Models
in
Hearing

All models are wrong but some are useful.

–Box (1979)

What is a model?

Why model?

Models in hearing

The example of Pitch

What is a model?

"a *thing* that represents a *thing* in a way that is useful"

--> theory, analogue, map, metaphor, schema, simulation...

"The best material model of a cat is another, or preferably the same, cat" (Norbert Wiener, 1945).

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not a very useful concept...

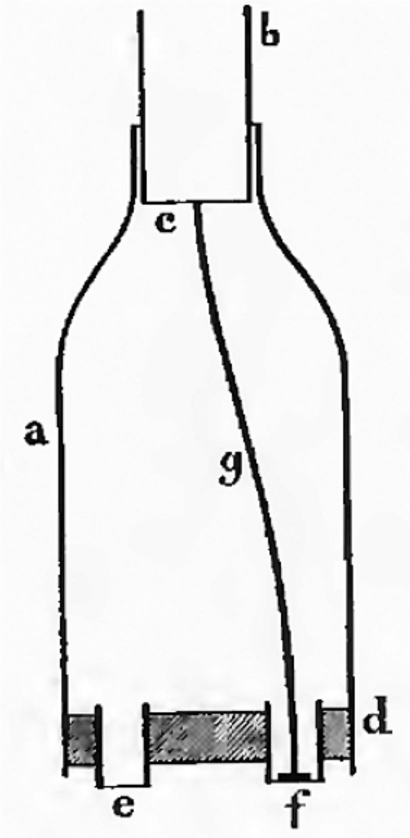
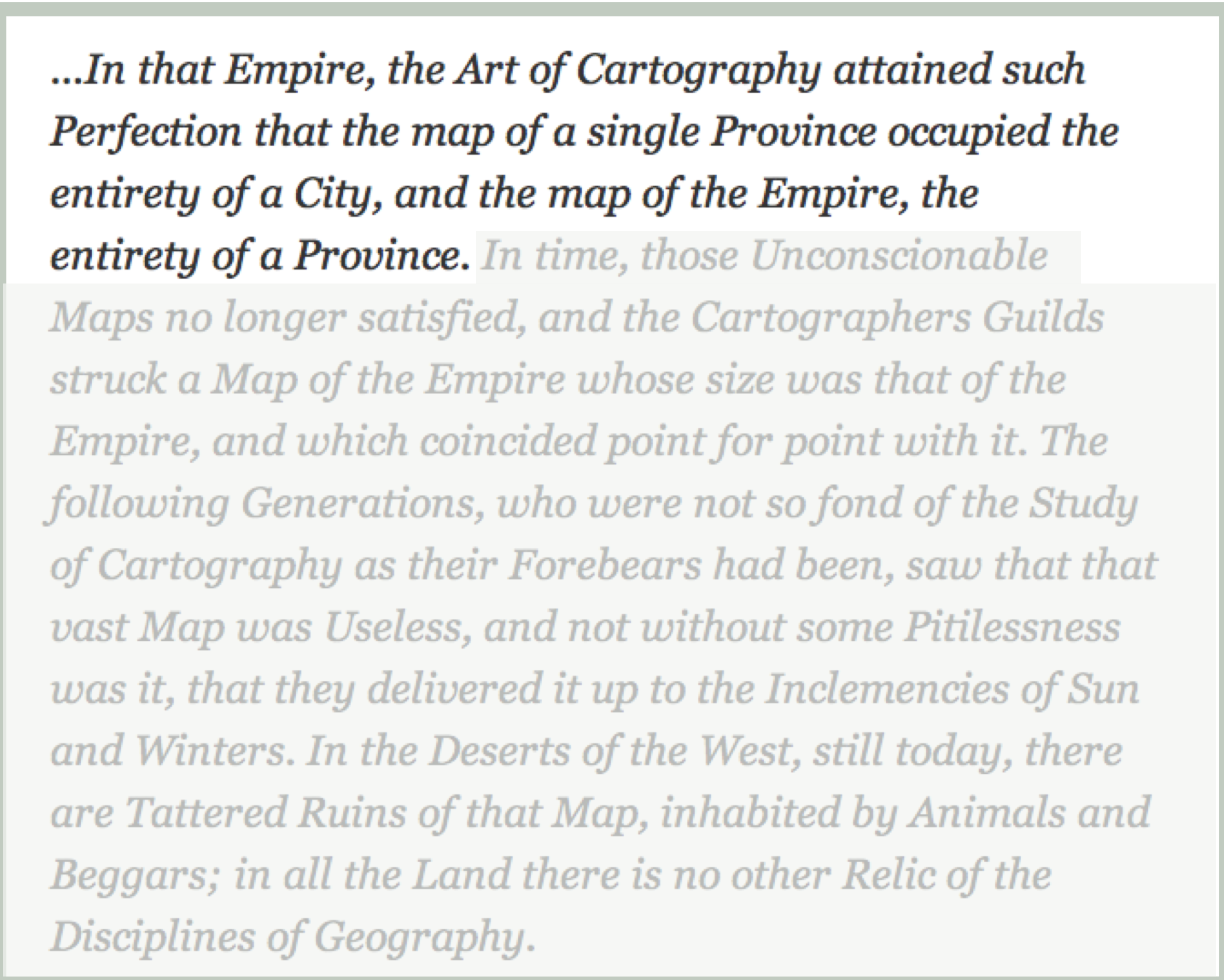
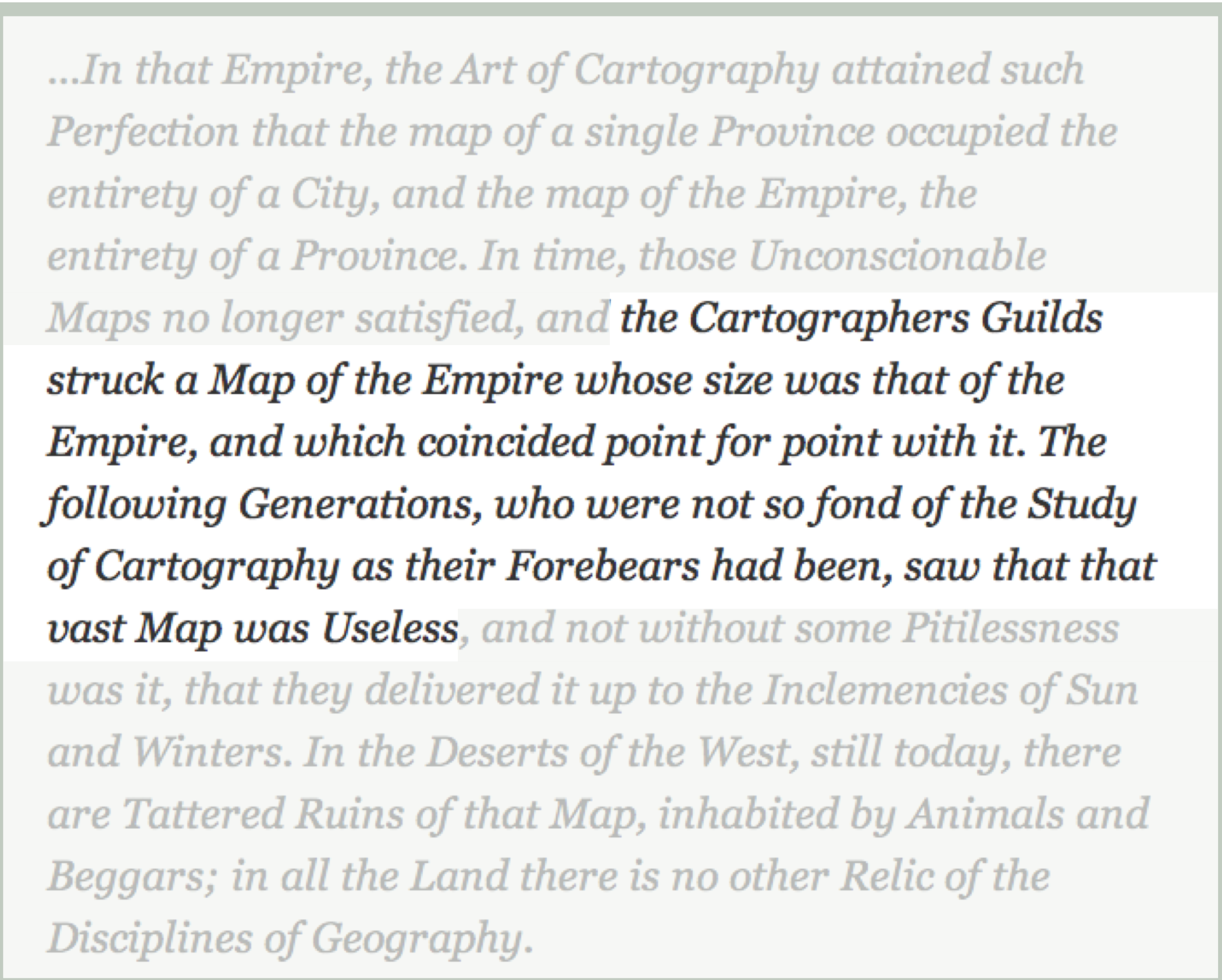


Figure 3. Johannes Müller built this model of the middle ear to convince himself that sound is transmitted from the ear drum (c) via the ossicular chain (g) to the oval window (f), rather than by air to the round window (e) as was previously thought. The model is obviously "false" (the ossicular chain is not a piece of wire) but it allowed an important advance in understanding hearing mechanisms (Müller 1838; von Békésy and Rosenblith 1948).



…In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. *In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.*

Jorge Luis Borges (1946), "On exactitude in Science"



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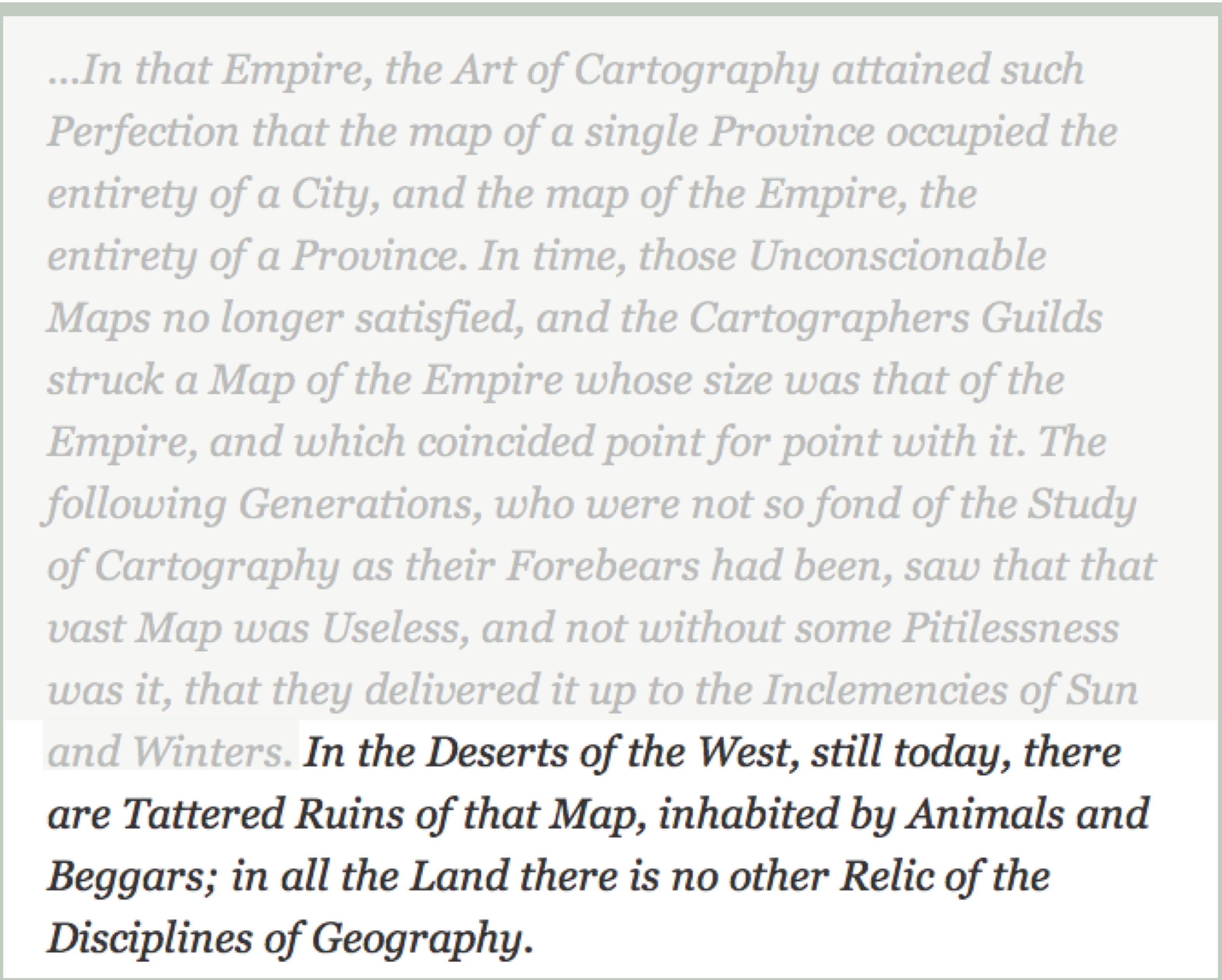

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Jorge Luis Borges (1946), "On exactitude in Science"

"all good models are wrong" (D.O. Hebb)

- Model ≠ reality
  - belong to different spaces
  - the quality of fit is <u>multidimensional</u>

- an "ecology" of models?
  - "biodiversity" of models
  - competition (→ "survival of the fittest")
  - "ecological niche" (→ protect new ideas)
  - "speciation" (→ new theories)

how to recognize a good model?

- internally **consistent**
- **good fit** with world
- **easy to understand** and handle
- **few parameters** (Occam's razor)
- able to **generalize** & predict

The metric depends on how these criteria are weighted.
The "fit score" depends on which aspect of the data is judged to be most important.

➔ *no "best" model*

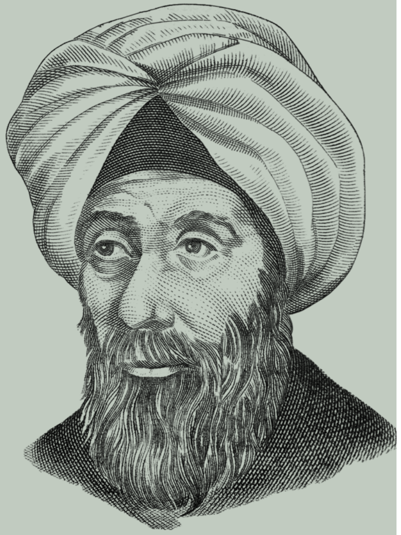
a plea for multiple models

> The idea is simply to carry around in your head as many formulations as you can that are self-consistent and consistent with the empirical facts you know. Then, when you make an observation or read a paper, you find yourself saying, for example, “Well that certainly makes it look bad for the idea that sharpening occurs in the cochlear excitation process”.

JCR Licklider
1959

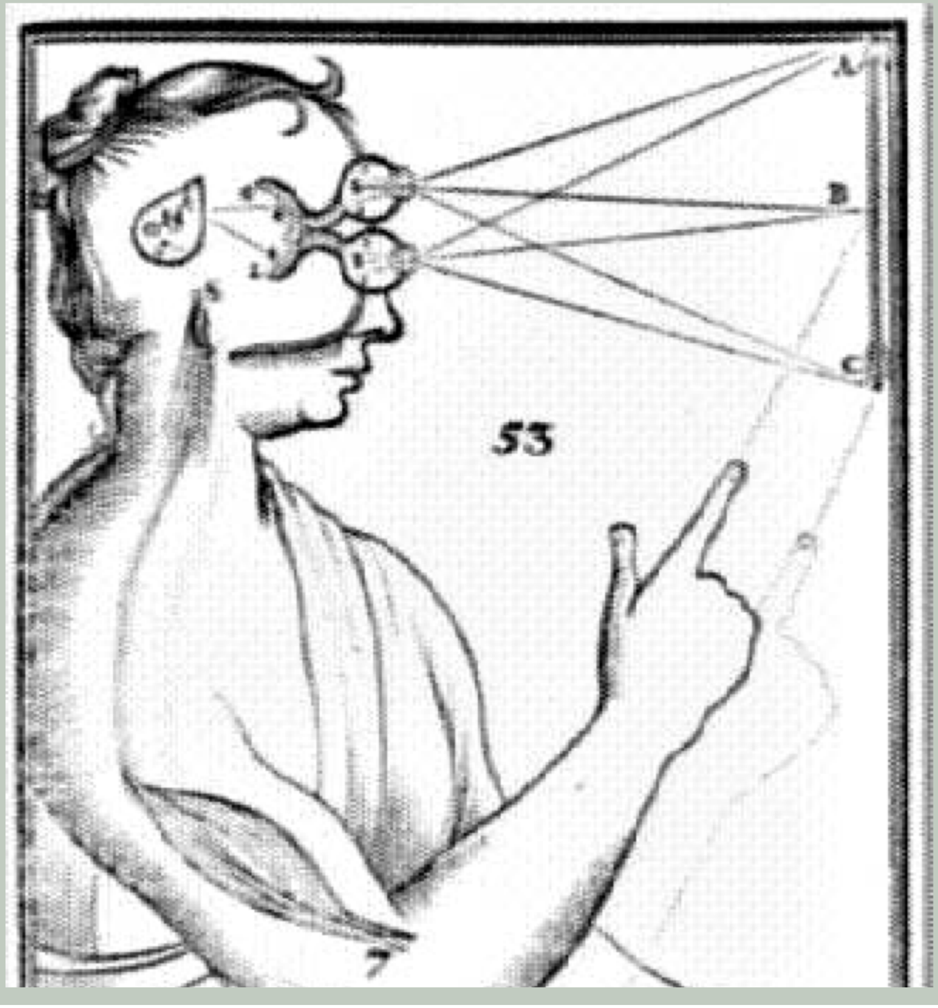
→ doctrine of unconscious inference (Helmholtz, borrowed from Alhacen)

Helmholtz (1967)



Alhacen (c.a. 1030)

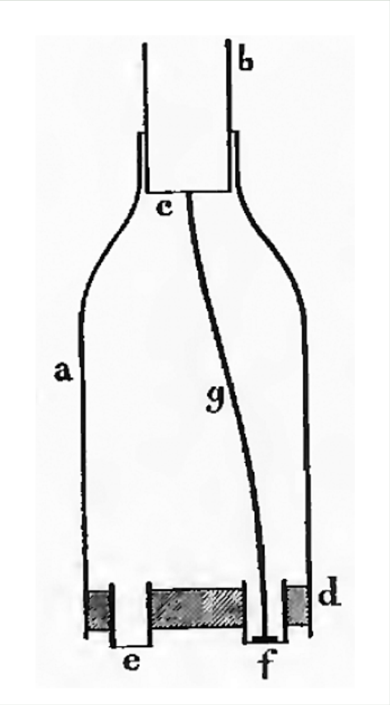
sensory information is matched to an internal model of the outside world.



model-making is analogous to perception

Why model?

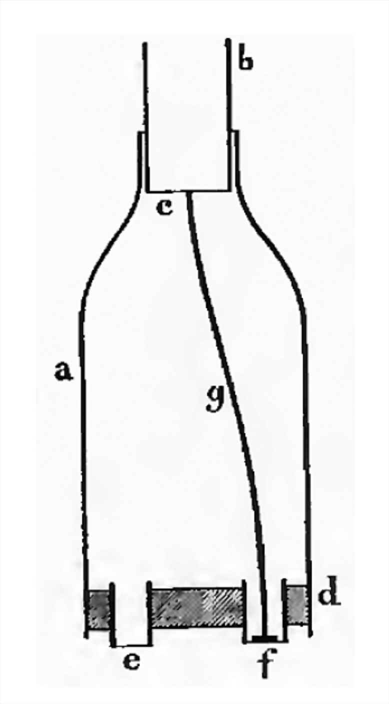
- *gain intuitive* ***understanding***
- *organize &* ***summarize knowledge*** *(→ "theory")*
- *generate* ***predictions***
- *design experiments*
- ***communicate*** *ideas*



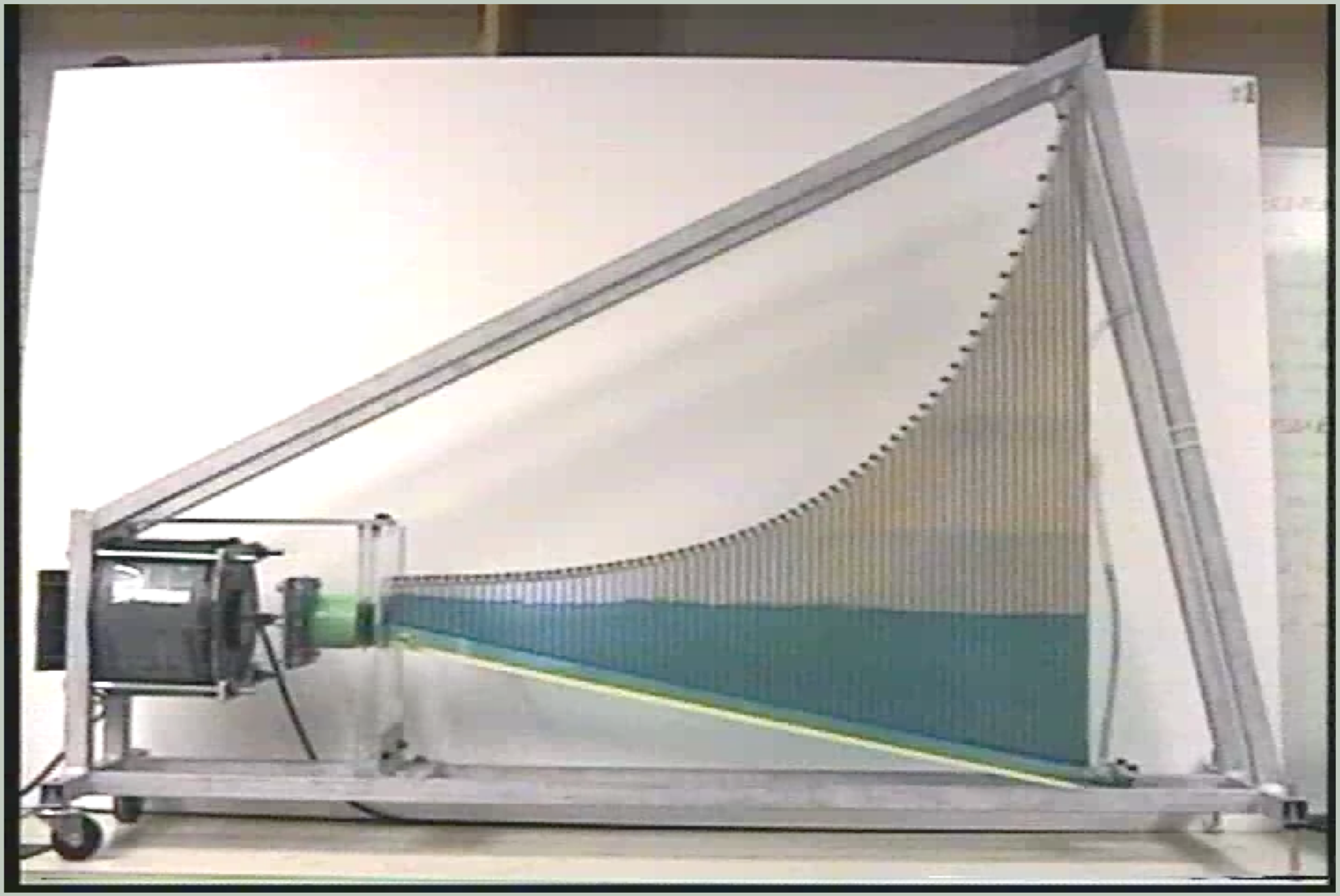
many types of model:

- *material model*
- *computer model*
- *animal model*
- *theoretical*
- *metaphorical*

...



