EE E6820: Speech & Audio Processing & Recognition

Lecture 4: Auditory Perception

1. Motivation: Why & how
2. Auditory physiology
3. Psychophysics: Detection & discrimination
4. Pitch perception
5. Speech perception
6. Auditory organization & Scene analysis

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1 Why study perception?

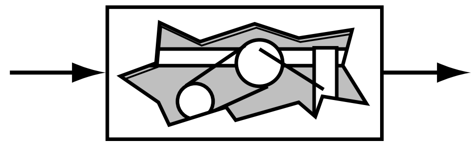
- **Perception is messy: Can we avoid it?**

  No!
- **Audition provides the 'ground truth' in audio**
  - what is relevant and irrelevant
  - subjective importance of distortion (coding etc.)
  - (there could be other information in sound...)
- **Some sounds are 'designed' for audition**
  - co-evolution of speech and hearing
- **The auditory system is very successful**
  - we would do extremely well to duplicate it
- **We are now able to model complex systems**
  - faster computers, bigger memories

How to study perception?

Three different approaches:

- **Analyze the example: physiology**



  - dissection & nerve recordings

- **Black box input/output: psychophysics**

  - fit simple models of simple functions

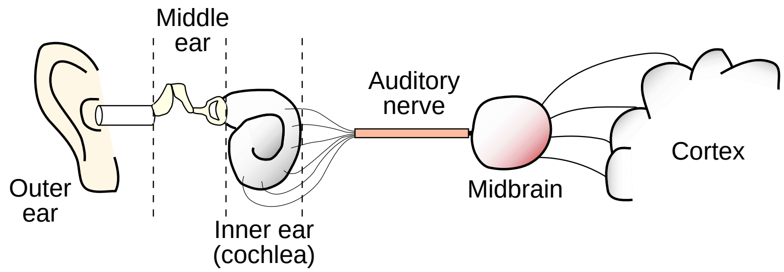
- **Information processing models**
  - investigate and model complex functions
  - e.g. scene analysis, speech perception

Outline

1. Motivation
2. **Physiology**
   - Outer, middle & inner ear
   - The Auditory Nerve and beyond
   - Models
3. Psychophysics
4. Pitch perception
5. Speech perception
6. Scene analysis

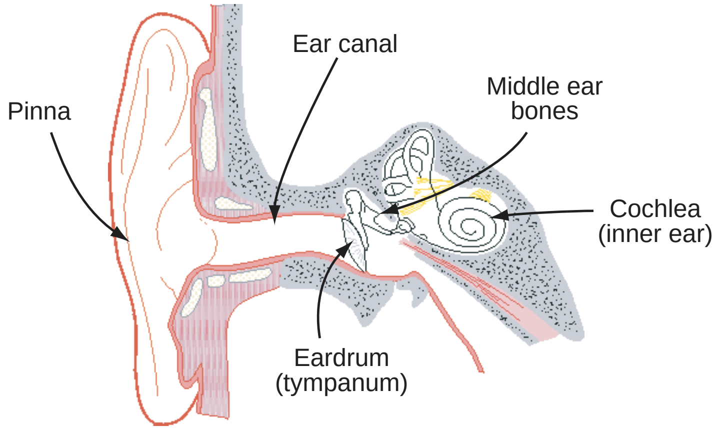
2 Physiology

- **Processing chain from air to brain:**



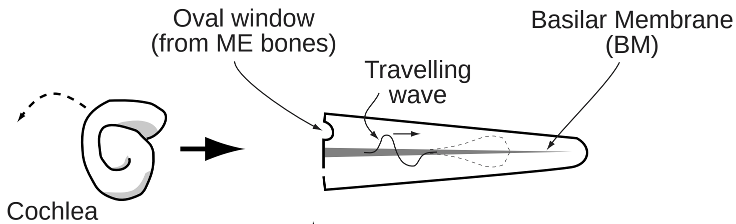
- **Study via:**
  - anatomy
  - nerve recordings
- **Signals flow in both directions**

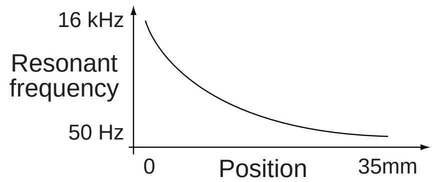
Outer & middle ear



- **Pinna 'horn'**
  - complex reflections give spatial (elevation) cues
- **Ear canal**
  - acoustic tube
- **Middle ear**
  - bones provide impedance matching

Inner ear: Cochlea

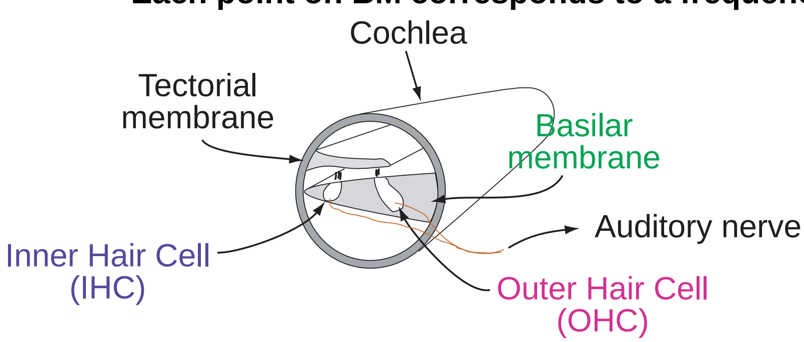




- **Mechanical input from middle ear starts traveling wave moving down Basilar Membrane**
- **Varying stiffness and mass of BM gives results in continuous variation of resonant frequency**
- **At resonance, traveling wave energy is dissipated in BM vibration**
  → Frequency (Fourier) analysis

