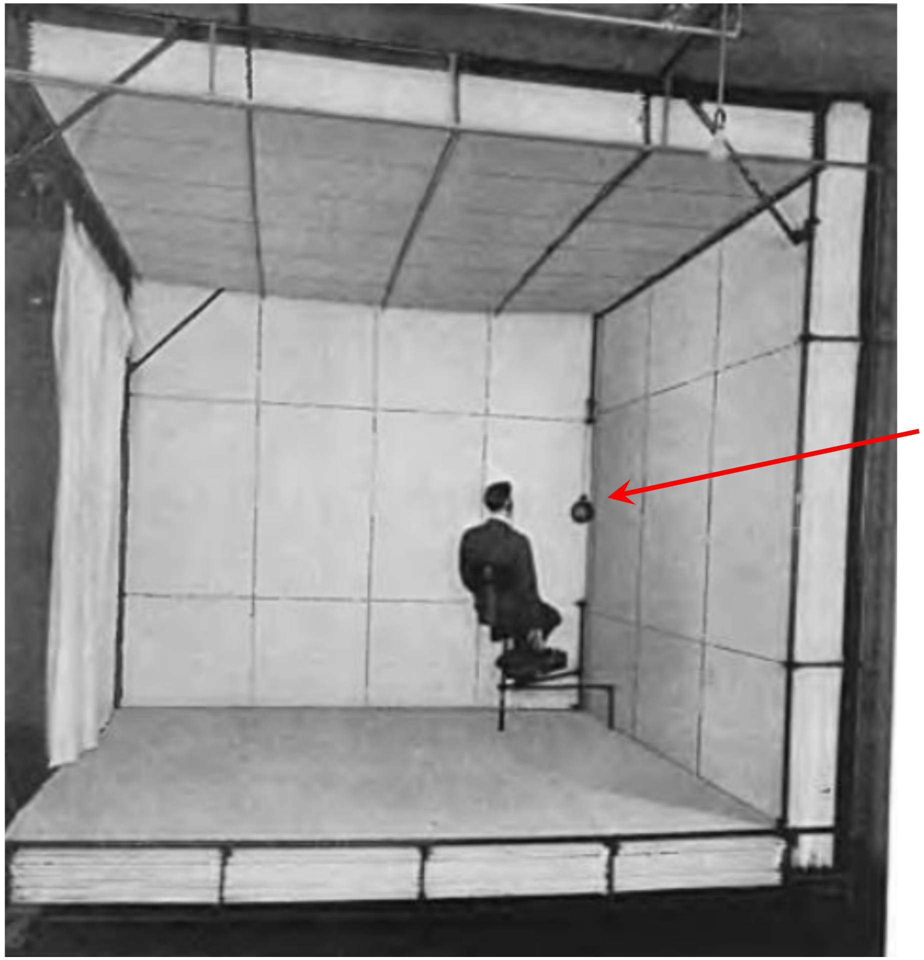
AUDL GS08/GAV1
Signals, systems, acoustics and the ear

Loudness &
Temporal resolution

Absolute thresholds & Loudness

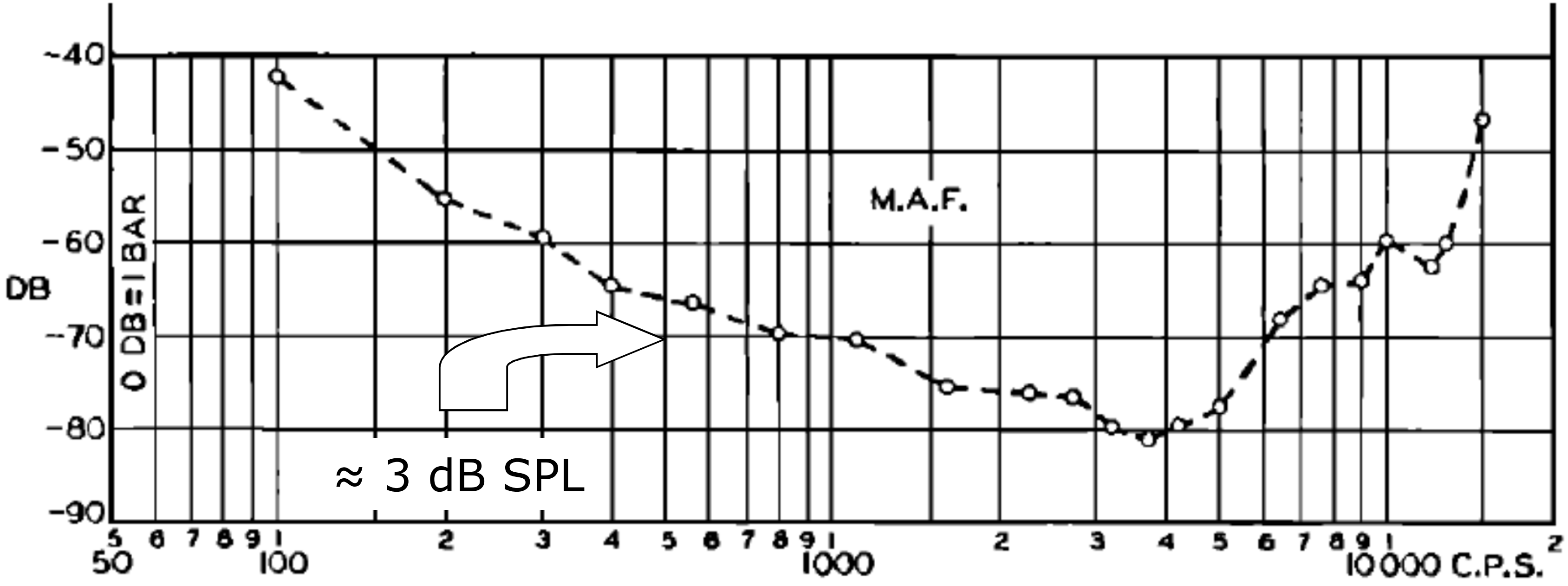
Name some ways these concepts are crucial to audiologists

Sivian & White (1933) JASA



sound source

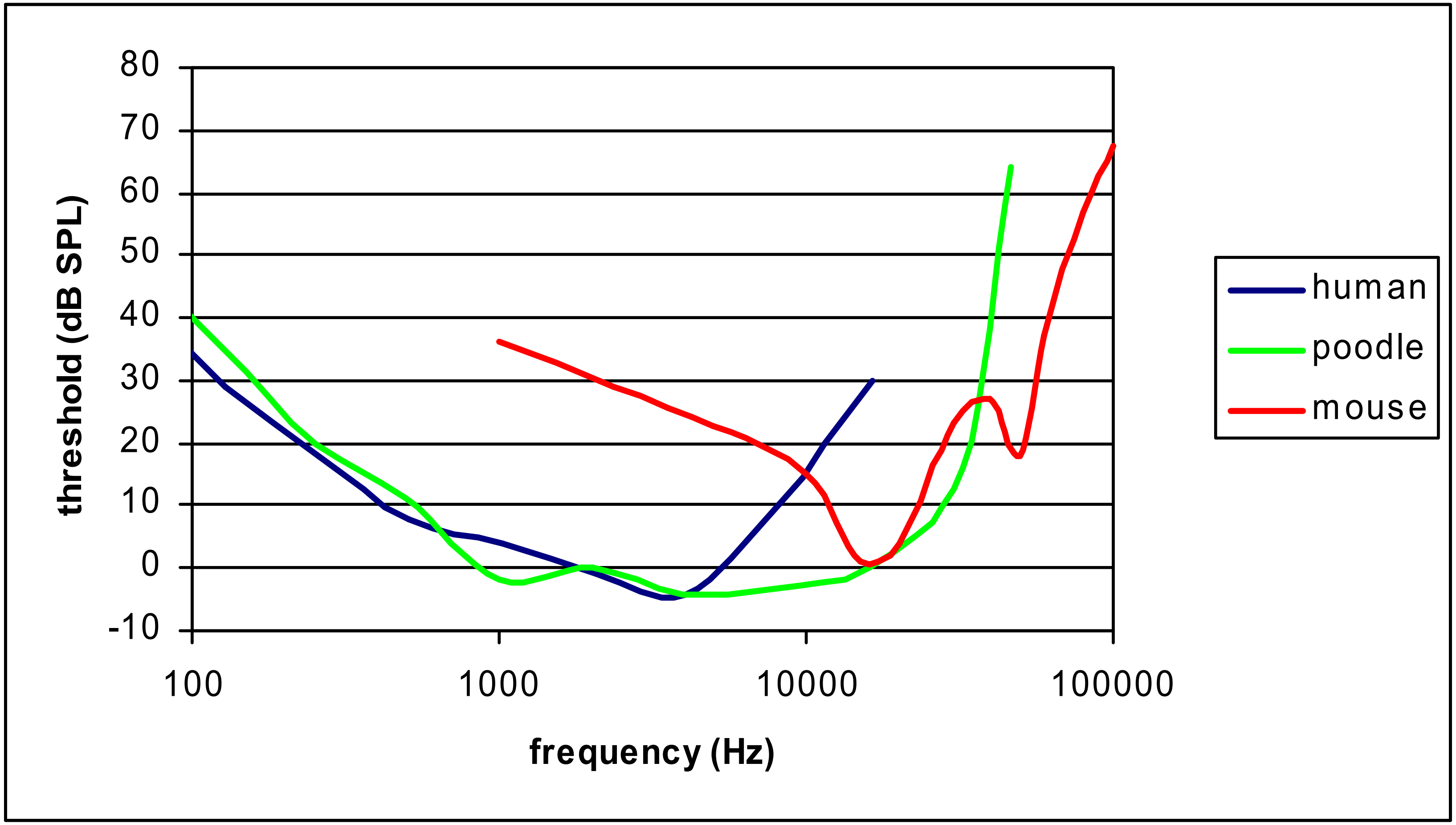
Sivian & White 1933



≈ 3 dB SPL

FIG. 3. *Monaural M.A.F., group A.*

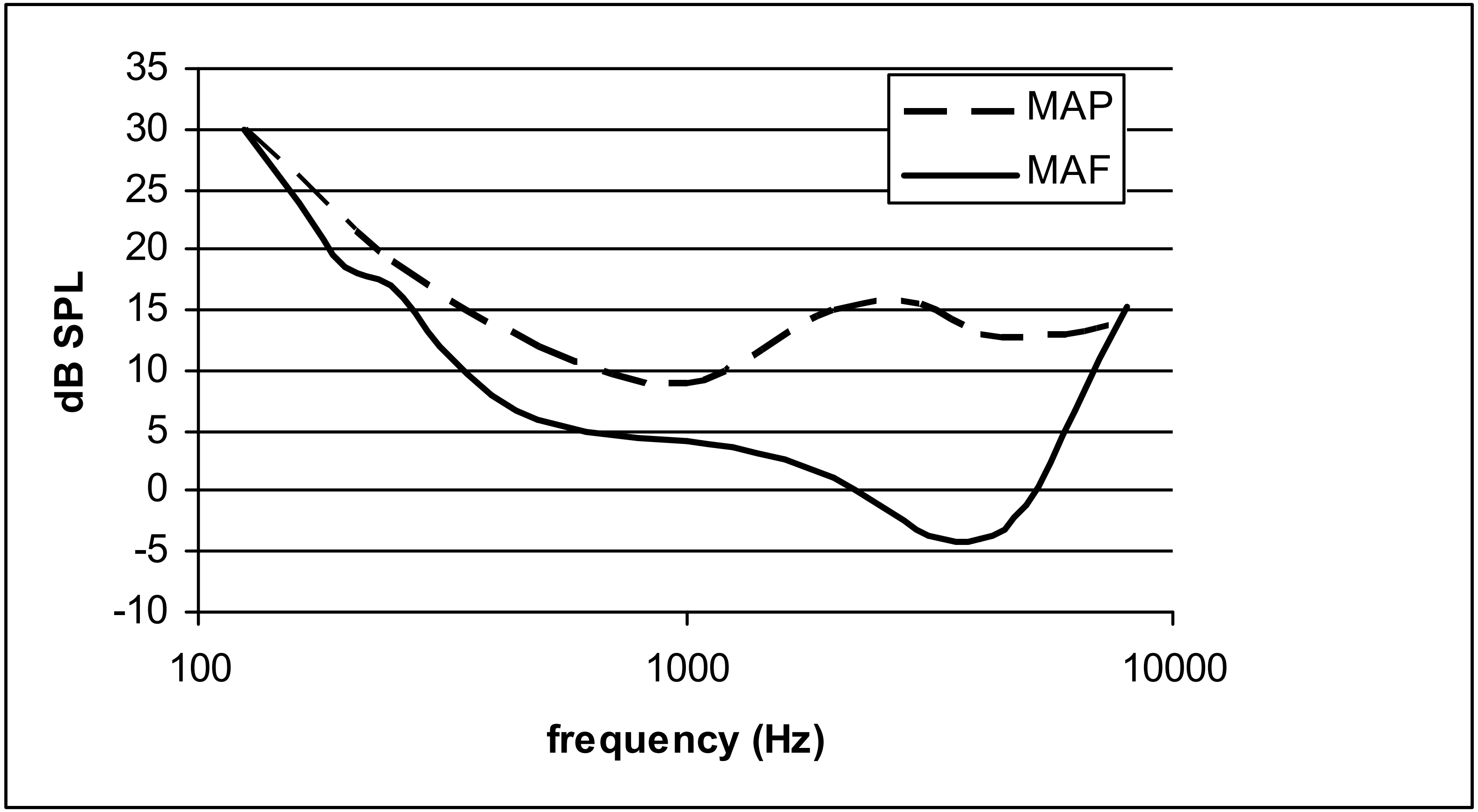
Thresholds for different mammals



Two ways to define a threshold once determined

- minimum audible field (MAF)
  - in terms of the intensity of the sound field in which the observer's head is placed
- minimum audible pressure (MAP)
  - in terms of the pressure amplitude at the observer's ear drum
  - often used with reference to headphones, and even more so, insert earphones
- MAF includes effect of head, pinna & ear canal