Example 1: water-filled cochlear model



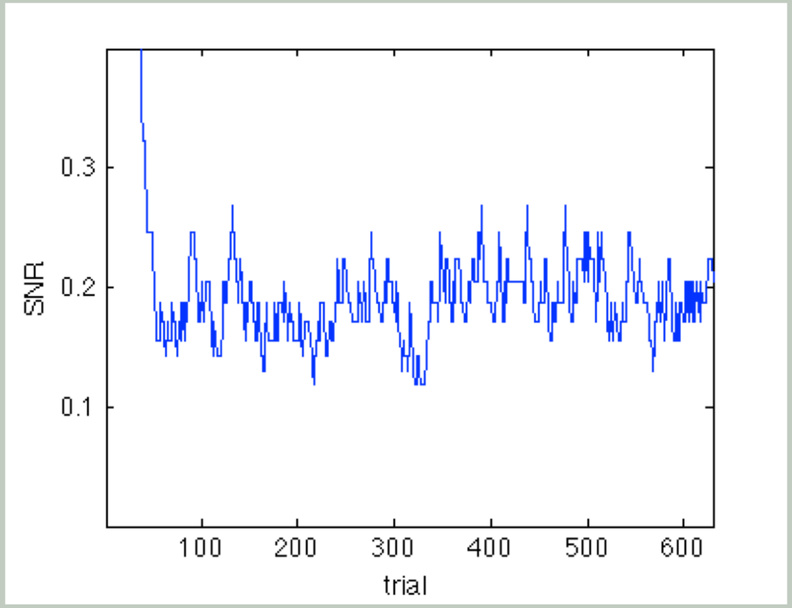
Example 2: model of detection at threshold

question: does brain state affect sensory processing?

experiment: mesure EEG during behavioral task

stimulus: random series of tone pips, variable signal-to-noise ratio

task: detect pips

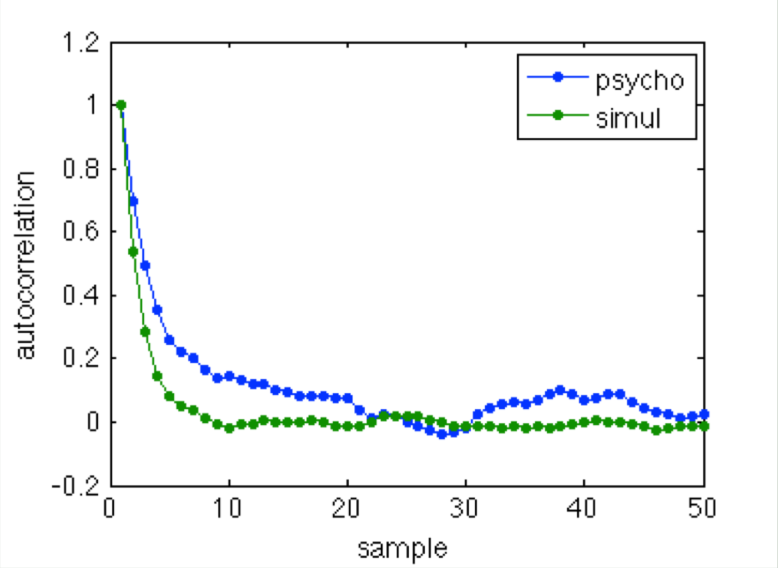


adaptive procedure: SNR varied to converge on 50% success

hypothesis: threshold fluctuates with brain "state"

"Sanity check" before running the experiment:

*- "**model listener**" with no state, i.e. that performs the task only on the basis of the instantaneous SNR, compare to real listeners*



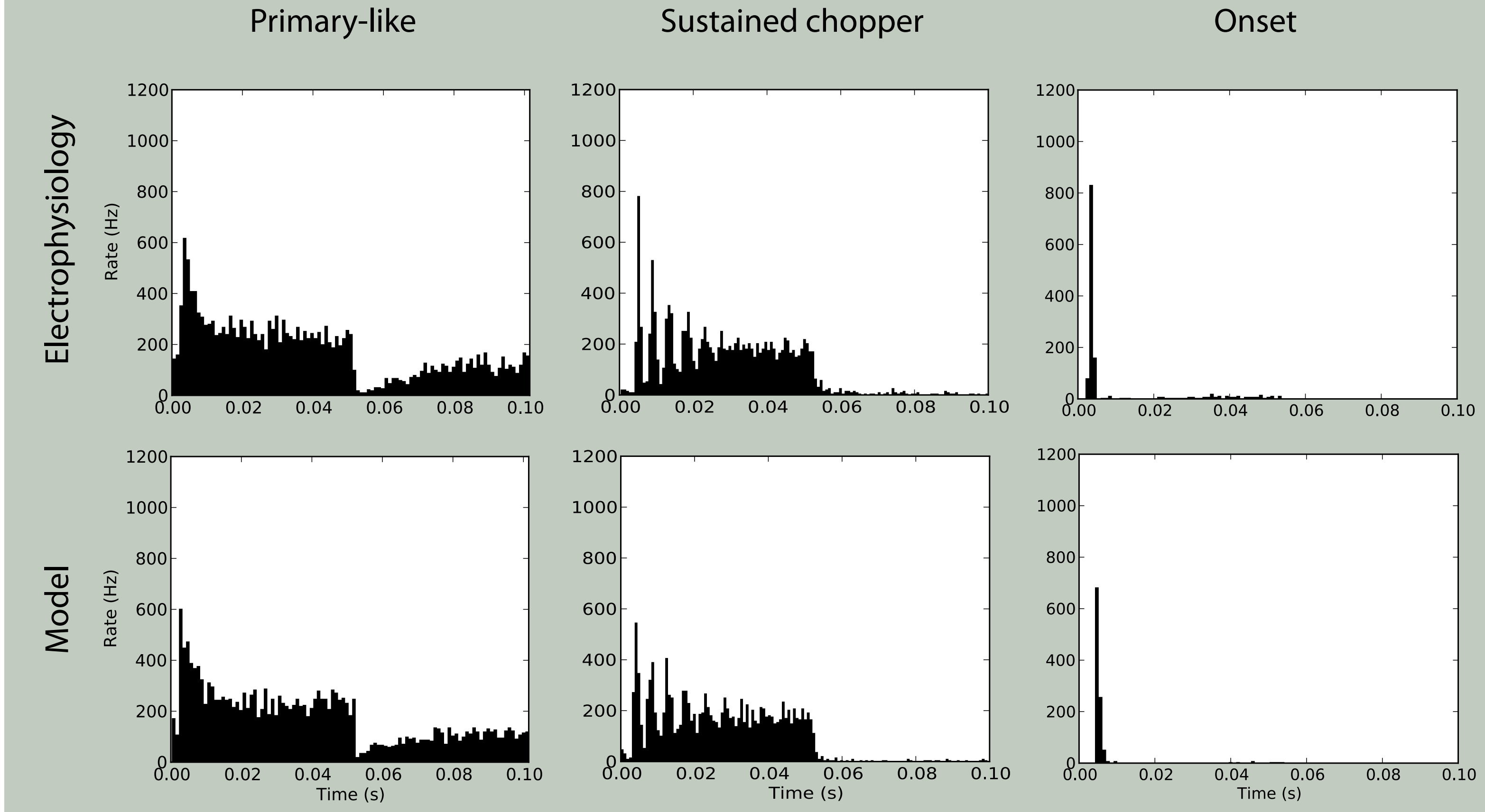
- *if "state" hypothesis is true, correlations should be greater for listeners*

- *correlelations differ → OK to proceed with experiment*

Example 3: animal and computer models of human hearing impairment

- *Aim:* ***understand hearing impairment*** *in humans.*
- *Hypothesis:* ***degraded phase-locking*** *in auditory nerve (cf cours de Christian Lorenzi)*
- *To test the hypothesis, we record from hearing-impaired* ***guinea pigs*** *(= animal model).*
- *To understand the recorded patterns, we use a* ***computer model*** *of guinea pig CN cells.*
- *To drive that model, we need a* ***computer model*** *of auditory-nerve fiber spike generation.*
- *To* ***calibrate*** *that model, we use real data from guinea pig auditory nerve fibers, etc...*

measured and modeled CN cell responses:



Goodman et al. 2018

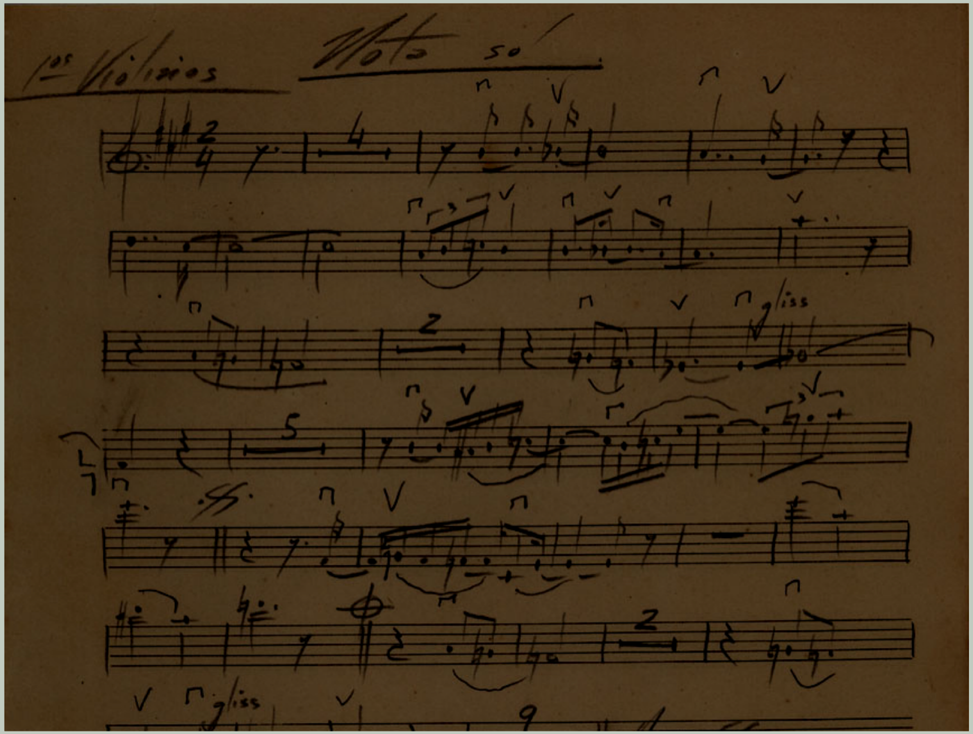
good match → OK to proceed

Pitch models

What is pitch?

everyday definition:

"pitch is the stuff of which music is made"



psychological definition:

"that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high"

ANSI (1973)

psychophysical definition:

"that attribute of auditory sensation, related to the frequency of a periodic sound, in terms of which sounds may be judged as dull or sharp according to whether the frequency is low or high

AFNOR (1977)

The quantitative relation between pitch and frequency was established by Mersenne, (1636)

Some facts

pure tone frequency discrimination limens:

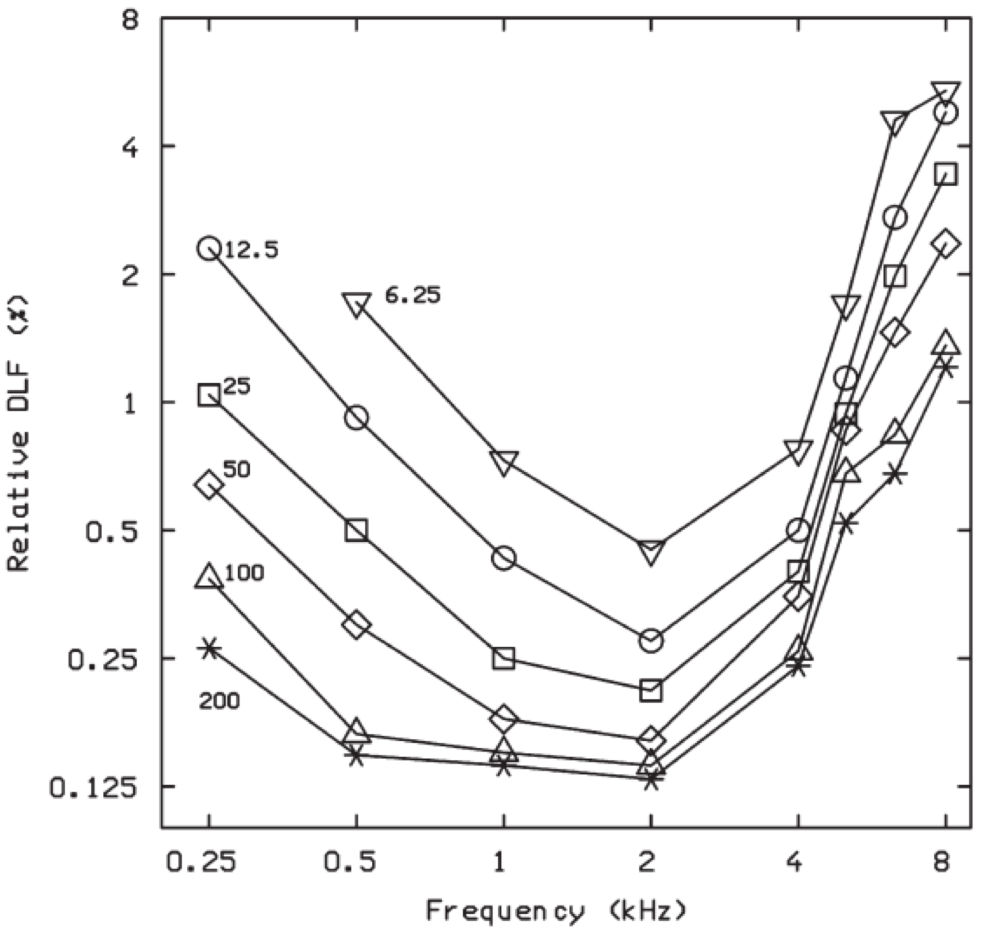


Fig. 4.2 Frequency difference limens (smallest detectable relative frequency difference) for pure tones. Each curve is for a different stimulus duration (in ms). Discrimination is best for frequencies near 2 kHz and degrades rapidly above 4 kHz. Discrimination is better for longer durations. From Moore (1973) with permission.

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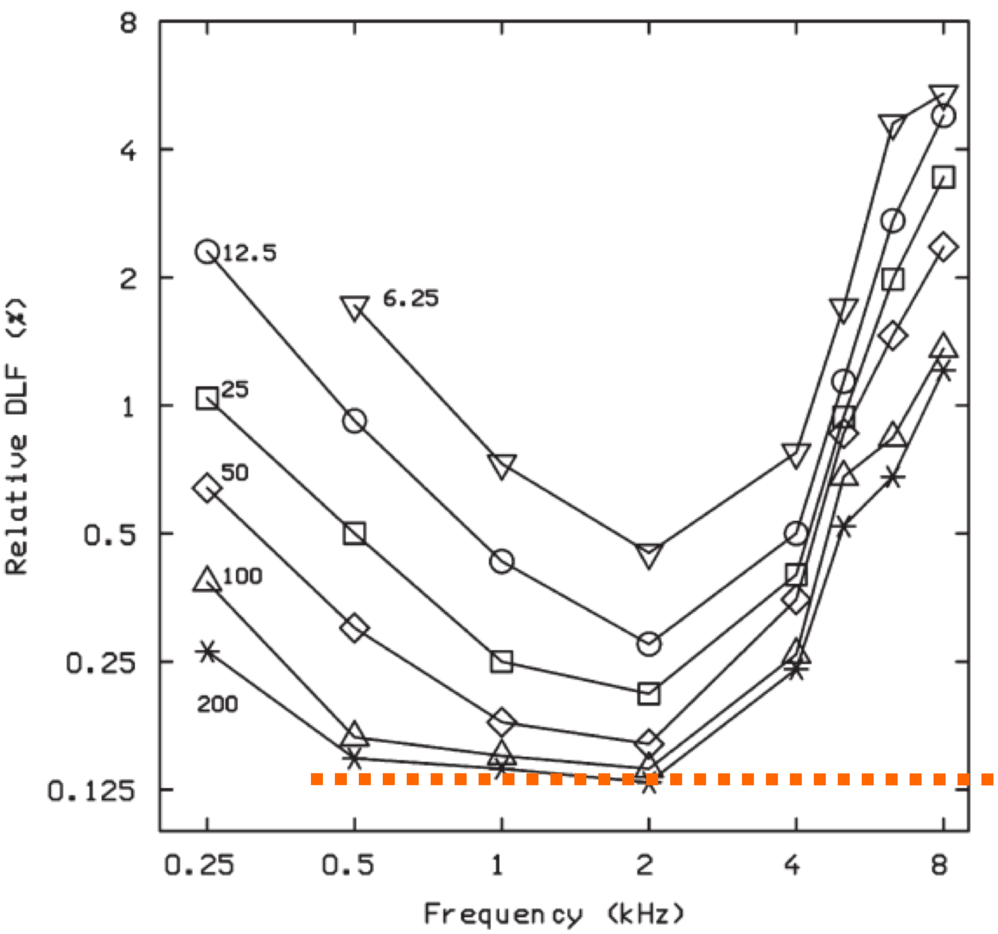

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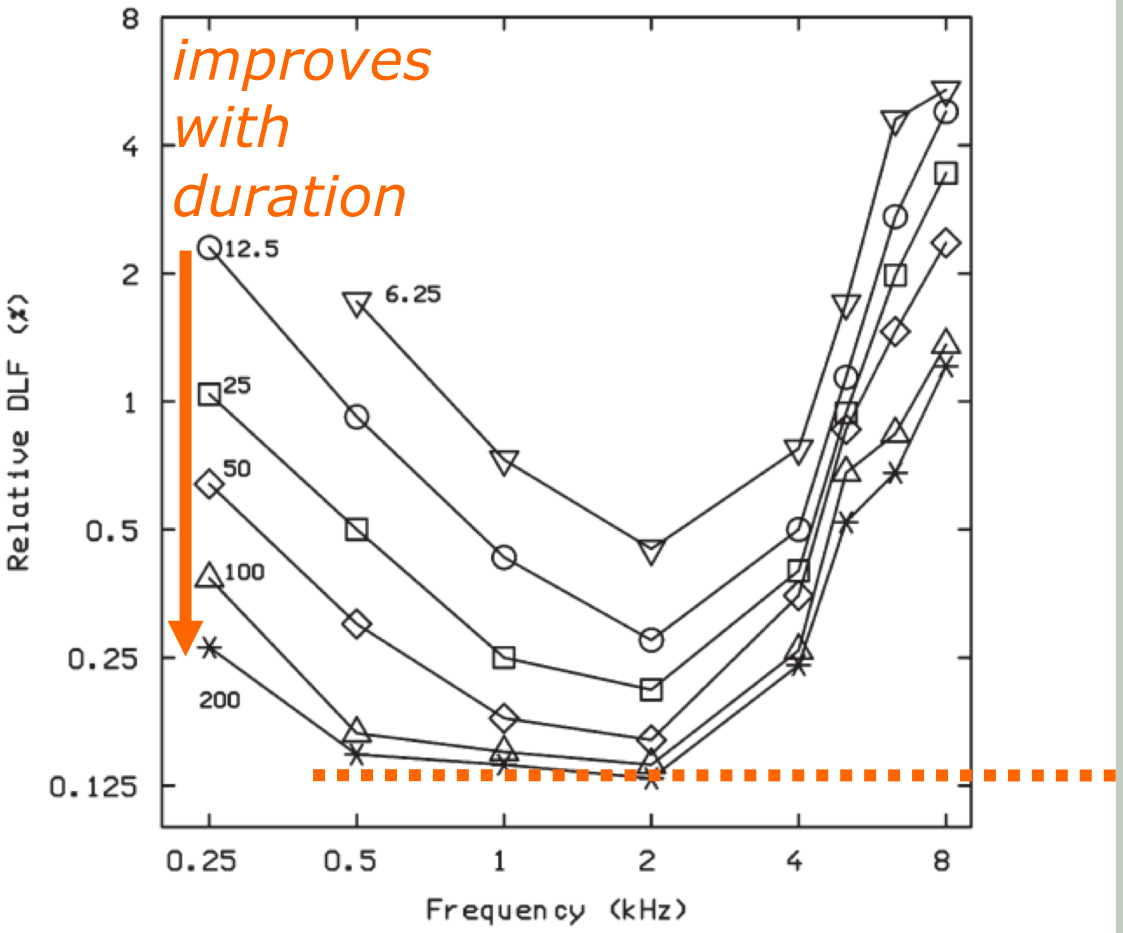
<0.2%

pure tone frequency discrimination limens:



improves with duration

<0.2%

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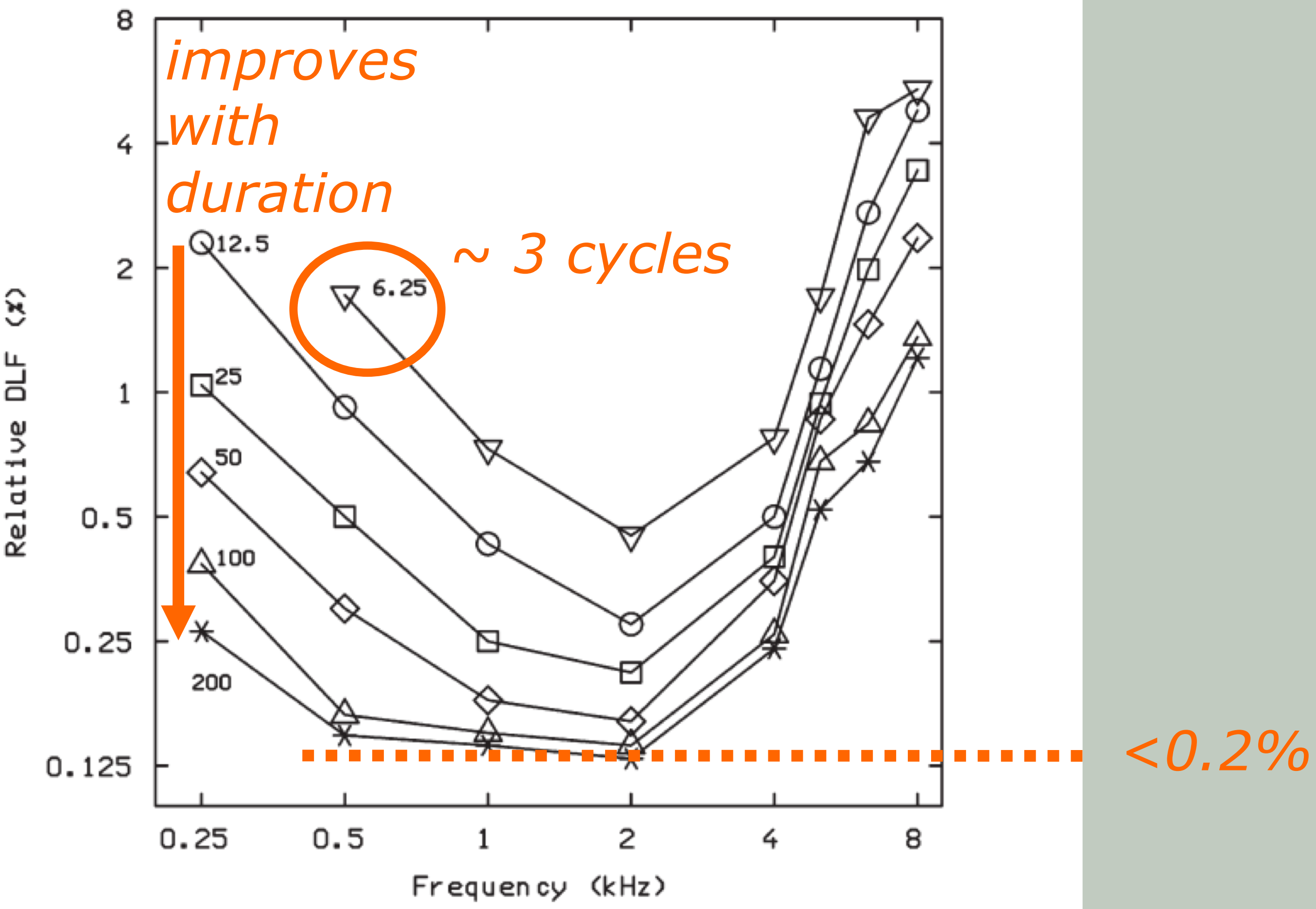

improves with duration

~ 3 cycles

<0.2%

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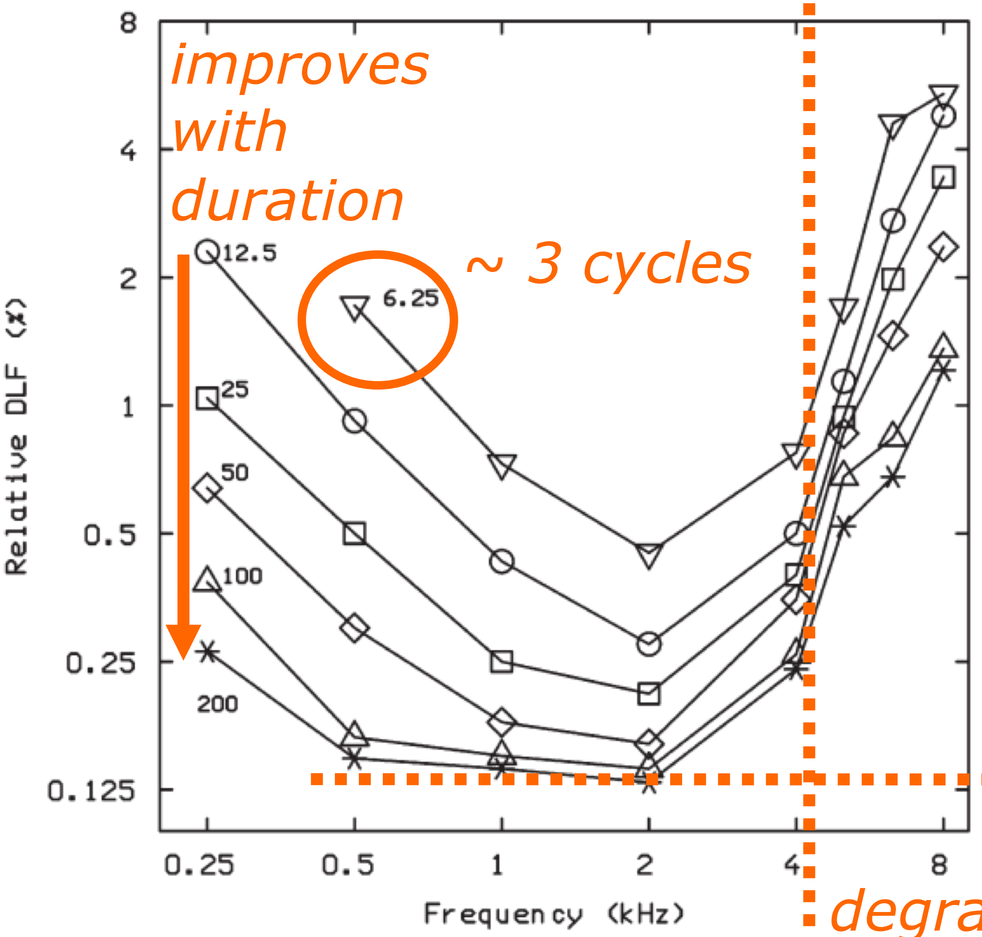

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improves with duration

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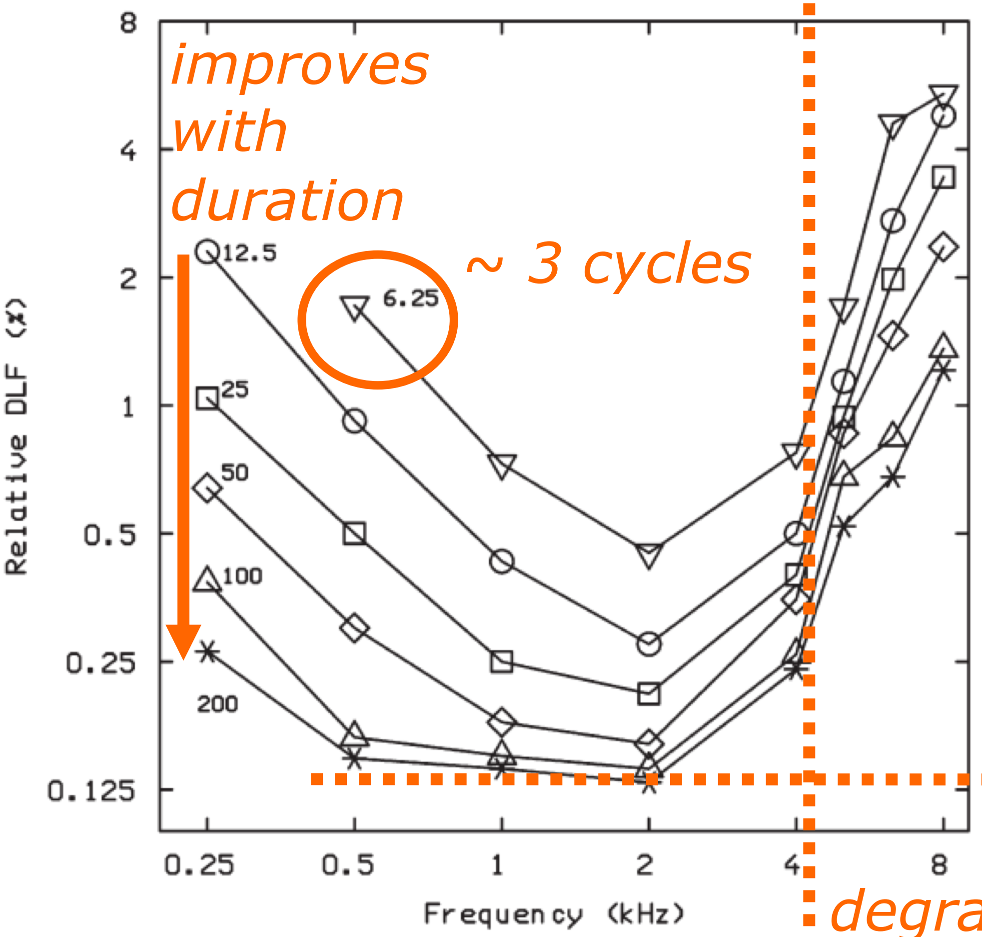

