1. Direction Perception

The paired nature of human hearing makes it possible to determine the direction from which sound originates. One of the most important properties of spatial hearing in connection to this is its ability, to isolate a piece of sound information from a host of sounds coming from various directions and to more or less suppress all the others. For example this happens by concentrating on a certain speaker while the sounds of several other voices arrive at the ear with equal loudness. This analytic ability of the ear is called "intelligent listening". In general it is supported by simultaneous optical information. Such selective hearing also exists for perception of sound pitch and sound color.

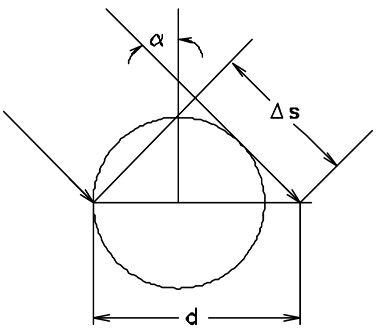
Directional perception in the horizontal plane is based on the subconscious comparison of nerve signals coming from both ears. In the case of sound coming from frontal direction these signals are identical; in the case of a lateral shift in the direction of origin, they differ, corresponding to the angle of incidence. The hearing determines the direction of sound source origin with help of these differences. The signals arrive at the two ears with delay time differences and, depending on the spectrum, with intensity differences. Delay time and intensity differences always occur at the same time; separate investigation of the two influences is only possible with the help of "earphone experiments". Directional perception in the vertical plane is possible on the basis of sound color differences.

1.1 Directional perception due to delay time differences

In the case of sound incidence from lateral directions there is a distance difference [Ä s] which corresponds to a delay time difference [Ä t] between the signals at the two ears, depending on the distance [d] between the two ears and the angle of sound incidence. The following equation was derived from experiments (see Fig. 1).

The biggest delay time difference due to sound incidence from one side amounts to about 0,6 ms; the smallest delay time difference which can be perceived amounts to about 0.03 ms, corresponding to [Ä s] = 1 cm. The definition of time delay differences is unambiguous for sound which contains many impulses such as speech and in general also music.

$$\Delta t = \frac{d}{c}\left(1 + \frac{\sin\alpha}{4}\right)\sin\alpha$$



Ä t = delay time difference (s)

d = dist. between ears (m)

á = angle of incidence (°)

c = speed of sound (m/s)

Fig. 1

For continuous sound on the other hand the delay time difference appears as a phase difference which, however, is dependent not only on direction but also on frequency. Above about 800 Hz the correspondence direction of incidence - phase difference is moreover ambiguous. So directional perception due to delay time differences is mainly possible for impulse sound; the accuracy of location is highest in the direction of sight.

1.2 Directional perception due to intensity differences

Besides the delay time differences, intensity differences between the two ears caused by the sound shadow of the human head also arise. Below about 500 Hz there are no intensity differences because of the refraction of sound around the head; above 500 Hz the intensity differences increase with rising frequency. It is difficult to give detailed and vivid representations of these situations, measured by various authors by a variety of objective and subjective procedures, since the dependency of intensity differences on frequency is quite complicated and irregular. Fig. 2 therefore shows a practical case, the course of sound level at the two ears for speech in dependence of the angle of incidence . For short distances the intensity difference due to the distance difference between source and the two ears has a certain influence.