Cochlea hair cells

- **Ear converts sound to BM motion;**
  Each point on BM corresponds to a frequency

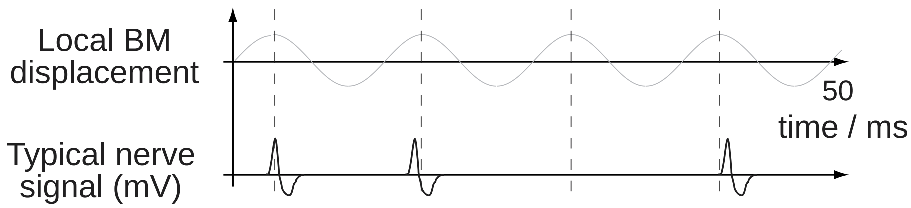


- **Hair cells on BM convert motion into nerve impulses (firings)**
- **Inner Hair Cells detect motion**
- **Outer Hair Cells? Variable damping?**

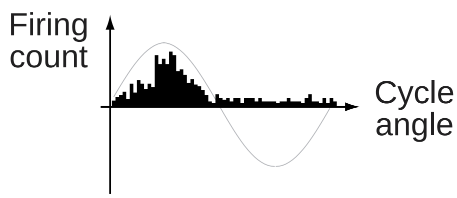
[BM animation]

Inner Hair Cells

- **IHCs convert BM vibration into nerve firings**
- **Human hear has ~3500 IHCs;**
  Each IHC has ~7 connections to Auditory Nerve
- **Each nerve fires (sometimes) near peak displacement:**



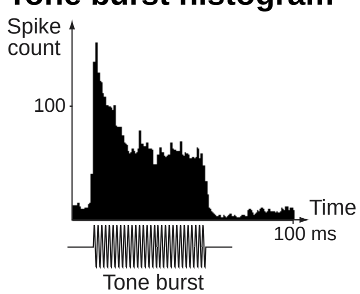
- **Histogram to get firing probability:**



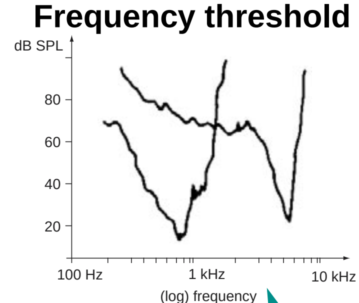
Auditory nerve (AN) signals

- **Single nerve measurements:**

Tone burst histogram

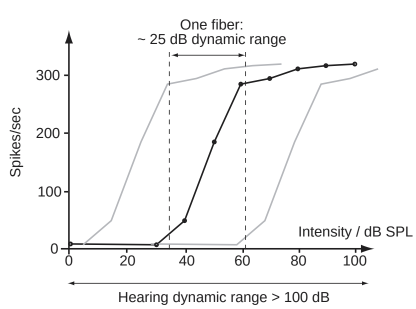


Frequency threshold



(approx. constant-Q)

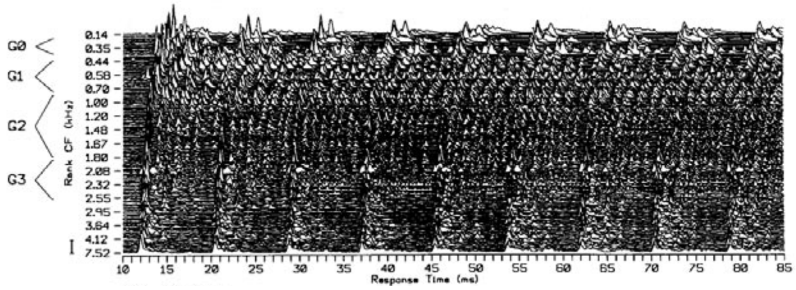
Rate vs. intensity



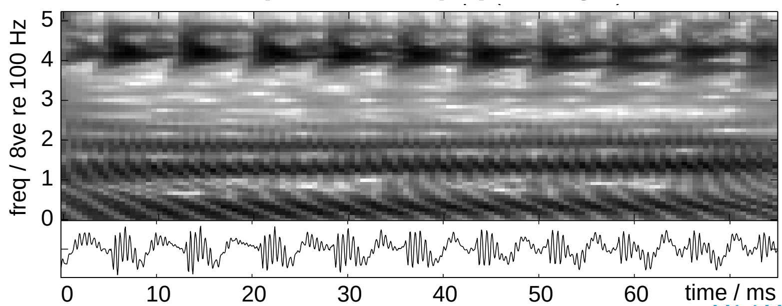
- **Hard to measure: probe living ANs?**

AN population response

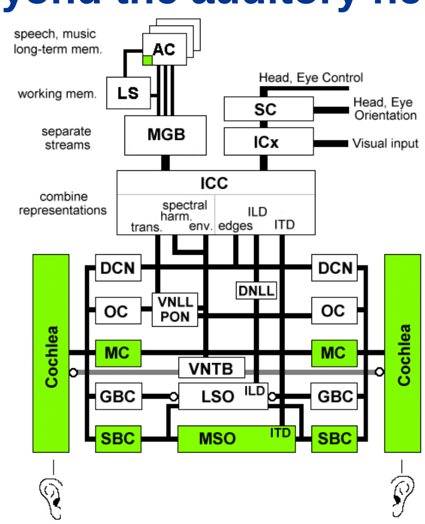
- **All the information the brain has about sound:**
  - average rate & spike timings on 30,000 fibers