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improves with duration

~ 3 cycles

<0.2%

degrades above 4 kHz

musical pitch 30Hz - 4 kHz (~7 octaves)

lower limit of melodic pitch:

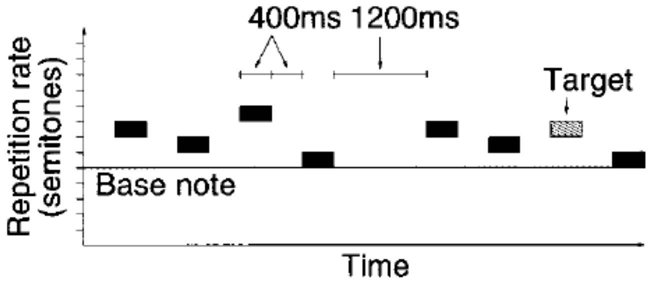
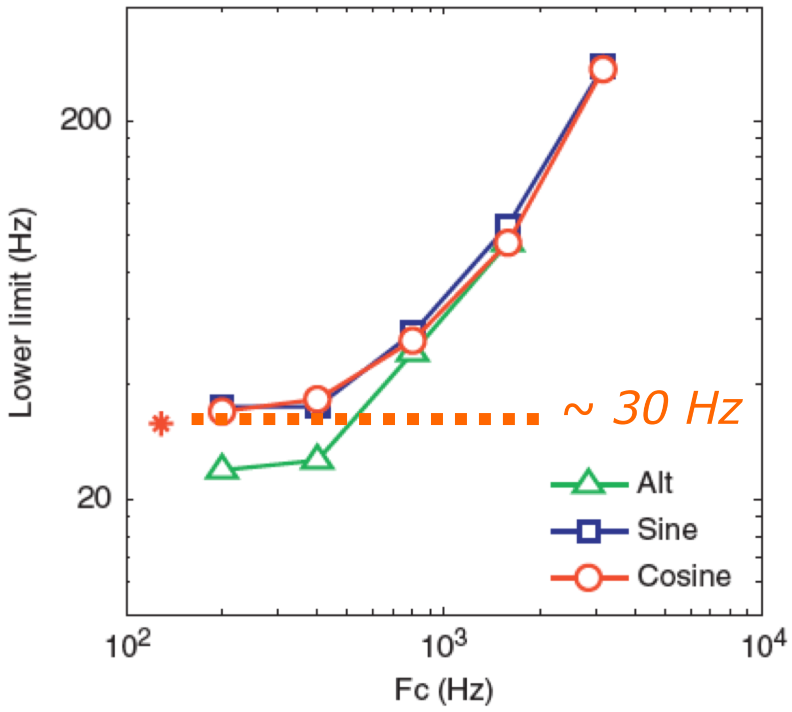
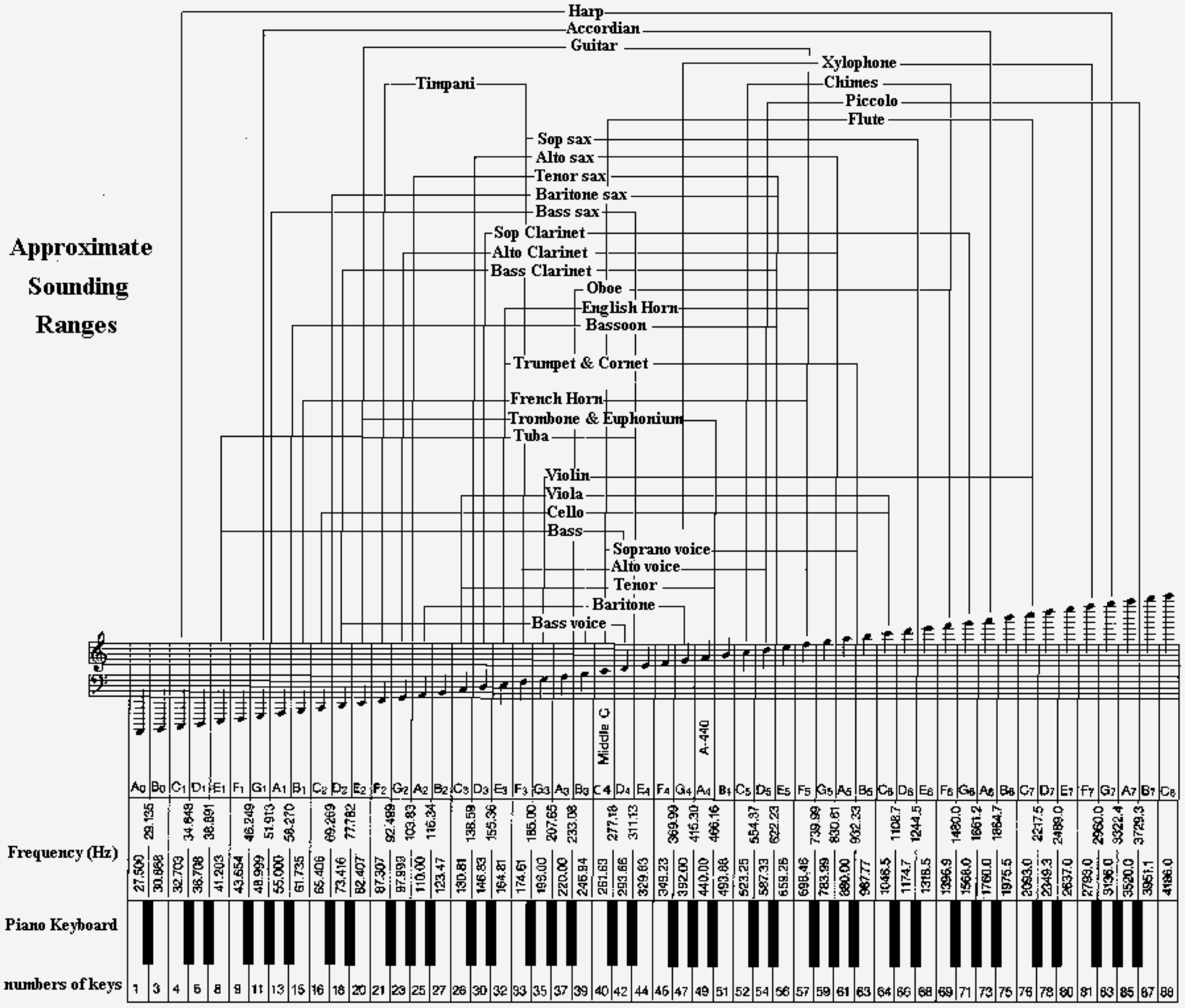


FIG. 1. Schematic of the melody task used in all experiments.

Pressnitzer et al 2001



~ 30 Hz


Approximate
Sounding
Ranges
Harp
Accordian
Guitar
Xylophone
Chimes
Piccolo
Flute
Timpani
Sop sax
Alto sax
Tenor sax
Baritone sax
Bass sax
Sop Clarinet
Alto Clarinet
Bass Clarinet
Oboe
English Horn
Bassoon
Trumpet & Cornet
French Horn
Trombone & Euphonium
Tuba
Violin
Viola
Cello
Bass
Soprano voice
Alto voice
Tenor
Baritone
Bass voice
Middle C
A-440
A0 B0 C1 D1 E1 F1 G1 A1 B1 C2 D2 E2 F2 G2 A2 B2 C3 D3 E3 F3 G3 A3 B3 C4 D4 E4 F4 G4 A4 B4 C5 D5 E5 F5 G5 A5 B5 C6 D6 E6 F6 G6 A6 B6 C7 D7 E7 F7 G7 A7 B7 C8
Frequency (Hz)
29.135 34.648 38.891 46.249 51.913 58.270 69.269 77.782 92.499 103.83 116.54 138.59 155.56 185.00 207.65 233.08 277.18 311.13 369.99 415.30 466.16 554.37 622.25 739.99 830.61 932.33 1108.7 1244.5 1480.0 1661.2 1864.7 2217.5 2489.0 2960.0 3322.4 3729.3
27.500 30.868 32.703 36.708 41.203 43.654 48.999 55.000 61.735 65.406 73.416 82.407 87.307 97.999 110.00 123.47 130.81 146.83 164.81 174.61 196.00 220.00 246.94 261.63 293.66 329.63 349.23 392.00 440.00 493.88 523.25 587.33 659.26 698.46 783.99 880.00 987.77 1046.5 1174.7 1318.5 1396.9 1568.0 1760.0 1975.5 2093.0 2349.3 2637.0 2793.0 3136.0 3520.0 3951.1 4186.0
Piano Keyboard
numbers of keys
1 3 4 6 8 9 11 13 15 16 18 20 21 23 25 27 28 30 32 33 35 37 39 40 42 44 45 47 49 51 52 54 56 57 59 61 63 64 66 68 69 71 73 75 76 78 80 81 83 85 87 88

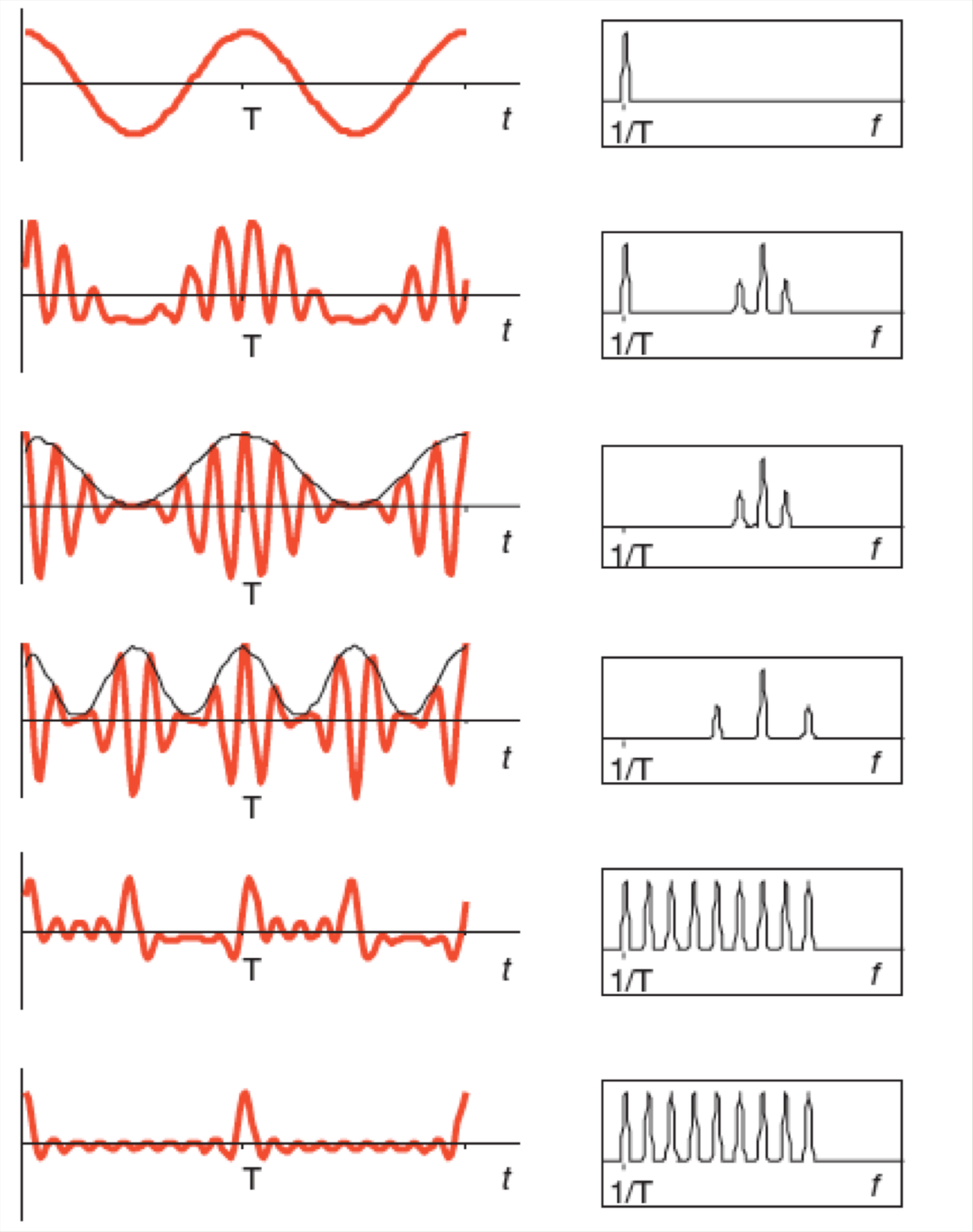
30 Hz

4 kHz

other properties of pitch:

- ⌘ phase insensitive (Ohm's law)
  at least for complexes with harmonics of low rank
- ⌘ stable over wide range of amplitudes
  a few % shift for pure tones, less for complex
- ⌘ stable over wide range of durations
  slight shift for very short stimuli

overall: pitch is highly <u>invariant</u> to changes over stimulus dimensions other than F0



Pitch is an abstraction, a many-to-one mapping

How do we explain pitch?

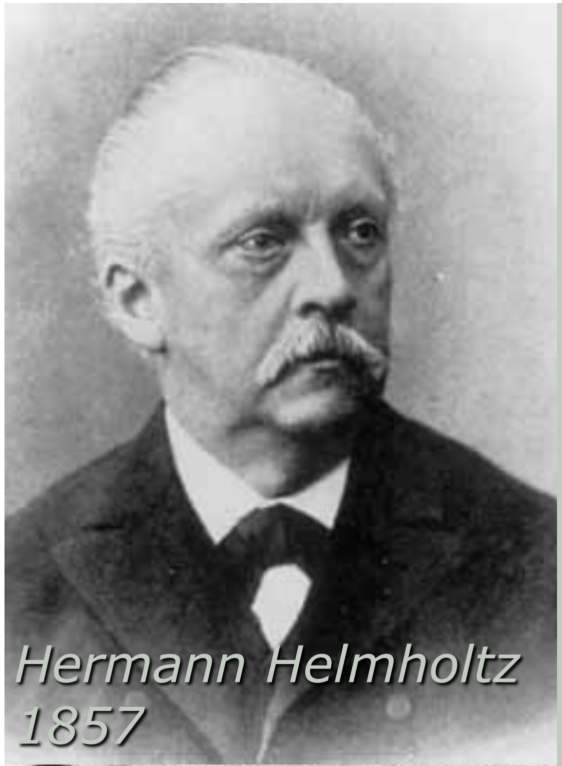
How do we explain pitch?

4 main theories:

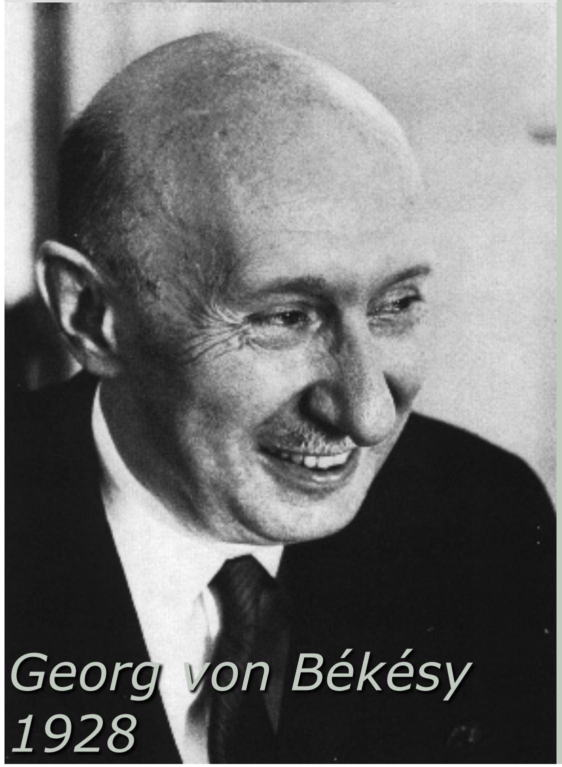
- *place*
- *time*
- *pattern-matching*
- *autocorrelation*

2 things to explain:

- *exquisite sensitivity*
- *invariance*

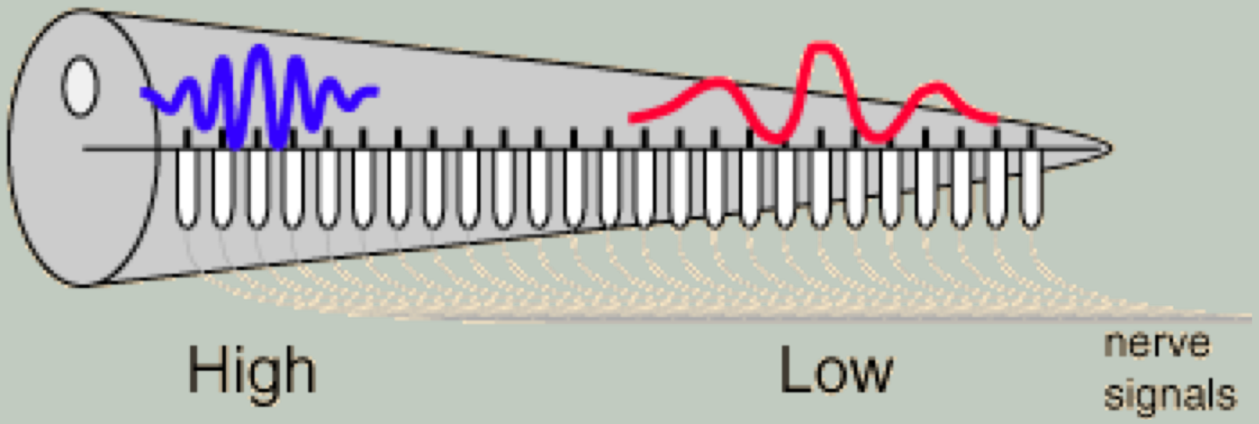


Hermann Helmholtz
1857



Georg von Békésy
1928

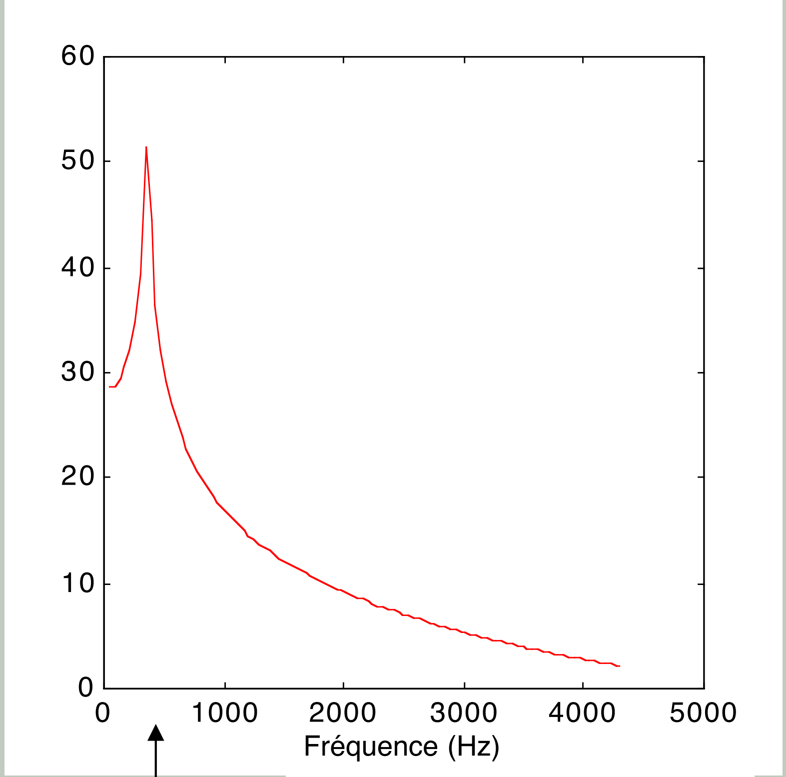
1. Place



position of maximum stimulation-->
pitch

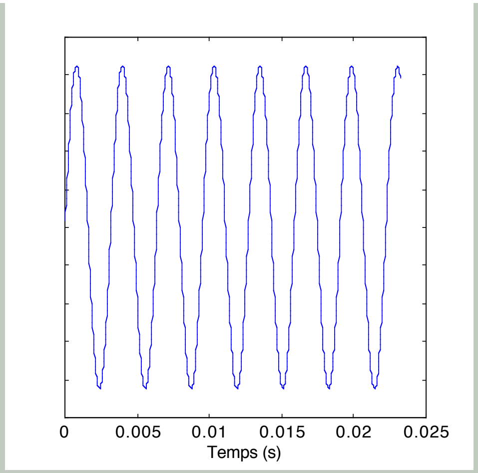
early roots: Duverney, etc.

problems with place...

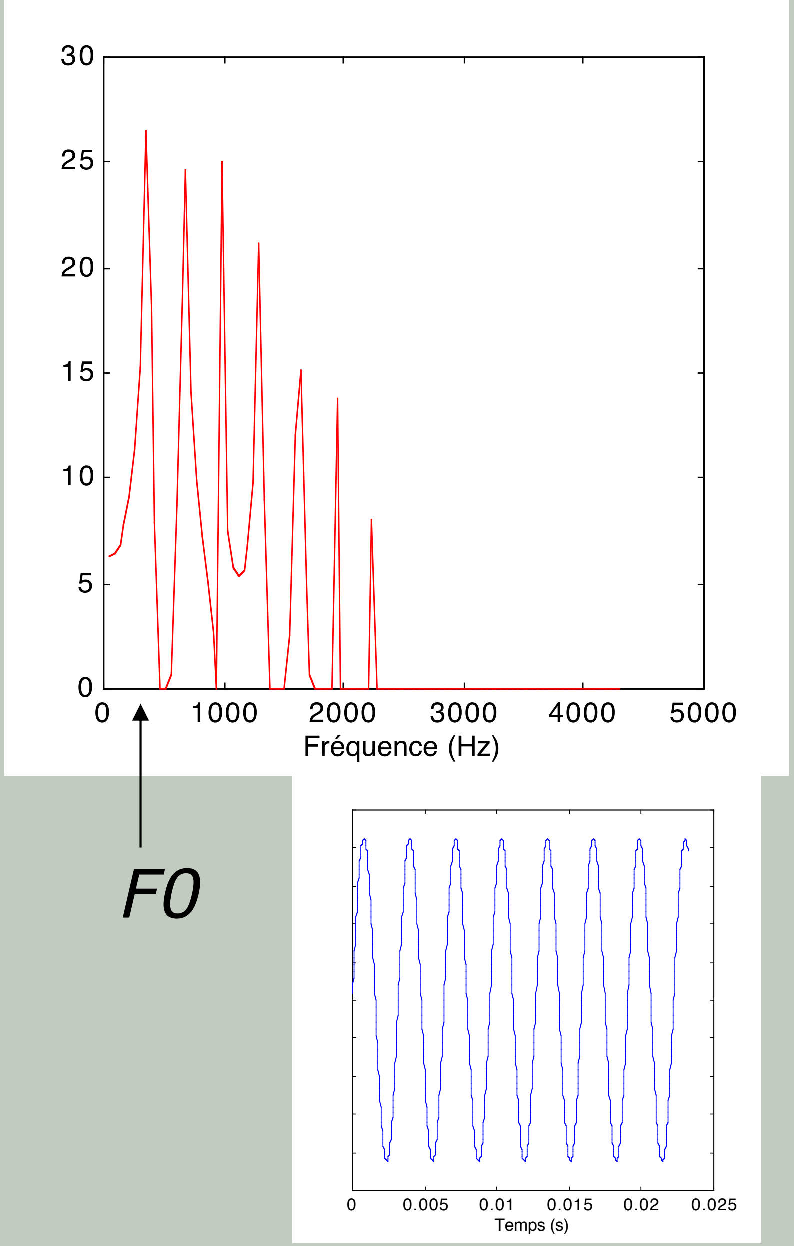


peak of spectrum?