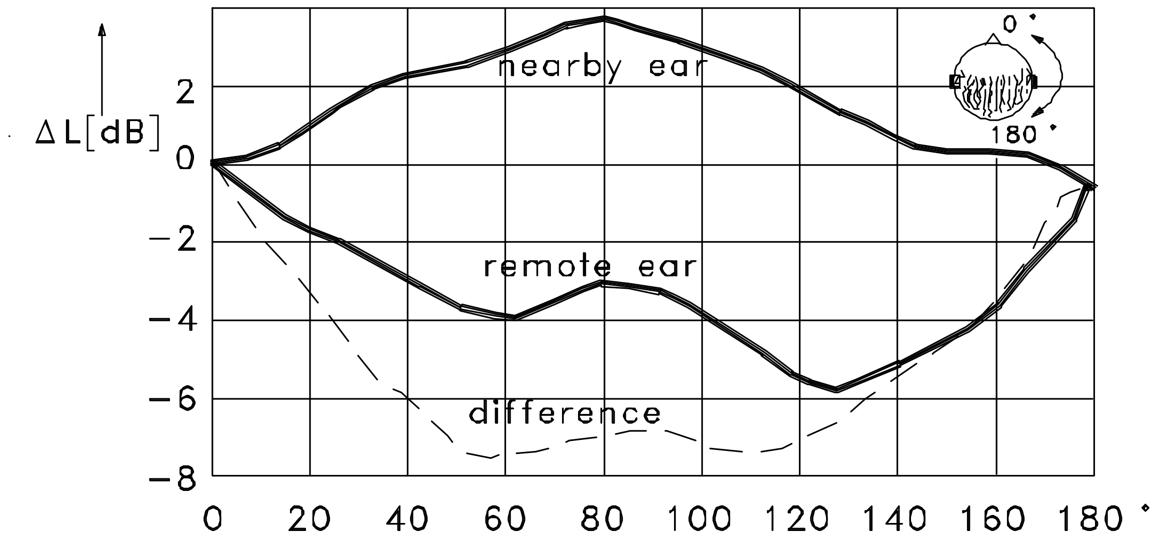


Fig. 2 *Course of sound level at the near and distant ear with reference to the sound level in the direction of sight (0 dB), in dependence of the angle of sound incidence (á).*

Due to the partly ambiguous relations between frequency, intensity and angle of incidence, sound localization solely on the basis of intensity differences is probably possible only to a very limited extent for stationary sound.

Differences in sound color, which surely play a role in sound localization, arise for wide-band sound signals due to the frequency dependency of sound intensity.

1.3 Accuracy of directional perception

During directional perception of natural sound sources, the time delay-, phase-, intensity- and sound color differences all occur simultaneously; it can be assumed that they are interactively effective. Accuracy reaches 2° to 3° in the direction of sight; it declines to about 4° to 5° for sound coming from lateral sides. A change of direction from left to right is perceived after about 150 ms, from front to back after about 250 ms. Sound with impulse content - as radiated by most sound sources - is significantly easier to localize than stationary continuous sound.

If two identical sound events reach the listener one shortly after another, which is the case for wall and ceiling reflections in a closed room, the law of the first wave front, also called the "Haas-effect", is valid for a delay of about l to 30 ms: the first sound to arrive determines the direction impression independently of the direction from which the following sound comes.

For time delay differences between 5 and 30 ms the level of the following sound can be as much as 10 dB higher than the primary sound without invalidating the law of the first wave front.

1.4 Directional perception in the vertical plane

A localization of the sound source is also possible in the vertical plane. Since the vertical plane is the plane of symmetry of the head, sound incident from this plane does not lead to different signals at the two ears. However, sound color differences occur in relation to the sound color coming from the direction of sight. These are caused by the shape and characteristics of the head and ears. Depending on the direction of incidence certain frequency bands, the so-called "direction determining frequency bands", are accentuated. (Fig. 3) The forward and bachward location accuracy is greater than above.