MAP vs. MAF
Accounting for the difference

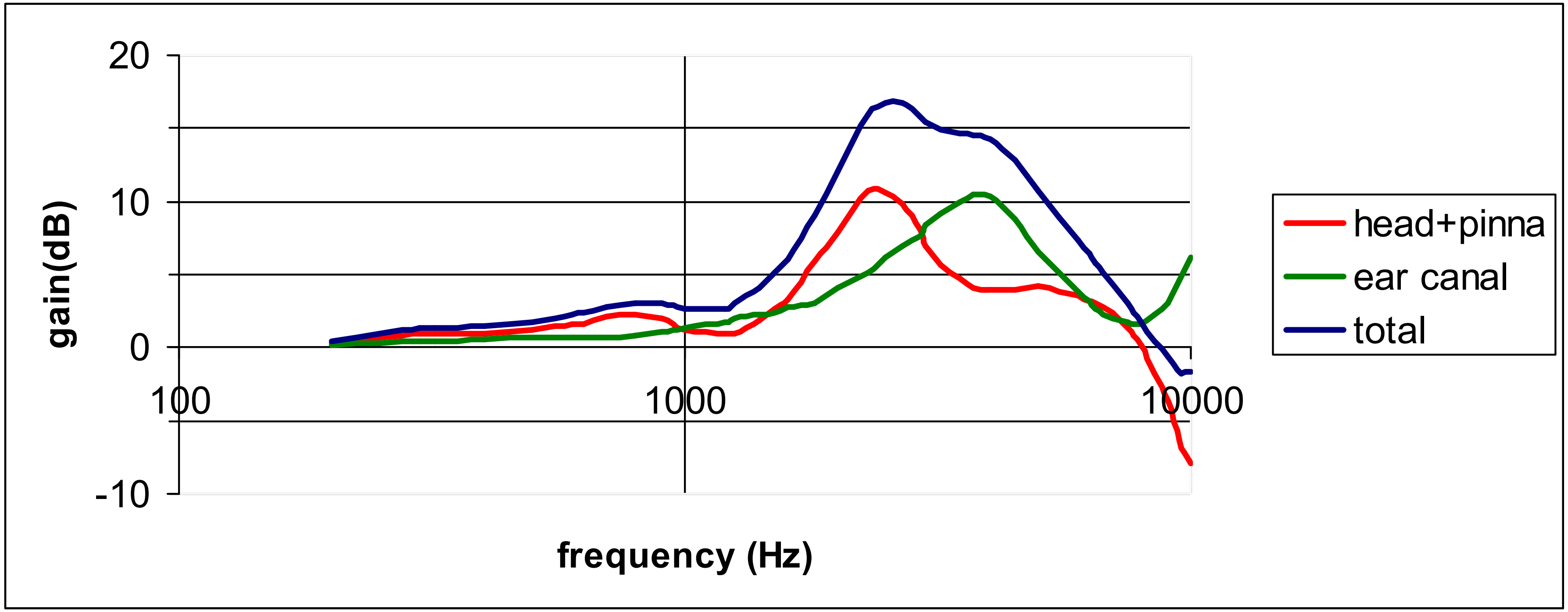


Frequency responses for:

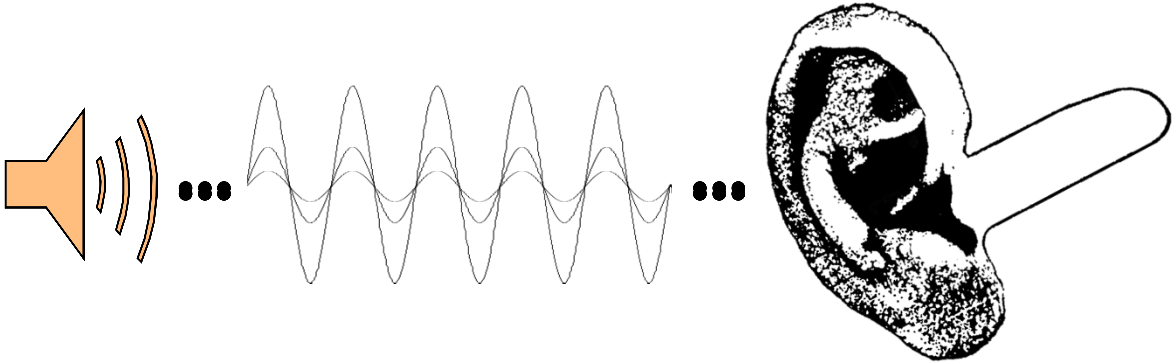
$$\frac{\text{ear-canal entrance}}{\text{free-field pressure}} \qquad \frac{\text{near the ear drum}}{\text{ear-canal entrance}}$$

Total Effect:

$$\frac{\text{near the ear drum}}{\text{free-field pressure}}$$

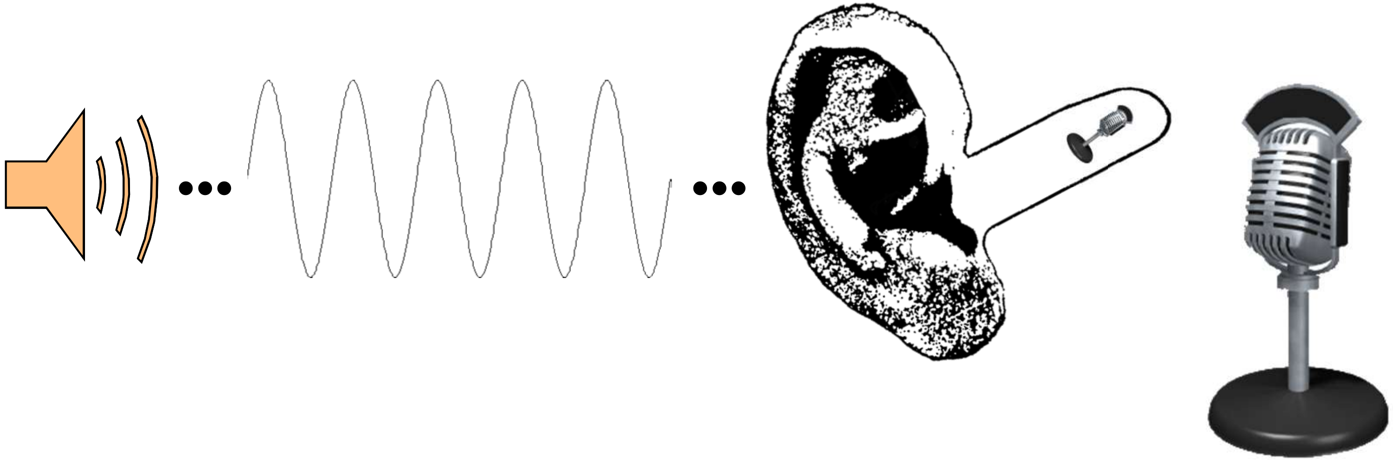


Determine a threshold for a 2-kHz sinusoid using a loudspeaker



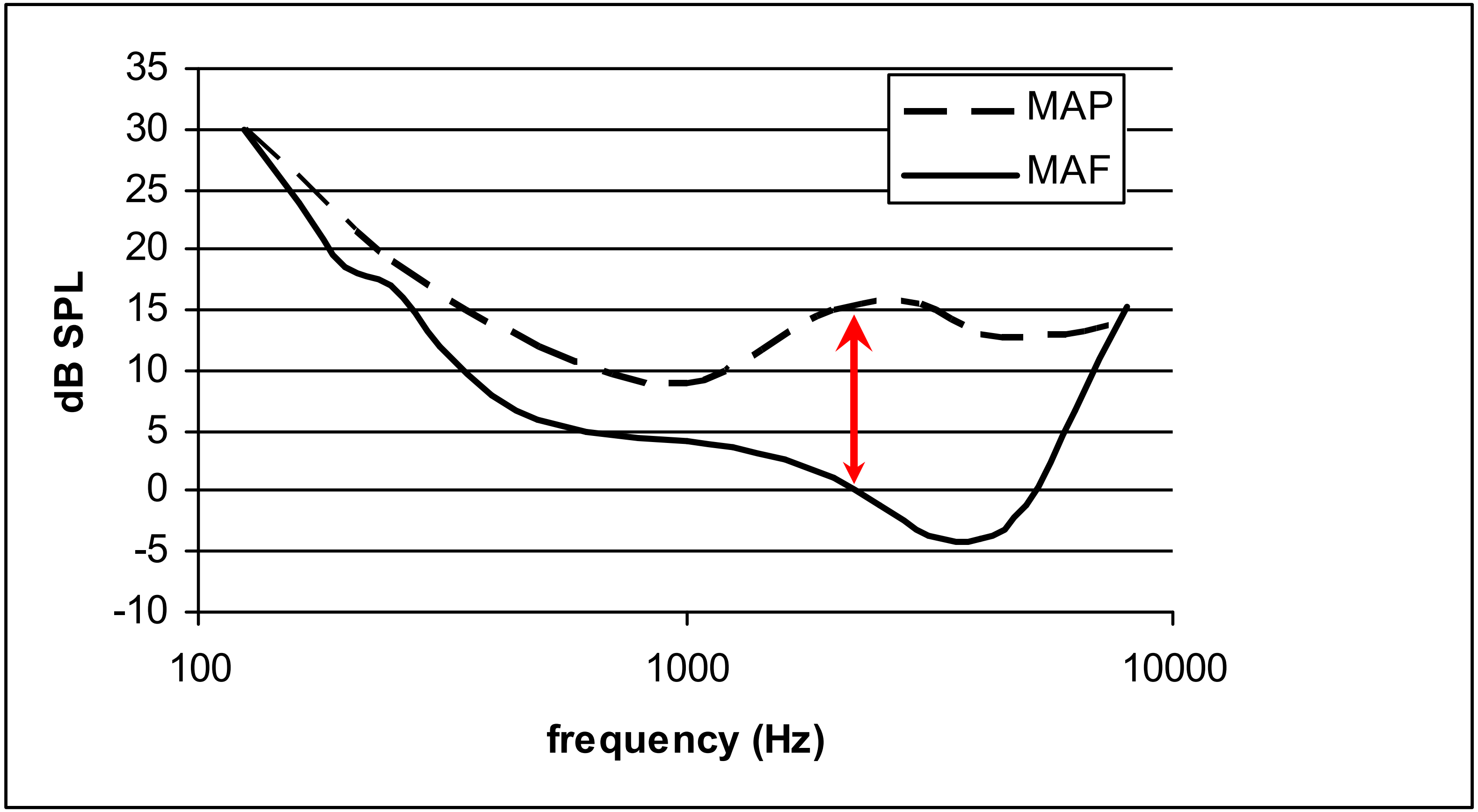
Now measure the sound level

at ear canal (MAP):
15 dB SPL



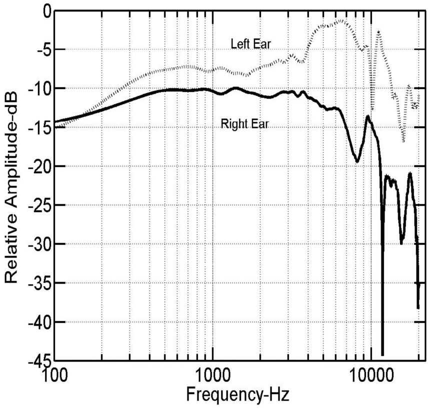
at head position without
head (MAF): 0 dB SPL

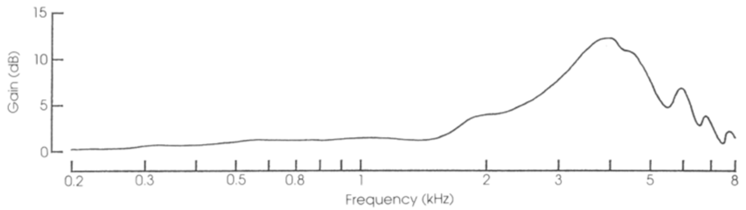
Accounting for MAP/MAF difference

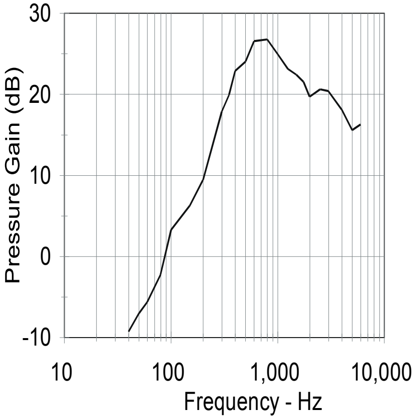


Accounting for the ‘bowl’