F0



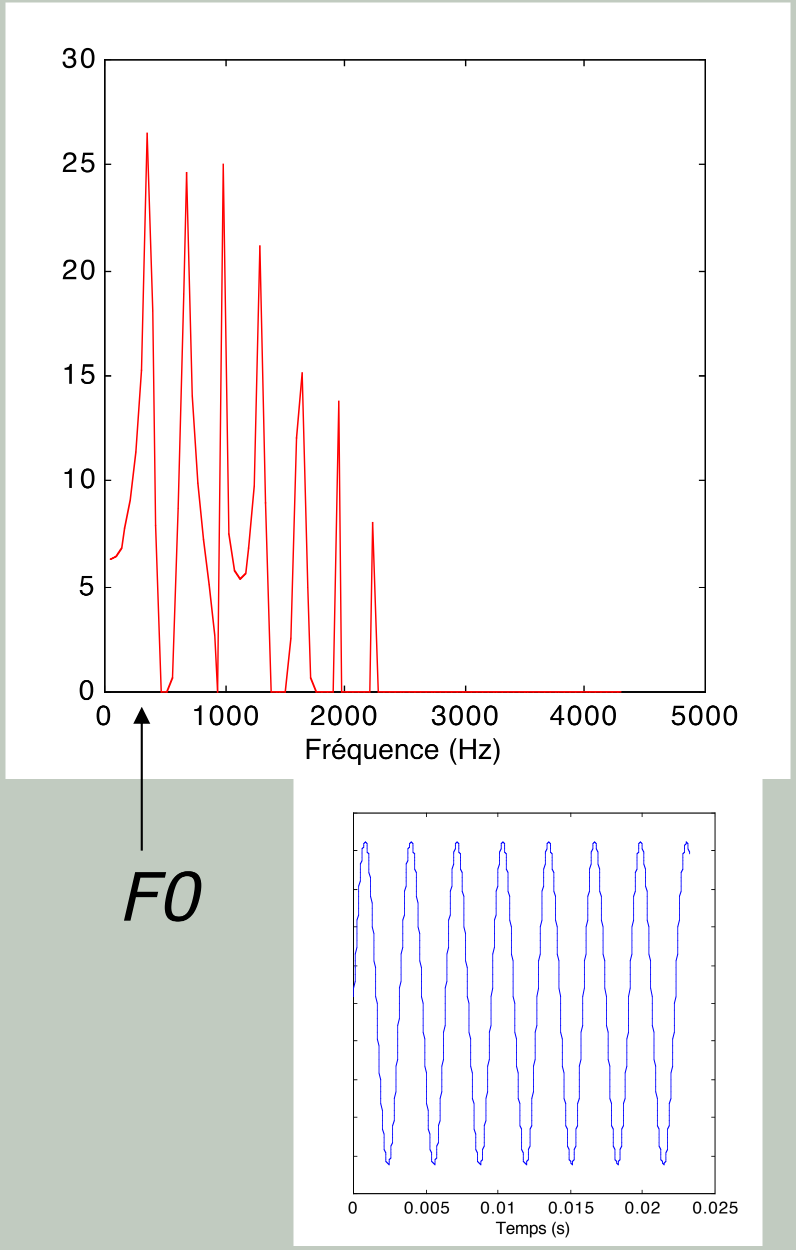
problems with place...



peak of spectrum?

→ fails if multiple peaks

problems with place...

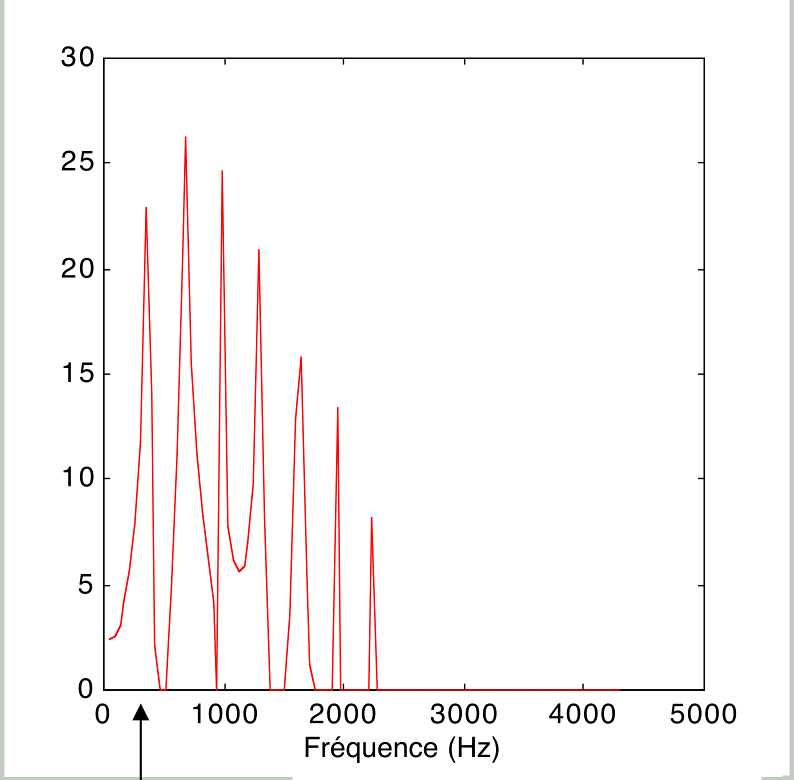


peak of spectrum?

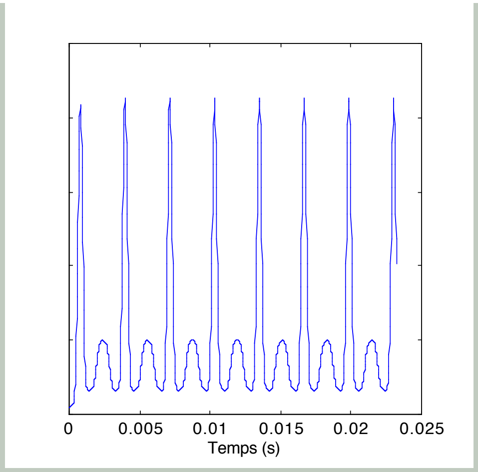
→ fails if multiple peaks

highest peak?

problems with place...



F0



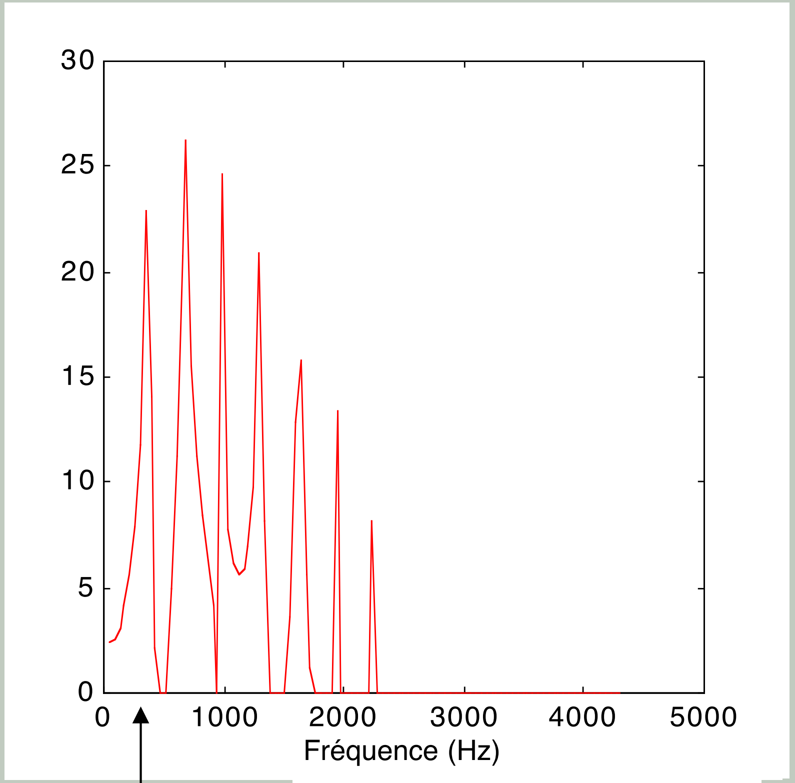
peak of spectrum?

→ fails if multiple peaks

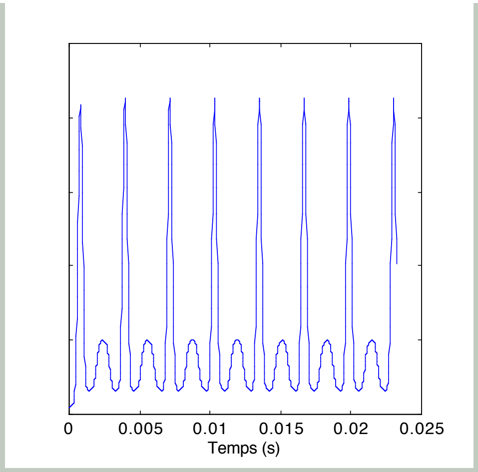
highest peak?

→ fails if harmonic stronger

problems with place...



F0



peak of spectrum?

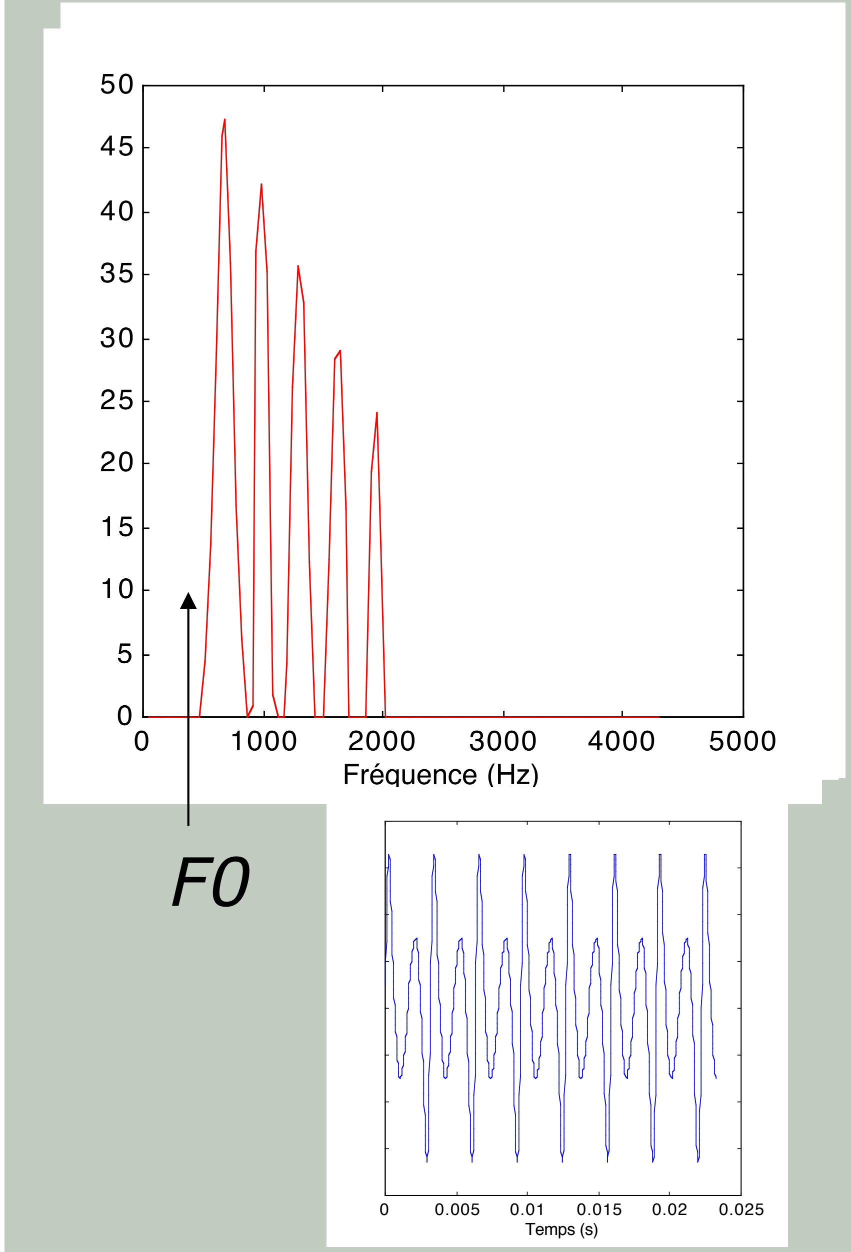
→ fails if multiple peaks

highest peak?

→ fails if harmonic stronger

first peak?

problems with place...



peak of spectrum?

→ fails if multiple peaks

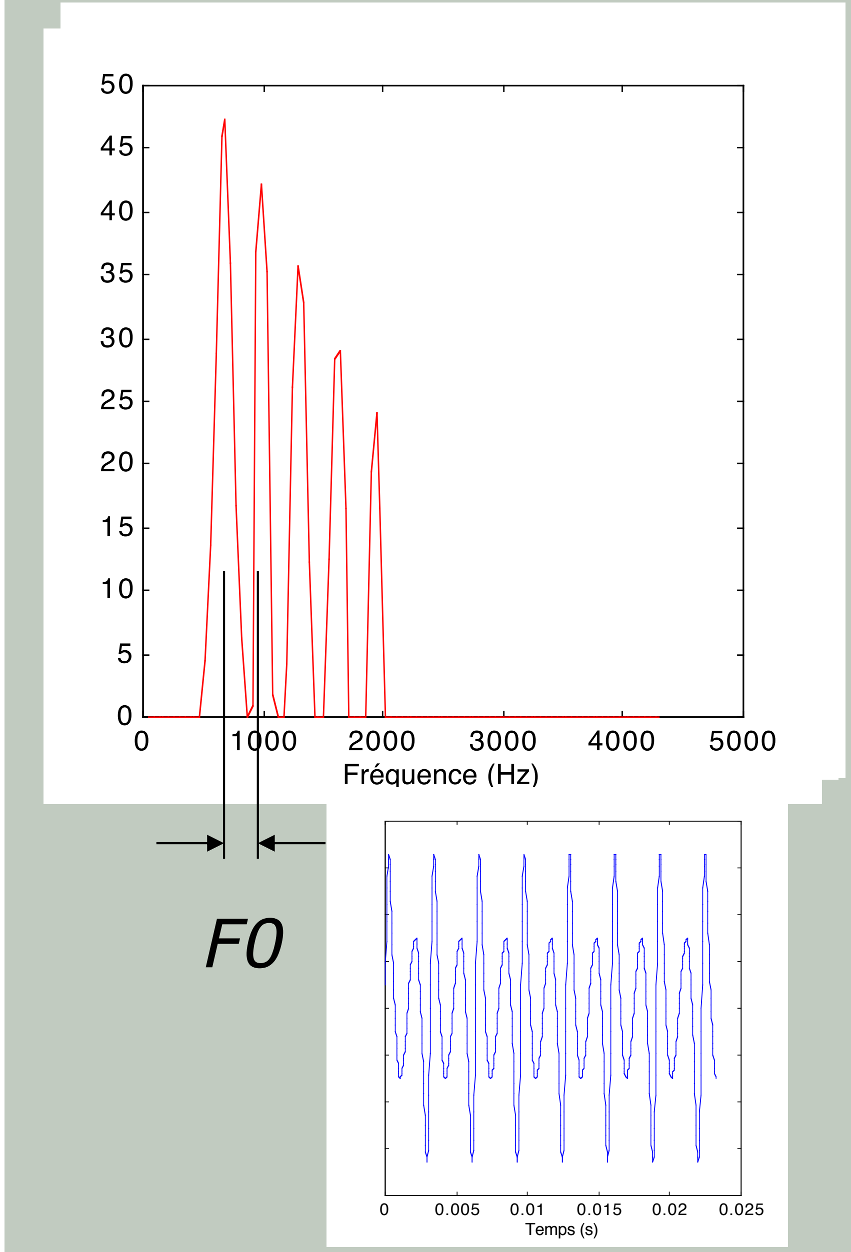
highest peak?

→ fails if harmonic stronger

first peak?

→ fails if missing fundamental

problems with place...



peak of spectrum?

→ fails if multiple peaks

highest peak?

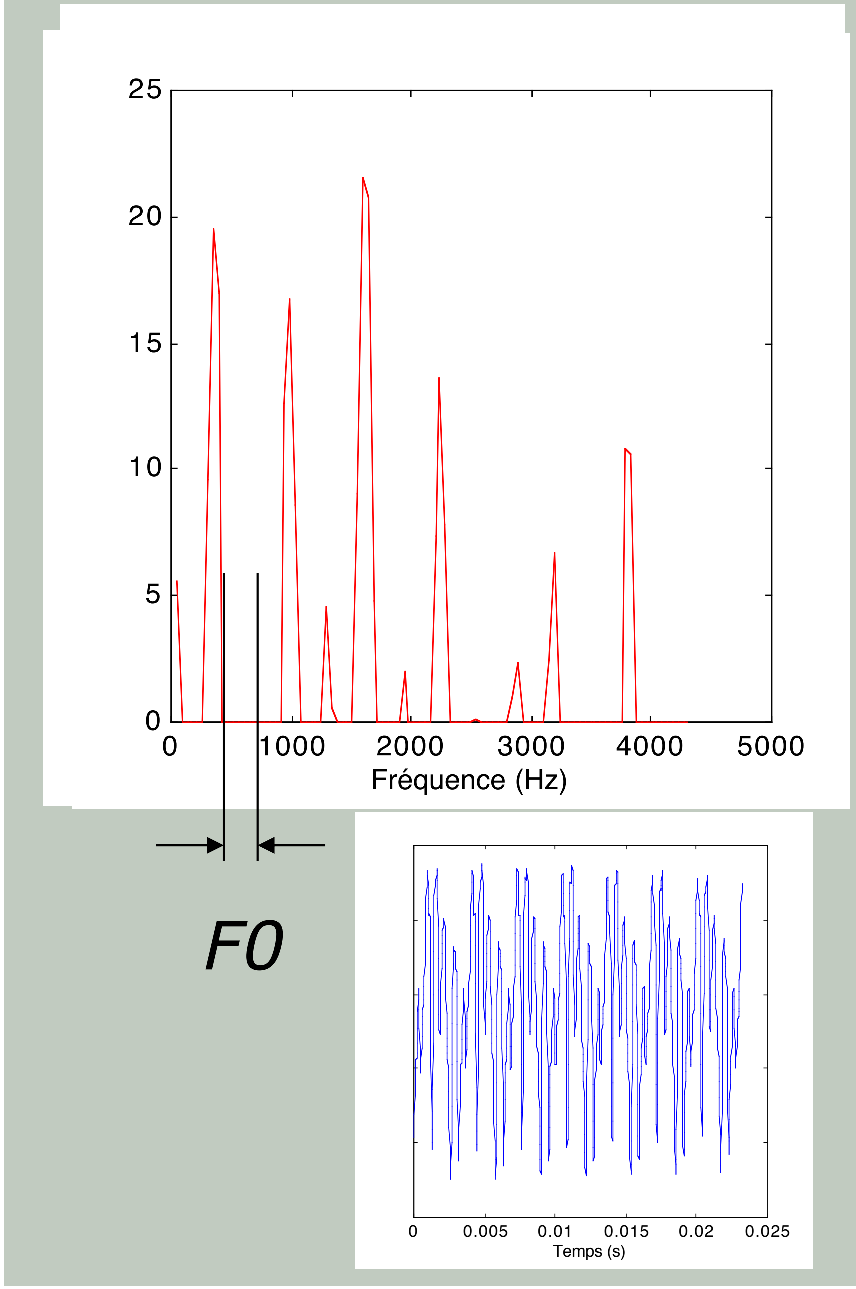
→ fails if harmonic stronger

first peak?

→ fails if missing fundamental

spacing between partials?

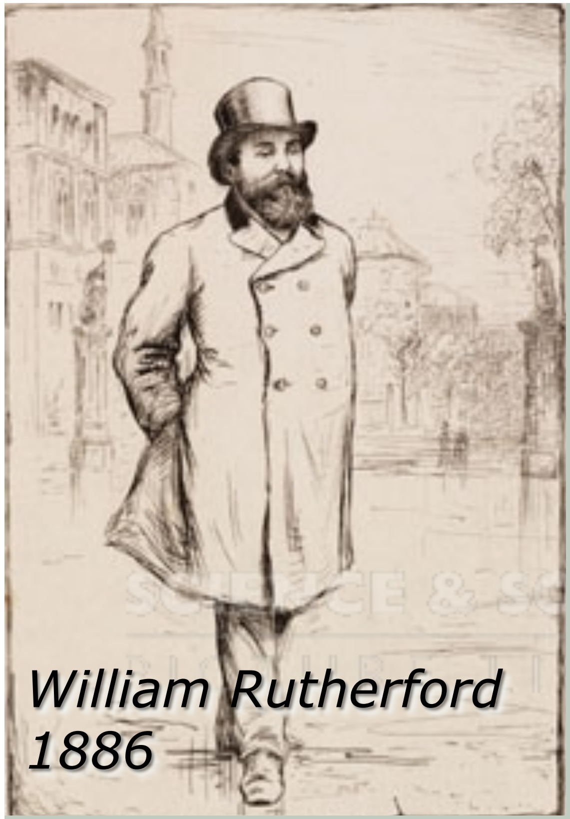
problems with place...

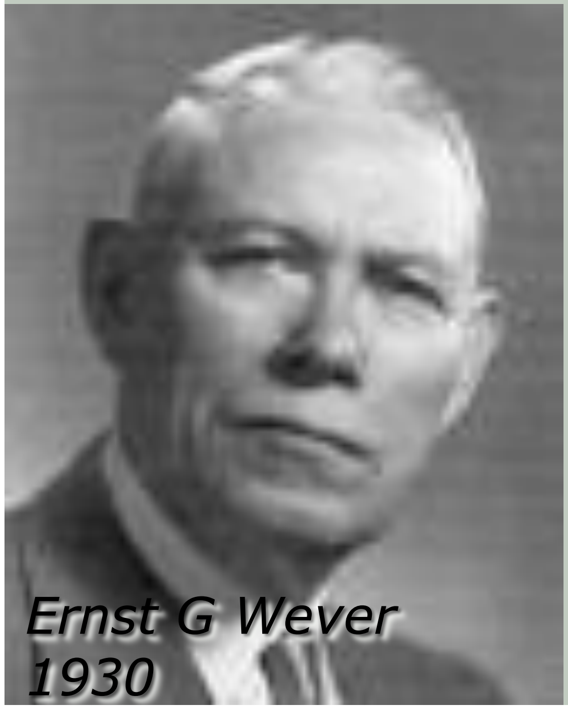


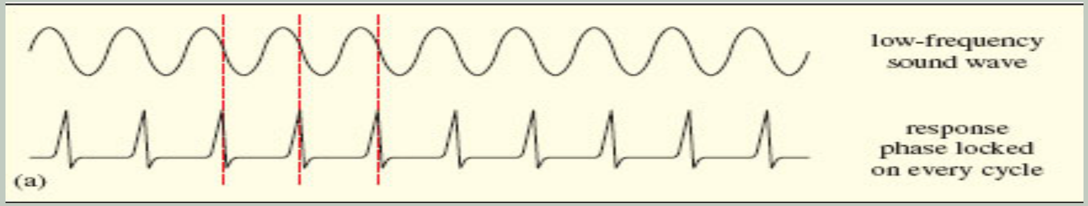
peak of spectrum?
→ *fails if multiple peaks*
highest peak?
→ *fails if harmonic stronger*
first peak?
→ *fails if missing fundamental*
spacing between partials?
→ *fails if irregular*

... not easy to fix

2. Time


William Rutherford
1886

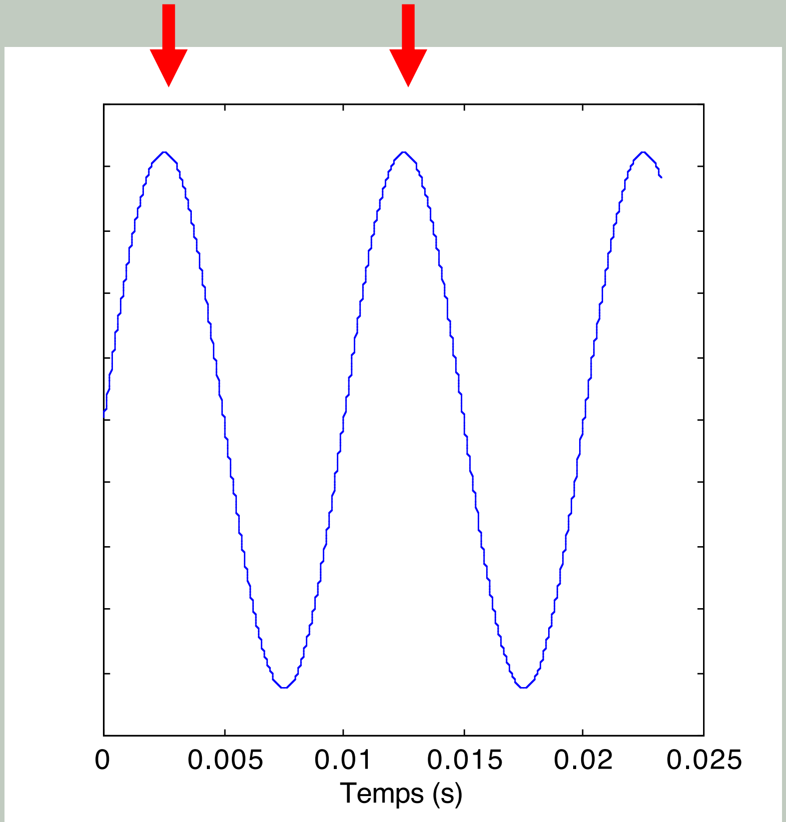

Ernst G Wever
1930



interval between pulses → pitch

earlier roots: Nichomachus (2nd century AD)

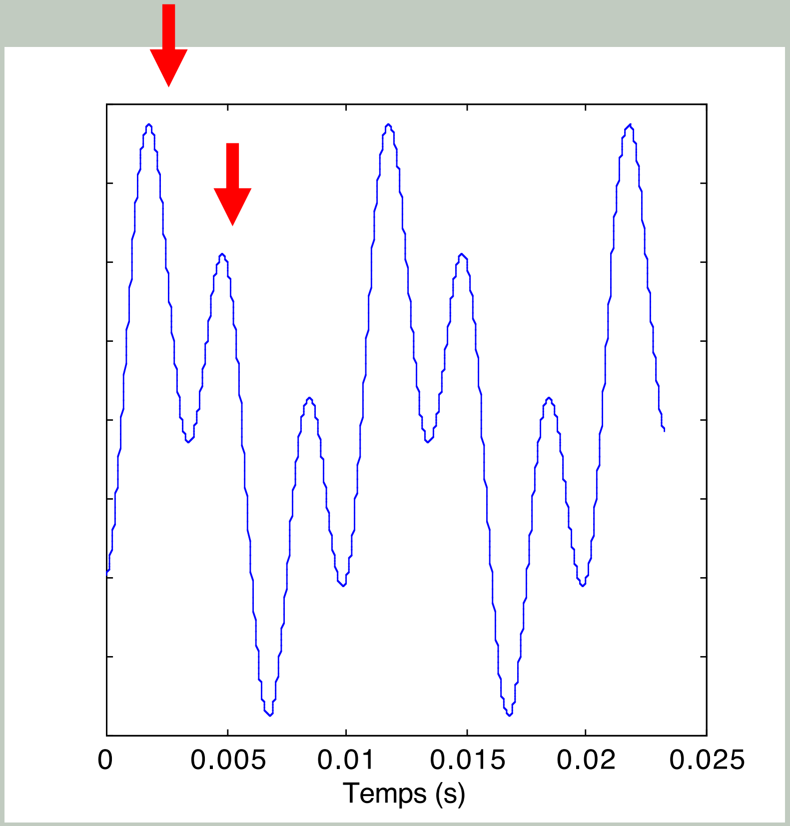
problems with time...



markers on peaks?

inter-marker interval
→ period → pitch

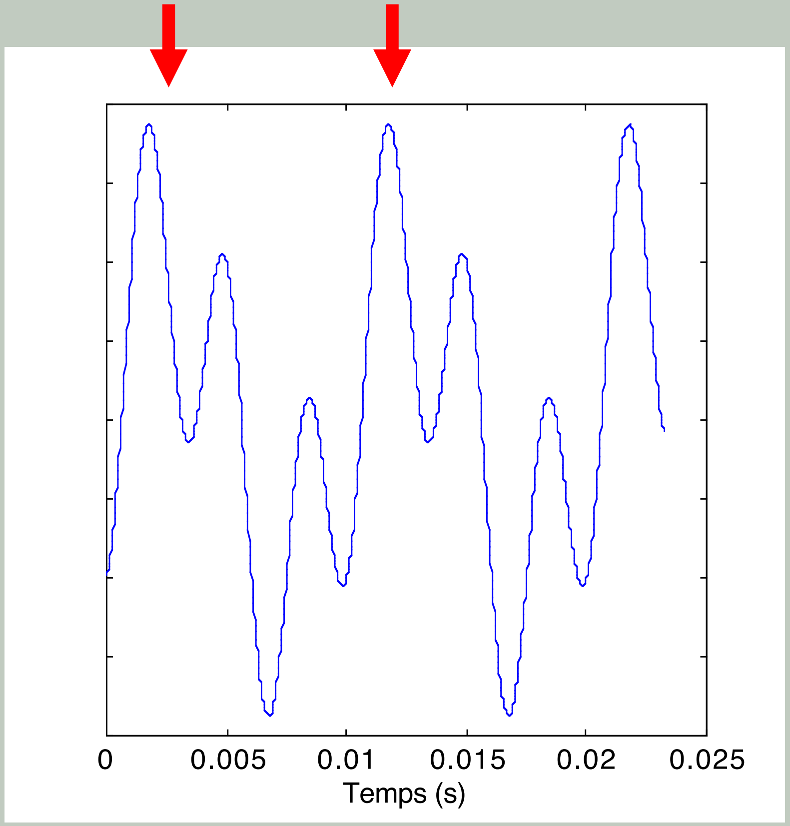
problems with time...



markers on peaks?
→ fails if multiple peaks

inter-marker interval
→ period → pitch

problems with time...