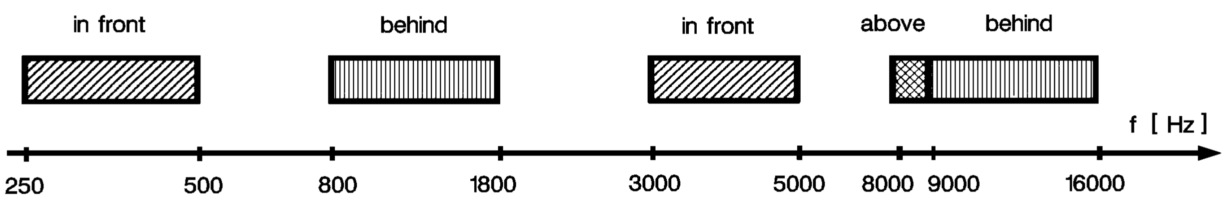


Fig. 3

2. Distance perception

The hearing can estimate the distance to a sound source with a single ear. In natural listening the simultaneousness of the optical and acoustical distance impressions play an important rol. In absence of the optical distance impression, the sensed auditory event distance is generally not in agreement with the actual sound event distance. The auditory event distances cannot be judged with certainty; the individual judgements scatter rather strongly. For distances under 0,5 m, the distance perception becomes markedly more exact with decreasing distance.
Experimental results suggest that the auditory event distance cannot be arbitrarily large, that the auditory event space is limited.

The largest auditory event distance is stated to be about 15 m. Several factors contribute to the constitution of the auditory event distance, including tone color, loudness and room acoustic influences.
The tone color of the auditory event plays a significant role in the recognition of distance. Nearby sound sources sound duller, their share of low frequencies is higher whereas more distant sources sound brighter. This fact is related to the laws of sound radiation. For a given size of the sound source, the sound waves whose wave lengths are large in comparison with the size of the sound source are radiated spherically, with a 6 dB level decline for each doubling of distance.

In contrast, the comparatively high frequencies are radiated directionally with a level decline less than 6 dB for each doubling of distance. The dominant sound is thereby shifted to higher frequency components with growing distance to the sound source. This shift in tone color with changing distance is further supported by the frequency dependency of the loudness level. Nearby sound sources are louder than more distant ones; so low frequency sound components are still audible very nearby, which, for more distant and therefore softer sound sources, lie under the limit of audibility. The tone color of a sound event therefore becomes brighter with declining volume level.
The louder an auditory event seems, the nearer it seems. The changes in loudness are important for the distance of the auditory event, especially for moving sound sources. The way in which the hearing evaluates loudness has not yet been clarified. Perhaps a comparison is made between the heard loudness and a "learned" auditory event distance reference value; a certain listener experience is probably a necessary condition for distance perception on the basis of loudness perception.
In closed rooms an estimation of the distance of the auditory event is possible on the basis of the relationship between direct and diffuse sound (reverberation), since the diffuse sound remains constant, independent of the distance from the sound source, whereas the direct sound declines with increasing distance. However, since room volume and the reverberation time influence the relationship of direct and diffuse sound, prior knowledge of the room acoustics, i.e. a certain listener experience, is required here too.

A borderline case of distance perception is the "in the head localization" of an auditory event which is observed especially in head phone replay of mono and room related stereo, but which also occurs in loudspeaker replay. Various hypothesis on the cause for this have been put forward.

3. Resultant localization effect

If two loudspeakers L1 and L2, radiating exactly the same signal simultaneously, are set up at a certain distance - b - (basis width) from one another, a listener - H - does not hear two separate signals at L1 and L2 but a single fictitious sound source - S - in the middle of the basis. (Fig. 4) If level and/or time delay differences of the signals are produced and continuously varied within certain limits the fictitious sound source - S - moves along the loudspeaker basis until it finally stops at one of the two loudspeakers. This effect is fundamental for space related stereophonic sound reproduction; it makes the illusion of spatial sound reproduction possible and is called "resultant localization effect".

