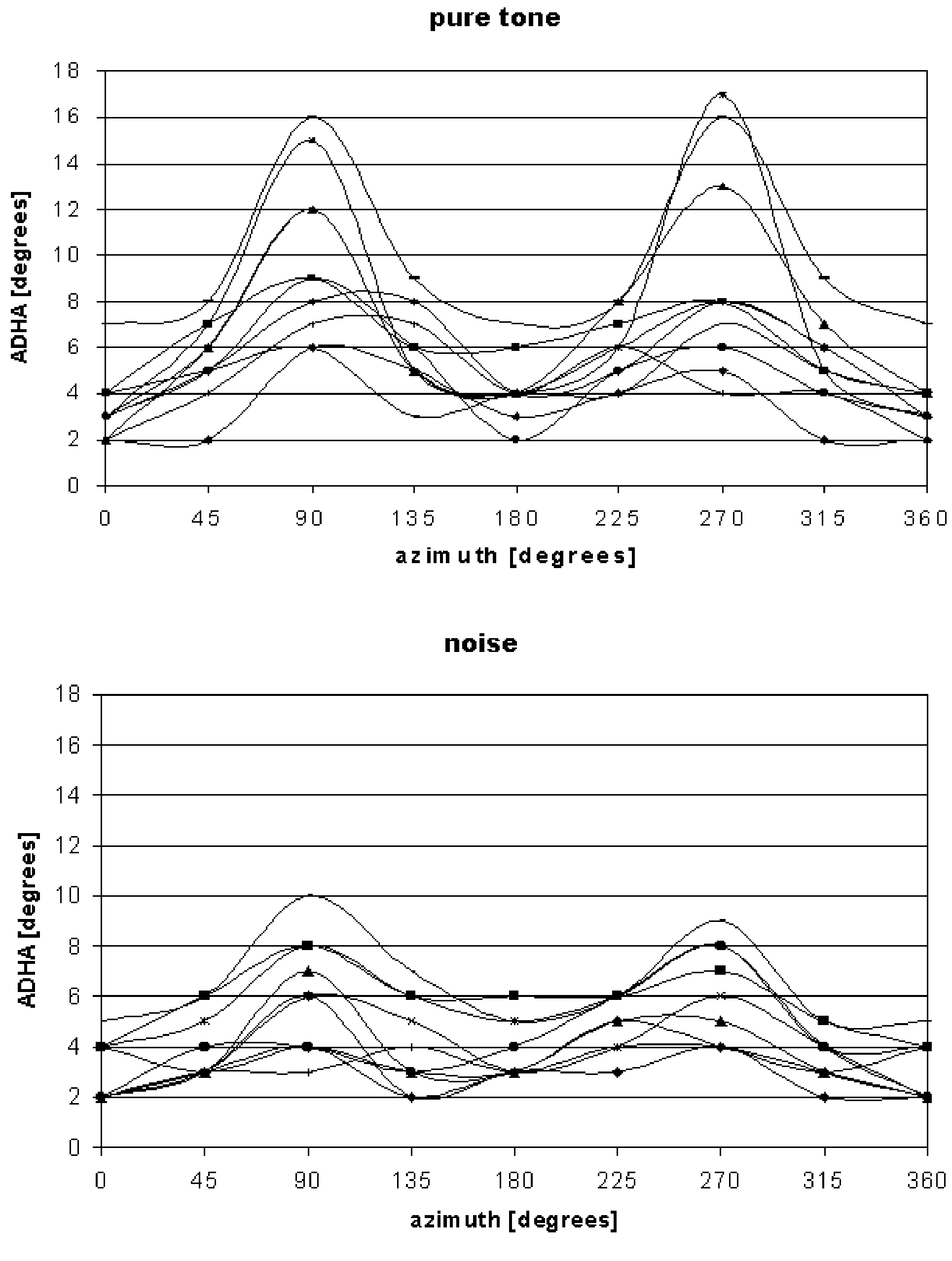

Fig. 6. Comparison of ADHA values for individual listeners for pure tone and band noise (500 Hz).

4. Conclusions

Based on the data presented above, the following conclusions can be drawn:

1. For all types of signals the best localization ability was recorded for the sources located directly in front of the listener's head (azimuth 0° or 360°).
2. The worst localization ability was recorded for lateral azimuth (90° and 270°); the only exception was the sinusoidal signal of the frequency 4000 Hz, for which maximum ADHA value was recorded at the azimuth 180°.
3. Much lower ADHA values (better localization ability) were obtained for noises than for sinusoidal signals (differences between the results obtained modulated and non-modulated noises were relatively small).
4. Smaller differences between the responses given by individual listeners were recorded for noise signals than for sinusoidal signals.
5. Much larger ease and certainty of answers given by the listeners was noted when noise signals were evaluated: it is concluded that these signals, rather than pure tones, should be used in testing the hearing-impaired people to evaluate some aspects of their hearing pathology.

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