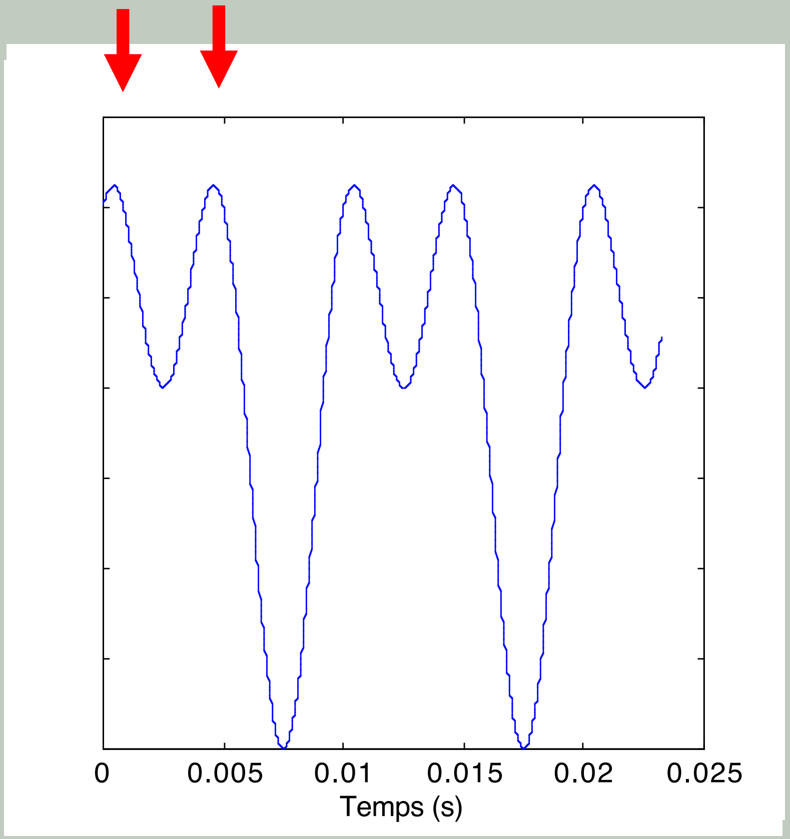
markers on peaks?

→ fails if multiple peaks

markers on biggest peaks?

inter-marker interval
→ period → pitch

problems with time...



markers on peaks?

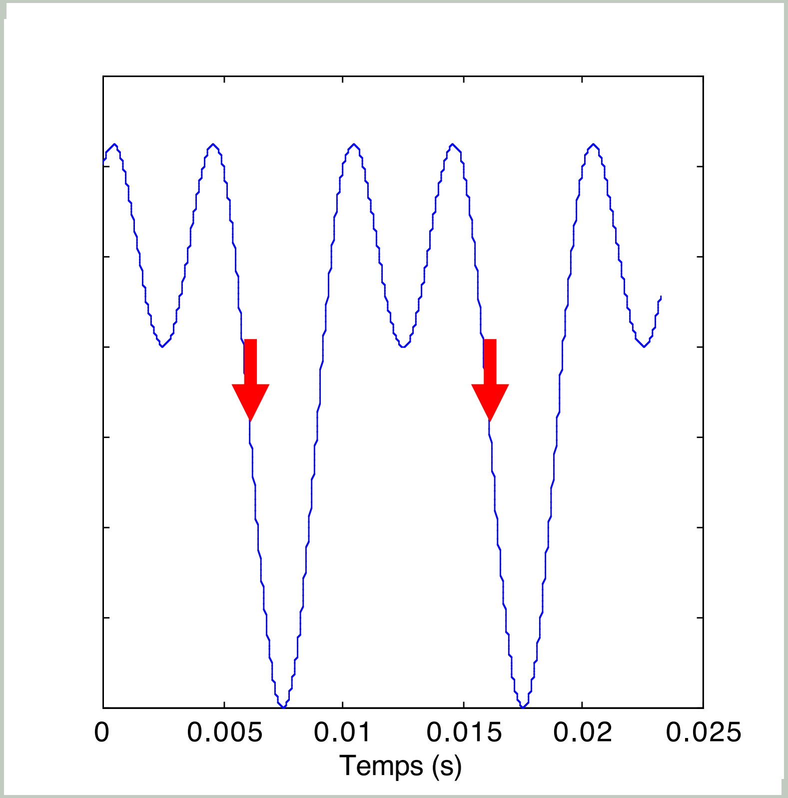
→ fails if multiple peaks

markers on biggest peaks?

→ fails if multiple "biggest"

inter-marker interval
→ period → pitch

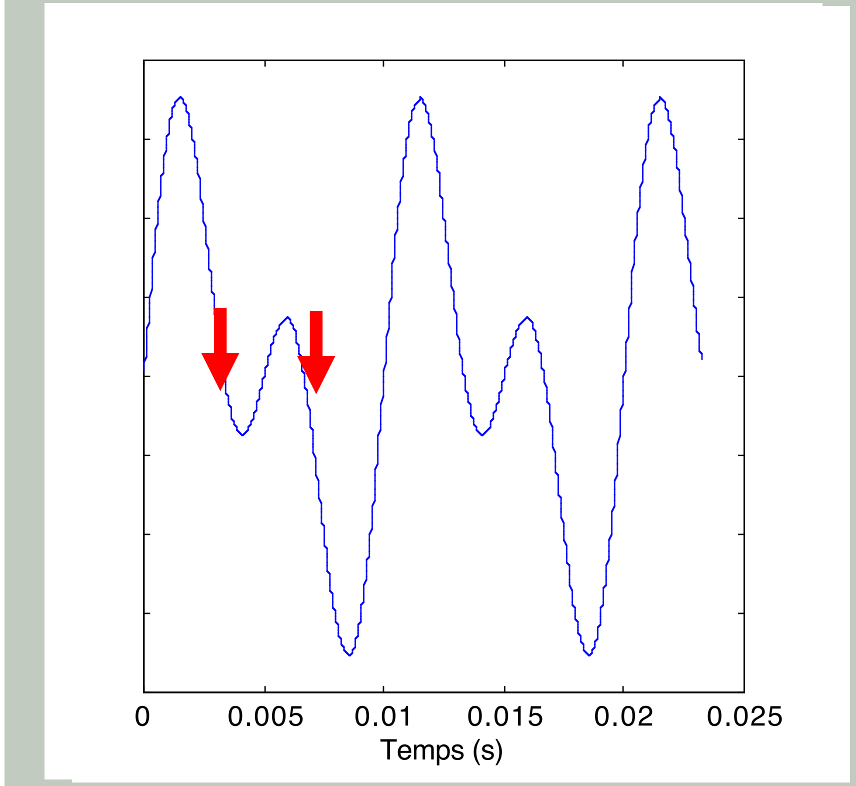
problems with time...



markers on peaks?
→ *fails if multiple peaks*
markers on biggest peaks?
→ *fails if multiple "biggest"*
markers on zero crossings?

inter-marker interval
→ *period* → *pitch*

problems with time...

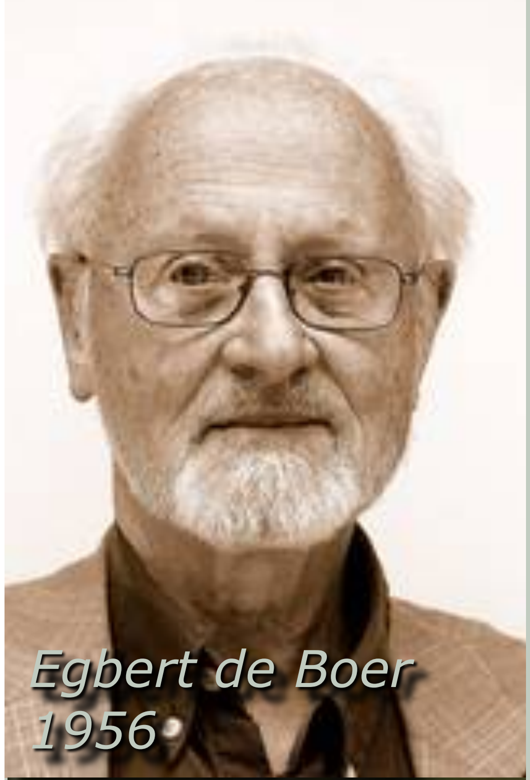


markers on peaks?
→ *fails if multiple peaks*
markers on biggest peaks?
→ *fails if multiple "biggest"*
markers on zero crossings?
→ *fails if more than one*

inter-marker interval
→ *period* → *pitch*

... not easy to fix

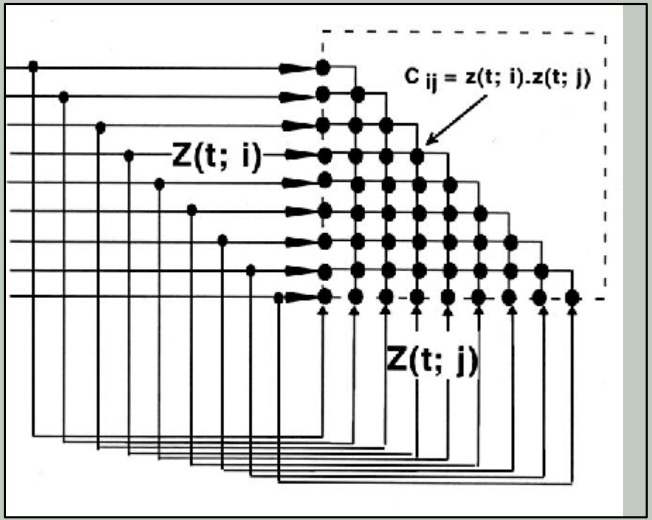
3. Pattern matching



Egbert de Boer
1956

Ernst Terhardt
1974

spectrum →

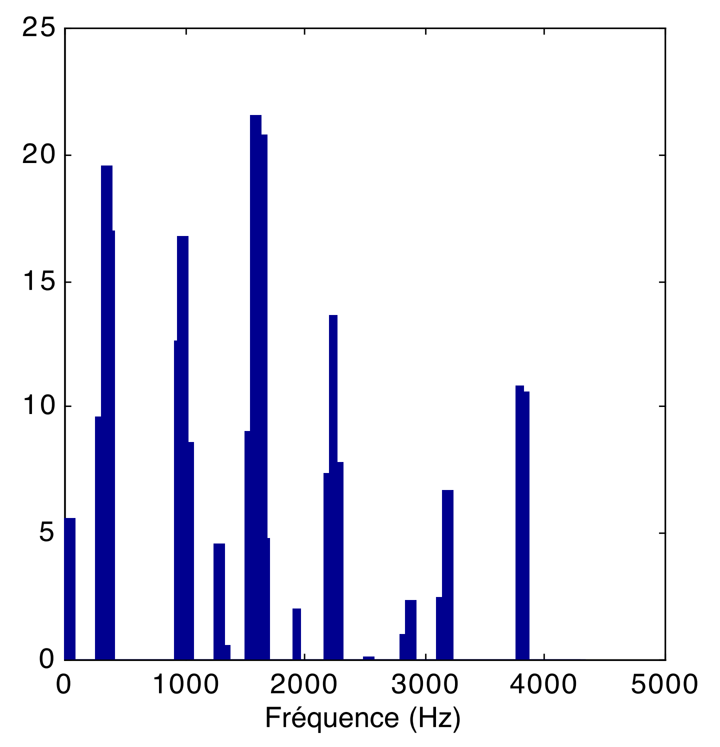


→ *pitch*

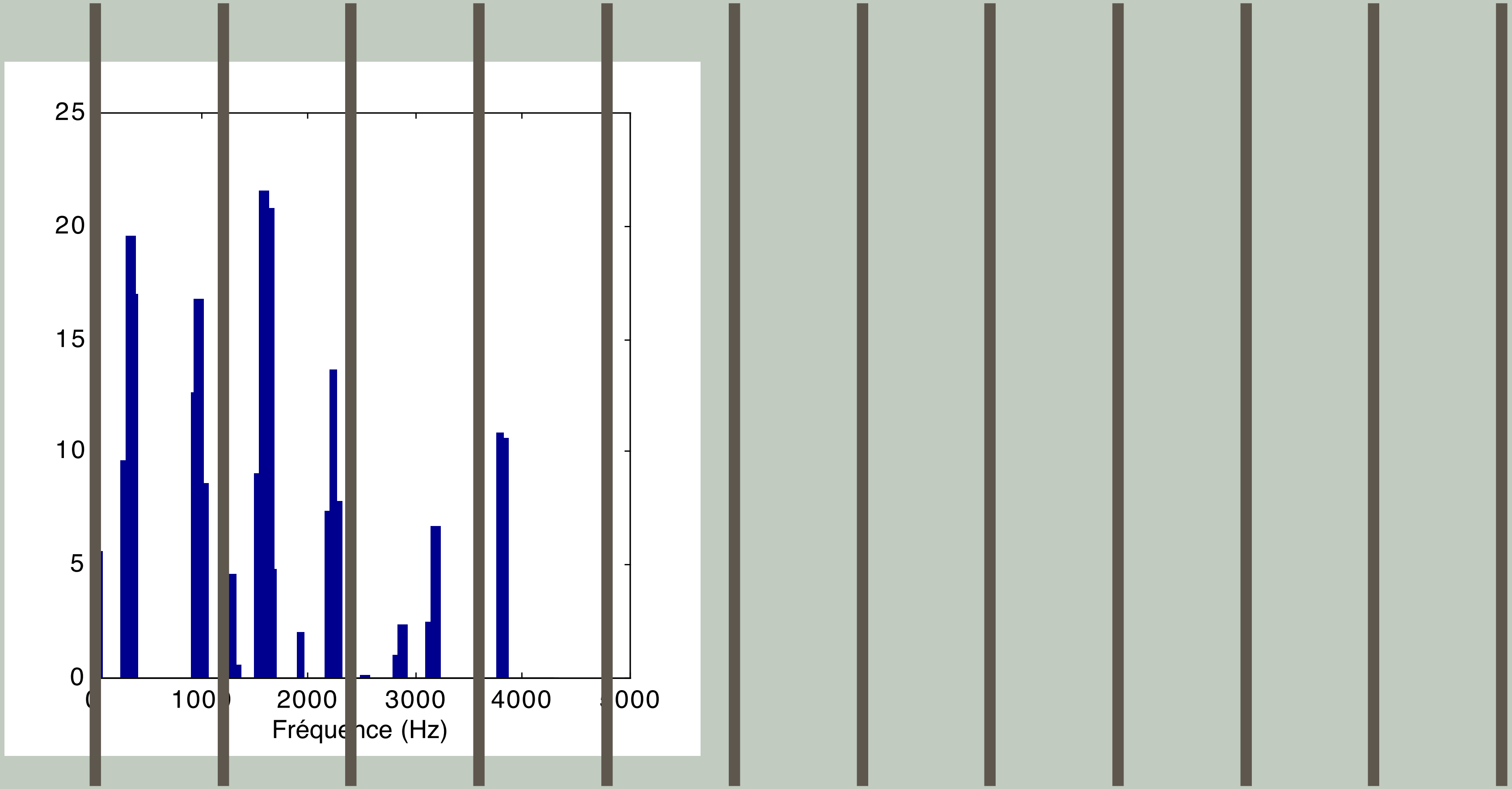
harmonic pattern matcher

earlier roots: Helmholtz, Alhazen (11 th century)

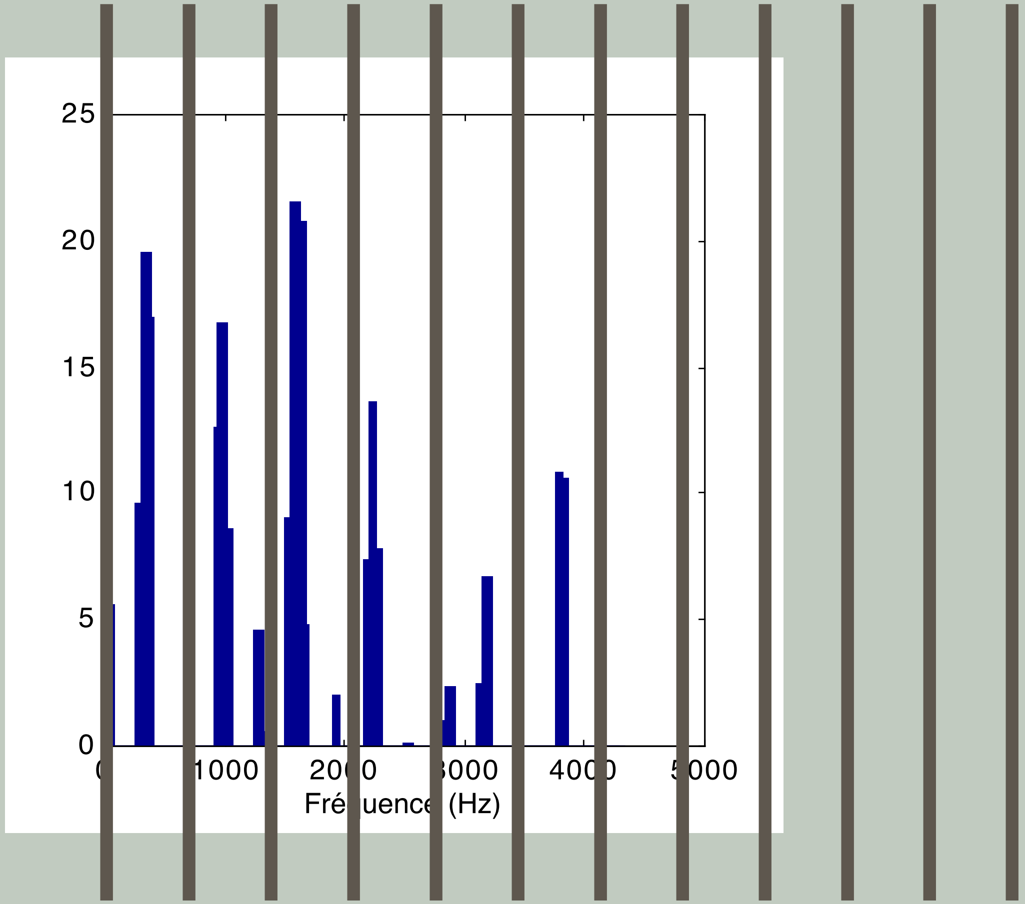
Pattern matching



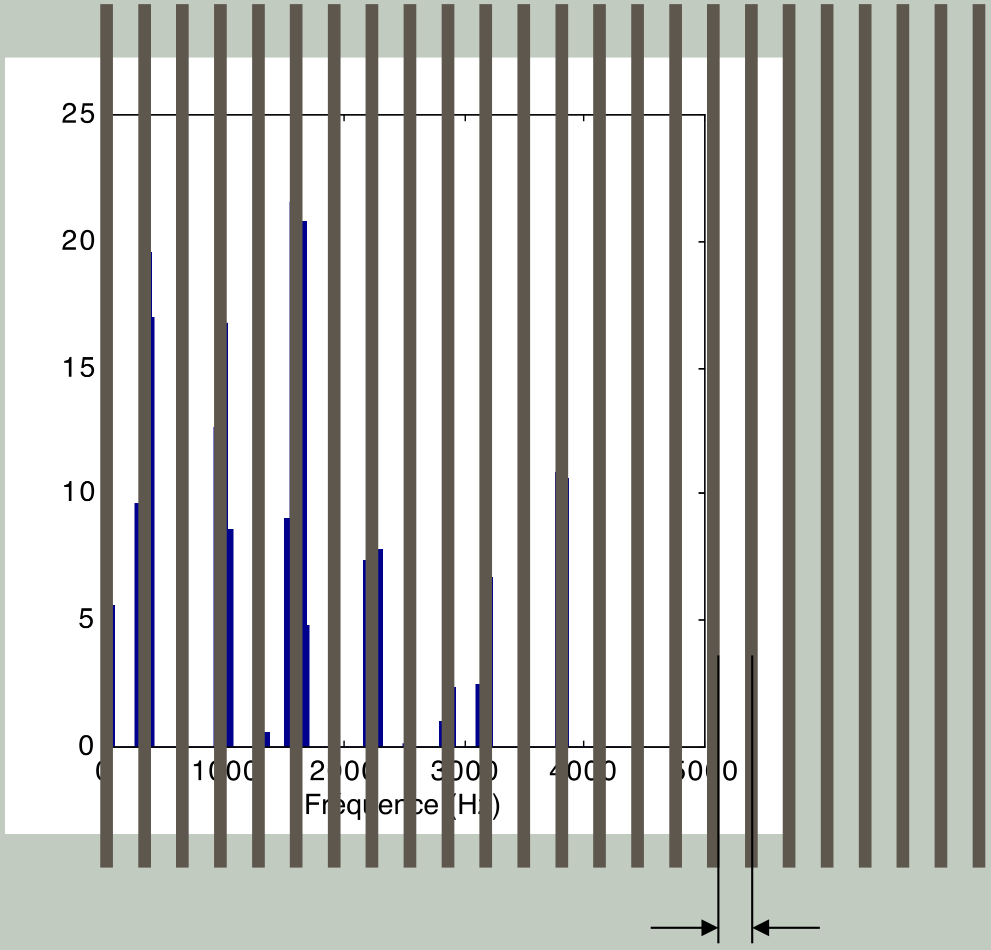
Pattern matching



Pattern matching



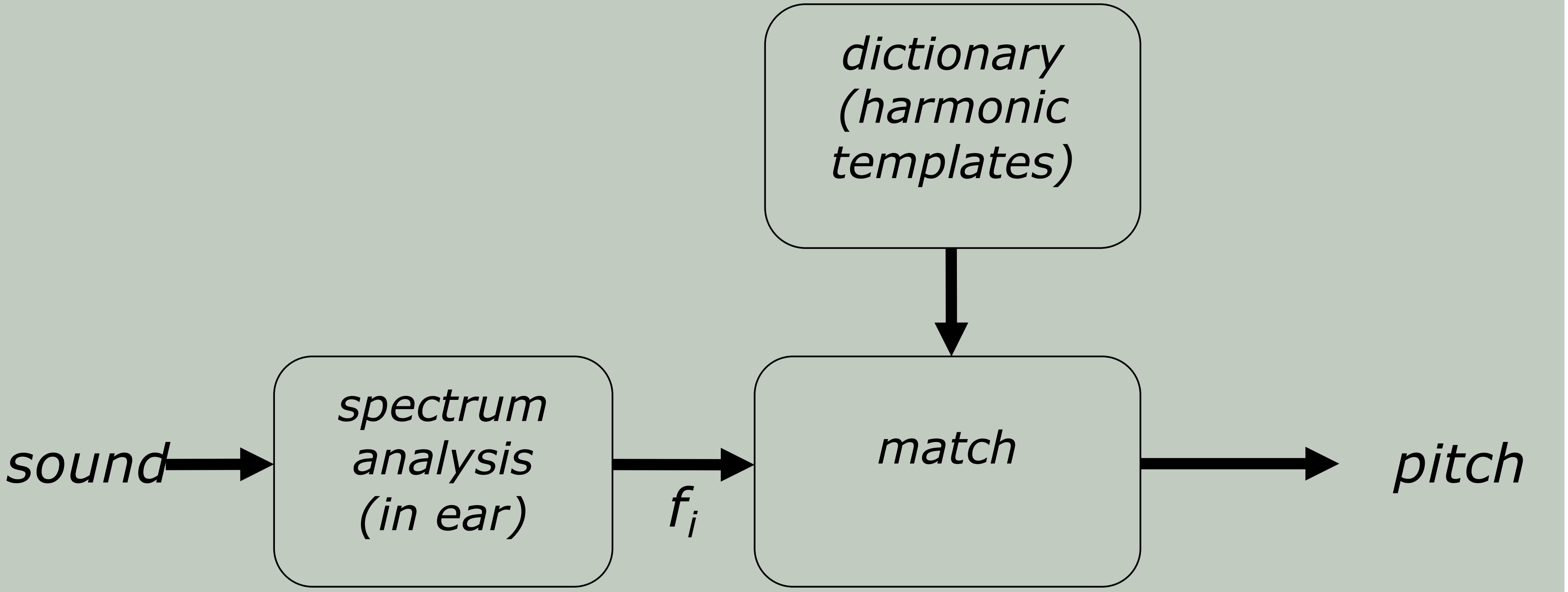
Pattern matching



best match → pitch

F0

Pattern matching



dictionary (harmonic templates)

sound

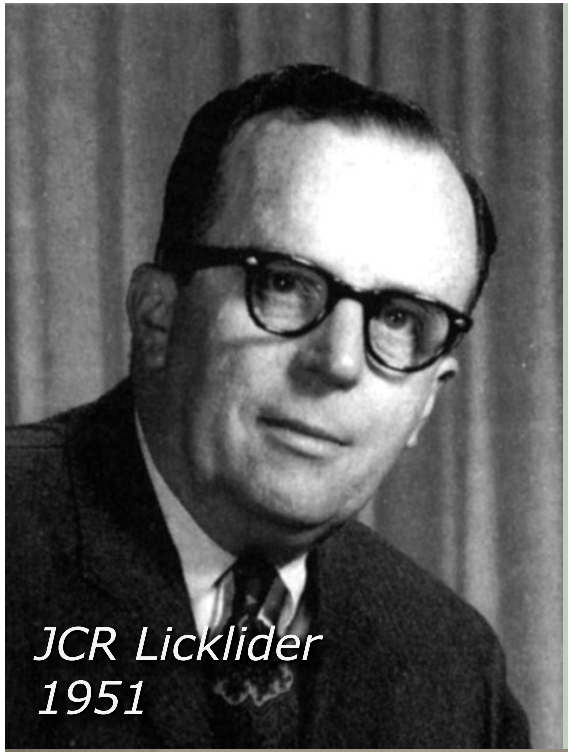
spectrum analysis (in ear)

