

### Binaural Phenomena

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Aim

To understand binaural hearing

Objectives

- Understand the cues used to determine the location of a sound source
- Understand sensitivity to binaural spatial cues, including interaural time differences (ITDs) and interaural level differences (ILDs)
- Understand binaural unmasking
- Learn about the precedence effect
- Learn about neural mechanisms underpinning binaural hearing

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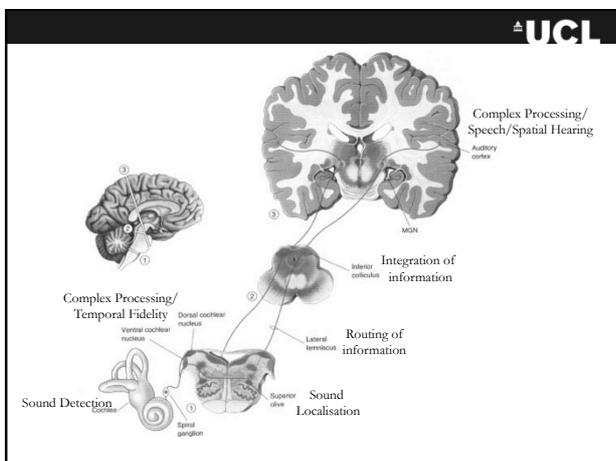
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**UCL**

**The primary representation in the auditory system**

The BM is tuned for sound frequency

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**Sound frequency is mapped at many levels in the CNS**

21*	15*	5.9	+5.7		
22*	16*	13*	8.2	+7.0	+8.1
21*	15*	11	+10	+6.0	
21*	15*	11	+3.5	+3.3	
12*	12*	11	5.0	+7.0	
11*	11*	10	7.1		
		2.0			

*The percept of auditory space is computed in the CNS from information that is not spatial per se*

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**Spatial Hearing**

For normal-hearing listeners it is clear that sounds can be ascribed a spatial position

Two main mechanisms for achieving this:-

- 1) The filter properties of the outer ear
- 2) Binaural hearing

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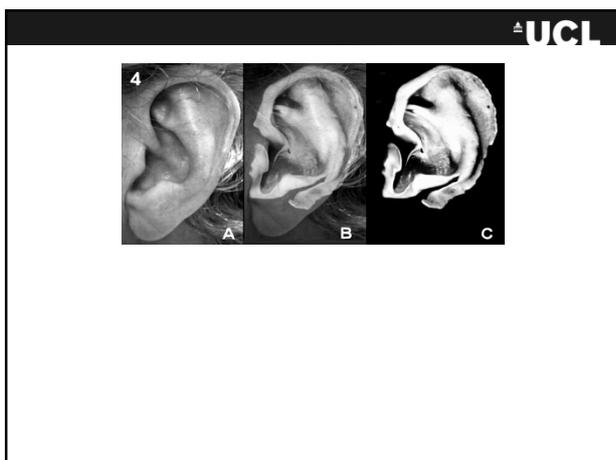
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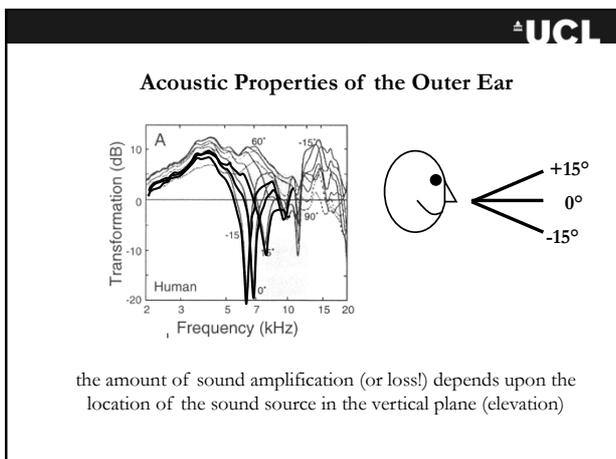
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**Binaural Hearing**

The ability to extract specific forms of auditory information using two ears, that would not be possible using one ear only.

