Interactions between tones:

Consonance & dissonance:

Consonance and dissonance: relevance

- Pitch interactions between notes
- Musical intervals
- Euphoniousness, smoothness, clarity
- Determine choice of musical intervals (scales)
- Vertical Harmonies - concurrent notes, chords
- Horizontal Harmonies - melodies
- May provide a foundation for tonal structure
- Tonal tension-relaxation, pitch stability
- Bernstein on intervals (movie, see Blackboard)

Tonal consonance: interactions of tones

- Pythagorean experiments
- Beating, roughness, fusion
- Psychophysics of consonance
  - Meanings of "consonance" and "dissonance"
  - Euphonious, "pleasant" vs. jarring, unpleasant
  - Smooth, well-defined, unified vs. rough, buzzy, unsettled
- Neural correlates of roughness (cochlear filtering)
  - Periodicities below the range of the pitch mechanism
  - Population-wide fluctuations in discharge rates
- Neural correlates of tonal fusion (pitch)
- Consonance in music
  - Tuning systems and scales
  - Instability-Stability (tension-resolution)

Predicted consonance of harmonic complexes (n=1-6)

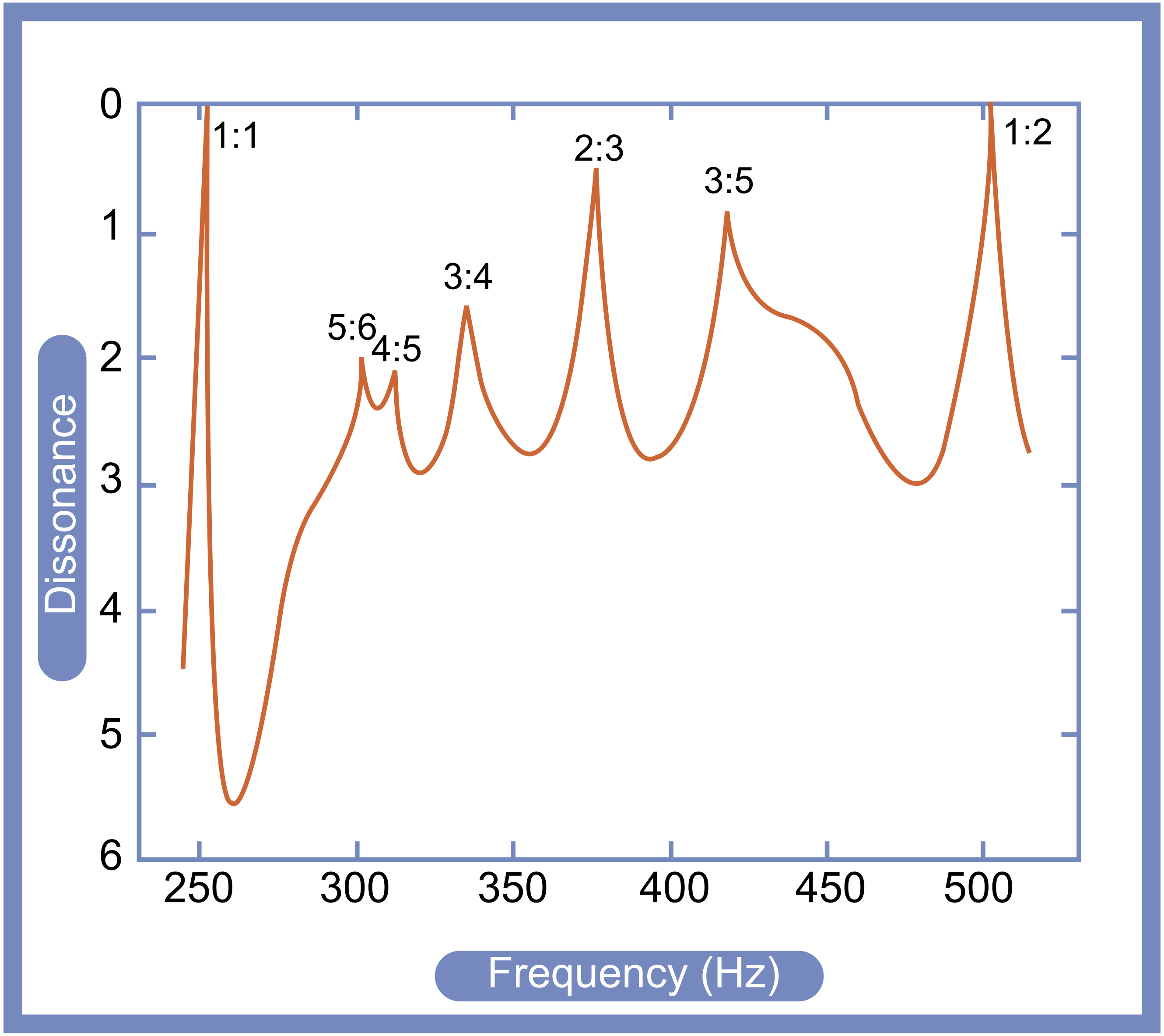


Figure by MIT OpenCourseWare.

Consonant intervals

In most tonal contexts, these intervals are perceived as more consonant. However there can be contexts where some of these intervals can be dissonant.

CONSONANT INTERVALS

Name of Interval	Octave	Fifth	Fourth	Major third	Minor third	Major sixth	Minor sixth
Notes (in Key of C Major)	C-C	C-G	C-F	C-E	E-G	C-A	E-C
Ideal Frequency Ratio	2	3/2	4/3	5/4	6/5	5/3	8/5
Number of Semitones	12	7	5	4	3	9	8

Figure by MIT OpenCourseWare.

C-Major diatonic scale (white keys CDEFGABC)

C-Minor diatonic scale (CD

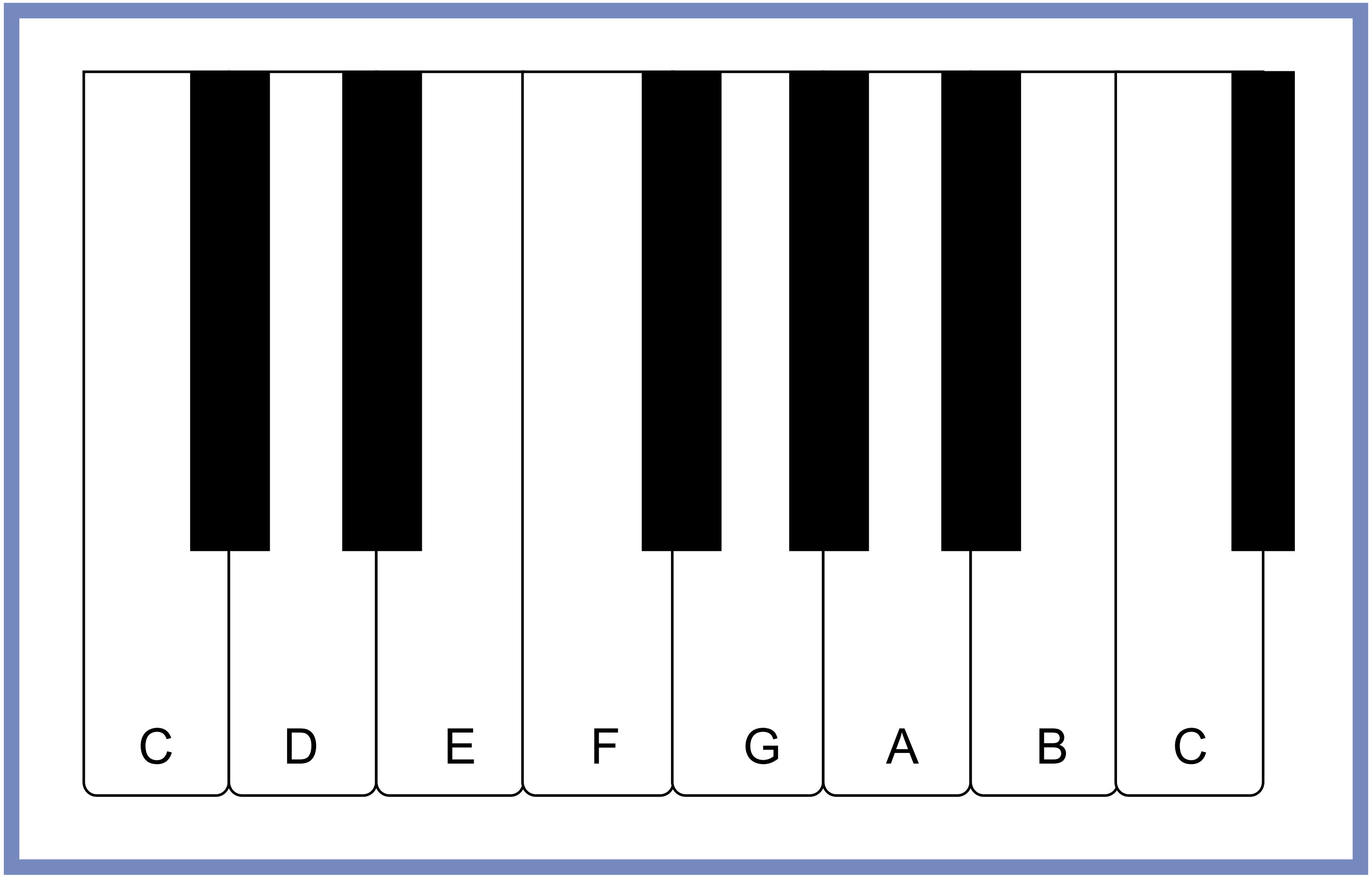


Figure by MIT OpenCourseWare.

Pythagoreans (6th c. BCE)

interplay of music,
science, & mysticism

quaternery (1+2+3+4)
contains consonances

music of the spheres
universal harmonies
numerologies
physics, acoustics

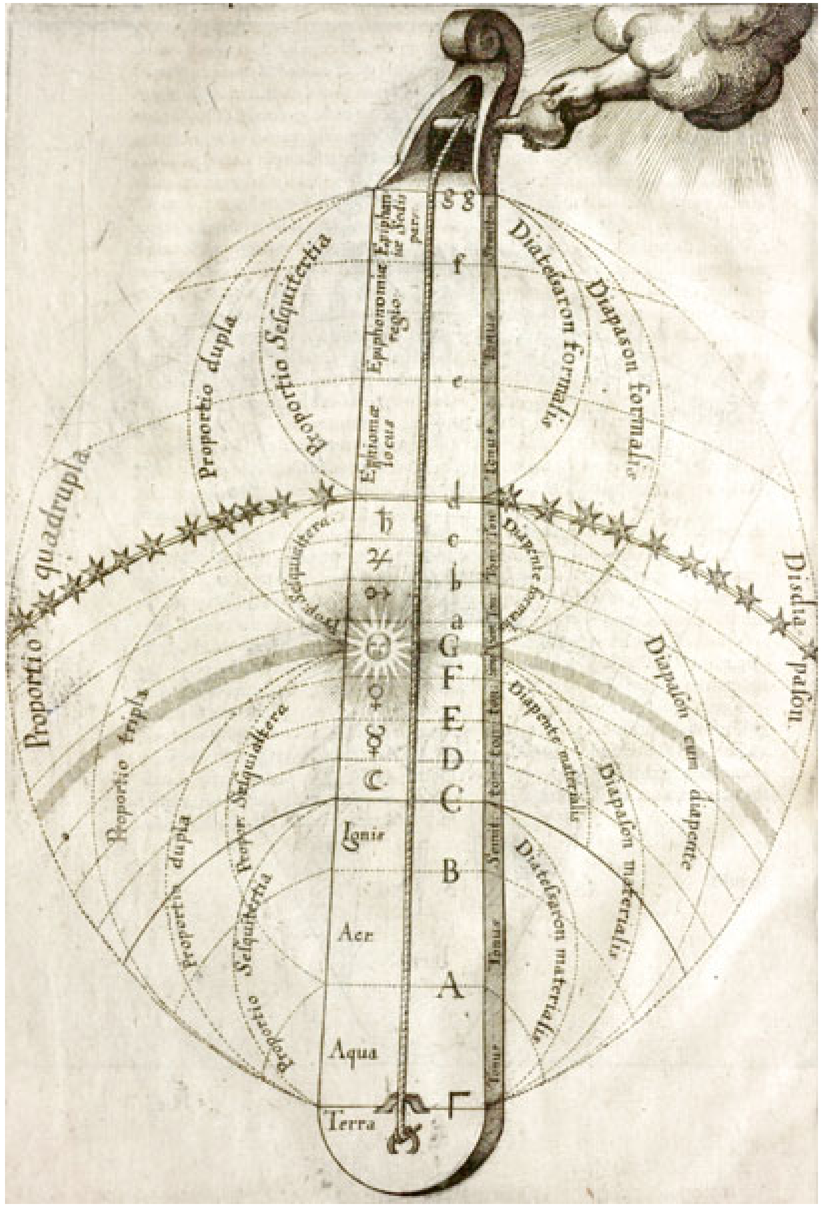
Galileo (father & son)
Descartes
Mersenne, Saveur
Rameau
Fourier, Ohm, Helmholtz
Seebeck

music of the spheres

universal harmonies

numerologies

physics, acoustics



Wikipedia: ***Musica universalis***:

The three branches of the Medieval concept of musica were presented by Boethius in his book *De Musica*:

- *musica universalis* (sometimes referred to as *musica mundana*)
- *musica humana* (the internal music of the human body)
- *musica instrumentalis* (sounds made by singers and instrumentalists)

Pythagorean ratios

Images removed due to copyright restrictions.
Figure 2-5 and 2-6 in Pierce, John R. *The Science of Musical Sound.* Revised ed. New York, NY: W. H. Freeman, 1992.

Figure 2-5. Greek citharis. The cithara was sacred to Apollo.

Pierce, The Science of Musical Sound

Spectrum of a string

Image removed due to copyright restrictions. See Fig. 2.6 in Sethares, W. A. *Tuning, Tibre, Spectrum, Scale*. 2nd ed. New York, NY: Springer, 2005. ISBN: 9781852337971. [Preview in Google Books]

Spectrum of plucked strings

Image removed due to copyright restrictions. See Fig. 2.5 in Sethares, W. A. *Tuning, Tibre, Spectrum, Scale*. 2nd ed. New York, NY: Springer, 2005. ISBN: 9781852337971. [Preview in Google Books]

From beating to roughness to tonal separation

Image removed due to copyright restrictions. See Fig. 2.17 in Sethares, W. A. *Tuning, Tibre, Spectrum, Scale.* 1st ed. New York, NY: Springer, 1998. ISBN: 9783540761730.

Sensory dissonance (roughness)

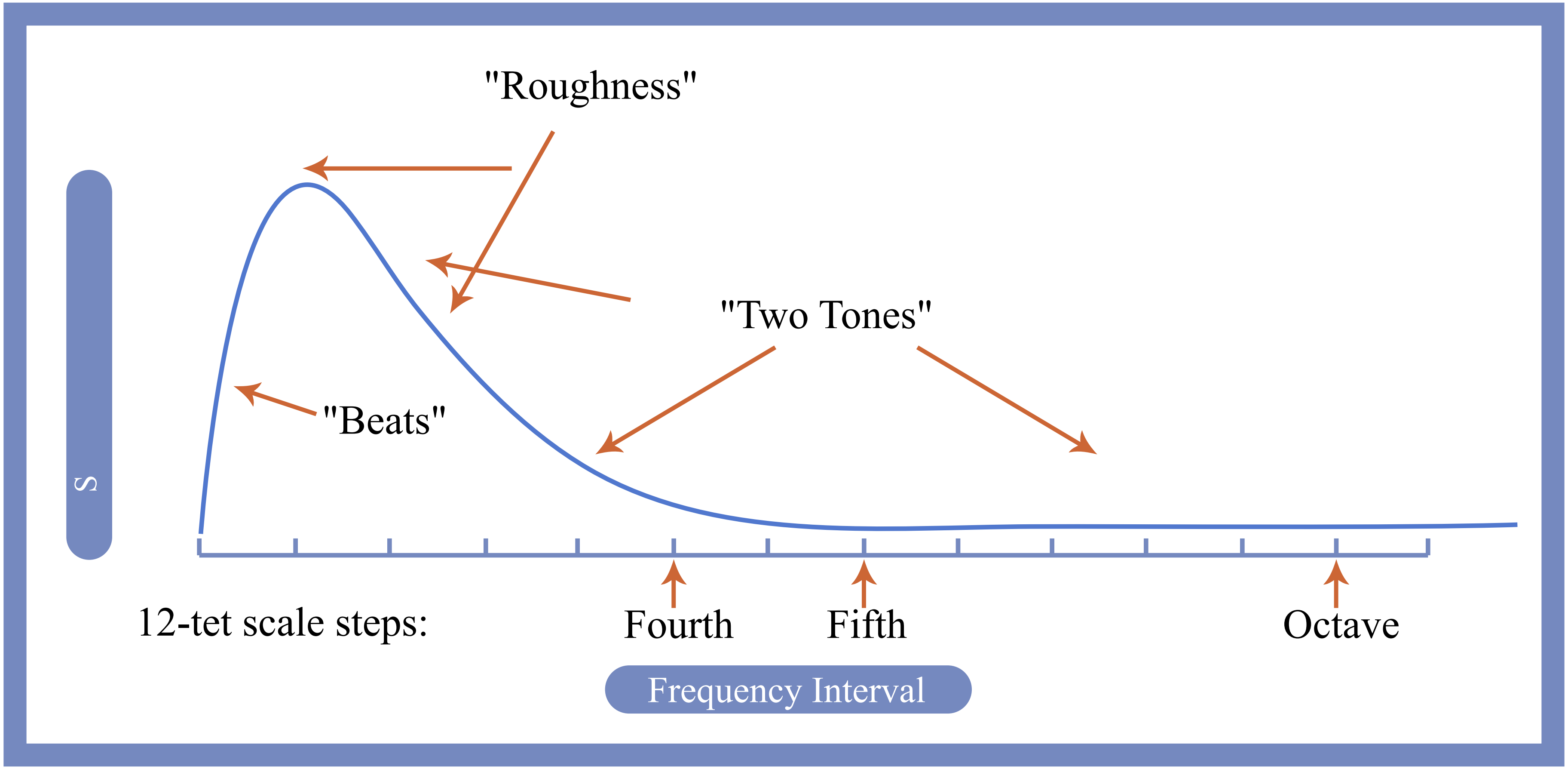


Figure by MIT OpenCourseWare.