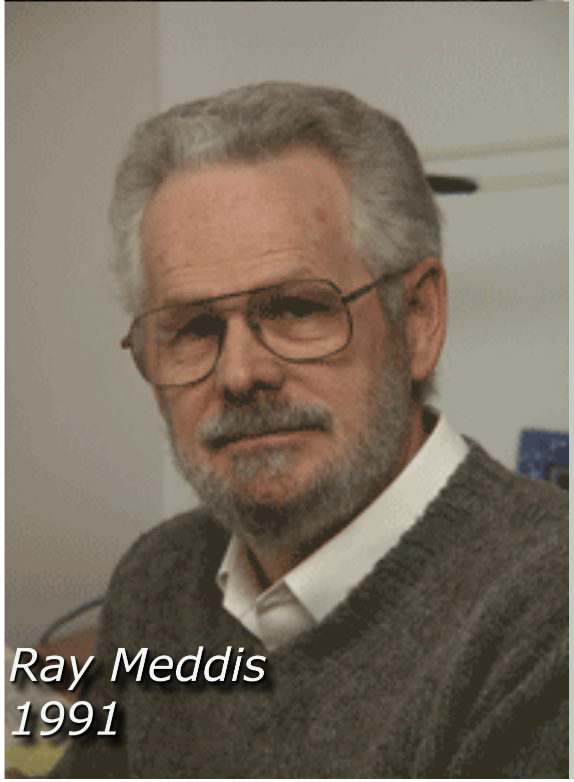
f_i

match

pitch

Autocorrelation


JCR Licklider
1951


Ray Meddis
1991

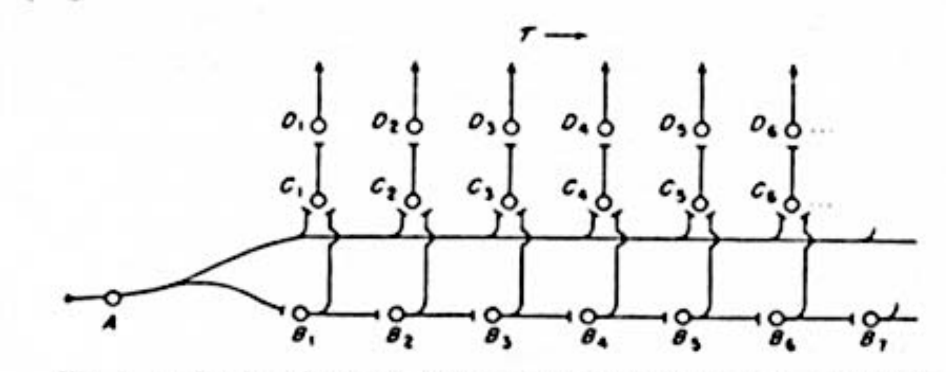


Fig. 1. – *Basic schema of neuronal autocorrelator. A is the input*

peak in autocorrelation function → pitch

Autocorrelation

$$x(t)$$

- *acoustic waveform (pressure function of time)*

Autocorrelation

$$x(t)x(t-\tau)$$

time lag

- *acoustic waveform (pressure function of time)*

- *delay it, multiply with original*

Autocorrelation

$$A_t(\tau) = \sum_W x(t)x(t - \tau)$$

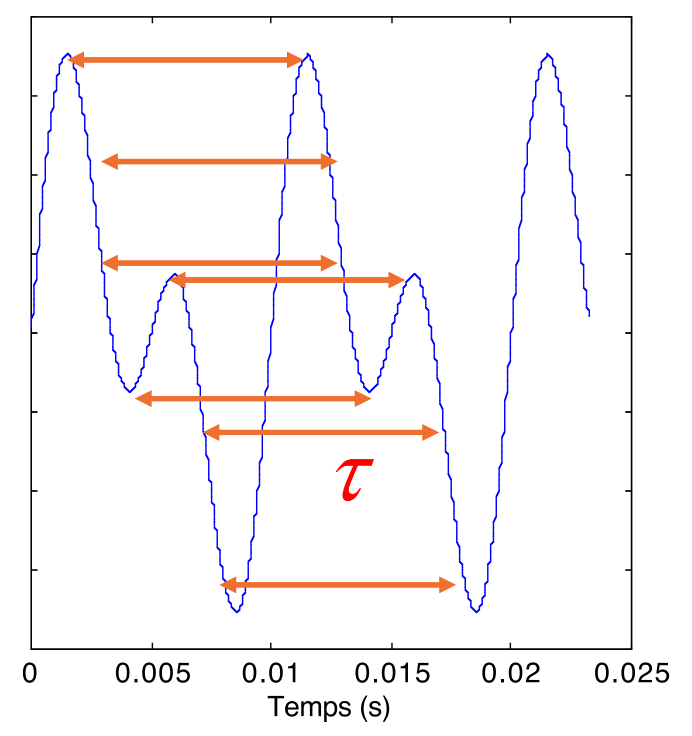
integration window

product

time lag

- acoustic waveform (pressure function of time)
- delay it, multiply with original
- sum over a time window

Autocorrelation



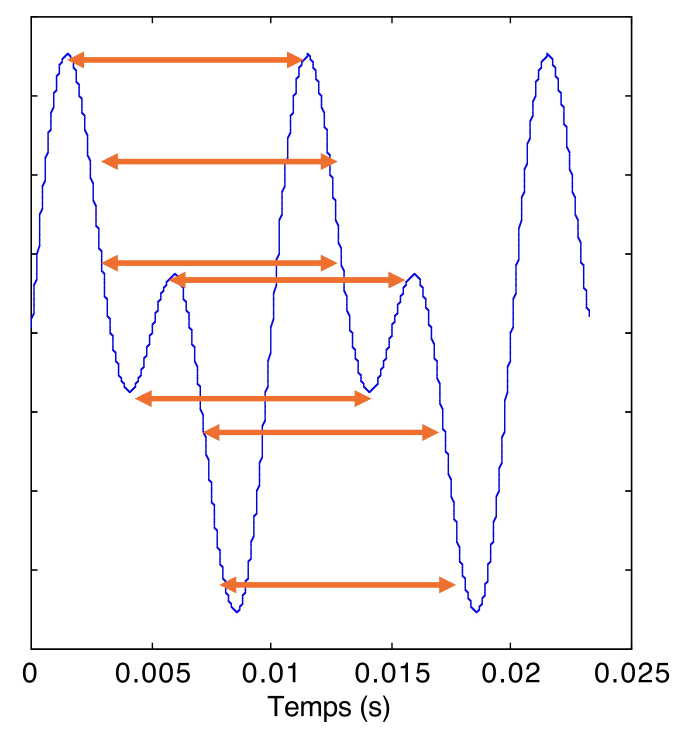
$$A_t(\tau) = \sum_{W} x(t)x(t-\tau)$$

product

time lag

integration window

Autocorrelation



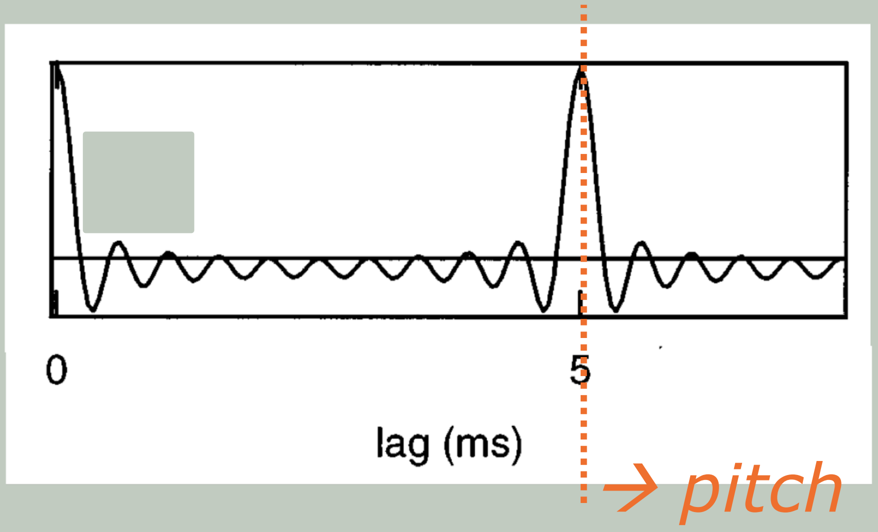
"shift and compare"

$$A_t(\tau) = \sum_{W} x(t)x(t-\tau)$$

product

time lag

integration window



→ pitch

Pros & cons:

place:

- *time honored (Duverney, Helmholtz, von Békésy), gives role to cochlea*
- *only works for pure tones*

time:

- *time honored (Nicomachus, Rutherford, Wever)*
- *phase-sensitive, "brittle", no role for cochlea*

pattern matching:

- *works for all stimuli (if partials can be resolved)*
- *requires extra "pattern matching" stage, fails if partials can't be resolved*

autocorrelation:

- *works for all stimuli*
- *no neural correlate found, can't explain all aspects of psychophysics*

Summary:

- *pitch ←→ F0 (mainly)*
- *exquisite discrimination (~0.2 %)*
- *invariant to other dimensions*
- *still not sure how it is perceived*

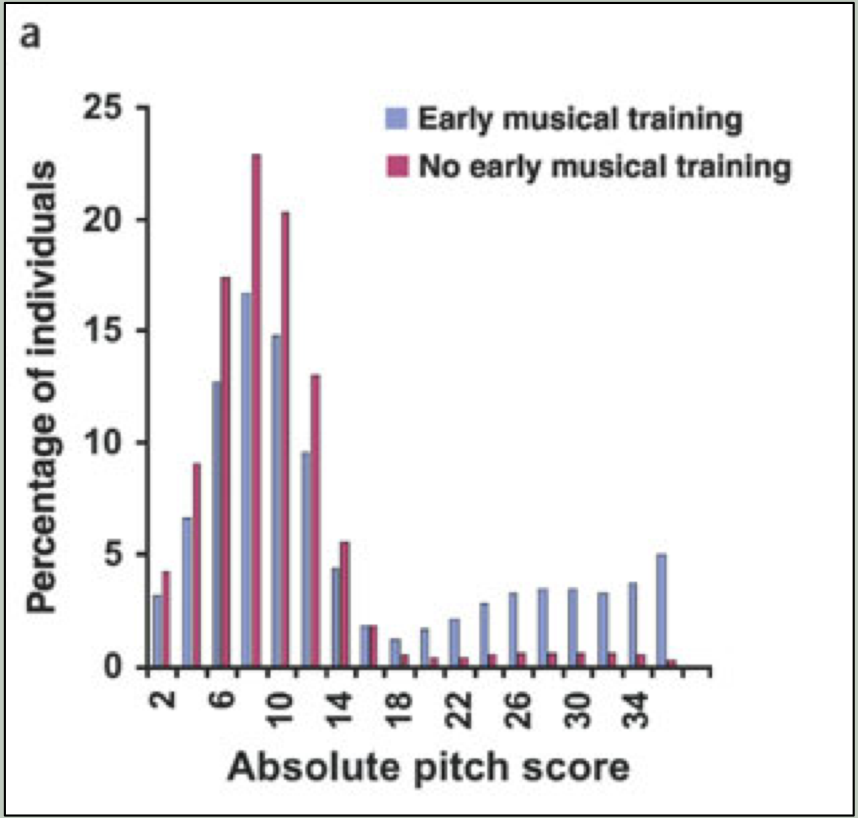
Some mysteries

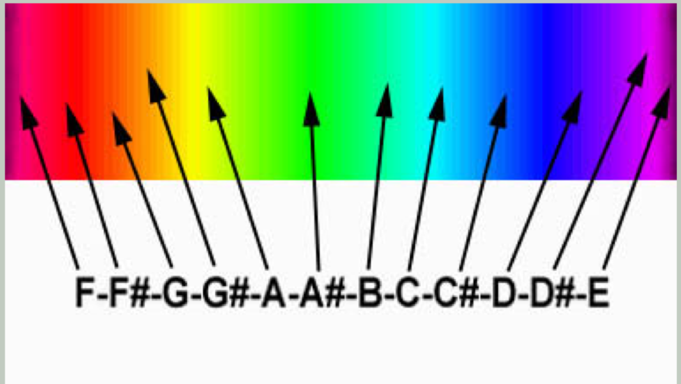
relative vs absolute pitch

- *most are sensitive to pitch interval (F0 ratio)*
- *few are sensitive to absolute pitch (F0)*

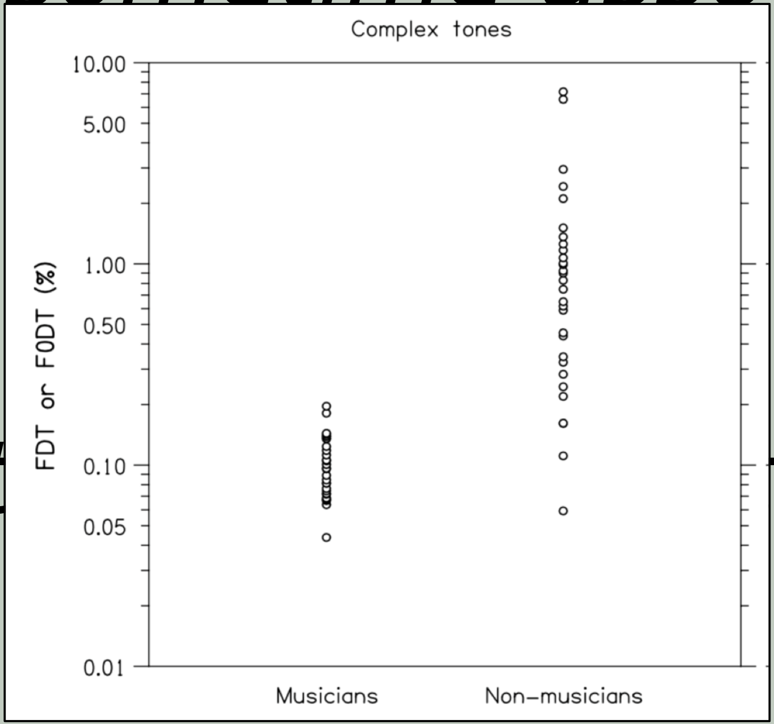
all of our models predict absolute pitch...

absolute pitch:





sometime associat



often associated wit *rai*

one aspect of inter

multiple pitches

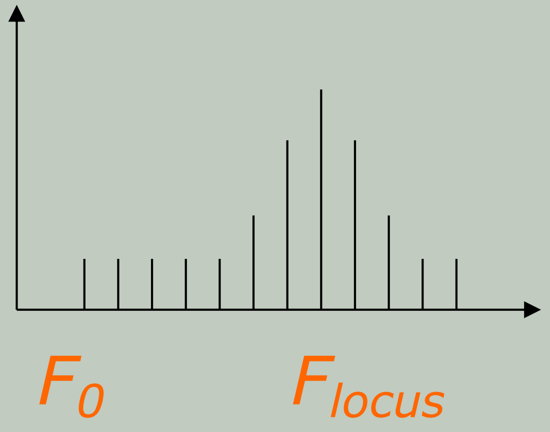
a stimulus sometimes evokes multiple pitches:

- *ambiguous pitch*
- *concurrent pitches*

our models assume a single pitch...

multiple pitches

throat singing:



courtesy Tran Van Quai

polyphony:

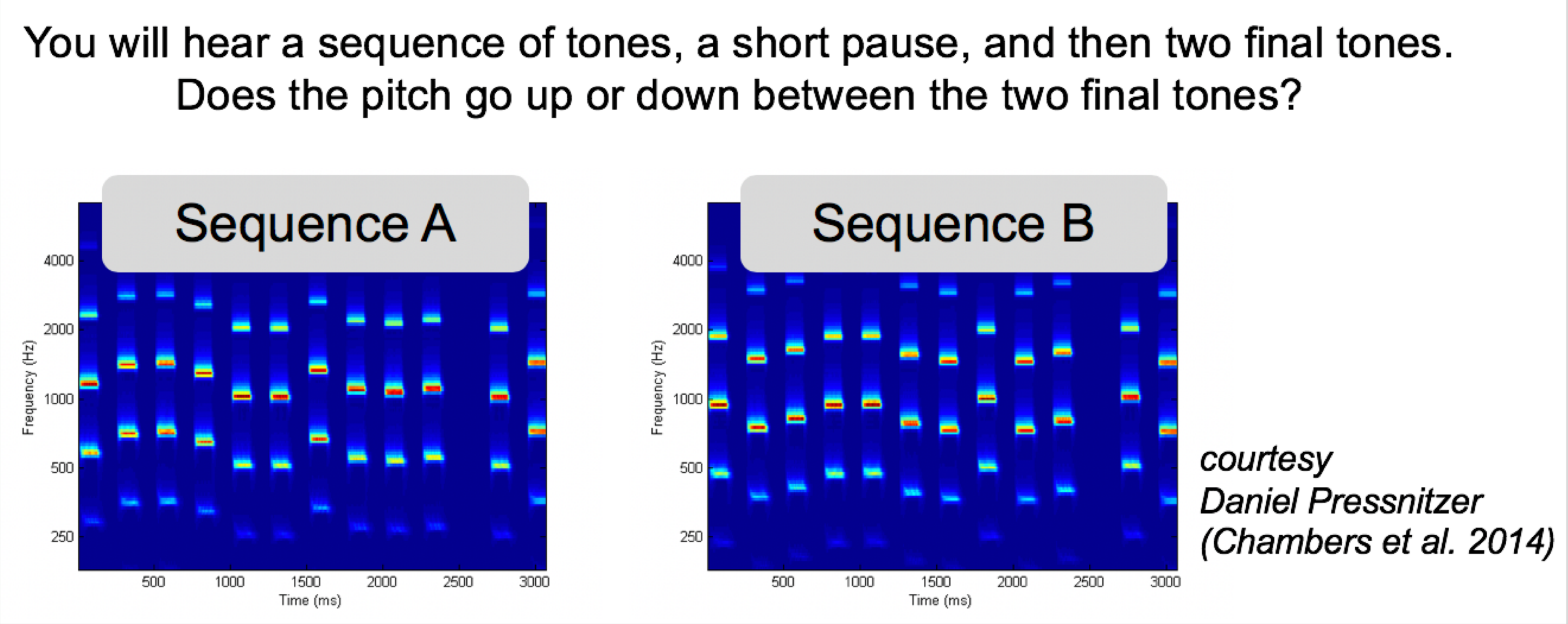
Bach"s musical offering
(orchestrated by Webern)

effect of context

- *pitch, interval depend on context*
    - *harmonic*
    - *melodic*
- *tonality (related to pitch?)*

our models are mostly context-blind...

effect of context



You will hear a sequence of tones, a short pause, and then two final tones.
Does the pitch go up or down between the two final tones?

Sequence A

Sequence B

courtesy
Daniel Pressnitzer
(Chambers et al. 2014)

last two tones are physically identical!

Conclusion

- *Pitch is important*

  *"Pitch perception is considered to represent the **heart of hearing theory**, and is, without doubt, the topic most discussed over the years" (Plomp, 2002)*

- *Many models:*

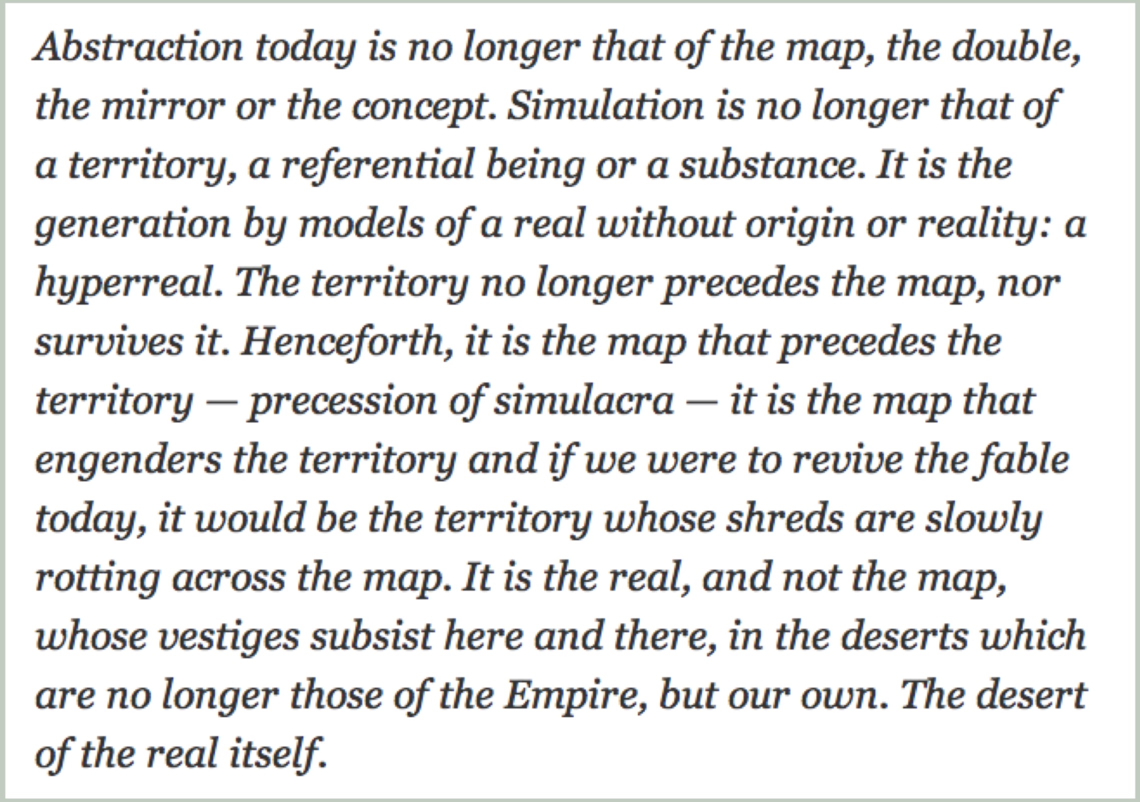
  place, time, pattern matching, autocorrelation

- *Still no consensus! (after more than 100 years...)*

- *Pitch probably involves:*
  - *temporal fine structure*
  - *+ peripheral filtering*

- *Pitch is complex:*

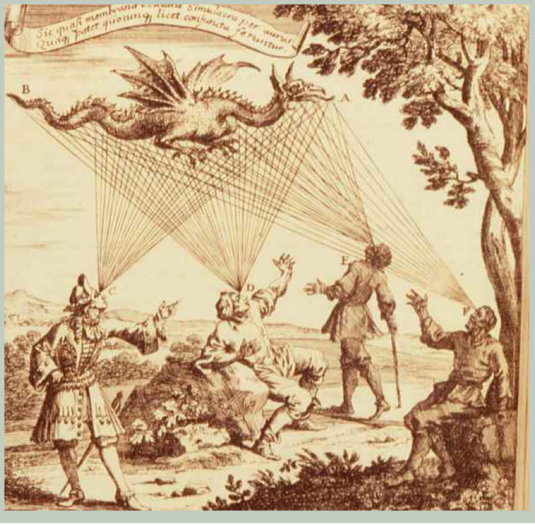
  many aspects (harmony, context, individual differences, absolute/relative pitch) <u>do not fit any simple model</u>



Abstraction today is no longer that of the map, the double, the mirror or the concept. Simulation is no longer that of a territory, a referential being or a substance. It is the generation by models of a real without origin or reality: a hyperreal. The territory no longer precedes the map, nor survives it. Henceforth, it is the map that precedes the territory — precession of simulacra — it is the map that engenders the territory and if we were to revive the fable today, it would be the territory whose shreds are slowly rotting across the map. It is the real, and not the map, whose vestiges subsist here and there, in the deserts which are no longer those of the Empire, but our own. The desert of the real itself.