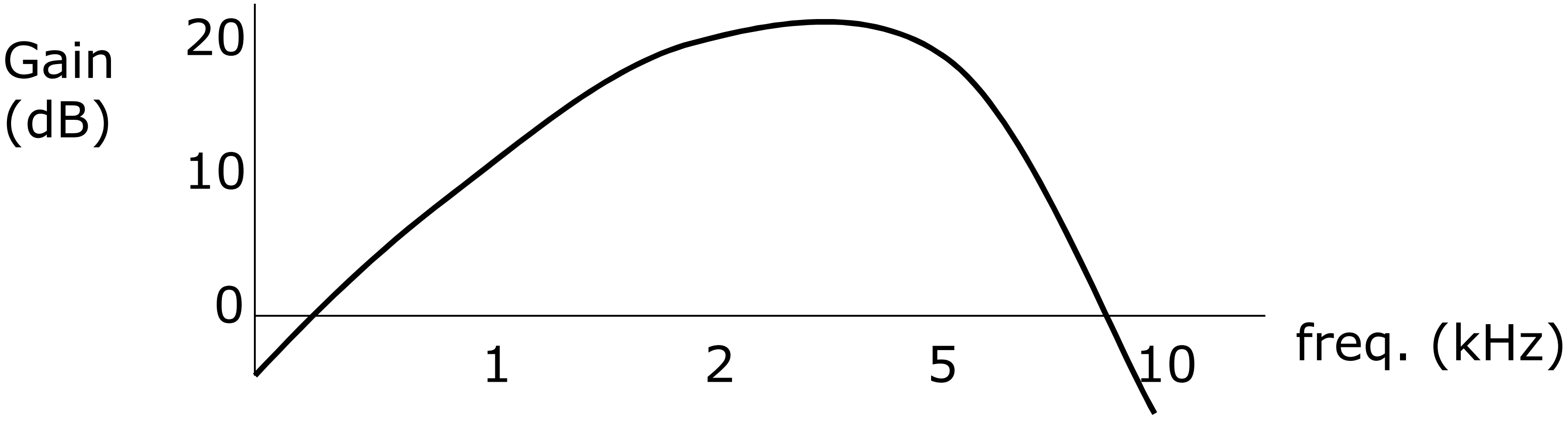
Combine head+pinna+canal+middle ear



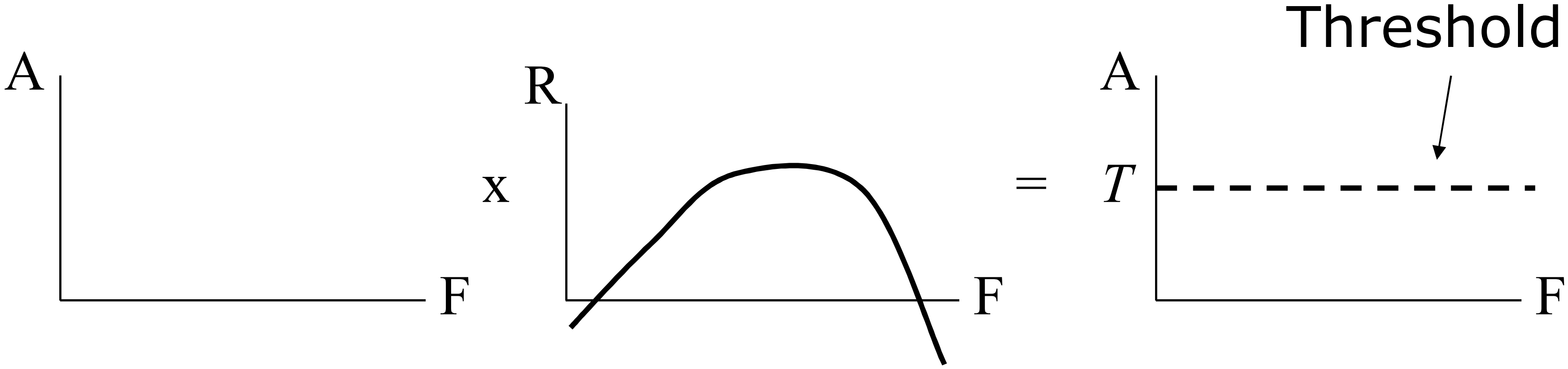




Overall

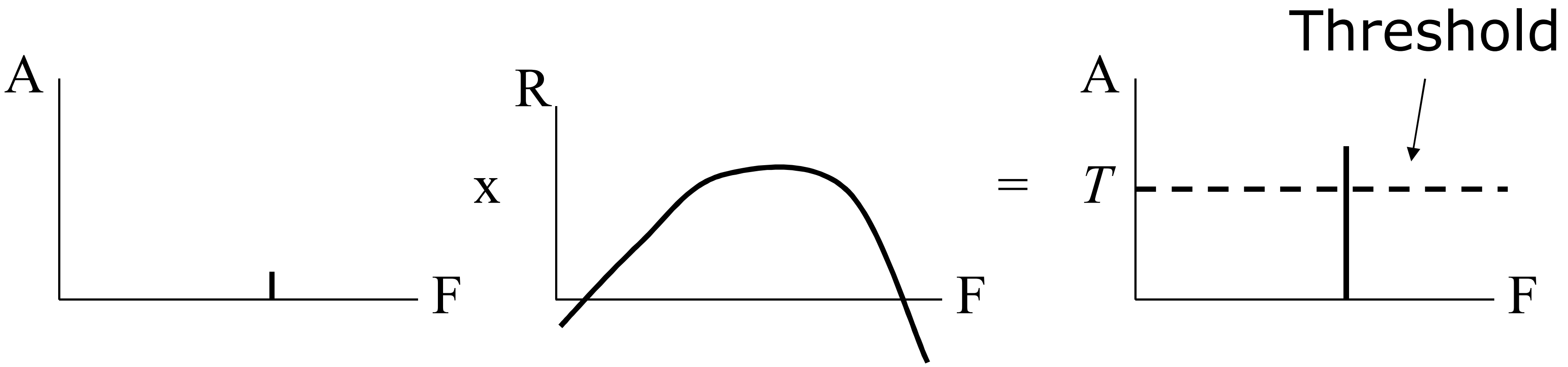


Detection of sinusoids in cochlea



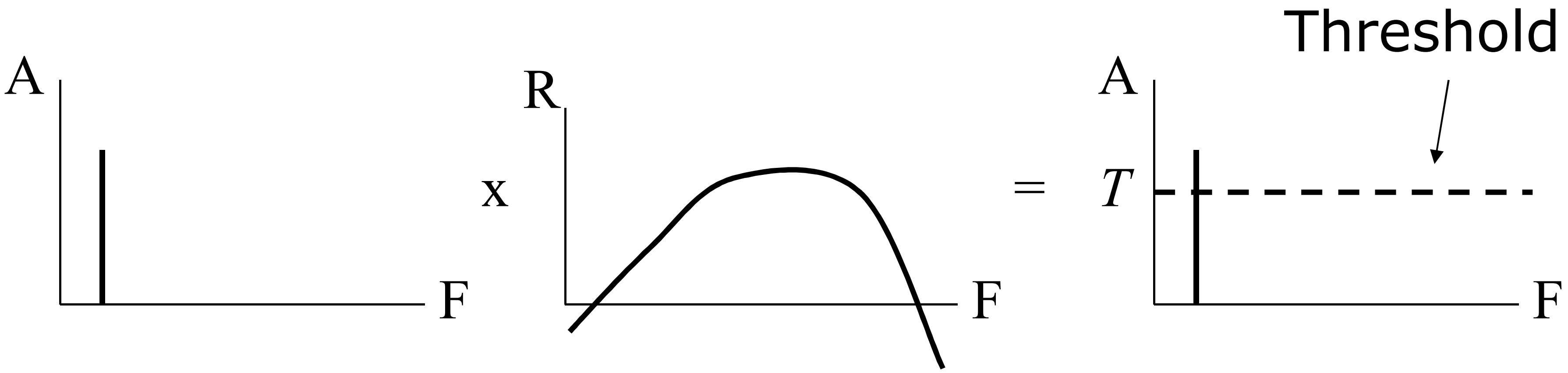
- How big a sinusoid do we have to put into our system for it to be detectable above some threshold?
- Main assumption: once cochlear pressure reaches a particular value, the basilar membrane moves sufficiently to make the nerves fire.

Detection of sinusoids in cochlea



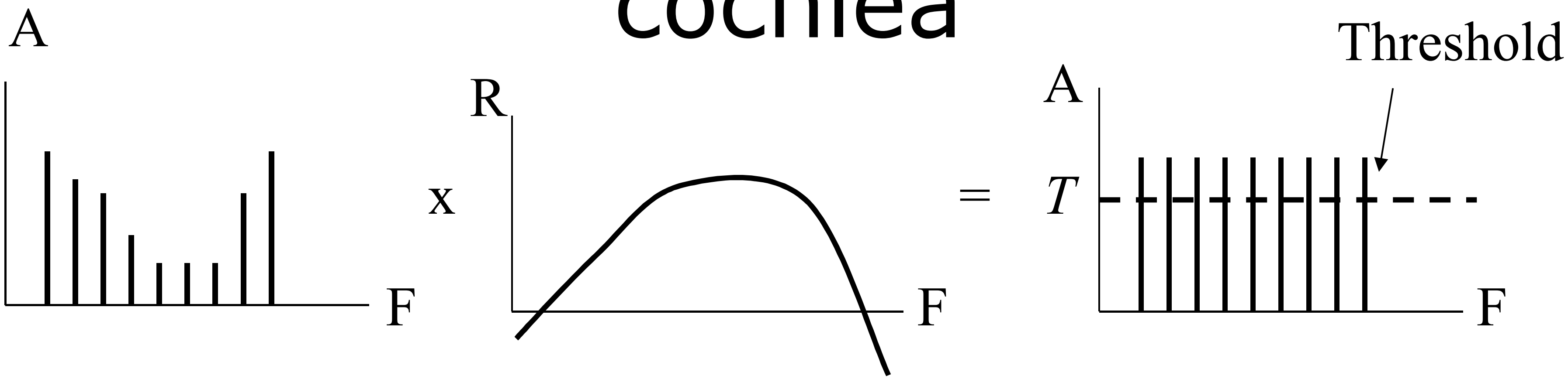
- A mid frequency sinusoid can be quite small because the outer and middle ears amplify the sound

Detection of sinusoids in cochlea



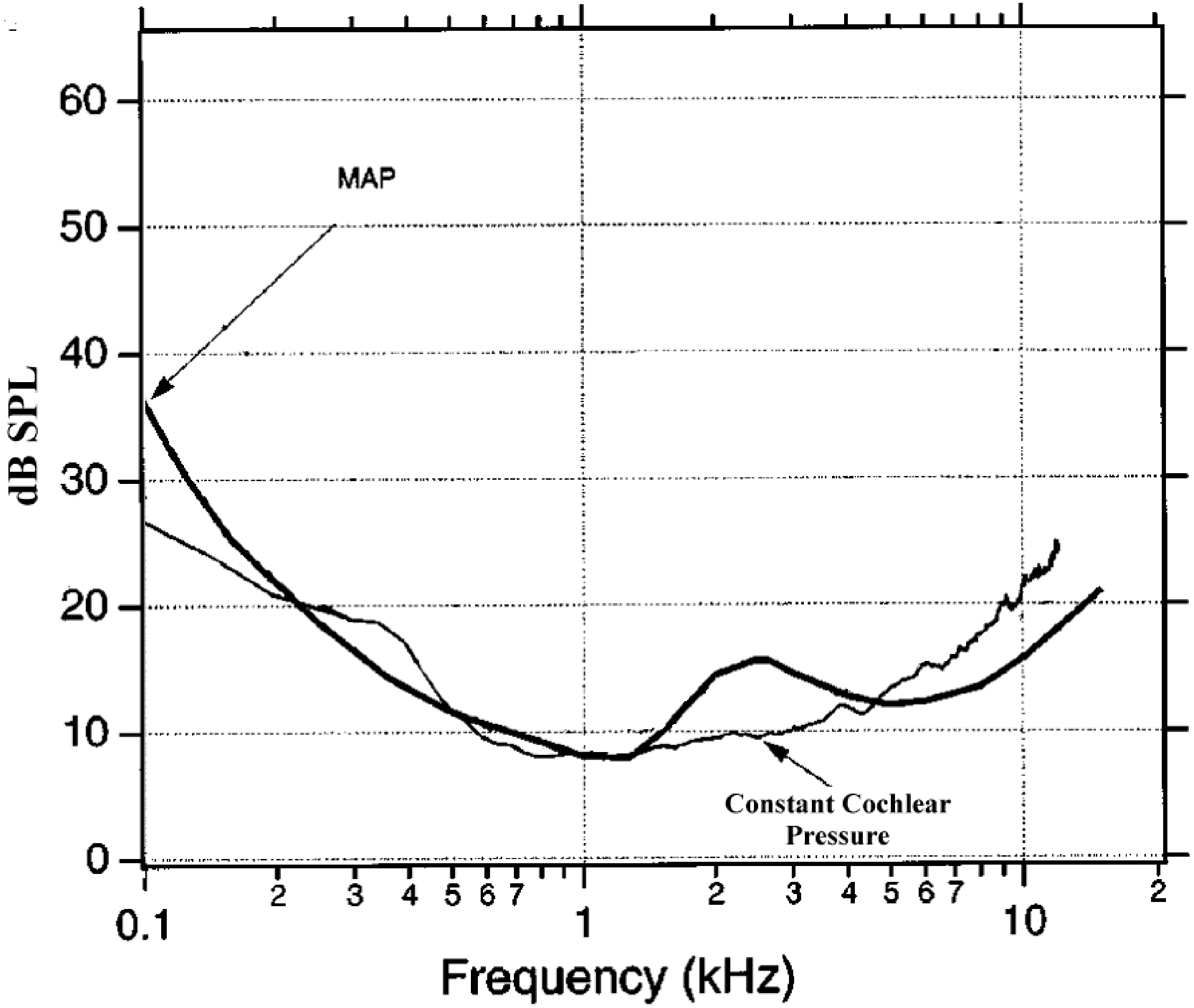
- A low frequency (or high frequency) sinusoid needs to be larger because the outer and middle ears do not amplify those frequencies so much

Detection of sinusoids in cochlea



- So, if the shape of the threshold curve is strongly affected by the efficiency of energy transfer into the cochlea …
- The threshold curve should look like this response turned upside-down: like a bowl.

Use MAP, and ignore contribution of head and ear canal



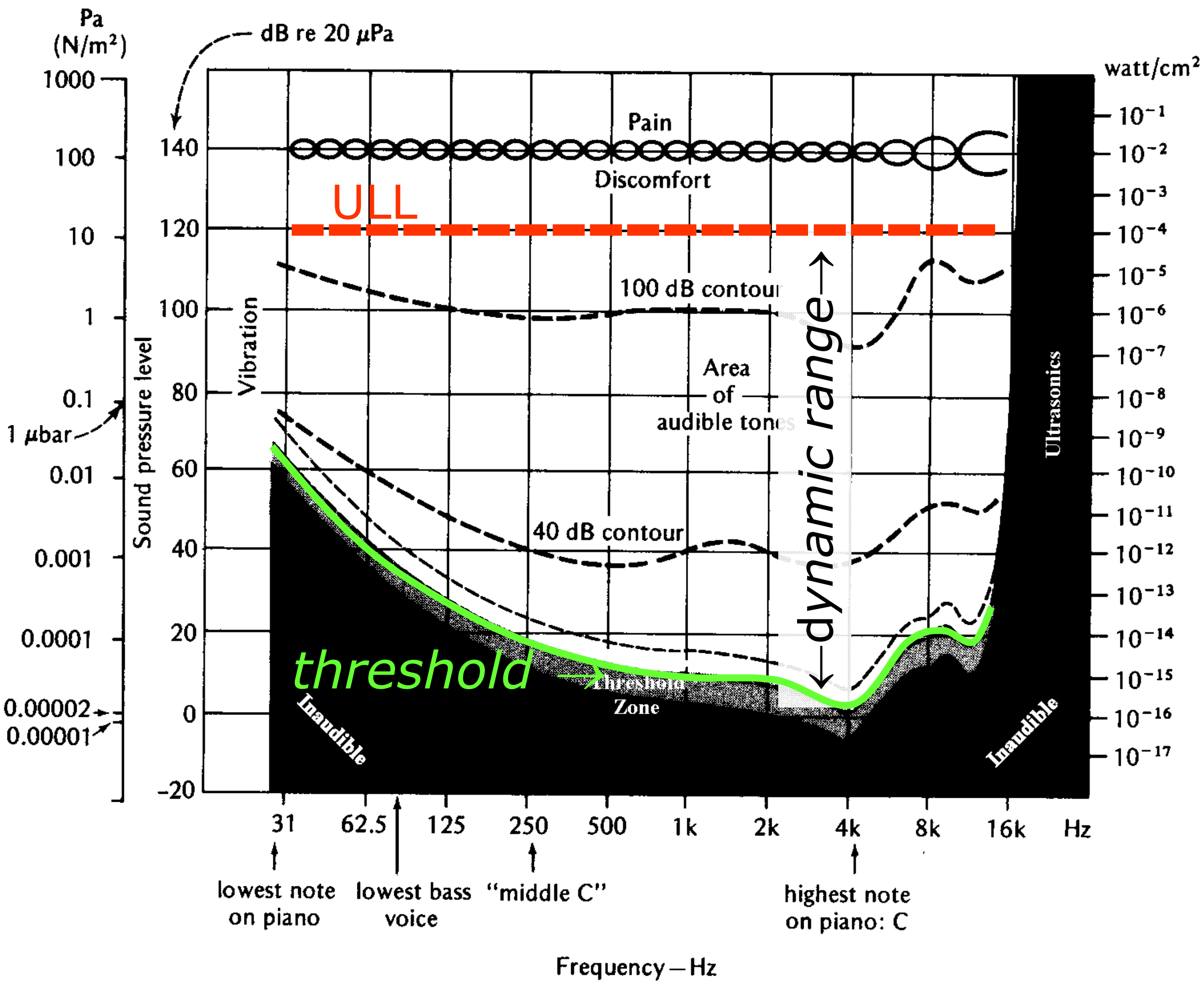
Much of the shape of the threshold curve can be accounted for by the efficiency of energy transfer into the cochlea

(from Puria, Peake & Rosowski, 1997)

What determines how loud a sound is?