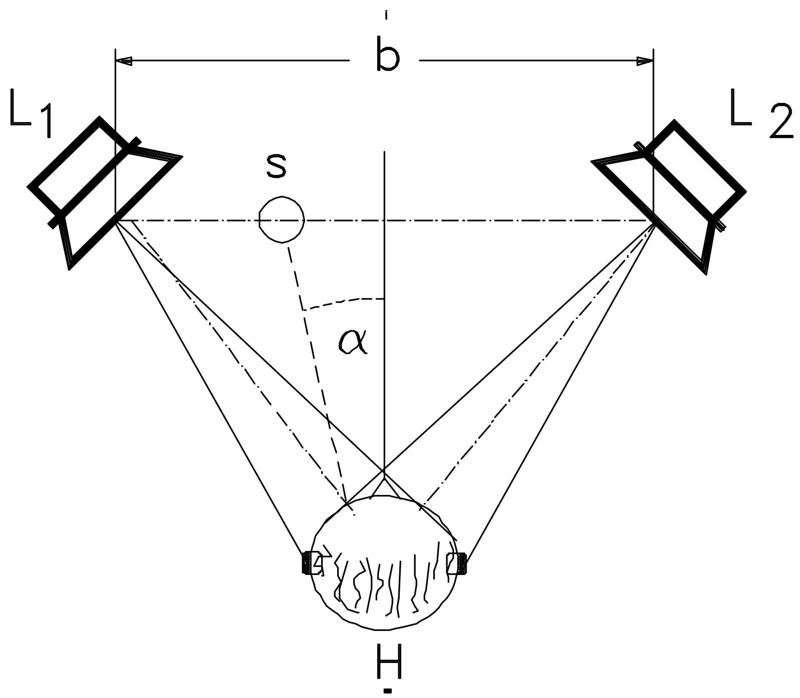


Fig. 4

In the case of stereophonic loudspeaker replay two sound fields are superimposed, whereas in locating a real sound source, the directional impression is won from a single sound field. Each ear receives from each of the two loudspeakers a certain sound share; from the level and delay time differences of these signals a directional impression of a fictitious sound source arises due to the resultant localization effect.

Necessary conditions for a satisfactory localization by means of the resultant localization effect are that the loudspeakers radiate signals from the same sound source without phase reversal, that the level and/or delay time differences remain within certain limits and that the listener's position is in a certain relation to the loudspeakers, which means inside the stereo-listening area (See Fig. 8).

3.1 Resultant localization due to level differences

If both loudspeakers are set up according to Fig. 4 and radiate the same similarly phased signal and the levels of L1 and L2 are equal, then a fictitious sound source - S - is heard exactly in the middle of the basis - b -. In the case of level differences, the fictitious sound source moves laterally along the basis until it ends, with a level difference of about 20 to 30 dB, exactly at the location of the loudspeaker with the higher level. However, with a level difference of only 15 dB, the fictitious sound source is already so near to one loudspeaker that in practice a level difference of about 15 dB leads to the impression "at the side". The experimentally found relation between angle of fictitious sound arrival and level difference L is shown in Fig. 5.

