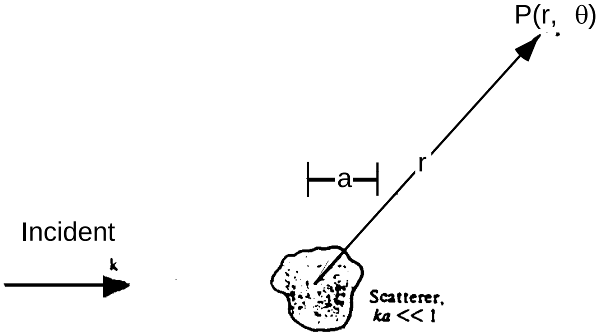
# Lecture 4:The Interaction of Sound and Objects: Scattering and Diffraction

## A. Definitions:

### *1. Scattering*

*Scattering* refers to the alteration in sound path produced by the interaction of a sound 'ray' and an object. Scattering implies that the incident sound wave front is broken into multiple waves by the scatterer. The smearing of propagation directions introduced by interaction with a rough surface is also an example of scattering (AD Pierce "Acoustics: An introduction to its physical principles and applications" Acoustical Society of America,1981).



Scattering of a plane wave by a rigid immovable object.
(From Pierce 1981)

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### *2. Diffraction*

*Diffraction* is another result of interaction of sound waves and objects. Practically, diffraction is the name used to explain the results of such interactions that can not be explained by ray theory. The basic tool for analyzing diffraction is *Hyugen's principle*: any wave front can be approximated by a series of in-phase and equal strength simple sources placed along the front.

## B. Examples of Scattering and Diffraction

Image removed due to copyright considerations.
Source: Olsen, H. F. *Music Physics and Engineering.* Dover Press, 1967.

Figure 4.1: Scattering and Diffraction by a large slit and a small slit (from Olsen, Music Physics and Engineering). Which of these examples is better fit by ray theory and which is better explained by diffraction?

Image removed due to copyright considerations.
Source: Olsen, H. F. *Music Physics and Engineering*. Dover Press, 1967.

Figure 4.2 Scattering and Diffraction by a large and small object (From Olsen). Which of these situations is better explained by ray theory and which by wave theory and diffraction?

Image removed due to copyright considerations.
Source: Olsen, H. F. *Music Physics and Engineering.* Dover Press, 1967 .

Figure 4.3 (a) Scattering from an object positioned at an angle relative to the direction of propagation of the incident wave. The angle of reflection is equal to the angle of incidence. (b) Scattering and transmission by an imperfectly rigid barrier. The energy transmitted equals the incident energy minus the reflected energy. (From HF Olsen “Music, Physics and Engineering” Dover Press 1967)

## *C. Model's of Diffraction.*

Hyugen's principle (from Halliday & Resnick 1970)

*"All points on a wavefront can be considered as point sources for the production of spherical secondary wavelets. After a time, the new position of the wavefront will be the surface of tangency of these secondary wavelets."*

This principle allows us to model diffraction by a combination of simple sources. The tools used to analyze diffracted light at a distance far from a slit (called Fruanhofer diffraction) are essentially the tools we used to determine the sound pressure far from an array of sources.

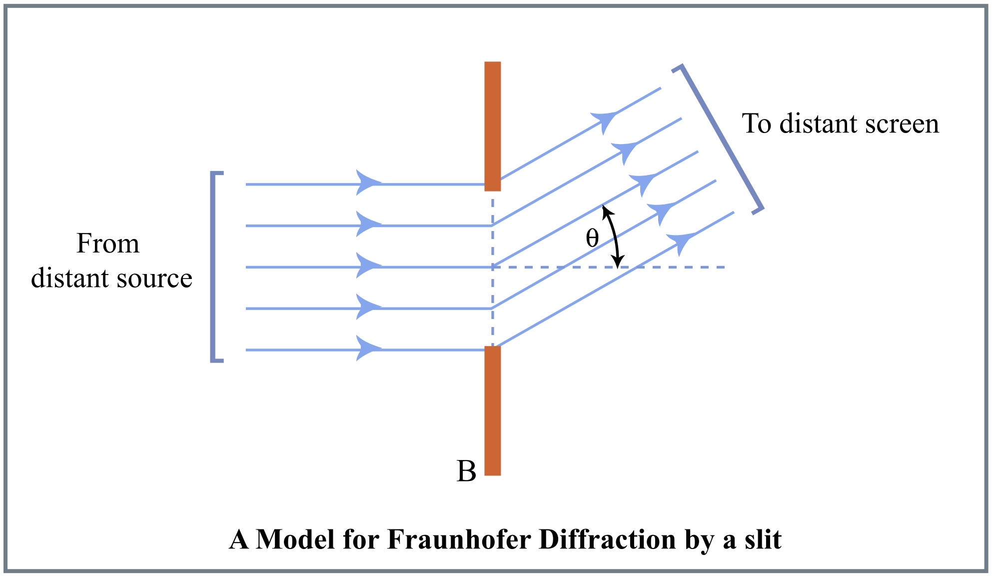
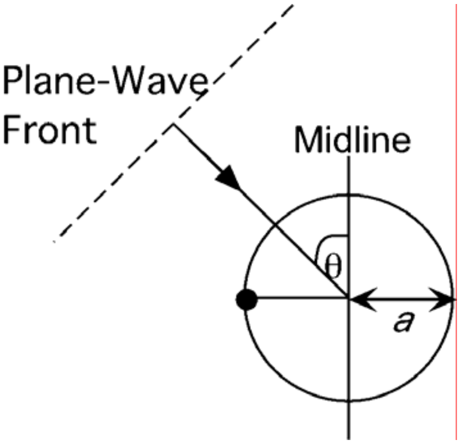


