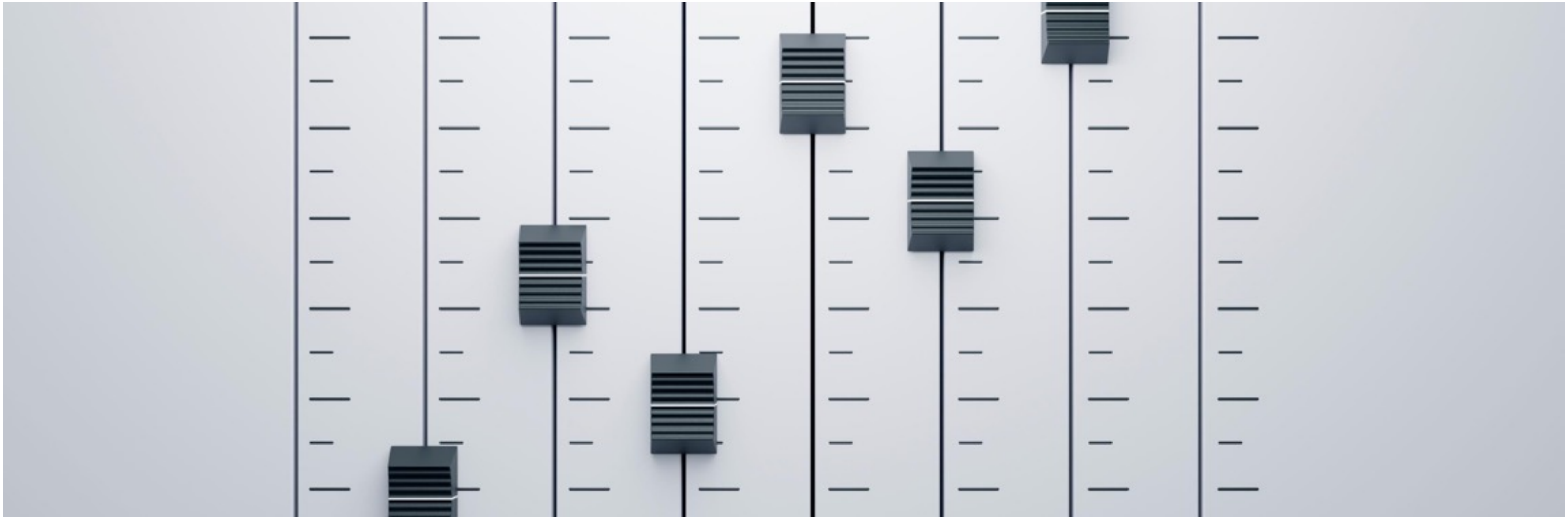
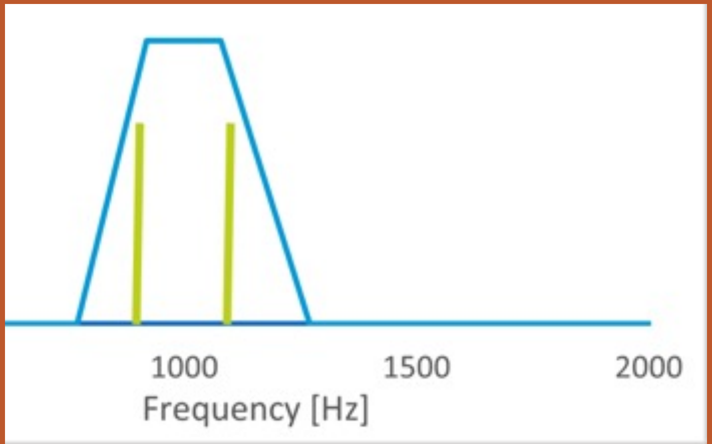


Frequency resolution

Frequency resolution of our hearing system



Which is the precision of our hearing system to resolve (separate) different components (partials) of a sound stimulus?

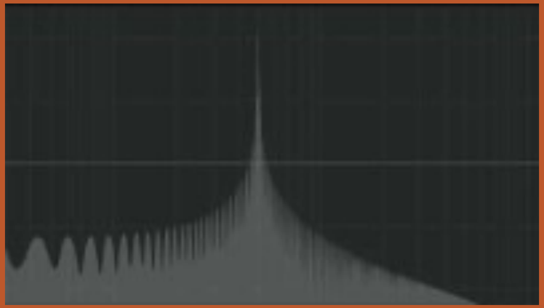
Most of our knowledge about that comes fromstudies about *masking*

Implications for:

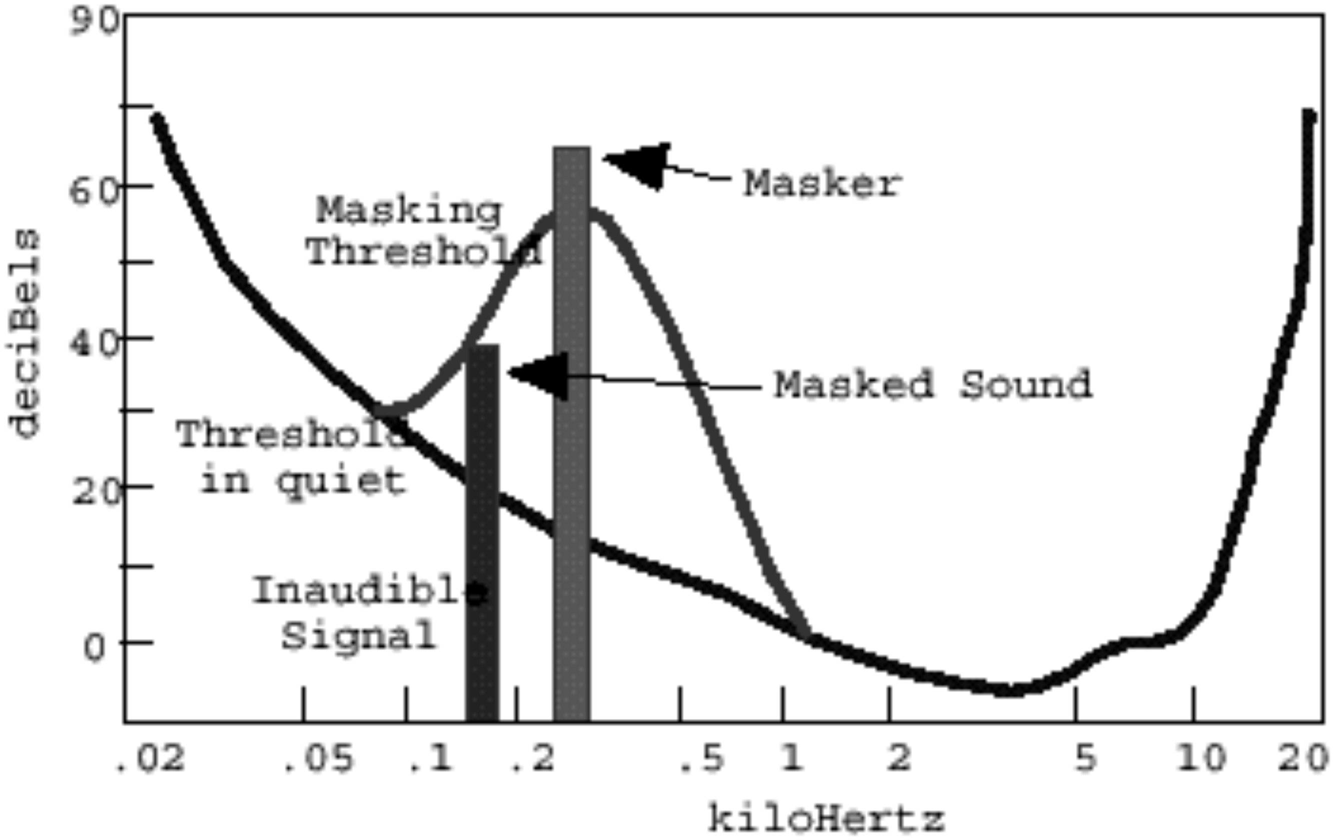
-> Loudness

-> Pitch

-> Timbre



Masking



90
60
40
20
0
deciBels
Masking
Threshold
Masker
Masked Sound
Threshold
in quiet
Inaudible
Signal
.02
.05
.1
.2
.5
1
2
5
10
20
kiloHertz

Basilar membrane behaviour

- Travelling wave with multiple "peaks"
- Peaks corresponding to loud "partials" of the sound
- Tonotopic distribution (high frequencies close to oval window)