Tonal interactions
(tone generator demo)

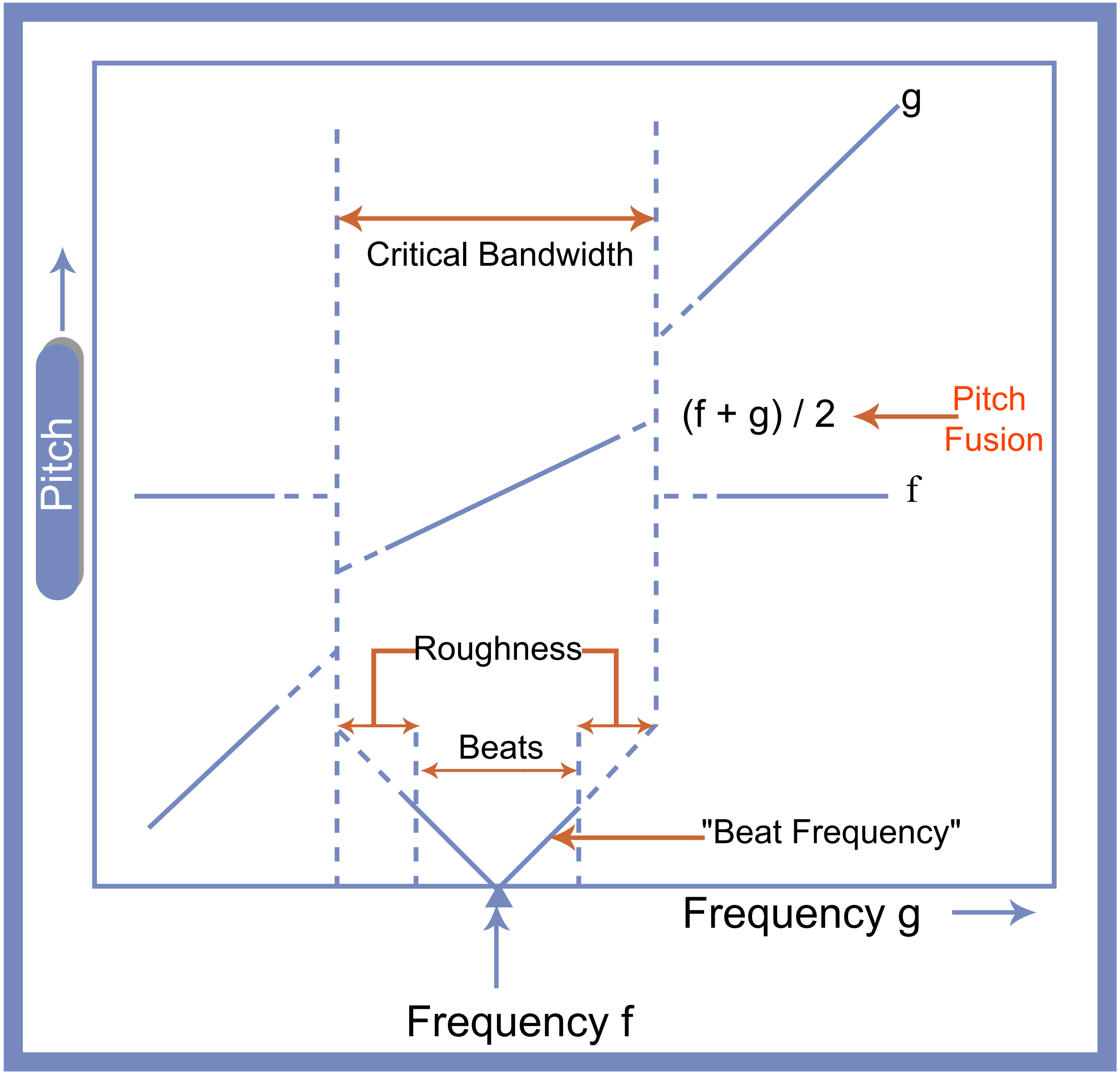
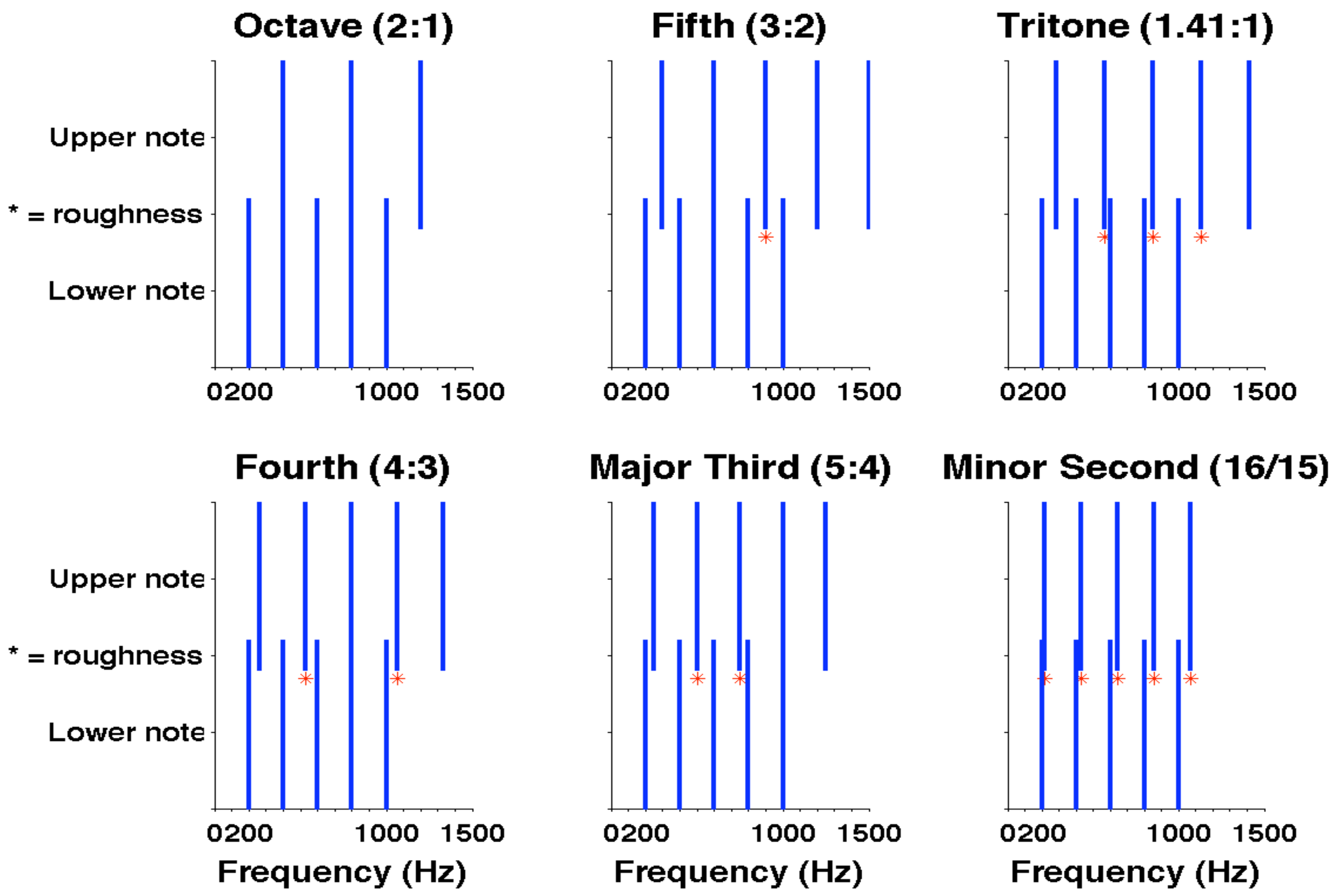


Figure by MIT OpenCourseWare.

Beating of harmonics



Spectral fusion

Image removed due to copyright restrictions. See Fig. 2.15 in Sethares, W. A. *Tuning, Tibre, Spectrum, Scale.* 1st ed. New York, NY: Springer, 1998. ISBN: 9783540761730.

Beating of harmonics and corresponding fluctutations in neural discharge rates

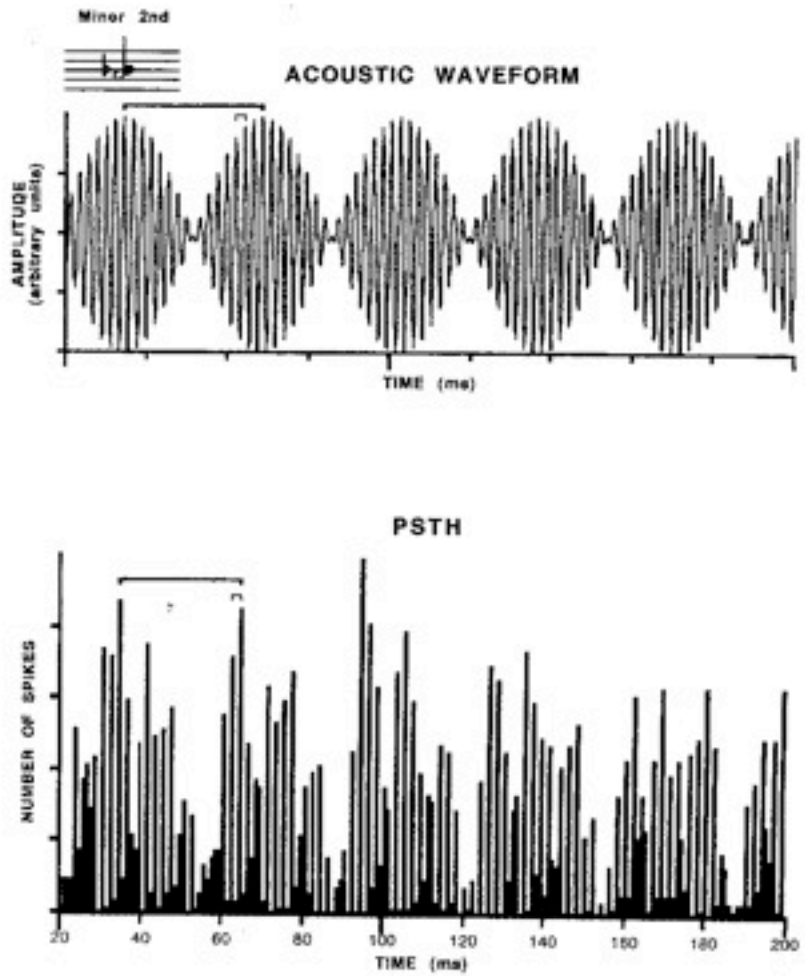


FIGURE 5. (*Top*) Acoustic waveform of a minor second composed of two pure tones with the root at A_4. *Thick bars* show the period of envelope fluctuations that render the minor second rough ($P = 1/\Delta F = 34.1$ ms). *Thin bars* show the period of fluctuations under the envelope that corresponds to the mean frequency of the tones and the pitch of the interval ($P = 2.20$ ms). (*Bottom*) Poststimulus time histogram (PSTH) showing the number of spikes fired by a single auditory nerve fiber during the steady state portion of its response to the minor second. Note that the global and local fluctuations in firing rate mirror those seen in the acoustic waveform of the minor second. This fiber was sensitive to frequencies at both the root and the interval at 60 dB SPL. Bin width = 1 ms. Number of stimulus repetitions = 100.

Neural coding of roughness

Discharge rate fluctuations in neuronal ensembles in the 20-120 Hz range encode beatings of nearby harmonics

These fluctuations exist in ensembles of auditory nerve fibers (CF band) and across the whole AN population (population PST)

They are seen at the level of the midbrain (IC) -- work by McKinney, Delgutte, & Tramo

Roughness as infra-pitch -- too slow for pitch mechanisms, too fast for resolving individual events (rhythm)

Not clear to me whether it is the rate fluctutations per se or existence of low periodicities below the pitch range (longer than the duration of the interval analysis window) that cause the roughness quality per se

Kameoka & Kuragawa, 1969a, Pure tone ratings
Japanese audio engineers, "sunda/nigotta" (clearness/turbidity)

Plomp & Levelt (1965) Dissonance of pure tone dyads

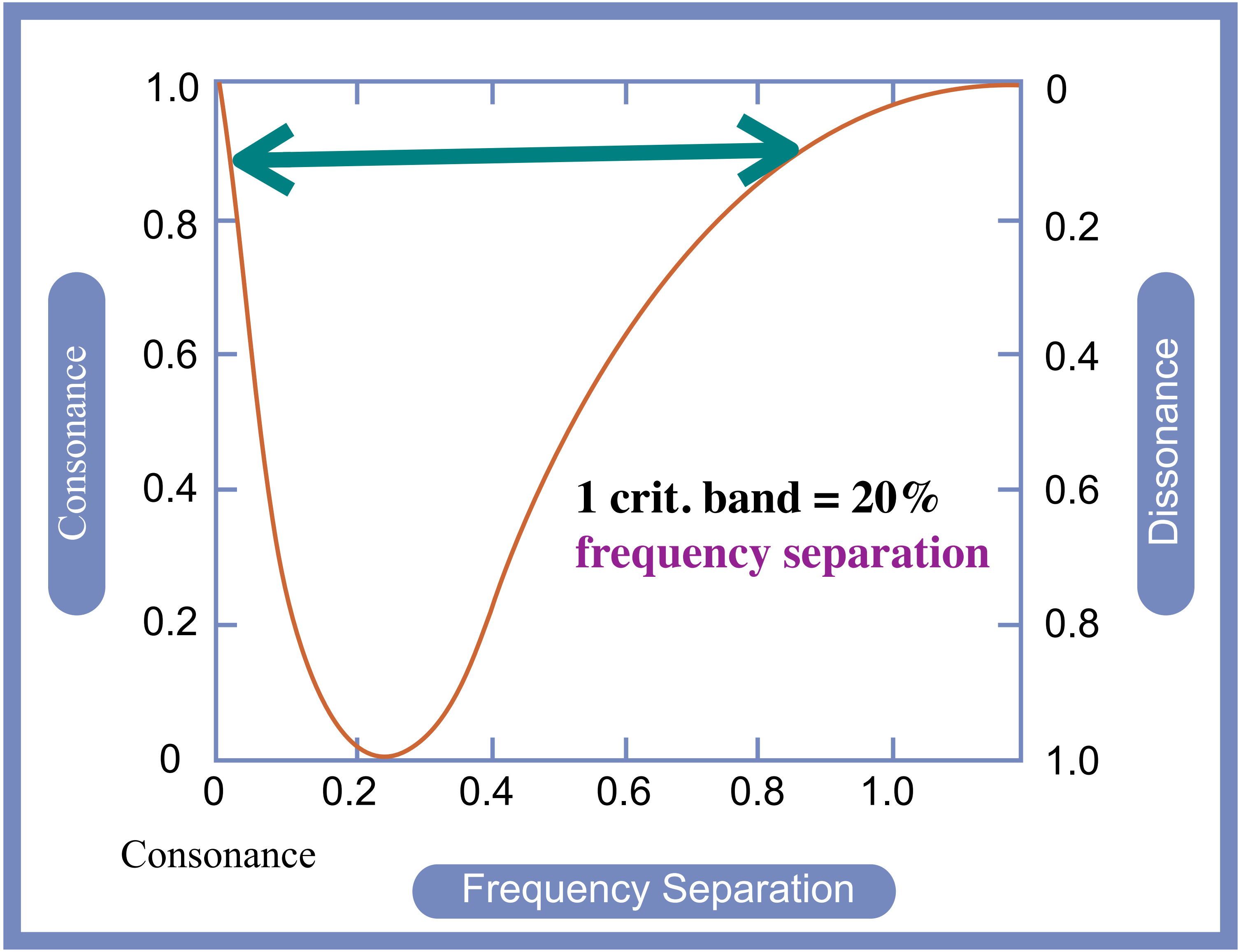


Figure by MIT OpenCourseWare.