Figure 4.4 Adapted from Halliday & Resnick. *Fundamentals of Physics.* Wiley, 1970.

## *D. Diffraction and Scattering of plane waves by a rigid Sphere.*

While broad-band descriptions of diffraction and scattering get complicated, as you add more and more simple sources, one "simple" system for which there is an analytic solution is the diffraction and scattering of plane waves by a rigid sphere. This solution based on a simple geometric view of spherical symmetry ( only *a* and θ are significant) is mathematically complicated (Rayleigh, 1986; Morse & Ingard 1968).



<u>Figure 4.5A</u>

A geometry to describe the sound pressure at a point located on the surface of a spherical artificial head where the angle between the source and the midline of the sphere perpendicular to the measurement point is controlled.

Figure 4.5B
An alternative geometry to describe the sound pressure at a point located on the surface of a sphere where the angle between the source and the midline of the sphere that contains the measurement point is controlled.

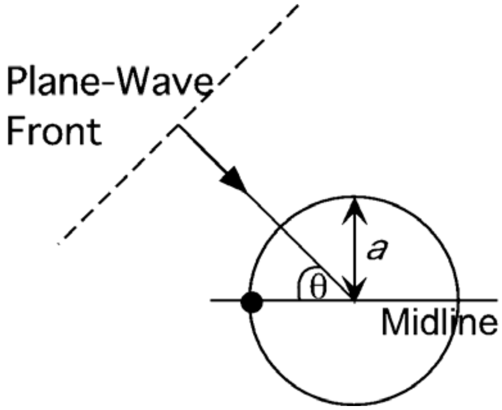


Figure 4.6 Mathematical predictions of sound diffraction around a sphere (from Shaw 1974)

Image removed due to copyright considerations.

Source: Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

A) The sound pressure measured at the surface of a sphere, relative to the free-field pressure in the stimulating plane wave, as a function of *ka* (the x-scale at the top) or frequency assuming a sphere of the size of the human head (the x-scale at the bottom). The parameter is θ, the angle between the sound source and the mid-line of the sphere. The sound measurement point is located on the surface of the head at θ=90°. The angular position of the source is the parameter. When the source is pointed directly at the measurements point on the sphere's surface, θ=90° and the sound pressure is a maximum. When the source is directed at a point directly on the opposite side of the sphere, θ=-90° and the sound pressure is either equal to or a little larger than the pressure of the plane-wave stimulus. When the source is on the other side of the head but not at -90°, the measured sound either equals or is less than the pressure in the incident wave.

Image removed due to copyright considerations.

Source: Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

B) The mathematical predictions illustrated in figure Abut now shown on a directional plot with frequency as a parameter. The radial distance between the center of the plot and the plotted functions codes the level of the measured sound at a point on the surface of the sphere at θ=0°, the direction of the source is varied from -180°< θ < 180°. Directionality functions are shown for 1 & 6 kHz. (From Shaw 1974).

These theoretical diffraction patterns are compared to sound pressure measurements on the surface of a sphere on the next page. Again, with a human sized head, *ka*=1 corresponds to a frequency of about 0.6 kHz.

## *E. Measurements of Sound Pressure on the surface of a sphere P(a, $\theta$):*

Wiener FM (1947). J. Acoust. Soc. Am. 19: 444-451.