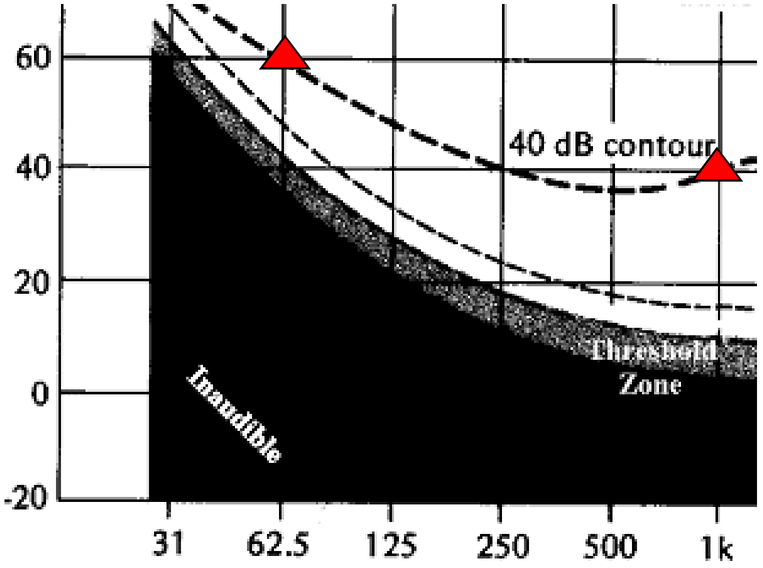
- Intensity, certainly but …
  - much else
- Duration
  - Temporal integration (up to ~ 250 ms)
- How intensity varies over time
- Context
  - Loudness adaptation (over seconds or mins)
- Frequency content
  - Sinusoids as a special case

Loudness of supra-threshold sinusoids



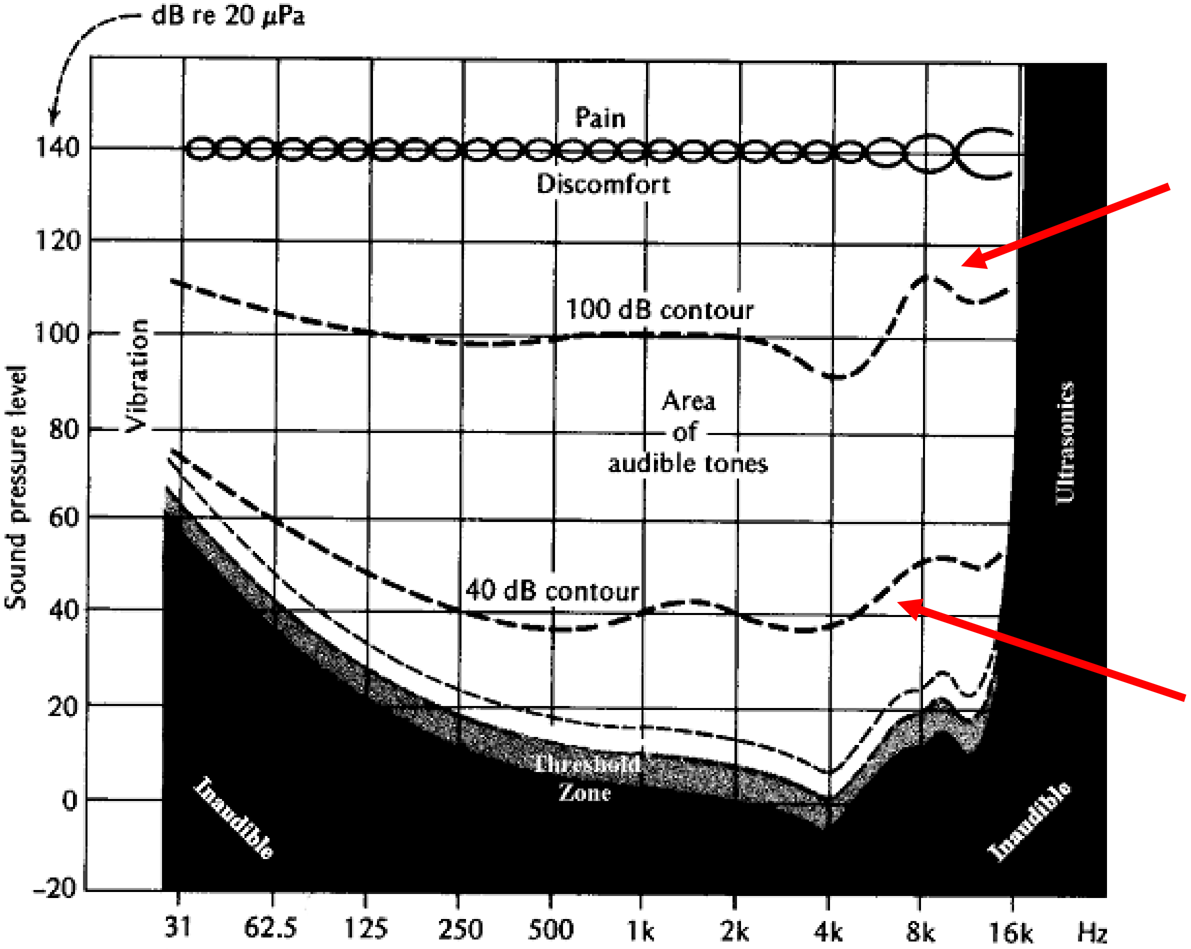
The Phon scale of loudness

- 'A sound has a loudness of *X* phons if it is equally as loud as a sinewave of *X* dB SPL at 1kHz'



e.g. A 62.5Hz sinusoid at 60dB SPL has a loudness of 40 phons, because it is equally as loud as a 40dB SPL sinusoid at 1kHz

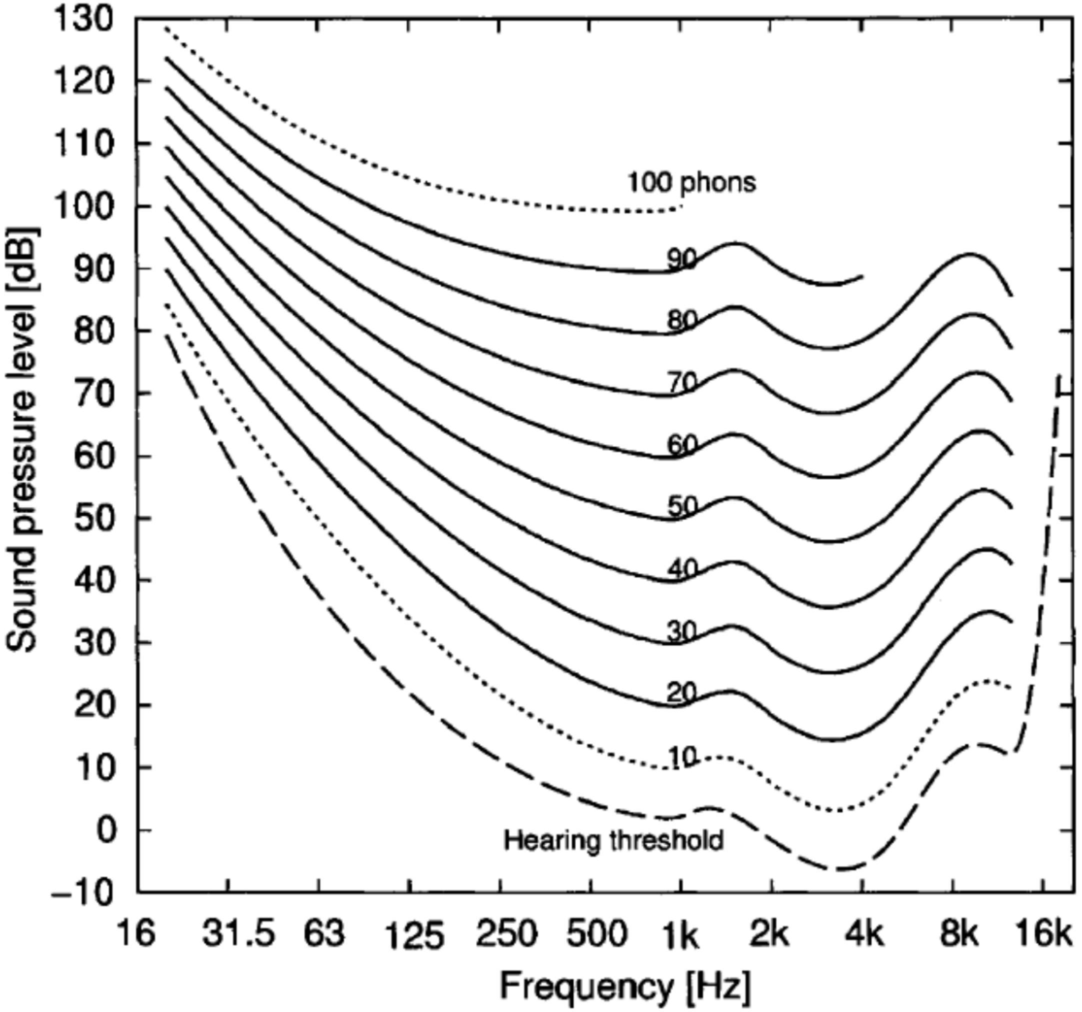
Equal loudness contours



Contour of tones equal in loudness to 100 dB SPL sinusoid @ 1kHz

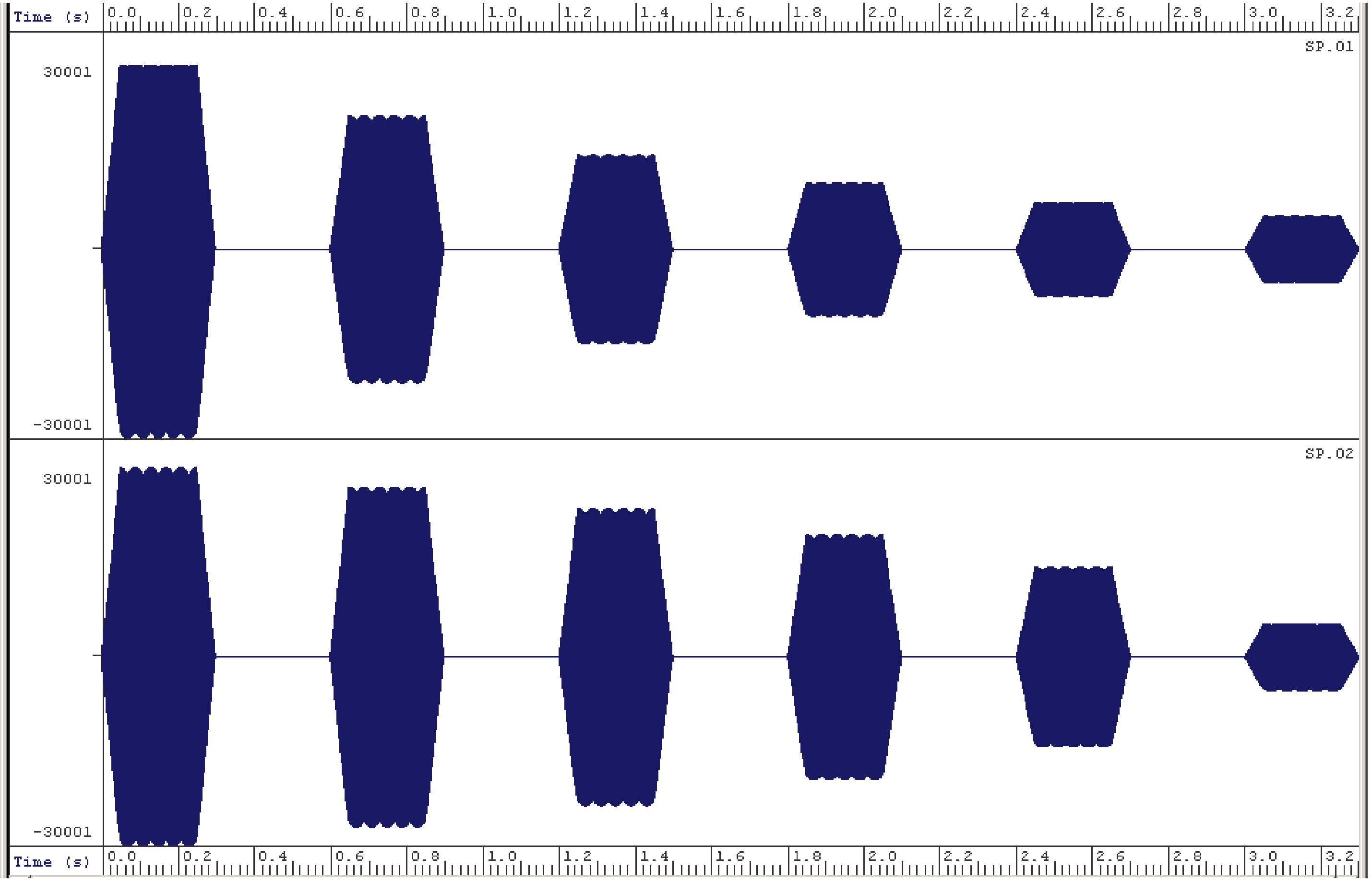
Contour of tones equal in loudness to 40 dB SPL sinusoid @ 1kHz