Harmonics completely fuse if Δf < 2%
Harmonics beat and cause roughness if 2% < Δf < 20%

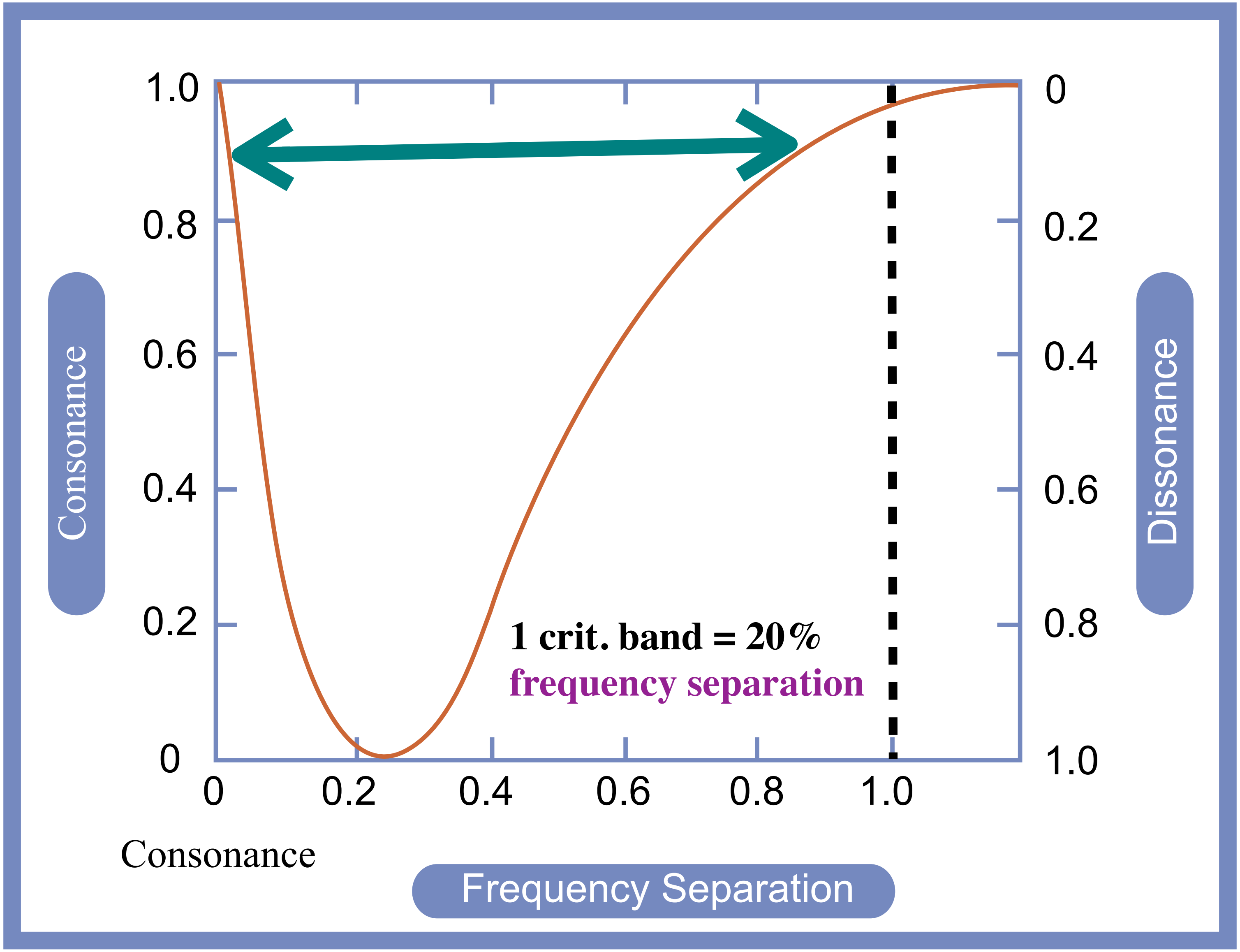


Figure by MIT OpenCourseWare.

Frequency discrimination is much finer than tonal fusion

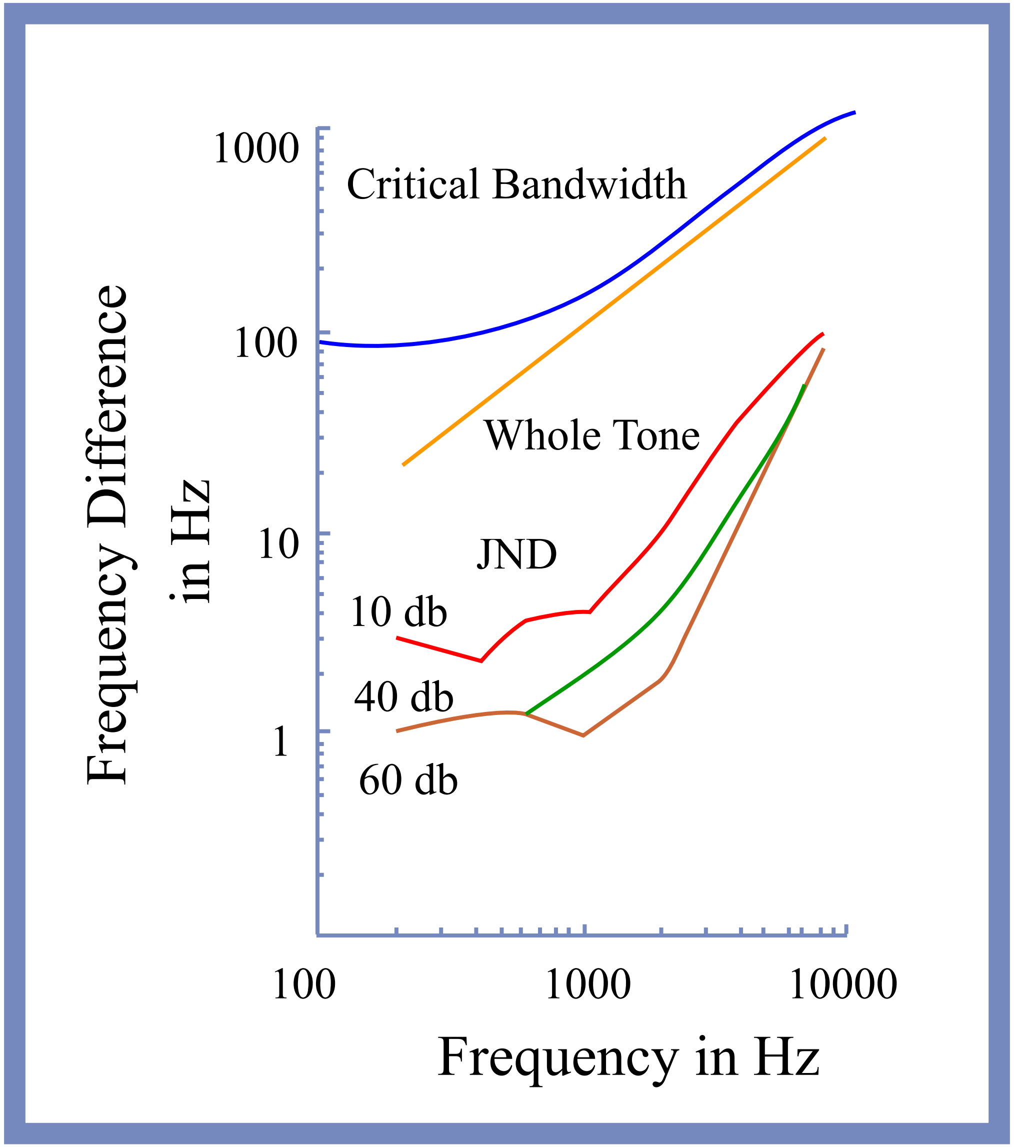
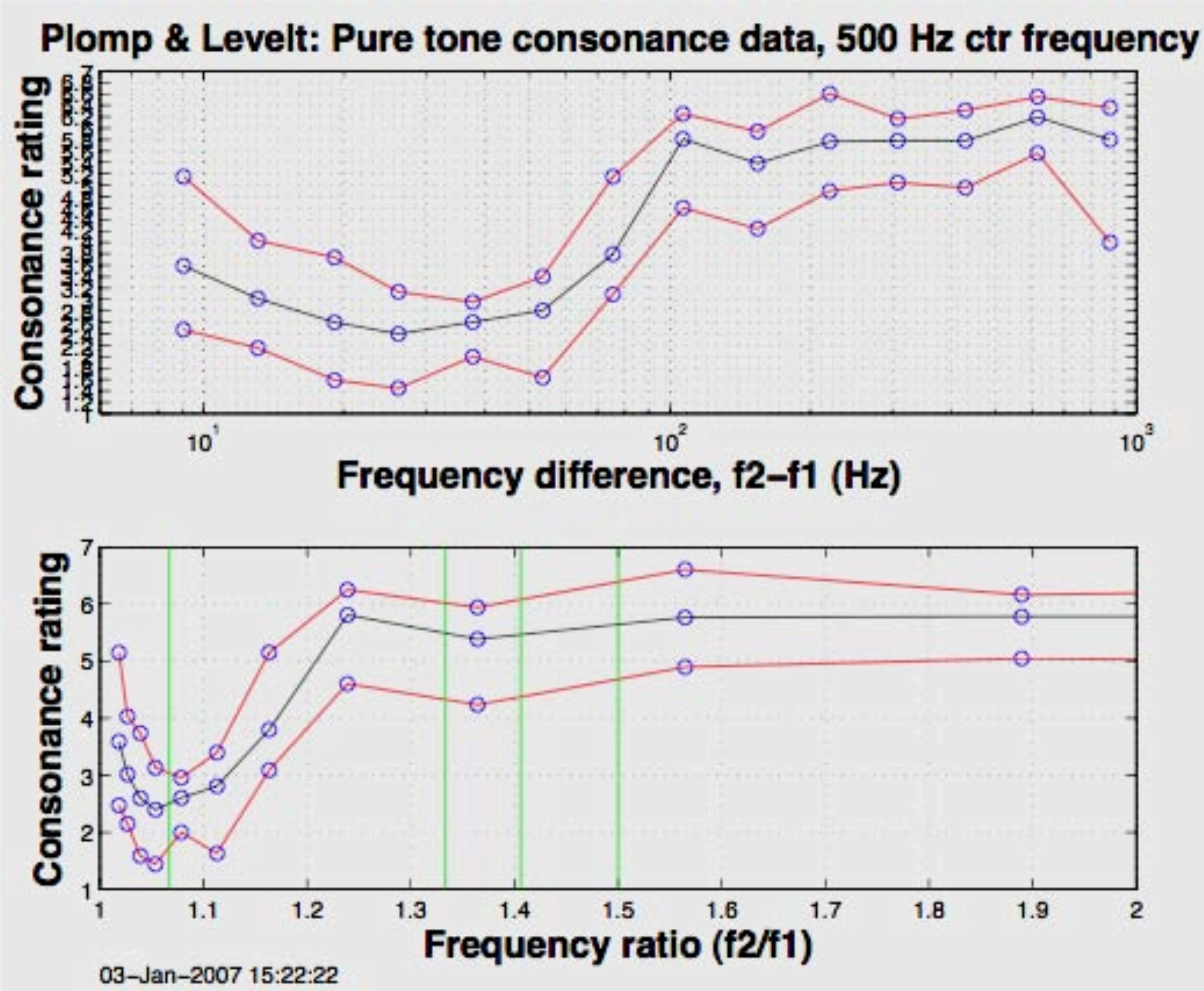
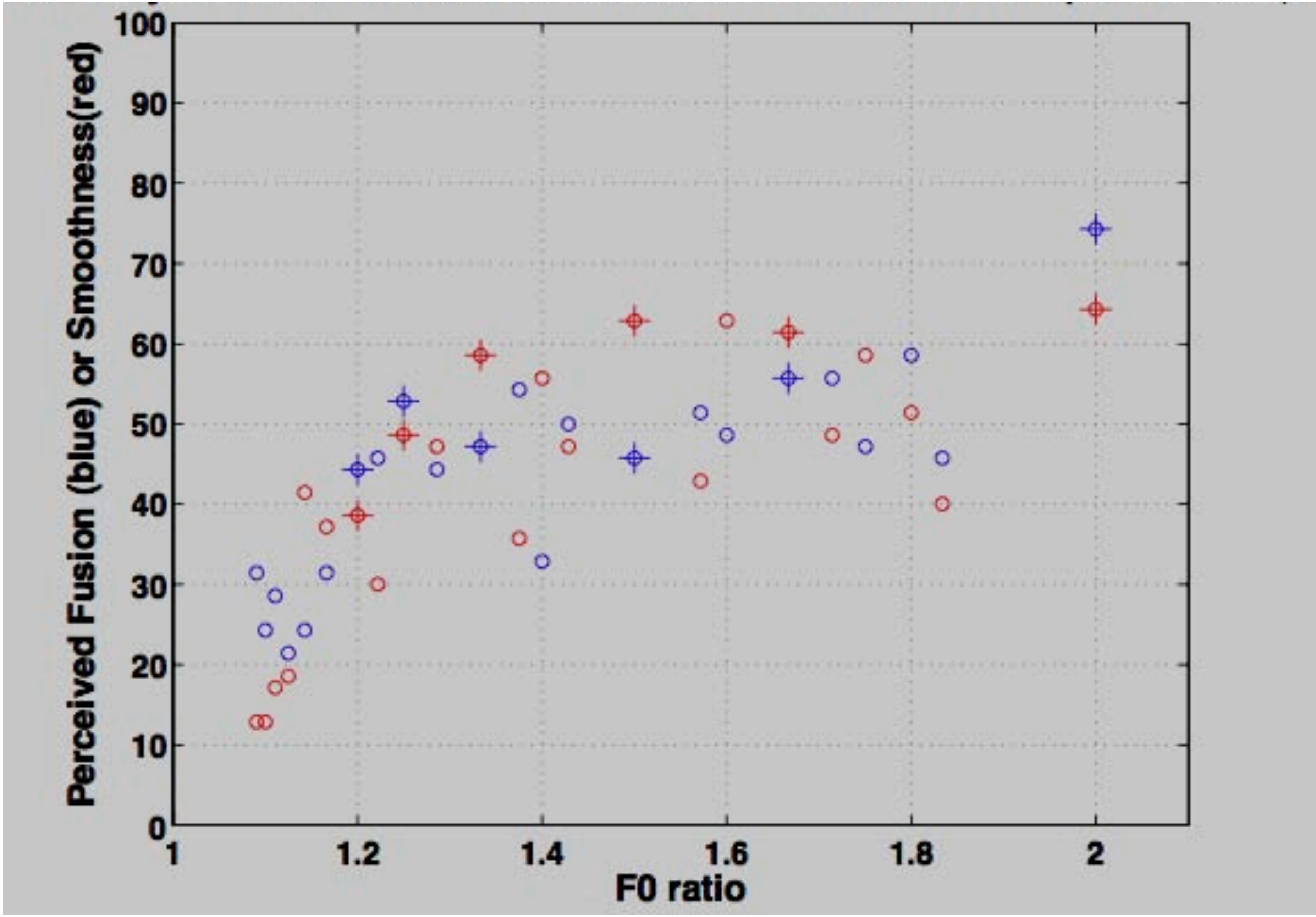


Figure by MIT OpenCourseWare.