**F.M. Wiener (1947)**

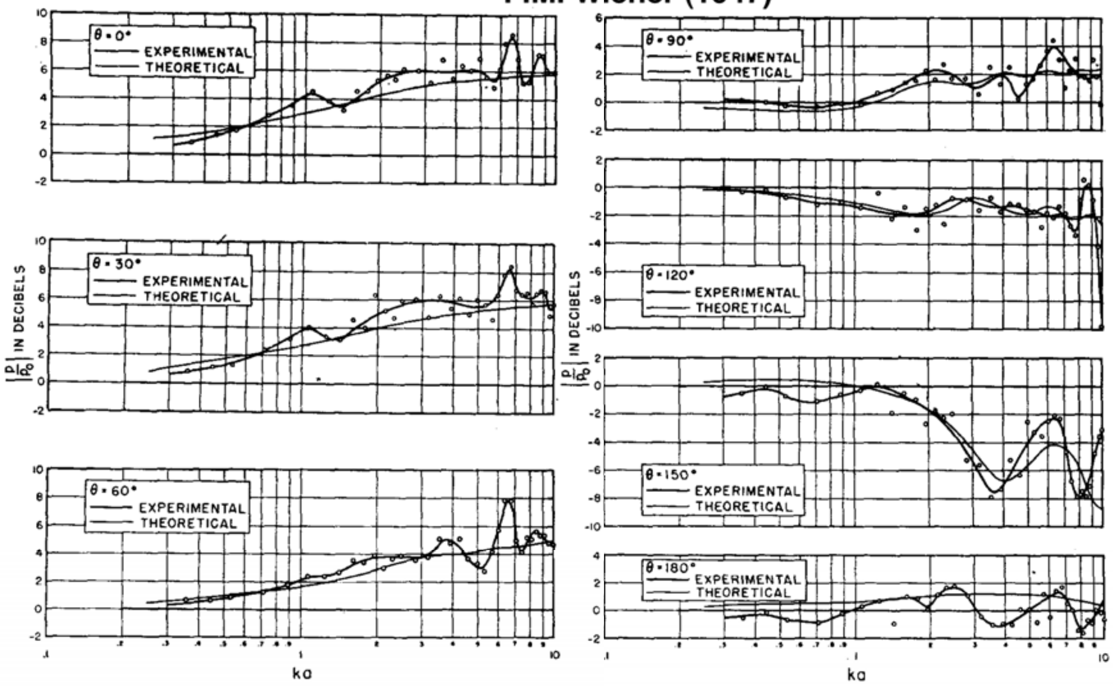


FIG. 1. Showing the ratio of the sound pressure $p$ to the free-field pressure $p_0$ on the surface of a rigid sphere in a plane wave of wave number $k$. The magnitude of this ratio is plotted, in decibels, as a function of $ka$ ($a=9.7$ cm). For comparison, the theoretical values are also shown.

