Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Acoustics I: hearing

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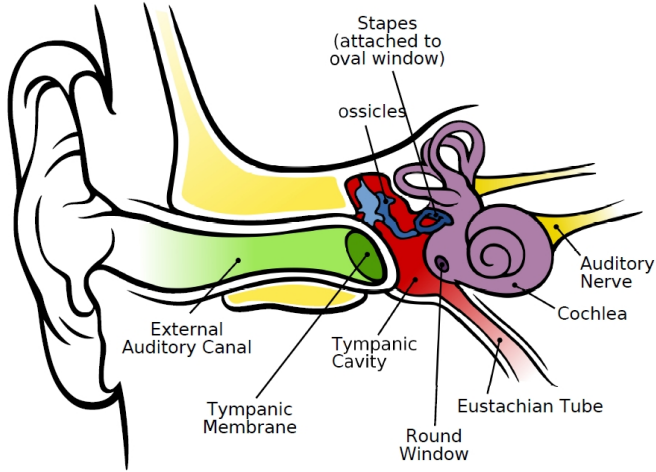
2022-12-12

structure and principle of operation of the ear

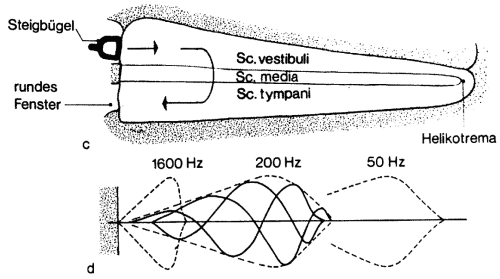
structure of the ear

outer ear, middle ear, inner ear



inner ear: principle of operation

- excitation by oval window → traveling wave along basilar membrane
- maximal amplitude depends on frequency → frequency ↷ location transformation



- movement of basilar membrane detected by hair cells → electrical pulses to brain

frequency dependency of the hearing threshold

frequency dependency of the hearing threshold

demo Nr. 6, Tracks 17,18, preparation of a protocol:

	125	250	500	1 k	2 k	4 k	8 k
0 dB							
-5 dB							
-10 dB							
-15 dB							
-20 dB							
-25 dB							
-30 dB							
-35 dB							
-40 dB							
-45 dB							

frequency dependency of the hearing threshold

demo Nr. 6, Track 18, procedure:

- new frequency
  - tones with decreasing level (-5 dB steps)
  - count the number of steps
  - staircase is repeated
  - put a mark in the table
- new frequency, ...

frequency dependency of the hearing threshold

typical hearing threshold:

	125	250	500	1 k	2 k	4 k	8 k
0 dB							
-5 dB							
-10 dB							
-15 dB							
-20 dB	x						
-25 dB							x
-30 dB		x					
-35 dB			x	x			
-40 dB					x		
-45 dB						x[1]	

[1] resonance of the ear canal

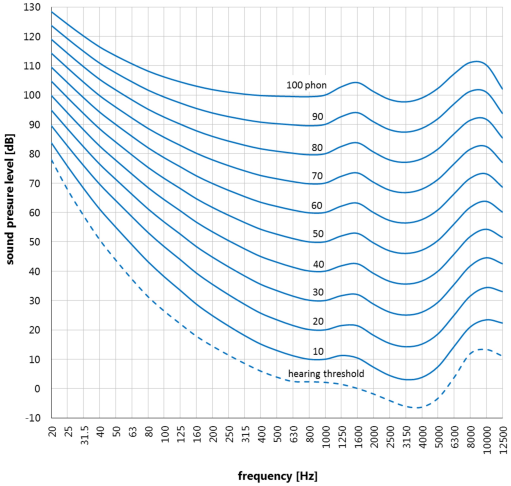
loudness

loudness in phon L_N

- description of the intensity of the sensation in phon
- subjective evaluation:
  - adjust a 1 kHz reference signal for equal loudness as the test signal
  - $\text{phon}_{\text{test.signal}} = \text{dB}_{\text{reference.signal}}$

loudness in phon L_N

equal loudness contours for tones:



loudness in sone N

- description of the intensity of the sensation in sone
- sone scale is proportional to sensation

relation between L_N and N

- definition: $L_N = 40$ phon $\rightarrow N = 1$ sone
- above 40 phon:
  - $L_N + 10$ phon $\rightarrow N \cdot 2$ sone
  - $N = 2^{\frac{L_N - 40}{10}}$
  - $L_N \approx 40 + 33 \cdot \log(N)$
- below 40 phon:
  - N cuts half for $\Delta L_N < 10$.