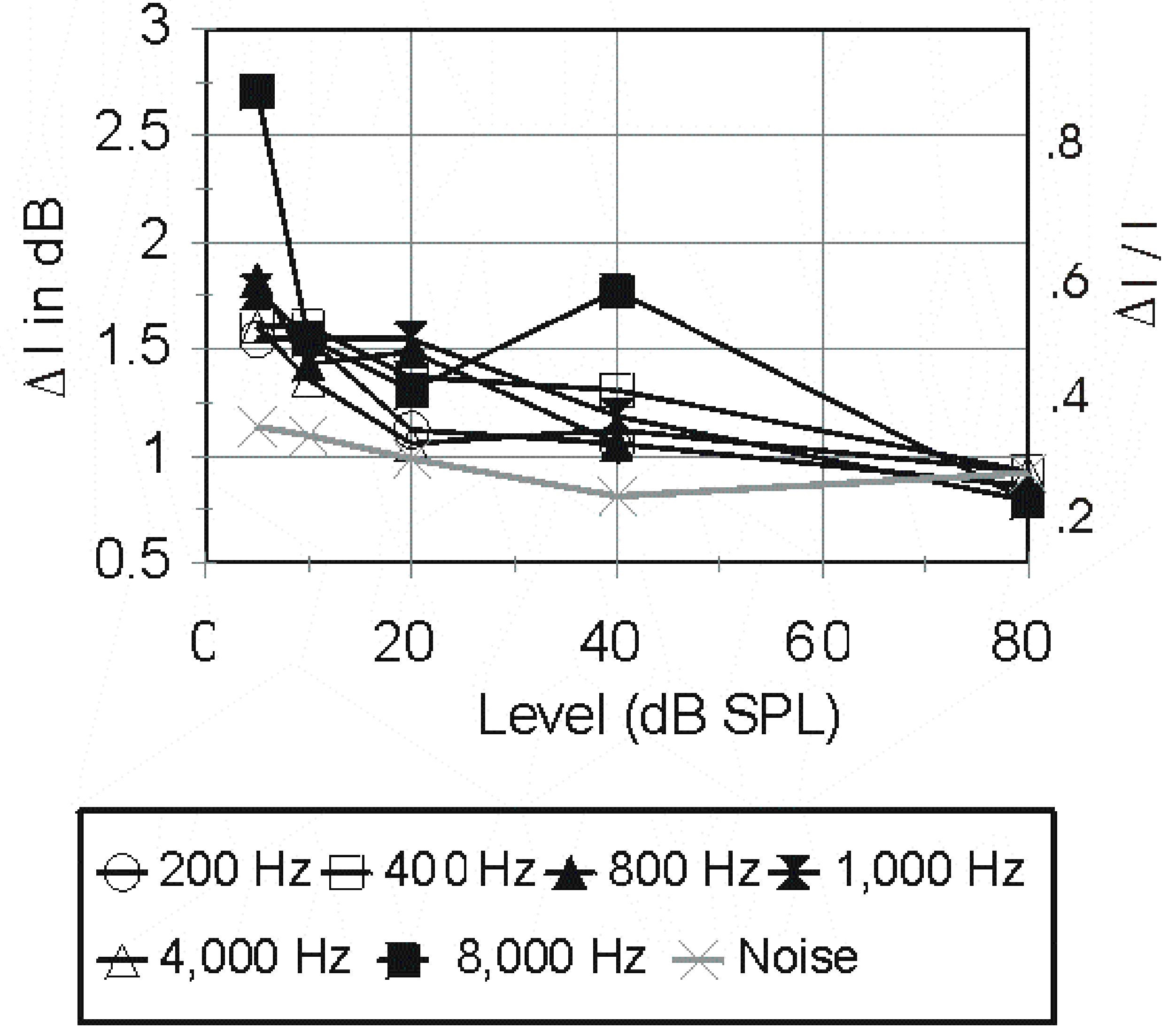
Contemporary equal loudness contours



From Suzuki & Takeshima (2004) JASA

Perceived loudness is (roughly) logarithmically related to pressure



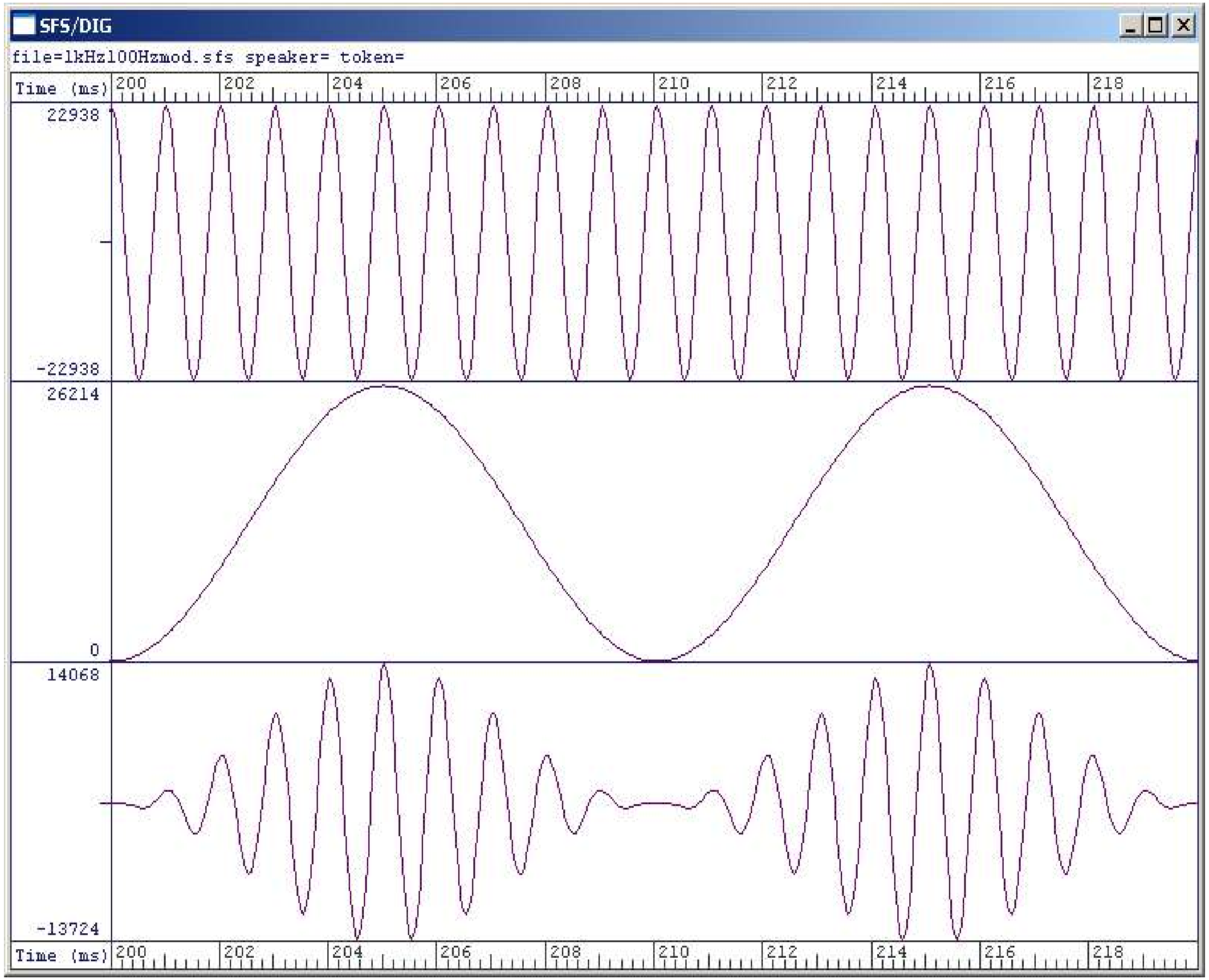


Just-noticeable differences (jnds) in intensity are roughly constant in dB

from Yost (2007)

Temporal resolution

Remember: Modulating a sinusoid



carrier at 1 kHz

(temporal fine structure)

x

modulator at 100 Hz

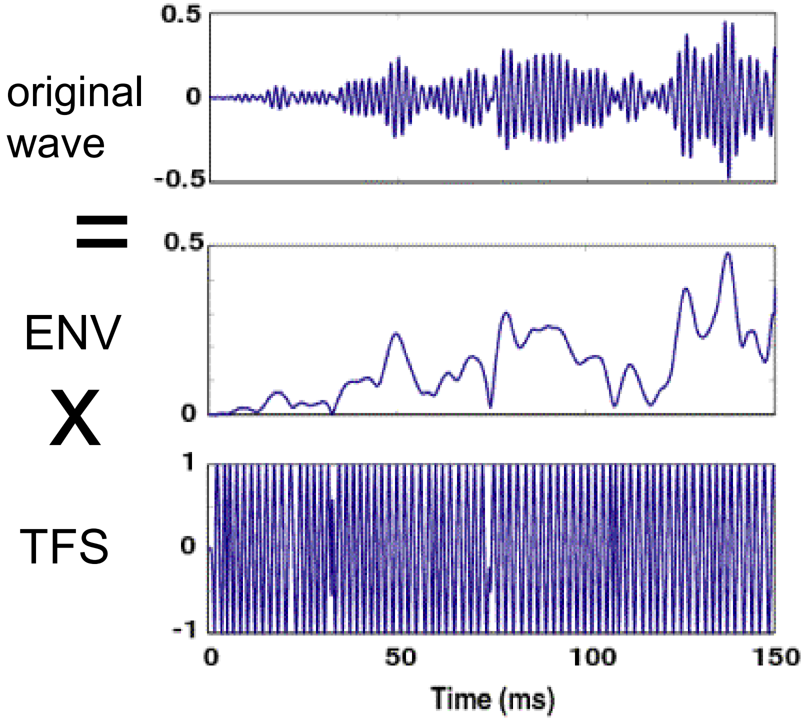
(envelope)

=

amplitude-modulated wave

Remember: *Envelope* (ENV) & *Temporal Fine Structure* (TFS)

- Any wave can be a product of an envelope multiplied by a carrier
- TFS – fast – reflects spectral components of sounds in the sound waveform
- ENV is the slower stuff



Temporal resolution …

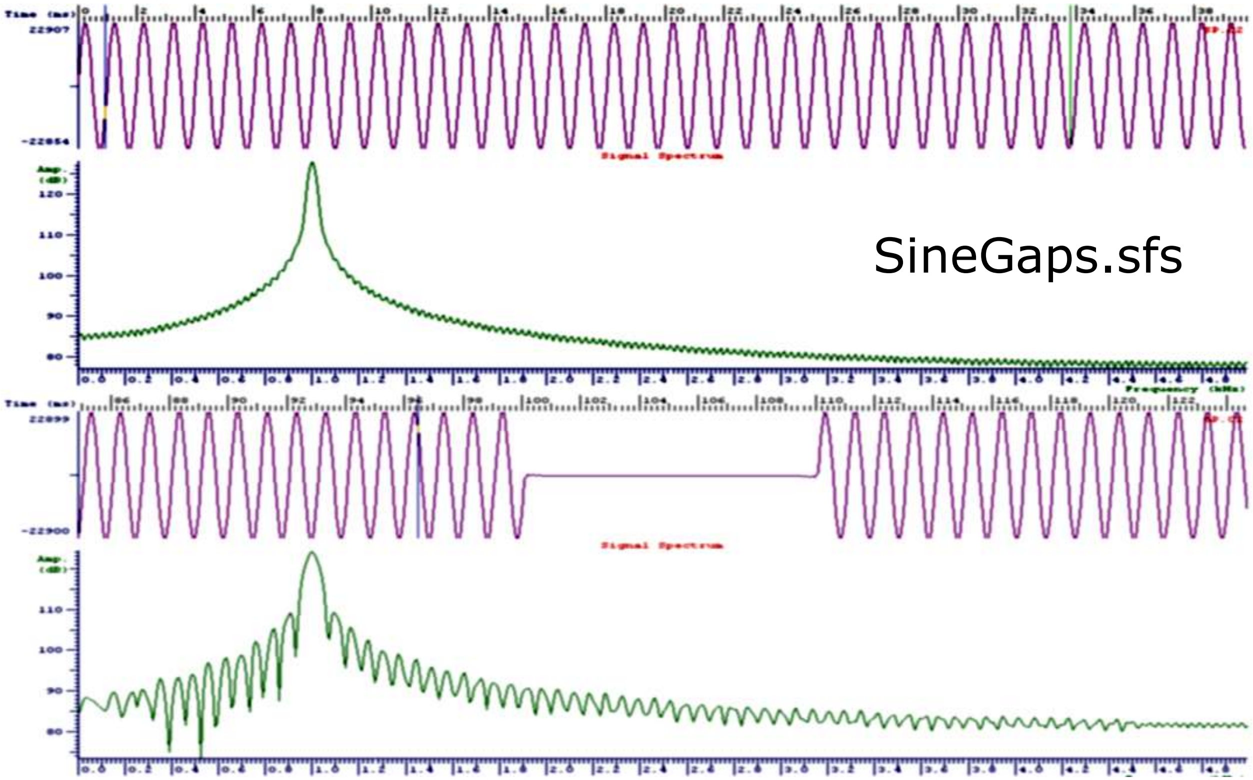
- Typically defined as reflecting perception of variations over time in …
  - *envelope*
  - rather than *fine-structure*
- But could concern temporal variations, for example, in:
  - frequency of a sinusoid
    - heard as changes in pitch
  - ITD
    - heard as changes in location
  - others?

Temporal Resolution for envelope most often tested in two ways

- Both involve *modulation* of the amplitude of waveforms …
  - Gap detection
  - Amplitude modulation
- but this almost always results in spectral changes.
- In other words, you usually cannot change the temporal (envelope) properties of a signal without also changing its spectrum
  - leading to a difficulty of interpretation unless special measures are taken

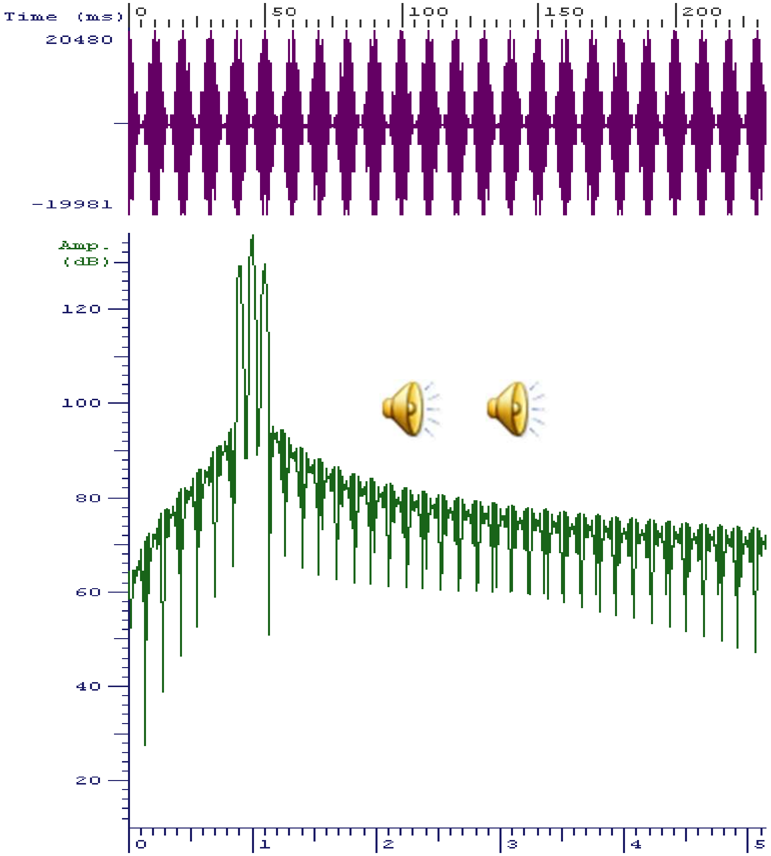
The need to eliminate spectral cues

- Modulating signals in envelope usually results in spectral changes (broadening, known as *splatter*)
  - e.g., effect of 10 ms gap in spectrum of 1 kHz sinusoid
- Need to avoid listeners hearing spectral changes