- **Not unlike a (constant-Q) spectrogram?**



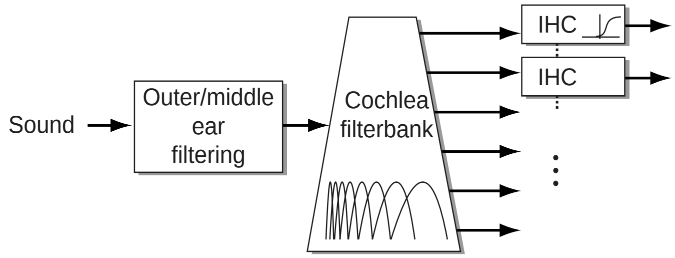
Beyond the auditory nerve



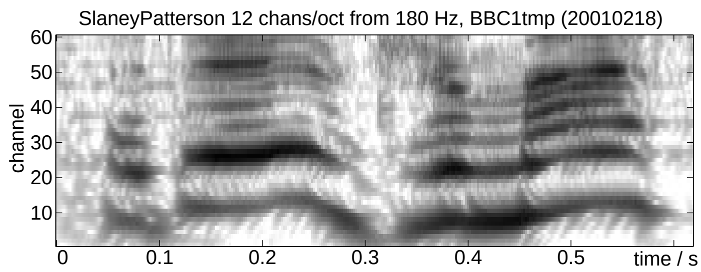
(from lloydwatts.com)

- **Ascending and descending**
- **Tonotopic × ?**
  - modulation - position - source??

Periphery models



- **Modeled aspects:**
  - outer/middle ear
  - hair cell transduction
  - cochlea filtering
  - efferent feedback?
- **Result: ‘neurogram’ / ‘cochleagram’**



Outline

1. Motivation
2. Physiology
3. **Psychophysics**
   - Detection theory modeling
   - Intensity perception
   - Masking
4. Pitch perception
5. Speech perception
6. Scene analysis

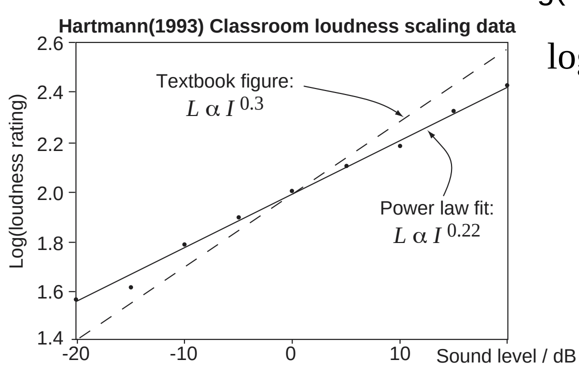
Psychophysics

3

- **Physiology looks at the implementation; Psychology looks at the function/behavior**
- **Analyze audition as signal detection:** $p(\omega | O)$
  - psychological tests reflect internal decisions
  - assume optimal decision process
  - infer nature of internal representations, noise, ...
  - → lower bounds on more complex functions
- **Different aspects to measure**
  - time, frequency, intensity
  - tones, complexes, noise
  - binaural
  - pitch, detuning

Basic psychophysics

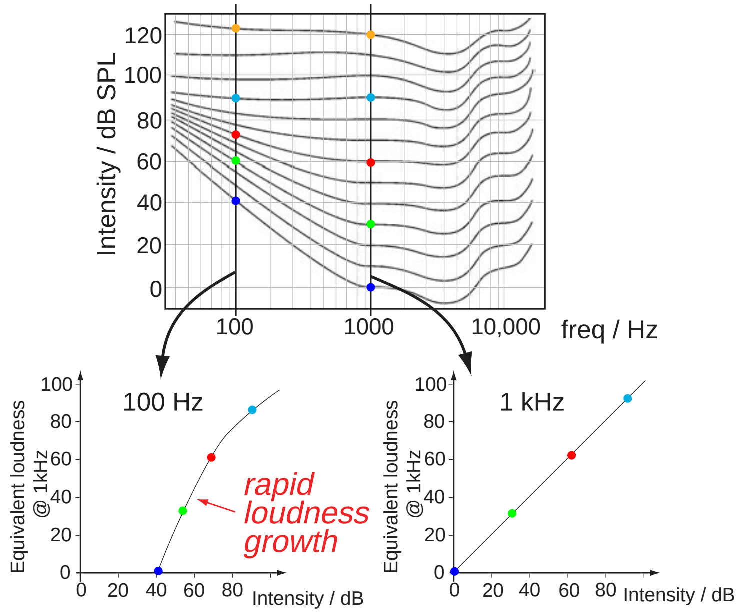
- **Relate physical and perceptual variables**
  - e.g. intensity → loudness
    frequency → pitch
- **Methodology: subject tests**
  - just noticeable difference (jnd)
  - magnitude scaling e.g. 'adjust to twice as loud'
- **Results for Intensity vs. Loudness:**
  Weber's law $\Delta I \propto I \rightarrow \log(L) = k \cdot \log(I)$



$$\log_2(L) = 0.3\log_2(I)$$
$$= 0.3 \cdot \frac{\log_{10} I}{\log_{10} 2}$$
$$= \frac{0.3}{\log_{10} 2} \cdot \frac{dB}{10}$$
$$= dB / 10$$