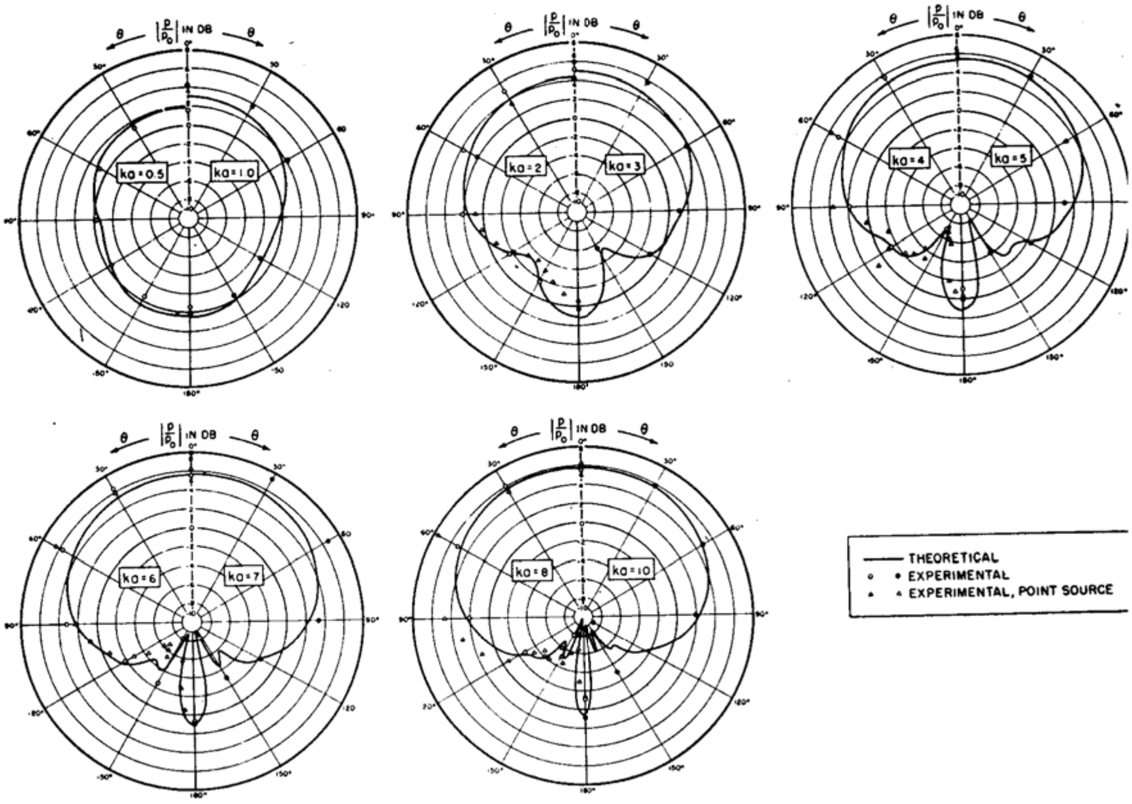


FIG. 2. Some of the data from Fig. 1 are re-plotted in polar form and data obtained with a point source of sou are added. Note that $p$ near $\theta=180°$ is substantially equal to $p_0$.

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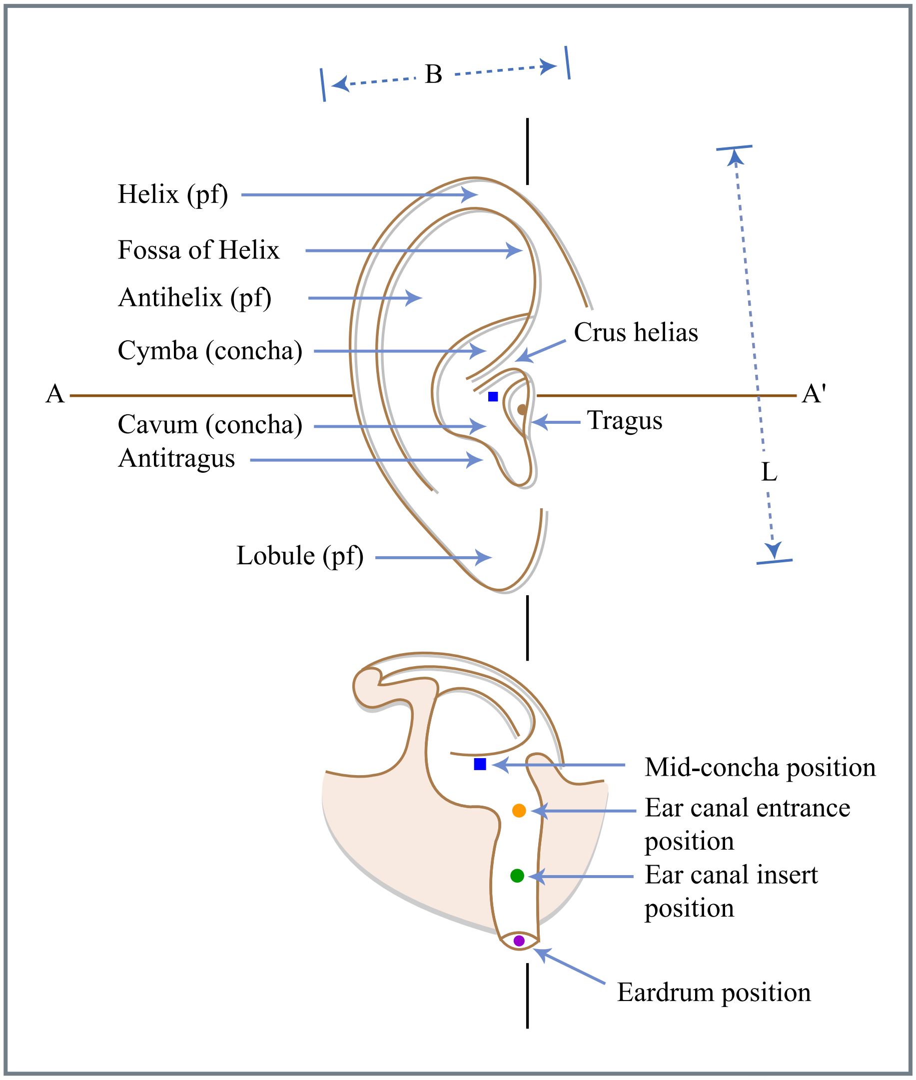
## *F. The contribution of the external ear to the directionality of the human auditory system.*



To the Left:
The human external ear is made up of the pinna flange (the flap that sticks out from the head), the complicated concha or bowl, and the tube like external-auditory canal. Each of these structures affects the sensitivity and the directionality of the human ear. The eardrum is the termination of the external ear and the first structure in the middle ear. (Shaw 1974).

