Masking, The Critical Band and Frequency Selectivity

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Aims

- Define the different forms of sound masking: simultaneous, forward and backward.
- Define auditory filter, tuning curve and critical band.
- Describe common psychoacoustical methods to measure auditory filters.
- Define masking pattern and describe its common interpretation.
- Describe the neurophysiological basis of masking.
- Define frequency selectivity and describe its main characteristics in normal-hearing listeners.
- Analyze the main consecuences of hearing impairement on auditory frequency selectivity.

Acknowledgements

- This presentation is inspired on a lecture prepared by author to be taught as part of the international Audiology Expert degree of the University of Salamanca (Spain).

- Some figures and examples were adapted from several sources (see references).

What is (sound) masking?

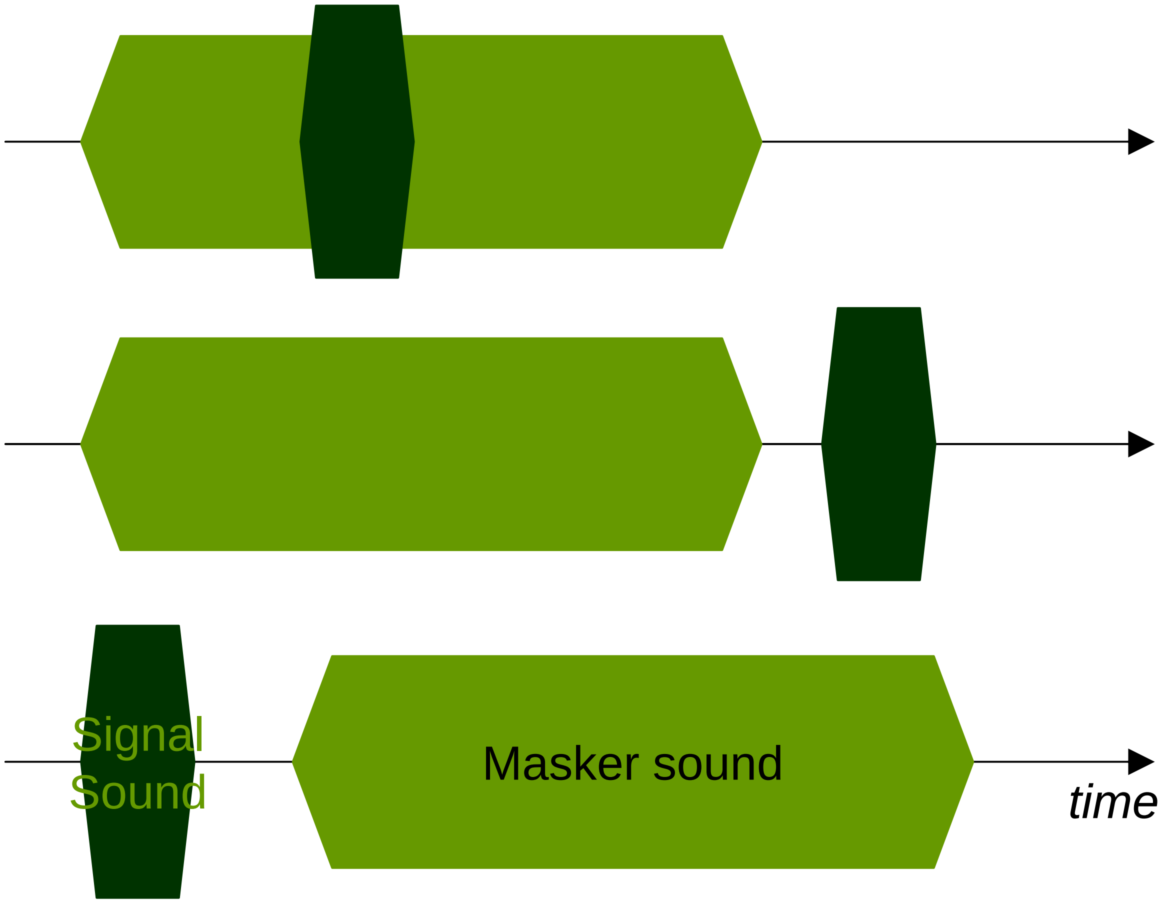
Just like a face mask hides the identity of its wearer, a sound can mask another sound making its perception (or detection) more difficult.

In psycoacoustics

Masking is the process by which the detection threshold of a sound (called ‘the signal’) is increased by the presence of another sound (called ‘the masker’).

The **amount of masking** is defined as the increase (in decibels) in the detection threshold of a sound (signal) due to the presence of a masker sound.

Types



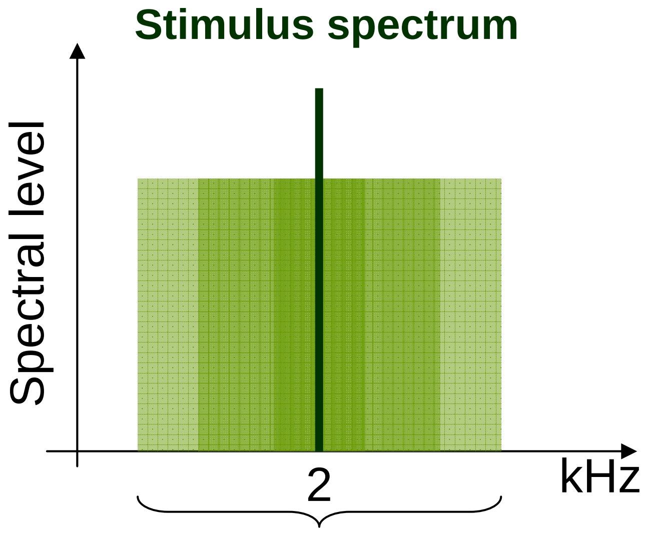
Simultaneous masking

Forward (post-stimulatory) masking

Backward (pre-stimulatory) masking

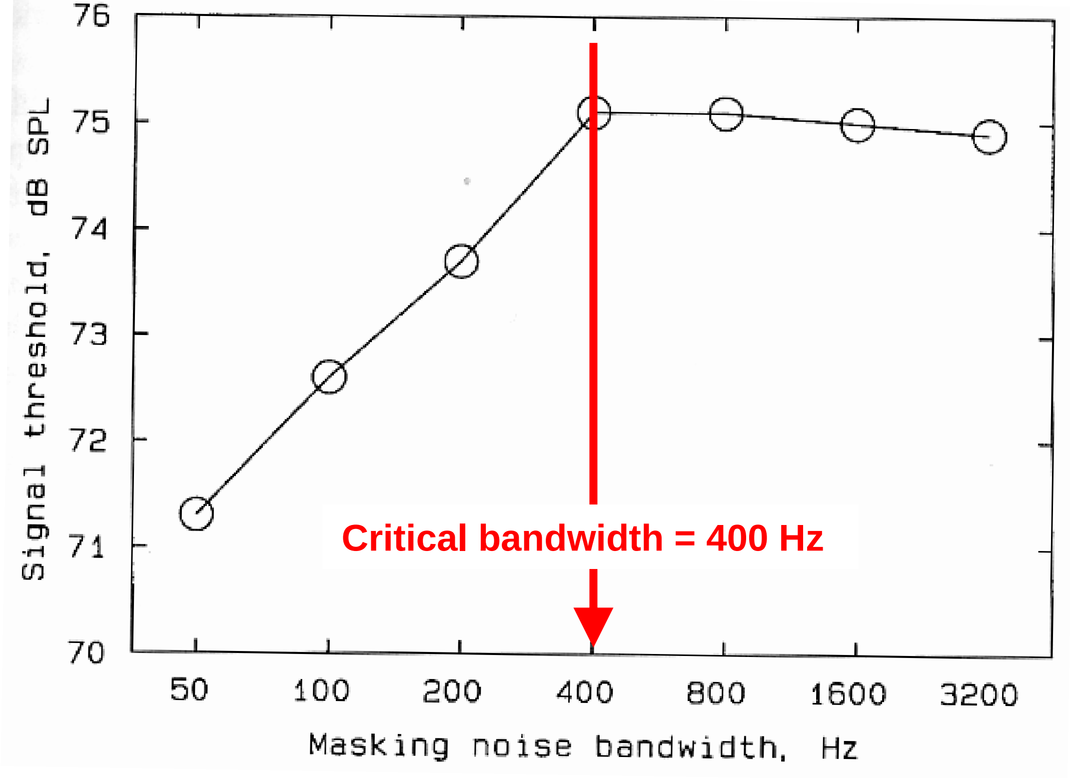
Simultaneous masking: Auditory filters

The “critical band”



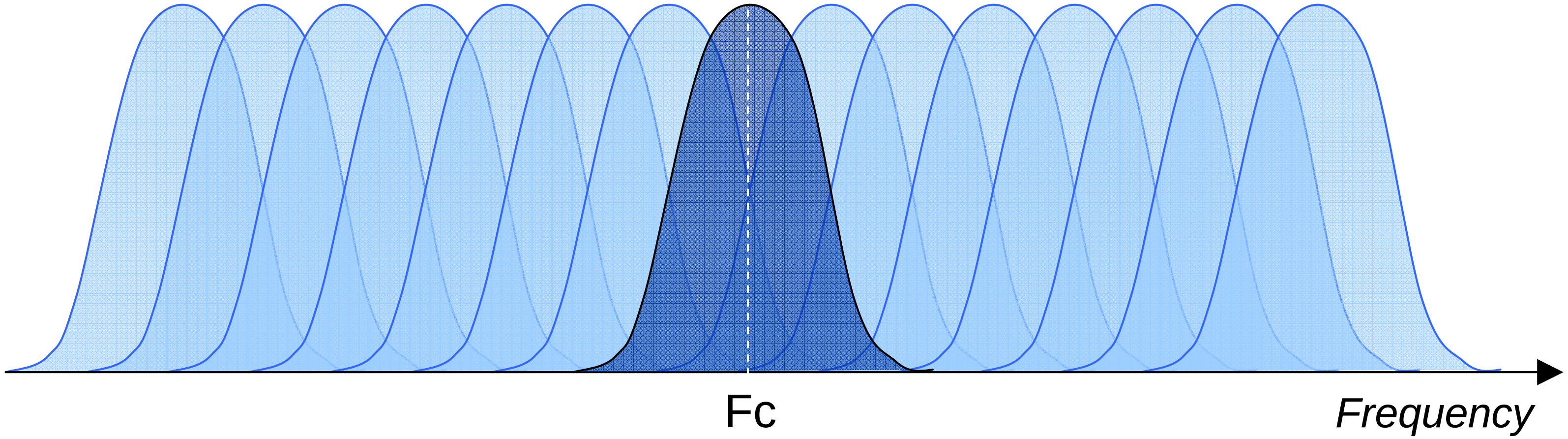
Signal detection threshold increases with increasing masking noise bandwidth up to a point after which signal threshold becomes independent of masker bandwidth.

Adapted from Schooneveldt & Moore (1989)



Schooneveldt GP, Moore BCJ. (1989). Comodulation masking release for various monaural and binaural combinations of the signal, on-frequency, and flanking bands. J Acoust Soc Am. 85(1):262-272.

Auditory filters



To explain the previous result, Fletcher (1940) suggested that the auditory system behaves like a bank of overlapping bandpass filters. These filters are termed “**auditory filters**”.

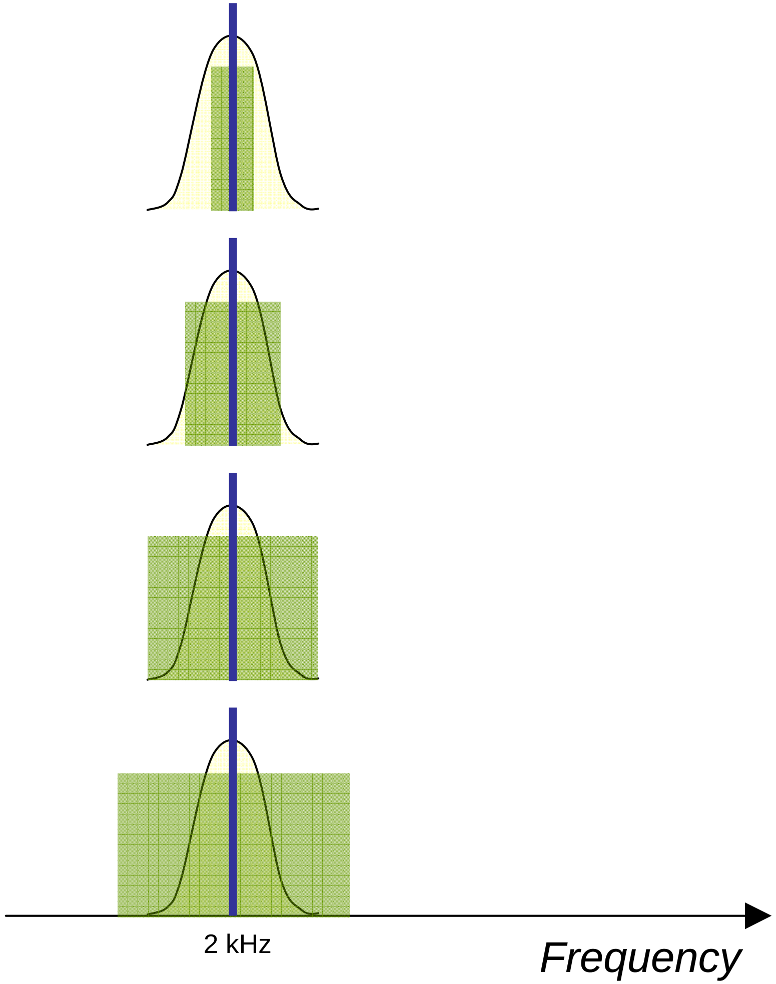
Fletcher H. (1940). Auditory patterns. Rev. Mod. Phys. 12, 47-65.

An explanation of the critical band

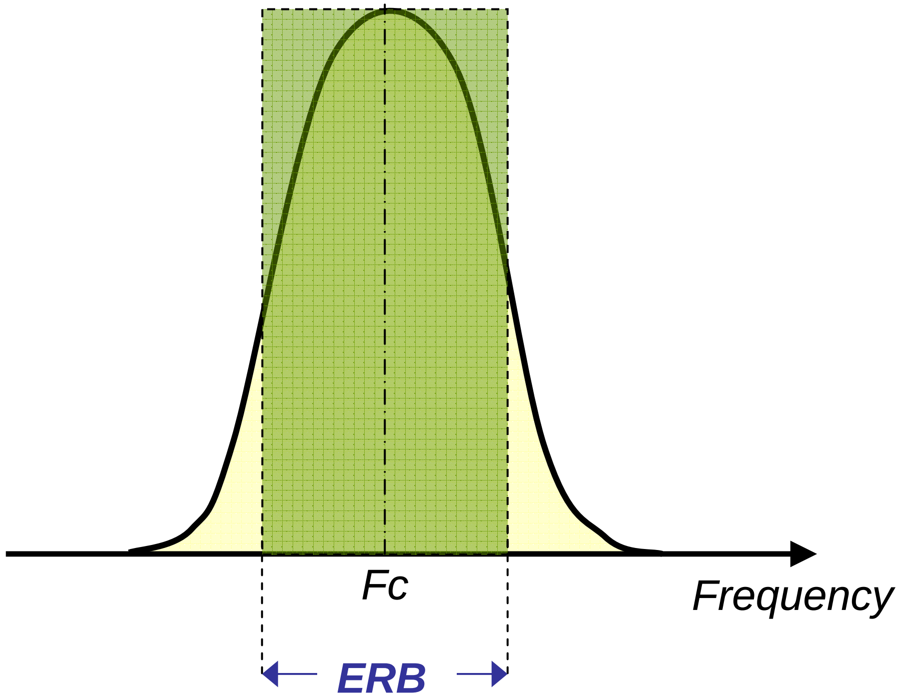
The amount of masking increases with increasing the noise (masker) energy that gets through the filter.

Up to a point…!

Further increases in noise bandwidth do not increase the masker energy through the filter.



Equivalent rectangular bandwidth (ERB)



An auditory filter (yellow area) and its ERB filter (green area). Both have different shapes but equal height and total area. That is, both let the same energy through.

The masking threshold according to Fletcher’s power spectrum model

Fletcher (1940) proposed that the masking threshold occurs when the acoustic power of the signal (*S*) at the filter output is proportional to the acoustic power of the masker (*M*) at the filter output:

$S/M = k$, with k being a proportionality constant.

For a noise masker with constant spectral density (*N*), and a critical band *W*, masking threshold occurs when:

$S/(W \times N) = k$, hence $W = S/(k \times N)$.

Thus measuring *S* and knowing *N*, we can infer *W*.

Caution!

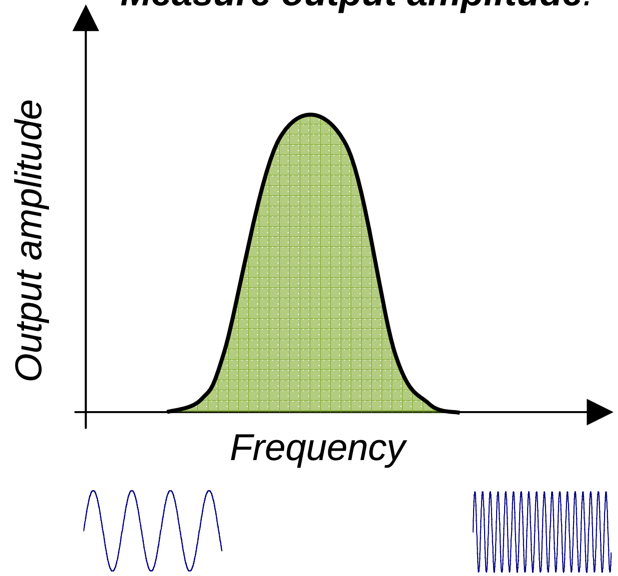
Fletcher’s model is useful to explain several auditory phenomena, but is just a model!

More details to come...

How to estimate the shape of a filter?

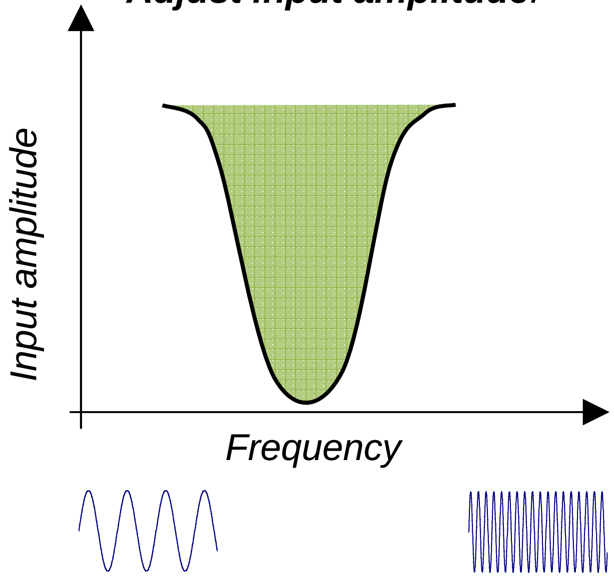
Iso-stimulus curve

*Same **input** amplitude,*
Different input frequency.
***Measure output amplitude**.*



Iso-response (tuning) curve

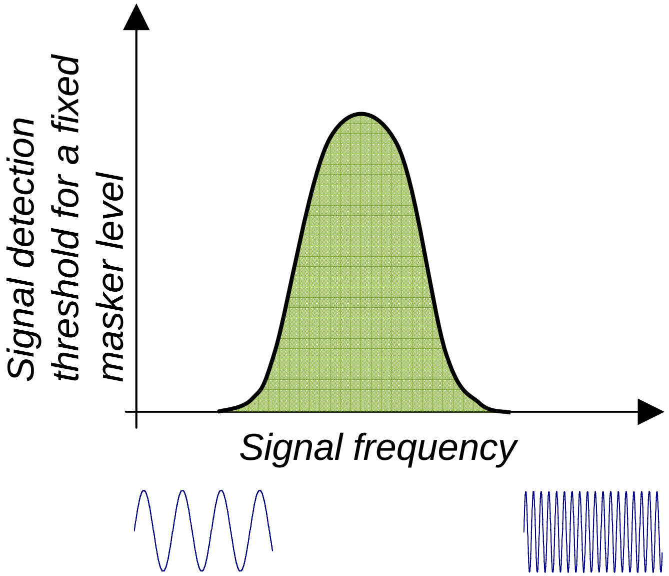
*Same **output** amplitude,*
Different input frequency.
***Adjust input amplitude**.*



How to estimate the shape of an **auditory** filter?

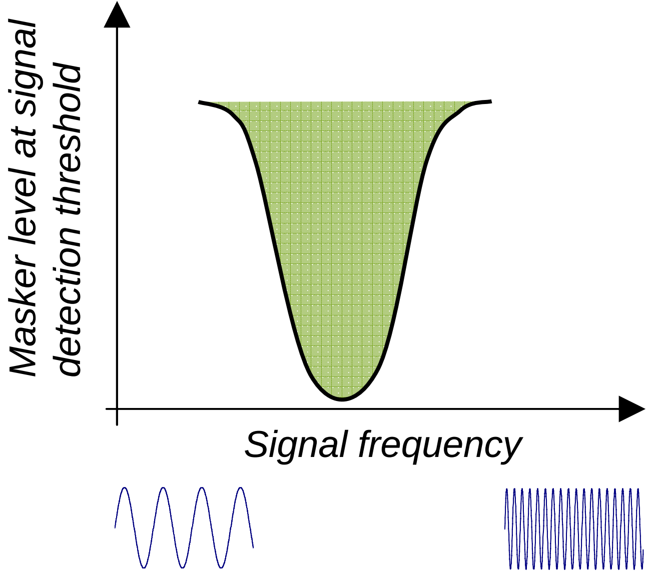
Iso-stimulus curve

Same masker level,
Measure signal detection threshold.



Iso-response (tuning) curve

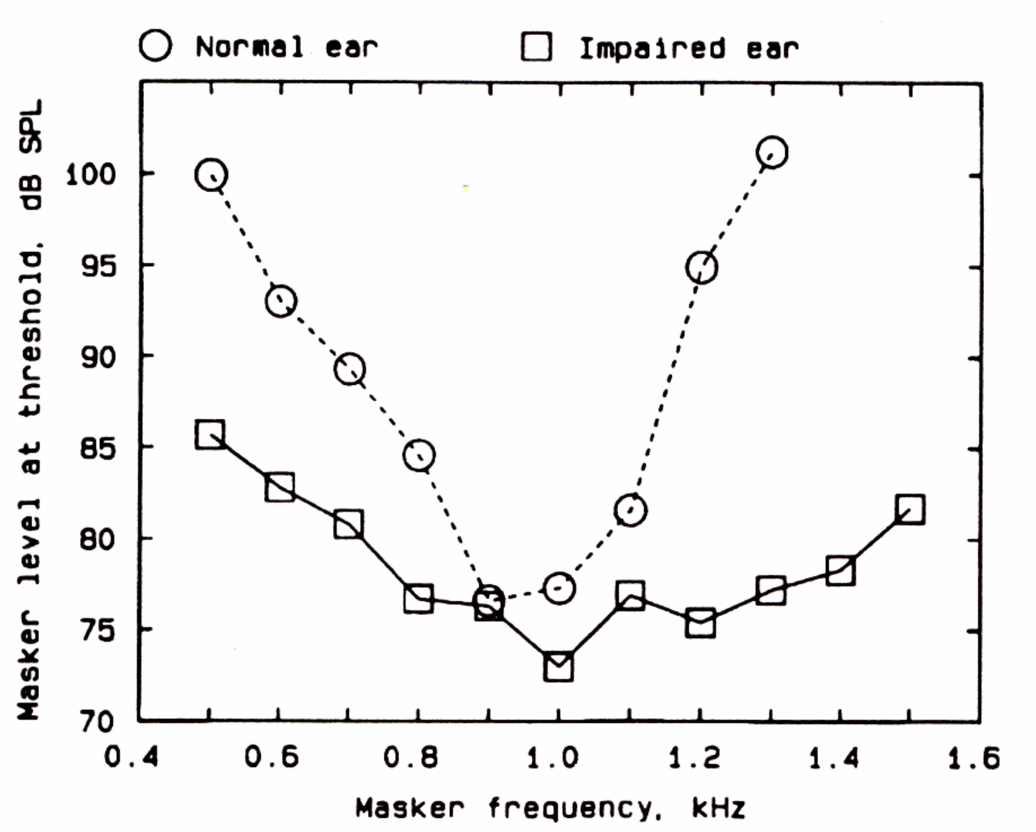
Same signal level,
Measure masker level at signal detection threshold.