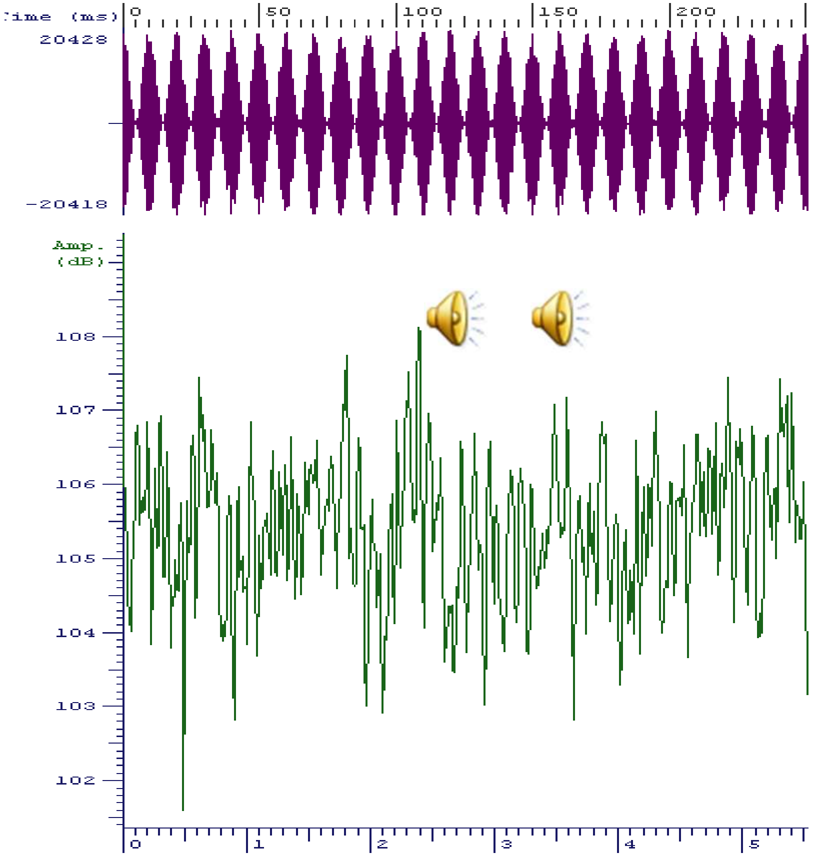
SineGaps.sfs

Effects of AM on spectrum



100 Hz AM of 1 kHz sinusoid

Spectral sidebands at 900 and 1100 Hz



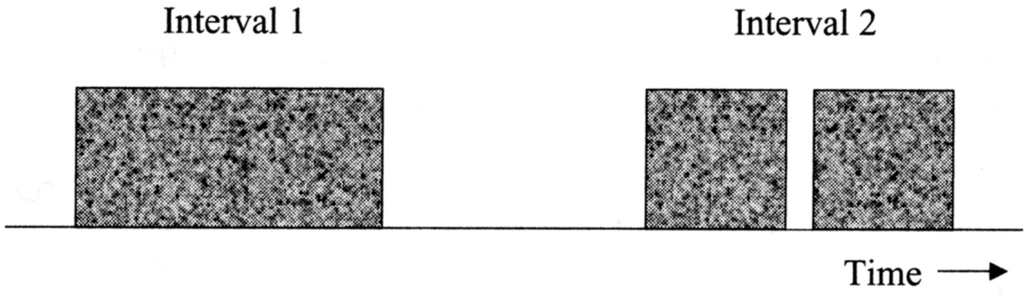
100 Hz AM white noise

Spectrum remains flat

Three possibilities

- Modulate wideband noise stimuli
- Minimise audibility of spectral changes by
  - keeping any sidebands in the same auditory filter as the original signal – allows use of low AM rates with sine carriers
  - and/or adding masking noise to make spectral changes inaudible
- Modulate wideband noise stimuli and filter into bands afterwards
  - but can change extent/form of modulation

Gap thresholds



- Pick the sound with the gap – vary the gap duration to find threshold
- Thresholds for wide-band noise are around 3 ms

Effects of noise spectrum on gap detection

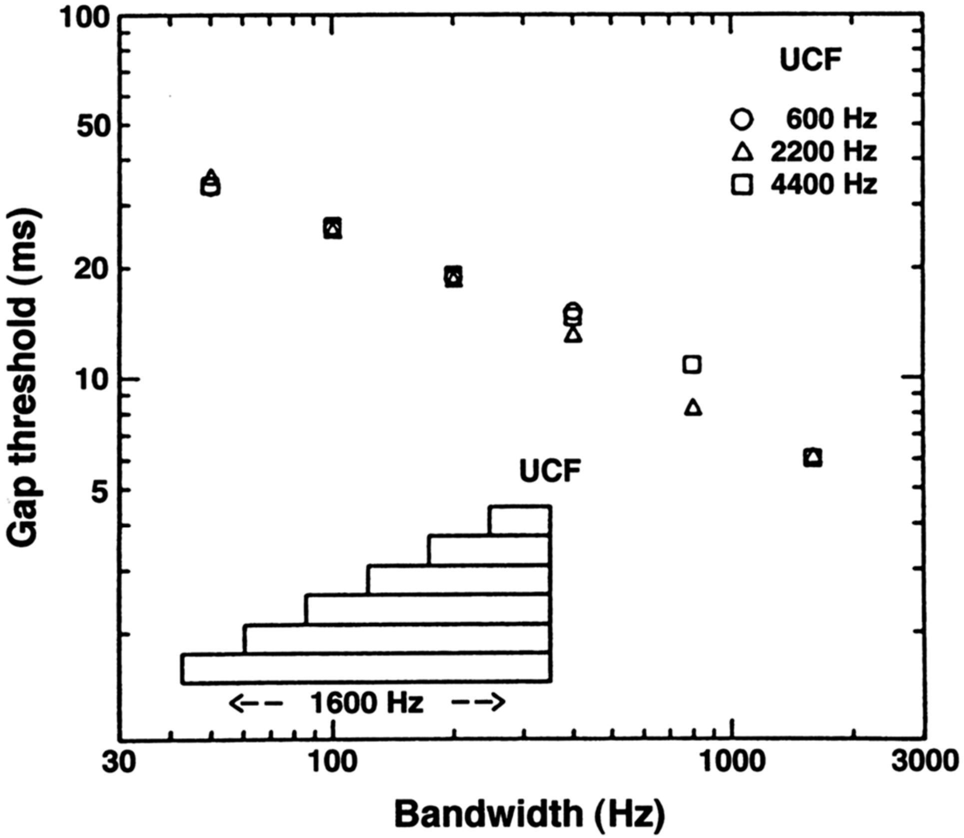


FIGURE 5.4 Gap thresholds for noise bands plotted as a function of the bandwidth of the noise bands. The upper cutoff frequency (UCF) of the noise bands was fixed at one of three values: 600, 2200, and 4400 Hz. The inset bars illustrate schematically how the bandwidth was varied keeping the UCF fixed. Gap thresholds decrease progressively with increasing bandwidth, but are almost independent of UCF. The data are from Eddins *et al.* (1992).

Wider noise bandwidth gives smaller gap thresholds

Upper Cutoff Frequency (spectral location) has little effect

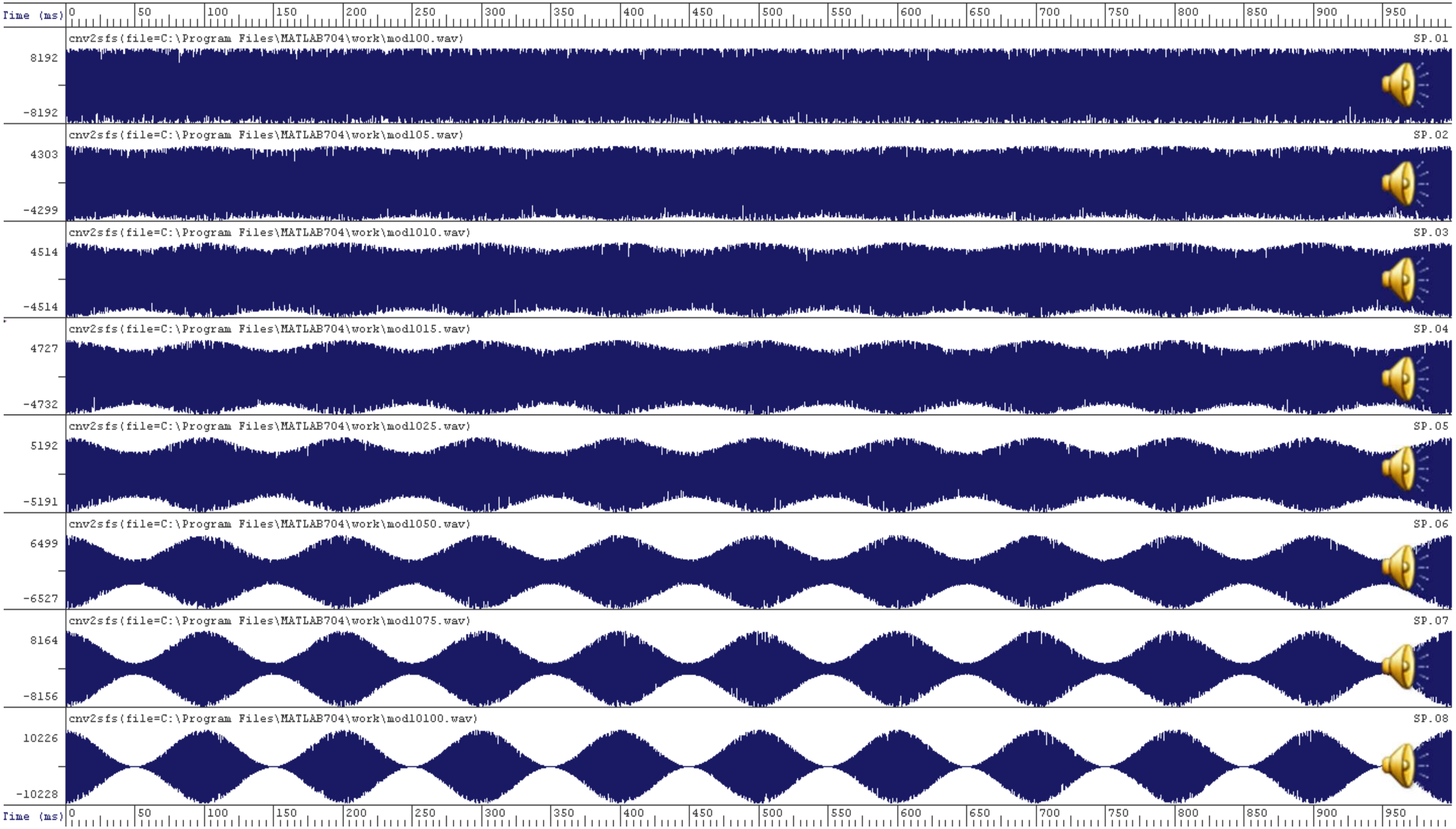
Perhaps wider bandwidths allows listeners to ‘listen to’ larger numbers of filter channels

Important in interpreting gap detection from listeners with high frequency hearing loss

AM detection - TMTF

- TMTF – temporal modulation transfer function
- Analogous to an ordinary transfer function or frequency response
  - dealing with frequencies of *modulation* rather than frequencies of a sinusoidal waveform directly
- Analytic approach to temporal resolution
  - Considers temporal modulation across different single frequencies of sinusoidal AM
    - cf gap detection where in effect the modulator is a pulse comprising wide range of modulation frequencies
  - As for gap thresholds, wide-band noise is an ideal signal because of the lack of spectral changes.
  - Fixed modulation rate – vary depth of modulation to determine minimum detectable depth

10 Hz modulation rate



m = 0

0.05

0.10

0.15

0.25

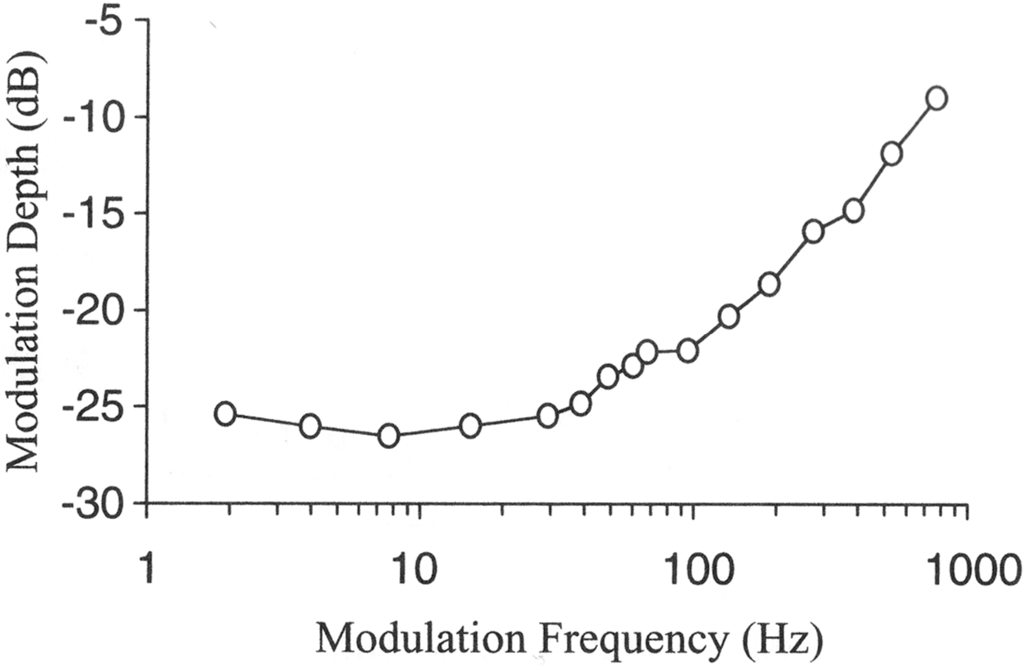
0.50

0.75

m = 1

TMTF data

- Thresholds expressed in dB as 20 log(m) where m is modulation index



m = 1 gives 0 dB (modulation depth = carrier amplitude)

m = 0.05 gives -26 dB

The function looks very much like a low-pass filter (here inverted)

Upper limit of amplitude modulation detection between 500 and 1000 Hz

Amplitude Modulation Detection

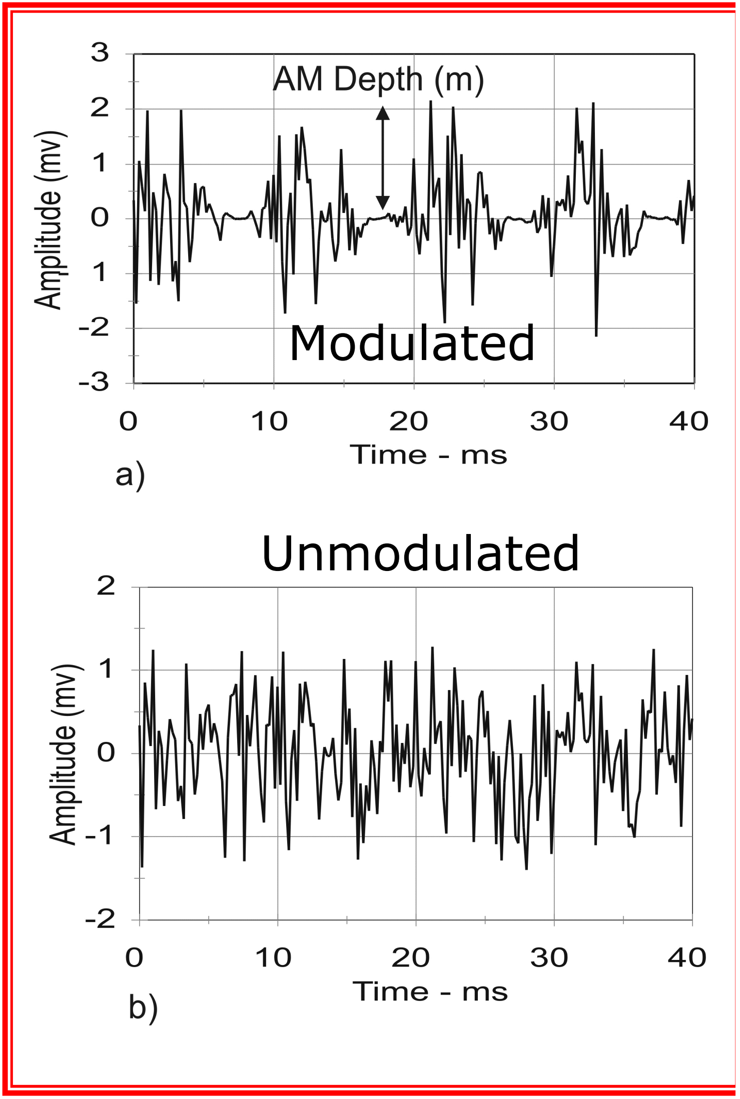
Four sets of amplitude modulated noises each of 500-msec duration with modulation rates of 4, 16, 64, and 256 Hz

For each set: ten comparisons of an unmodulated noise followed by the amplitude modulated noise

The depth of modulation starts at 50% or 20log(m) = -6 dB and decreases in 5% steps ending at 5%.