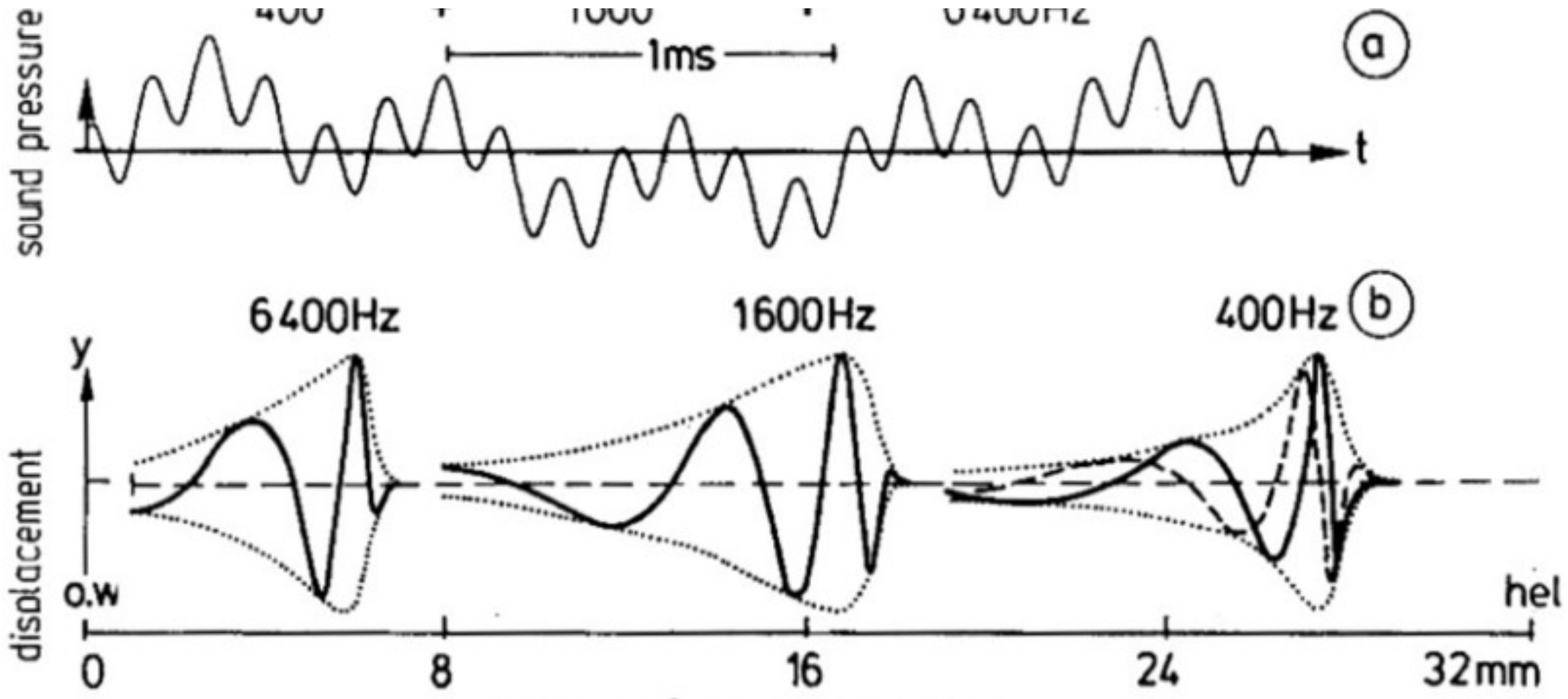


Fig. 3.5a, b. Schematic drawing of the transformation of frequency into place along the basilar membrane. In (**a**) three simultaneously presented tones of different frequencies expressed as compound time function produce travelling waves (**b**), that reach their maximum at three different places corresponding to the characteristic frequencies

Causal mechanisms of masking (I): basilar membrane

- Assimetry of masking: upwards spreading
- The louder, the more masked range

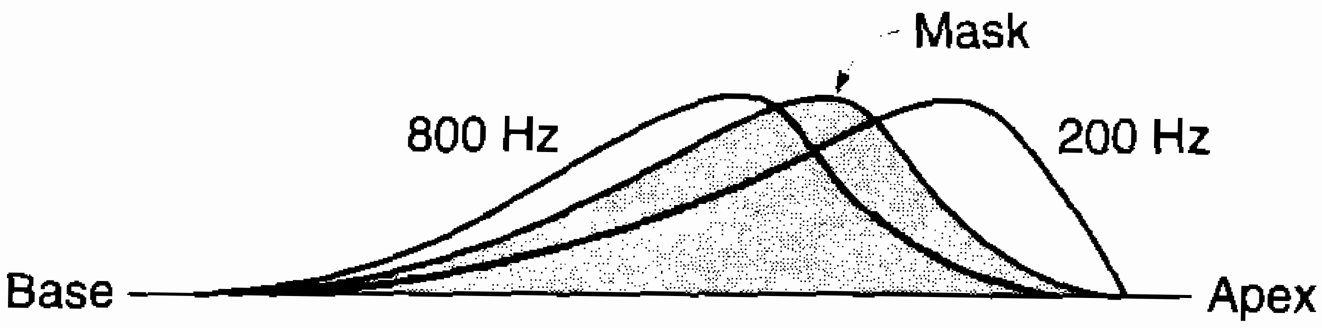
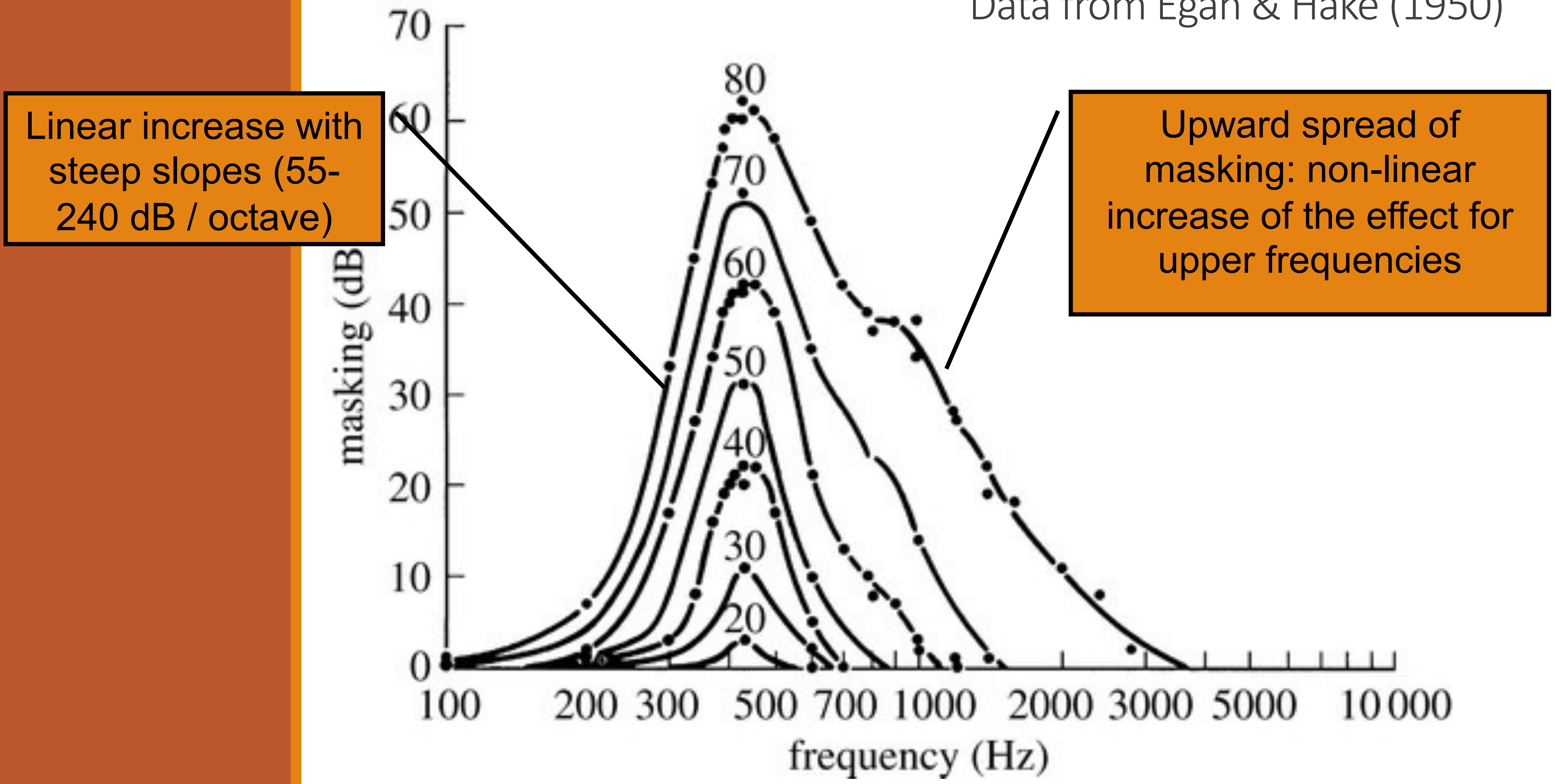


Figure 10.35
Vibration patterns caused by 200- and 800-Hz test tones and the 400-Hz mask, taken from basilar membrane vibration patterns in Figure 10.29. The pattern for a 400-Hz tone is used for the masking pattern (shaded). Since the mask actually contains a band of frequencies, the actual pattern would be wider than is shown here. It would, however, still be asymmetrical and would overlap the 800-Hz vibration more than the 200-Hz vibration.