Loudness as a function of frequency

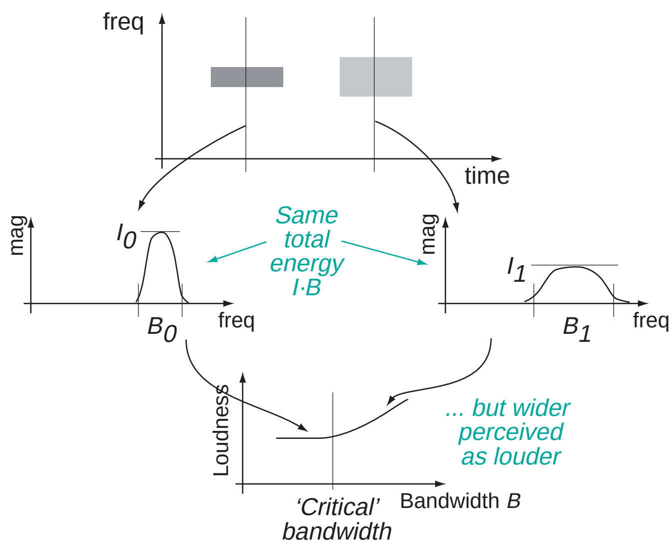
- **Fletcher-Munson equal-loudness curves:**



- **Hearing impairment: exaggerates**

Loudness as a function of bandwidth

- **Same total energy, different distribution:**

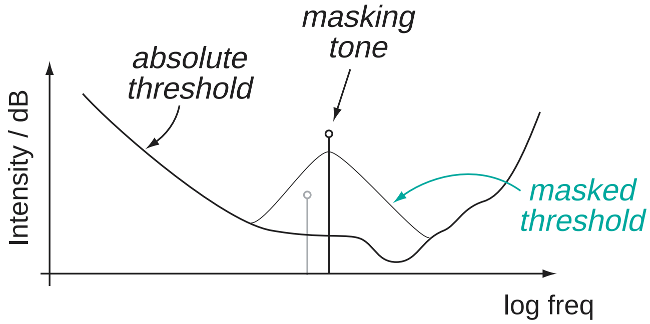


  - e.g. 2 chans at -6 dB (not -10 dB)

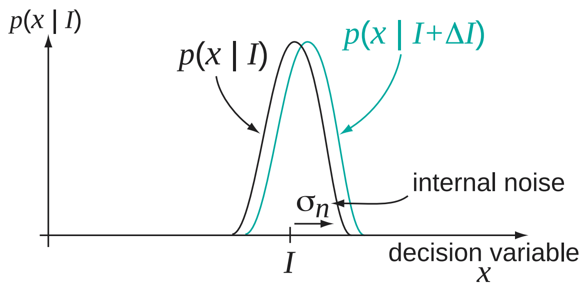
- **Critical bands: independent freq. channels**
  - ~ 25 total (4-6 / octave) [sndex]

Simultaneous masking

- **A louder tone can 'mask' the perception of a second tone nearby in frequency:**

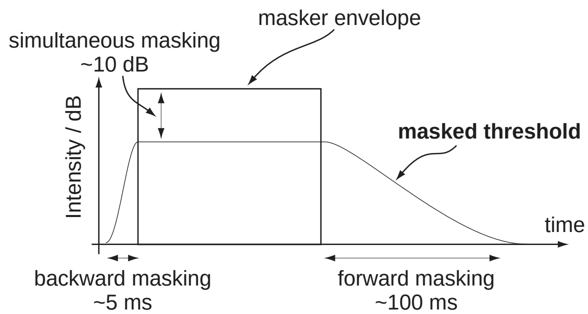


- **Suggests an 'internal noise' model:**



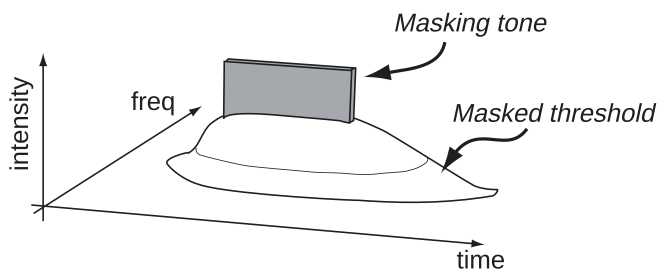
Sequential masking

- **Backward/forward in time:**

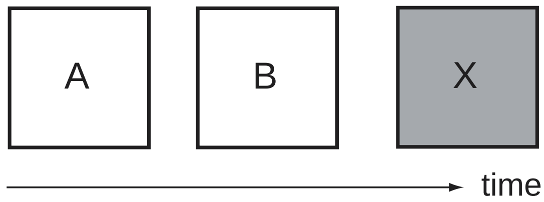


- suggests temporal envelope of decision var.

→ **Time-frequency masking 'skirt':**



What we do and don't hear



"two-interval forced-choice":

X = A or B?