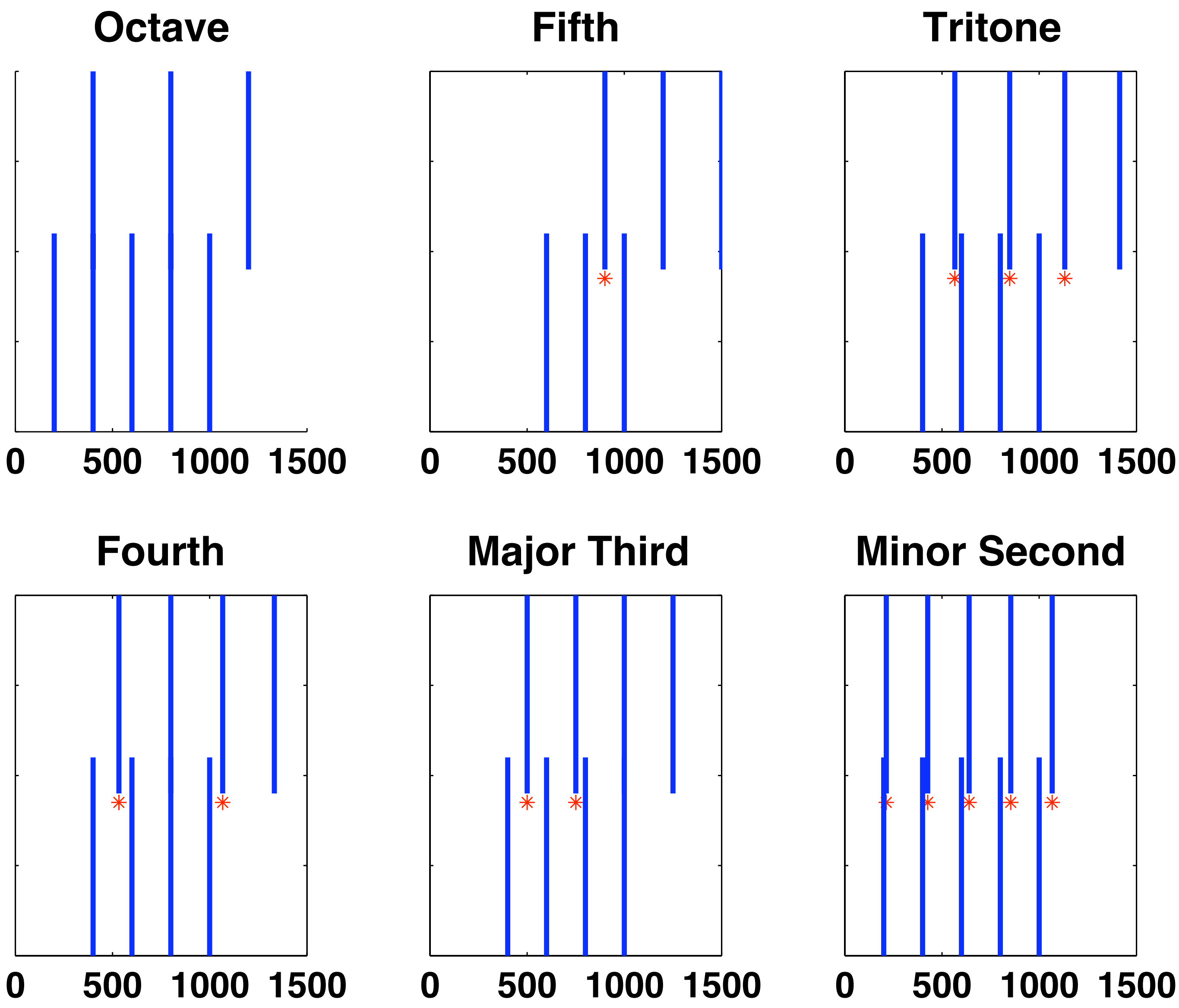
Plomp & Levelt (1965) Dissonance of pure tone dyads



Van de Geer et al (1962) Consonance of pure tone dyads



Beating of harmonics



Predicted consonance of harmonic complexes (n=1-6)

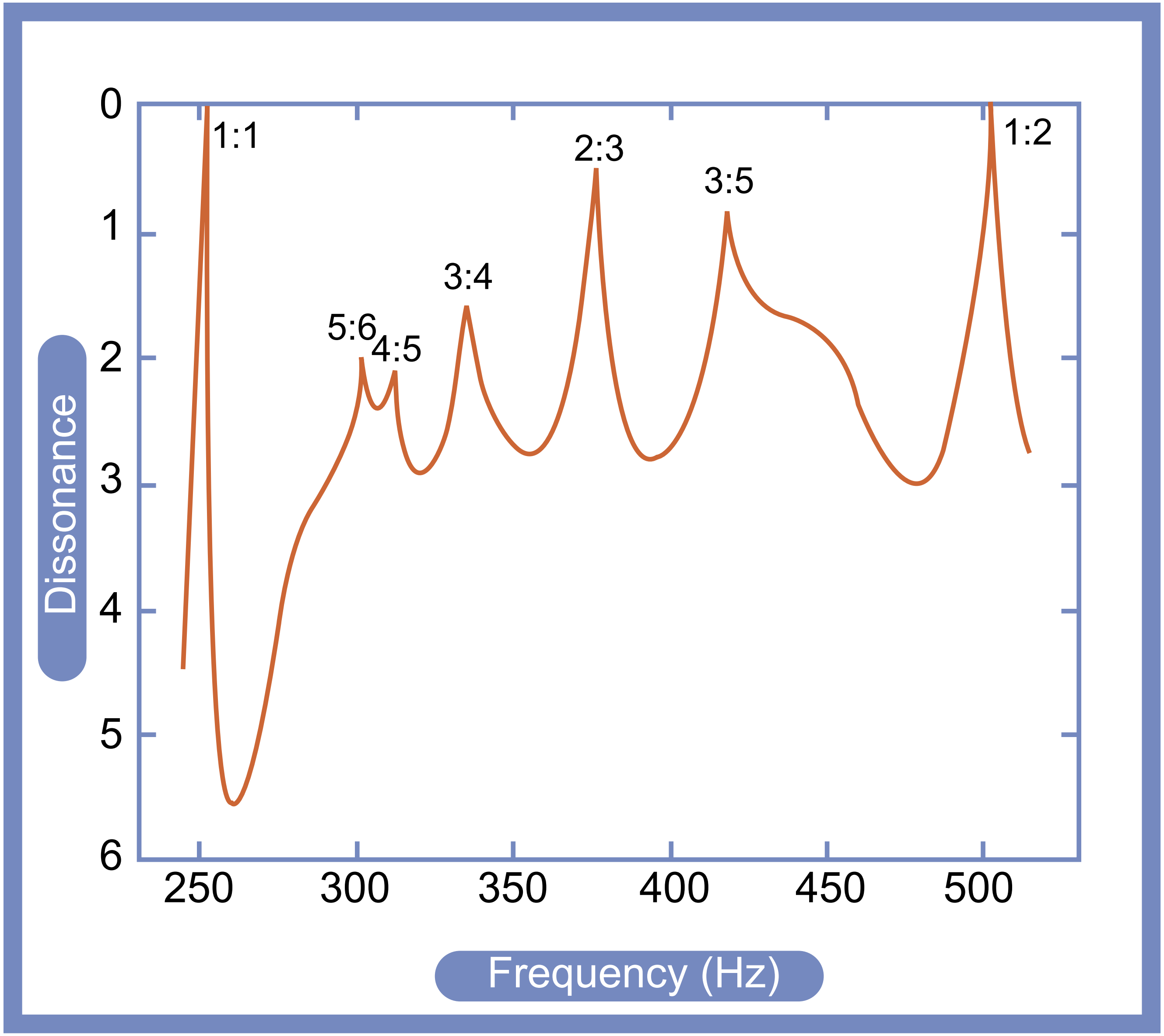


Figure by MIT OpenCourseWare.

Consonance perception: different conceptions

- Psychophysics of consonance
  - Meanings of "consonance" and "dissonance"
  - Euphonious, "pleasant" vs. jarring, unpleasant
  - Smooth, well-defined, unified vs. rough, buzzy, unsettled
  - see Sethares (1999), Ch. 4 for more depth

  - Tenney (1988) book, History of 'Consonance' and 'Dissonance'
    - melodic: relatedness of pitches sounded successively
    - polyphonic: interval between two simultaneous tones
      - pleasant vs unpleasant combinations; fusion of tones
    - contrapuntal: from music theory voice leading techniques(4th diss)
    - functional: relationship of individual tones to root or tonic
    - sensory: roughness and presence of beats

Roughness isn't all there is to consonance.....

Part of the difficulty of obtaining consonance judgements is the meaning of 'consonance' for listeners.

Van de Geer, Levelt & Plomp (1962) used the same stimulus set of pure tone dyads but asked subjects to rate the stimuli according to 10 criteria.

Van de Geer, Levelt & Plomp (1962) carried out an important study where they asked Dutch listeners to judge tone pairs according to ten different scales:

from David Huron's website

English	Dutch
high-low	(hoog-laag)
sharp-round	(scherp-rond)
beautiful-ugly	(mooi-lelijk)
active-passive	(actief-passief)
consonance-dissonant	(consonant-dissonant)
euphonious-diseuphonious	(welluidend-onweeluidend)
wide-narrow	(wijd-nauw)
sounds like one tone-sounds like more tones	(klinkt als een toon-klinkt als meer tonen)
tense-quiet	(gespanen-rustig)
rough-smooth	(ruw-glad)

Roughness isn't all there is to consonance.....

Non-musician listeners judged each harmonic interval using a 7-point scale for each semantic term. Using factor analysis, van de Geer, Levelt and Plomp found that the responses grouped into three independent factors. The analysis produced three statistically significant factors. One factor (dubbed pitch) included the scales high, sharp, tense, narrow, and active. A second factor (dubbed pleasantness) included the scales euphonious, consonant, and beautiful. A third factor (dubbed fusion) included the scales rough, more tones and fusion.

The first factor (pitch) was found to correlate directly with the mean frequency of the pitches used in the interval.

Vand de Geer et al (1962) conclusions (D. Huron)

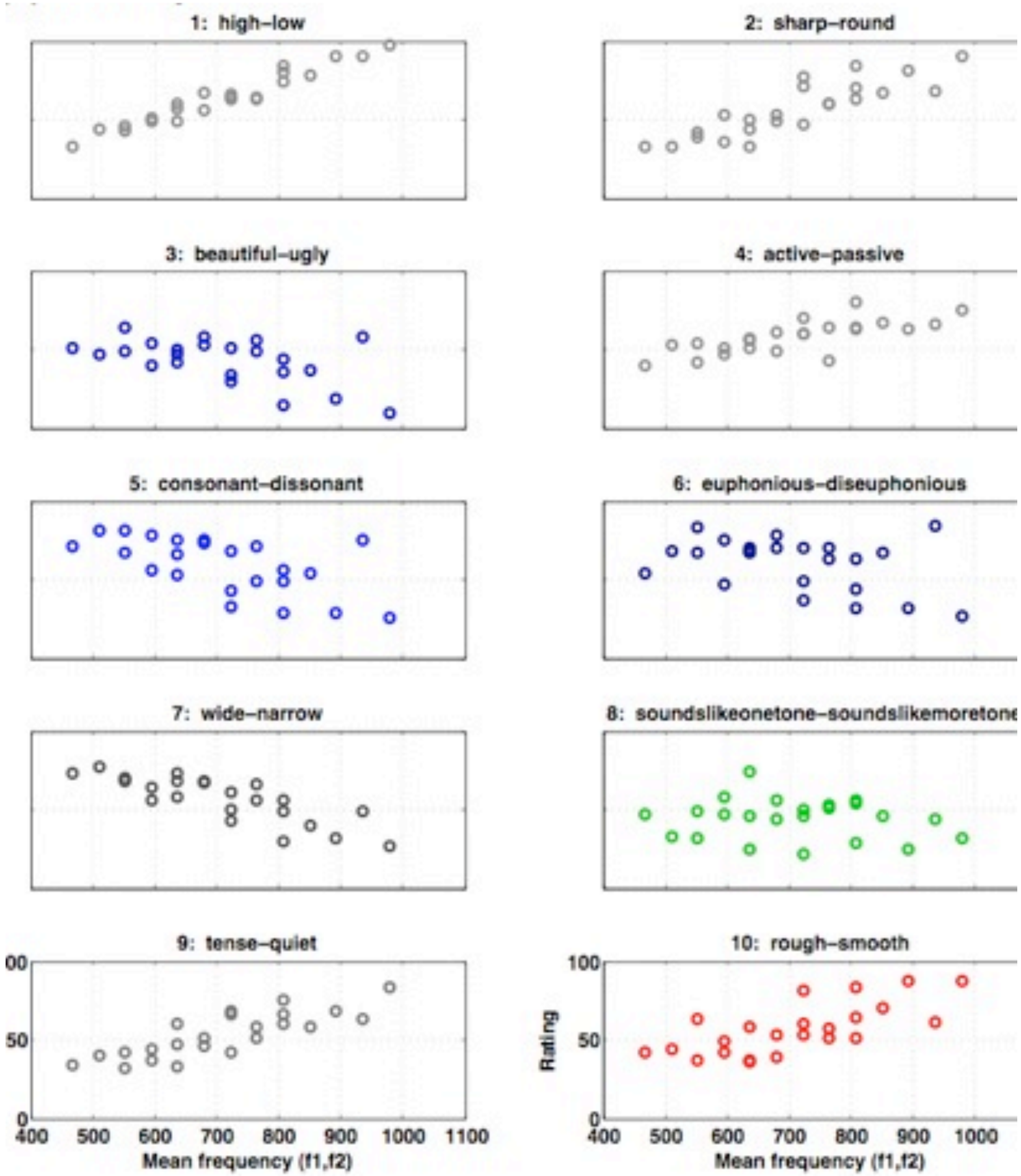
Van de Geer et al made the following 3 conclusions:

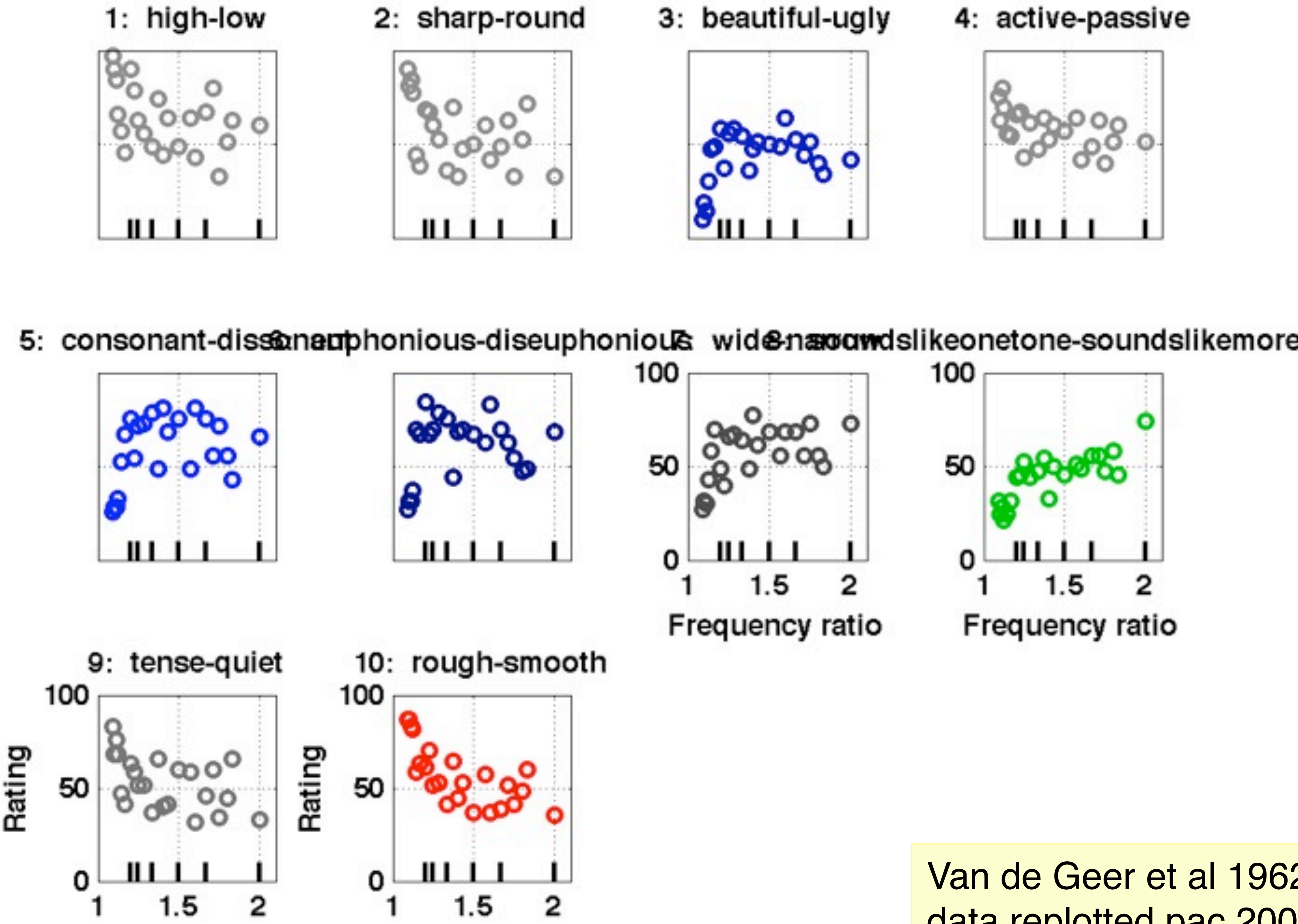
1. Musical intervals are judged using three basic dimensions: pitch height, pleasantness, and fusion.
2. Musicians and non-musicians use the term "consonant" differently. Musicians typically consider unisons, octaves, fifths and fourths as the most consonant, whereas non-musicians typically experience thirds and sixths as being more consonant.
3. Non-musicians conceive of "consonance" primarily in terms of pleasantness.

No straightforward relationship between consonance & fusion. **[for Pure tone stimuli! -- pac]**

The main lesson is that care must be taken when instructing listeners to judge intervals. Some terms are largely synonymous (such as euphonious and pleasant), whereas other terms are not interchangeable (such as pleasant and fused).

van de Geer et al





Van de Geer et al 1962
data replotted pac 2007

Consonance perception: theories

Cultural conditioning

Small Is beautiful, simple

- small integer ratios (1:1, 2:1, 3:2, 4:3, 5:4)
- simpler, smoother waveforms
- less complex interspike interval patterns

Roughness: interactions of nearby tones in filters
(Helmholtz, cochlear & neural filtering)

Fusion of tones

- consonance related to number of competing pitches, unity of perception (Stumpf)

Dual theories: Terhardt, Helmholtz: sensory (peripheral beating) & cognitive (expectations, context); sensory vs. musical consonance

Roughness isn't all there is to consonance.....