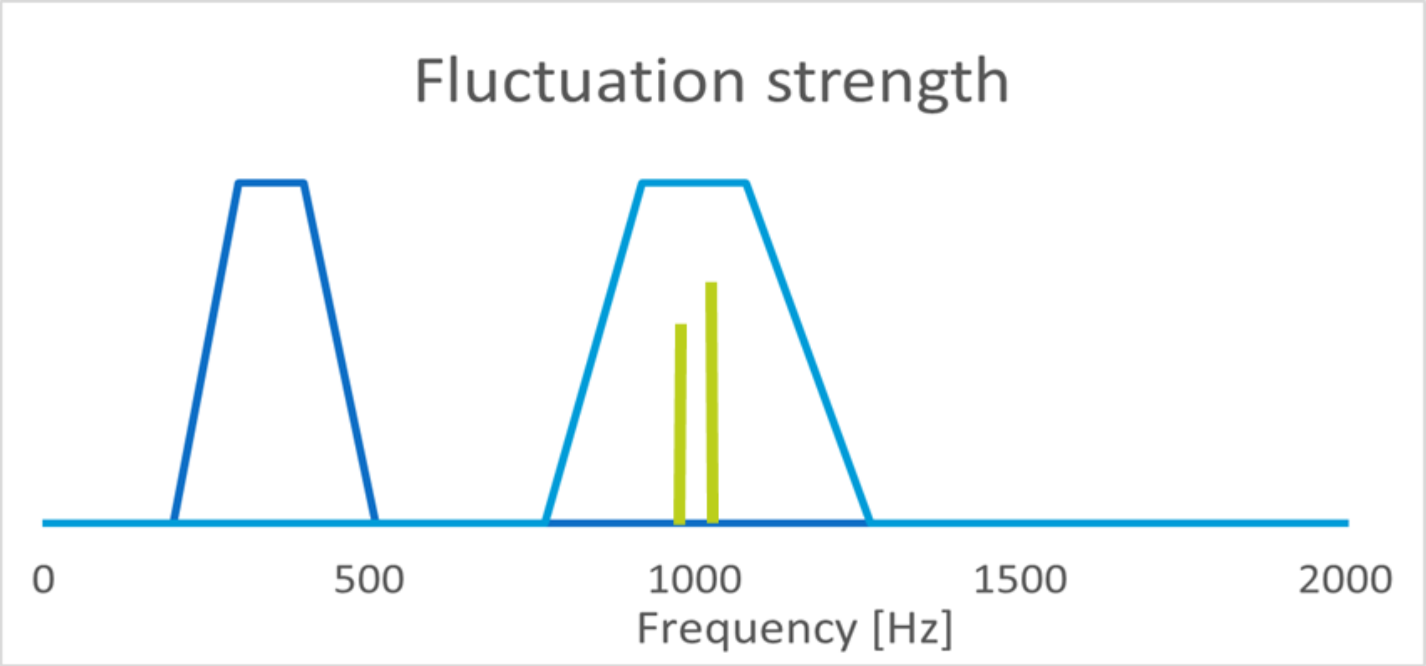
Masking patterns

Example for a narrowband noise masker centred at 410 Hz.
Each curve shows the elevation in threshold of a pure-tone signal as a function of signal frequency.
The overall noise level in dB SPL (signal-noise difference) for each curve is indicated in the figure.

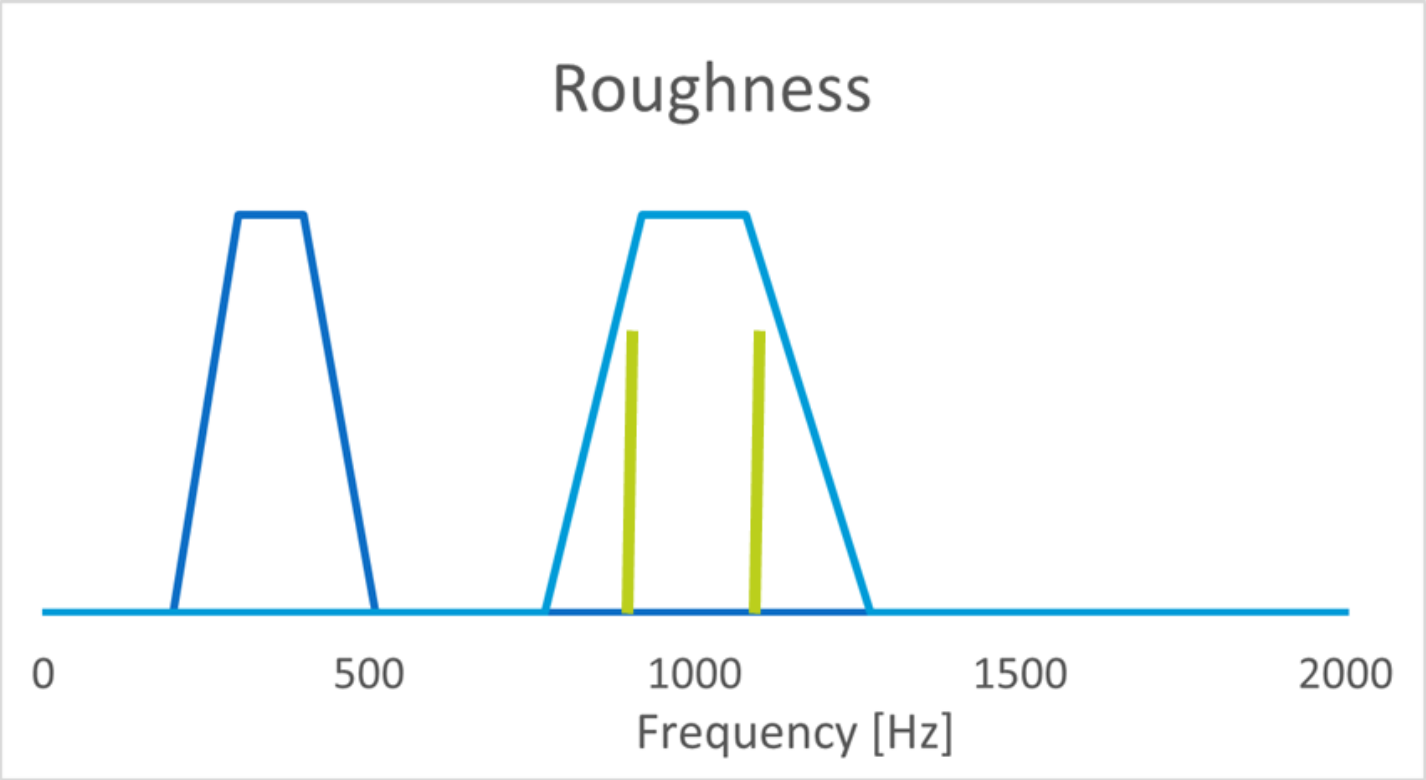
Data from Egan & Hake (1950)



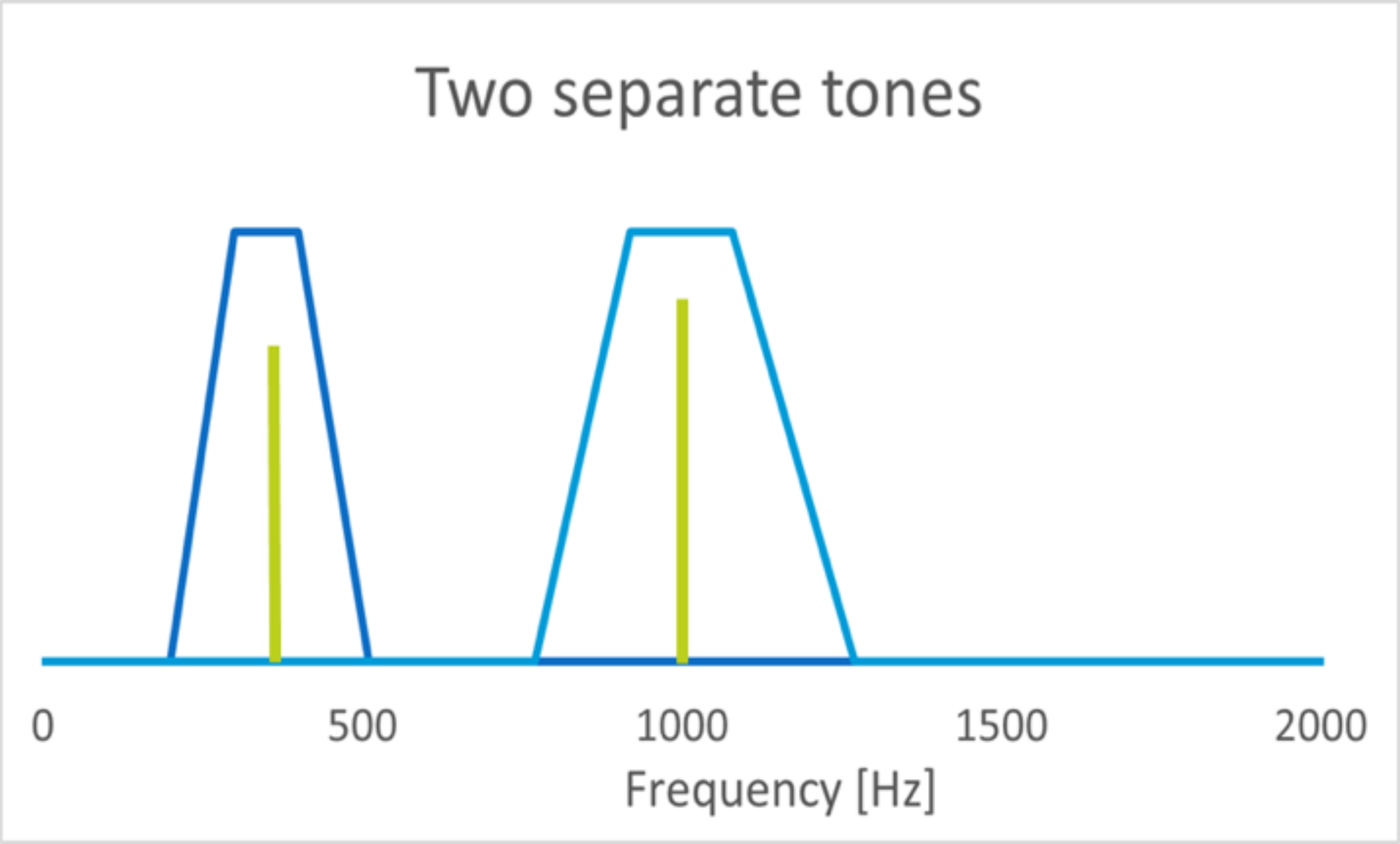
Beating
(or *fluctuation strength*)