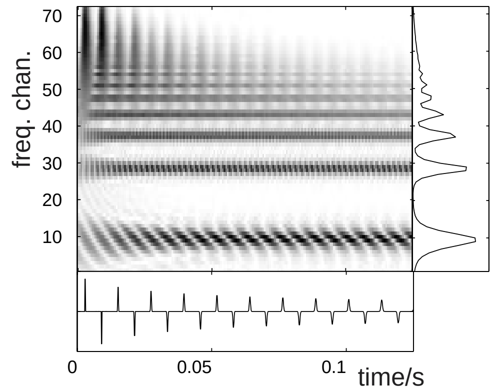
- **Timing: 2ms attack resolution, 20ms discrim**
  - but: spectral splatter
- **Tuning: ~ 1% discrimination**
  - but: beats
- **Spectrum: profile changes, formants**
  - variable time-frequency resolution
- **Harmonic phase?**
- **Noisy signals & texture**
- **(Trace vs. categorical memory)**

Outline

1. Motivation
2. Physiology
3. Psychophysics
4. **Pitch perception**
   - 'Place' models
   - 'Time' models
   - Multiple cues & competition
5. Speech perception
6. Scene analysis

4 Pitch perception: A classic argument in psychophysics

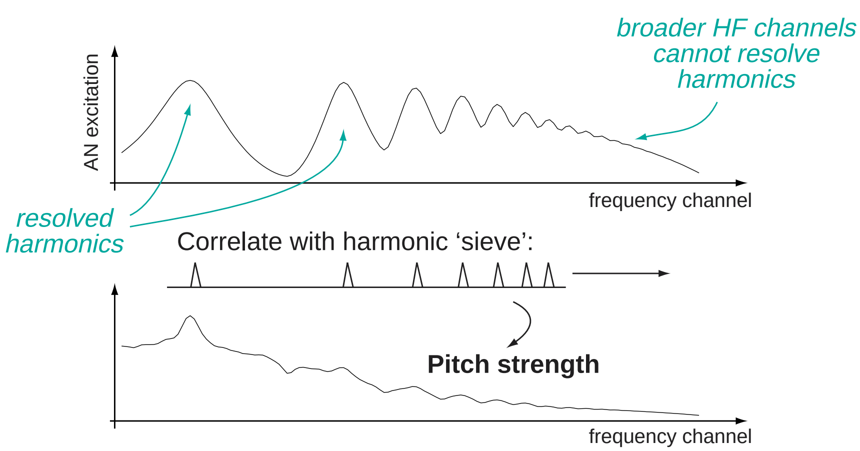
- **Harmonic complexes are a pattern on AN**



  - .. but give a *fused* percept (ecological)
- **What determines the pitch percept?**
  - *not* the fundamental
- **How is it computed?**
  Two competing models: place and time

Place model of pitch

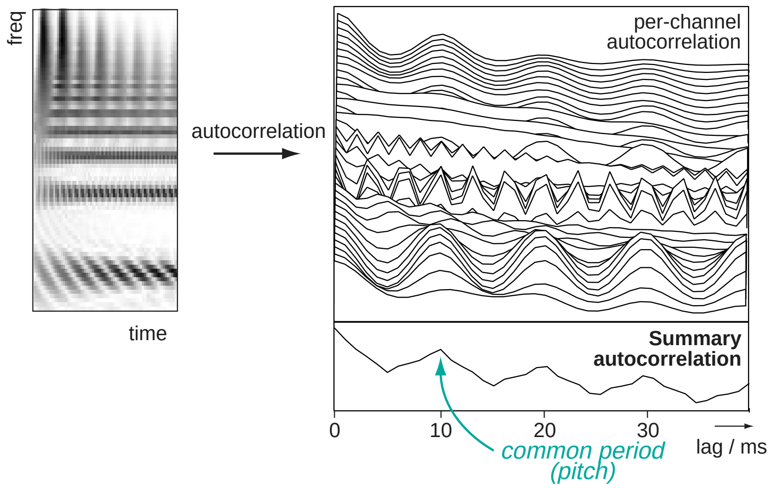
- **AN excitation pattern shows individual peaks**
- **'Pattern matching' method to find pitch:**



- **Support:**
  Low harmonics are very important
- **But: Flat-spectrum noise can carry pitch**

Time model of pitch

- **Timing information is preserved in AN down to ~ 1ms scale**
- **Extract periodicity by e.g. autocorrelation & combine across frequency chans:**



- **But: HF gives weak pitch (in practice)**

Alternate & competing cues

- **Pitch perception could rely on various cues**
  - average excitation pattern
  - summary autocorrelation
  - more complex pattern matching
- **Relying on just one cue is brittle**
  - e.g. missing fundamental

→ **Perceptual system appears to use a flexible, opportunistic combination**

- **Optimal detector justification?**

$$\underset{\omega}{\operatorname{argmax}}\ p(\omega|\mathbf{o})$$
$$= \underset{\omega}{\operatorname{argmax}}\ \frac{p(\mathbf{o}|\omega)\cdot p(\omega)}{p(\mathbf{o})}$$
$$= \underset{\omega}{\operatorname{argmax}}\ p(o_1|\omega)\cdot p(o_2|\omega)\cdot p(\omega)$$