Psychoacoustical tuning curves

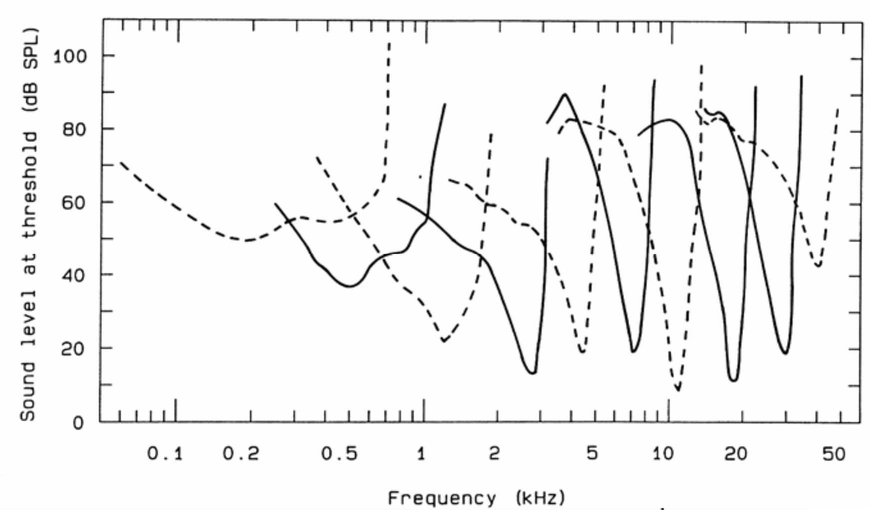
Method B produces **PSYCHOACOUSTICAL TUNING CURVES (PTCs)**.

Psychoacoustical tuning curves for normal-hearing and hearing-impaired listeners. Signal was a 1-kHz pure tone at 10 dB SL. Masker was narrowband noise (Moore & Glasberg, 1986).

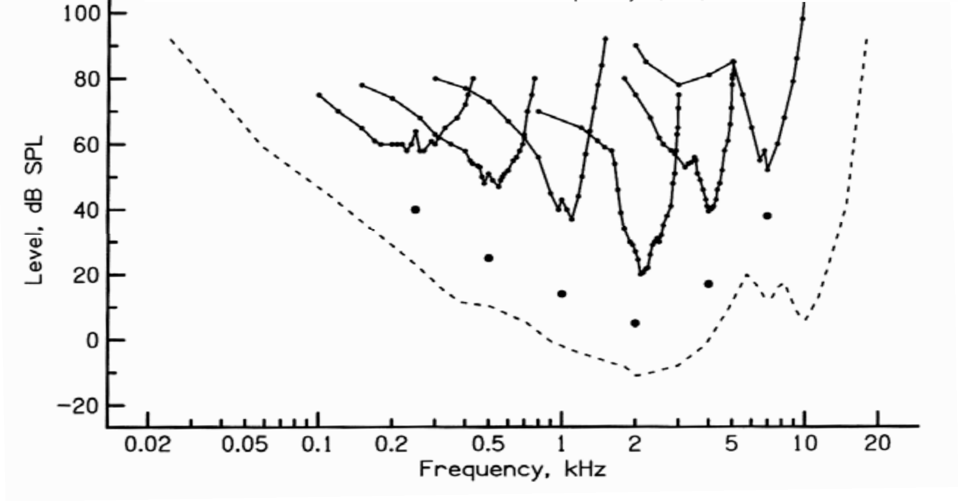


Moore BCJ, Glasberg, BR (1986). Comparisons of frequency selectivity in simultaneous and forward masking for subjects with unilateral cochlear impairments. J. Acoust. Soc. Am. 80, 93-107.

Physiological and psychoacoustical tuning curves



Auditory nerve fiber tuning curves (Palmer, 1987).

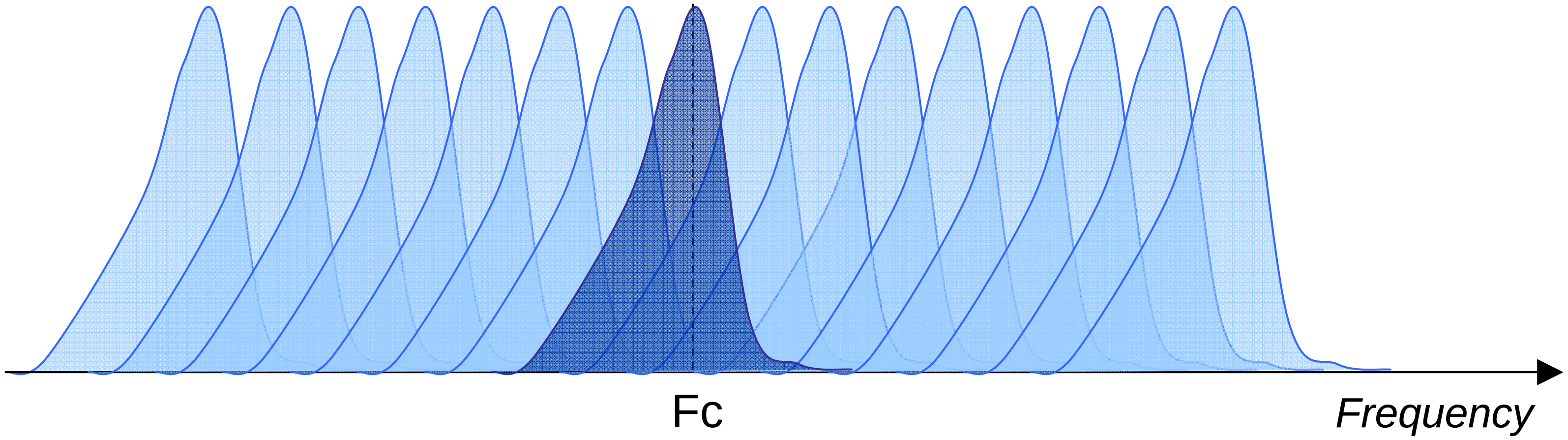


Psychoacoustical tuning curves (Vogten, 1974).

Palmer AR (1987). Physiology of the cochlear nerve and cochlear nucleus, in *Hearing*, edited by M.P. Haggard y E.F. Evans (Churchill Livingstone, Edinburgh).
Vogten, L.L.M. (1974). Pure-tone masking: A new result from a new method, in *Facts and Models in Hearing*, edited by E. Zwicker and E. Terhardt (Springer-Verlag, Berlin).

Off-frequency listening

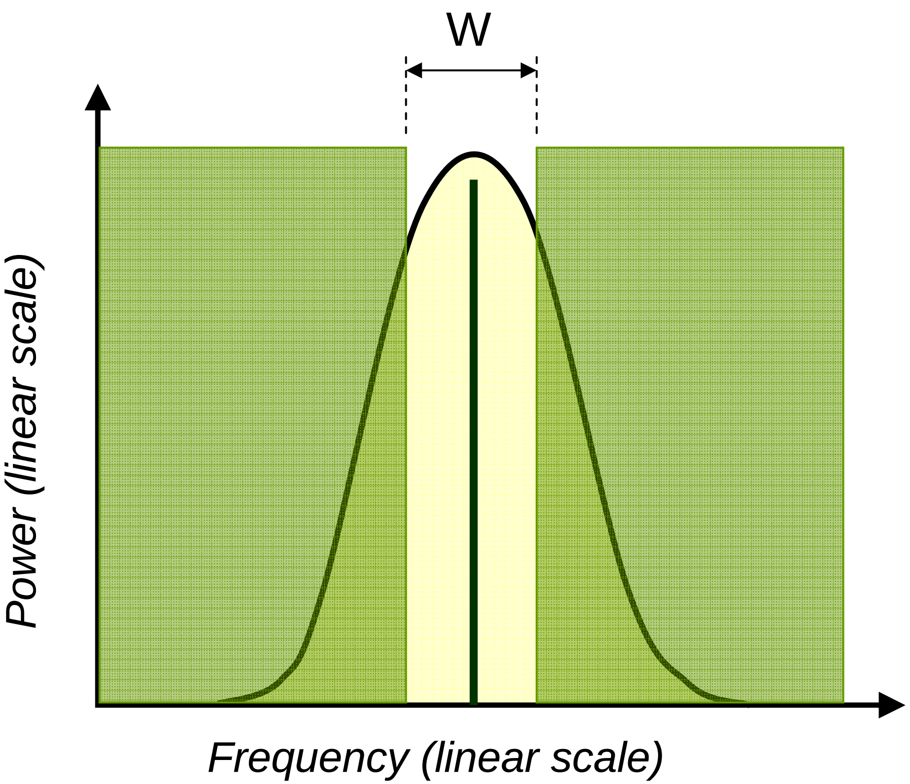
Off-frequency listening is said to occur when the signal is detected through a filter different from the one with a center frequency (Fc) equal to the signal frequency.



Off-frequency listening occurs because auditory filters are asymmetric and have steep high-frequency slopes (Moore, 1998).

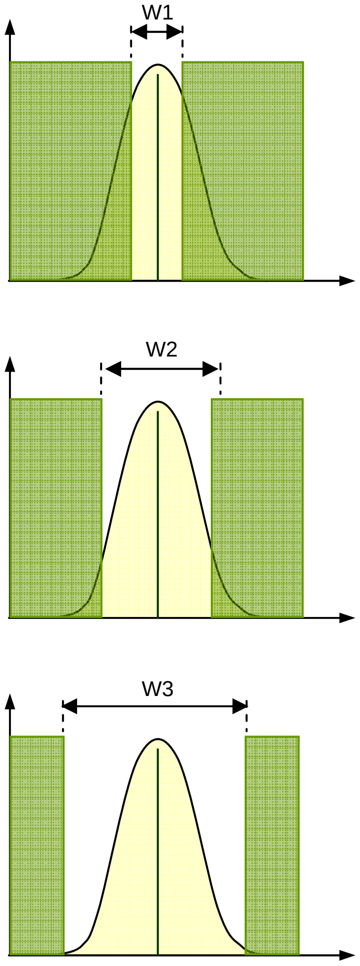
Moore BCJ (1998). Cochlear Hearing Loss, Whurr Publishers, London.

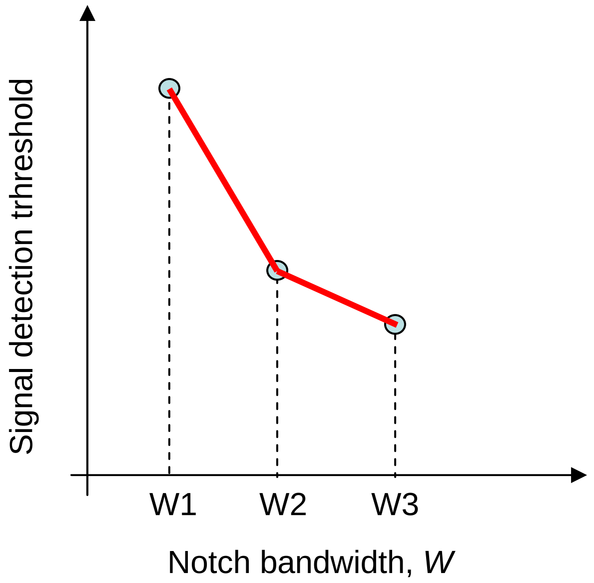
The notch-noise method of Patterson (1976)



Notch-noise spectrum (green area) versus auditory filter shape (yellow area).

The notch noise method

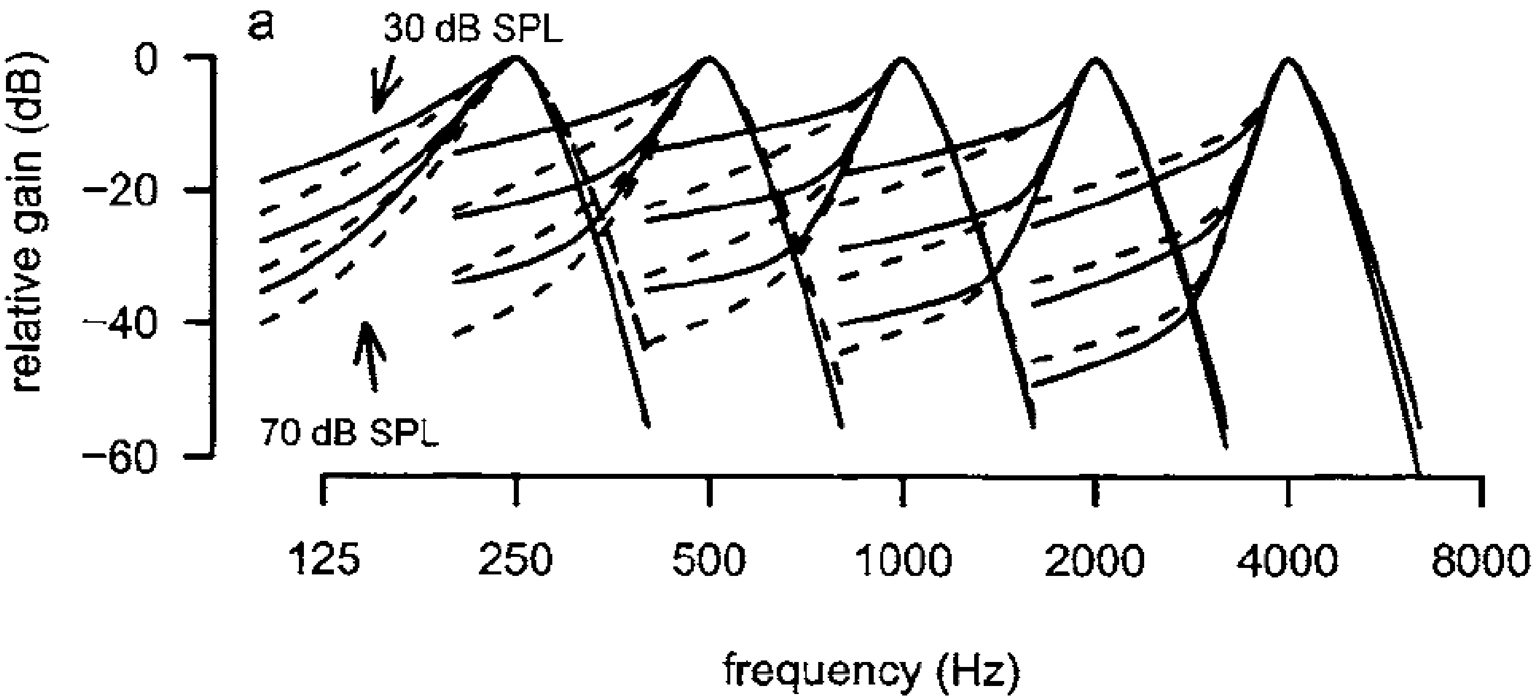




Signal detection threshold decreases with increasing notch bandwidth. Filter shape is the integral of the red curve (Patterson, 1976). This method reduces off-frequency listening.

Patterson RD. (1976). "Auditory filter shapes derived with noise stimuli." J. Acoust. Soc. Am. 59, 640-654.

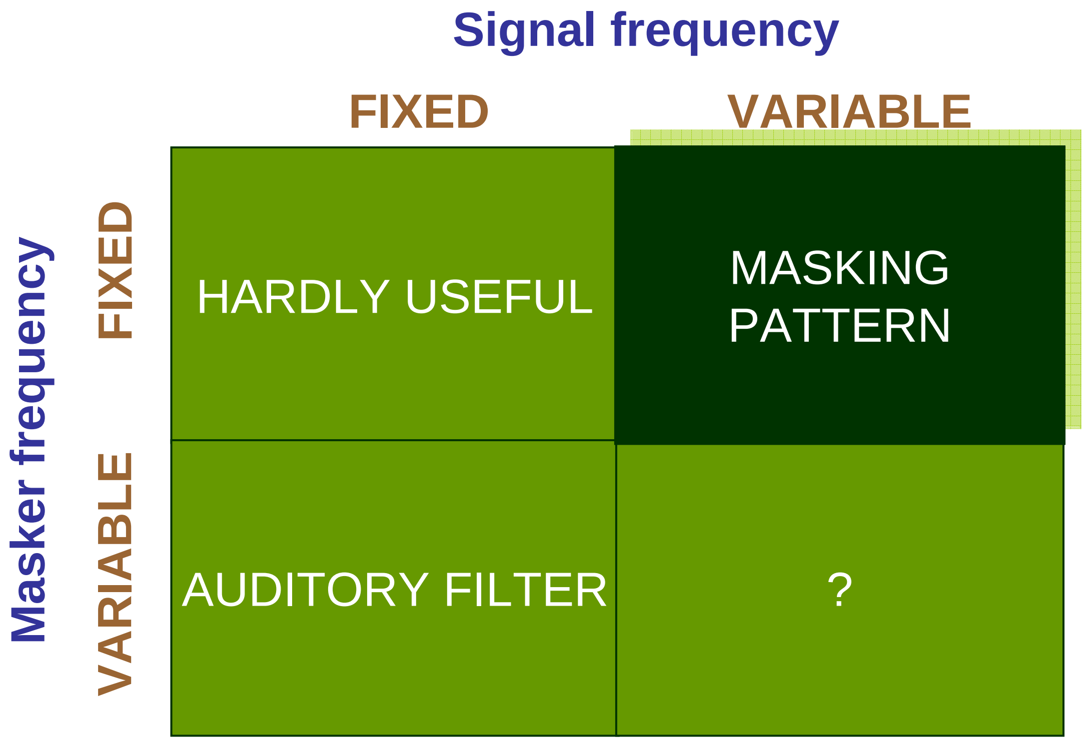
Auditory filters obtained with the notch-noise method



From: Baker S, Baker RJ. (2006). Auditory filter nonliearity across frequency using simultaneous notched-noise masking. J. Acoust. Soc. Am. 119, 454-462.

Simultaneous masking: Masking patterns

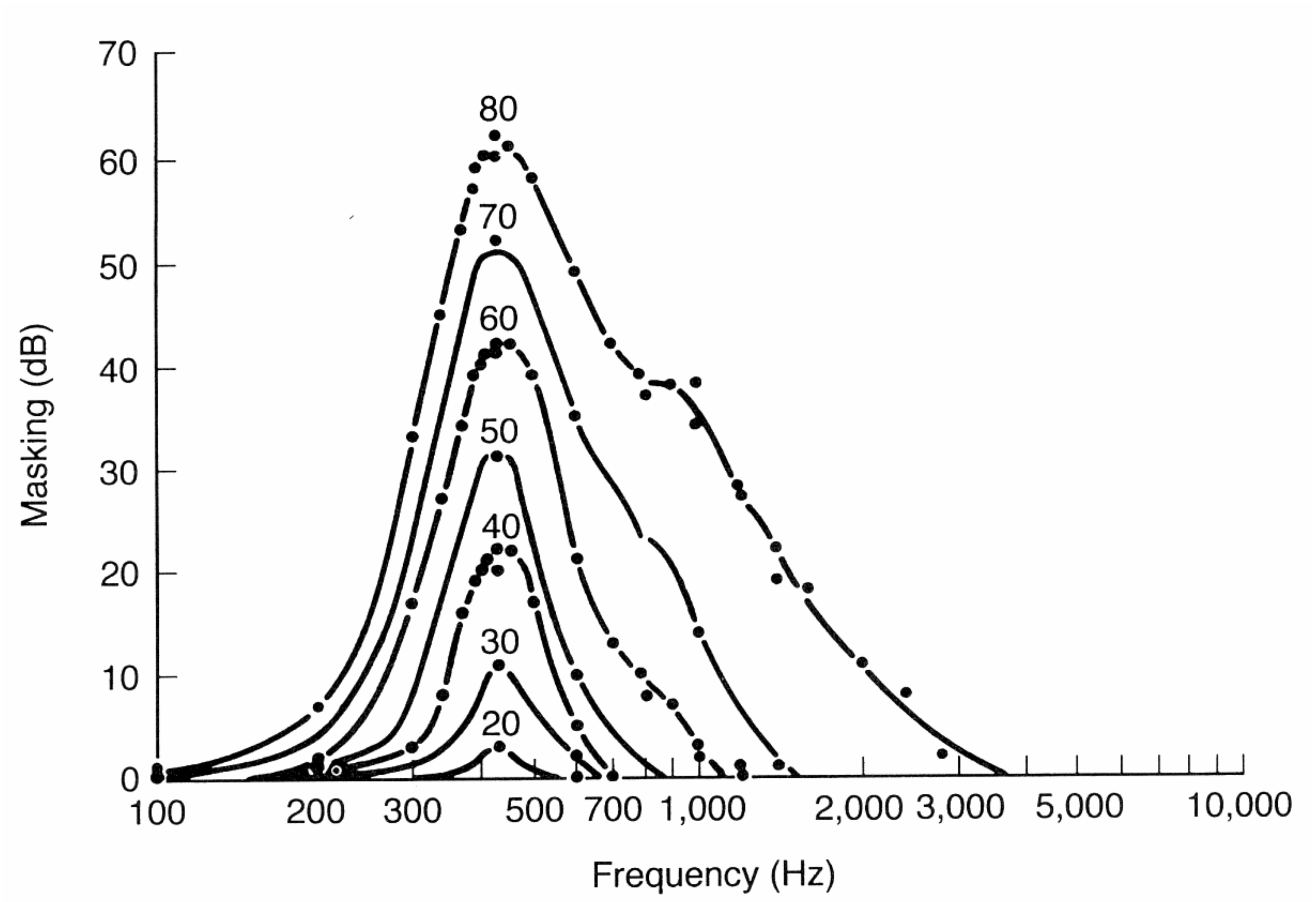
What is a masking pattern?



		Signal frequency	
		FIXED	VARIABLE
Masker frequency	FIXED	HARDLY USEFUL	MASKING PATTERN
	VARIABLE	AUDITORY FILTER	?

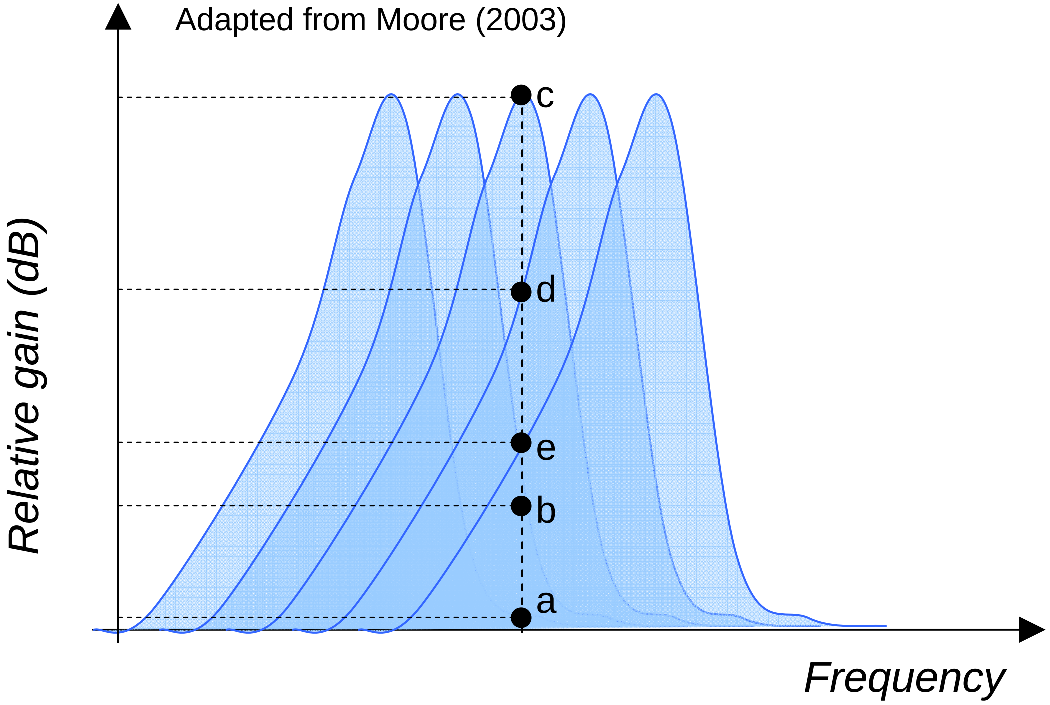
A masking pattern is a masked audiogram, i.e., a graphical representation of the audiogram measured while pure tones of different frequencies are presented in the presence of a masker sound (with any spectrum).