Roughness (Helmholtz)

Pitch fusion/tonal fusion (Stumpf)

Number of voices ("chorus effect", Huron)*

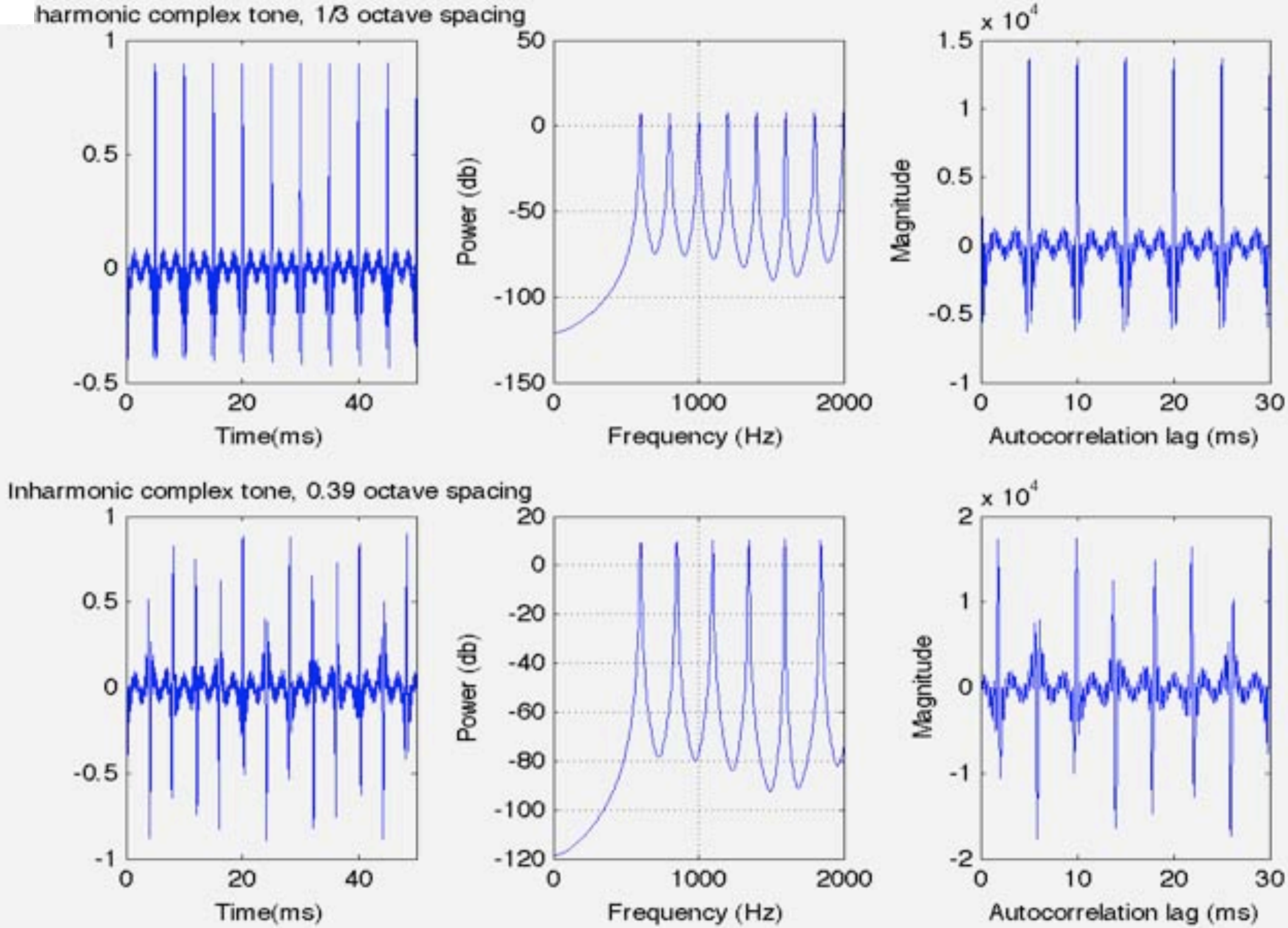
Shrillness (high frequency partials, Huron)

Presence of noise (conjecture)

http://www.harmony-central.com/Effects/Articles/Chorus/

Roughness isn't all there is to consonance.....

Harmonic complex w. upper harmonics

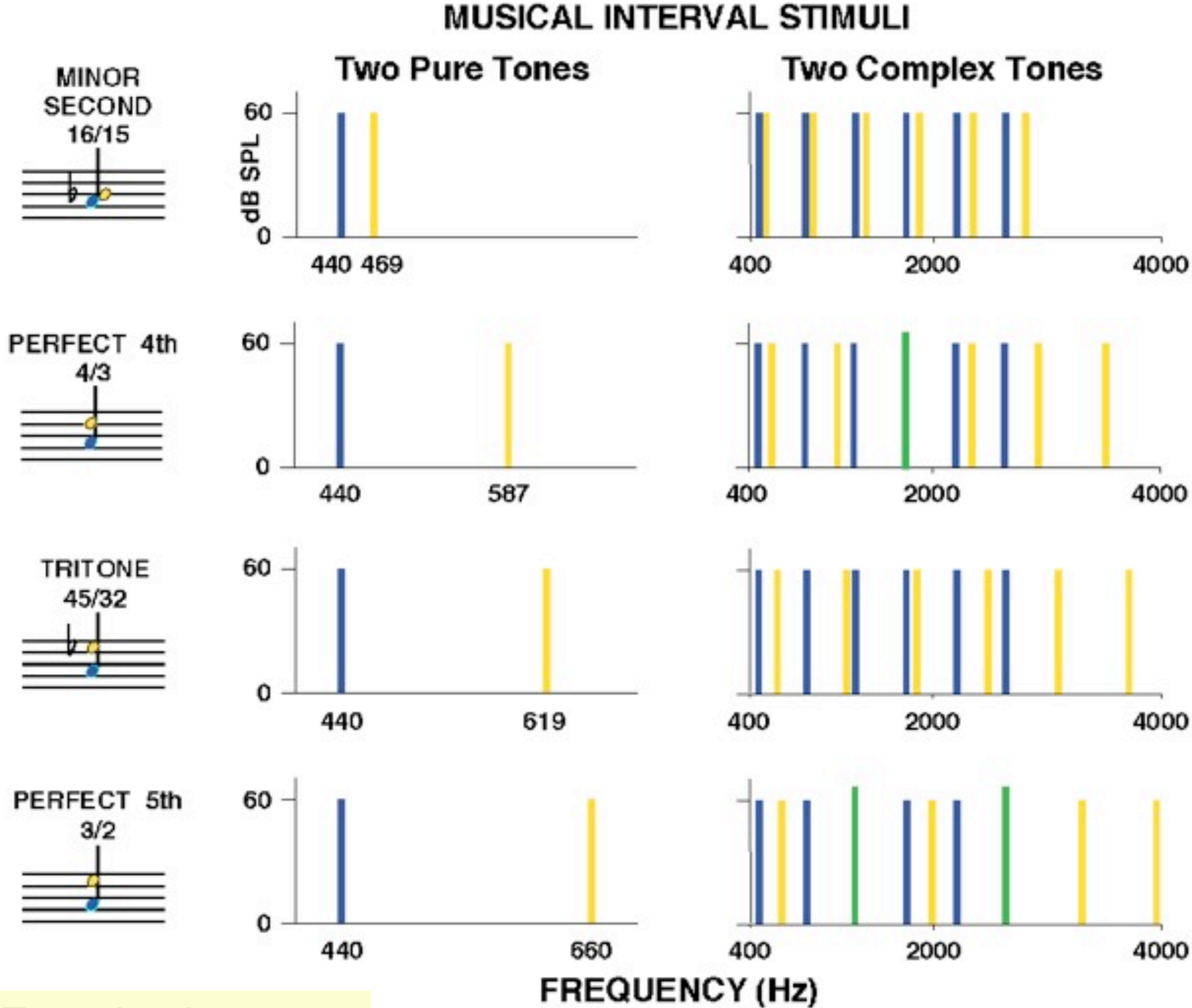


Neural basis of consonance

In the 1990's we (Mark Tramo, Peter Cariani, and Bertrand Delgutte did an extensive neuro-physiological study of the neural basis of consonance in the cat auditory nerve.

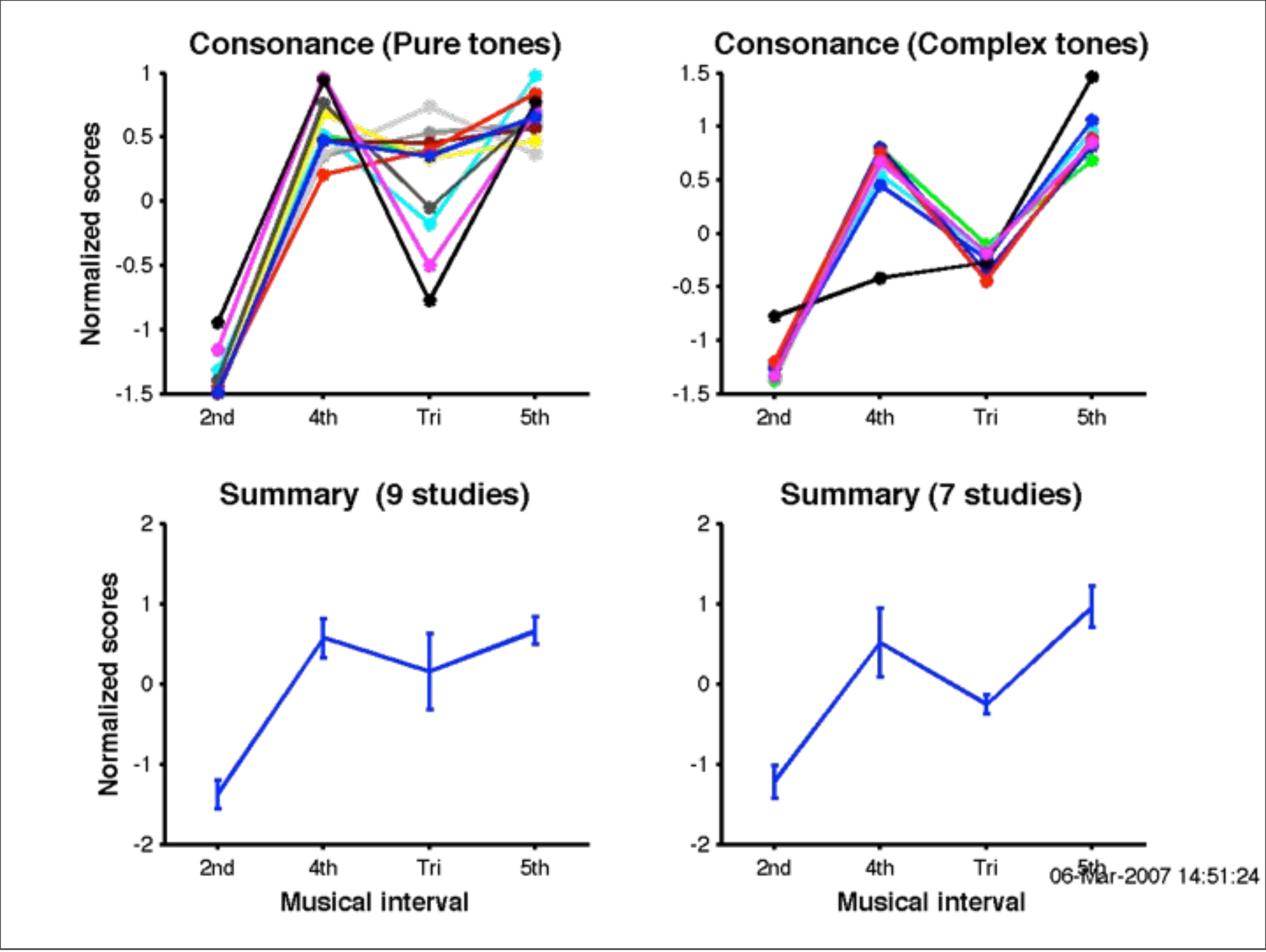
We found neural correlates both
for roughness and pitch fusion.

These neural correlates both match up with human listener judgments quite well.



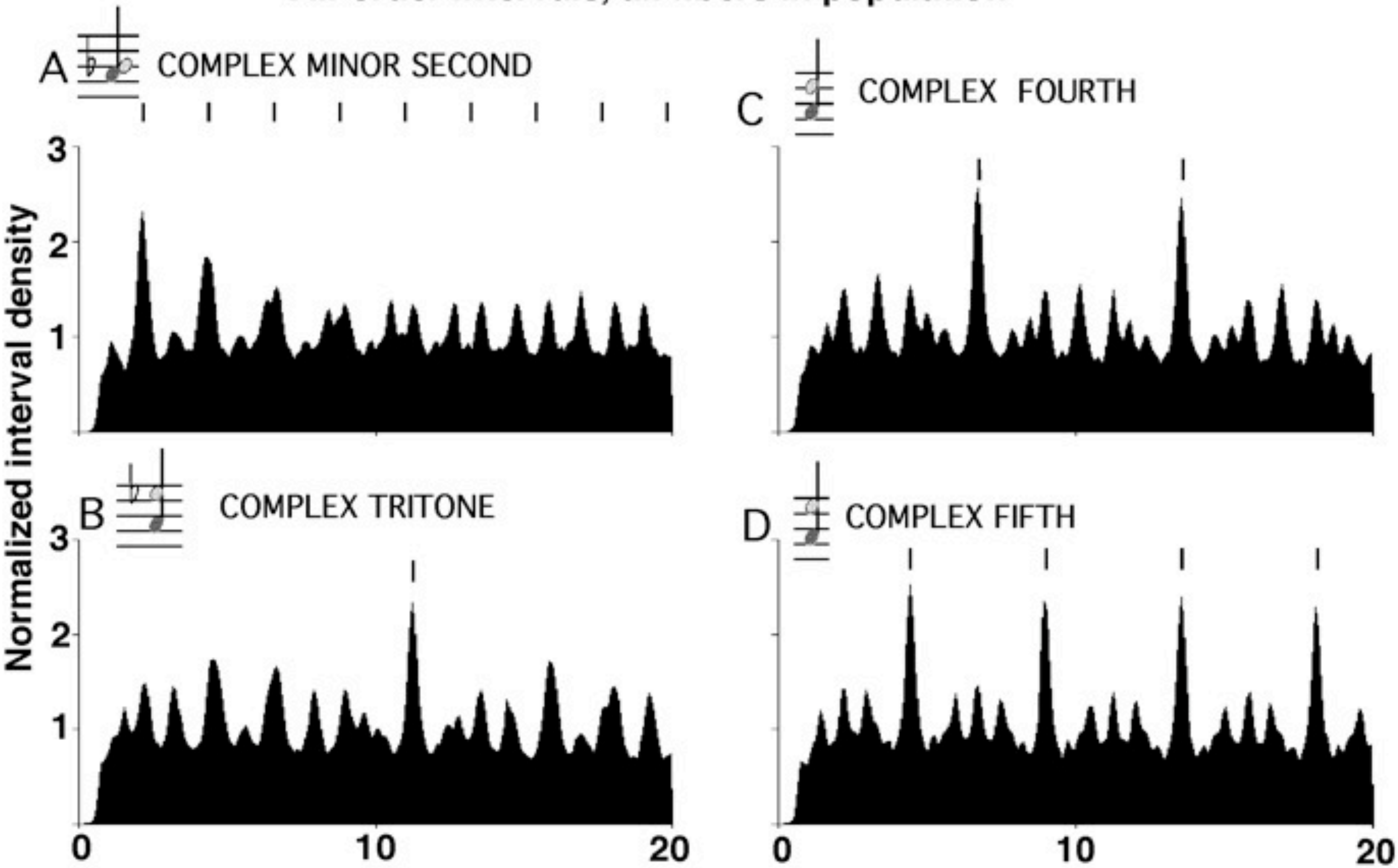
Mark Tramo's stimulus set

Courtesy of Prof. Mark J. Tramo, M.D., Ph.D. Used with permission.