### *1. Contribution of the external-ear components to the sensitivity of the ear*

The effect of different external-ear structures on the gain between the sound pressure at the eardrum and the free-field sound pressure for a sound source positioned on the horizontal plane at 45° relative to the midline (the azimuth=45°; elevation = 0°). (After Shaw 1974).

Image removed due to copyright considerations.

Source: Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

## *2. The External-Ear and the Directionality of the Ear: Head-Related Transfer Functions*

The magnitude of the eardrum to free-field sound pressure ratio for the human head for sound sources located on the horizontal plane (Shaw 1974).

Image removed due to copyright considerations.

Source: Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

Normalized HRTF vs Azimuth
sound frequency is the parameter

Interaural Level Differences vs Azimuth
sound frequency is the parameter

Image removed due to copyright considerations.

Source: Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

Measurements and theoretical values for azimuthal dependence (HRTF normalized by HRTF(0)left ) and interaural intensity differences (right) of the magnitude of sound pressure at the ear drum normalized by the stimulus pressure in the plane wave. (SHAW 1974).

Normalized HRTF vs Azimuth
sound frequency is the parameter

Interaural Level Differences vs Azimuth
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Source: Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

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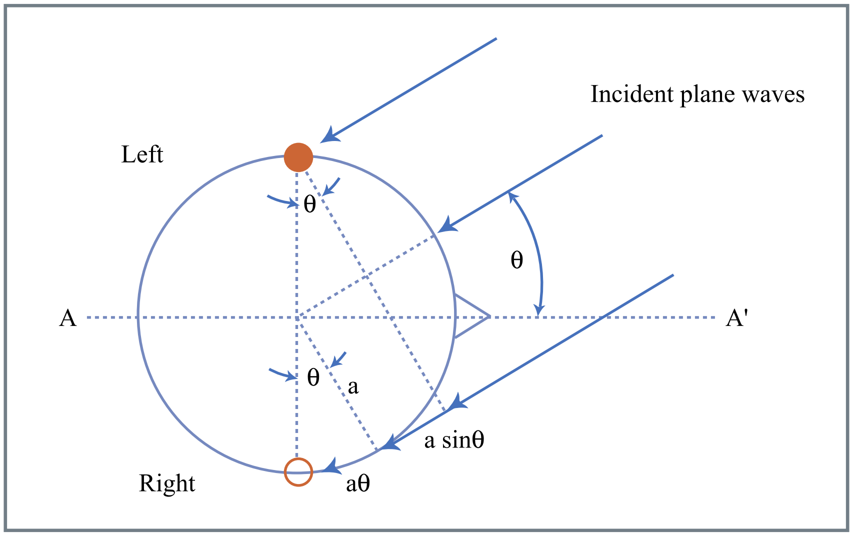
Measurements and theoretical values for azimuthal dependence (HRTF normalized by HRTF(0)left ) and interaural intensity differences (right) of the magnitude of sound pressure at the ear drum normalized by the stimulus pressure in the plane wave. (SHAW 1974)

## *G. Interaural time and phase differences*

A simple model of the interaural time differences is presented below:



4.13 The Geometric model of Interaural Time Difference (*ITD*) produced by a source in the horizontal plane for a spherical head of radius a:

$$ITD = \frac{a}{c}(\theta + \sin\theta).$$

Note that ITD in this model is independent of Frequency..

In the sinusoidal steady state, the interaural phase difference is:

$$IPD = \omega\, ITD = \frac{2\pi}{period}\, ITD$$

Adapted from Shaw, E. A. G. "The External Ear." In *Handbook of Sensory Physiology: Vol V/1: Auditory System.* Edited by W. D. Keidel, and W. D. Neff. New York: Springer-Verlag, 1974, pp. 455-490.

Estimates of ITD based on scattering and diffraction theory match the simple spherical model predictions at *ka > 2 but* underestimates ITD (and IPD) at frequencies where *k*< 0.3 .