The masking pattern of a pure tone



From: Egan JP, Hake HW. (1950). On the masking pattern of a simple auditory stimulus. J. Acoust. Soc. Am. 22, 622-630.

The interpretation of a masking pattern

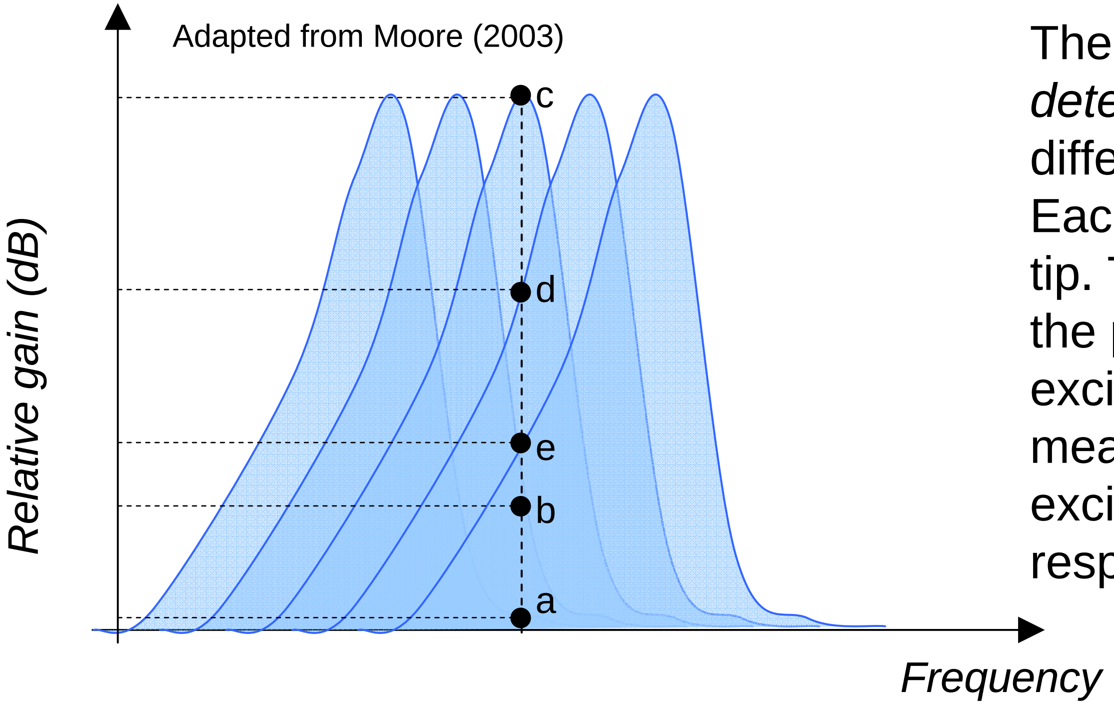


It is assumed that the signal is detected through the auditory filter giving the greatest signa-to-masker ratio at the output.

Therefore, a different detection auditory filter is used as the signal frequency changes. The frequency of the masker tone is fixed.

From: Moore BCJ. (2003). An introduction to the psychology of hearing. 4 Ed. Academic Press, London.

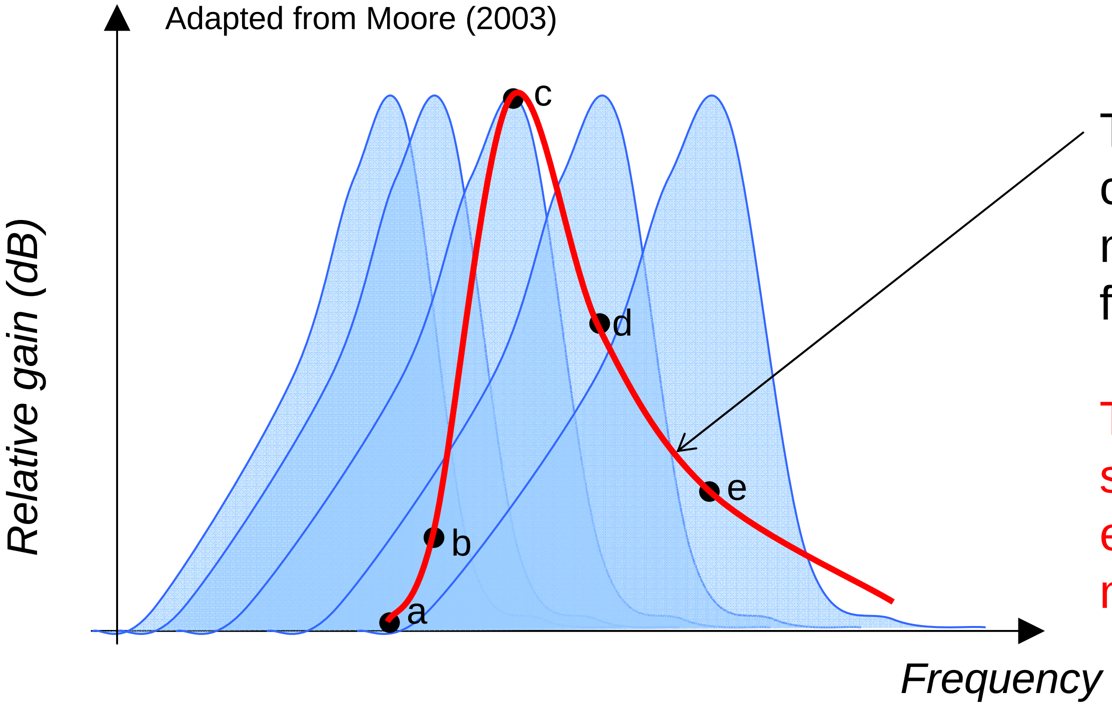
The interpretation of a masking pattern



The illustration shows five *detection* auditory filters with different center frequencies. Each filter has 0-dB gain at its tip. The vertical line illustrates the pure tone signal whose excitation pattern is to be measured. The dots illustrate the excitation of each filter in response to the *masker* tone.

Moore BCJ. (2003). An introduction to the psychology of hearing. 4 Ed. Academic Press, London.

The excitation pattern



The excitation pattern (red curve) would be a plot of the masker output from each filter to the masker tone.

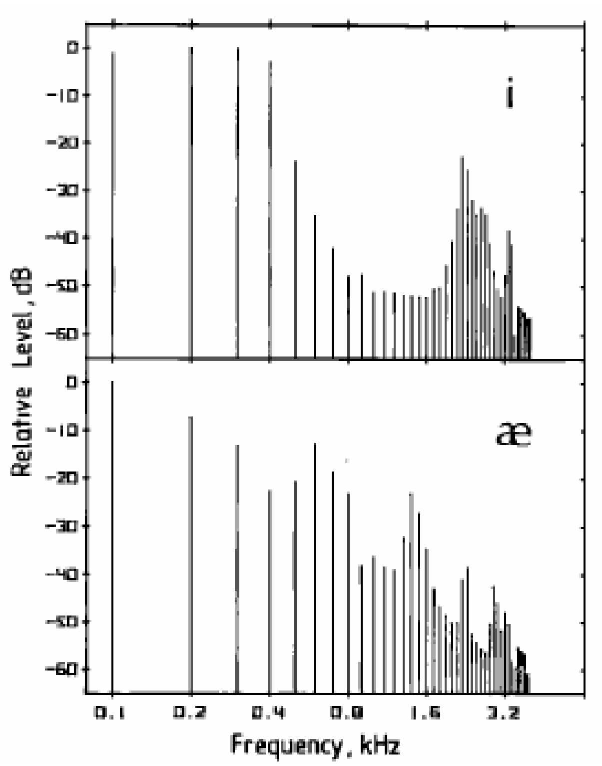
Therefore, it represents something akin to the internal excitation pattern of the masker spectrum.

Indeed, it is possible to measure a masking patter for any masker…

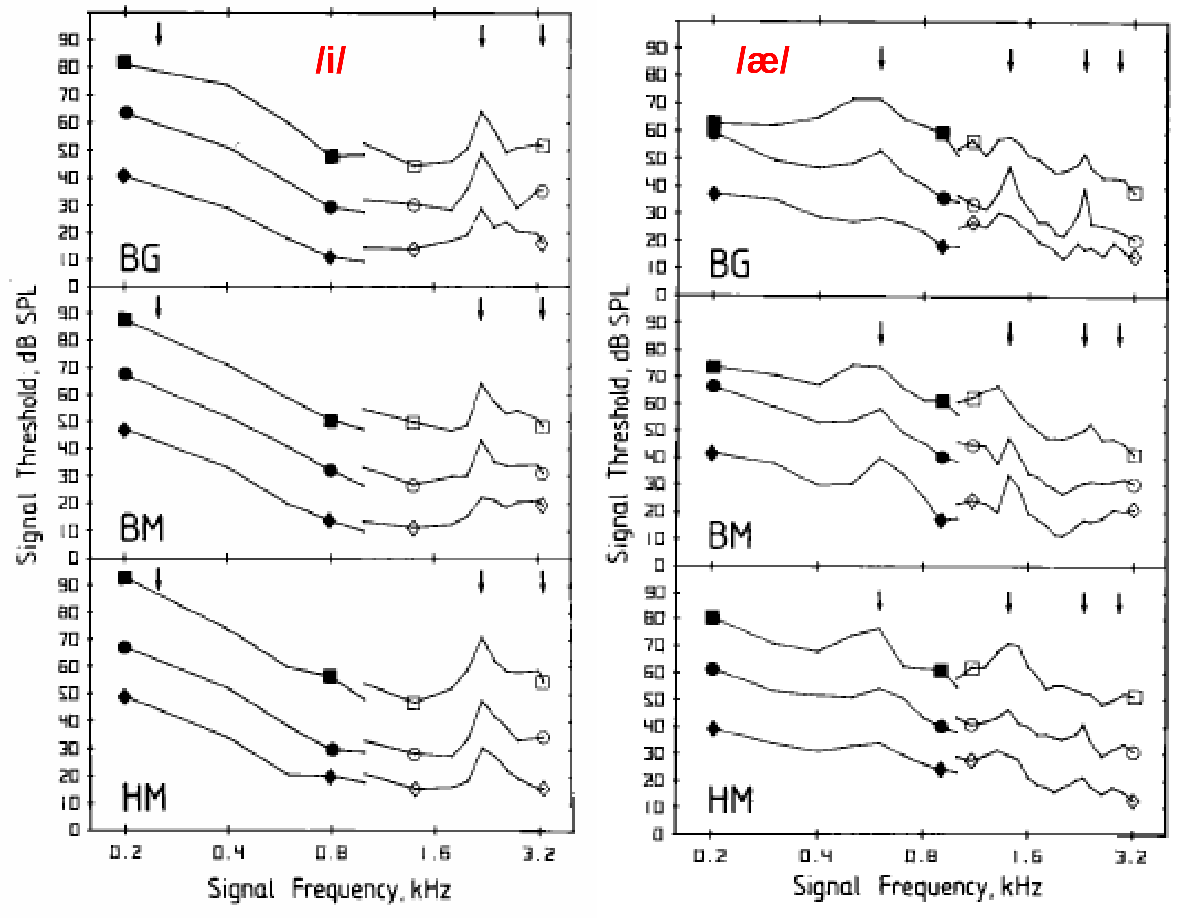
…and the result is thought to represent approximately the ‘internal’ excitation evoked by the masker.

For example: The excitation pattern of a vowel

Espectra of synthesized
***/i/* & */æ/* vowels**

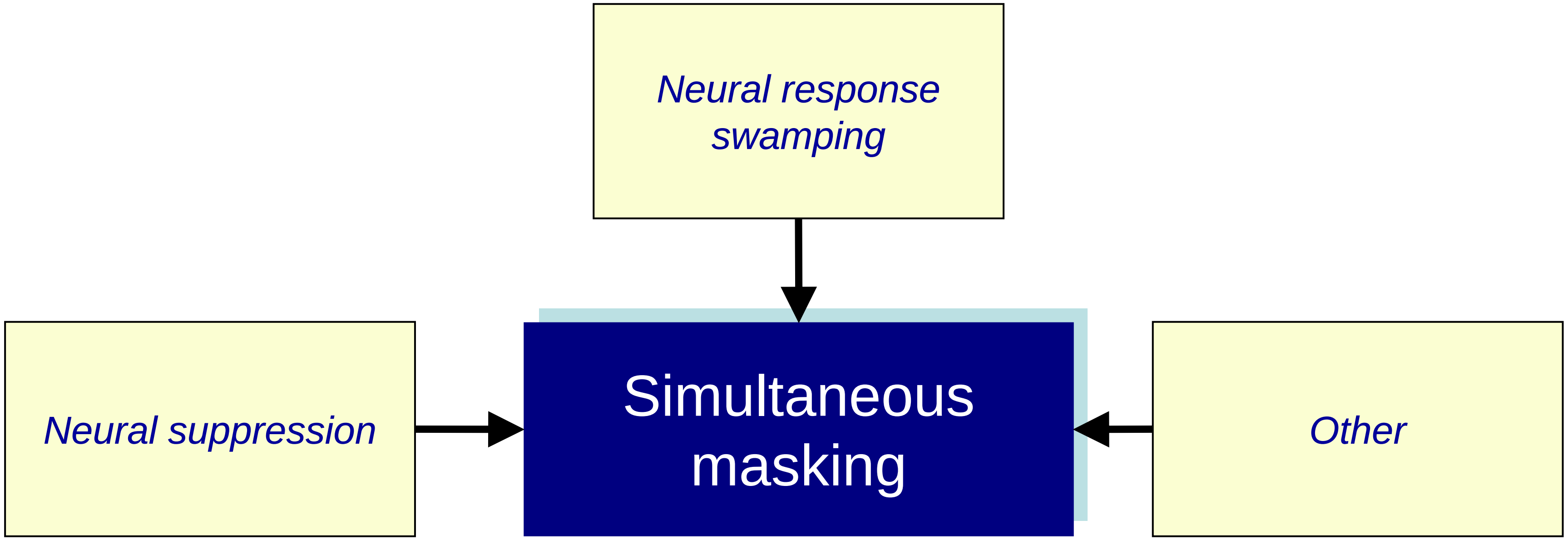


Excitation patterns for three different
subjects at different sound levels



From Moore BCJ, Glasberg BR. (1983). "Masking patterns for synthetic vowels in simultaneous and forward masking," J. Acoust. Soc. Am. 73, 906-917.

The neurophysiological bases of simultaneous masking



Neural response swamping

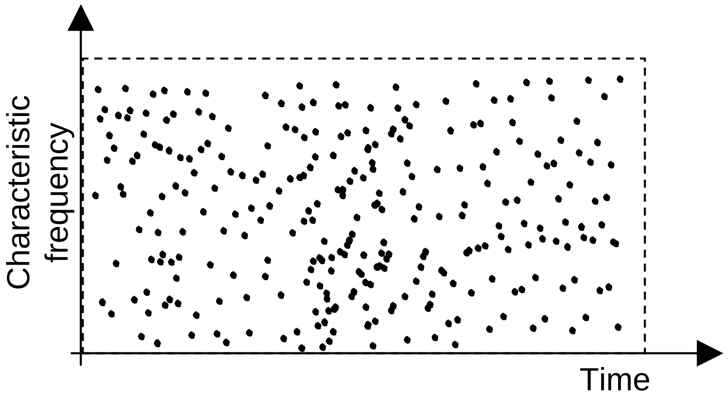
Neural suppression

Simultaneous masking

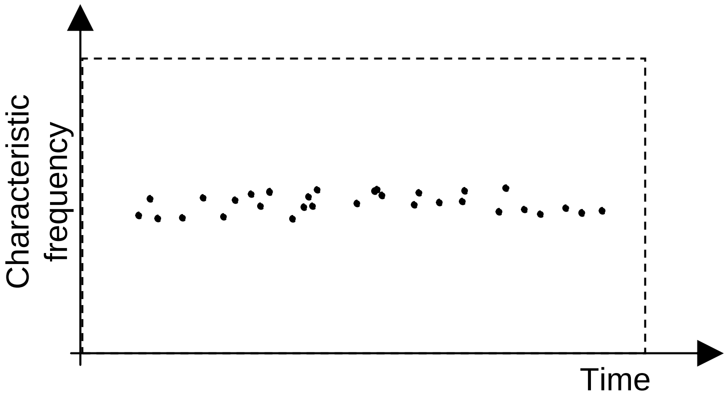
Other

Simultaneous masking may reflect swamping of neural responses

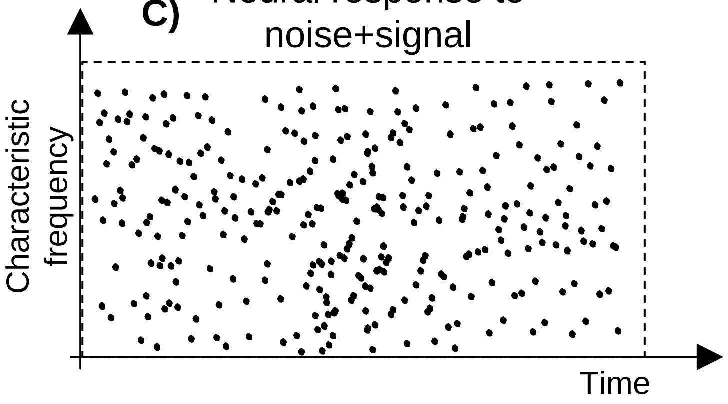
A) Neural response to masking noise



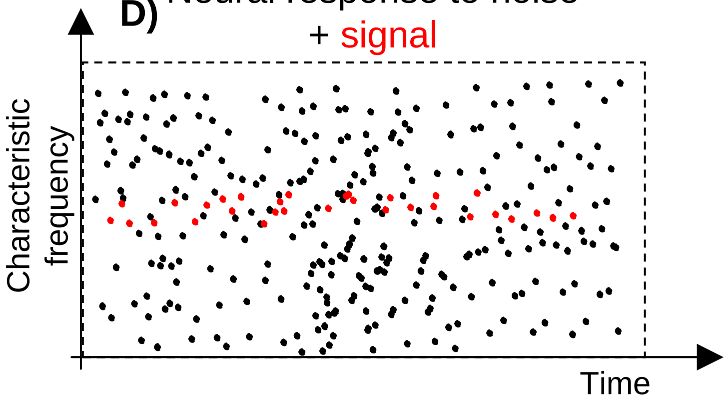
B) Neural response to pure tone (signal)



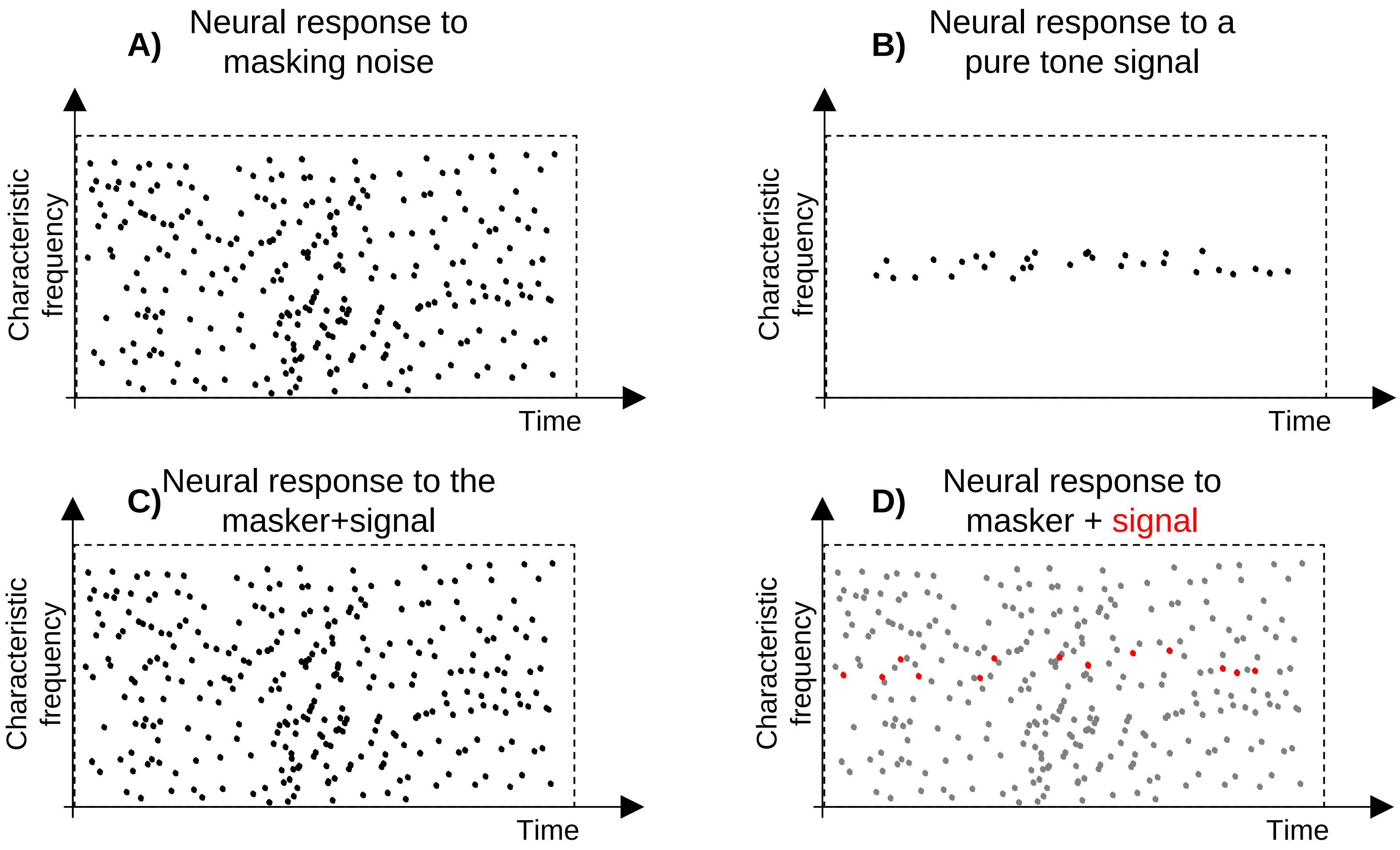
C) Neural response to noise+signal



D) Neural response to noise + signal



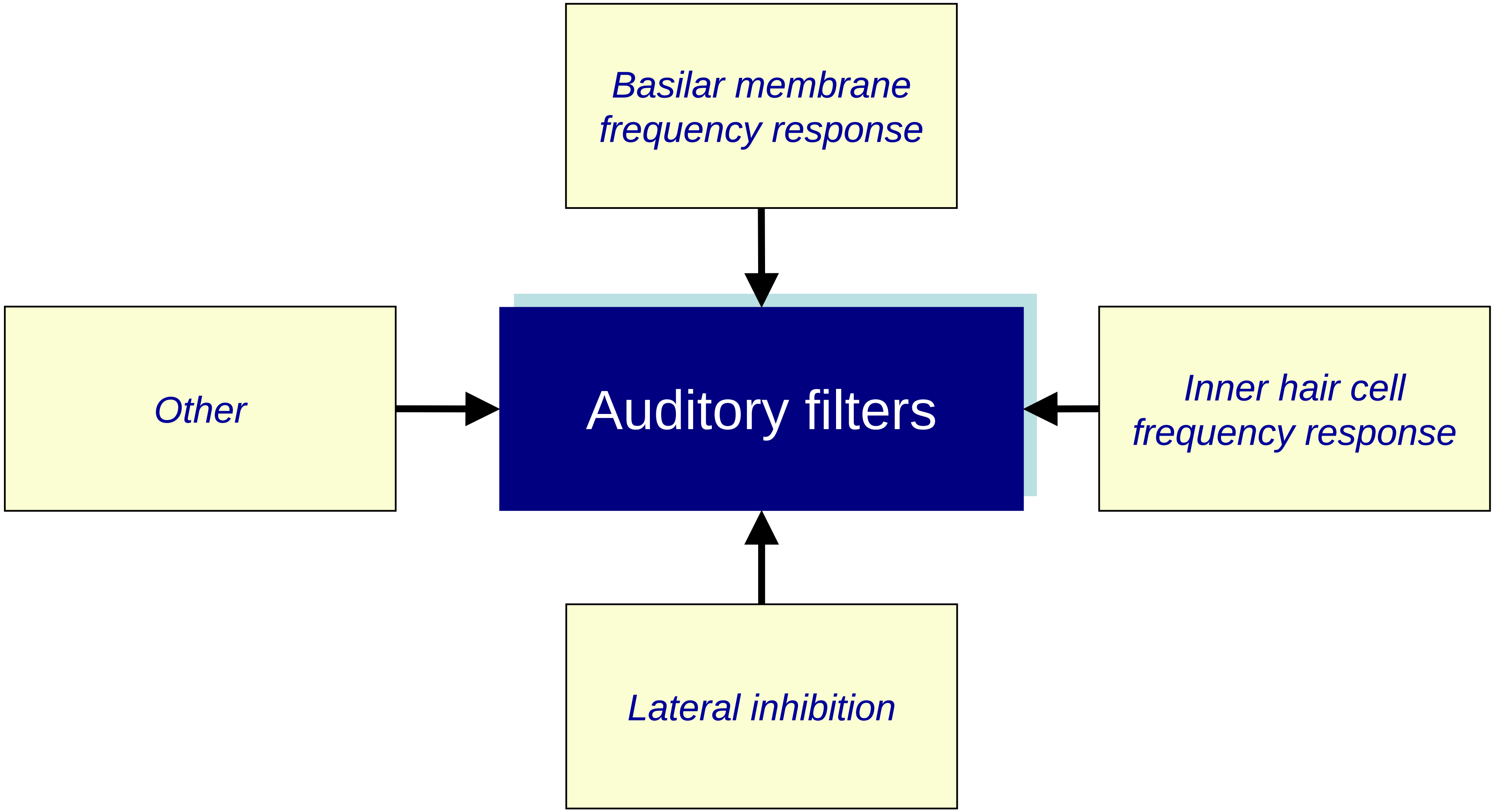
Simultaneous masking may reflect suppression of neural activity to the signal