Consonance (Pure tones)
Consonance (Complex tones)
Summary (9 studies)
Summary (7 studies)
Normalized scores
2nd
4th
Tri
5th
Musical interval
06-Mar-2007 14:51:24

Interspike interval distributions

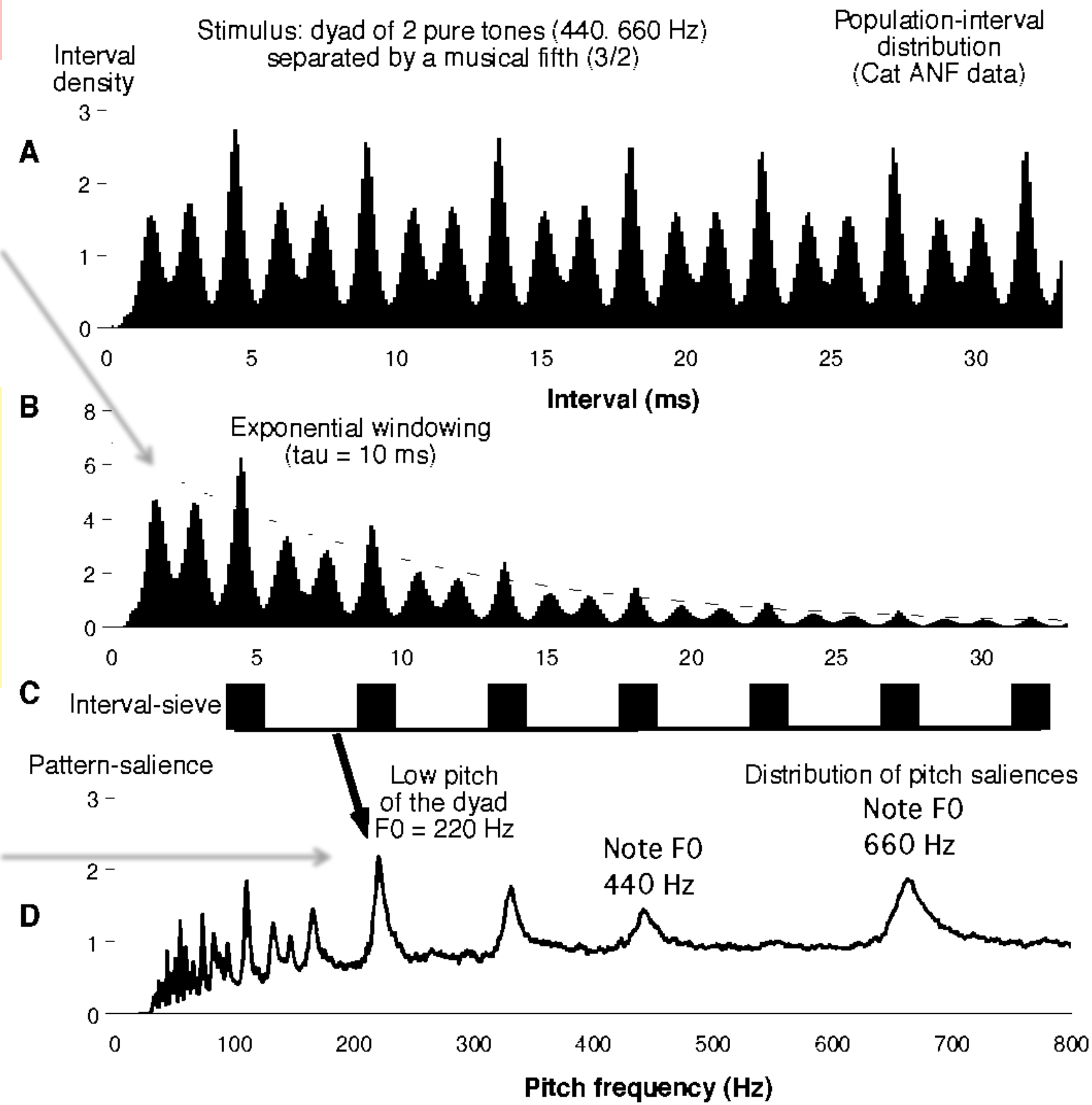
All-order intervals, all fibers in population



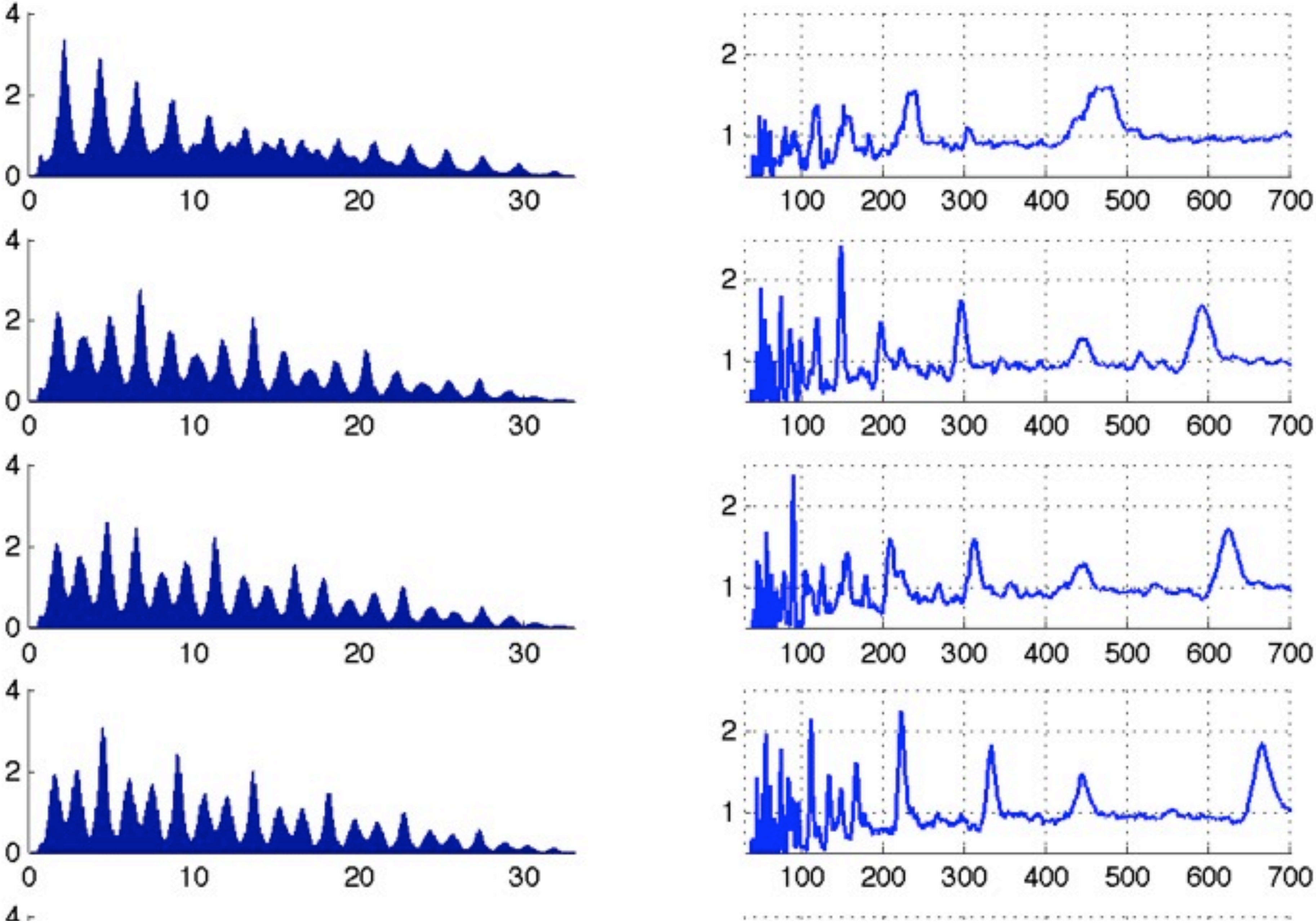
Step 2
B. Apply tapering interval window of ~30 ms to the Pop-interval distribution account for limited frequency resolution and lower limit of musical pitch

Step 3
C. Estimate the relative numbers of intervals associated with each pitch periodicity (30-800 Hz) using a dense array of interval pattern sieves.

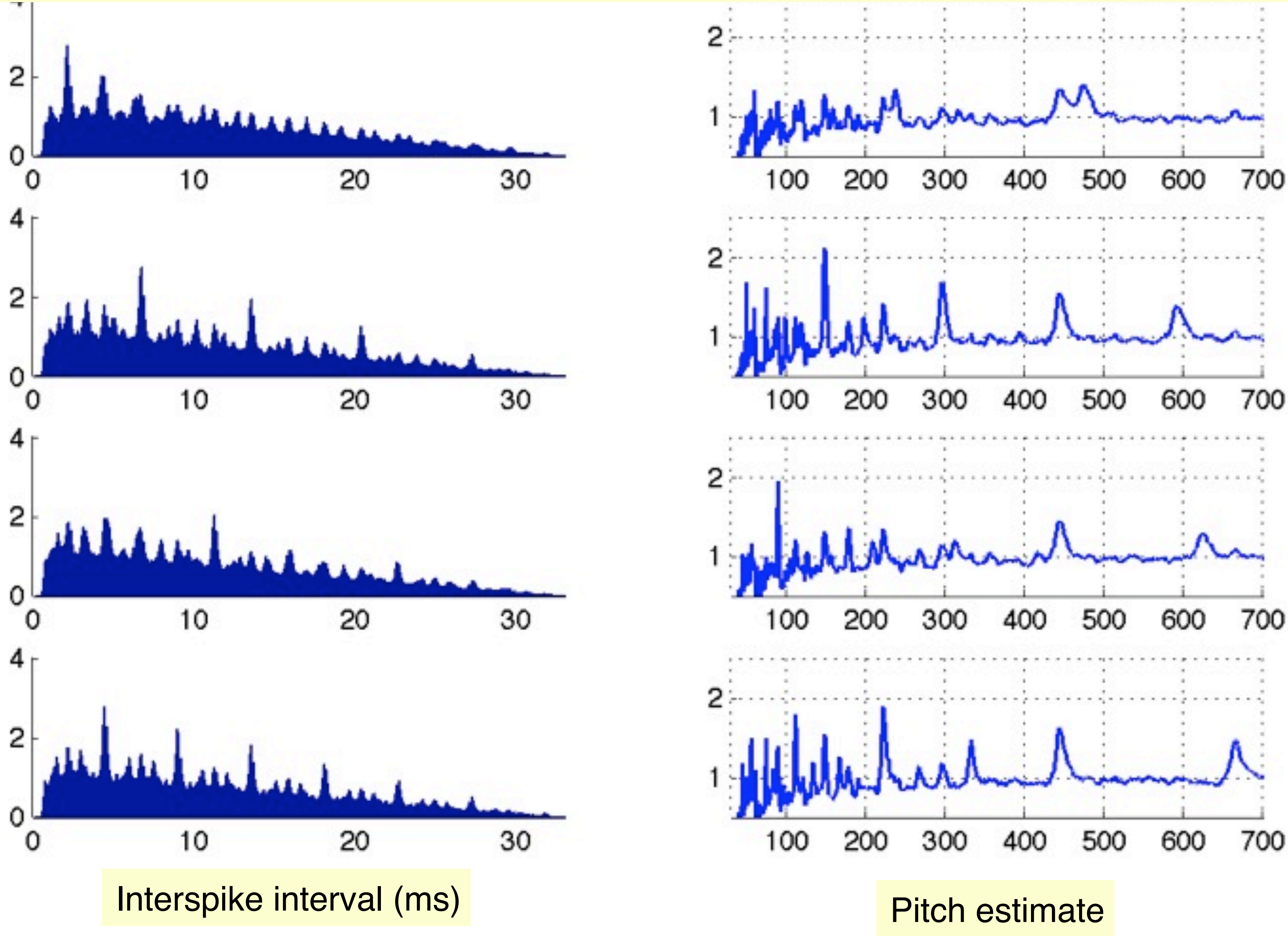
Step 4
D. Compute "pattern salience" = the ratio of pitch-related intervals/bin to mean # intervals/bin. Pitches with saliences > 1.3 should be audible. Max salience is taken as the index of pitch stability, consonance.

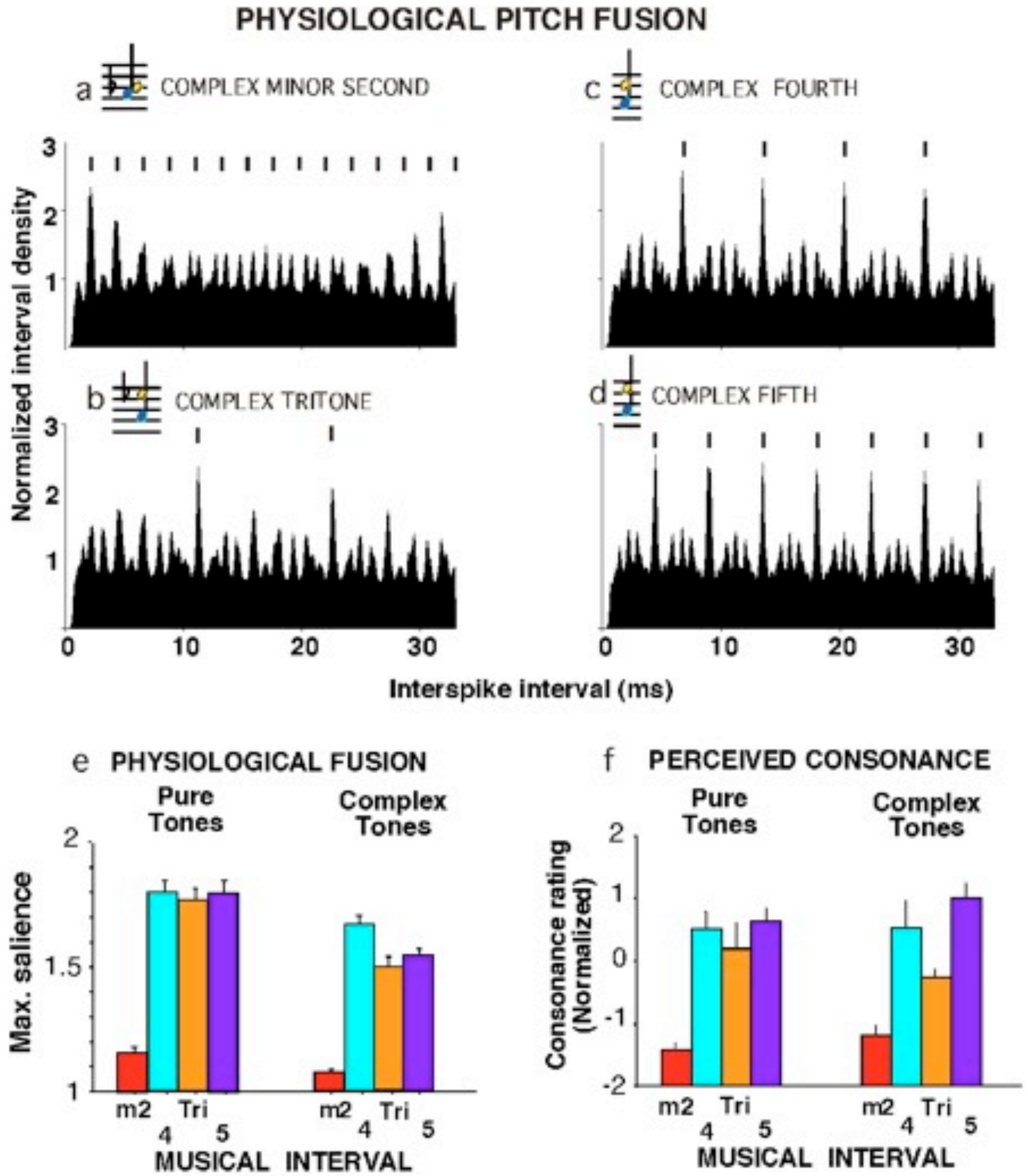


Pitch salience maps - pure tone dyads 440 Hz root (16/15, 4/3, 45/32, 3/2)



Pitch salience maps - complex tone dyads 440 Hz root n=1-6, (16/15, 4/3, 45/32, 3/2)