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frequency discrimination

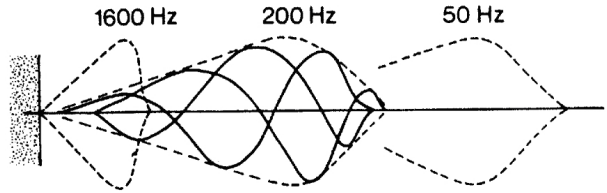
frequency discrimination

- frequency range of hearing (16...16'000 Hz) contains around 620 audible frequency steps
- maximal resolution for a frequency modulation with 4 Hz:
  - $f < 500$ Hz $\rightarrow \Delta f = 3.5$ Hz
  - $f \geq 500$ Hz $\rightarrow \Delta f = f \cdot 0.007$ Hz

critical bands

critical bands

inner ear: blurred frequency $\curvearrowright$ location transformation



- even in case of pure tone excitation, an extended zone on the basilar membrane is put to motion
- this zone can be expressed as frequency range $\rightarrow$ *critical band*
  - $f < 500$ Hz $\rightarrow$ width $= 100$ Hz
  - $f \geq 500$ Hz $\rightarrow$ width $= f \cdot 0.2$ Hz ($\approx$ third octave band)

critical bands - loudness summation

loudness of combined sounds → two cases:

- two signals with overlapping critical bands
  - summation of intensities
  - 40 phon + 40 phon = 43 phon
- two signals clearly separated in frequency → *no* overlapping critical bands
  - summation of loudness
  - 1 sone + 1 sone = 2 sone
  - 40 phon + 40 phon = 50 phon

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critical bands - loudness summation

loudness comparison of test signals of different bandwidth ΔB but equal power:

demo nr. 3, track 7, procedure:

reference (ΔB 145 Hz) and test signal in alternating sequence

- test signal 1: narrow band noise ΔB 145 Hz
- test signal 2: narrow band noise ΔB 167 Hz
- test signal 3: narrow band noise ΔB 192 Hz
- test signal 4: narrow band noise ΔB 221 Hz
- test signal 5: narrow band noise ΔB 254 Hz
- test signal 6: narrow band noise ΔB 292 Hz
- test signal 7: narrow band noise ΔB 336 Hz
- test signal 8: narrow band noise ΔB 386 Hz

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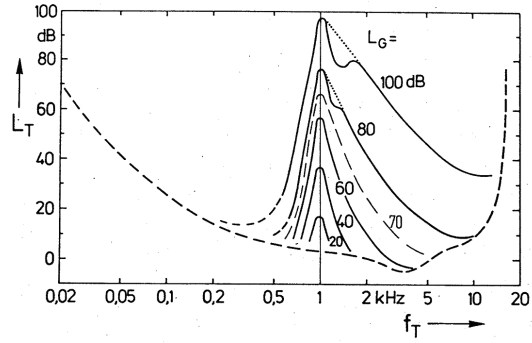
masking

masking

presentation of a tone lifts the hearing threshold → frequency components in the vicinity may be masked.



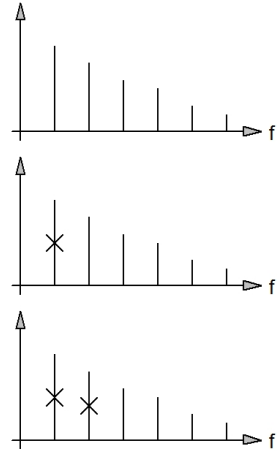
- masking effect more pronounced towards higher frequencies
- the higher the level of the masker, the wider the masking range

virtual pitch

virtual pitch

a missing fundamental in a complex sound can be complemented by the brain.

demo nr. 20, track 37:



virtual pitch

possible applications:

- virtual bass in organs
  - pipe with frequency f_1
  - pipe with frequency $f_2 = \frac{3}{2} f_1$
  - $\rightarrow$ virtually audible frequency $f = \frac{1}{2} f_1$
- reproduction of low frequencies with small loudspeakers

nonlinear distortions

nonlinear distortions of the ear

- nonlinear transfer function from the tympanic membrane to the inner ear
- generation of frequencies that are not contained in the original signal
  - sum-tones: f_1 and $f_2 \rightarrow f_1 + f_2$
  - difference-tones: f_1 and $f_2 \rightarrow f_2 - f_1$
- difference-tones are critical as they are not masked
- empirical model for the level of difference-tone: $L(f_2 - f_1) \approx L(f_1) + L(f_2) - 130dB$
  - e.g. $L(f_1) = L(f_2) = 80dB \rightarrow L(f_2 - f_1) \approx 30dB$
- distortion factor:

excitation[dB]	70	80	90	100	110	120
distortion[%]	0.05	0.2	0.5	1.5	5	16

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loudness as a function of signal duration