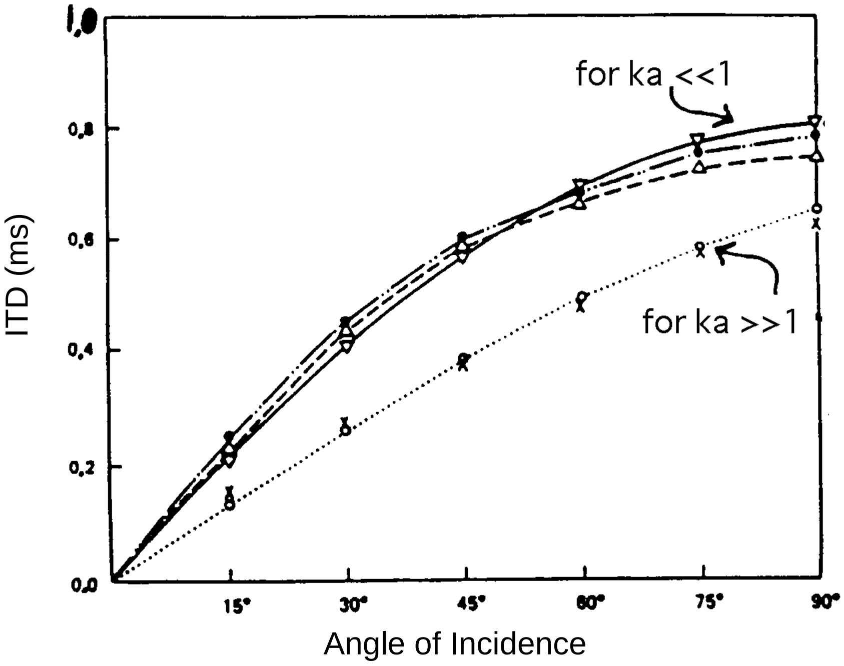


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Figure 4.14
The symbols are measurements made of the interaural time difference at different angles of incidence at high (o,x) and low frequencies (the square, dot and triangle). The line labeled 'for *ka*>>1' is the prediction of the simple spherical model for all frequencies, and scattering and diffraction theory for *ka >> 1.* The line labeled for *ka* <<1 is based on scattering and diffraction around a rigid sphere for that condition. (From Kuhn GF (1977). Model for the interaural time differences in the azimuthal plane. J. Acoust. Soc. Am. 62: 157-167).

The root of the simple model's underestimation of interaural time is that, ITD varies with frequency, being longer at low frequencies than at higher. This frequency-dependent interaural time is consistent with models of diffraction about a rigid sphere.

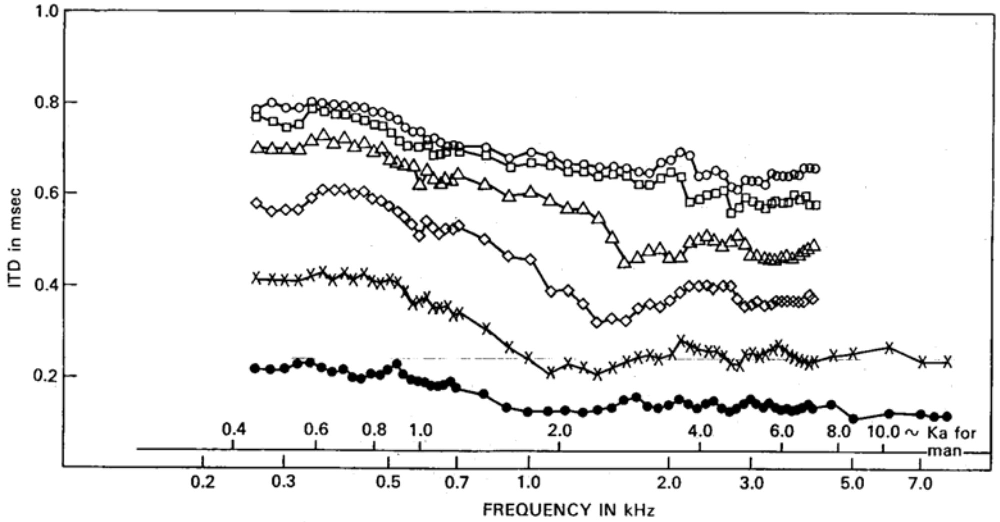

**FIG. 8.** Interaural time difference measured on the manikin's head surface as a function of frequency and angle of incidence with no torso (●●● $\theta_{inc}=15°$, ××× $\theta_{inc}=30°$, ◇◇◇ $\theta_{inc}=45°$, △△△ $\theta_{inc}=60°$; □□□ $\theta_{inc}=75°$; ○○○ $\theta_{inc}=90°$).

From Kuhn 1977.

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While the measured and calculated ITDs at frequencies above 1000 Hz in man *ka* > 2 are consistent with the spherical model of Figure 4.13: the Normalized ITD,:

$$\Pi = \frac{ITD}{(a/c)\sin\theta},$$

approximate is 2 in the spherical model and in the measurements in that high-frequency range. However. the measurements show it equals about 3 for *ka* < 1 (*f* < 600 Hz in man). This 50% increase in interaural time at low frequency is consistent with an *effective* increase in head dimensions by 50%.