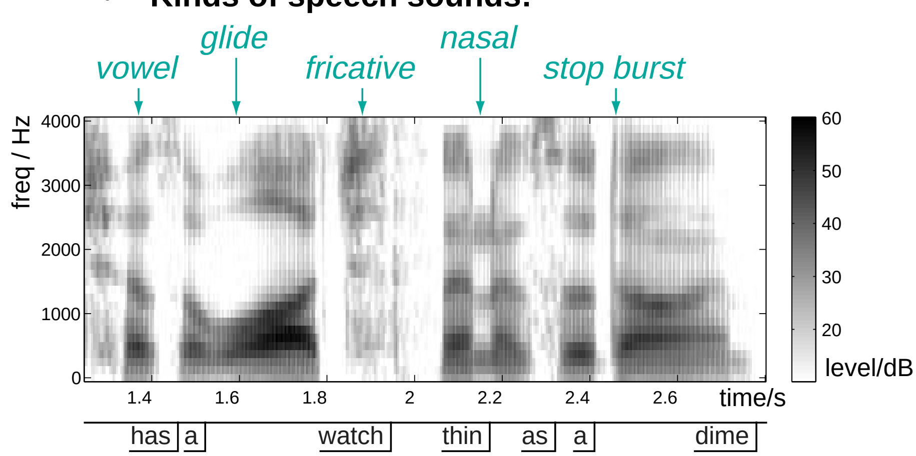
if o_1 and o_2 are *conditionally* independent

Outline

1. Motivation
2. Physiology
3. Psychophysics
4. Pitch perception
5. **Speech perception**
   - The sounds of speech
   - Phoneme perception
   - Context and top-down influences
6. Scene Analysis

5 Speech perception

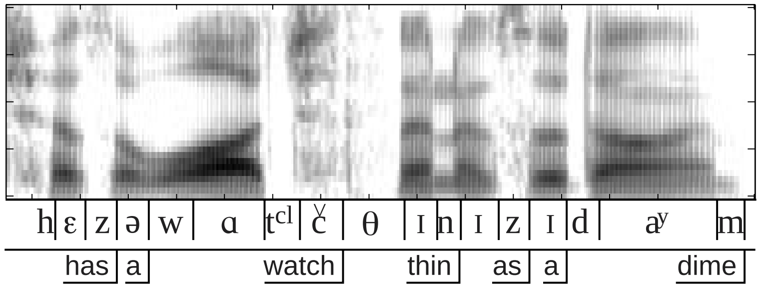
- **Highly specialized function**
  - subsequent to source organization?
  - .. but also can interact
- **Kinds of speech sounds:**



- vowels - glides - nasals
- stops - fricatives ...

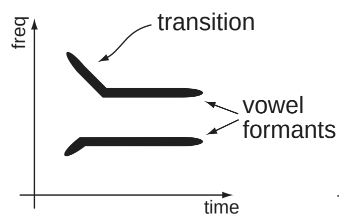
Cues to phoneme perception

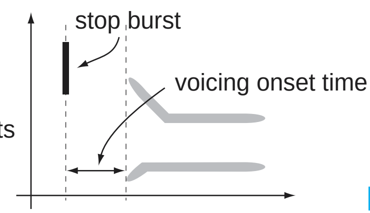
- **Linguists describe speech with *phonemes*:**



  - phonemes define minimal word contrasts

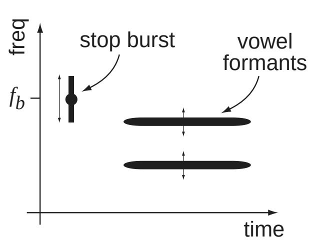
- **Acoustic-phoneticians describe phonemes by:**
  - **formants & transitions**
  - **bursts & onset times**

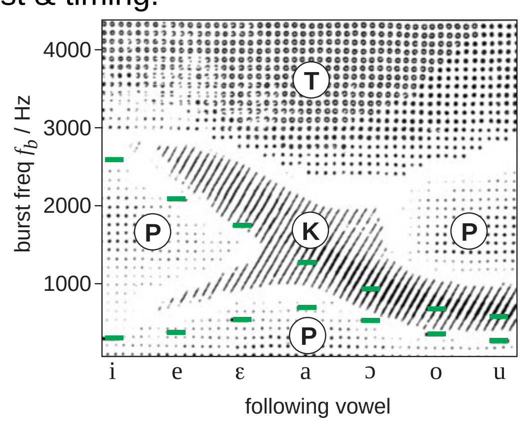




Categorical perception

- **(Some) speech sounds perceived *categorically* rather than *analogically***
  - e.g. stop-burst & timing:



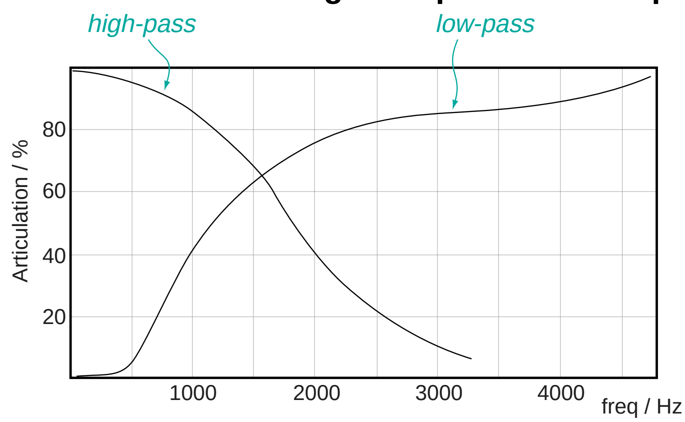


  - tokens within category are hard to distinguish
  - category boundaries are very sharp

- **Categories are learned for native tongue**
  - “merry” / “mary” / “marry”

Where is the information in speech?