Most probably, it is a combination of those two plus other phenomena

$$\begin{array}{lr} & \text{Swamping} \\ & \text{Suppression} \\ + & \text{Other} \\ \hline = & \text{Masking} \end{array}$$

The neurophysiological bases of (psychophysical) auditory filters



Basilar membrane frequency response

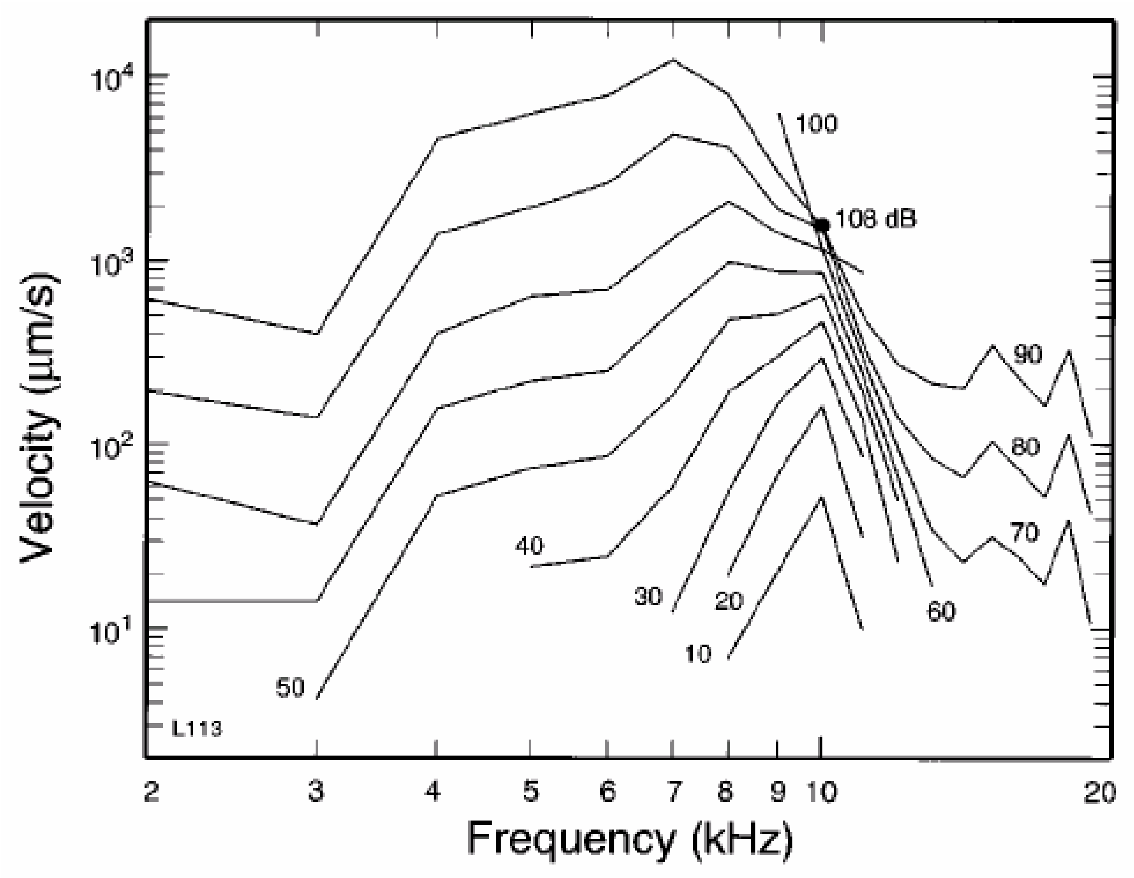
Other

Auditory filters

Inner hair cell frequency response

Lateral inhibition

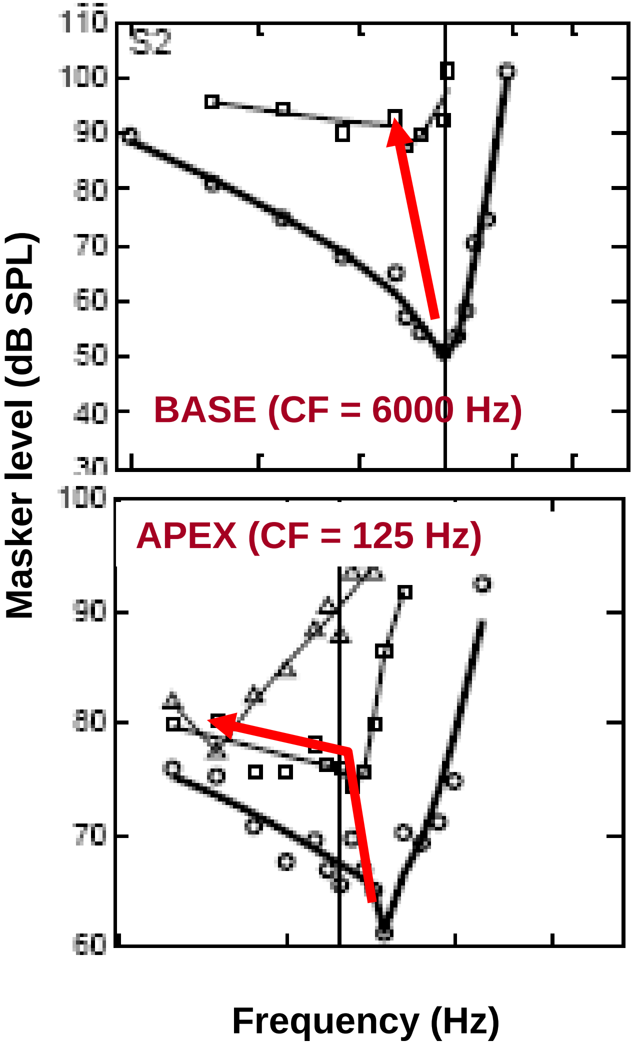
Auditory filters almost certainly reflect cochlear tuning



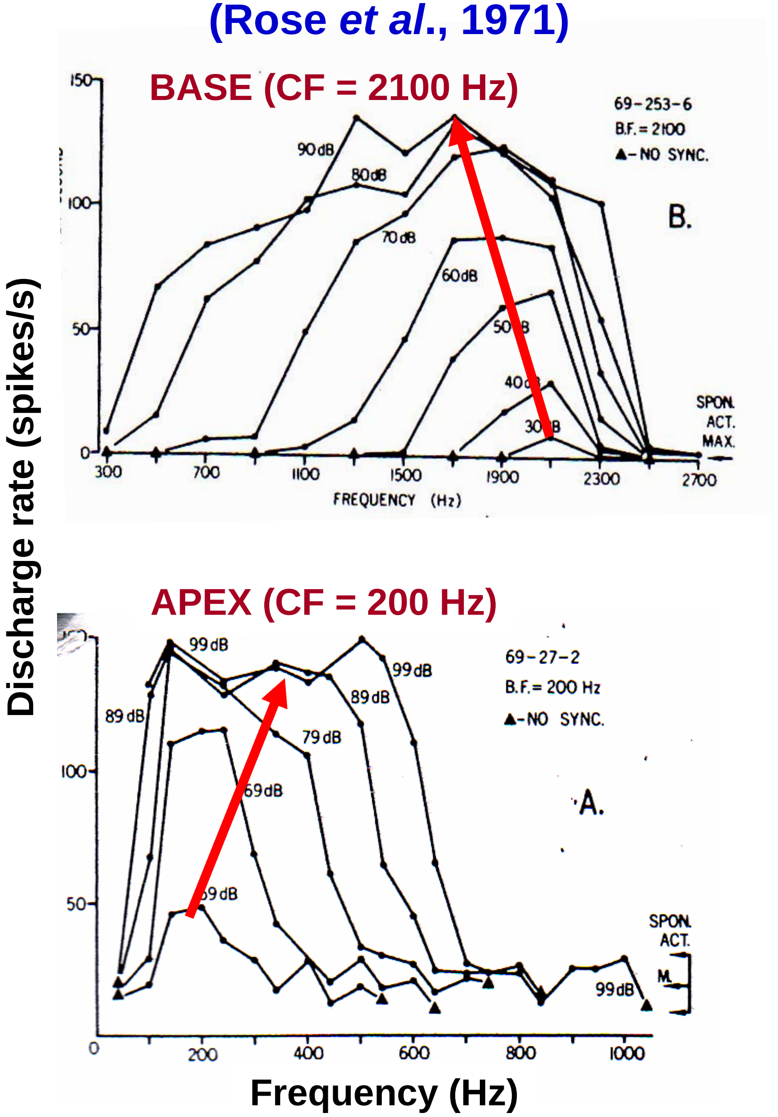
From: *Ruggero MA, Rich NC, Recio A, Narayan SS, Robles L. (1997). “Basilar-membrane responses to tones at the base of the chinchilla cochlea,” J Acoust Soc Am. 101(4):2151-63.*

But the inner hair cell may also contribute!

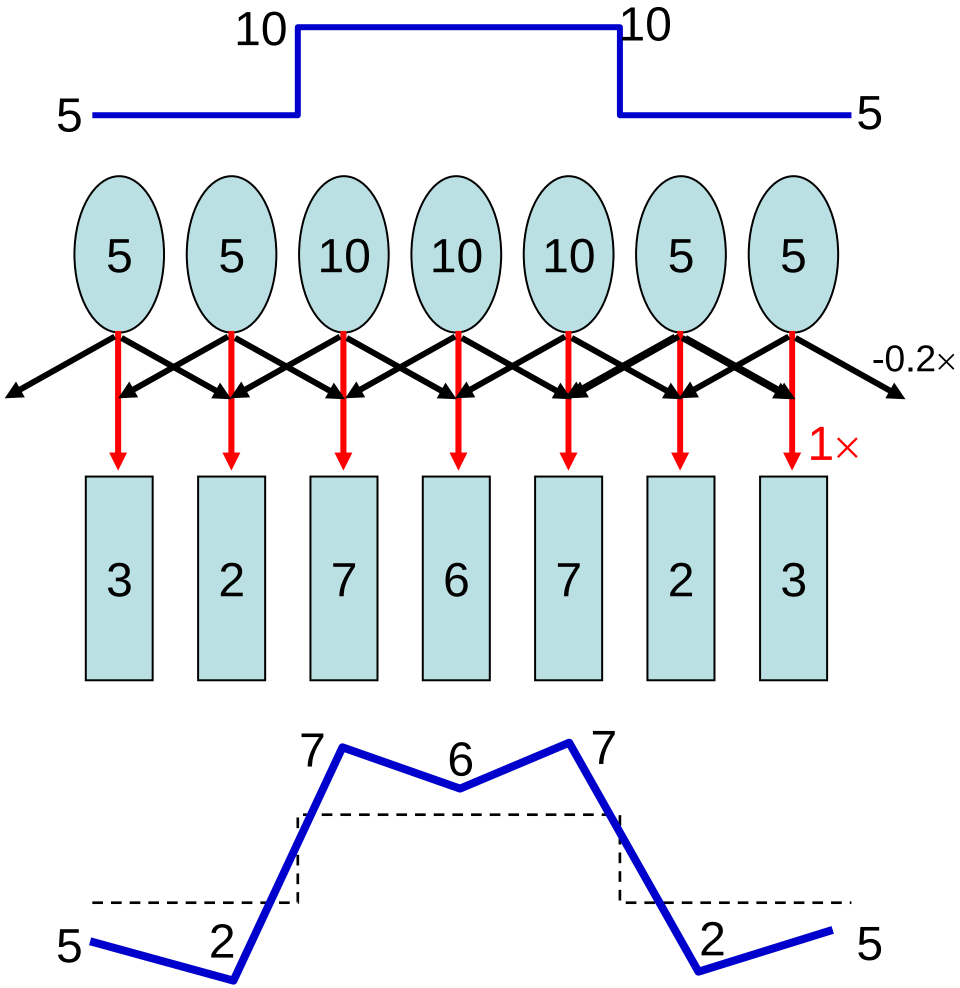
Psychoacoustics
(Lopez-Poveda et al., 2006)



Auditory nerve
(Rose *et al*., 1971)



Lateral inhibition may also contribute to "sharpen" auditory filters



Stimulus spectrum

Neurons

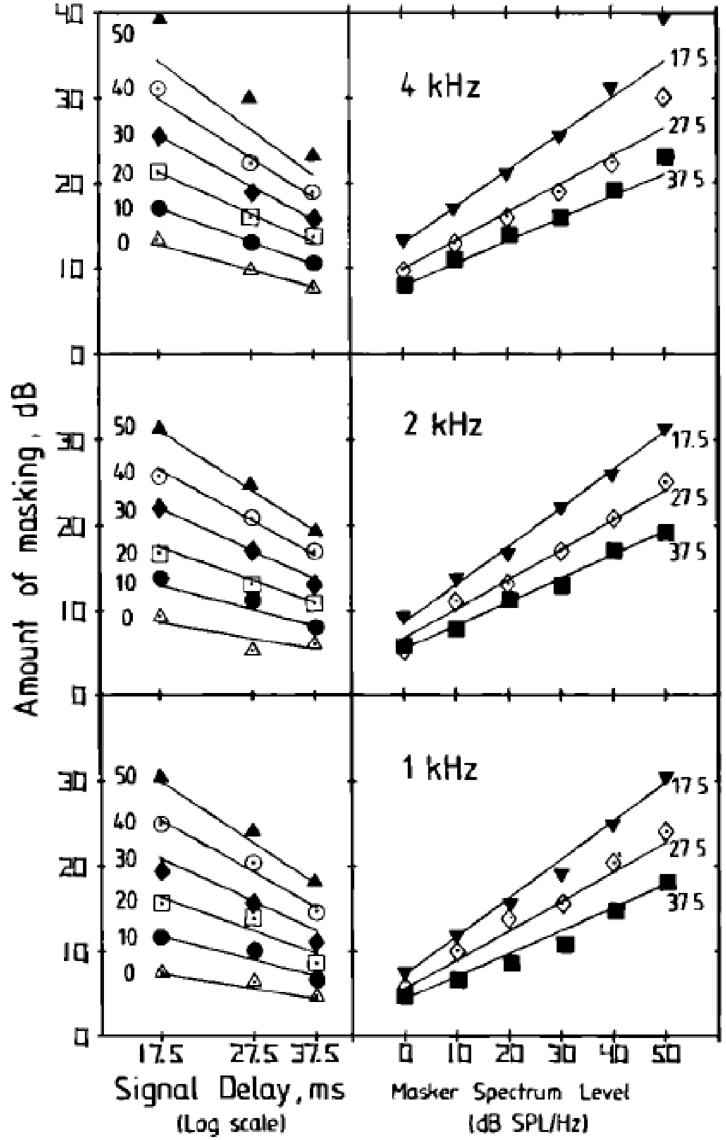
Output signal amplitude

Output spectrum

Yost, W. A. (2000). Fundamentals of hearing. Academic Press, San Diego.

Post-stimulatory (forward) masking

A sound may be masked by a preceeding sound



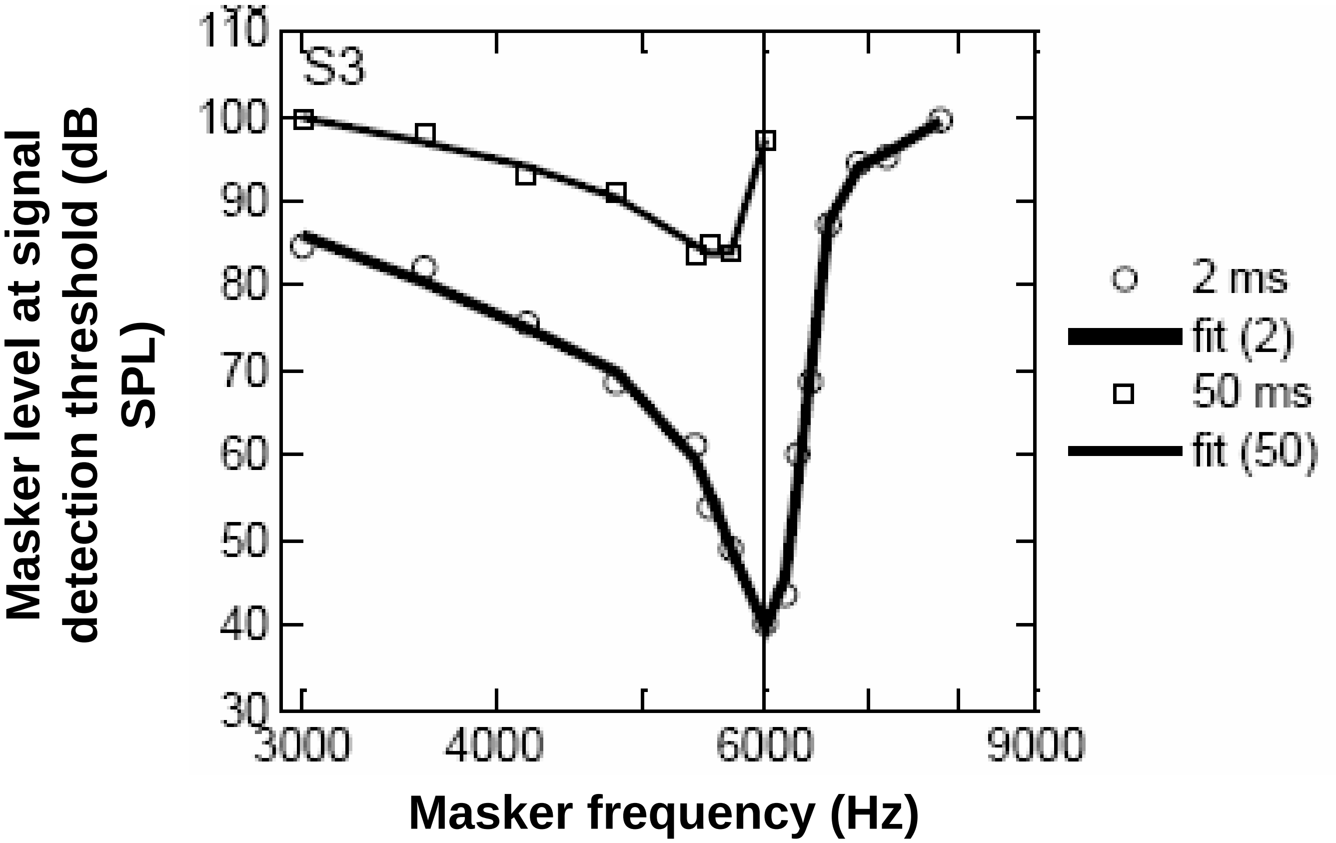
Left panels illustrate the amount of masking as a function of the time gap between the masker offset and the signal onset. The masker was a narrow-band noise. The signal was a pure tone. Each symbol is for a different masker level (in decibels).

Right panels illustrate the amount of masking as a function of the masker spectral level. Each symbol is for a different time gap (in ms).

Each row shows results for a different signal frequency (1, 2 and 4 kHz).

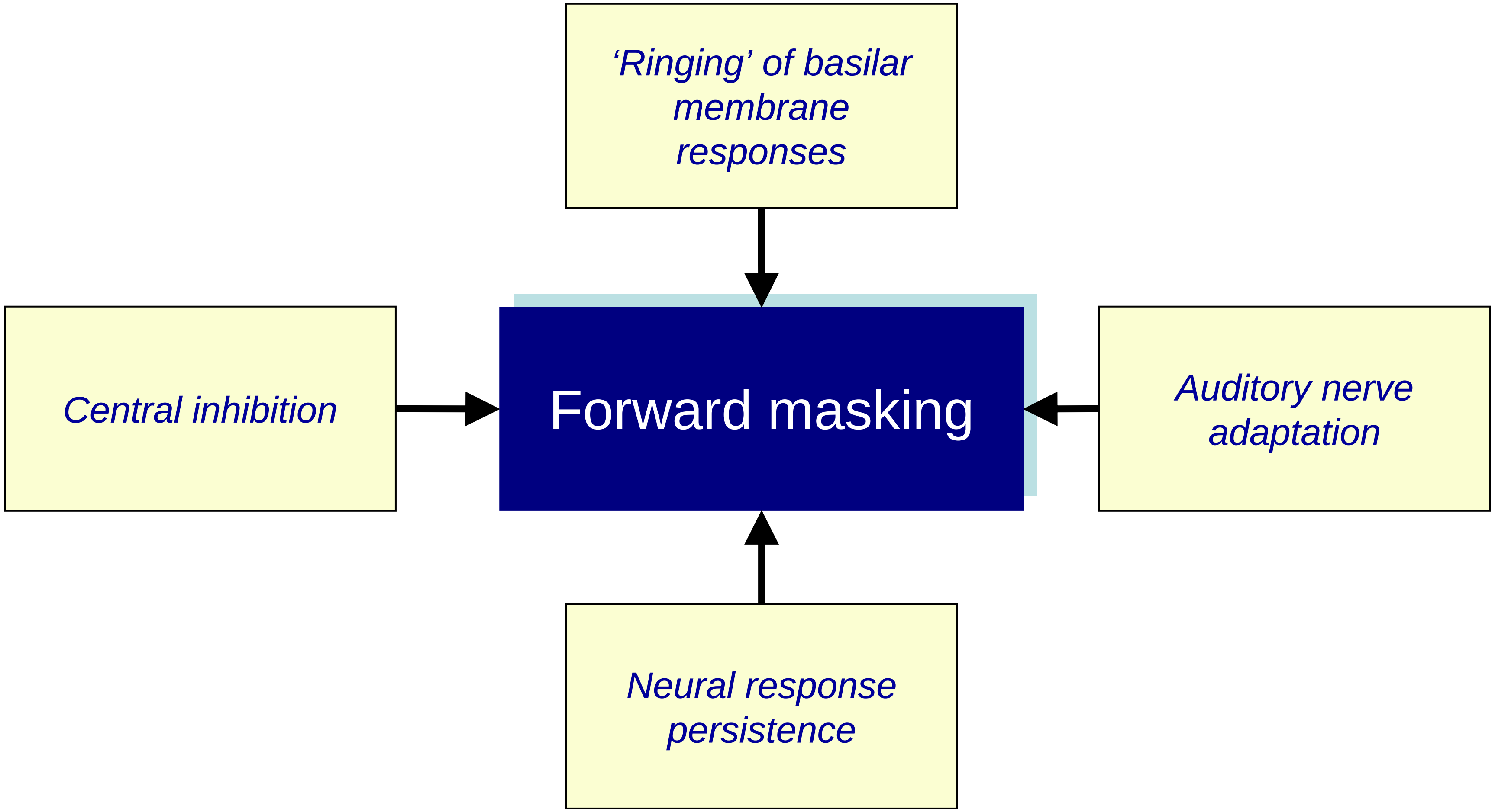
From: Moore BCJ, Glasberg BR (1983). Growth of masking for sinusoidal and noise maskers as a function of signal delay: implications for suppression in noise. J. Acoust. Soc. Am. 73, 1249-1259.