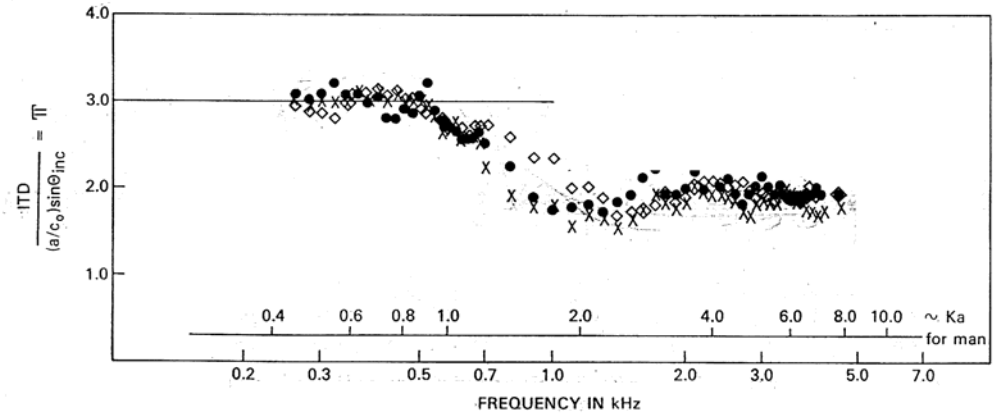

**FIG. 9.** Reduction of ITD measurements with no torso, normalized by $(a/c_0)\sin\theta_{inc}$ (●●● $\theta_{inc}=15°$, ××× $\theta_{inc}=30°$; ◇◇◇ $\theta_{inc}=45°$).

From Kuhn 1977.

Courtesy of Acoustical Society of America. Used with permission.

## *H. The 'Duplex Theory' for the localization of tones in the horizontal plane.*

The differences in interaural intensity produced by low frequency sounds *ka* <0.3 are too small to be useful in judging the location of sound in the horizontal plane. Instead, it is clear that some animals, including man, utilize interaural time (or phase) differences to locate sources of low-frequency tones in the horizontal plane. (Mills 1972).

### *1. Measurements of Minimum Audible Angle (Mills 1958)*

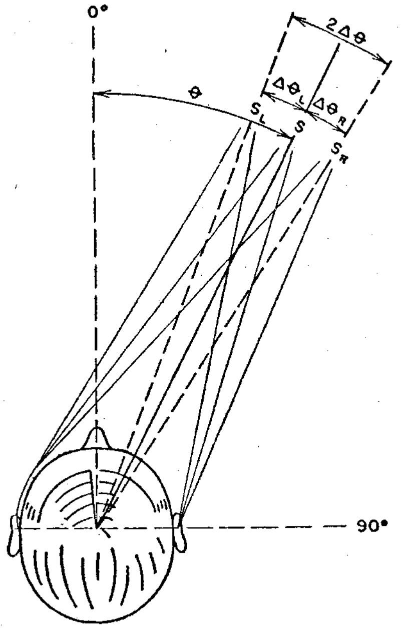

FIG. 1. The minimum audible angle ($\Delta\theta$). The position of the sound source at the reference azimuth ($\theta$) is indicated by $S$, and at each of the just noticeably different positions by $S_L$ and $S_R$. The light lines indicate hypothetical sound paths to the ears from each source.

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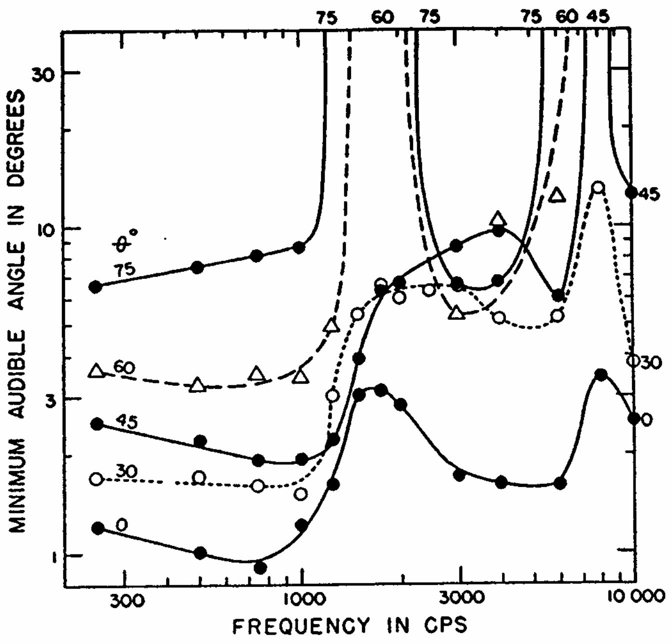
Minimum Audible Angle is the smallest angular deviation from a base azimuthal position θ that is detectable by human listeners. The stimuli used in its quantification are long duration tone bursts, and you can consider the system in the sinusoidal steady state. Localization performance is best (MAA is smallest) for sources on the midline.
(From Mills AW (1958). On the minimum audible angle. J. Acoust. Soc. Am. 30: 237-246.)