Roughness



Full resolution



More audio examples

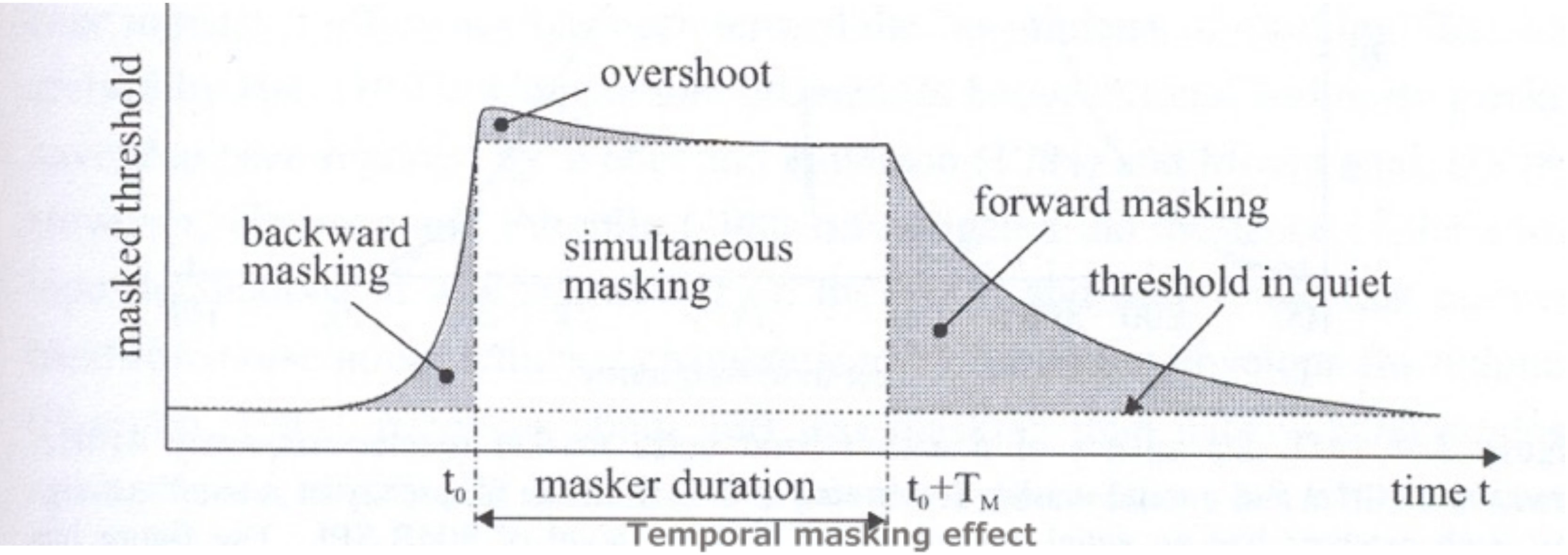
2470-2540 Hz roughness->beating.wav

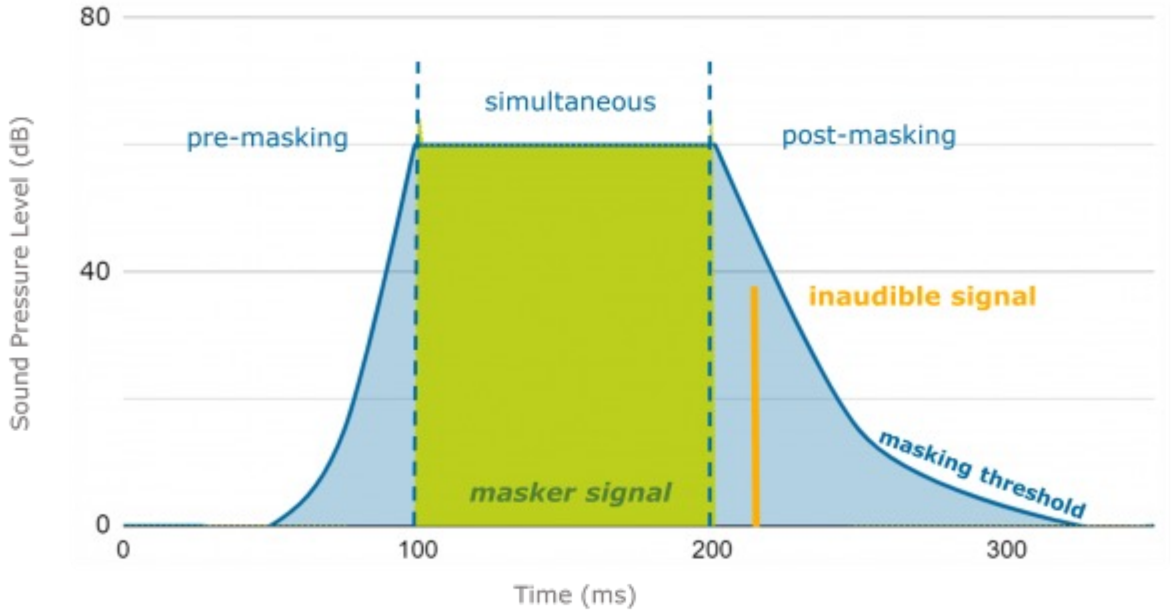
beating - roughness - fission 220-240Hz

220-440Hz sawtooth wave beating

Temporal masking

- Forward: 30-300ms
- Backward: 5ms





Herre, Jürgen & Dick, Sascha. (2019). Psychoacoustic Models for Perceptual Audio Coding—A Tutorial Review. Applied Sciences. 9. 2854. 10.3390/app9142854.

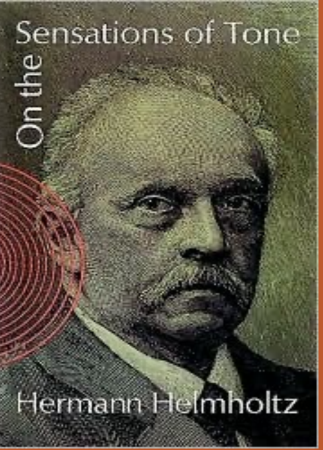
Causal mechanisms of masking (II): neural functioning

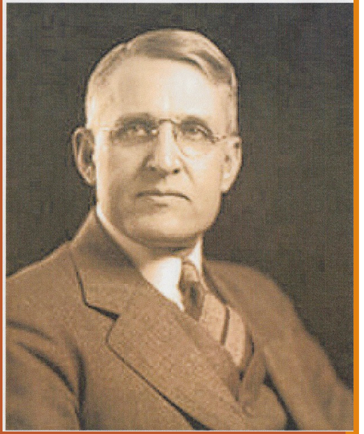
Forward masking:

- Response of the basilar membrane continues after the end of the masker ("ringing")
- Masker produces short-term adaptation or fatigue in the auditory nerve or higher centers in the auditory system
- Neural activity persists at some level in the auditory system (blocking that of the second tone)

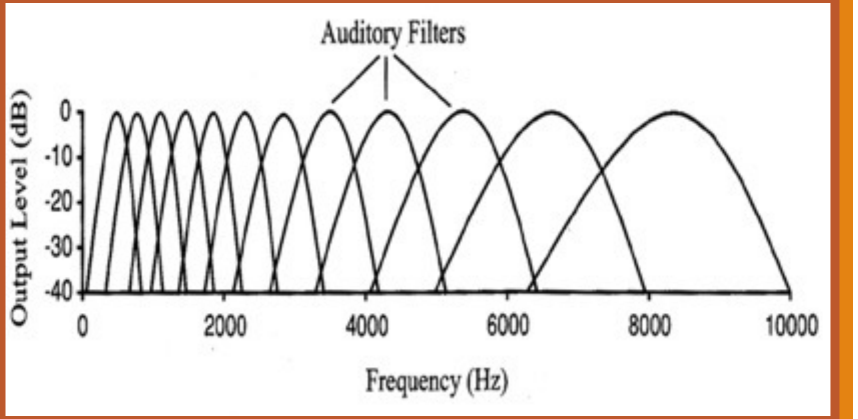
Backward masking:

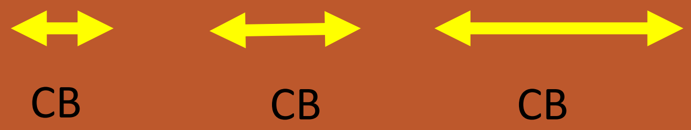
- Sensory memory of the first tone not properly formed





Auditory Filters





- Frequency selectivity can be modelled with a bank of bandpass filters with overlapping bands
- Each different point (~1mm) of basilar membrane corresponds to a filter with a different center frequency

