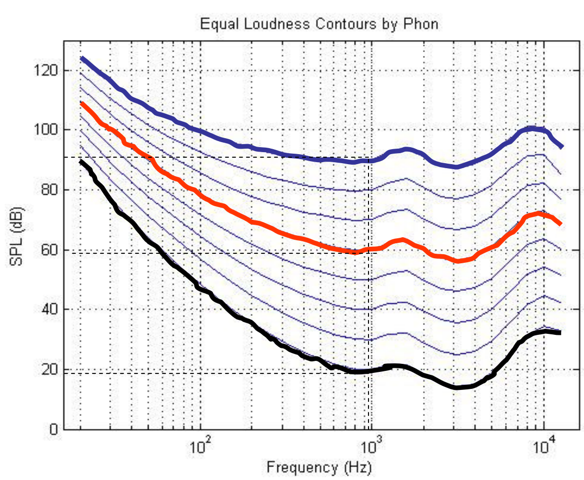
Perception of loudness

- What is loudness
- Dependence on frequency – equal loudness contours
- Measurements and comparisons of loudness
- Coding of loudness
- Loudness of complex/ superimposed tones
- Dependence of loudness on signal duration

Dependence of loudness on signal frequency

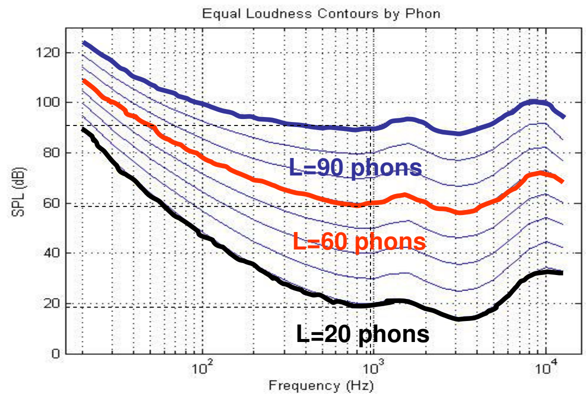


Equal loudness contours were originally measured by Fletcher and Munson in 1933

Each curve shows what the SPL of given frequency tone should be in order for it to have the same loudness as 1kHz tone of a given level

Loudness in *phons*

•A unit of LOUDNESS LEVEL (LL) of a given sound or noise.
•Derived from indirect loudness measurements (like Fletcher and Munson experiment)
•If SPL at reference frequency of 1kHz is X dB – the corresponding equal loudness contour is X phon line



Phon units can't be added, subtracted, divided or multiplied.
60 phons is not 3 times louder than 20 phons!

3

Loudness in *sones*

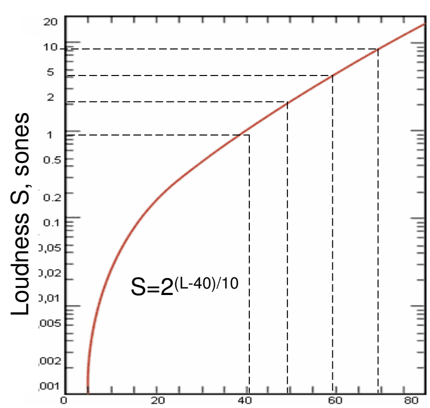
A unit to describe the comparative loudness between two or more sounds.

One SONE has been fixed at 40 phons *at any frequency* (40 phon curve)

Two sones describe sound two times louder than one sone sound.

A difference of ten phons is sufficient to produce the impression of doubling loudness, so two sones are 50 phons.

Four sones are twice as loud again, viz. 60 phons.



$S=K(f)\boldsymbol{I}^{0.3}$ - dependence of loudness in sones on intensity $\boldsymbol{I}$

4

Approximate relationship with the musical gradation of loudness

fff	FORTE-FORTISSIMO	100 phons	88 sones
ff	FORTISSIMO	90 phons	38 sones
f	FORTE	80 phons	17.1 sones
p	PIANO	50 phons	2.2 sones
pp	PIANISSIMO	40 phons	0.98 sones
ppp	PIANO-PIANISSIMO	30 phons	0.36 sones

5

JND for sound intensity

Methods of measuring intensity discrimination ΔI:

1. Modulation detection
2. Increment detection

Weber's law $\Delta I / I \approx const$ *(smallest detectable change in stimulus is proportional to the magnitude of the stimulus)*

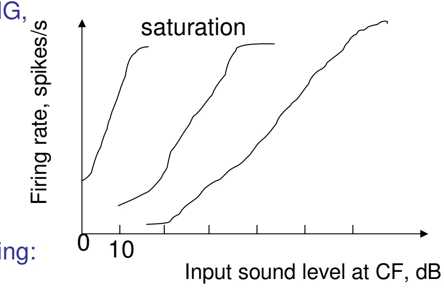
? Prove that smallest detectable change in intensity level $\Delta(IL)$ (in dB) is constant

Weber's law works better for noise than for pure tones of moderate intensity levels (agreement improves as intensity increases)

6

Neural coding of signal loudness

Common assumption – RATE/LEVEL CODING, I.e.loudness is related to the total neural activity evoked by sound in neurons with CF close to the frequency of sound



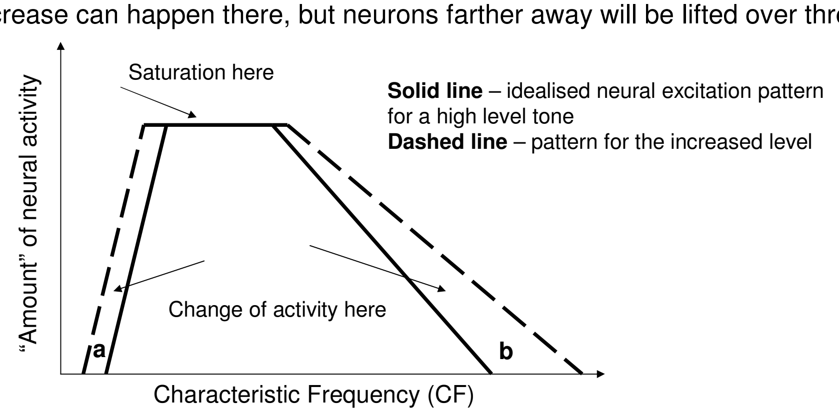
RATE/LEVEL CODING can't explain the following:

•Only 10% of neurons have dynamic range of more than 60dB, but auditory system dynamic range is 120dB!