Psychoacoustical tuning curves measured with forward masking



From: Lopez-Poveda, E. A., Barrios, L. F., Alves-Pinto, A. (**2007**). "Psychophysical estimates of level-dependent best-frequency shifts in the apical region of the human basilar membrane," J. Acoust. Soc. Am. 121(6), 3646-3654.

The neurophysiological bases of forward masking



‘Ringing’ of basilar membrane responses

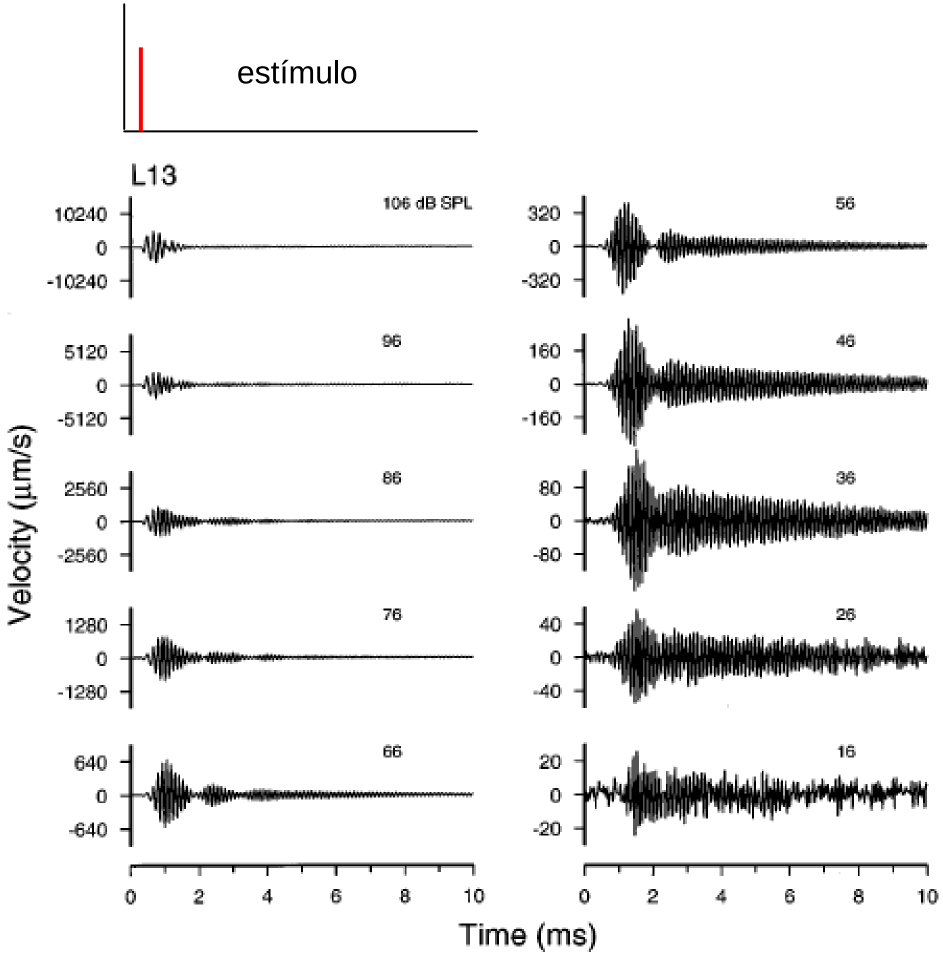
Central inhibition

Forward masking

Auditory nerve adaptation

Neural response persistence

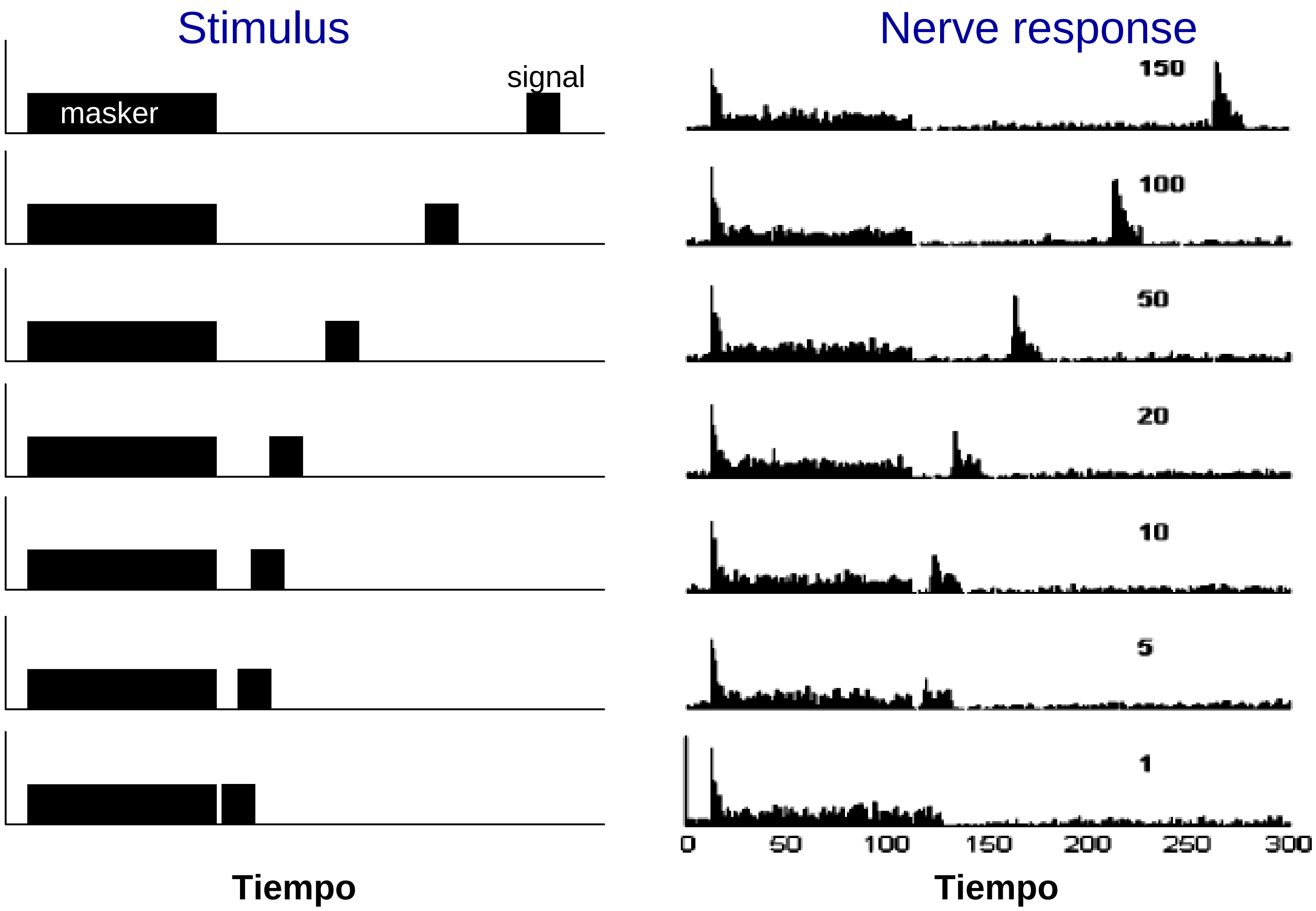
Persistence of basilar membrane responses after masker offset (‘ringing’)



The response of the basilar membrane does not end immediately after the stimulus offset. Instead, it persists over a period of time (as shown in the left figure). This ‘ringing’ effect may make the detection of the following signal more difficult.

From: Recio A, Rich NC, Narayan SS, Ruggero MA. (1998). “Basilar-membrane responses to clicks at the base of the chinchilla cochlea,” J. Acoust. Soc. Am. 103, 1972-1989.

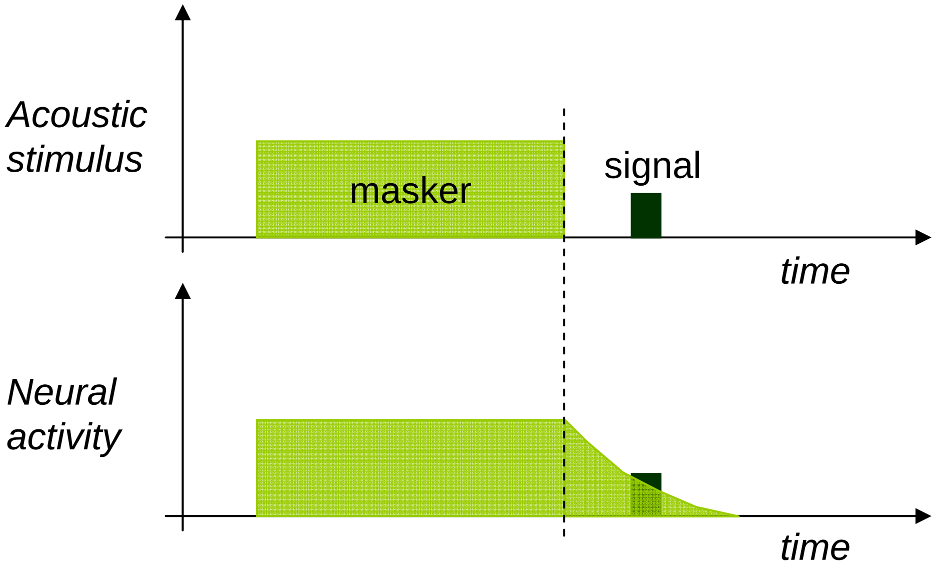
Auditory nerve fiber adaptation


Stimulus

Nerve response

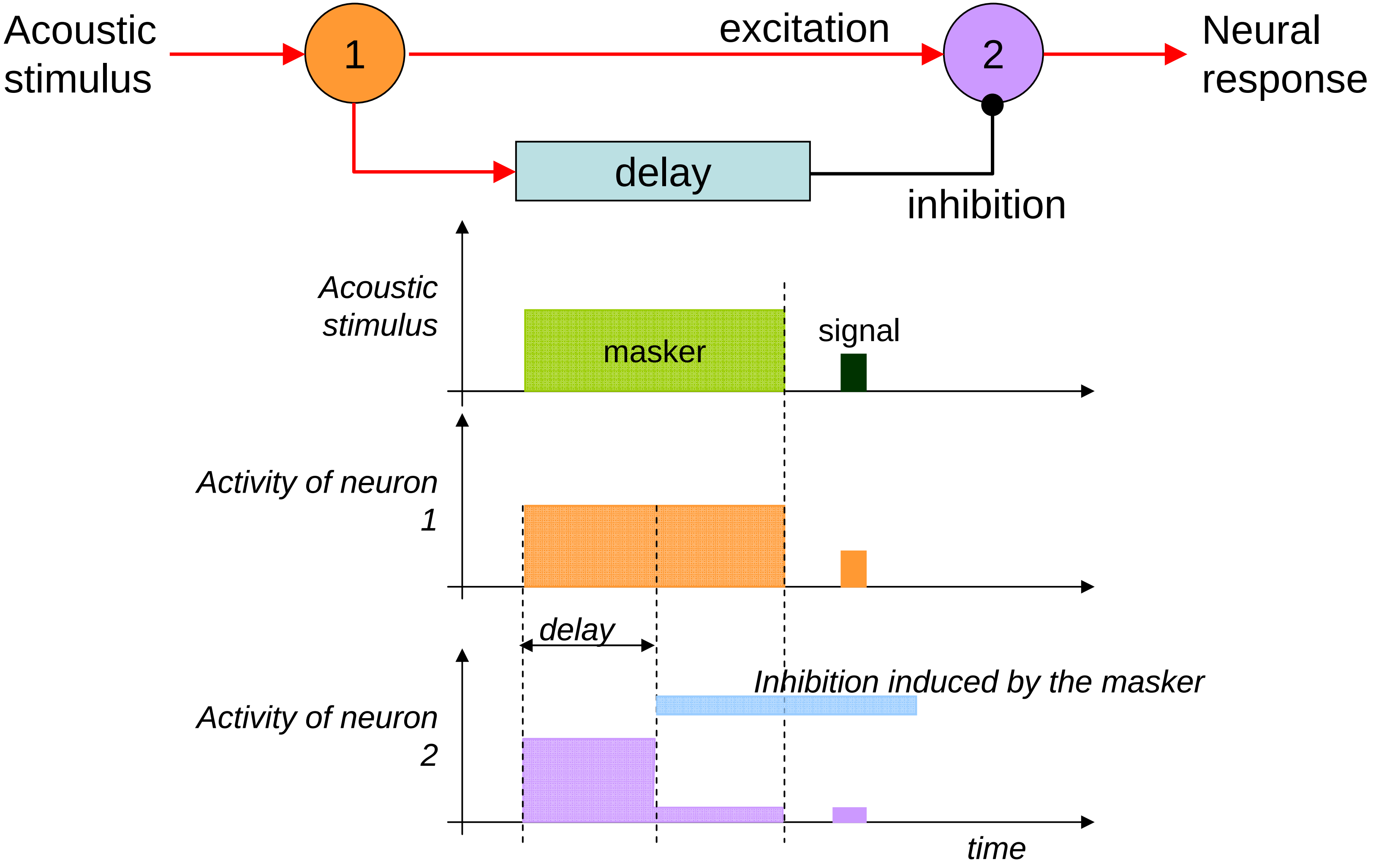
From: Meddis R, O'Mard LP. (2005). A computer model of the auditory-nerve response to forward-masking stimuli. J. Acoust. Soc. Am. 117, 3787-3798.

Persistence of neural activity



The persistence of neural activity may impair the detection of the signal.

Central inhibition



Pre-stimulatory (backward) masking

Backward masking

- Little is known about it.
- Hardly observed in well-trained subjects.
- Possibly, listeners misinterpret the brief signal with the start of the masker.

Frequency selectivity

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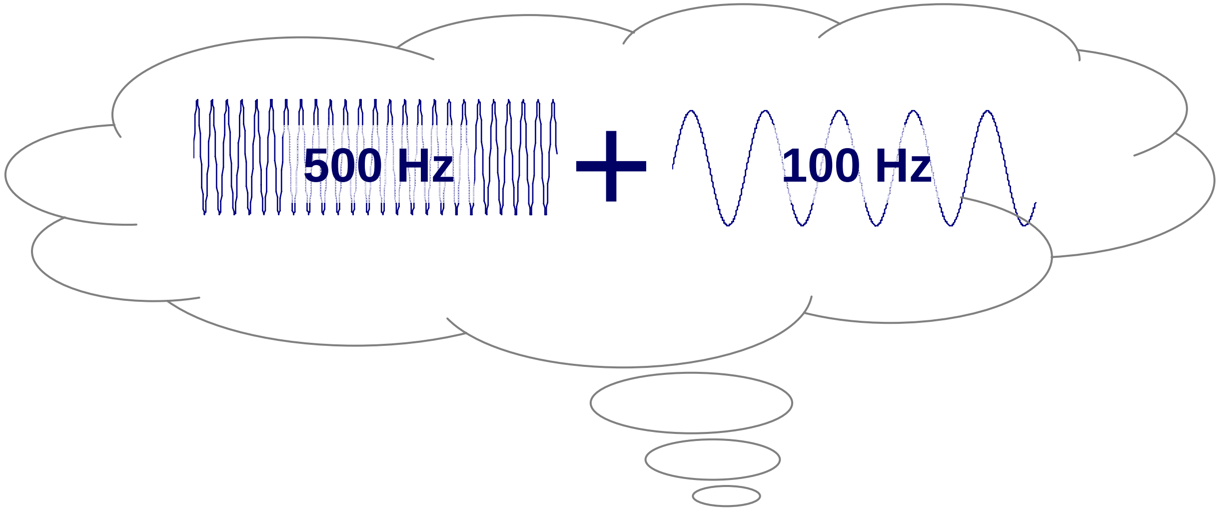
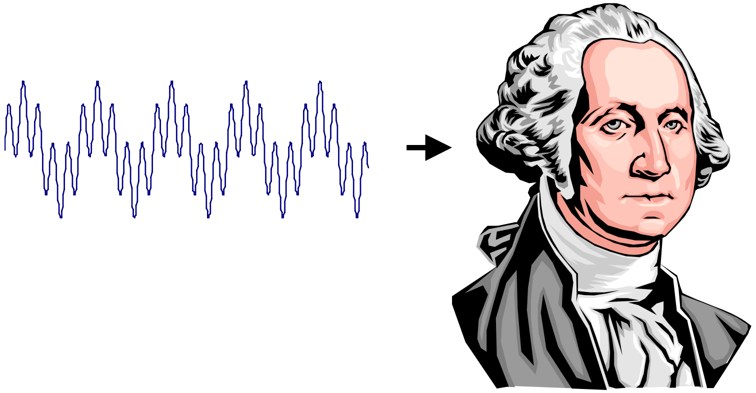
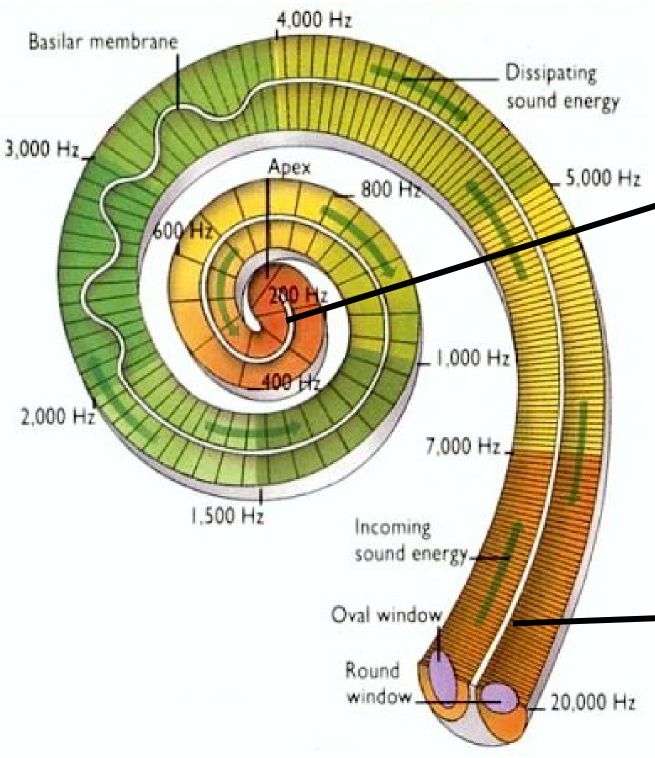
What is frequency selectivity?



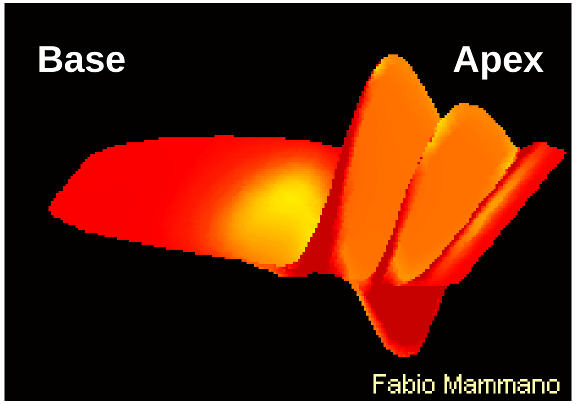
It is the ability to perceive separately multiple frequency components of a complex sound



How does it occur?