sound-source localisation

signal detection in noise (binaural unmasking)

sound-source grouping and segregation

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**Binaural hearing: a historical context**



Lord Rayleigh – first formalised the duplex theory of binaural hearing  
*provided evidence that timing differences between the ears were detectable*

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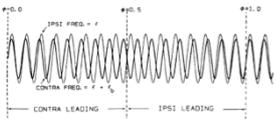
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**Sensitivity to binaural beats**

Presenting different frequencies to each ear creates binaural beats



*This is how Rayleigh discovered human sensitivity to ITDs*

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**Two binaural cues...**

A sinusoidal sound source located off to one side of the head will be delayed in time and will be less intense at the ear farthest from the sound source relative to the ear closest to the sound source

*Owing to the physical nature of sound, these cues are not equally effective at all frequencies*

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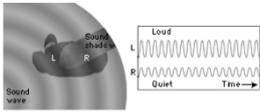
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### The duplex theory of binaural hearing

Sensitivity to Interaural Level Differences (ILDs)



Frequency-dependent – the effect is larger at higher frequencies

Head-size dependent – larger heads create bigger ILDs for the same frequency

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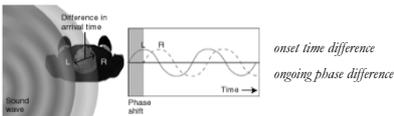
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### The duplex theory of binaural hearing

Sensitivity to Interaural Time Differences (ITDs)



Largely frequency-independent

Head-size dependent – larger heads create bigger range of ITDs

Requires extraordinarily exquisite temporal mechanisms (10 – 20  $\mu$ s sensitivity)

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### Support for the duplex theory

Stevens and Newman (1936) found that:-

1. Localisation was worst in the range 2-3 kHz
2. Front-back reversals were common, especially below 2 kHz

*This suggests two binaural mechanisms, one for frequencies below about 2 kHz and one for frequencies above about 3 kHz*

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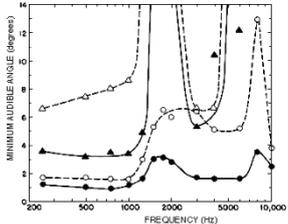
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### The minimum audible angle (MAA)

Minimum audible angle between successive pulses of tone as a function of the frequency and the direction of the source measured for angles (bottom to top at left hand side) 0°, 30°, 60° and 75° (from Mills, "Auditory Localization", in Tobias, ed. Foundations of Auditory Theory, Academic Press, 1972, p. 310, used by permission).



The graph shows the Minimum Audible Angle (MAA) in degrees on the y-axis (ranging from 0 to 14) against Frequency in Hz on the x-axis (logarithmic scale from 200 to 10,000). Four data series are plotted for source directions of 0°, 30°, 60°, and 75°. The MAA generally increases with frequency, especially above 1000 Hz, and is higher for larger source angles. The 0° series is the lowest, followed by 30°, 60°, and 75°.

*The MAA turns out to be about 1°, equivalent to about 10 μs of ITD.*

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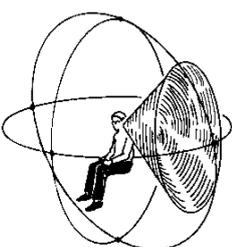
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### The "cone of confusion"

Sounds presented from many different spatial positions can provide the same ITD – this leads to localisation errors



The diagram shows a person sitting in the center of a large, transparent sphere. Several concentric circles are drawn on the sphere's surface, representing different spatial positions. A sound source is indicated by a speaker icon on the right side of the sphere, with lines radiating outwards to represent sound waves. The concept illustrates that multiple different spatial locations can result in the same interaural time difference (ITD) for a listener, leading to localization errors.