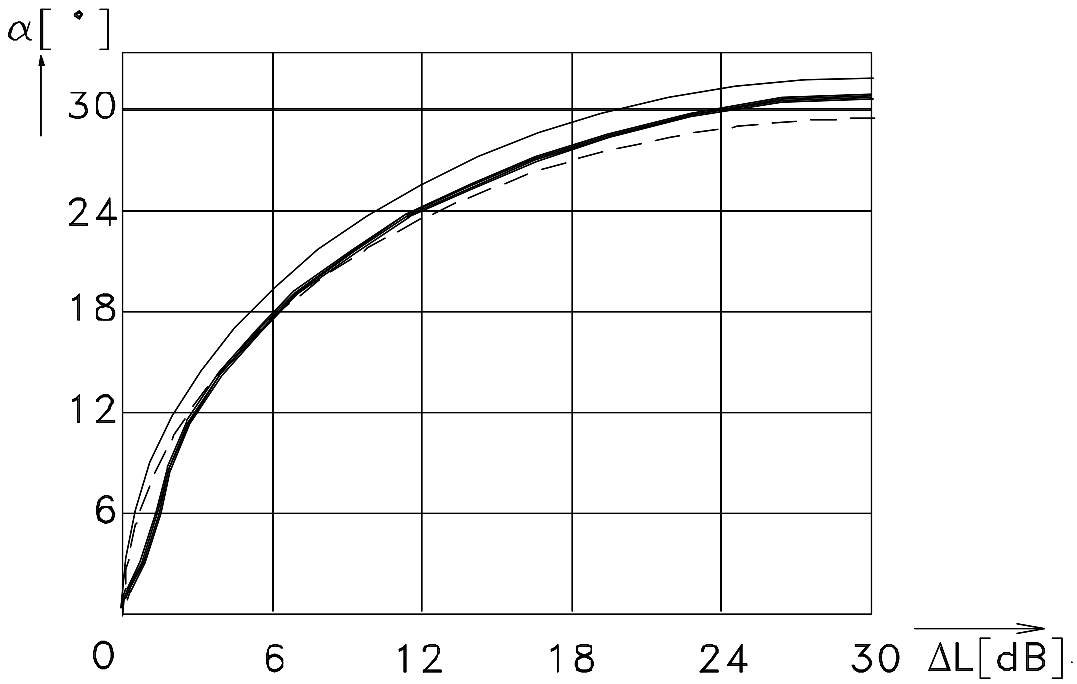


Fig. 5 *Subjectively determined dependence of localization angle à on level difference DL for two channel replay of click-free sinusoidal tones. The scattering area shown is valid for frequencies between 330 and 7800 Hz. The curves were determined for a basis width - b - of 3 m and an angle á of 60° (see Fig. 4).*

Resultant localization due to delay time differences

The relation between the delay time differences and the angle à at which the fictitious sound source appears is shown in Fig. 6.

Delay time differences do not give rise to such sharply defined fictitious sound sources as level differences. For frequencies below 100 to 200 Hz the delay time differences are imperceptible.
For delay time differences between 3 and 30 ms, the so called "Haas-Effect" is operative, according to which only that loudspeaker which radiates the sound signal first is heard as sound source, even if the level radiated by the other loudspeaker is 10 dB higher.

In the case of delay time differences of more than 40 to 90 ms (depending on the structure of the sound source) two signals - different in direction and time - are distinctly heard.