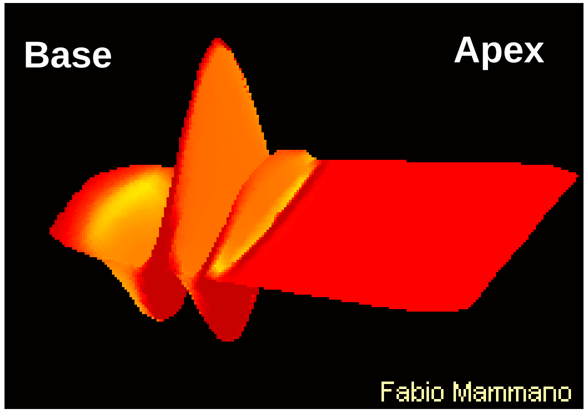


Low-frequency sound



Fabio Mammano

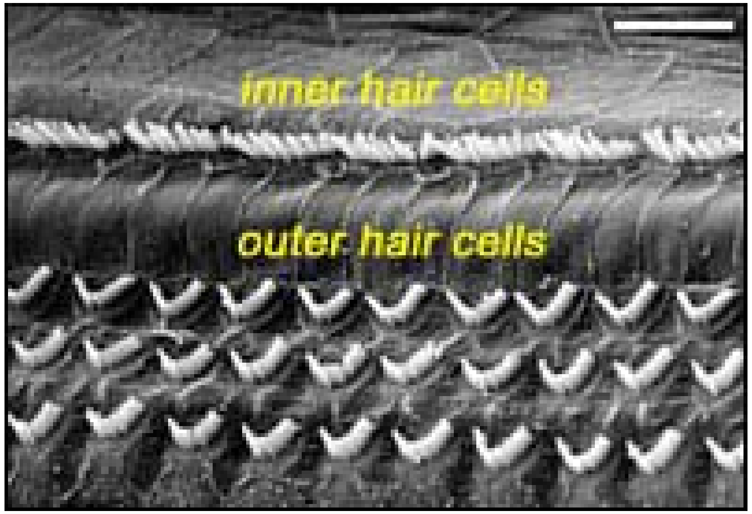
High-frequency sound



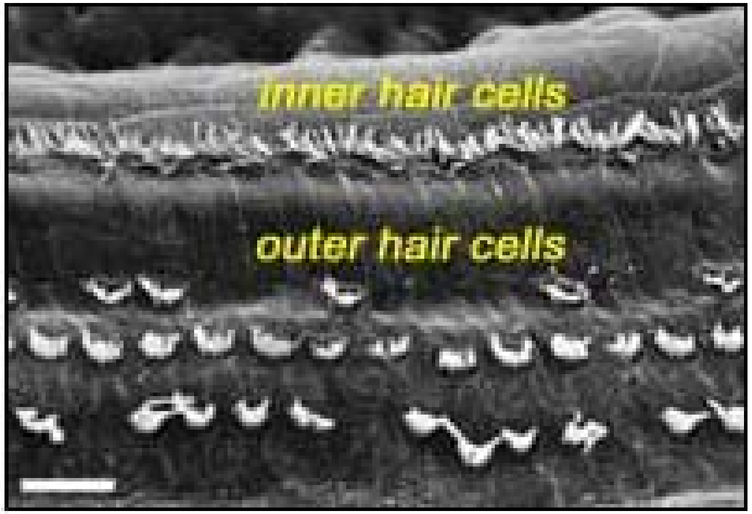
Fabio Mammano

It depends on the functional state of the cochlea

Normal cochlea

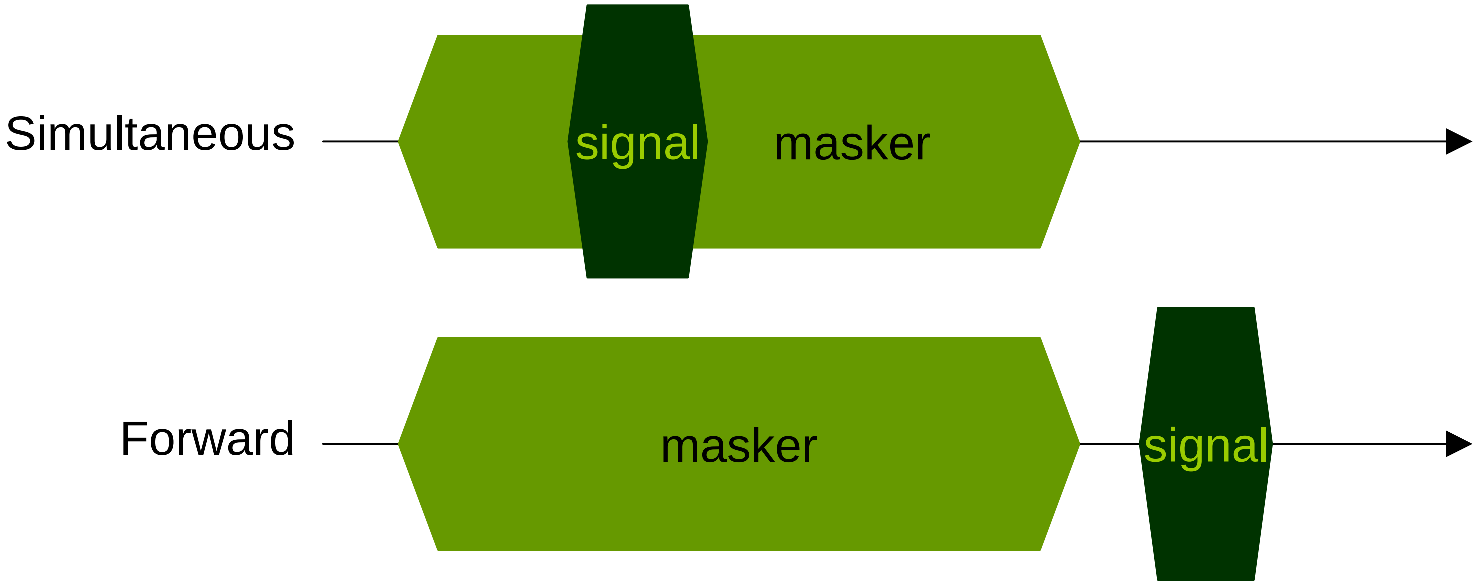


Damaged cochlea



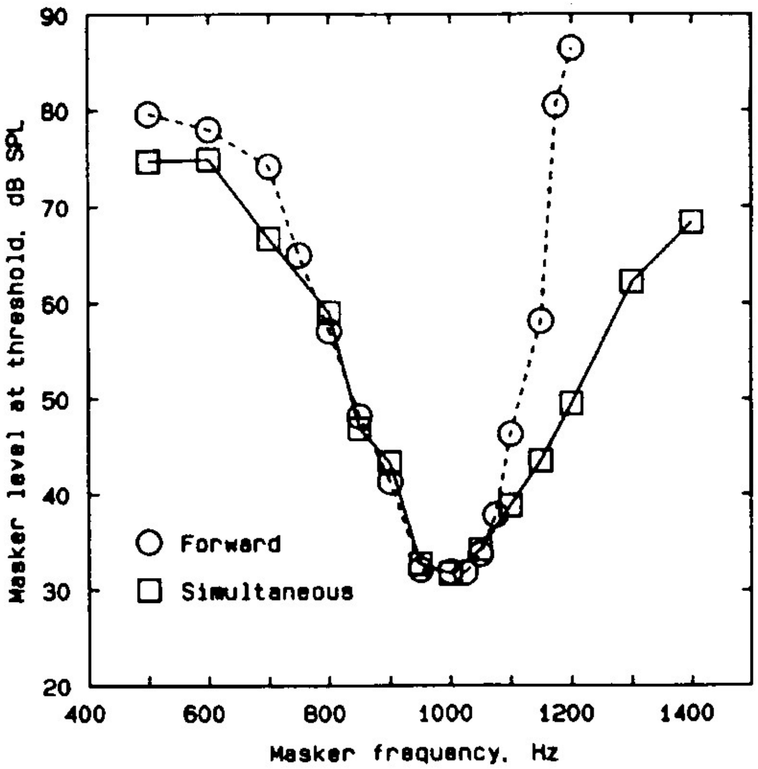
Psychoacoustical measures of frequency selectivity

Masking



Frequency selectivity may be measured using masking techniques like those previously described.

Psychophysical tuning curves are a measure of frequency selectivity

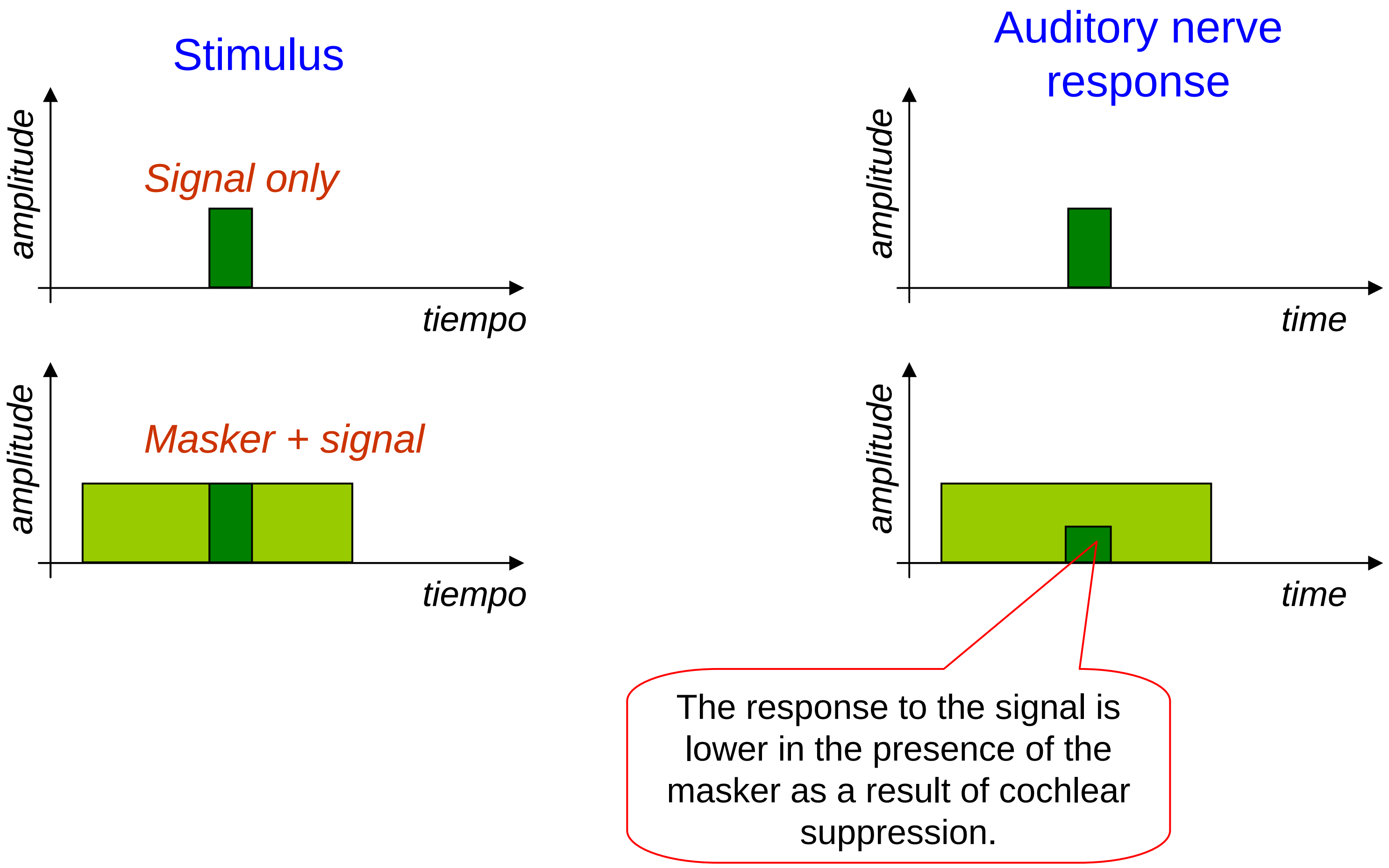


From: Moore BCJ. (1998). Cochlear Hearing Loss. Whurr Publishers, London.

Psychoacoustical tuning curves have different shapes depending on the masking method employed to measure them.

Curves measured with forward masking appear more tuned than those measured with simultaneous masking.

Cochlear suppression affects (psychoacoustical) frequency selectivity

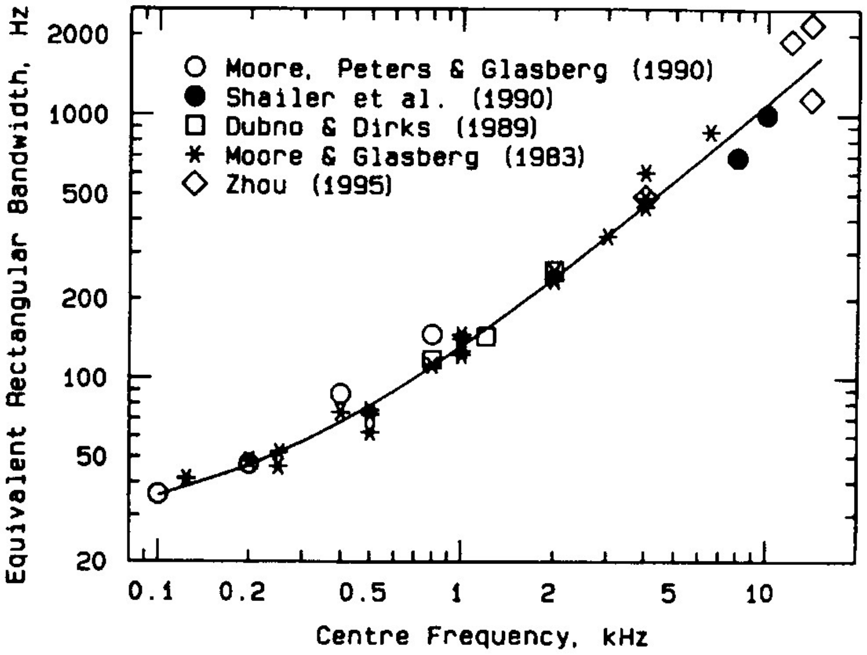


The response to the signal is lower in the presence of the masker as a result of cochlear suppression.

Frequency selectivity in normal-hearing listeners

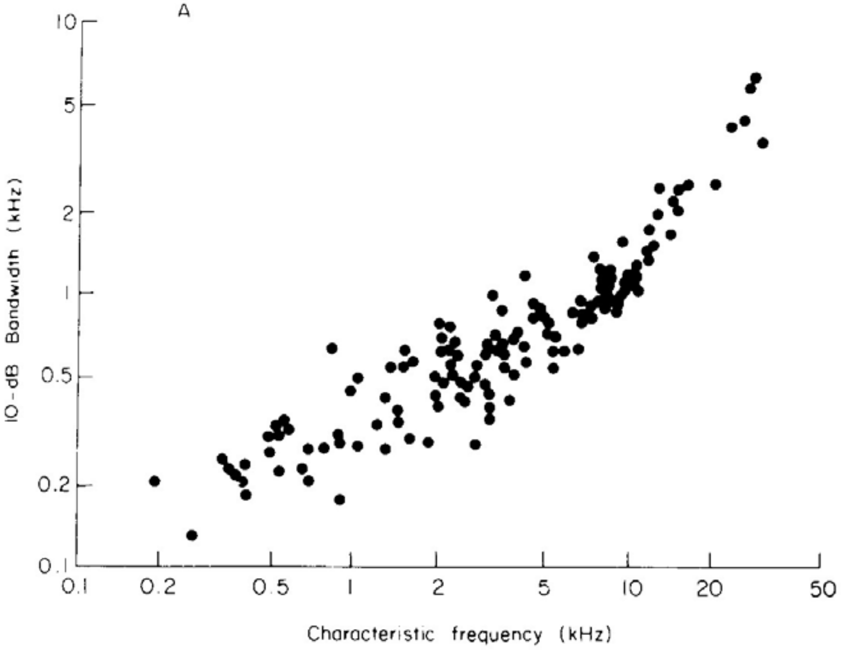
Filter bandwidth varies with center frequency

Psychoacoustical estimates for normal-hearing listeners



From: Moore BCJ (1998). Cochlear Hearing Loss. Whurr Publishers, London.

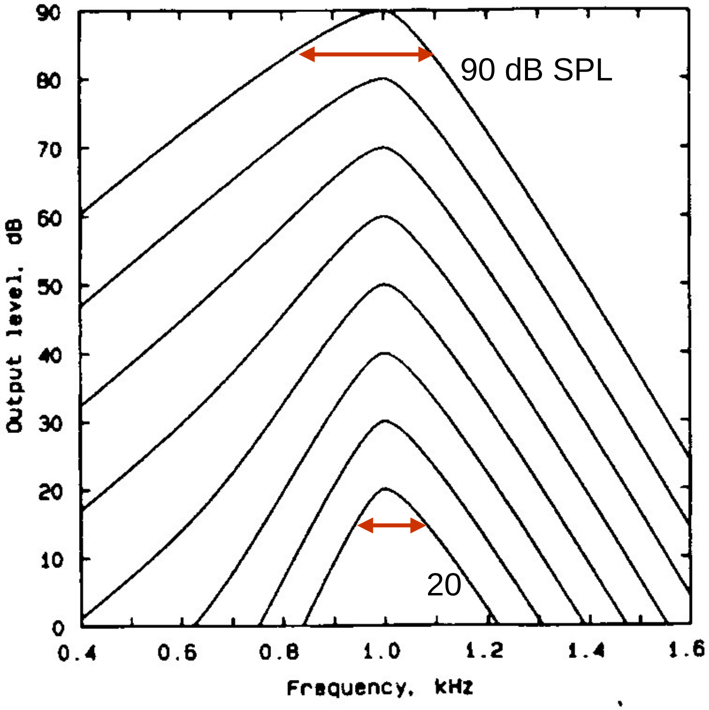
Auditory nerve data for cat



From: Pickles JO (1988). An Introduction to the Psychology of Hearing. Academic Press, London.

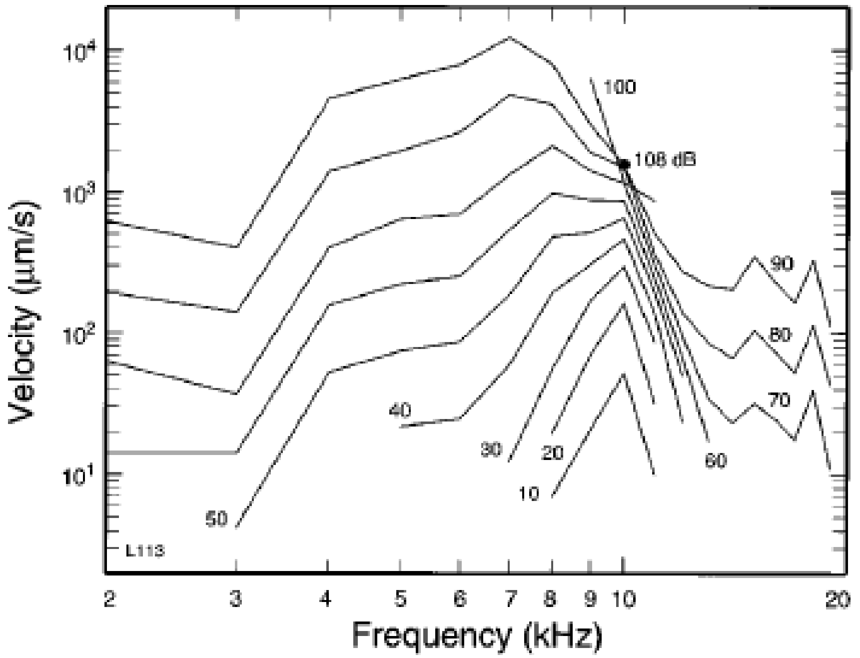
Filter tuning varies with sound level

Psychoacoustical estimates for normal-hearing listeners
CF = 1 kHz



From: Moore BCJ (1998). Cochlear Hearing Loss. Whurr Publishers, London.

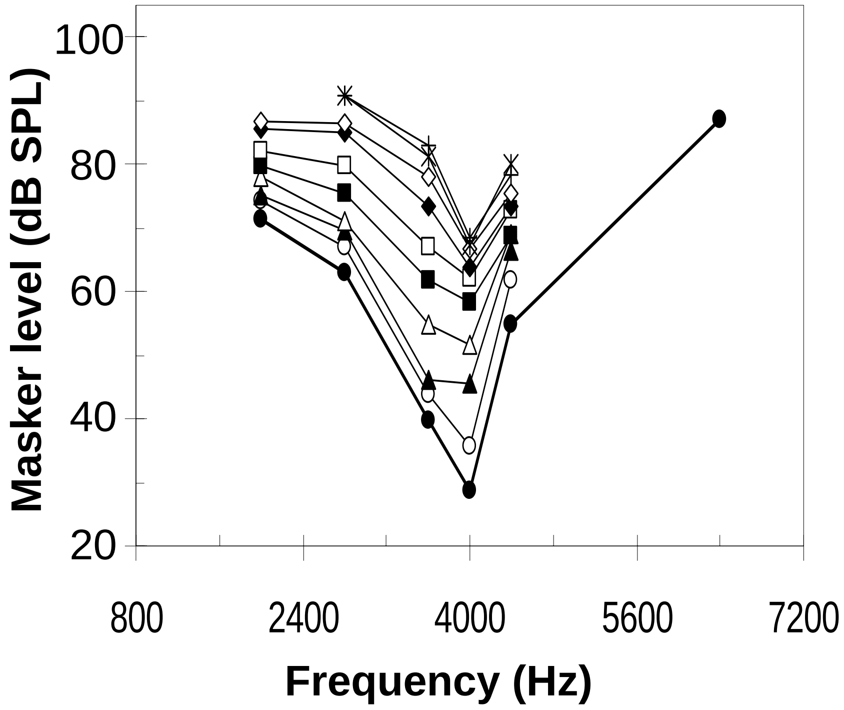
Guinea-pig basilar membrane response
CF = 10 kHz



From: Ruggero MA, Rich NC, Recio A, Narayan S, Robles L. (1997). Basilar membrane responses to tones at the base of the chinchilla cochlea. J. Acoust. Soc. Am. 101, 2151-2163.

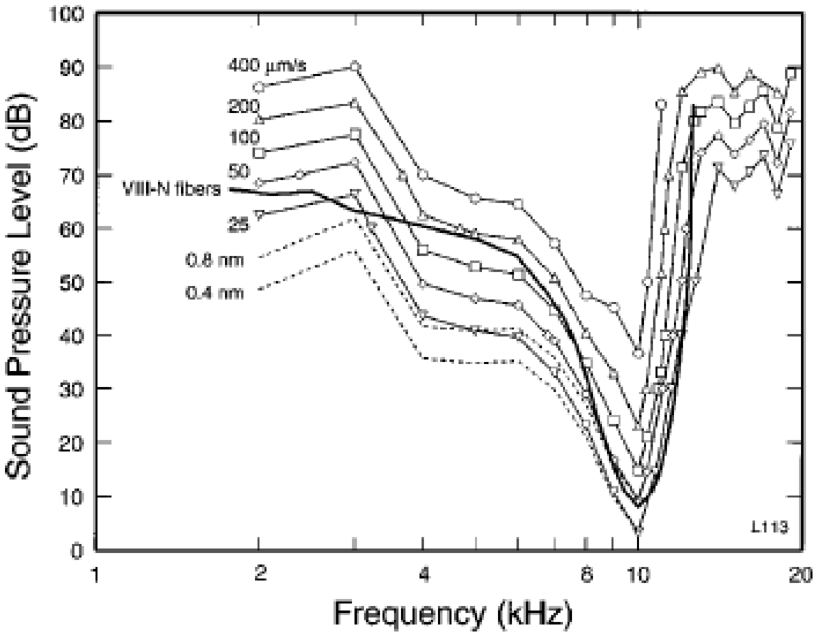
Tuning also varies with sound level: Tuning curves

Psychoacoustical estimates for normal-hearing listeners
CF = 4 kHz



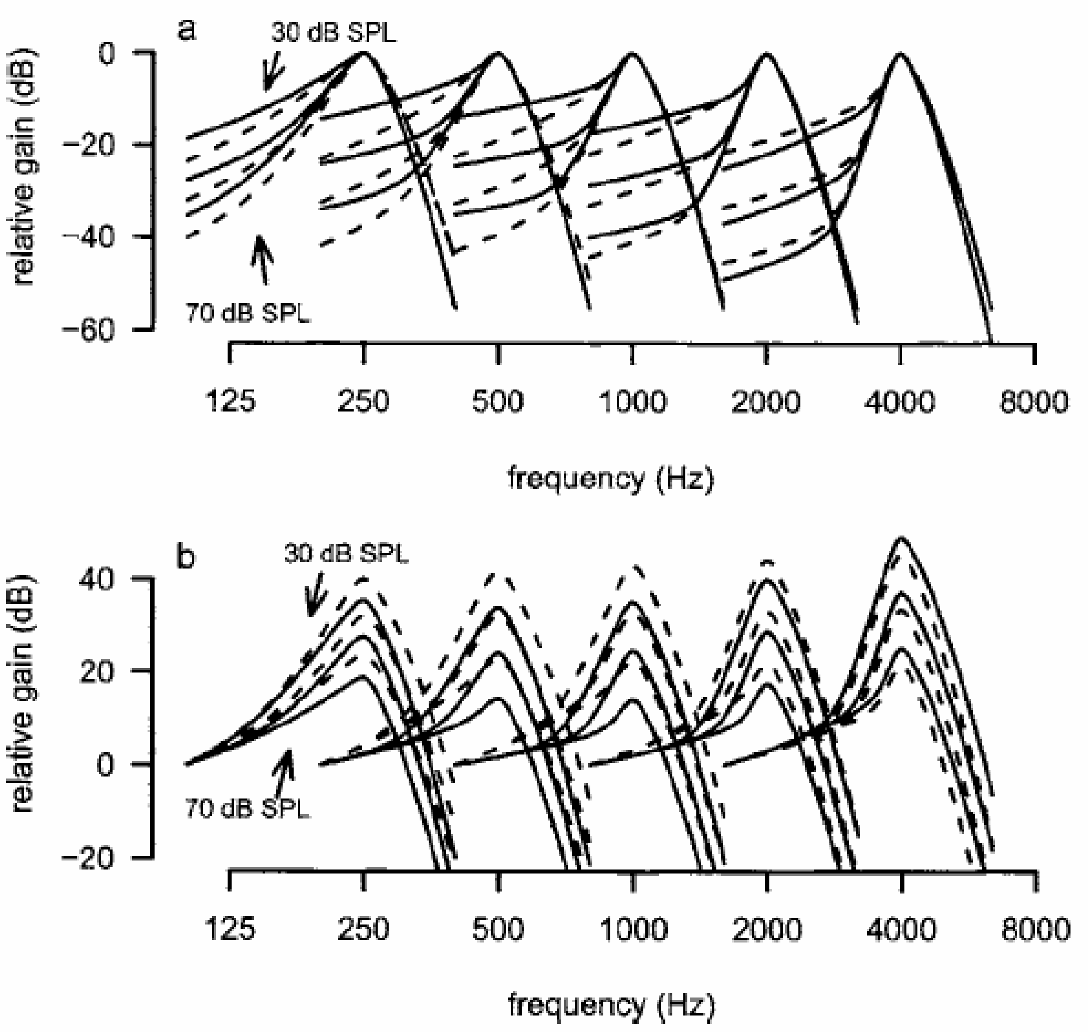
From: Lopez-Poveda, EA, Plack, CJ, and Meddis, R. (2003). "Cochlear nonlinearity between 500 and 8000 Hz in normal-hearing listeners," J. Acoust. Soc. Am. 113, 951-960.