Jean Baudrillard (1981) "Simulation and Simulacra"

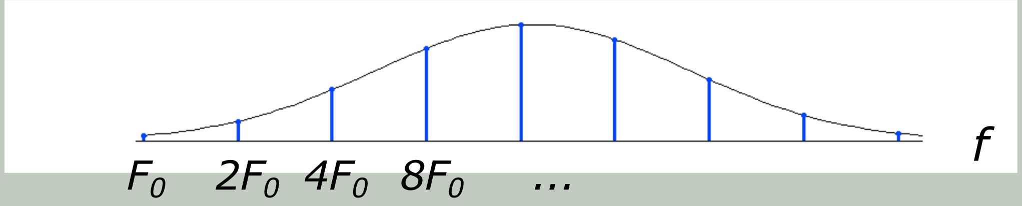
- *Definition of a model. Model ≠ World (Borges). The only good model is a false model.*
- *Modeling as metaphor of perception: Alhacen, Helmholtz, Bayesian theories. Up meets Down.*
- *Why model? Intuitive understanding. Theory. Organize past knowledge. Behavior model (design & interpret experiments). Computer model (Dan's AN work). Animal model. Mathematical model.*
- *How to judge a model?*
- *Models in hearing. Pitch.*
- *Summary: Perception is model-based. Understanding is model-based. Model quality criteria multidimensional. Fit is not most important (issue with falsifiability). Toolbox of models. Material/Animal/Computer/Mathematical/etc.*



1025 The Effect of Context in the Perception of an Ambiguous Pitch Stimulus

Claire Chambers[1], Daniel Pressnitzer[1]
[1]*Ecole Normale Supérieure*

ARO 2011



Shepard tone

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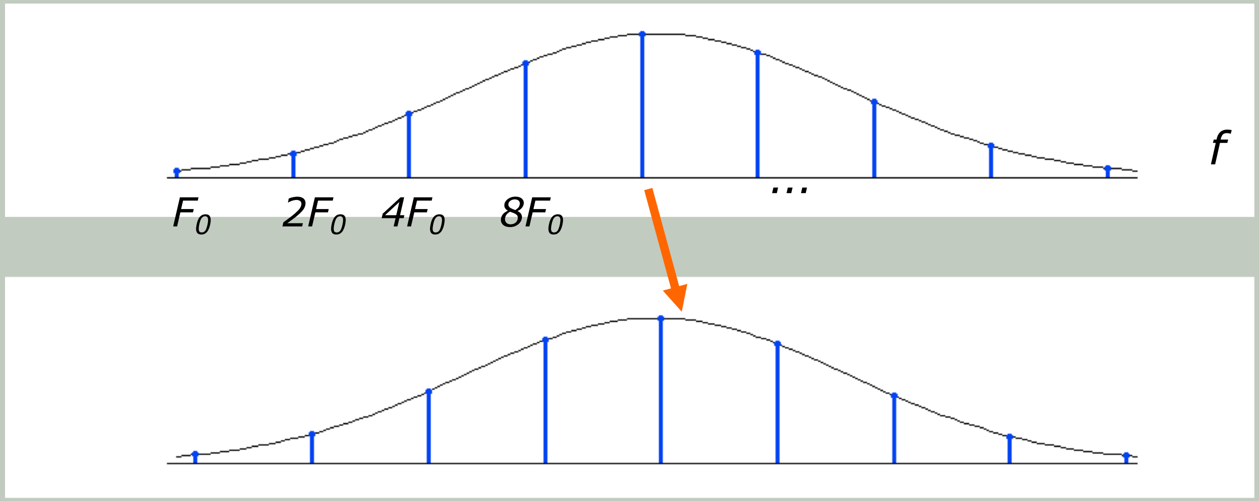

shepard tone

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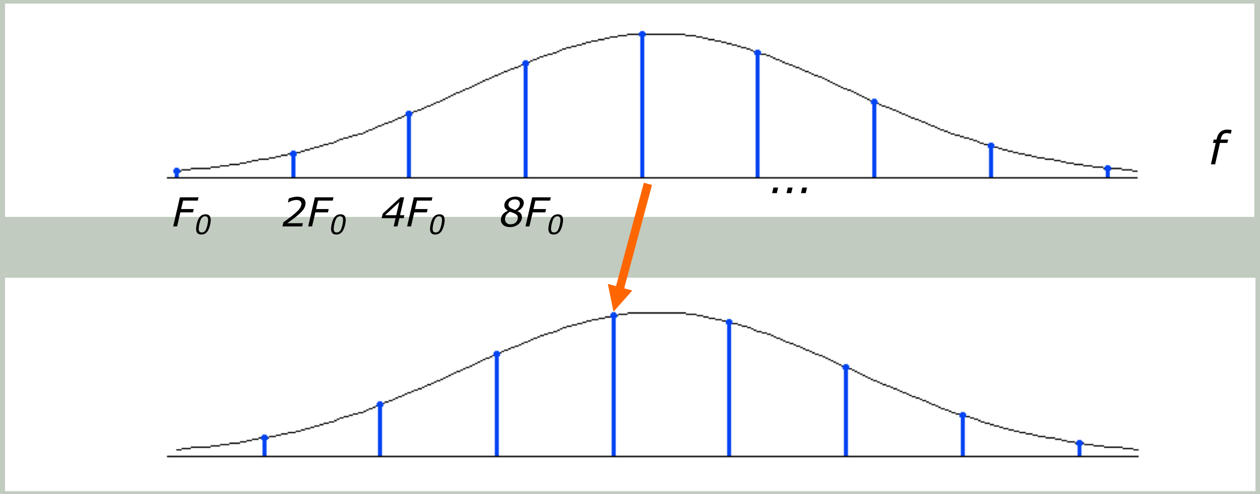

Shepard tone

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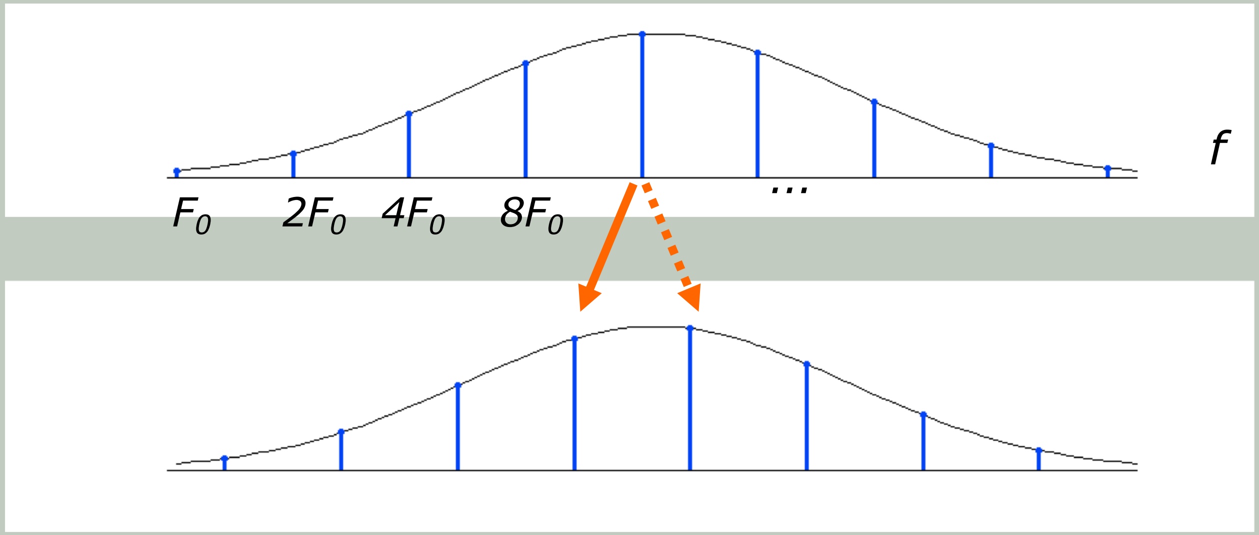

Shepard tone

Tritone (1/2 octave) intervals are ambiguous: can be heard as going up or down.

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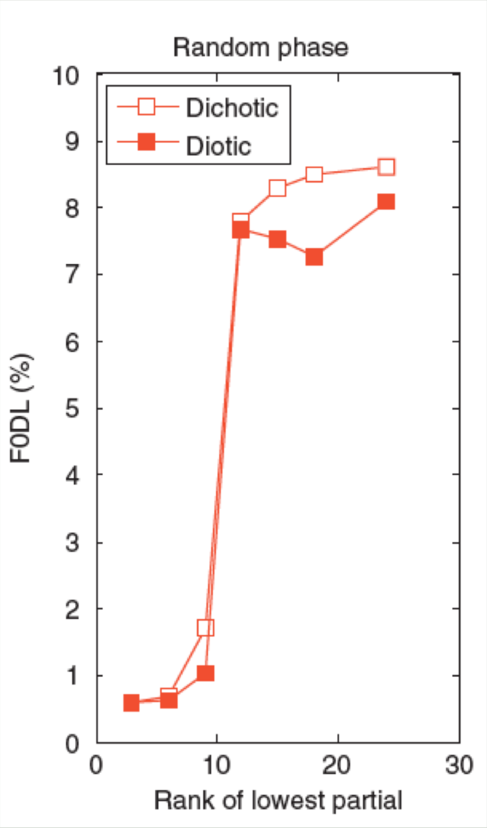
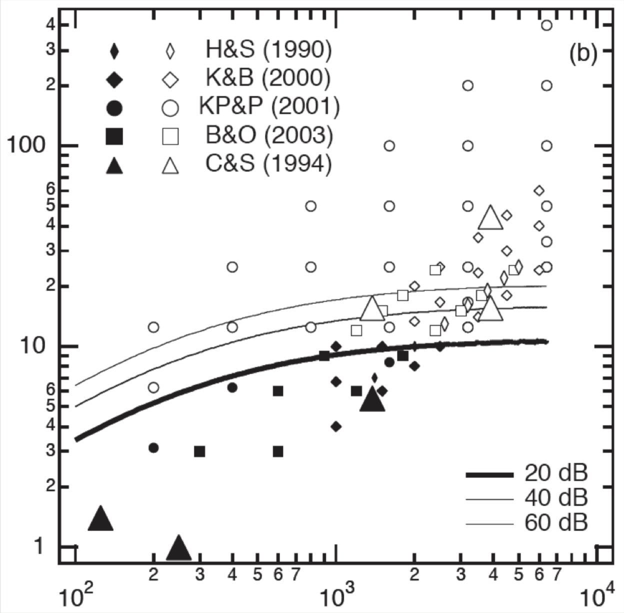
Same physical stimulus produces different percept according to context

The resolvability issue



Bernstein & Oxenham (2003)

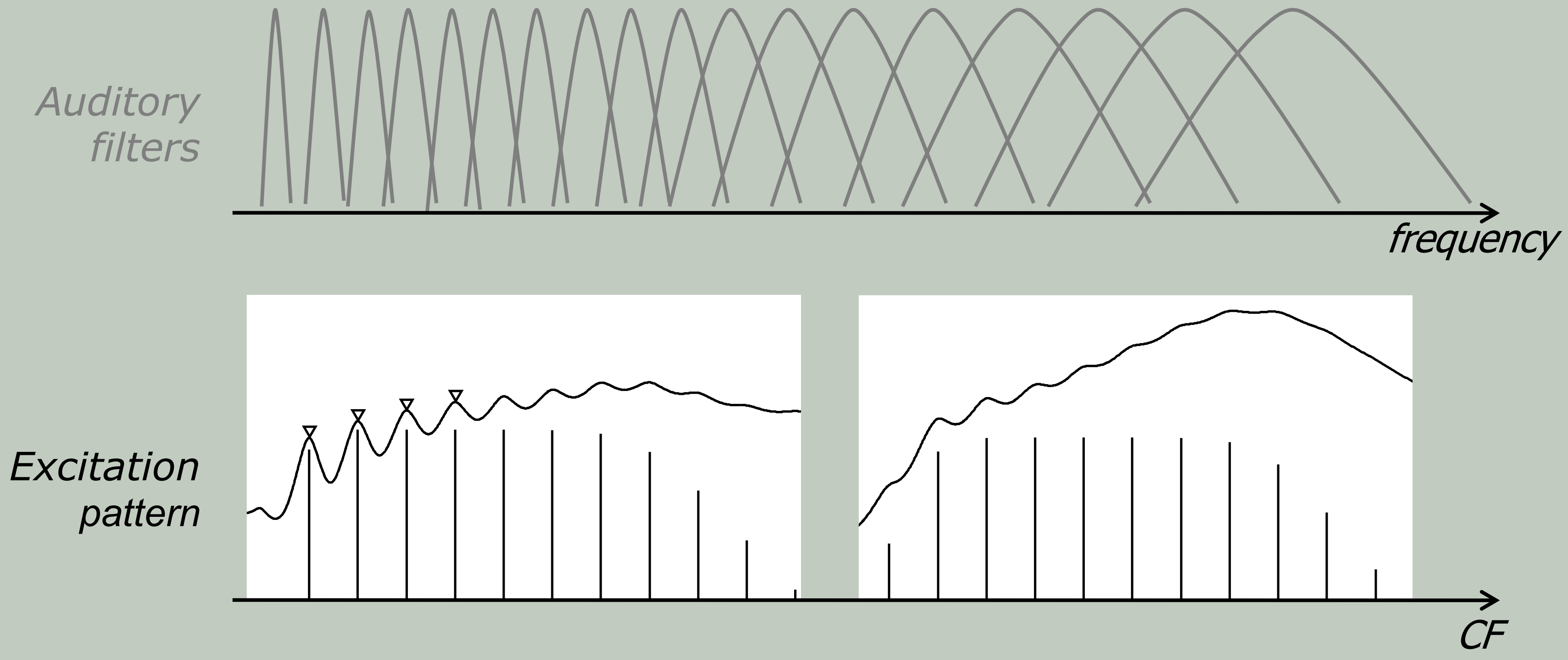


rank of lowest harmonic

frequency of lowest harmonic

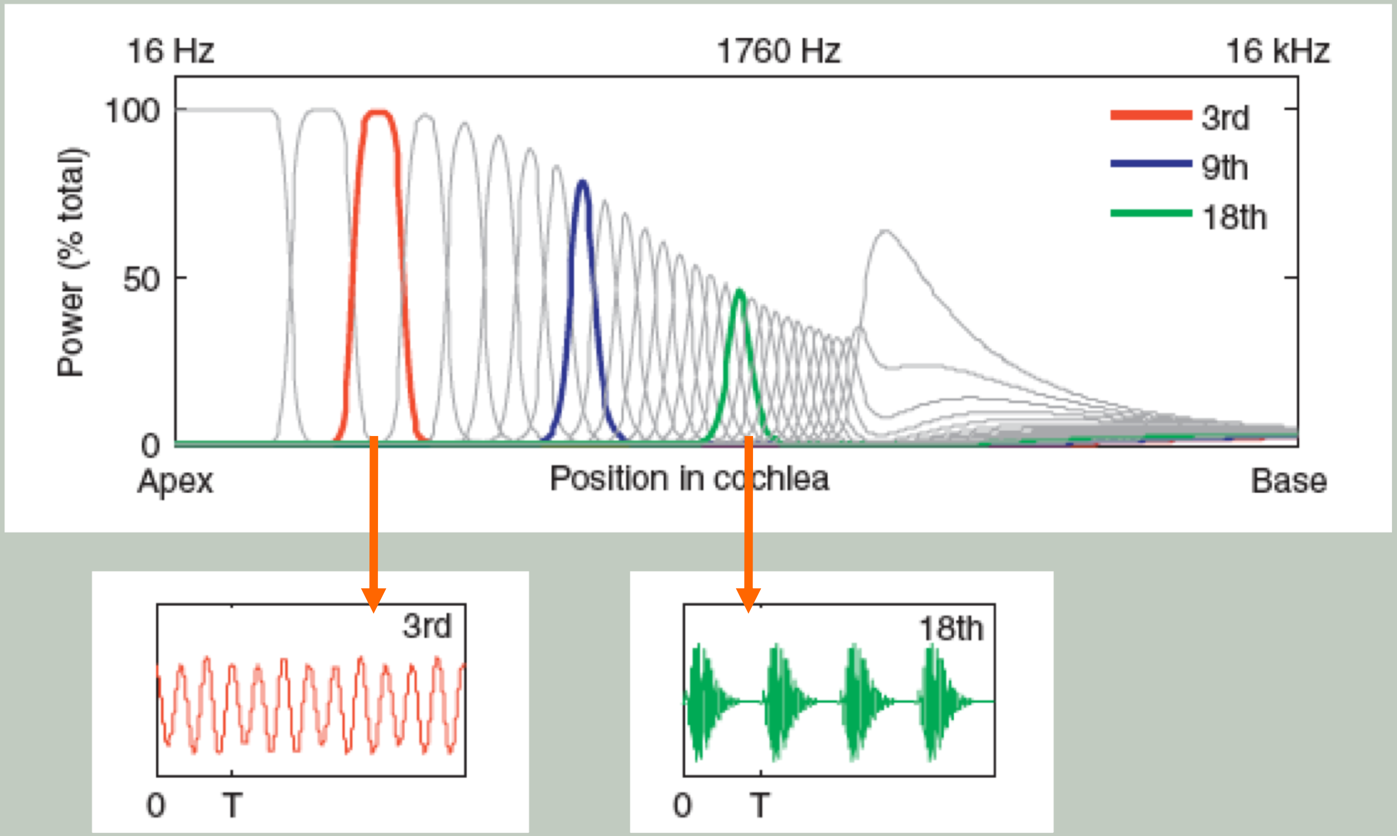
good performance iff stimulus contains harmonics of low rank (< ~10)

due to frequency resolution power of cochlea?



place estimation of partial frequencies fails if rank too high...

due to frequency resolution power of cochlea?



temporal estimation of partial frequencies fails if rank too high...

The coincidence between limit of cochlear resolution and performance limits strongly suggests pattern matching

BUT

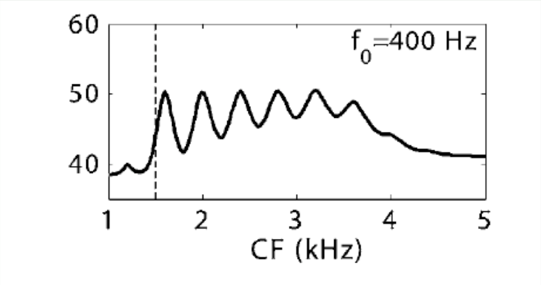
pitch is nevertheless heard for stimuli with no resolved harmonics, which pattern matching cannot explain...

Adrian Houtsma
1990

Bob Carlyon
1994

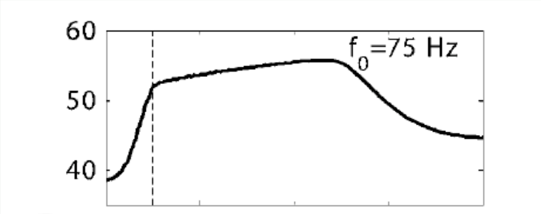
5. The dual-mechanism hypothesis

resolved:



pattern matching
--> pitch

unresolved:



autocorrelation
--> pitch

Pro:

- *works well (best of pattern matching and autocorrelation)*
- *predicts resolvability effects*

Con:

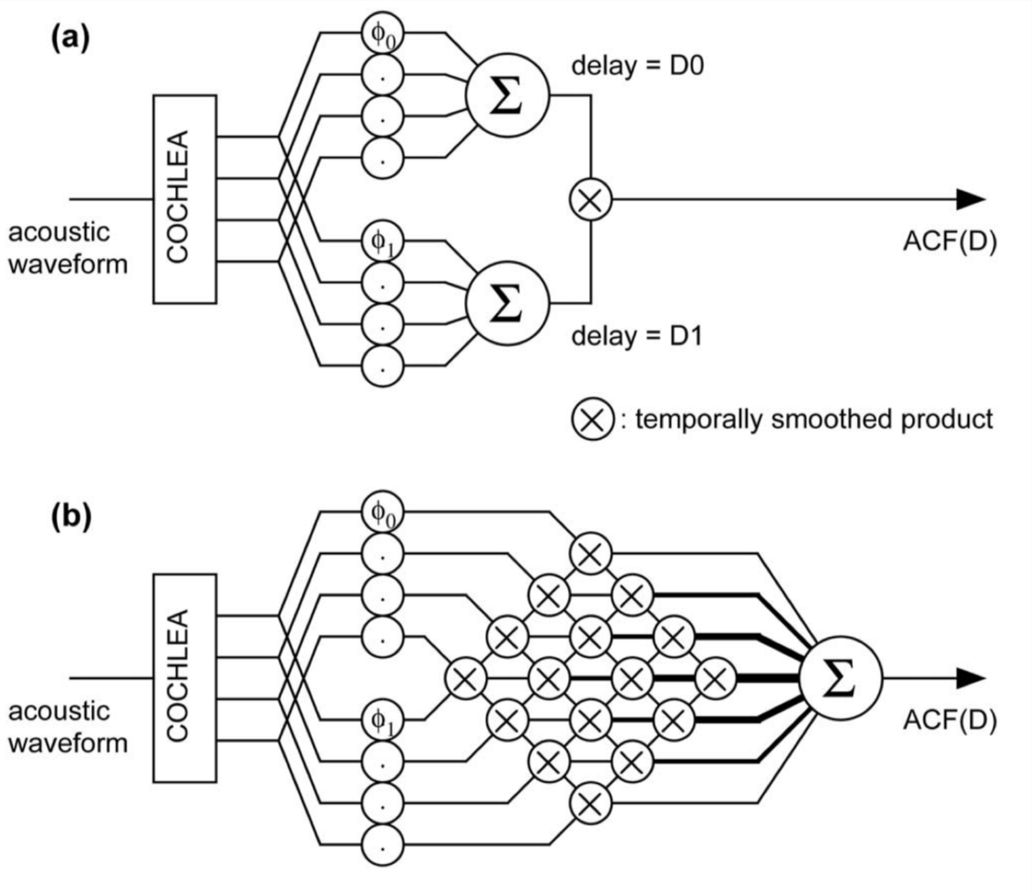
- *too easy! (it's like adding parameters to a model)*
- *requires three mechanisms:*
  - *pattern matching*
  - *autocorrelation*
  - *translation between the two...*

an alternative explanation:

The case of the missing delay lines: Synthetic delays obtained by cross-channel phase interaction

Alain de Cheveigné and Daniel Pressnitzer

Equipe Audition, FRE 2929, CNRS, Université Paris 5, ENS, 29 Rue d'Ulm, F-75230 Paris cedex 05, France



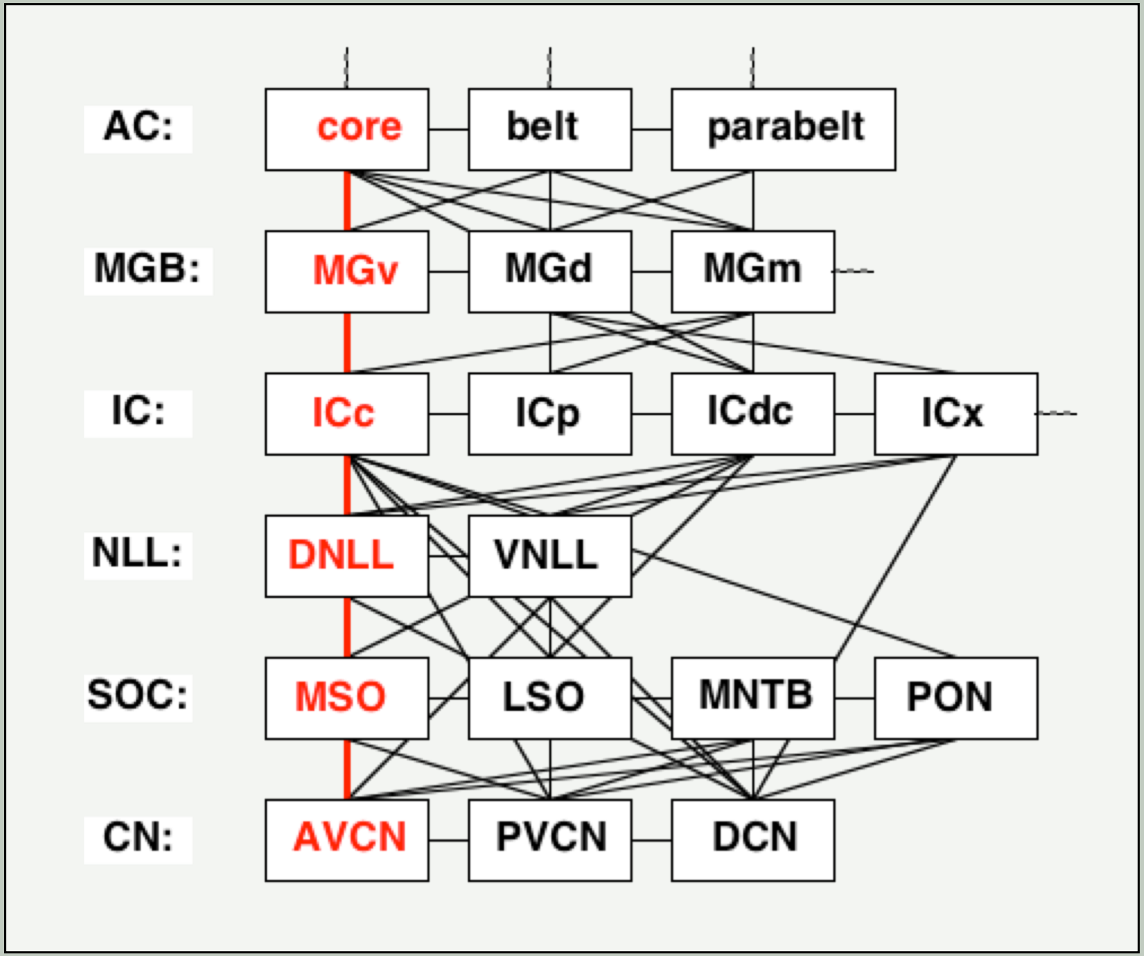
yet another model...