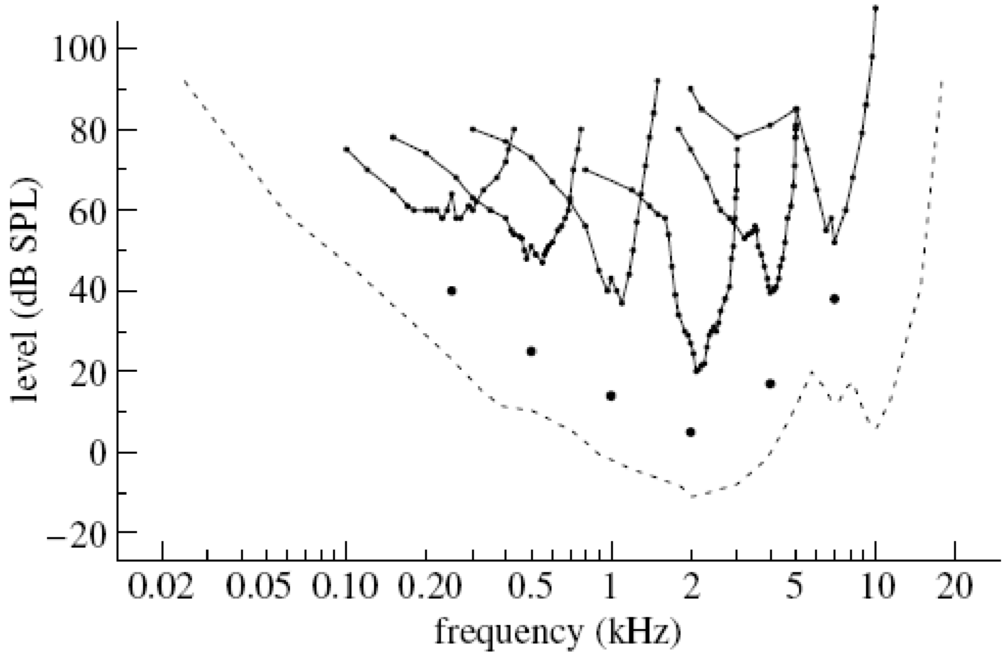
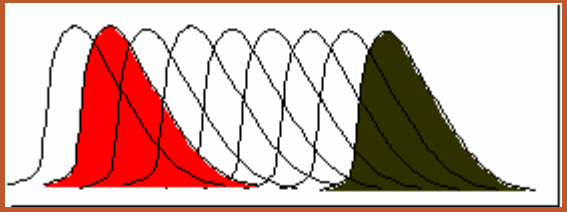
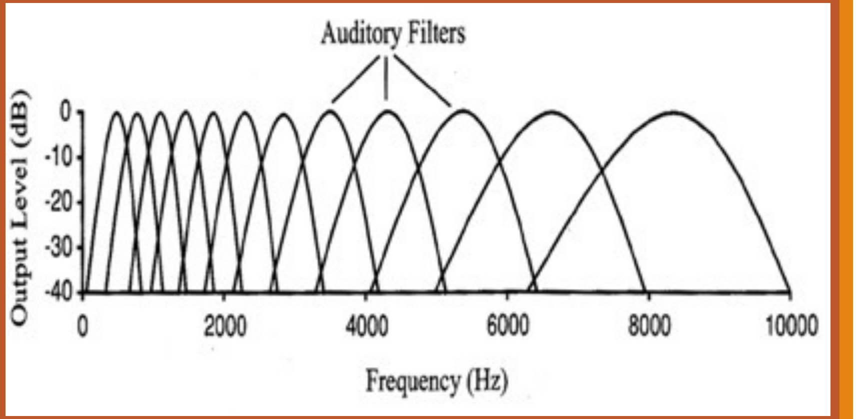


Figure 1. Psychophysical tuning curves (PTCs) determined in simultaneous masking, using sinusoidal signals at 10 dB SL. For each curve, the solid circle below it indicates the frequency and level of the signal. The masker was a sinusoid which had a fixed starting phase relationship with the 50 ms signal. The masker level required for threshold is plotted as a function of masker frequency on a logarithmic scale. The dashed line shows the absolute threshold for the signal. Data from Vogten (1978).

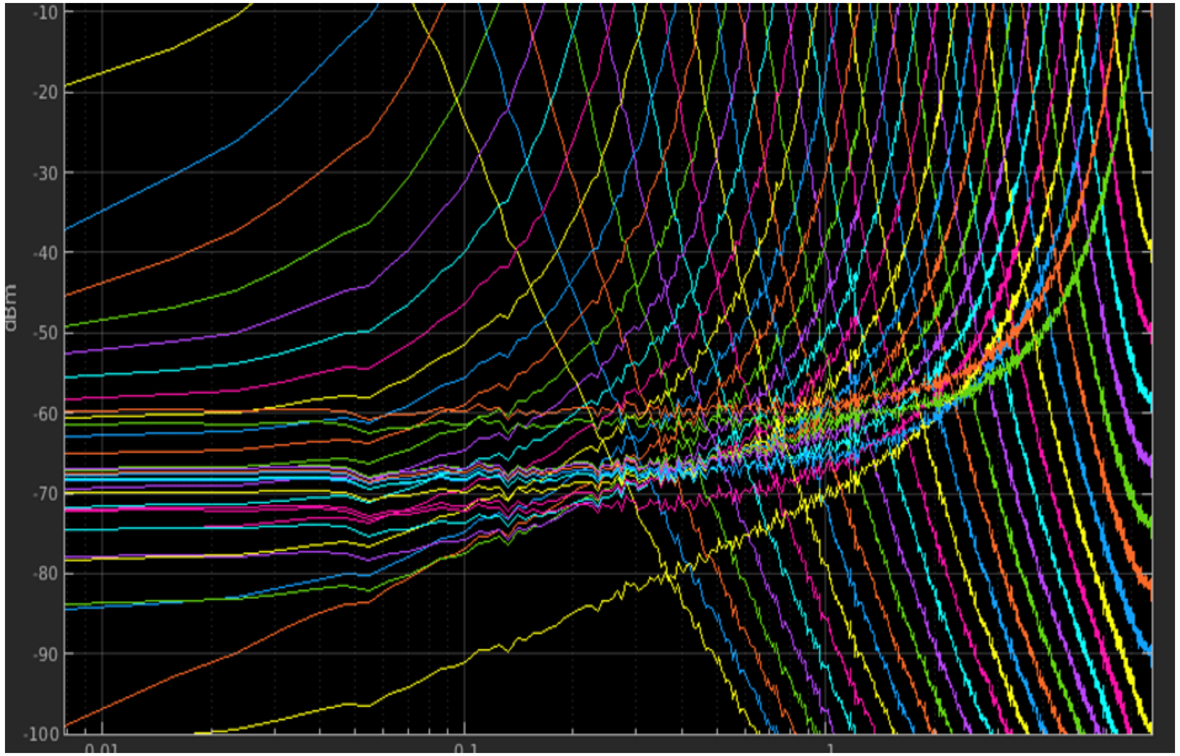


Critical Bands



CB CB CB

- The distance in the basilar membrane whereby two tones of different frequencies do not interfere themselves anymore
- A frequency region that is “critical” to masking, tone interactions and loudness summation
- A gammatone filterbank is the most accurate model of the auditory filters and their critical bands

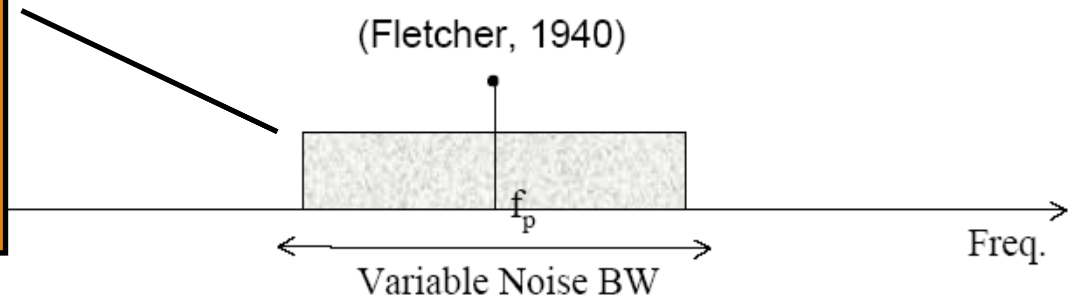


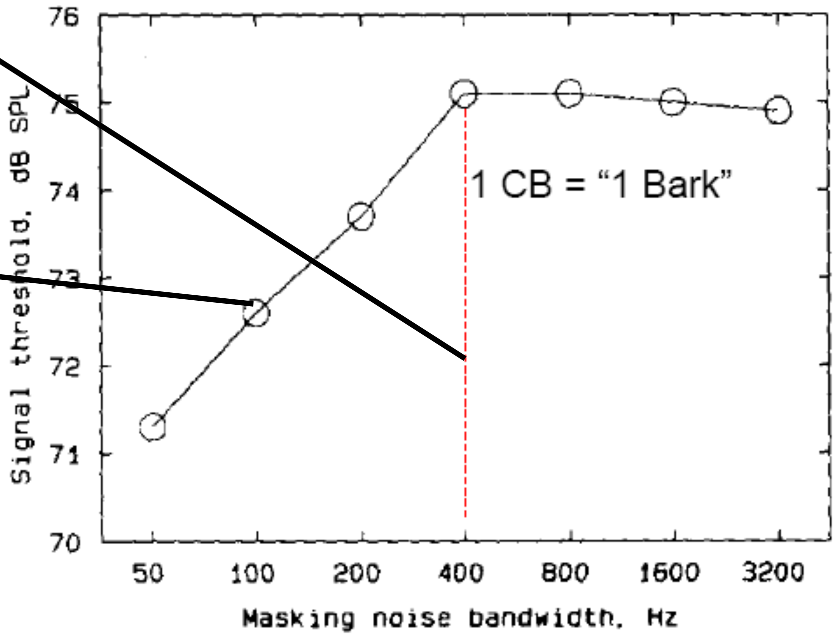
Measuring Critical Bands (Fletcher's experiment)