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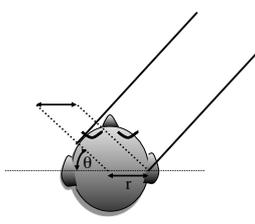
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### Measuring ITDs



The diagram shows a top-down view of a human head with two ears. A sound source is located to the right. Two lines represent the sound paths to the left and right ears. The path difference  $d$  is the extra distance the sound travels to reach the ear further from the source. The radius of the head is  $r$ , and the angle between the sound path and the midline is  $\theta$ .

path difference between the ears  
 $d = r.\theta + r.\sin \theta$

for a radius of 9 cm and a sound source located completely off to one side...  
 $d = 9.(\pi/2) + 9.\sin(\pi/2)$   
 $d = 23.1\text{cm}$

if the speed of sound is 343 m/s...  
 $\text{ITD} = 0.231/343 \text{ m/s}$   
 $\text{ITD} = 0.231/343 \text{ m/s}$   
 $\text{ITD} = .000673 \text{ s (673 } \mu\text{s)}$

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### Measuring ITDs

By convention:-

positive ITDs are those in which the sound is leading at the right ear...

and negative ITDs are those in which the sound is leading at the left ear...




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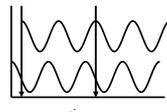
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### Measuring ITDs

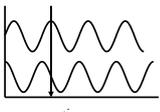
Presenting sounds over headphones enables independent control of binaural cues (and demonstrates sensitivity to IPDs *per se*)

*onset ITD and ongoing IPD*



time

*ongoing IPD only*



time

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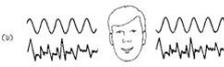
### The binaural masking level difference (BMLD)

Discovered independently by Licklider and Hirsh in 1948

Describes the ability to detect a signal in background noise when there are differences in interaural configurations of the signal and/or noise.

BMLDs for tones can be as much as 15 dB.

BMLDs are a low-frequency phenomenon (< ~1500 Hz) and rely on mechanisms contributing to ITD sensitivity



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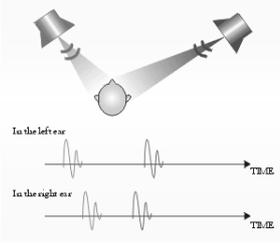
### The precedence effect – echo suppression

*(law of the first wavefront)*

**Summing Localisation:** < 1ms delay between the two sounds and the perception is of a fused sound image with a perceived location of the weighted sum of the two

**Precedence Effect:** 1-5 ms delay between the two sounds and only one sound is perceived with the location of the first sound

**Echo Threshold:** >5 ms delay and two sounds are heard




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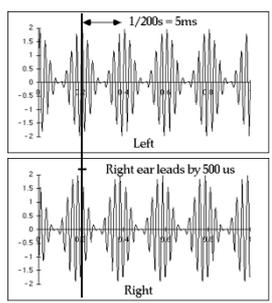
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### Sensitivity to high-frequency “envelope” ITDs

Modulating a high-frequency tone with a low-frequency modulation creates a modulated envelope

Sensitivity to ITDs between the envelopes of sounds was demonstrated by Henning (1974)

Thresholds for envelope ITDs are higher than for pure tones of the same frequency




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### Binaural Sluggishness

Although sensitivity to small ITDs is exquisite, sensitivity to moving sound sources, or changes in ITD, is “sluggish”

Binaural beats moving at > ~4 Hz are difficult to detect.

In fact, any change in the interaural signal that is faster than about 4 Hz is difficult to detect.

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### Neural Mechanisms of Binaural Hearing

binaural timing sensitivity requires monaural timing sensitivity

*IHCs show a.c. potentials at low-frequencies*

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### Temporal Sensitivity - Phase Locking

**A**

**B**

Number of spikes

Time

40 dB, 50 dB, 60 dB, 70 dB, 80 dB, 90 dB

**Movies**

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### Phase-locking is a low-frequency phenomenon

Phase-locking decreases as a function of sound frequency

*This means that information about the fine-time structure of a stimulus is lost at high-frequencies*

○ 25 ms duration  
+ long duration (Johnson, '80)

Joris et al., *J. Neurophysiol.*, vol 71, (1994), pp1022-1036

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### The Cochlear Nucleus

ANFs terminate in the cochlear nucleus (CN) of the brainstem

The diagram illustrates the cochlear nucleus (CN) and its components. Part A shows the CN's location in the brainstem, receiving input from the cochlear nerve (CN) via the vestibular cochlear nucleus (VCN). Part B shows the CN's internal structure, including the dorsal cochlear nucleus (DCN) and ventral cochlear nucleus (VCN), with ascending and descending bundles. Part C shows a detailed view of the VCN with various cell types: multipolar cells, spherical bushy cells (tuned to 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz), globular bushy cells, octopus cells, and pyramidal cells.