Guinea-pig basilar membrane response
CF = 10 kHz



From: Ruggero MA, Rich NC, Recio A, Narayan S, Robles L. (1997). Basilar membrane responses to tones at the base of the chinchilla cochlea. J. Acoust. Soc. Am. 101, 2151-2163.

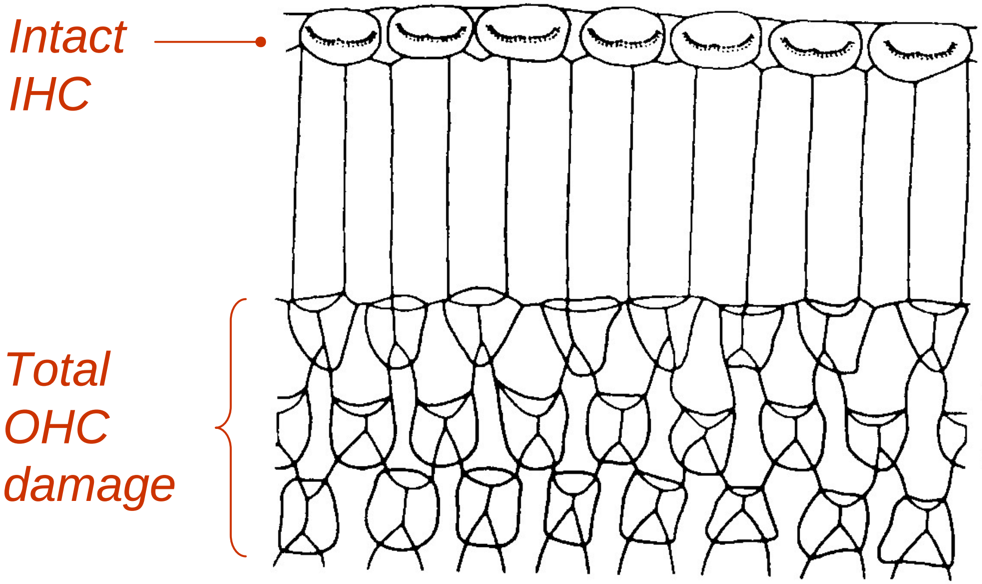
Auditory filters



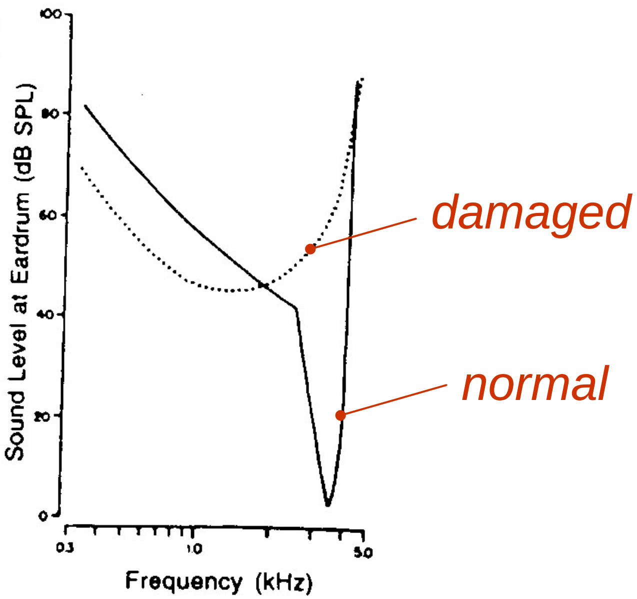
Adaptado de Baker y Rosen (2006)

Frequency selectivity in the auditory nerve: intact and damaged cochleae

Total outer hair cell (OHC) damage



Cochlear status

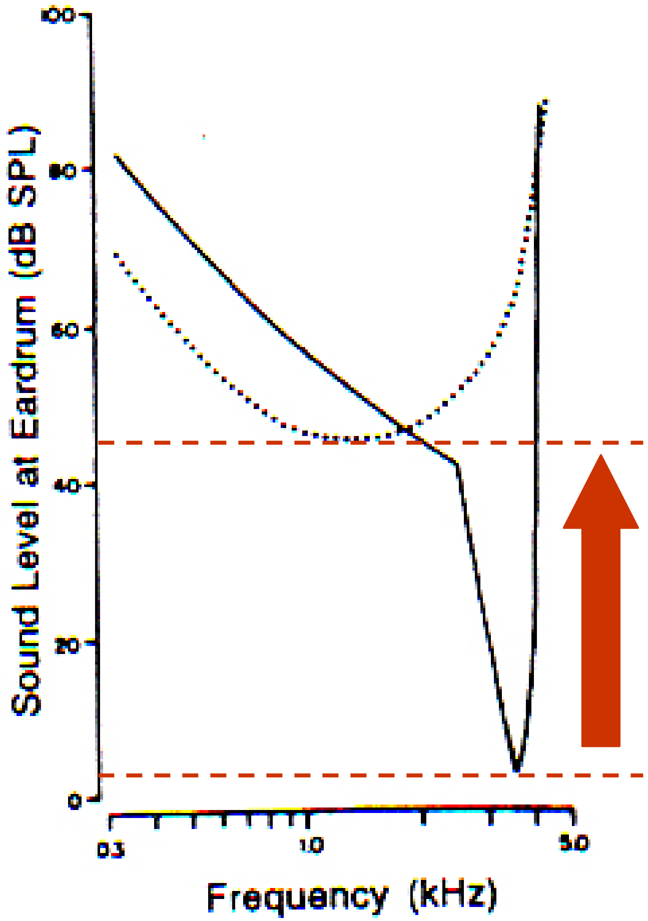


Tuning curves

Total OHC damage. Intact IHC.

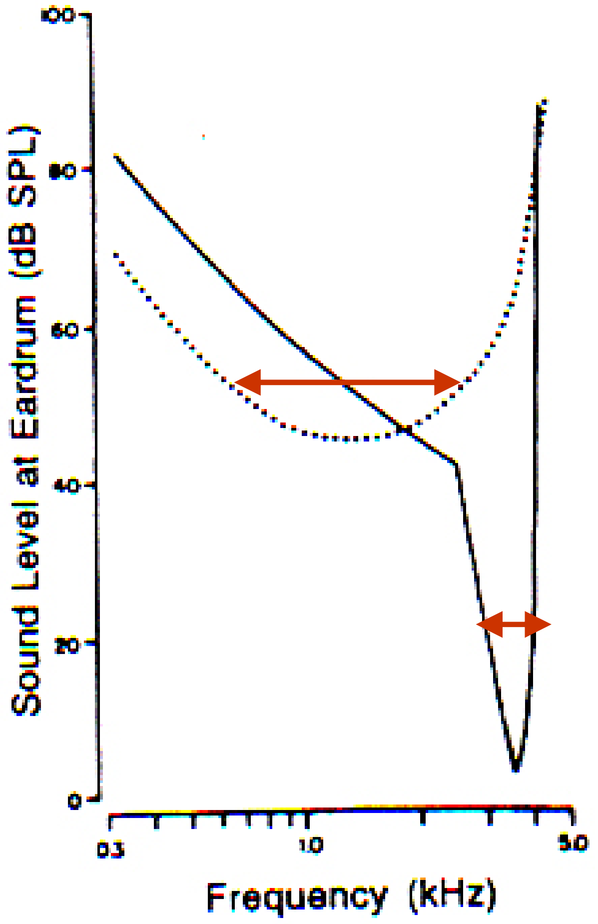
From: Liberman MC, Dodds LW, Learson DA. (1986). “Structure-function correlation in noise-damaged ears: a light and electrone-microscopy study.” in RJ Salvi, D Henderson, RP Hamernik, V Colletti. Basic and applied aspects of noise-induced hearing loss. (Plenum Publishing Corp, 1986).

Total OHC damage (cont.)



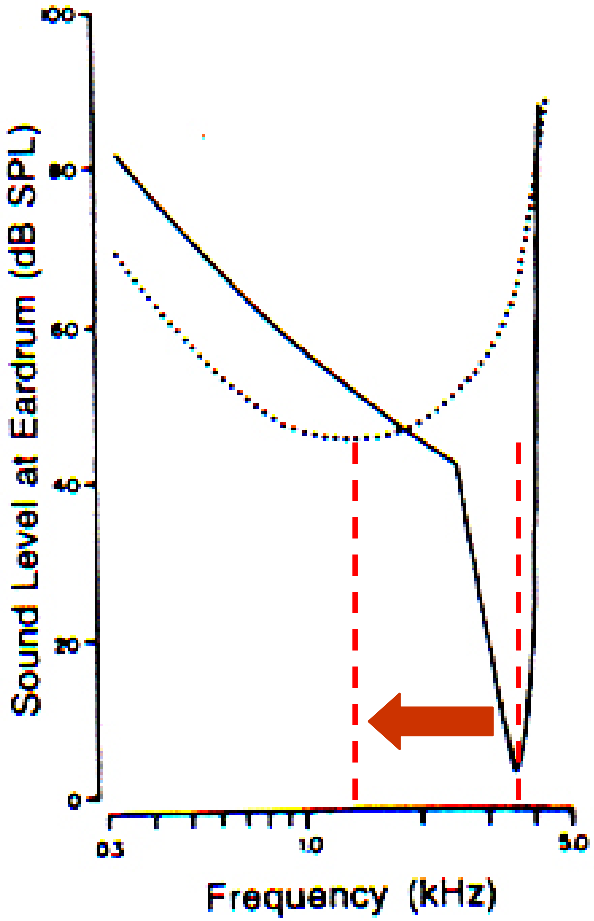
1. Reduced sensitivity, raised response threshold.

Total OHC damage (cont.)



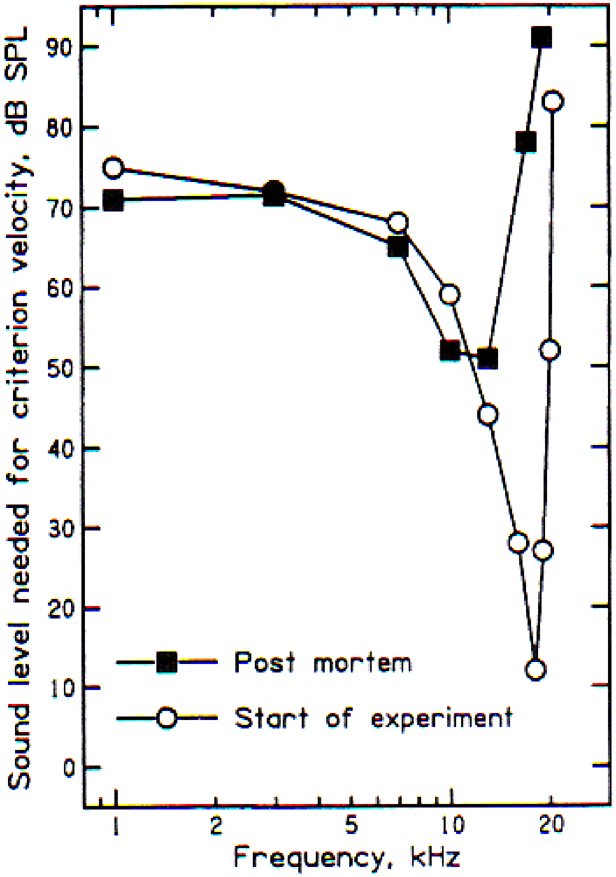
2. Broader tuning, reduced frequency selectivity.

Total OHC damage (cont.)



3. Lower characteristic frequency (CF).

In vivo and post-mortem basilar membrane responses



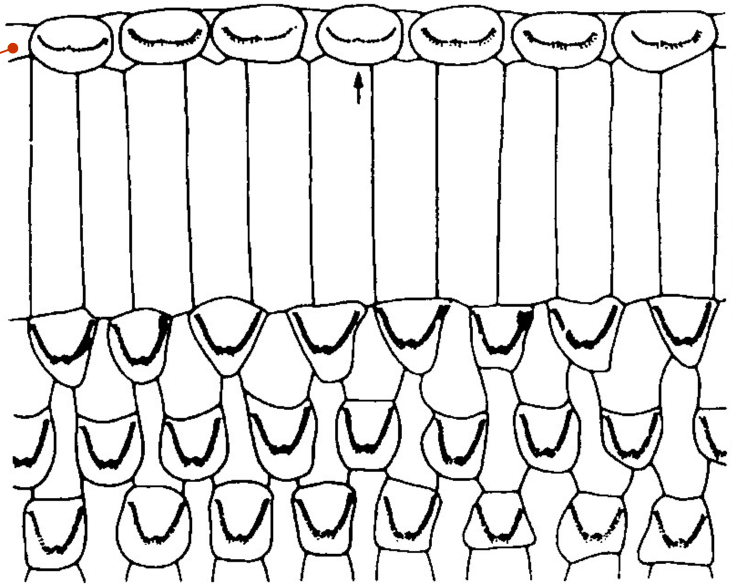
The effects described before are similar to those observed when comparing *in vivo* and post-mortem basilar membrane tuning curves for the same cochlear region (left figure).

Consequently, it is generally thought that auditory nerve tuning reflects basilar membrane tuning.

From: Sellick PM, Patuzzi R, Johnstone BM. (1982). Measurements of basilar membrane motion in ght guinea pig using the Mössbauser technique. J. Acoust. Soc. Am. 72, 131-141.

Partial inner hair cell (IHC) damage

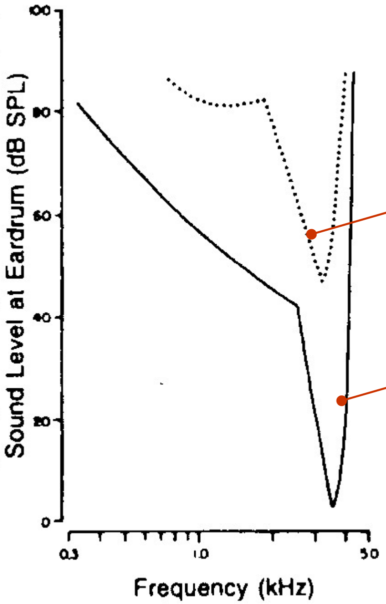
Cochlear status



Partial IHC damage

Normal OHCs

Tuning curves



damaged

normal

Partial IHC damage (arrow).
Intact OHCs

From: Liberman MC, Dodds LW, Learson DA. (1986). "Structure-function correlation in noise-damaged ears: a light and electrone-microscopy study." in RJ Salvi, D Henderson, RP Hamernik, V Colletti. Basic and applied aspects of noise-induced hearing loss. (Plenum Publishing Corp, 1986).

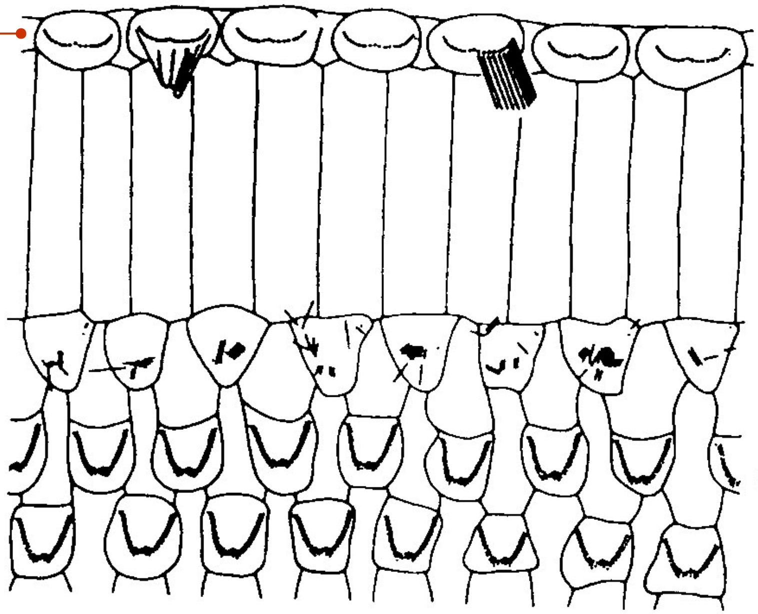
Severe OHC and IHC damage

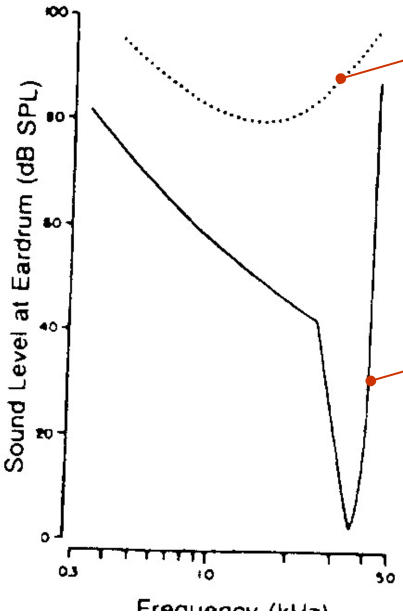
Cochlear status

Tuning curves

Severe IHC damage

Severe OHC damage





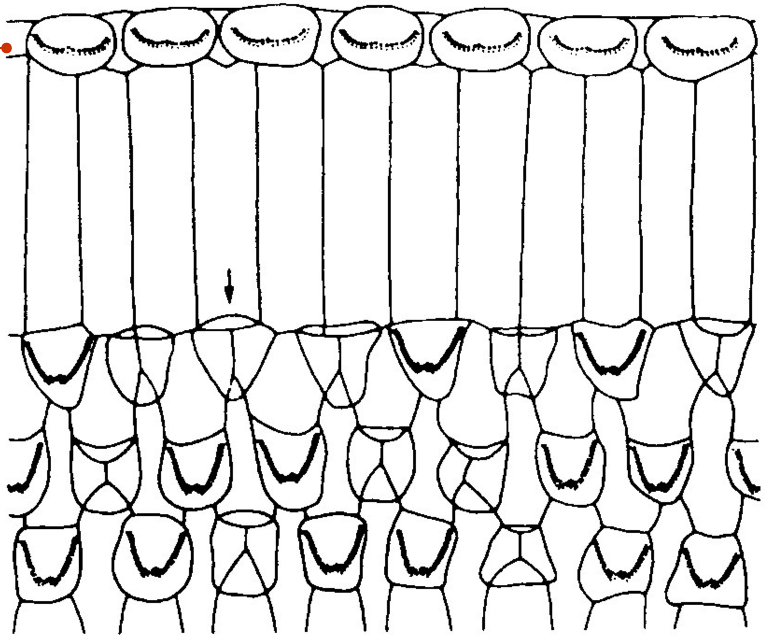
damaged

normal

From: Liberman MC, Dodds LW, Learson DA. (1986). “Structure-function correlation in noise-damaged ears: a light and electrone-microscopy study.” in RJ Salvi, D Henderson, RP Hamernik, V Colletti. Basic and applied aspects of noise-induced hearing loss. (Plenum Publishing Corp, 1986).

Partial (combined) OHC and IHC damage

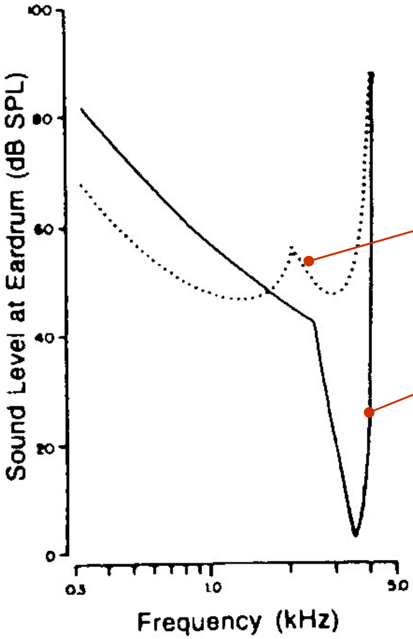
Cochlear status



Partial IHC damage

Partial OHC damage

Tuning curves



damaged

normal

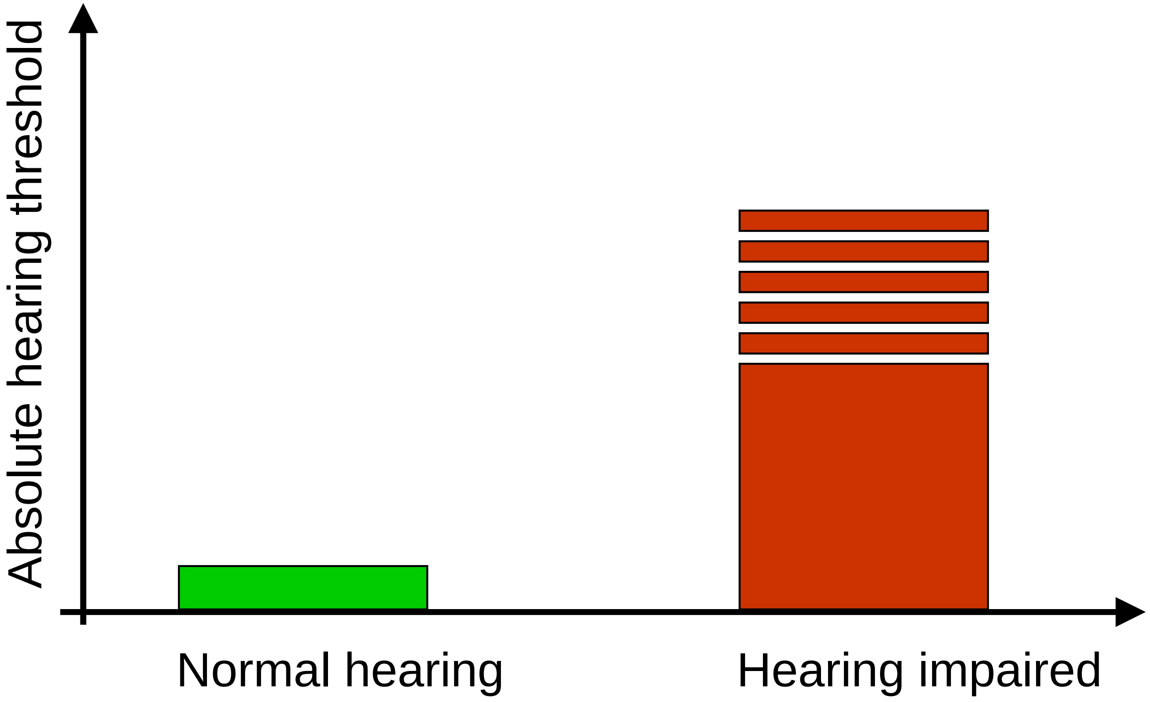
Partial IHC damage
Partial OHC damage

From: Liberman MC, Dodds LW, Learson DA. (1986). "Structure-function correlation in noise-damaged ears: a light and electrone-microscopy study." in RJ Salvi, D Henderson, RP Hamernik, V Colletti. Basic and applied aspects of noise-induced hearing loss. (Plenum Publishing Corp, 1986).