Uniform spectral density masker, increasing power as BW increases; sinusoidal signal (4KHz) to be masked

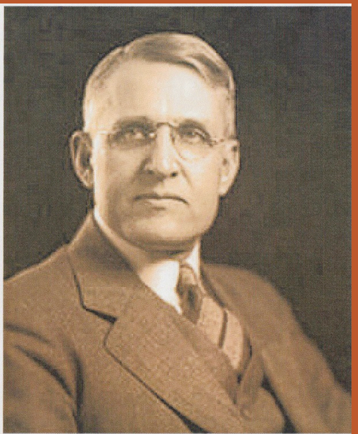
Critical band (~400Hz) for the test signal (4Khz)

The audibility threshold of the signal raises as more power is added to the mask





"Psychometric function"

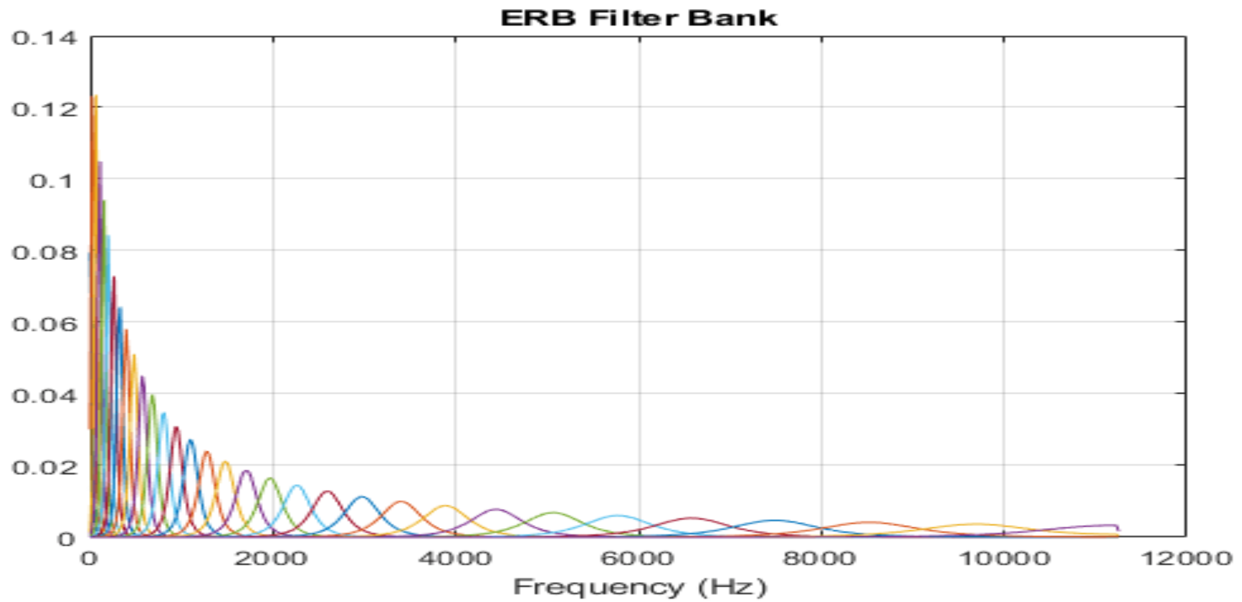


Critical Bands: Bark estimation

Zwicker et al. (München)

Barkhausen (proper name) -> Bark

$B_c = 52548 / (z^2 - 52.56\, z + 690.39)$, with z in bark



Critical band partition

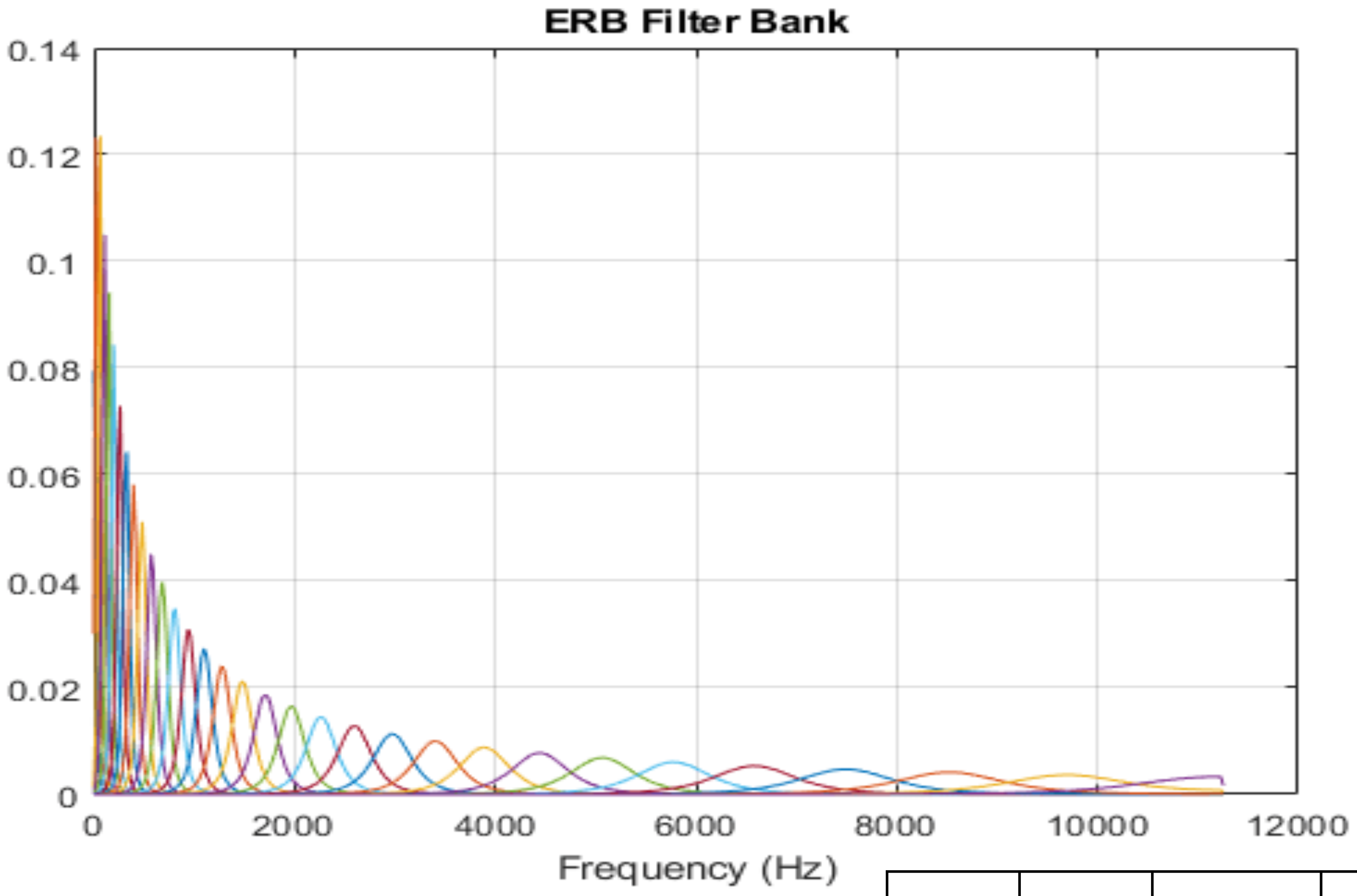
Z/Bark	f_u/Hz	f_o/Hz	Δf_G/Hz	f_m/Hz
0	0	100	100	50
1	100	200	100	150
2	200	300	100	250
3	300	400	100	350
4	400	510	110	450
5	510	630	120	570
6	630	770	140	700
7	770	920	150	840
8	920	1080	160	1000
9	1080	1270	190	1170
10	1270	1480	210	1370
11	1480	1720	240	1600
12	1720	2000	280	1850
13	2000	2320	320	2150
14	2320	2700	380	2500
15	2700	3150	450	2900
16	3150	3700+	550	3400

Critical Bands: ERB estimation

Moore et al. (Cambridge)