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### Spherical Bushy Cells

SBCs are the predominant neuron type in the AVCN

SBCs show primary-like responses (they respond like ANFs)

These synapses are responsible for maintaining the temporal processing capabilities of AVCN neurons

Figure A: Micrograph of a bushy cell with a labeled auditory nerve fiber and endbulb. Scale bar: 20 μm.

Figure B: Electrophysiological trace showing a prepotential and a spike. Scale bars: 20 mV, 1.0 ms.

Figure C: Delay plot showing the number of spikes (0 to 1000) versus delay (0 to 1.0 ms). The peak is at approximately 0.5 ms.

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### Physiological Basis of Binaural Hearing

The dichotomy between high- and low-frequency binaural hearing abilities is mirrored in an anatomical and physiological division

The ITD pathway (Interaural Time Difference) involves the AVCN (Auditory Vestibular Cochlear Nucleus) and MSO (Medial Superior Olive). The ILD pathway (Interaural Level Difference) involves the AVCN, MNTB (Medial Nucleus of the Trapezoidal Body), and LSO (Lateral Superior Olive). Both pathways receive input from the AN (Auditory Nerve) and COCHLEA. Excitatory connections are shown with solid arrows, and inhibitory connections with dashed arrows.

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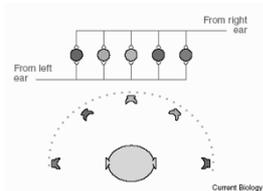
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Jeffress model of binaural coincidence detection

*ITD is the main cue used to localise the source of a sound*



Neural elements act as binaural coincidence detectors

Differences in conduction delay from each ear offset equal and opposite external ITDs

ITD is translated into a place code

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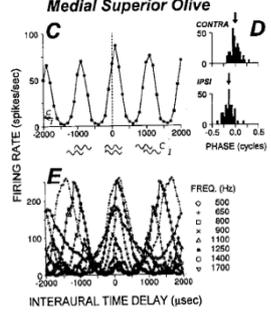
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**Binaural coincidence detection in mammals**

*Medial Superior Olive*



Yin and Chan, *J. Neurophysiol.*, vol 64, (1990), pp465-488

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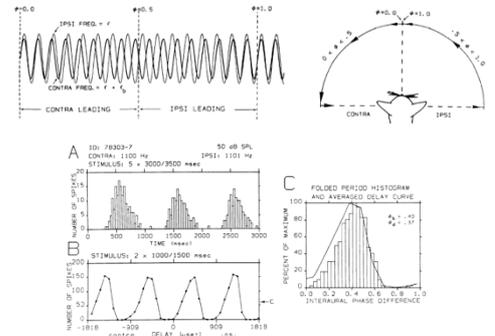
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**Sensitivity to interaural phase differences (IPDs)**



Yin and Kuwada, *J. Neurophysiol.*, vol 50, (1983), pp1000-1019

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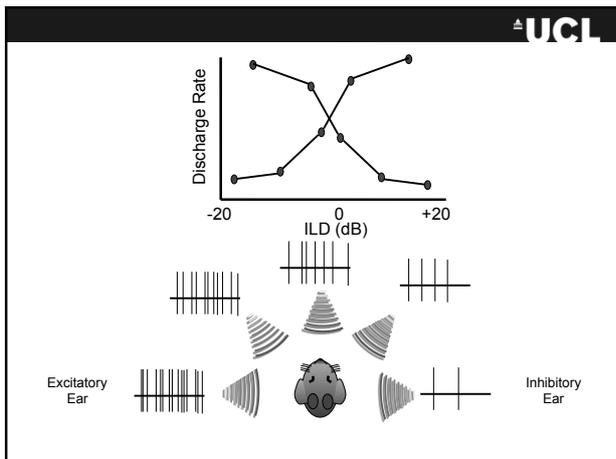
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