Measurements of MAA

From Mills AW (1958). On the minimum audible angle. J. Acoust. Soc. Am. 30: 237-246.)

**Figure 17: Measurements of the minimum audible angle reported by Mills (1958).**

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Low frequency (< 1000 Hz) MAA are consistent with the ability of the auditory system to detect interaural phase, while above 1000 Hz, the MAA are consistent with the ability of the listener to detect interaural intensity differences. (A jnd is a just notable difference.)

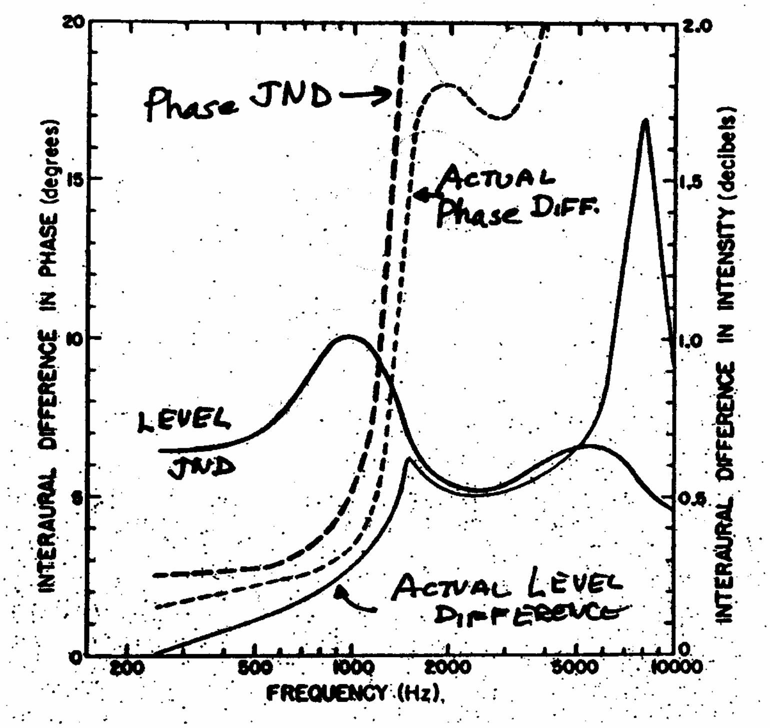

**Figure 18: Comparison of changes in interaural level and phase that occur when a source is moved from the median plane through a minimum audible angle with the minimal noticeable changes in interaural level and phase measured with earphones.**

From Mills AW (1958). On the minimum audible angle. J. Acoust. Soc. Am. 30: 237-246.)

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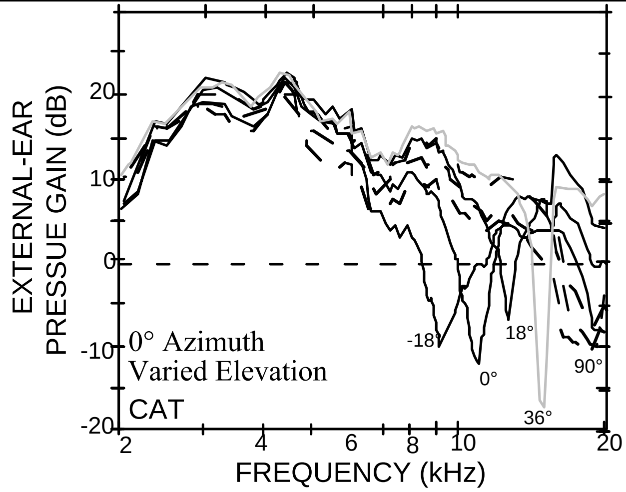
## *I. The Effect of Sound Elevation on the Sound Pressure Input to the Auditory System.*



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While the difference between elevation and azimuth is irrelevant when discussing the symmetric sphere, asymmetries in the placement of the external ear and in the structures of the external ear, generate differences in the frequency dependence of the ear with sounds of varied elevation. These differences take the form of "interference-notches" produced by interactions of small wave-length sounds with the pinna flange and the different structures within the concha. On the left are measurements of external-ear gain made at varied elevations in the cat from Musicant et al. 1990.

## References

Kuhn, GF, Model for the interaural time differences in the azimuthal plane. J. Acoust. Soc. Am. **62** (1977) pp. 157-167.

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