•Loudness discrimination is possible at high levels– where we might expect saturation.

Possible alternatives/ additions to rate/level coding scheme -1

Spread of excitation.
If neurons at CF are saturated and level is increased – no further rate increase can happen there, but neurons farther away will be lifted over threshold



Masking of bands a and b makes the intensity discrimination of high level sounds worse, BUT reasonable performance is still possible!

Possible alternatives/ additions to rate/level coding scheme -2

Improvement in phase locking.

Phase locking might become more efficient at high levels.
A change in temporal regularity of the patterns of neural firing might signal the intensity change.
Even saturated neuron might show improvements in phase locking

Rate versus level information from unsaturated neurons with CFs close to stimulus frequency.

There is a small amount of such neurons and they may carry enough information to perform intensity discrimination when no other coding is possible.

9

Loudness of superimposed tones and critical band

$x(t) = p_1 \cos(2\pi f_1 t) + p_2 \cos(2\pi f_2 t)$ -two tones are played together

$I_1 = \dfrac{p_1^{\,2}}{2\rho_0 c_0}, \quad I_1 = \dfrac{p_2^{\,2}}{2\rho_0 c_0}$ -their intensities

$S_1 = K(f_1) I_1^{\,0.3}, \quad S_2 = K(f_2) I_2^{\,0.3}$ -their loudnesses

What will be the combined loudness of the tones?

$\boxed{\Delta f = f_2 - f_1 < \Delta f_{CB}}$ (tones excite the same region on the Basilar membrane)

The combined loudness S varies as $(I_1 + I_2)^{0.3}$ (cube root of sum of their intensities)

$\boxed{\Delta f = f_2 - f_1 > \Delta f_{CB}}$ (tones excite different regions on the Basilar membrane)

Their loudnesses add: $S = S_1 + S_2$

10

Loudness of superimposed tones – set of rules

Same frequencies → ▪Sum intensities: $I = I_1 + I_2 + \ldots$

Different frequencies within the same critical band → ▪Then calculate loudness in sones

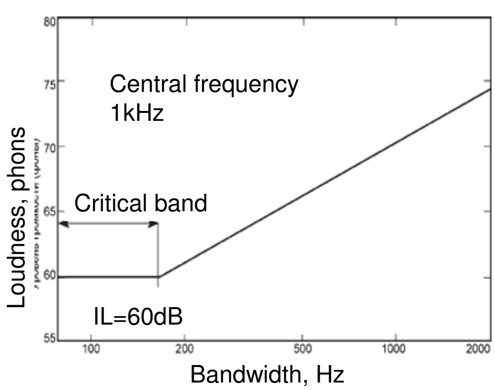
$$S \propto I^{0.3} = (I_1 + I_2 + \ldots)^{0.3}$$

Different frequencies outside critical band → ▪Louder than I–summation
▪Tends to $S = S_1 + S_2 + \ldots$ - sum of loudness contributions from different critical bands

Different frequencies, very large frequency separation → People tend to hear only one component. Difficult to establish overall loudness.

11

Loudness of complex tones – the role of the bandwidth



•If bandwidth is smaller than Δf_{CB} - the loudness does not vary with bandwidth. The ear lumps all the energy within the critical band and treats it as one item of sound.

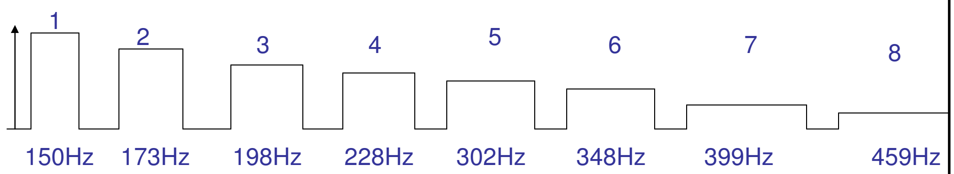
•If bandwidth extends beyond one critical band – brain appears to add the individual critical band responses together. Loudness increases, although intensity does not.

Wide band signals are louder than narrow band signals with the same intensity

12

Critical bands by loudness comparison

A noise band of 1kHz centre frequency and 15% bandwidth (930-1075Hz) is followed by a test band with the same centre frequency and bandwidth increasing in 7 steps of 15% each. The power of the test signal is kept constant.



At which step the loudness begins to increase?
Estimate the critical band for 1kHz tone.

Things you need to know

- ❑Equal loudness contours – experimental procedure, relationship with ear anatomy, implications for sound reproduction
- ❑Loudness scales – phons and sones
- ❑Neural coding of loudness. What is special about coding of high intensity tones?
- ❑Loudness of superimposed/ complex tones – dependence on critical band

Further reading

- JG Roederer pp.85-100
- BCJ Moore Chapter 4
- Howard and Angus, pp.82-91

15