- **'Articulation' of high/low-pass filtered speech:**

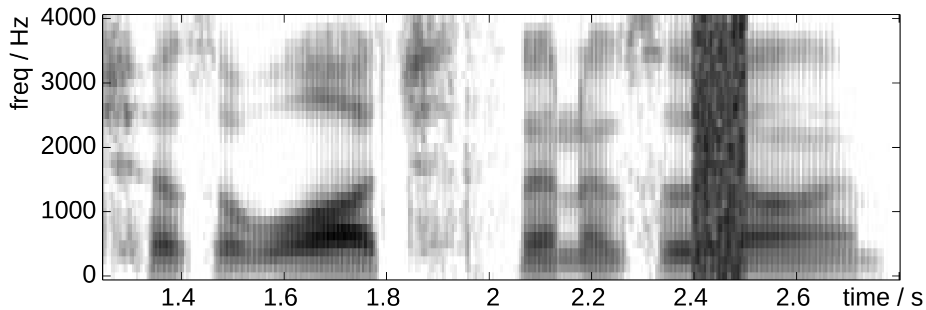


  - sums to more than 1...
- **Speech message is highly redundant**
  - e.g. constraints of language, context
  - →listeners can understand with *very few* cues

Top-down influences: Phonemic restoration

(Warren 1970)

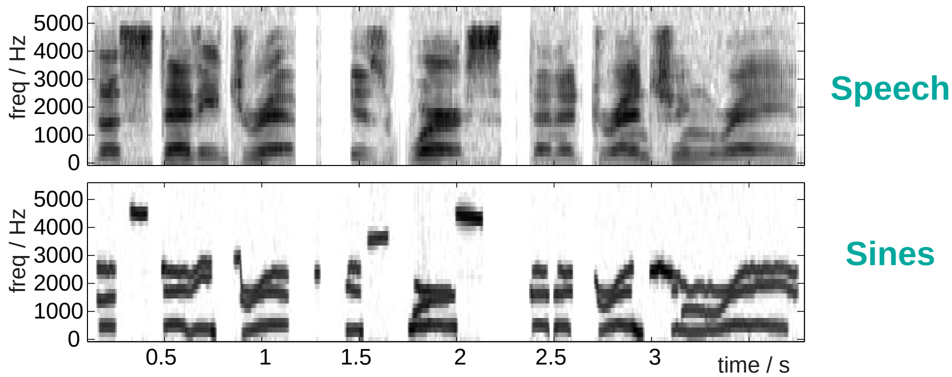
- **What if a noise burst obscures *speech*?**



  - auditory system 'restores' the missing phoneme
    ... based on semantic context
    ... even in retrospect!
- **Subjects are typically unaware of which sounds are restored**

A predisposition for speech: Sinewave replicas
(Remez et al. 1994)

- **Replace each formant with a single sinusoid:**

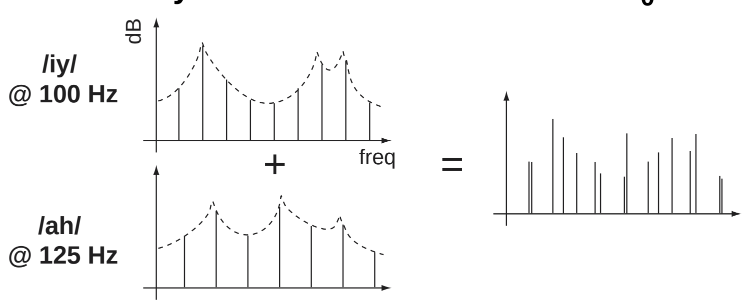


  - speech is (somewhat) intelligible
  - people hear both whistles and speech ("duplex")
  - processed as speech despite un-speech-like

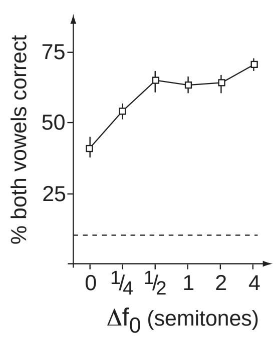
- **What does it take to be speech?**

Simultaneous vowels

- **Mix synthetic vowels with different f_0s:**

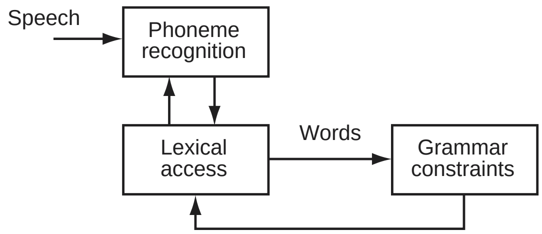


- **Pitch difference helps (though not necessary):**



Computational models of speech perception

- **Various theoretical - practical models of speech comprehension, e.g. :**



- **Open questions:**
  - mechanism of phoneme classification
  - mechanism of lexical recall
  - mechanism of grammar constraints
- **ASR is a practical implementation (?)**

Outline

1. Motivation
2. Physiology
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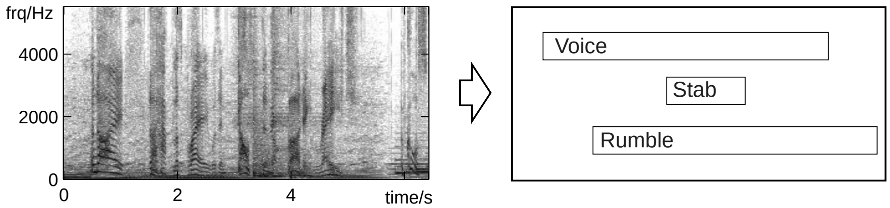
4. Pitch perception
5. Speech perception
5. **Scene analysis**
   - Events and sources
   - Fusion and streaming
   - Continuity & restoration
   - Simultaneous vowels