Physiological basis

2 potential ingredients:

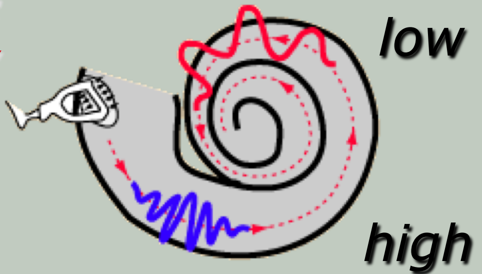
- *tonotopy,*
- *temporal fine structure*

Tonotopy

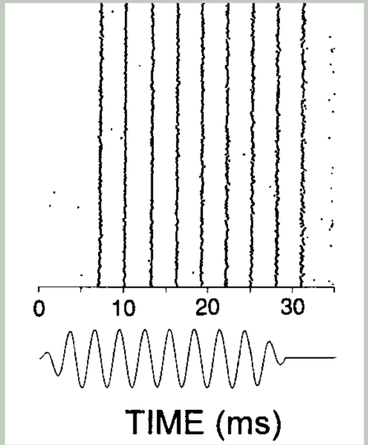


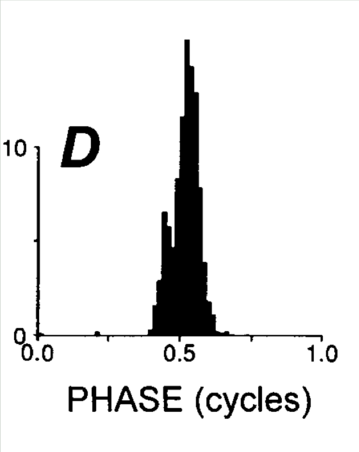
required by ***place*** *and place-based* ***pattern-matching*** *models*

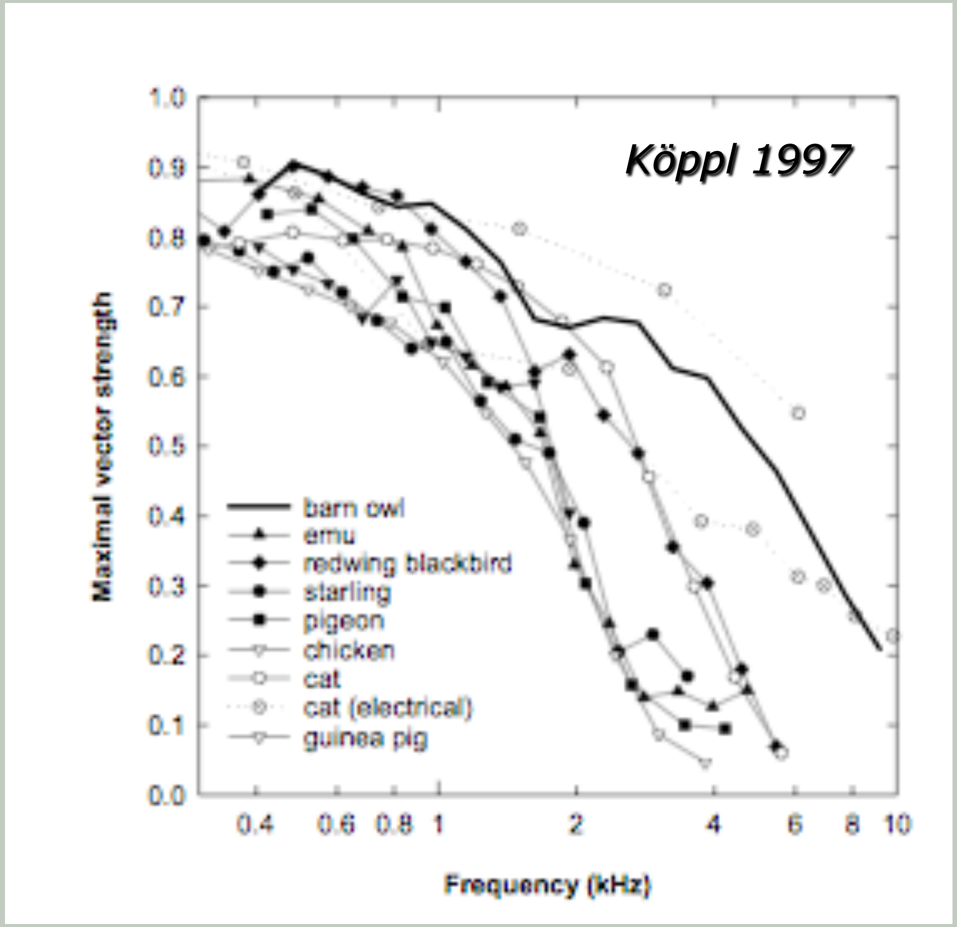
tonotopic pathway

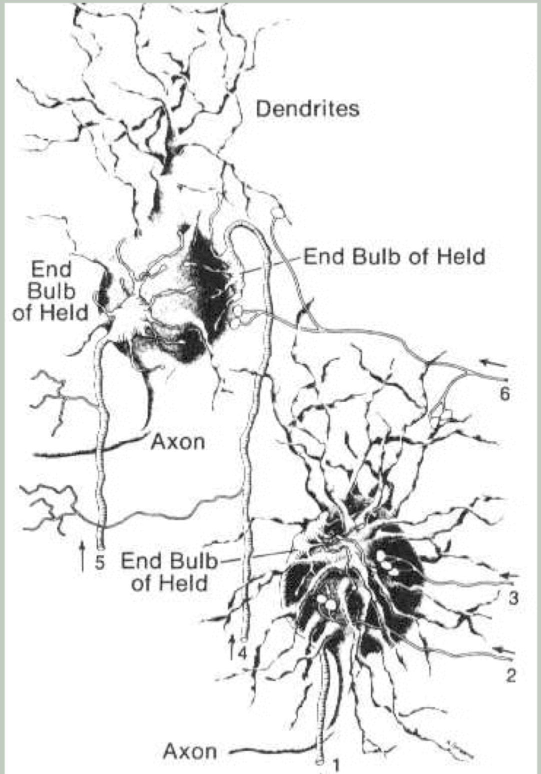


Phase-locking



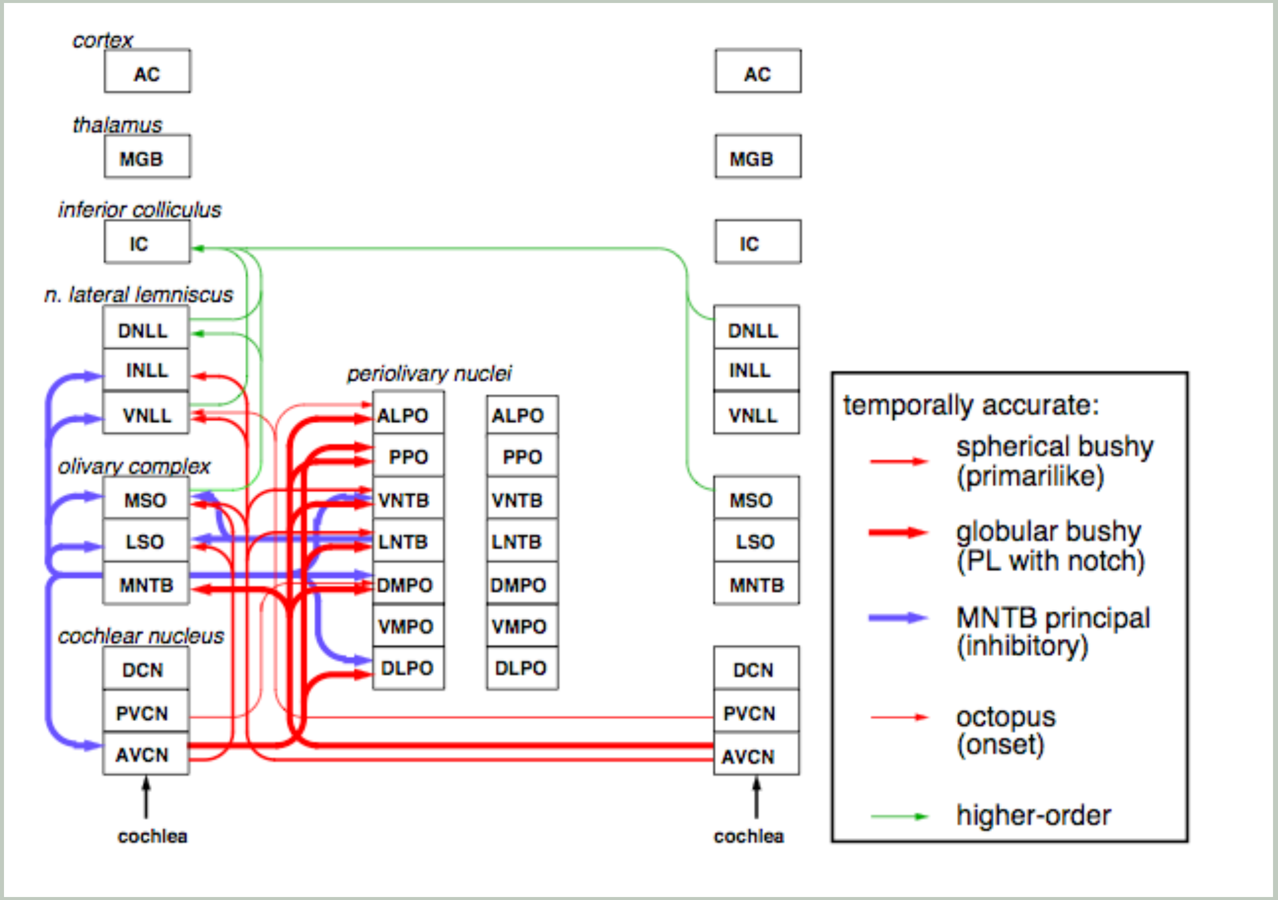



Köppl 1997



required by time, time-based pattern-matching, and autocorrelation models

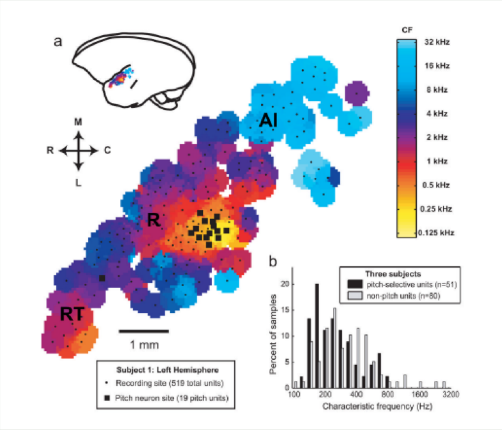
available at all levels in brainstem & midbrain



potential sites:
CN, MSO, DLPO, VNLL, etc.
<u>no definite evidence</u> (yet)

Future directions:

- *new techniques in electrophysiology (multielectrode, optical, genetic)*
- *new techniques in brain imaging (fMRI, MEG, acoustic?)*
- *better attention to theory and artifacts*



Bendor & Wang 2005

Recent developments

- resolvability
- memory and context
- pitch beyond 5 kHz
- sharp selectivity in humans
- pitch of mixtures of tones

memory and context:

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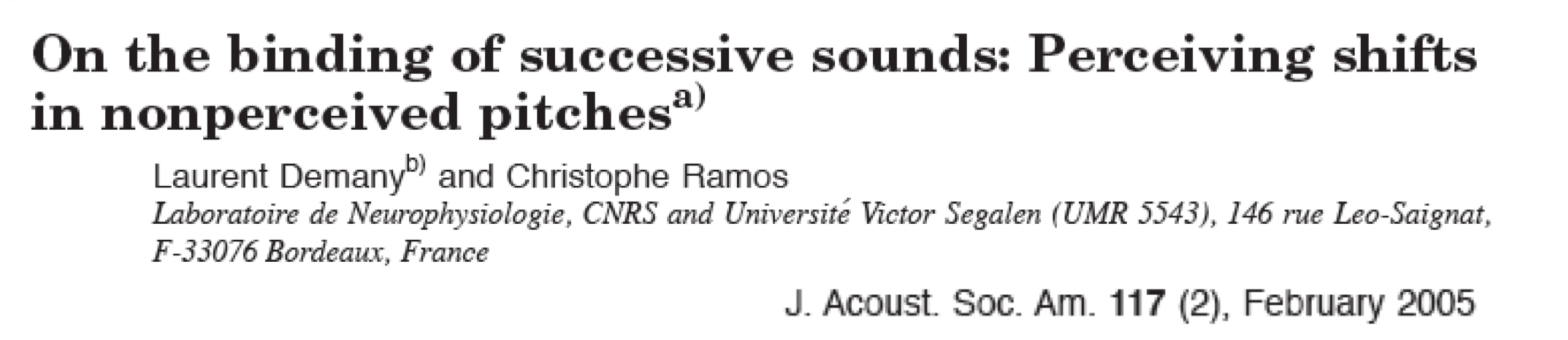


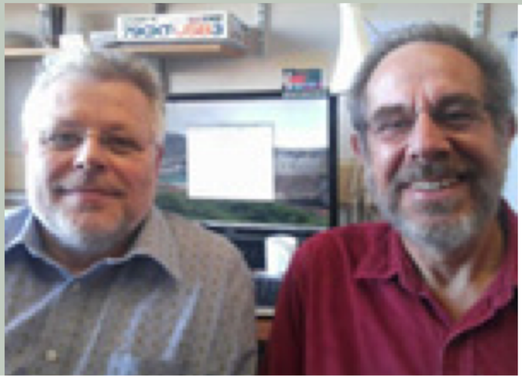
On the binding of successive sounds: Perceiving shifts in nonperceived pitches[a)]

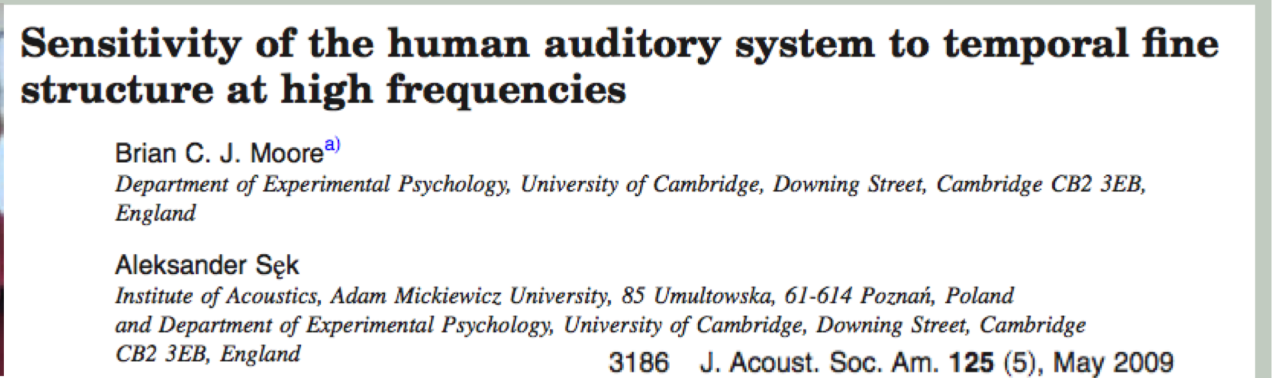
Laurent Demany[b)] and Christophe Ramos

Laboratoire de Neurophysiologie, CNRS and Université Victor Segalen (UMR 5543), 146 rue Leo-Saignat, F-33076 Bordeaux, France

J. Acoust. Soc. Am. **117** (2), February 2005

temporal pitch beyond 5 kHz ?:





Sensitivity of the human auditory system to temporal fine structure at high frequencies

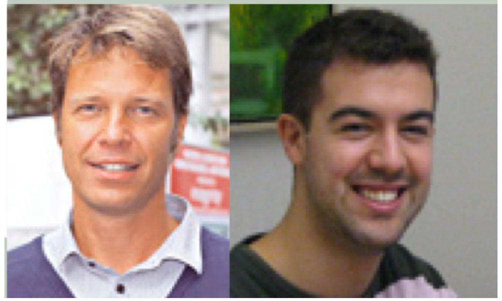
Brian C. J. Moore[a)]
Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England

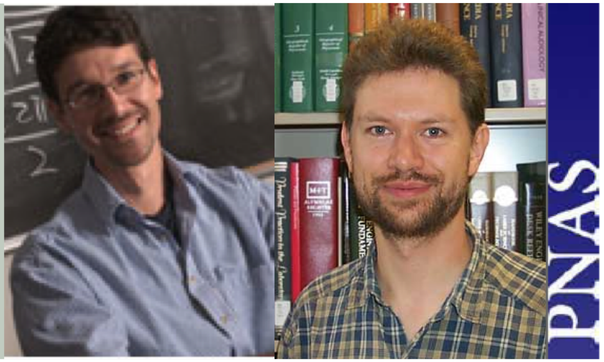
Aleksander Sęk
Institute of Acoustics, Adam Mickiewicz University, 85 Umultowska, 61-614 Poznań, Poland and Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England

3186 J. Acoust. Soc. Am. **125** (5), May 2009

The role of temporal fine structure information for the low pitch of high-frequency complex tones

Sébastien Santurette[a)] and Torsten Dau
Centre for Applied Hearing Research, Department of Electrical Engineering, Technical University of Denmark, DTU Bygning 352, Ørsteds Plads, 2800 Kongens Lyngby, Denmark





Pitch perception beyond the traditional existence region of pitch

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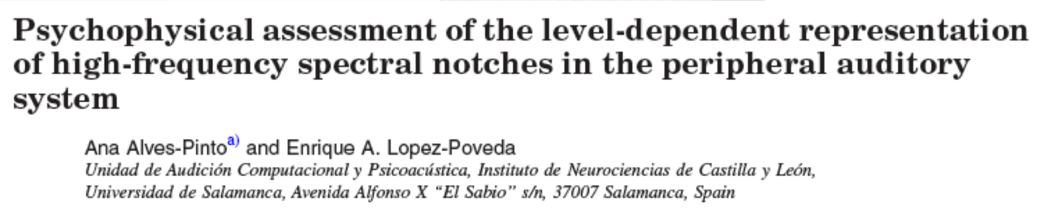
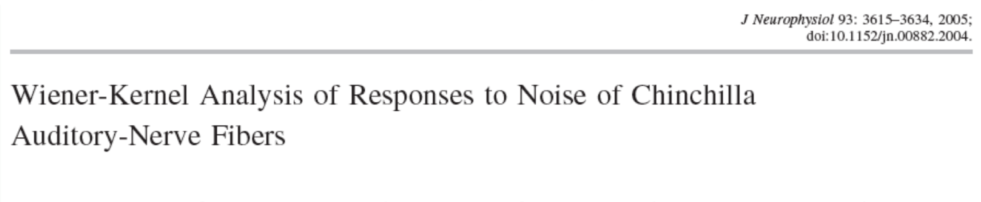
PNAS | May 3, 2011 | vol. 108 | no. 18 | 7629–7634



Psychophysical assessment of the level-dependent representation of high-frequency spectral notches in the peripheral auditory system

Ana Alves-Pinto[a)] and Enrique A. Lopez-Poveda
Unidad de Audición Computacional y Psicoacústica, Instituto de Neurociencias de Castilla y León, Universidad de Salamanca, Avenida Alfonso X "El Sabio" s/n, 37007 Salamanca, Spain



J Neurophysiol 93: 3615–3634, 2005;
doi:10.1152/jn.00882.2004.

Wiener-Kernel Analysis of Responses to Noise of Chinchilla Auditory-Nerve Fibers

Alberto Recio-Spinoso,[3] Andrei N. Temchin,[1] Pim van Dijk,[2] Yun-Hui Fan,[1] and Mario A. Ruggero[1]

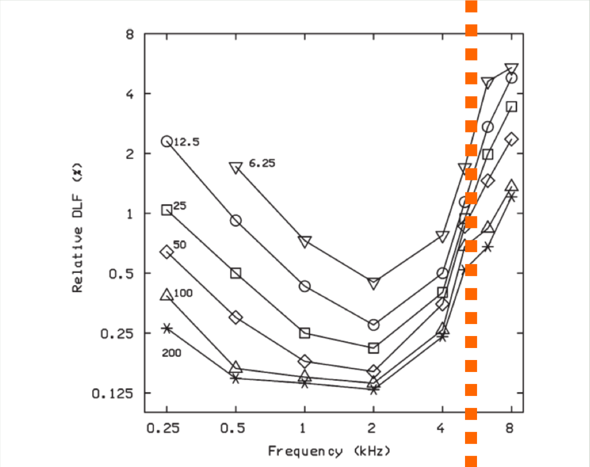


Fig. 4.2 Frequency difference limens (smallest detectable relative frequency difference) for pure tones. Each curve is for a different stimulus duration (in ms). Discrimination is best for frequencies near 2 kHz and degrades rapidly above 4 kHz. Discrimination is better for longer durations. From Moore (1973) with permission.

Moore 1973

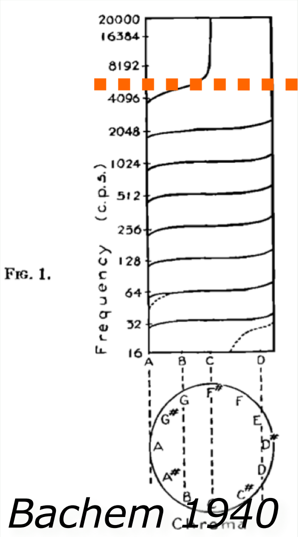
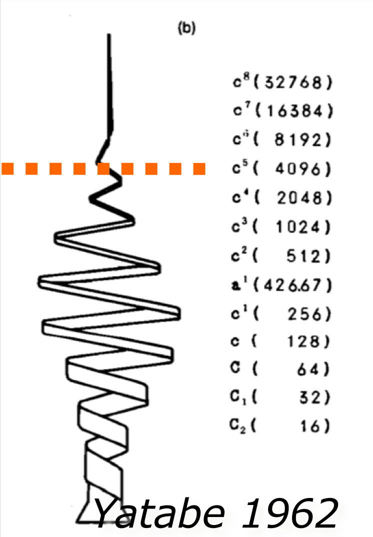
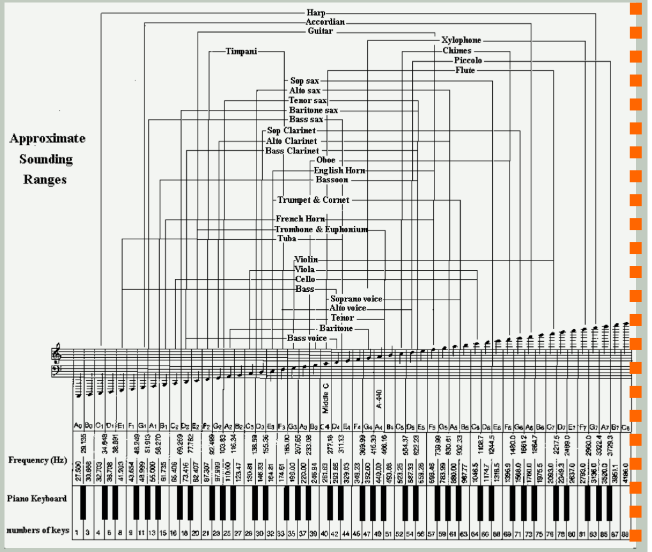


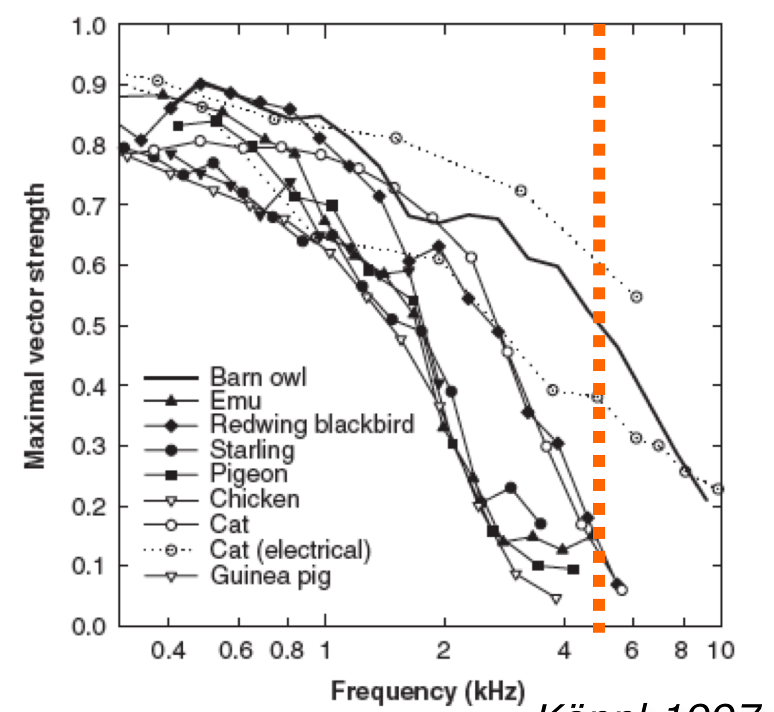
Fig. 1.

Bachem 1940



Yatabe 1962



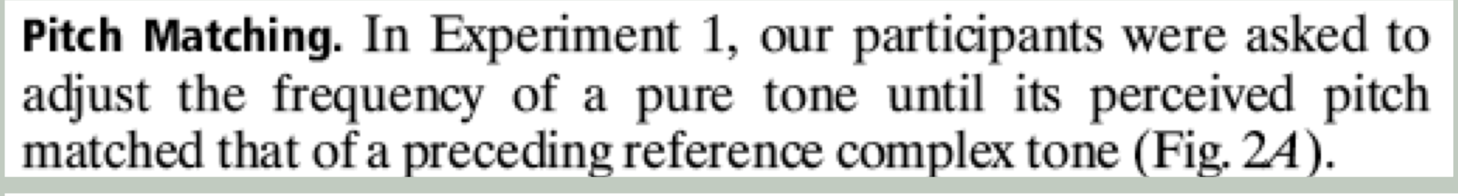


Köppl 1997

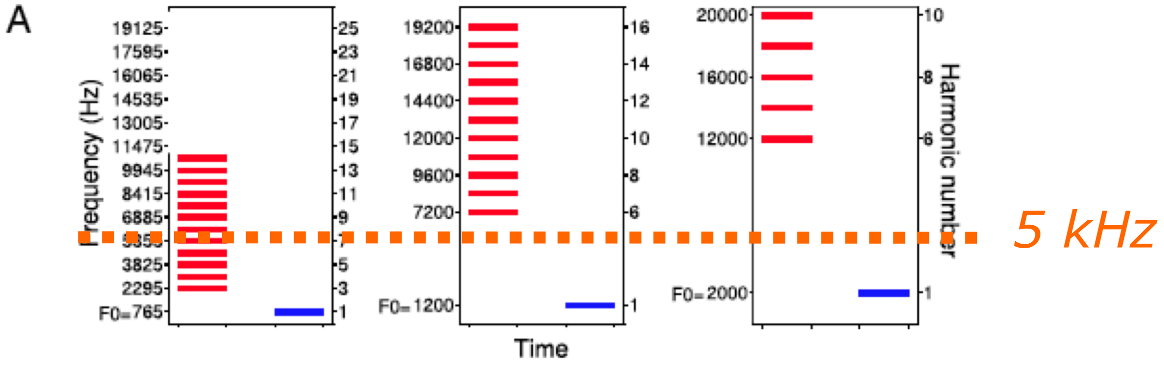
Behavioral limits (frequency resolution, musical properties, absolute pitch) are usually associated with the limit of phase locking observed in animal models, around 5 kHz.

New studies question whether this limit is strict, or whether there is pitch beyond 5 kHz.

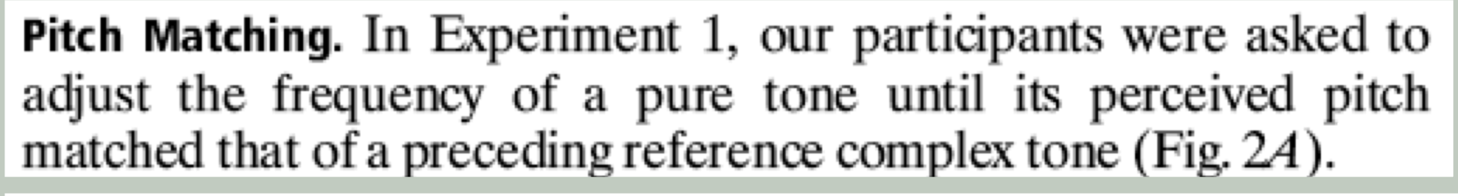
Oxenham et al 2011:



Pitch Matching. In Experiment 1, our participants were asked to adjust the frequency of a pure tone until its perceived pitch matched that of a preceding reference complex tone (Fig. 2*A*).



Oxenham et al 2011:



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