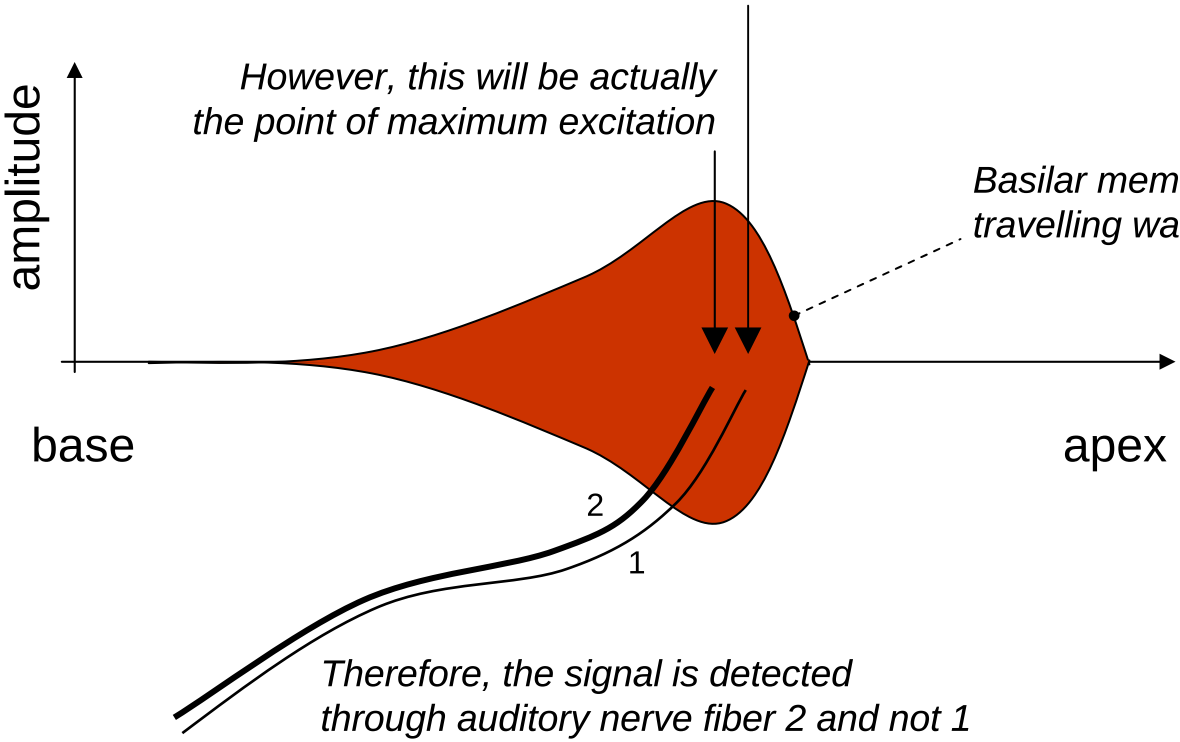
Frequency selectivity in normal-hearing listeners *vs*. listeners with cochlear hearing loss

Difficult comparison because sound level is different!

Filter shape varies with sound level and sound level is necessarily higher for hearing-impaired listeners.



Difficult comparison because of off-frequency listening!



The signal should produce the maximum excitation at this point on the basilar membrane…

However, this will be actually the point of maximum excitation

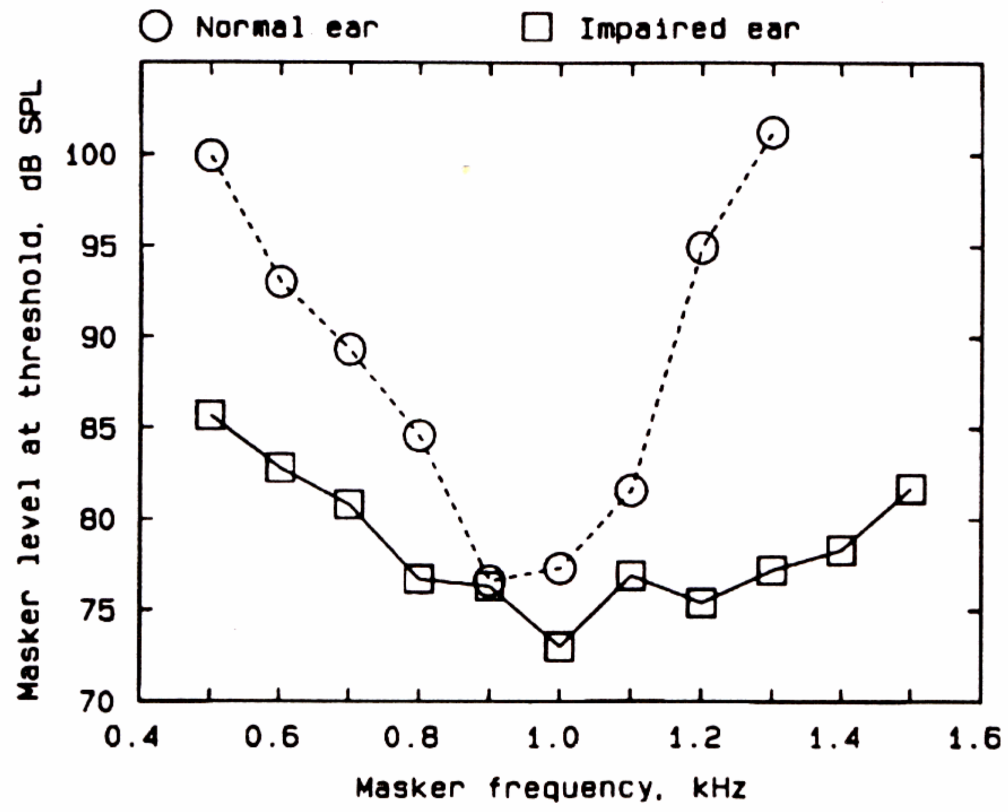
Basilar membrane travelling wave

Therefore, the signal is detected through auditory nerve fiber 2 and not 1 (despite the CF of the latter equals the signal frequency).

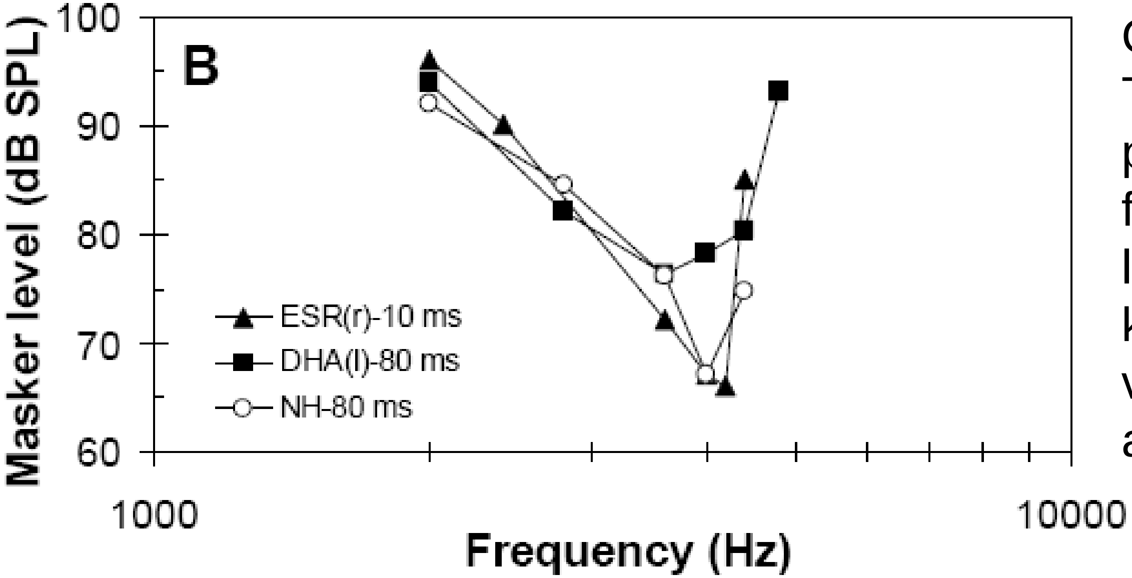
Psychoacoustical tuning curves

The signal was a pure tone of 1 kHz at 10 dB SL. The masker was a narrowband noise. From Moore & Glasberg (1986).

PTCs are broader for hearing-impaired listeners!



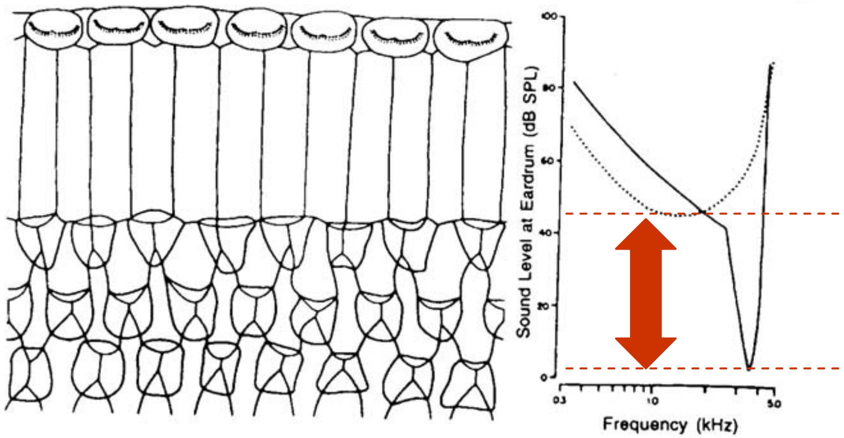
Does frequency selectivity decrease with amoung of hearing loss?



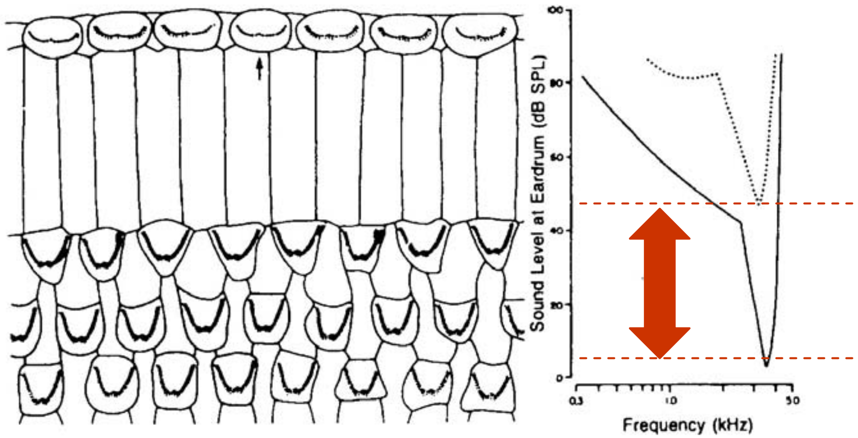
Generally yes, but not always! The figure compares psychoacoustical tuning curves for two hearing impaired listeners with similar losses at 4 kHz. Their tuning curves are very different (one of them is almost normal).

From: Lopez-Poveda, EA, Plack, CJ, Meddis, R, and Blanco, JL. (2005). "Cochlear compression between 500 and 8000 Hz in listeners with moderate sensorineural hearing loss," Hearing Res. 205, 172-183.

Why is this?

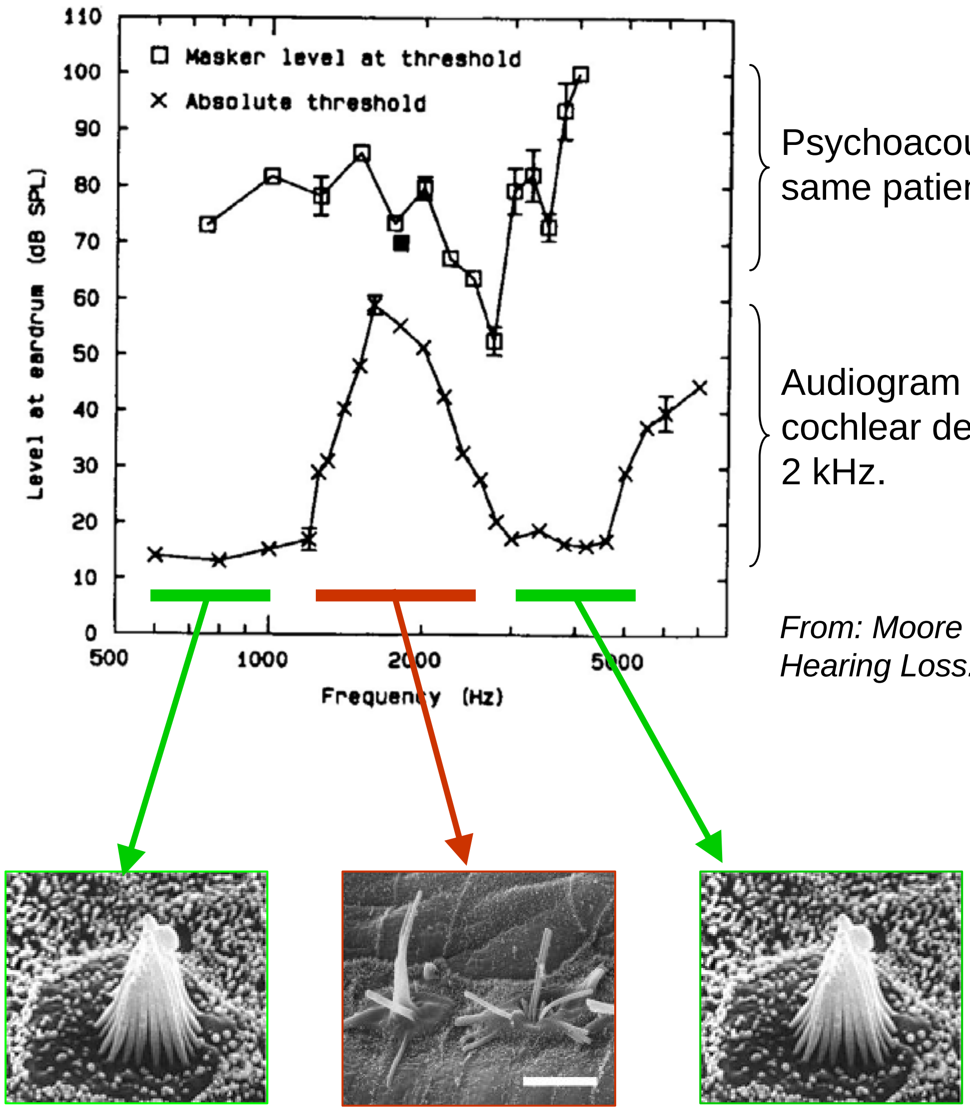


Possibly, the hearing loss of listener DHA is due to outer hair cell dysfunction…



…while that of listener ESR is due to inner hair cell dysfunction.

Dead (cochlear) regions



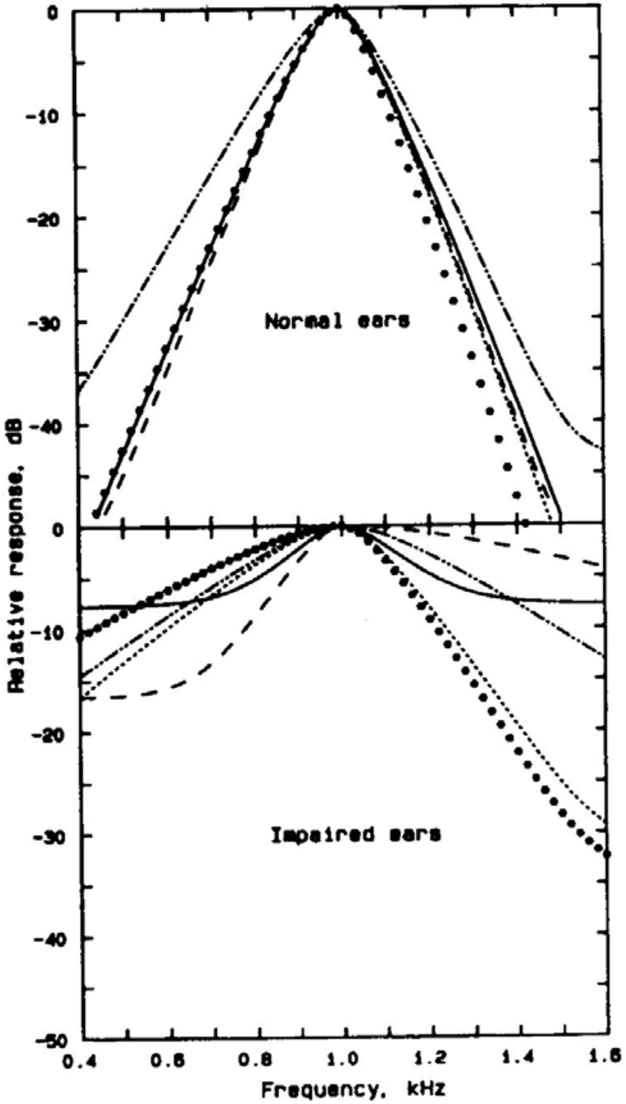
Psychoacoustical tuning curve of the same patient for a 2-kHz signal.

Audiogram of a patient with a cochlear dead region (in red) around 2 kHz.

From: Moore BCJ (1998). Cochlear Hearing Loss. Whurr Publishers, London.

IHC stereocilia in healthy (green) and dead (red) cochlear regions.

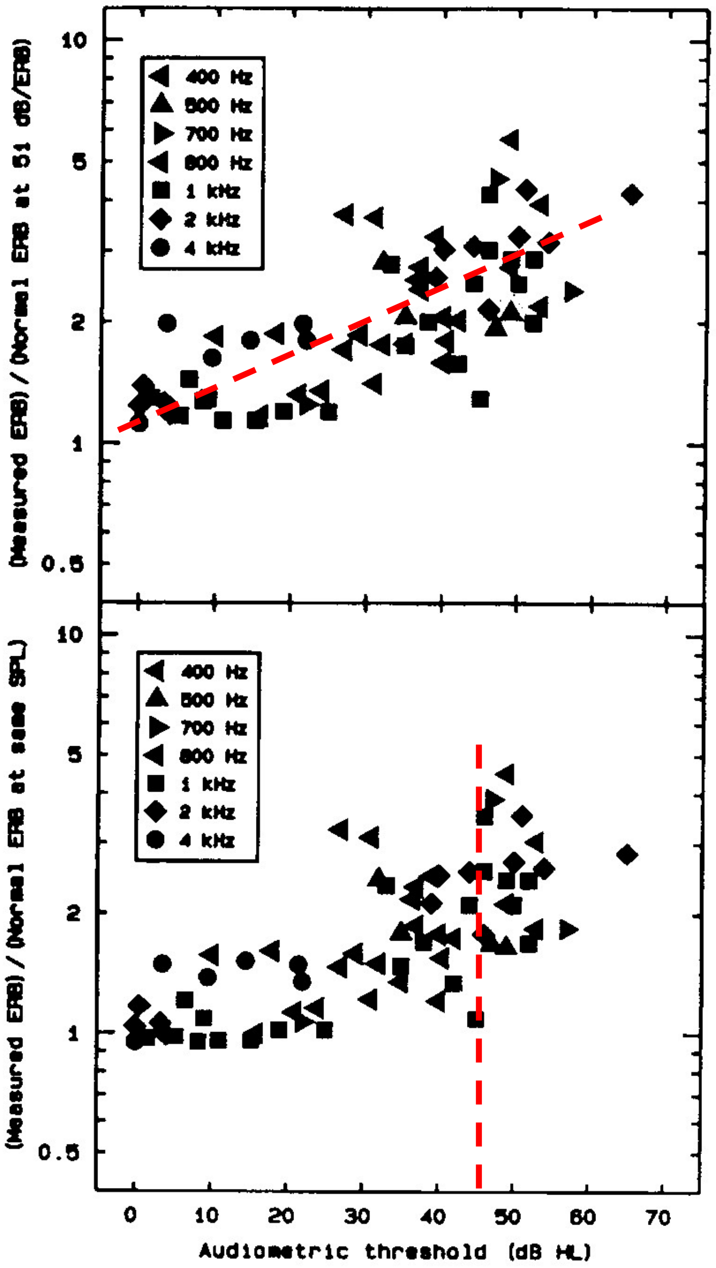
Auditory filters in listeners with cochlear hearing loss



Cochlear hearing loss is typically (but not always) accompanied by auditory filters that are broader than normal.

The figure illustrates 1-kHz filters for a collection of listeners with unilaterla cochlear hearing loss.

Moore BCJ (1998). Cochlear Hearing Loss. Whurr Publishers, London.



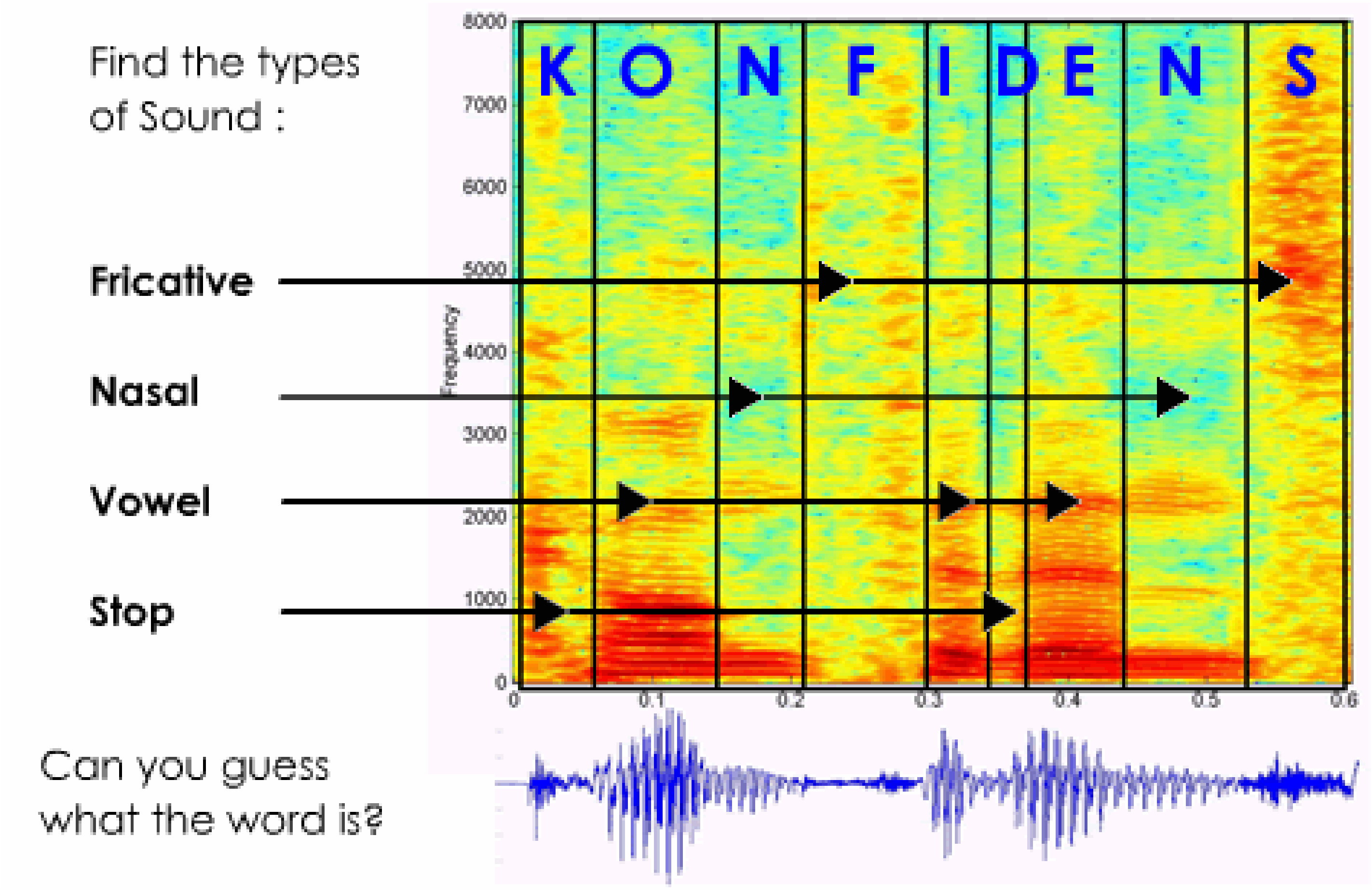
Filter bandwidth increases on average with increasing absolute threshold (thus the amount of hearing loss).

The wide spread of values indicates, however, that filter bandwidth cannot be predicted based on absolute threshold.

Moore BCJ (1998). Cochlear Hearing Loss. Whurr Publishers, London.

Impaired speech perception with less frequency selectivity

(HEARLOSS demo)



Thank you!