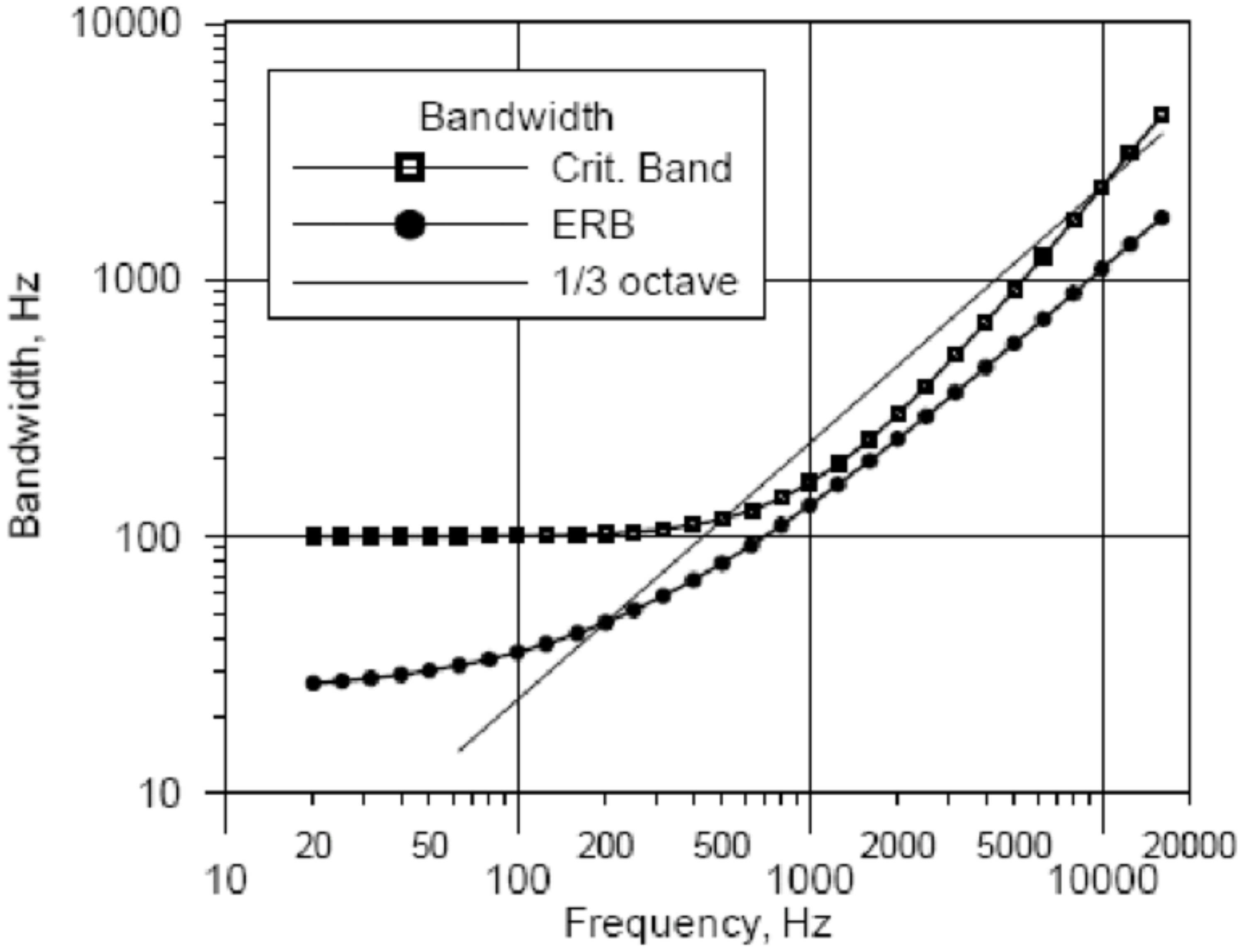
ERB(f) = 24.7 * (4.37 f / 1000 + 1)

ERB: Equivalent Rectangular Bandwidth



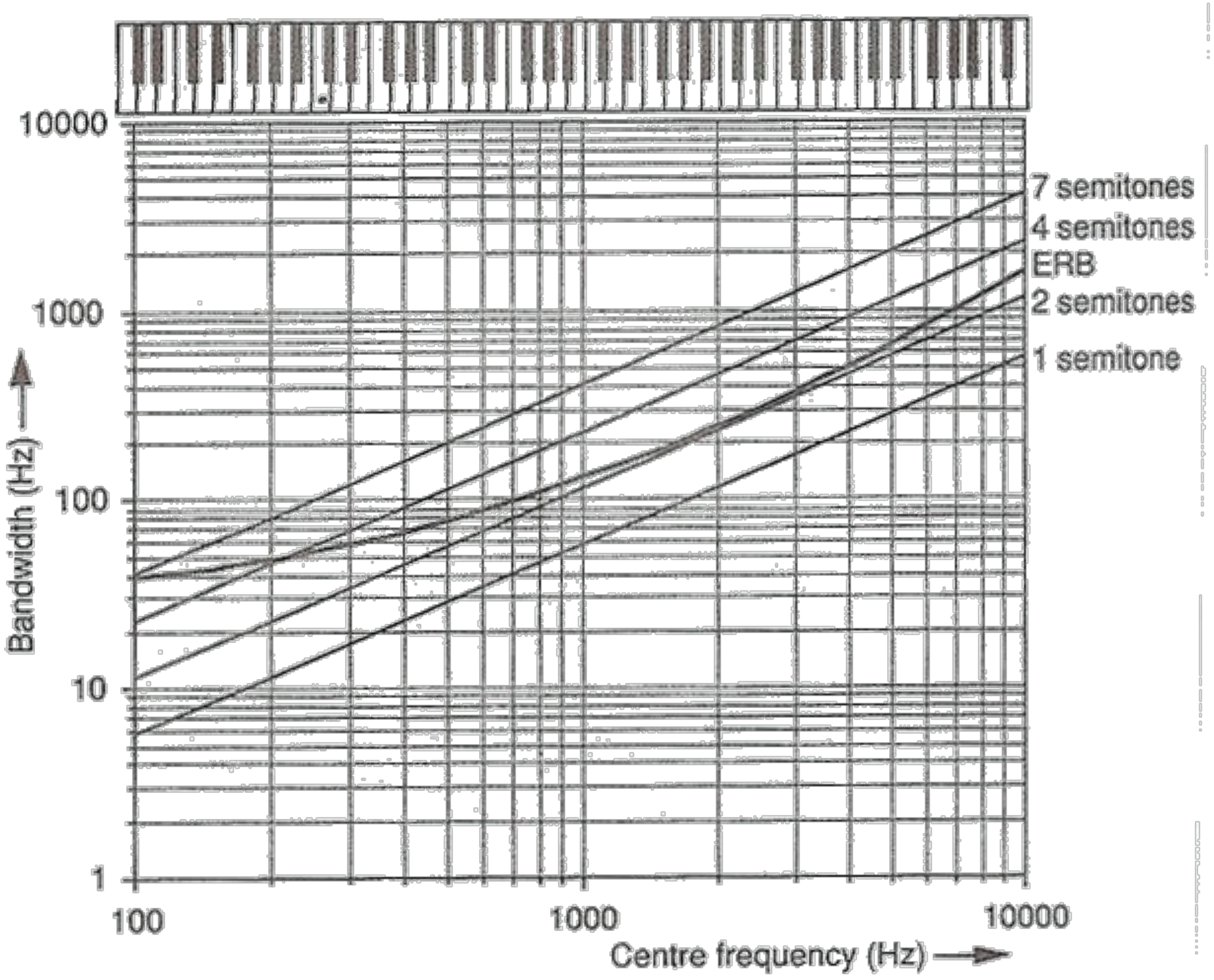
CF	ERB	CF	ERB
27.5	31.1	880	115.5
55	33.7	1760	212.2
110	38.9	3520	434.4
220	49.4	7040	994.8
440	70.8		

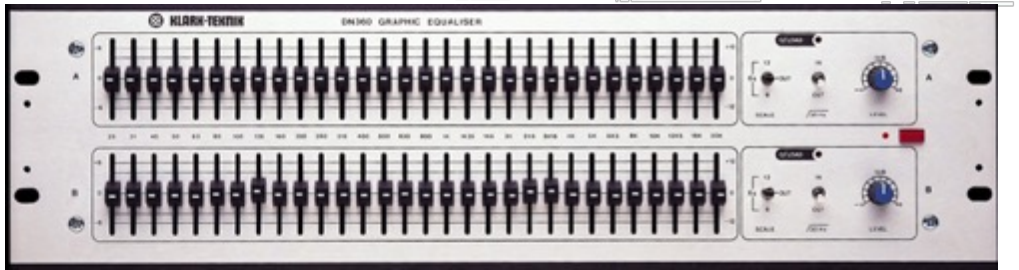
Critical Bandwidth comparison



Critical Bandwidth: application

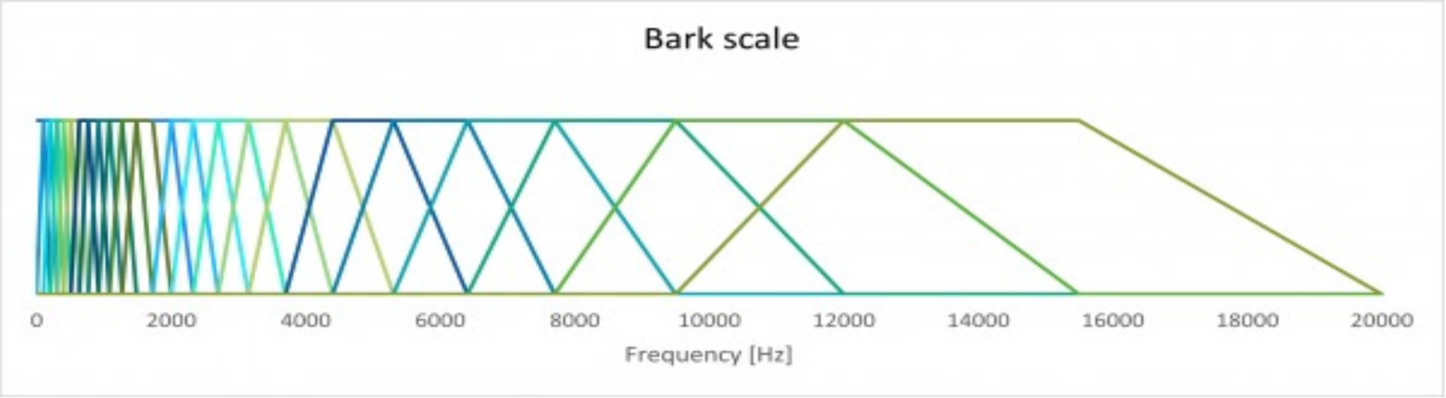
What is the relation between the figure and third-octave equalizers?