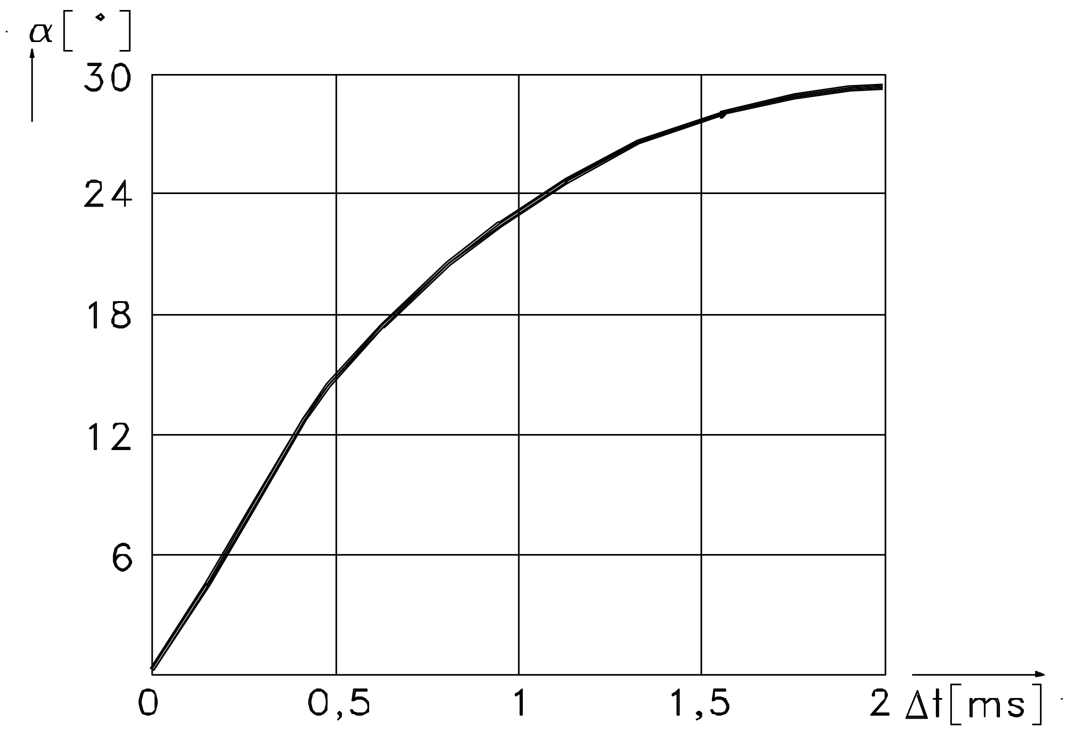


Fig. 6: *Subjectively determined dependence of the localization angle [á] from delay time difference [Ät] for two channel replay.*

3.3 Interaction of level and delay time differences

Level differences and delay time differences interact if theyoccur at the same time. If they are causing the same effect, they sum up. If they are causing contrary effects they cancel each other partly or entirely. This is valid for up to about 18 dB level differences and about 3 ms delay time differences. Fig. 7 shows the values of equivalent level and delay time differences. Experimental investigations give partly deviating results.

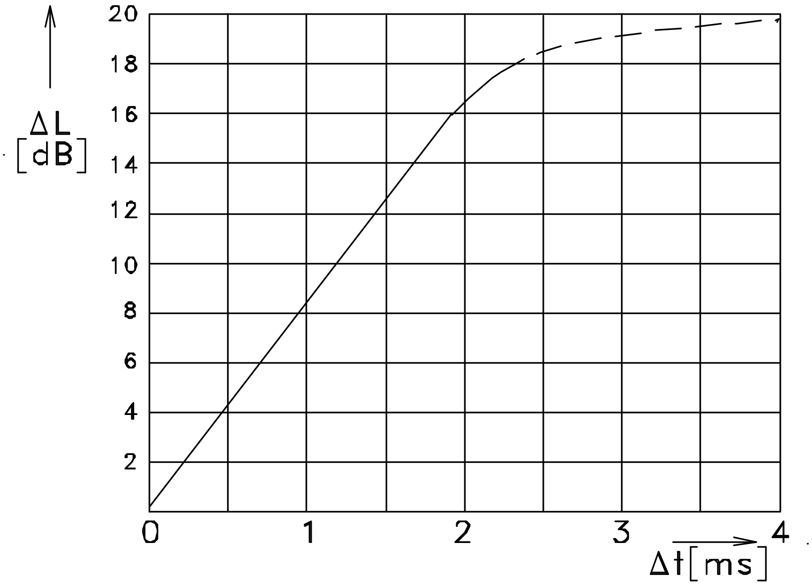


Fig. 7

4. Stereo listening area

For the realization of the resultant localization it is necessary for the listener to be located on the middle axis between the two loudspeakers in order that a fictitious sound source is heard at the middle of the basis when the loudspeaker signals are identical. Every deviation from the middle axis leads to intensity and delay time differences at the listener's position and thus to a movement of the fictitious sound source from the middle to the nearer loudspeaker. If a certain - still acceptable - degree of shifting the middle sound source is tolerated, then the area of sufficient middle localization, the so-called "stereo listening area" is a narrow area between the loudspeakers, limited by two hyperbolic branches. (Fig. 8)