6 Auditory Organization

- **Detection model is huge simplification**
- **Real role of hearing is much more general: Recover useful information from outside world**

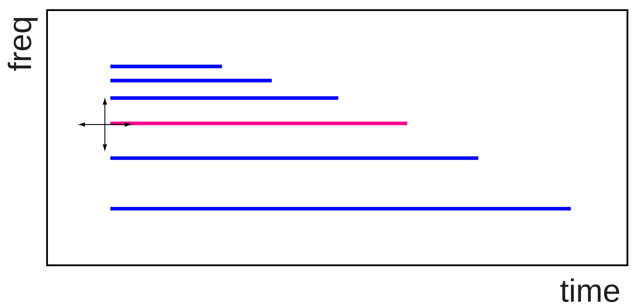
→ **Sound organization into events and sources:**



- **Research questions:**
  - what determines perception of sources?
  - how do humans separate mixtures?
  - how much can we tell about a source?

Auditory scene analysis: Simultaneous fusion

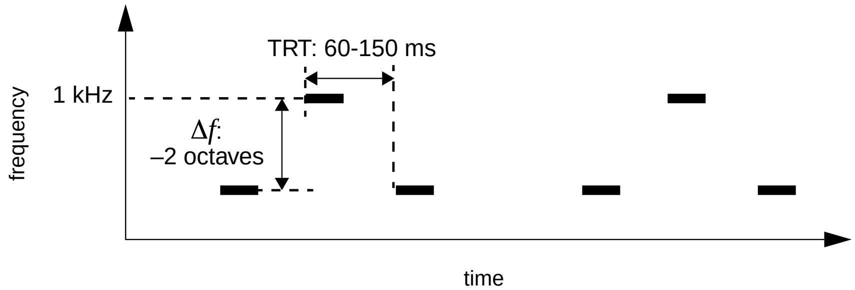
- **Harmonics are distinct on AN, but perceived as one sound (“fused”):**



  - depends on *common onset*
  - depends on *harmonicity* (common period)
- **Methodologies:**
  - ask subject how many ‘objects’
  - match attributes e.g. object pitch
  - manipulate higher level e.g. vowel identity

Sequential grouping: streaming

- **Pattern / rhythm: property of *set* of objects**
  - subsequent to fusion ∵ employs fused events?

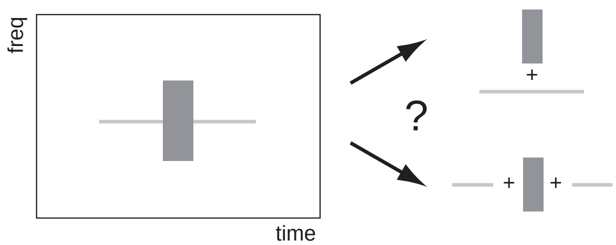


- **Measure by relative timing judgments**
  - cannot compare between streams
- **Separate 'coherence' and 'fusion' boundaries**
- **Can interact and compete with fusion**

[sndex]

Continuity & restoration

- **Tone is interrupted by noise burst: What happened?**

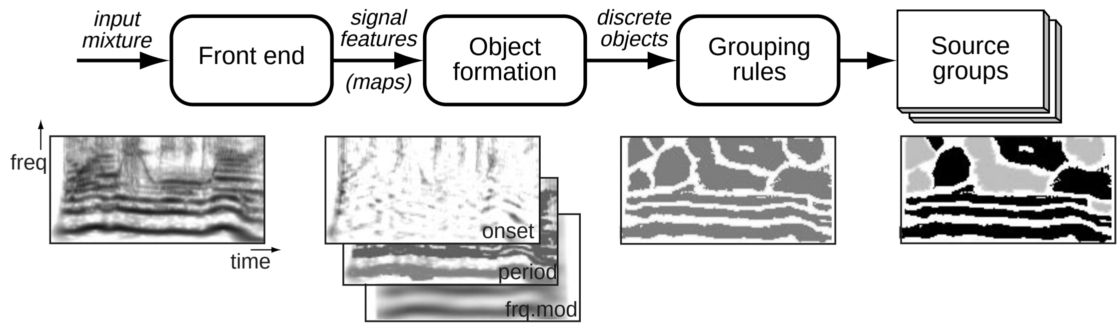


  - masking makes tone undetectable during noise
- **Need to infer most probable real-world events**
  - observation equally likely for either explanation
  - *prior* on continuous tone much higher → choose
- **Top-down influence on perceived events...**

pulsation threshold [sndex]

Models of auditory organization

- **Psychological accounts suggest bottom-up:**

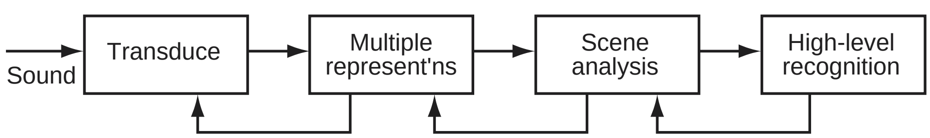


  - (Brown 1991)
- **Complications in practice:**
  - formation of separate elements
  - contradictory cues
  - influence of top-down constraints (context, expectations)

  ...

Summary

- **Auditory perception provides the 'ground truth' underlying audio processing**
- **Physiology specifies information available**
- **Psychophysics measures basic sensitivities**
- **Sound sources requires further organization**
- **Strong contextual effects in speech perception**



Parting thought:

Is pitch central to communication? Why?