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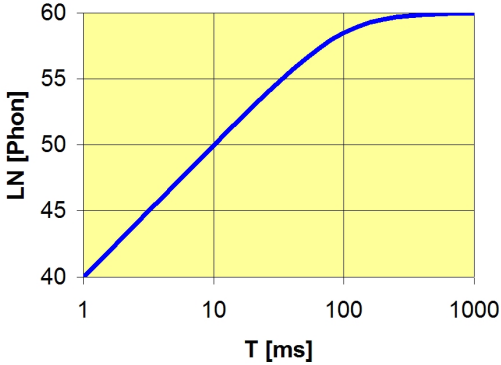
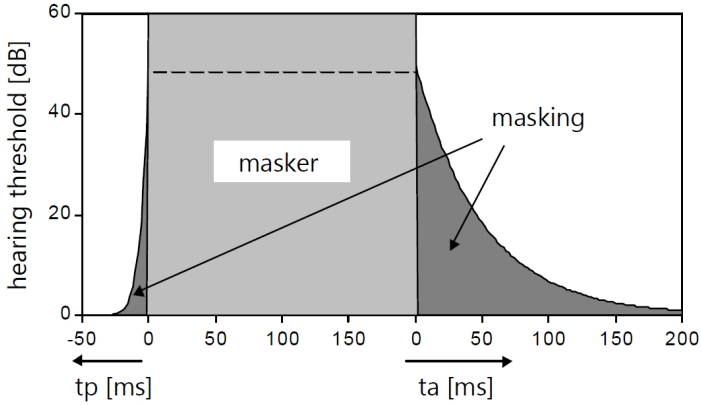
- hearing process exhibits a delay
- full loudness is reached for signal length > 0.5 s
- below 100 ms $\rightarrow$ loudness corresponds to signal energy



temporal masking

temporal masking

pre and post masking:



phase

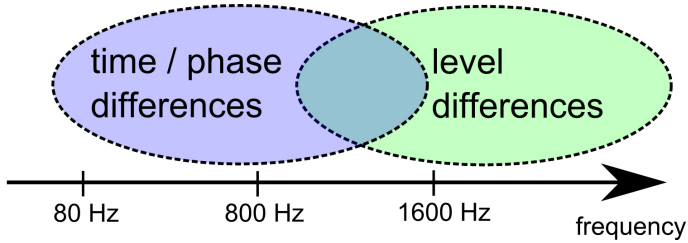
sensitivity with respect to phase

?

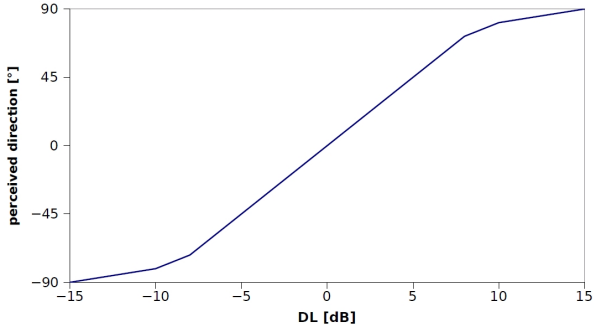
binaural hearing: localization

binaural hearing: localization in the horizontal plane

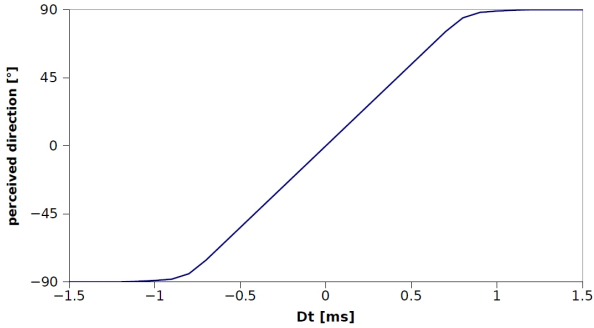
- evaluation of the two ear signals yields:
  - interaural level differences
  - interaural time differences
- maximal resolution: 1 degree



binaural hearing: localization in the horizontal plane: level differences



binaural hearing: localization in the horizontal plane: time differences



binaural hearing: localization in the vertical plane

detection of elevation:

- evaluation of the frequency response
- resolution: 10...45 degrees

detection of distance:

- evaluation of loudness (the more silent, the more distant)
- evaluation of spectrum (e.g. frequency dependent air absorption)
- reverberation (the more reverberant, the more distant)