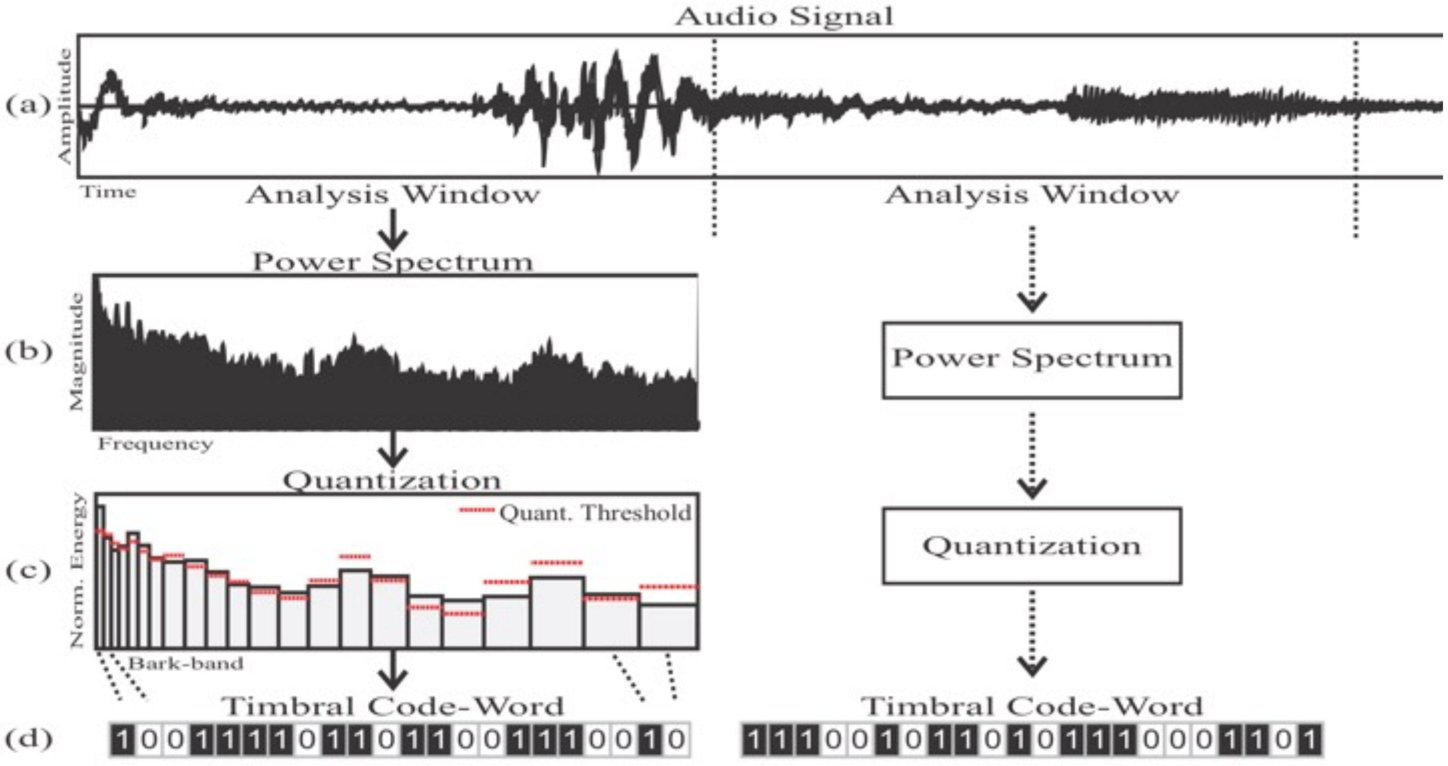




Critical Bands: application

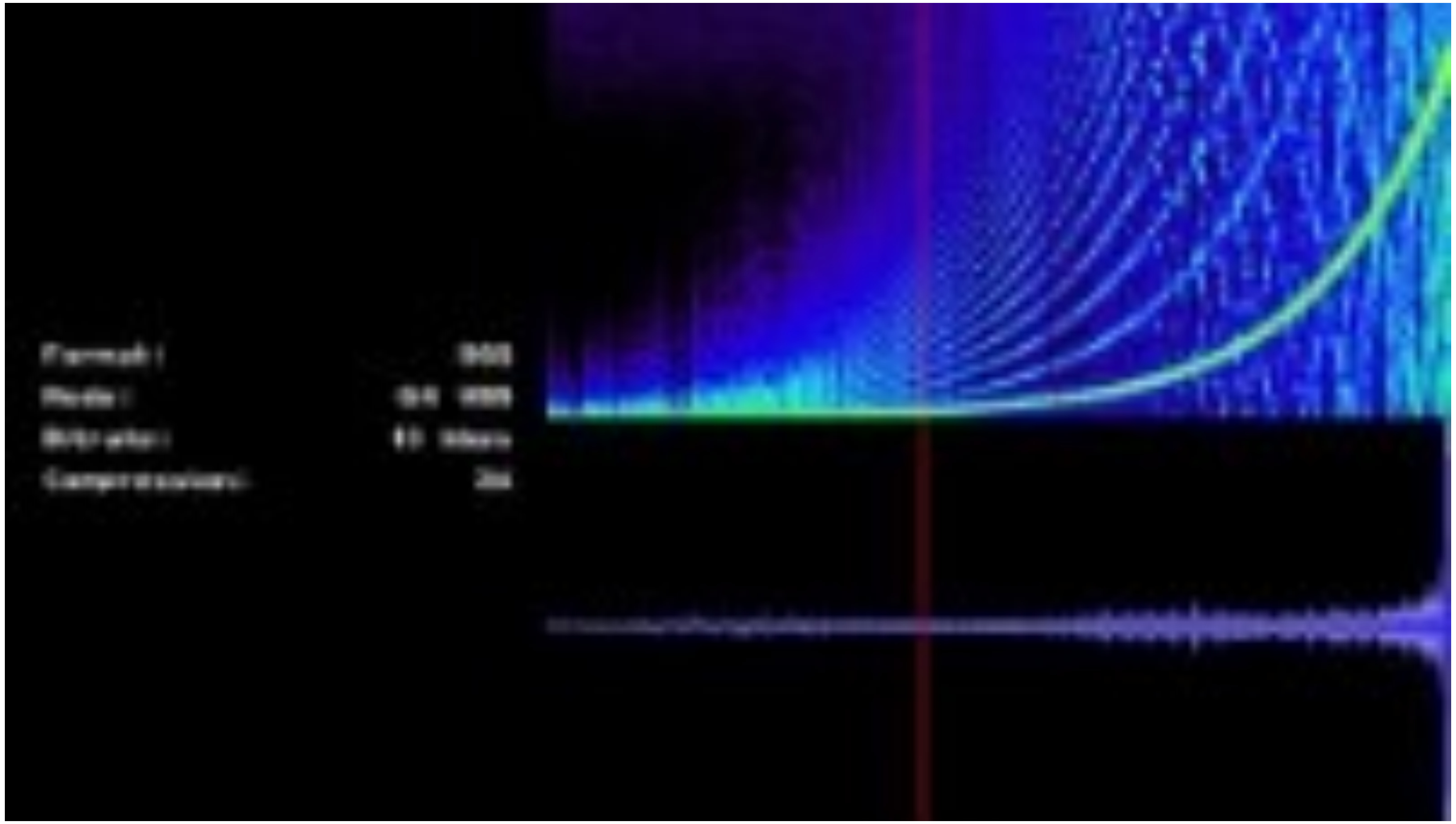
How can we encode the perceived spectral shape of sounds in a “compact” way?



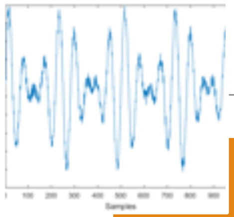


Haro M, Serrà J, Herrera P, Corral Á (2012) Zipf's Law in Short-Time Timbral Codings of Speech, Music, and Environmental Sound Signals. PLOS ONE 7(3): e33993

Perceptual coding models: what do they eliminate?

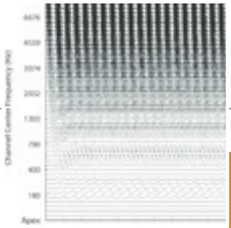


Physical properties / Sensations (perceptual properties) / Musical properties



Physical

- Frequency (periodicity)
- Amplitude
- Waveform
- Duration



Perceptual

- Pitch
- Loudness
- Timbre
- Length

Musical

- Melodies
- Dynamics
- Voices, instruments, texture, chords
- Figures, Rhythm