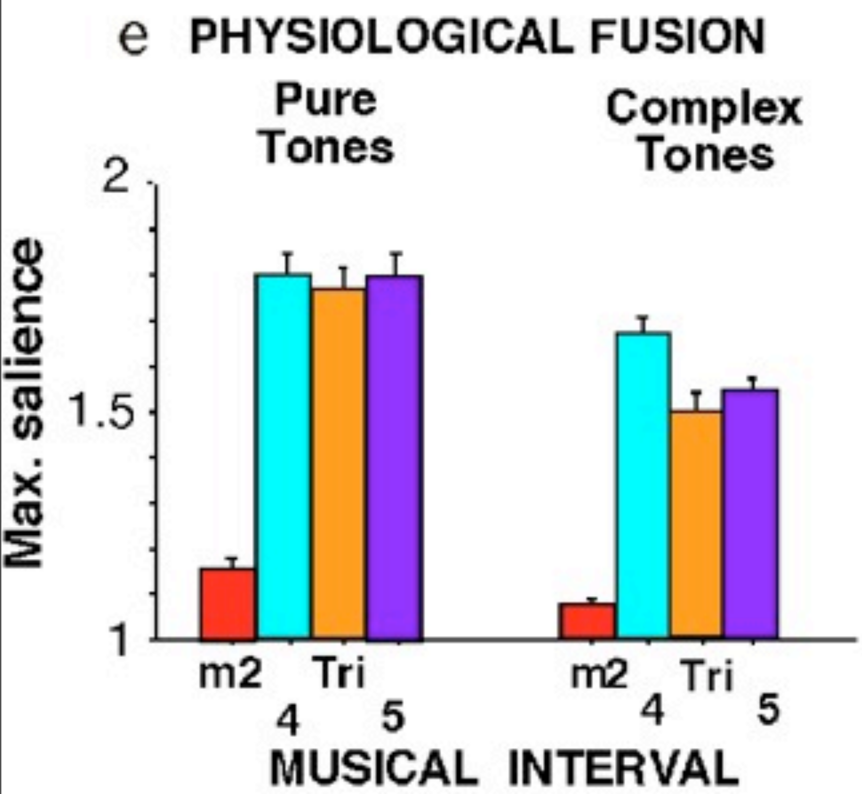


Friday, March 13, 2009

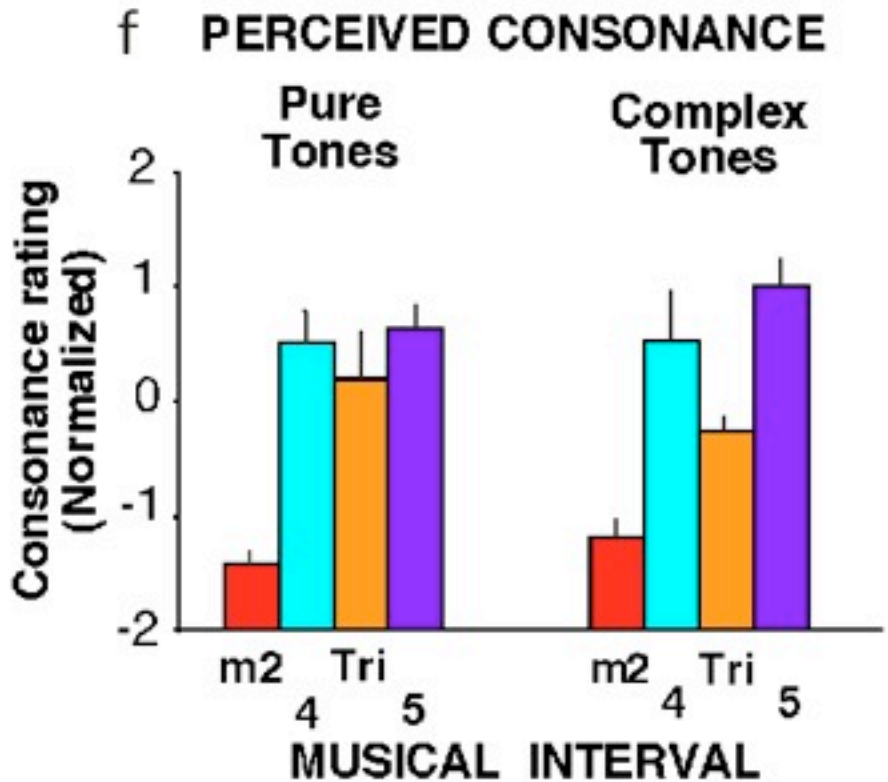
Estimated from interspike interval patterns in the auditory nerve

Measured via psychophysical tests

PITCH FUSION



CONSONANCE



Present results

Auditory nerve simulations enable putative neural representations and information-processing operations to be explored in more systematic fashion and compared with psychophysical data

I recently simulated the pure and complex tone consonance experiments of Kameoka & Kuragawa (1969) in order to test the robustness of consonance models based on population-interval representations and pitch salience estimates.

Auditory nerve model

Human middle ear

48 Gammatone filters

Parameters fit to replicate cat ANF responses (broader than "auditory filters")

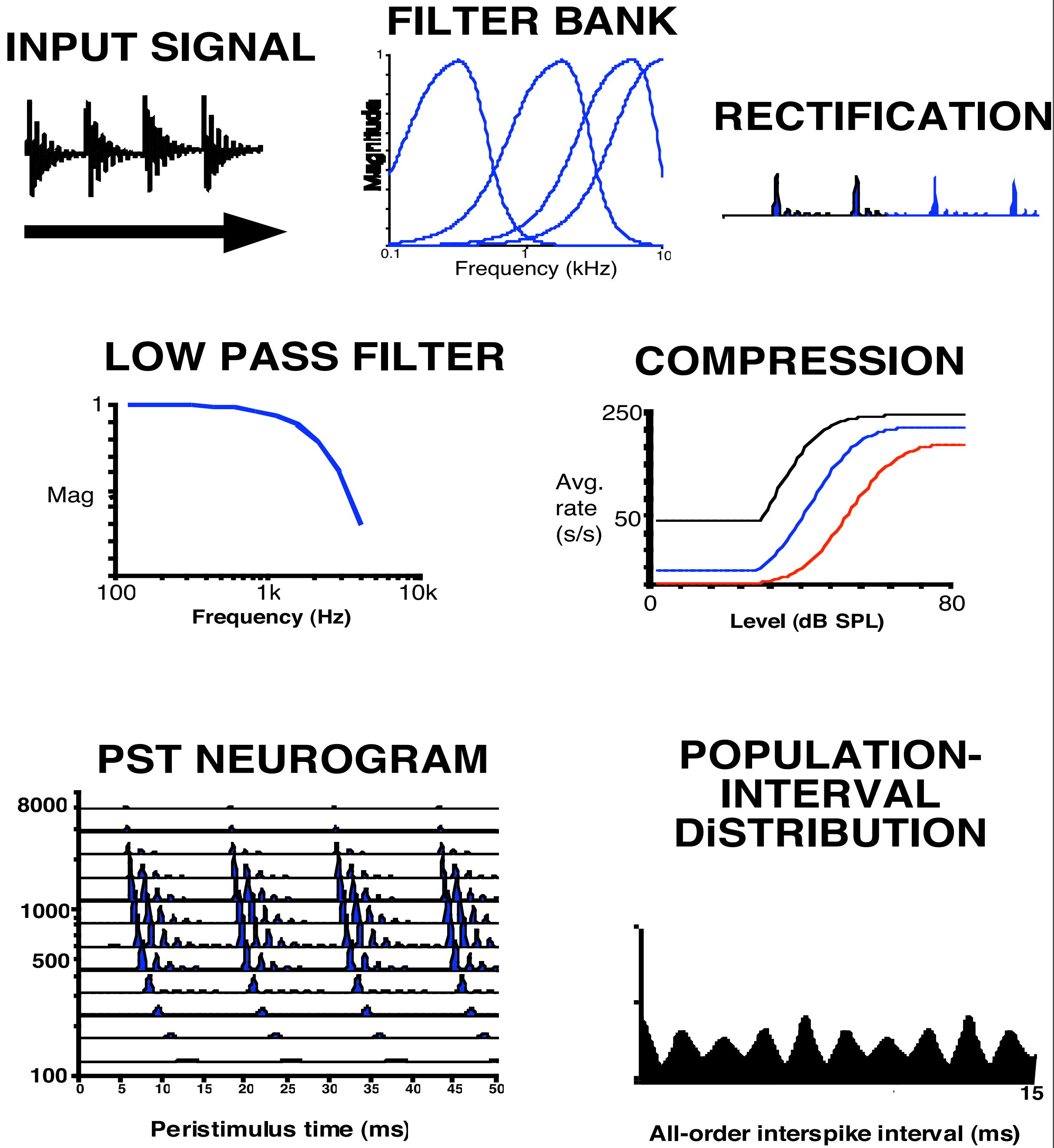
3 classes of fibers/CF

144 Simulated ANFs

Adaptive gain control

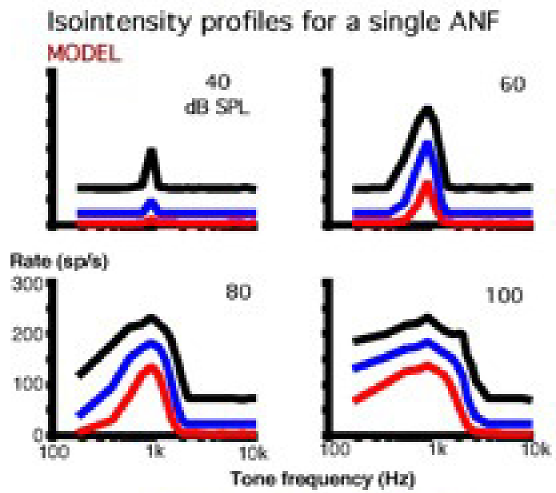
Geisler & Greenberg, 1986

Spontaneous activity
(Poisson)



Discharge rate as a function of frequency (constant SPL)

Image removed due to copyright restrictions.
Fig. 2 in Rose, J. E., et al. *J Neurophysiol* 30, no. 4 (1967): 769.



Temporal discharge patterns as a function of SPL

NEURAL DATA
(Rose et al, 1971)