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precedence effect

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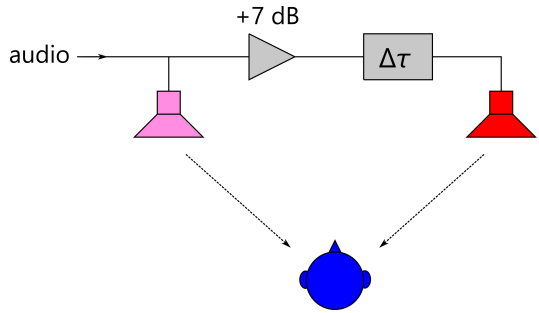
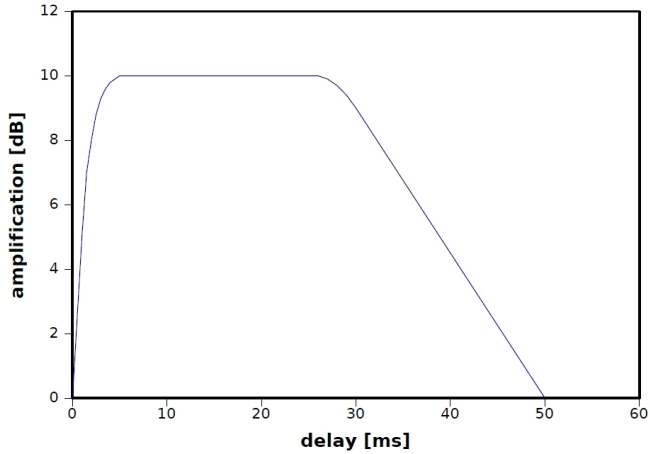


- $\Delta\tau = 20$ ms
- $\Delta\tau = 50$ ms
- $\Delta\tau = 80$ ms

precedence effect

capability of the ear to merge direct sound and echoes and to localize the direction of the direct sound



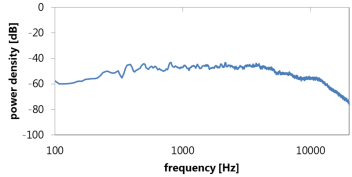
psychoacoustic parameters

psychoacoustic parameters: overview

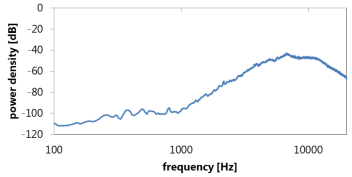
- *loudness*
- sharpness
- fluctuation strength
- roughness
- tonality

psychoacoustic parameters: sharpness

- sharpness of a signal depends on the relative frequency distribution of signal power



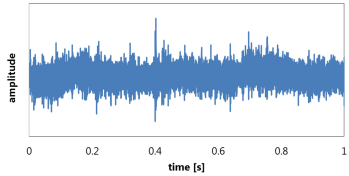
small river - original



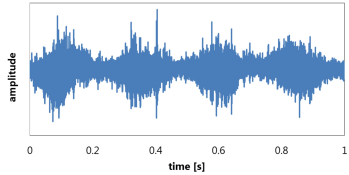
↑ high frequency contents

psychoacoustic parameters: fluctuation strength

- fluctuation strength describes slow amplitude modulations (a few Hz)



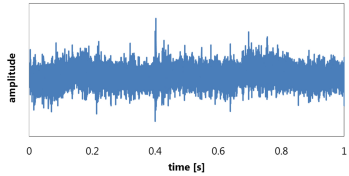
small river - original



4 Hz fluctuations

psychoacoustic parameters: roughness

- roughness describes fast amplitude modulations ($\rightarrow >$ ca. 15 Hz)



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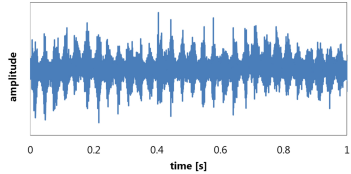
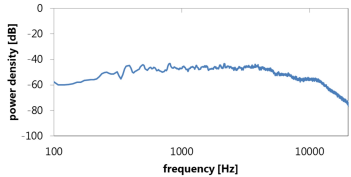


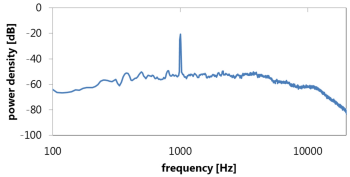
30 Hz fluctuations

psychoacoustic parameters: tonality

- tonality describes strength of possibly present tones



small river - original



with 1 kHz tone

eth-acoustics-1