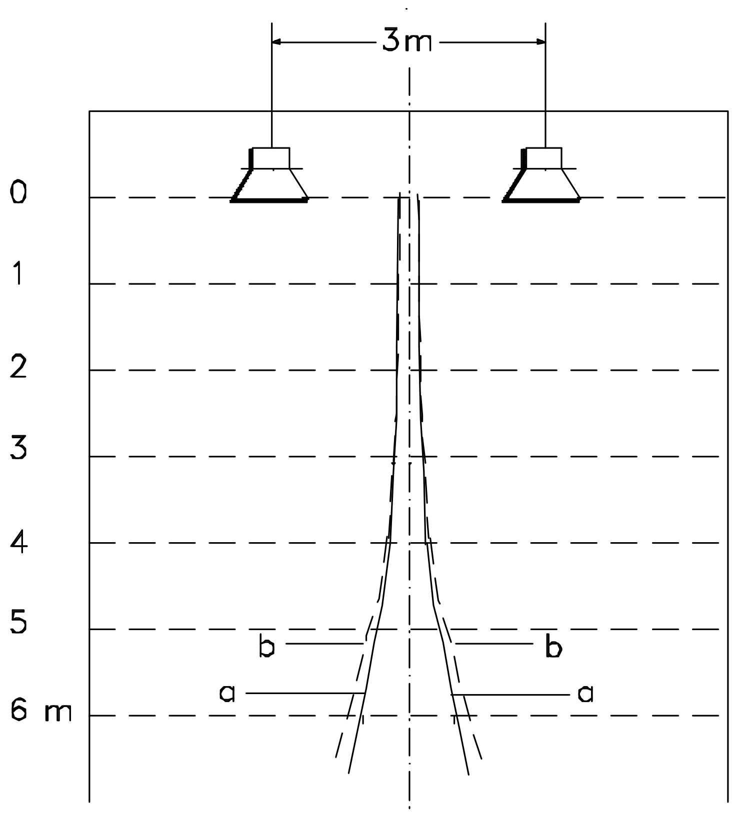


Fig.8: Stereo listening area

Zones of correct middle location for 3 m basis width:

a = for loudspeakers with normal directional characteristics

b = for loudspeakers with broad directional characteristics

The stereo listening area is very narrow. For a basis width of 3 m, the listening area at a listener's distance of 3 m is only 21 cm wide (for loudspeakers with normal directional characteristics).
At 5 m distance it is only 38 cm wide (reverberation time about 0,5 s). For a larger basis width the listening area is even narrower. Loudspeakers with a larger radiation angle (spherical loudspeakers) increase the width of the stereo listening area by a factor of about 1,5; they have, however, the disadvantage of reduced sharpness of localization.

STEREOPHONIC LISTENING I

Directional perception in the horizontal plane

The localization of a sound source in the horizontal plane is possible since both ears receive different signals. These signals can be different in intensity or/and delay time. As a rule, they are different in intensity and delay time.

Localization of / Due to	sine frequencies	impulses	noises
delay time differences	***For f < 800 Hz***	***yes***	***yes***
Intensity Differences	***For f 500 Hz***	***yes***	***yes***

Impression: "from the front" : no difference

Impression: "from right" delay diff.: 1 ms

Intens. diff.: 15 – 20 dB

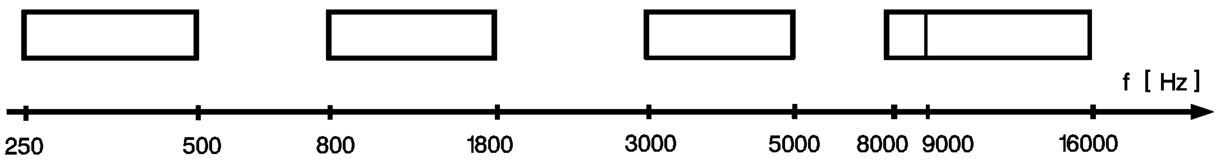
Accuracy of localization: in dir. of sight 2° - 3°

Lateral 4° - 5°

STEREOPHONIC LISTENING II

Directional perception in the vertical plane

The direction of sound in the vertical plane can be determined by small movements of the head. Especially the so called "direction determining frequency bands" determine the perceived impression of sound origin.



Perception of distance

The distance of a sound source can only be approximately perceived. The following factors have a certain influence:

volume (loudness)

sound colour

room influence

learning effect