Count how many of the ten pairs have a noticeable modulation compared to the 1st unmodulated noise

4 Hz **16 Hz** **64 Hz** **256 Hz**



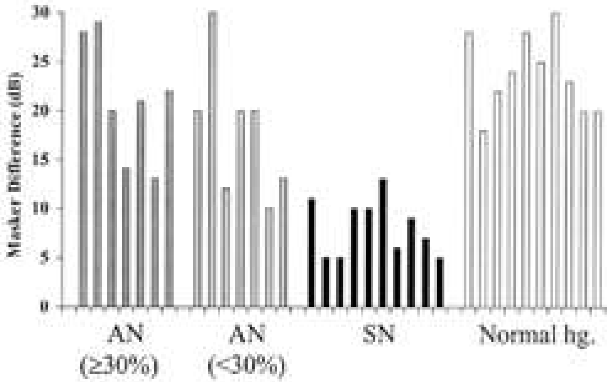
Translating to the clinic: Auditory Neuropathy Spectrum Disorder (ANSD)

Temporal resolution in ANSD

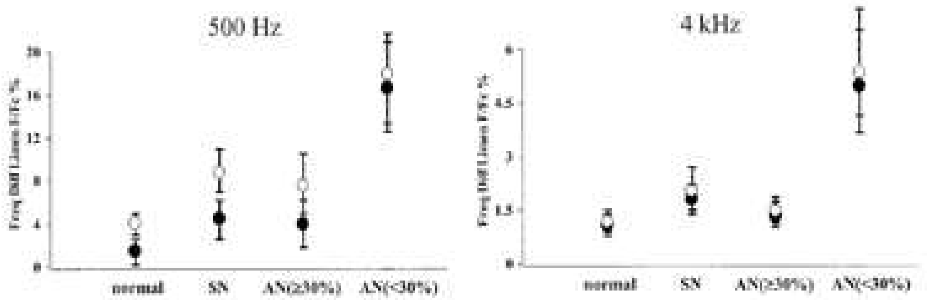
- ANSD: normal OAEs but lack of CAP and ABR responses.
- Sometimes near normal audiometric thresholds but often severe problems with speech perception, out of line with hearing loss in PTA
- Locus of impairment unclear
  - not like SNHL
  - probably not involving OHCs
- Likely involves disruption of phase-locking in auditory nerve

Rance, McKay and Grayden, 2004 (Ear & Hearing)

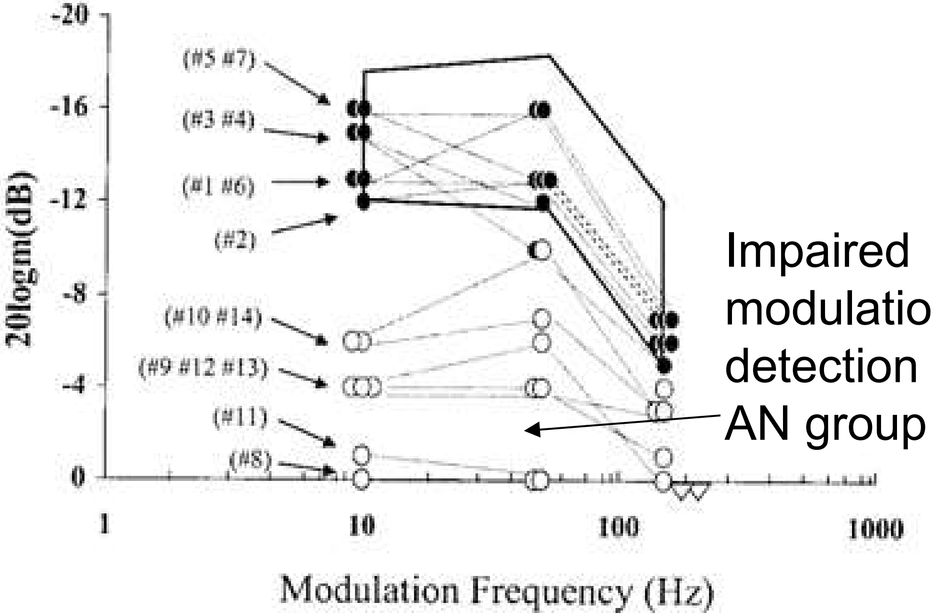
- Compared children with normal hearing, SNHL, and ANSD
- Measured
  - Frequency selectivity (simple notched noise method)
  - Sinusoid frequency discrimination
  - TMTFs
  - CNC word phoneme recognition



SNR difference for thresholds in wide-band and notched noise: 1 kHz probe, 500 Hz notch



Frequency discrimination thresholds at 500 Hz and 4 kHz



Impaired modulation detection in AN group

Figure 3. Amplitude modulation detection thresholds (AN subjects). Closed circles represent children in the AN ≥ 30% group, and open circles represent the children in the AN < 30% group. Open triangles show the findings for children in the AN < 30% group unable to detect a modulation depth of 0 dB. The enclosed area shows the mean ±2 SD range for the normal-hearing group.

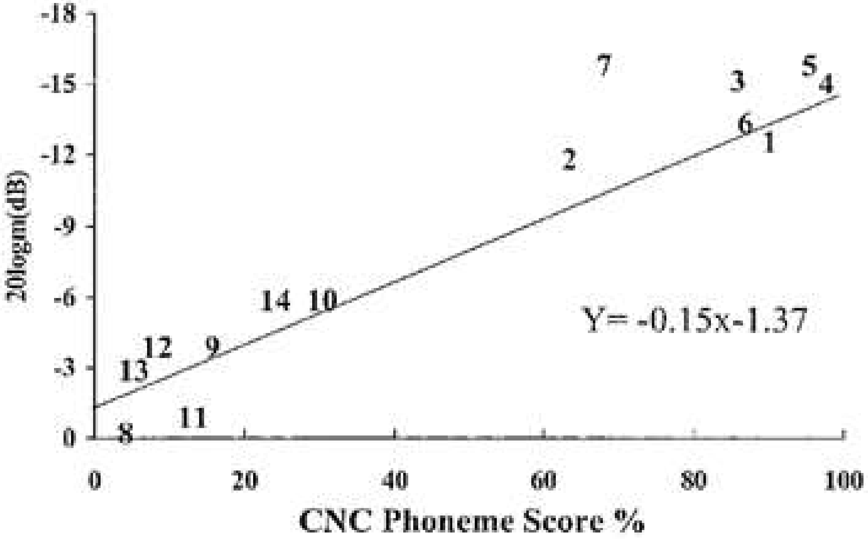


Figure 4. Amplitude modulation detection threshold (10 Hz MF) plotted as a function of CNC phoneme score (AN subjects). The data point for each child is represented by the subject identification number.

Temporal resolution and temporal frequency coding seems impaired in ANSD

- And both correlate highly with speech scores
- While auditory filtering seems near-normal in many of the ANSD subjects

A model of temporal resolution – the temporal window

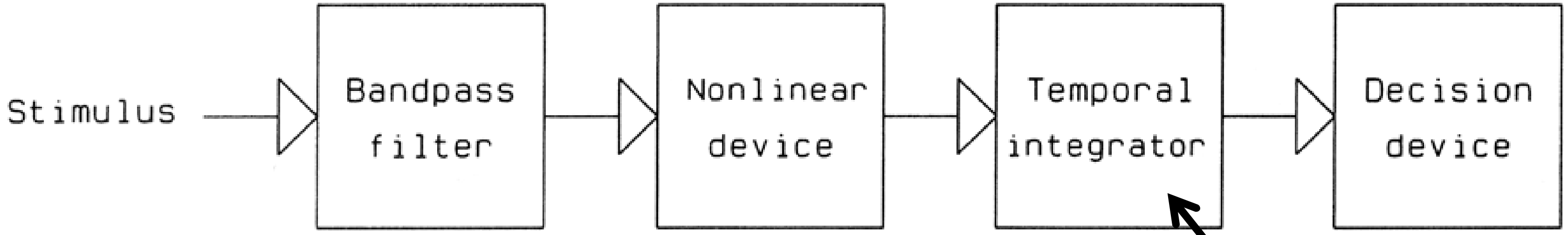
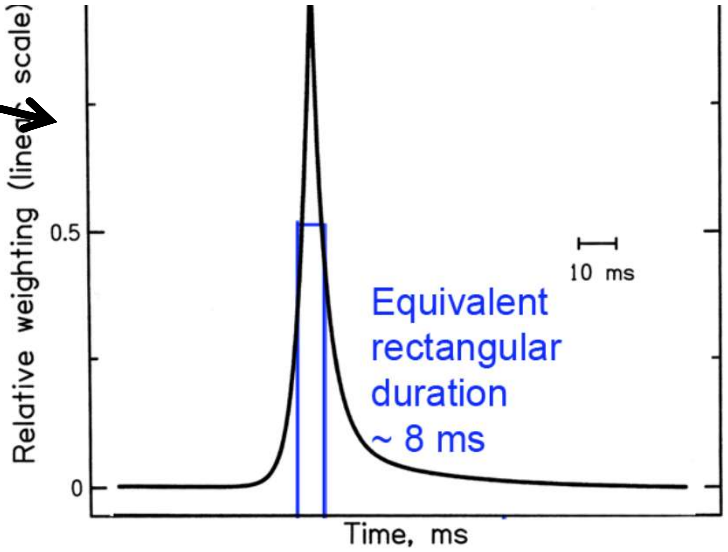


FIGURE 5.9 A block diagram of a model of temporal resolution.

An impulse response



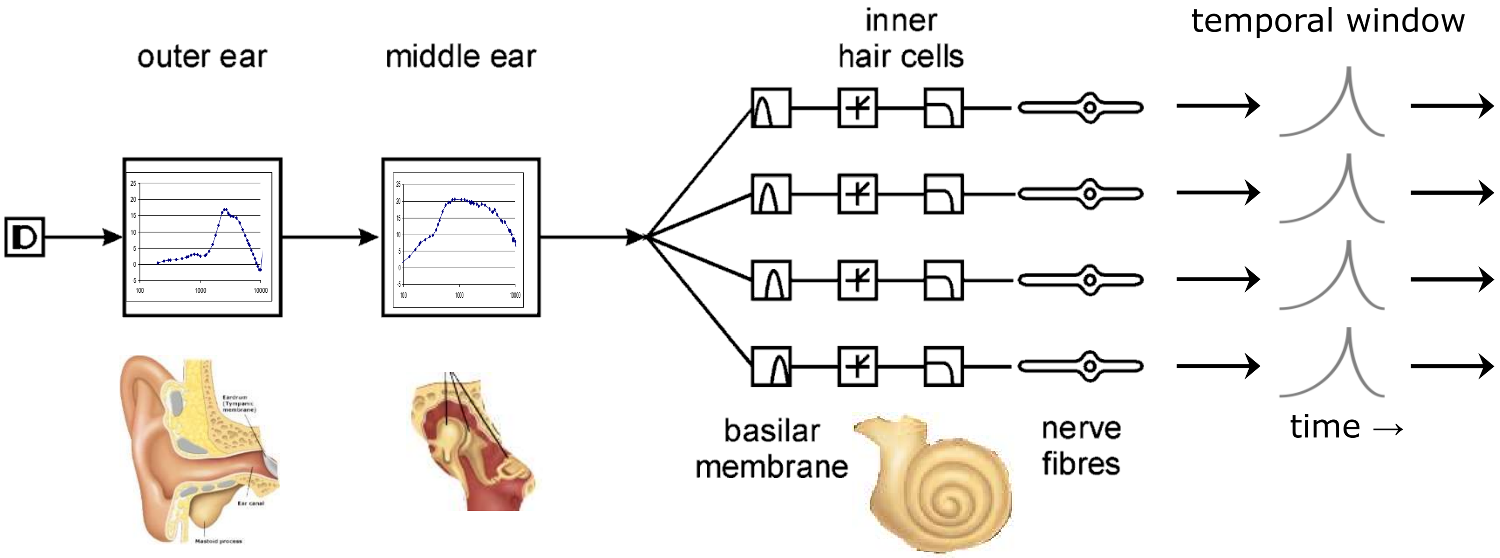
Equivalent rectangular duration ~ 8 ms

LTI system characterised by a frequency response

or … ?

FIGURE 5.10 The "shape" of the sliding temporal integrator (window). This is a weighting function applied to the output of the nonlinear device. It performs a weighted running average of the output of the nonlinear device. The shape is plotted on a linear scale as a function of time.

A model of the auditory periphery



outer ear

middle ear

inner
hair cells

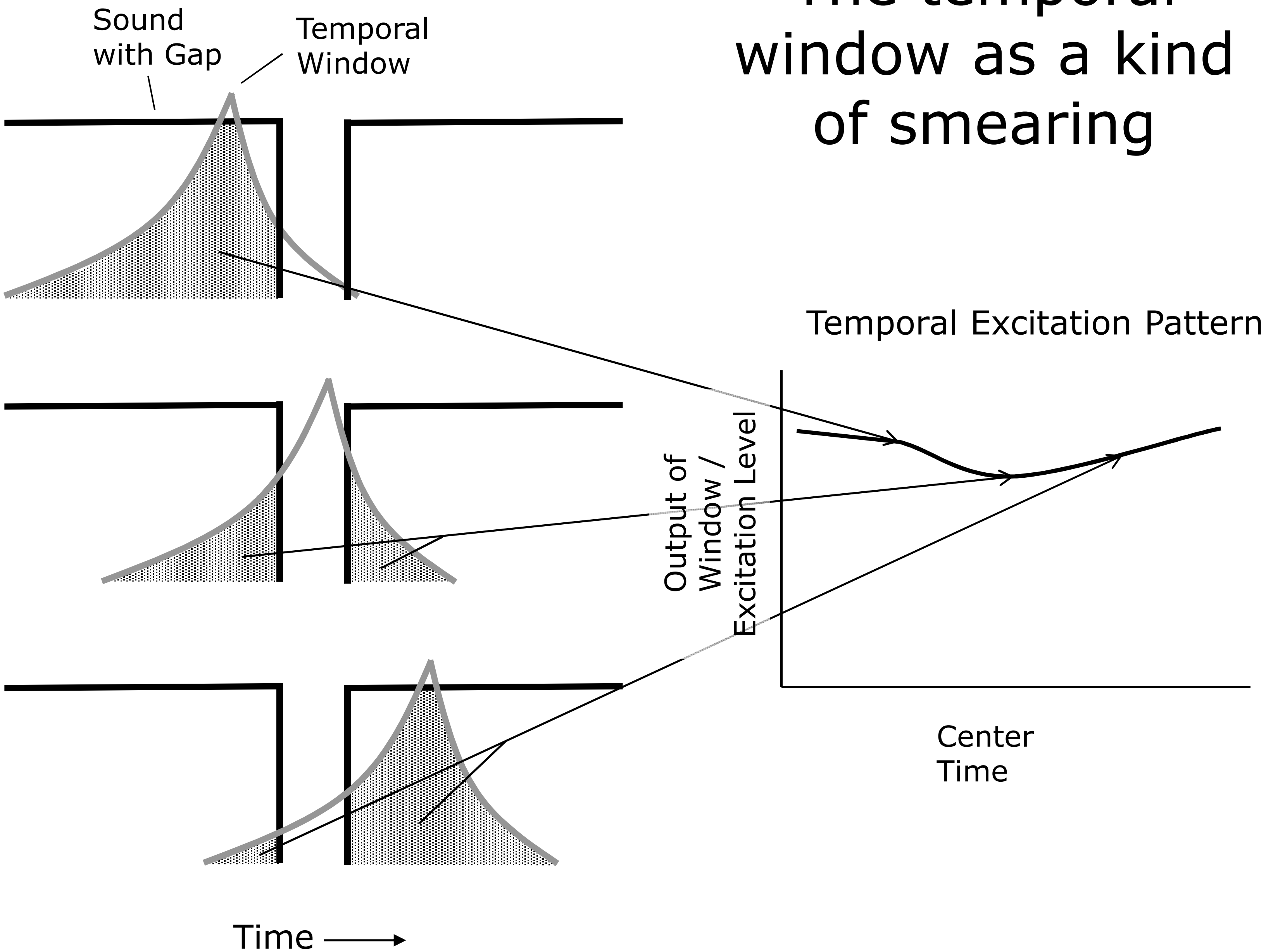
temporal window

basilar
membrane

nerve
fibres

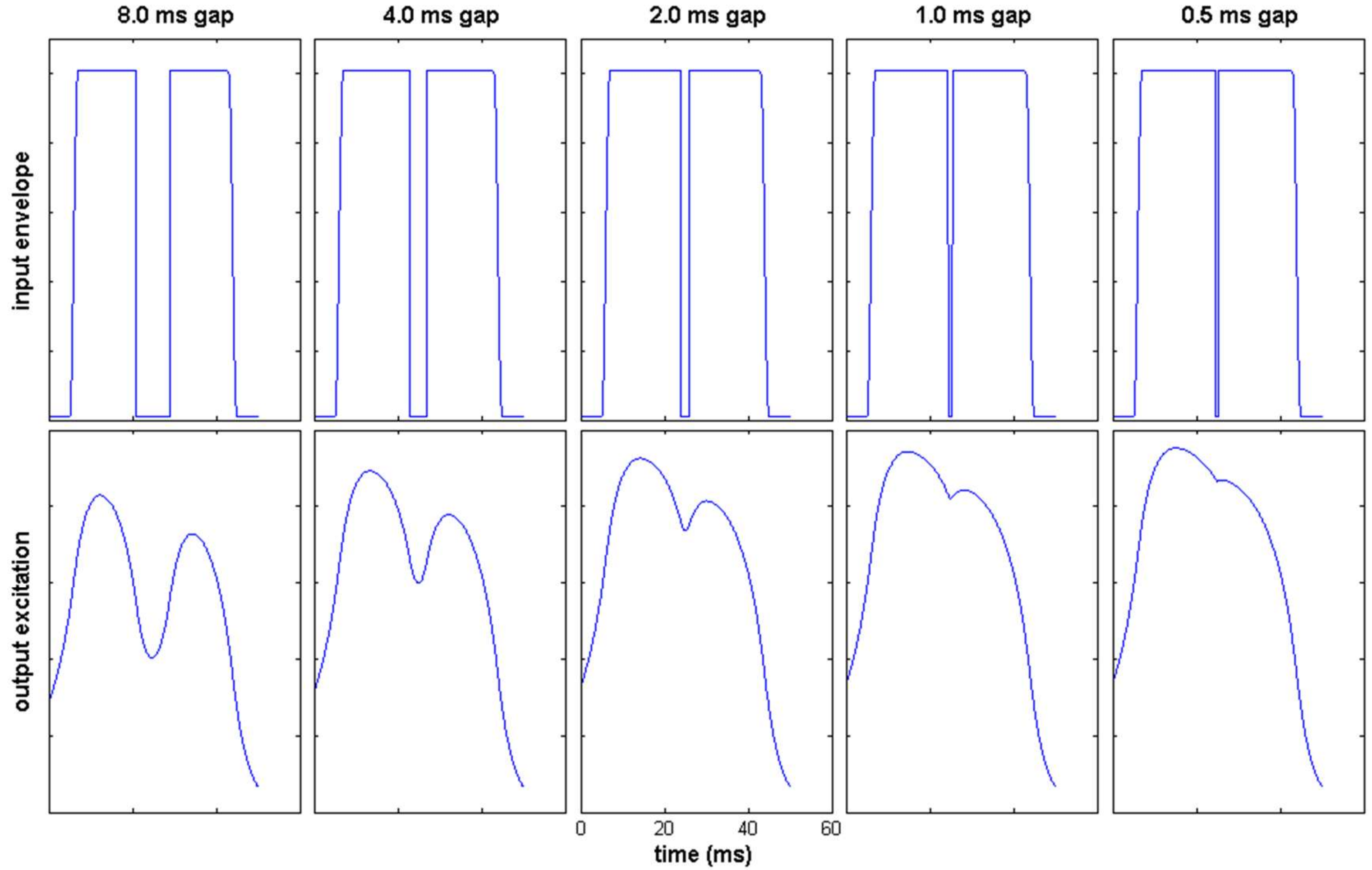
time →

The temporal window as a kind of smearing



slide courtesy of Chris Plack, 2013

gap detection seen through the temporal window model



Effects of temporal window on signals

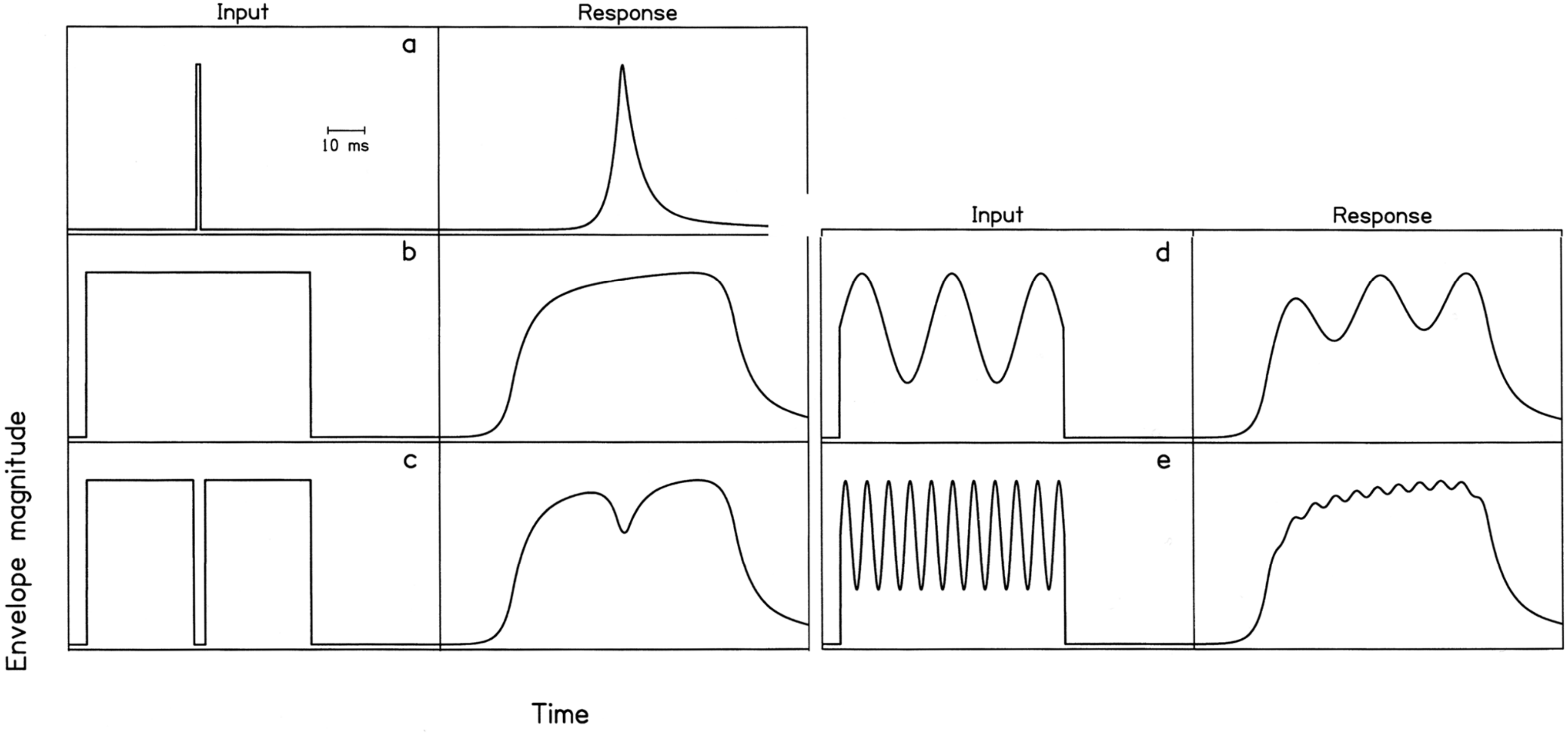
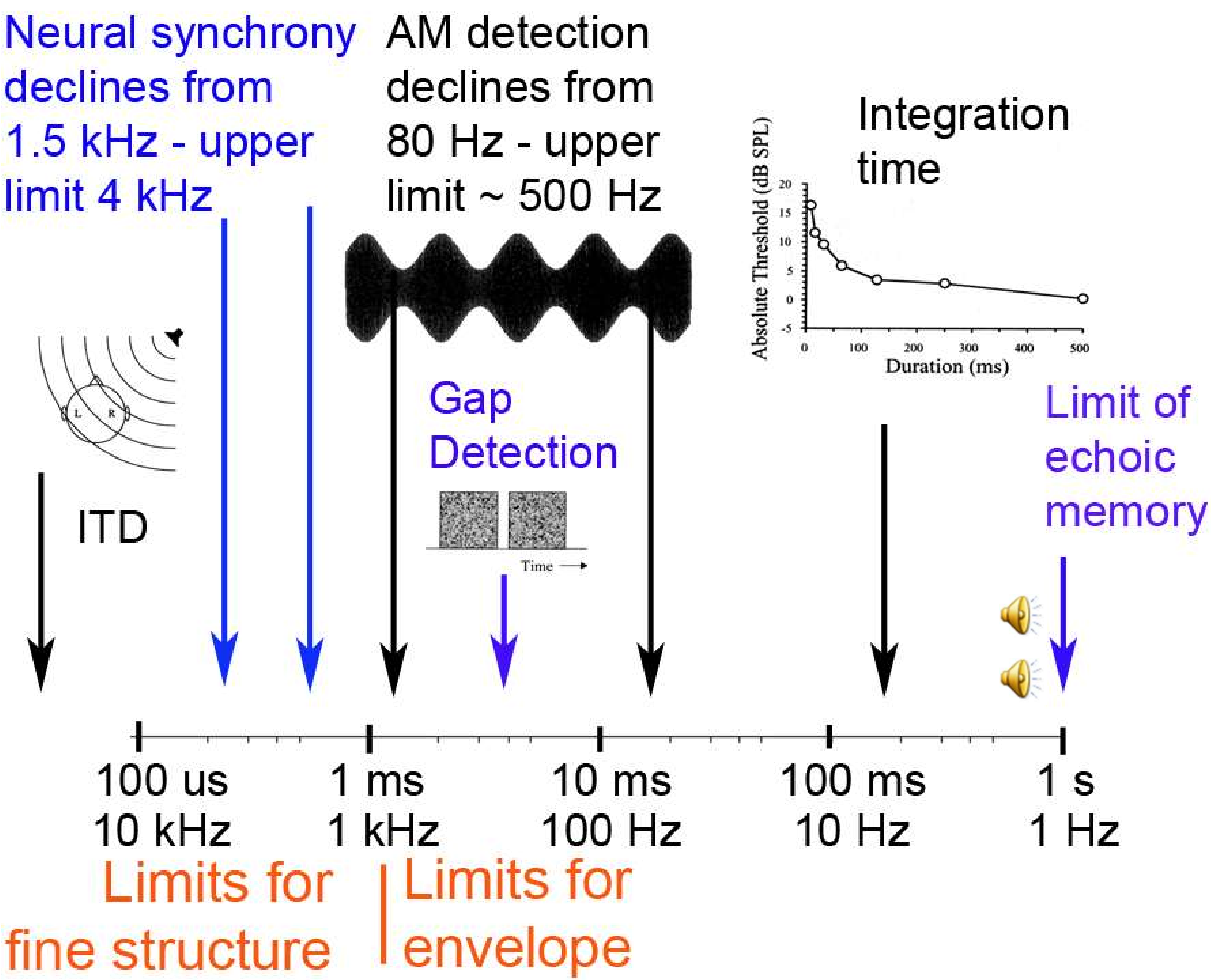


FIGURE 5.11 Examples of the influence of the sliding temporal integrator on the envelopes of sounds. The panels on the left show inputs to the sliding temporal integrator. The panels on the right show the corresponding outputs.

Decision device looks at evidence of level changes at output – a model of *within-channel* temporal resolution



Neural synchrony declines from 1.5 kHz - upper limit 4 kHz

AM detection declines from 80 Hz - upper limit ~ 500 Hz

Integration time

ITD

Gap Detection

Limit of echoic memory

100 us
10 kHz

1 ms
1 kHz

10 ms
100 Hz

100 ms
10 Hz

1 s
1 Hz

Limits for fine structure | Limits for envelope

Key Points

- Measures of temporal resolution typically relate to signal envelopes
- Measures must control spectral artefacts
- Gap detection and TMTF main measures
  - Both indicate limits in region of 1 to 3 ms in normal hearing
- Temporal window model can account reasonably well for within-channel temporal resolution
  - But this model is wrong in many respects! A full understanding appears to require the concept of a modulation filterbank