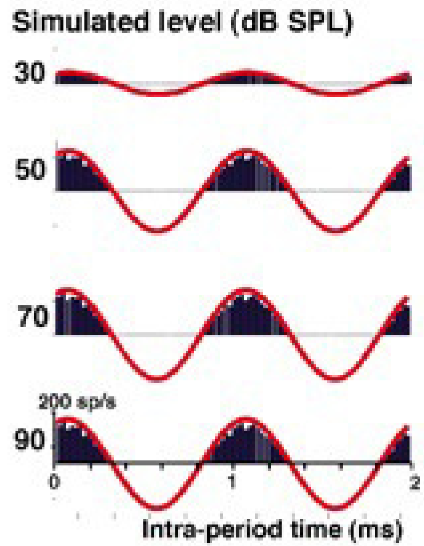
PERIOD HISTOGRAMS

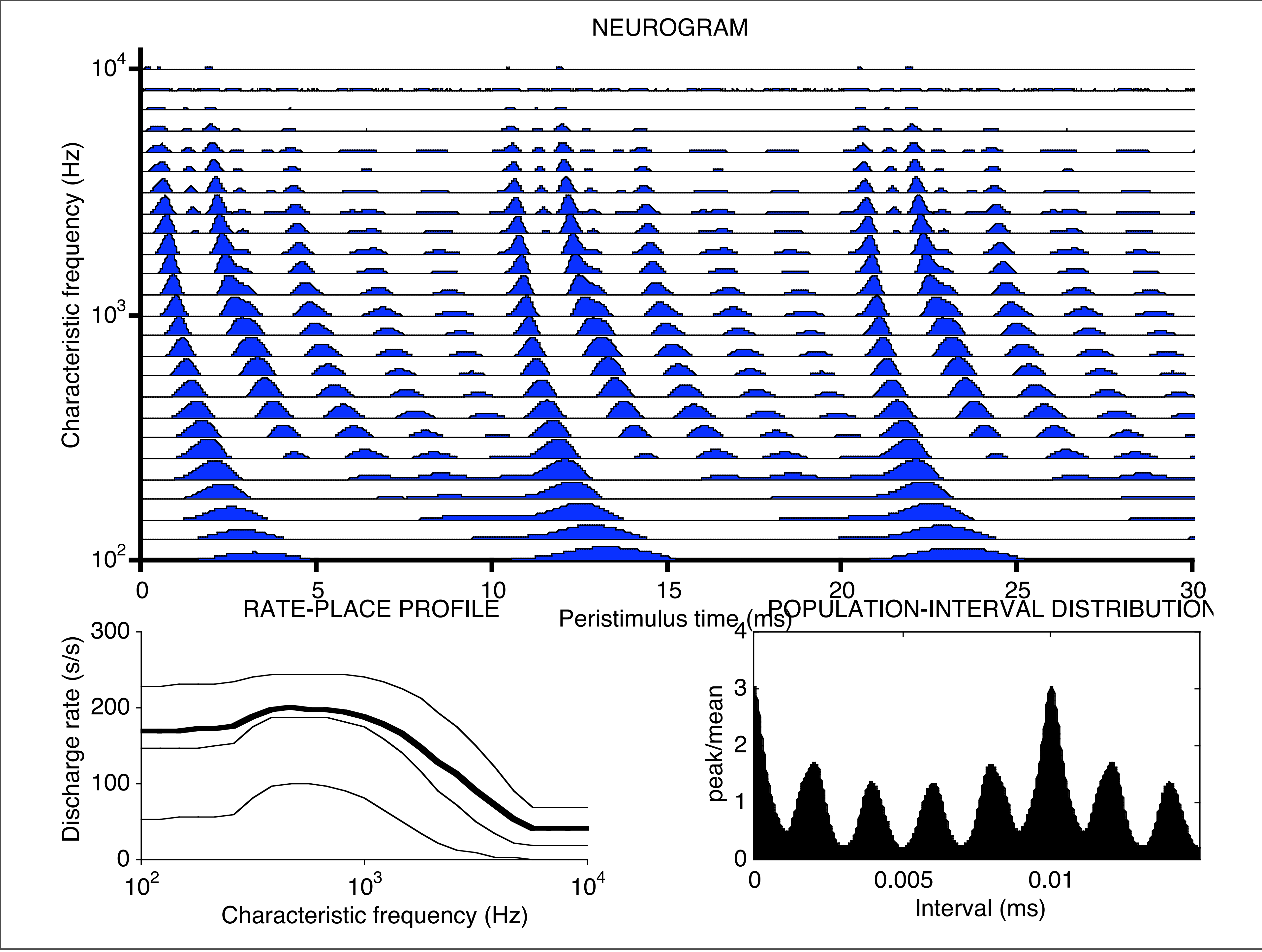
MODEL

Med SR ANF
CF = 1 kHz

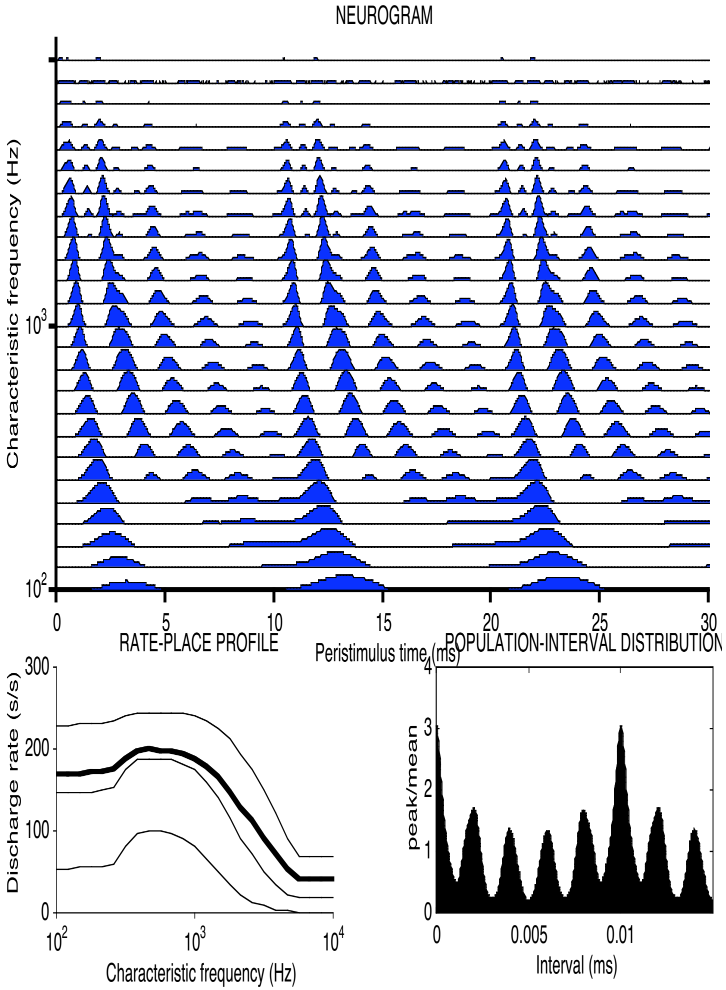
1 kHz pure tones

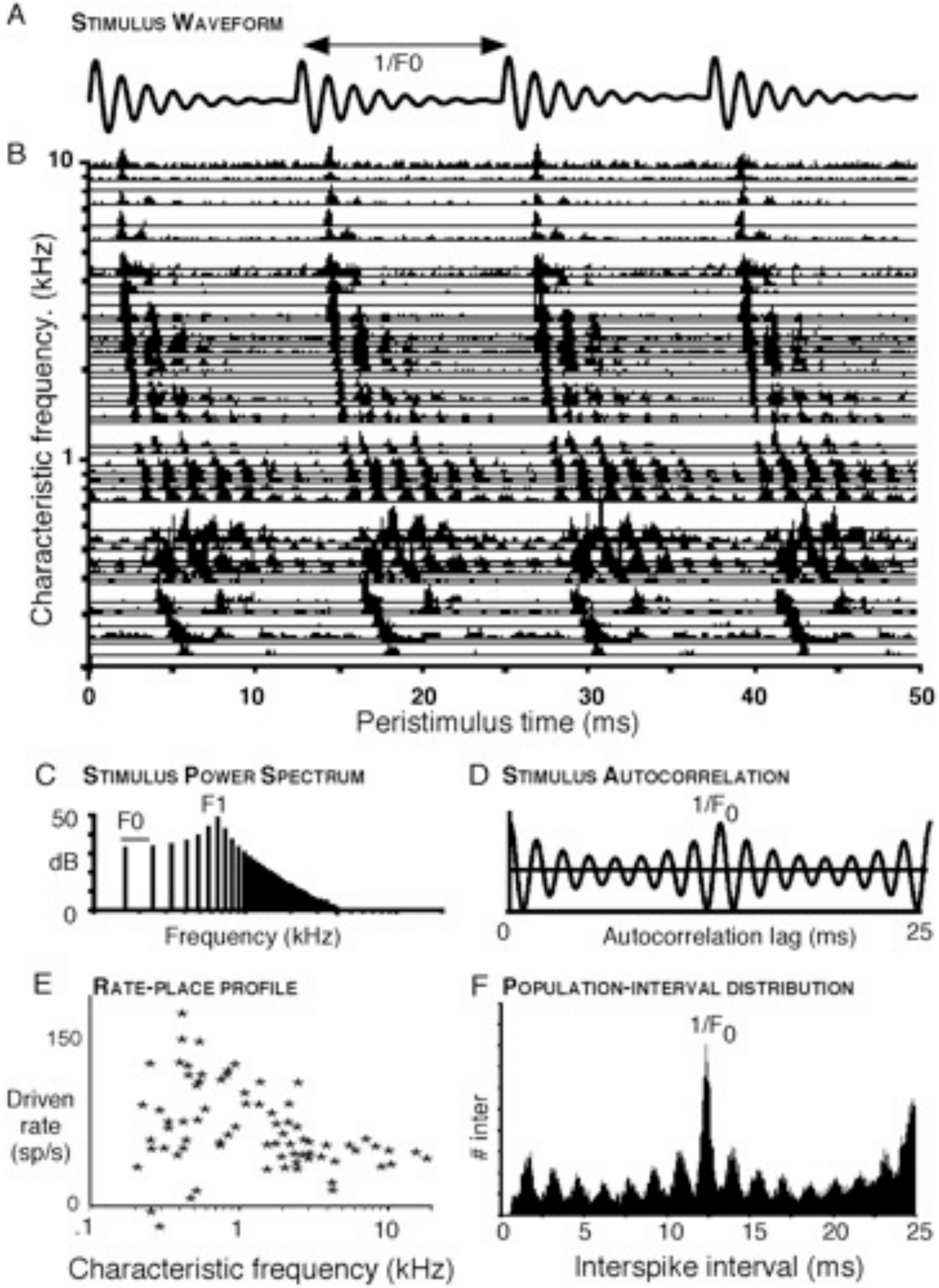
Image removed due to copyright restrictions.
Fig. 10 in in Rose, J. E., et al. *J Neurophysiol* 34, no. 4 (1971): 685–699.




NEUROGRAM
Characteristic frequency (Hz)
10^4
10^3
10^2
0
5
10
15
20
25
30
Peristimulus time (ms)
RATE-PLACE PROFILE
Discharge rate (s/s)
300
200
100
0
10^2
10^3
10^4
Characteristic frequency (Hz)
POPULATION-INTERVAL DISTRIBUTION
peak/mean
4
3
2
1
0
0
0.005
0.01
Interval (ms)

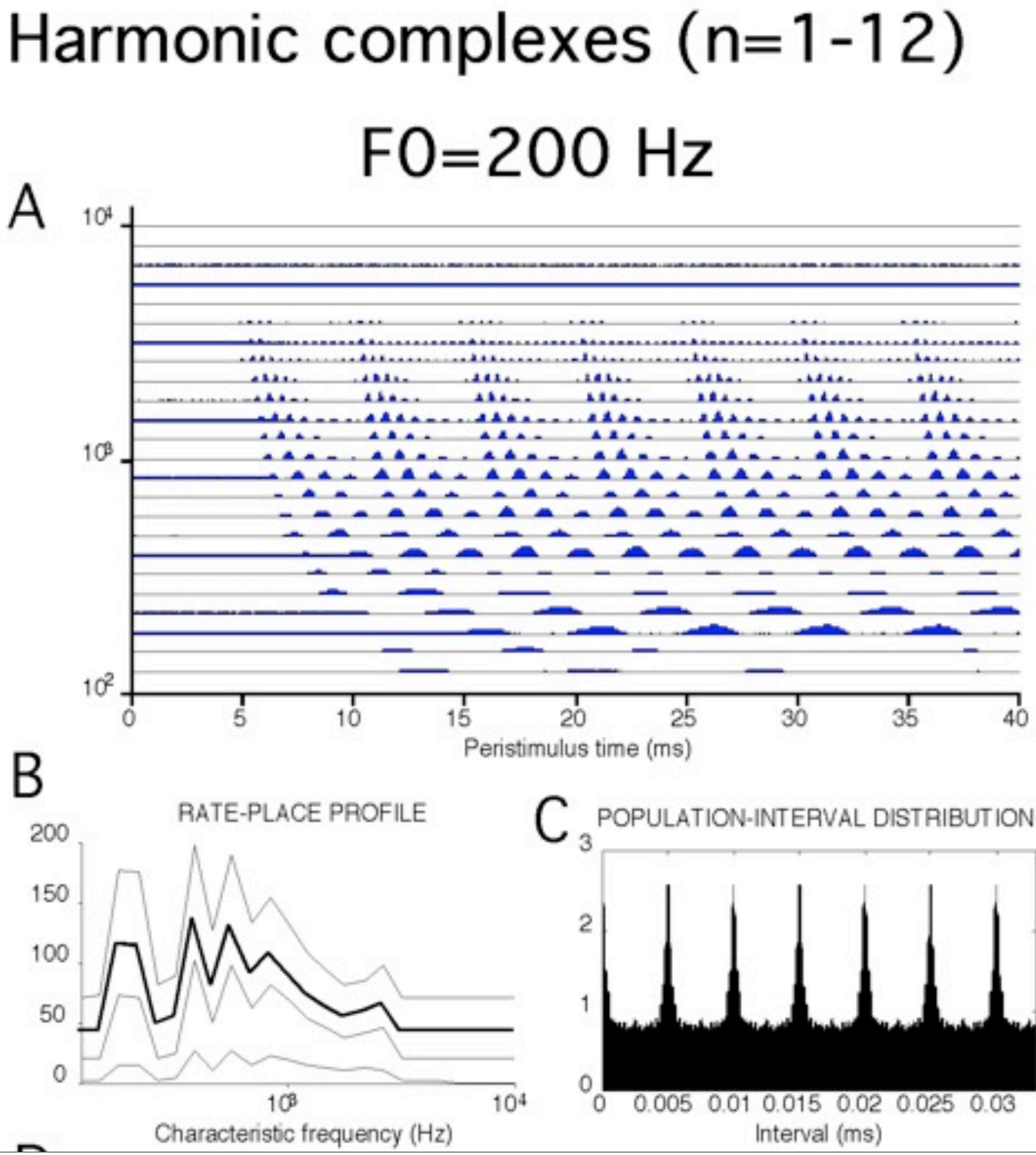
MODEL


NEUROGRAM
Characteristic frequency (Hz)
Peristimulus time (ms)
RATE-PLACE PROFILE
Discharge rate (s/s)
Characteristic frequency (Hz)
POPULATION-INTERVAL DISTRIBUTION
peak/mean
Interval (ms)


A Stimulus Waveform
1/F0
B
Characteristic frequency. (kHz)
Peristimulus time (ms)
C Stimulus Power Spectrum
F0
F1
dB
Frequency (kHz)
D Stimulus Autocorrelation
1/F0
Autocorrelation lag (ms)
E Rate-place profile
Driven rate (sp/s)
Characteristic frequency (kHz)
F Population-interval distribution
1/F0
inter
Interspike interval (ms)

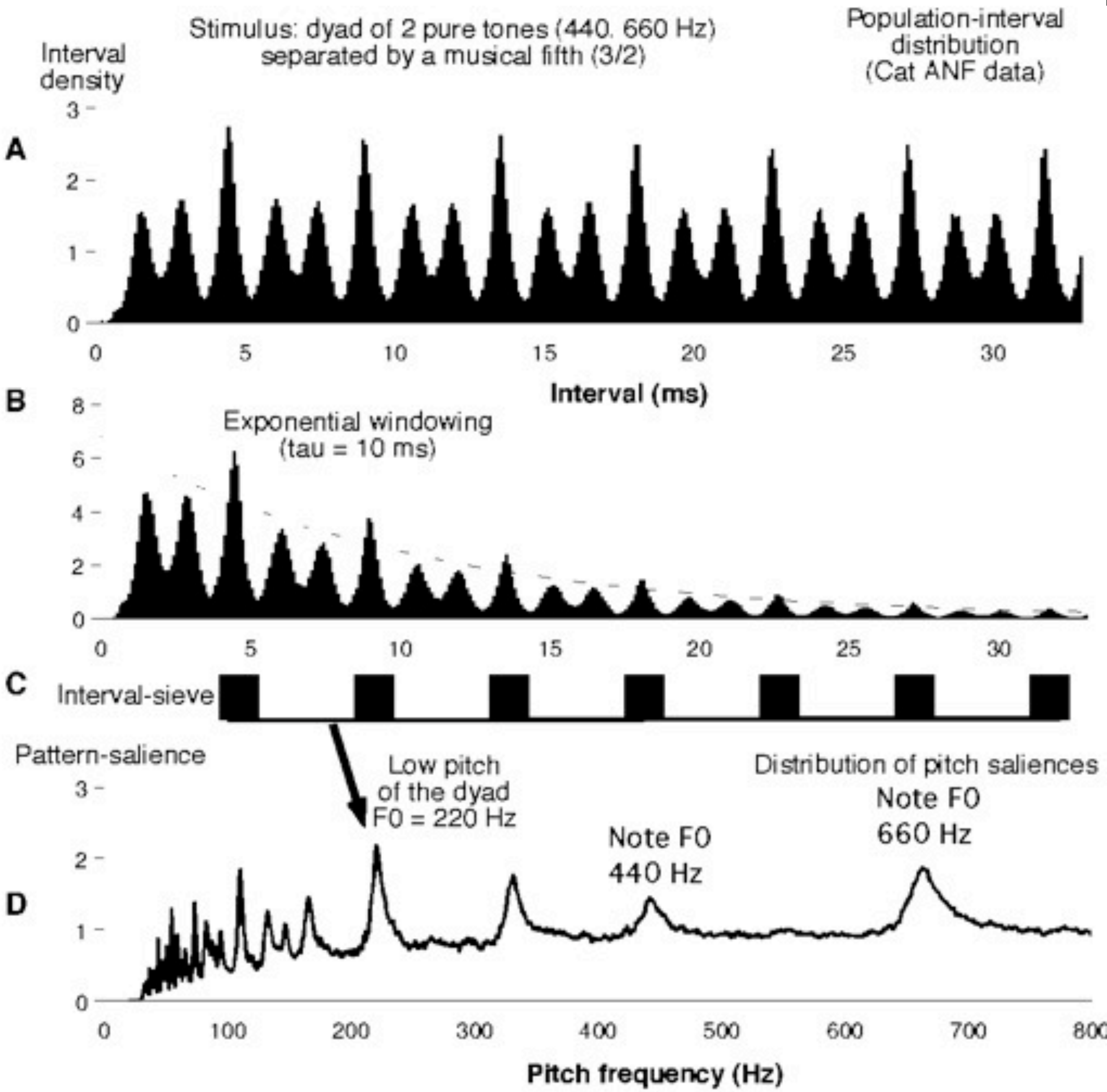
How does a temporal model predict whether a pitch should be audible?

Step 1 Simulate auditory nerve response to stimulus



Step 2
Apply exponential interval weighting tau = 10 ms

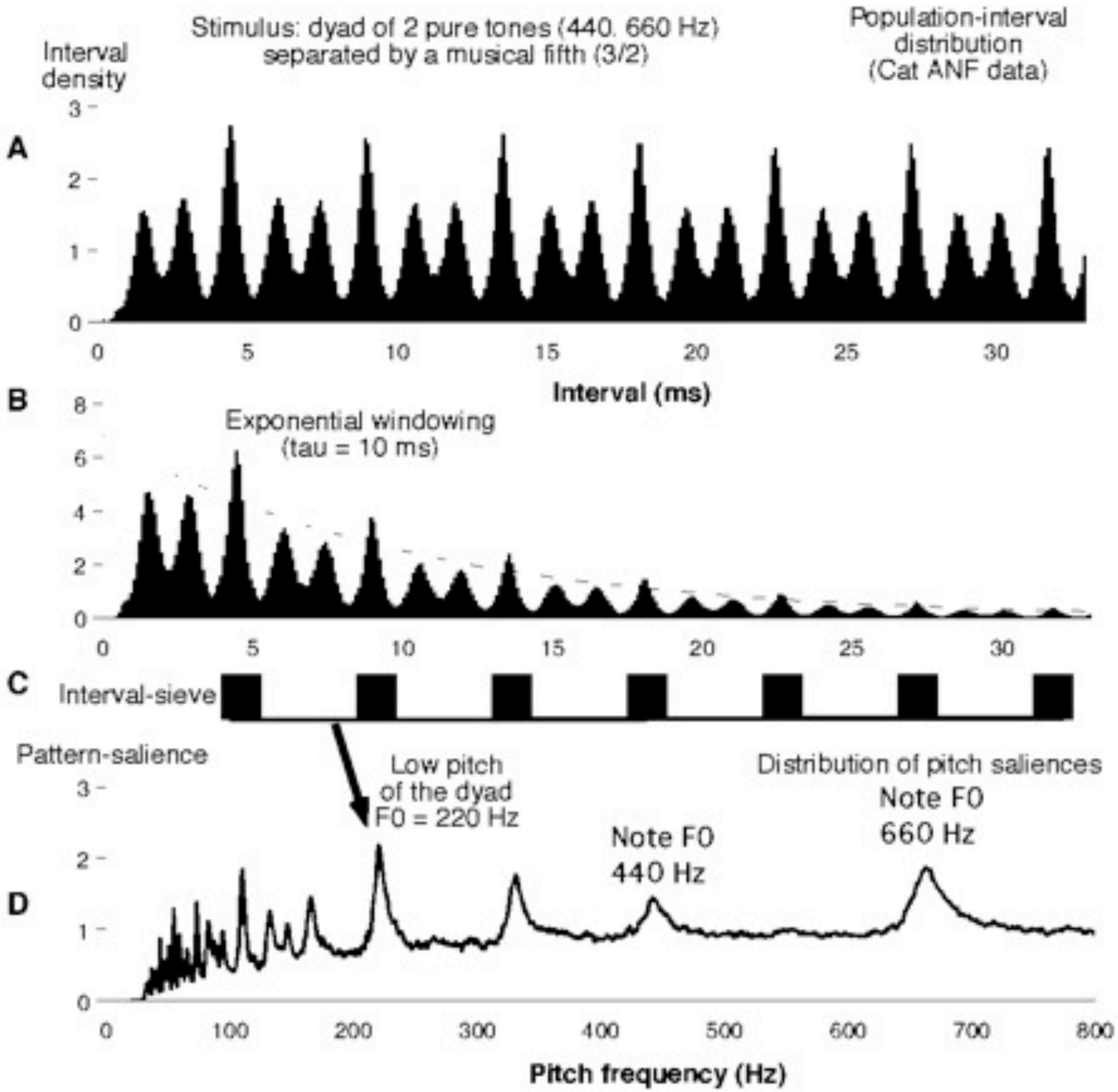
Step 3
Estimate saliences of all alternative pitches using subharmonic interval sieves



Nonexclusive allocation of intervals:

Harmonically related pitches share intervals and interfere minimally.

Non-harmonically related pitches interfere maximally.

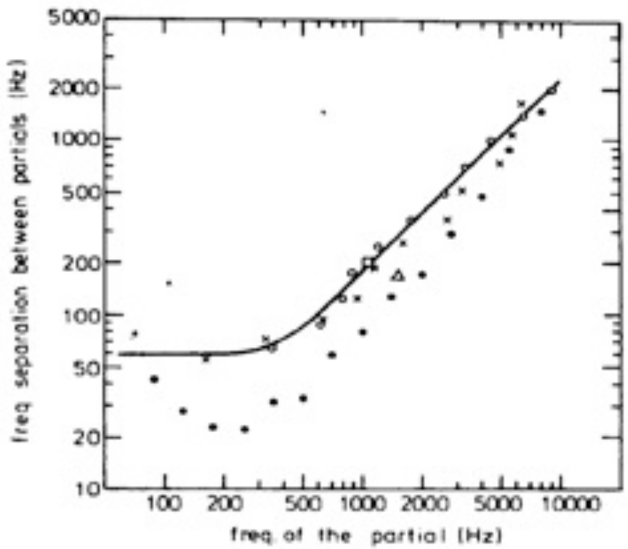


Some observations

1. The all-order interspike interval distribution at the level of the auditory nerve constitutes an autocorrelation-like representation of the stimulus.
2. Since each low harmonic generates intervals at its own period and its multiples, the representation includes all subharmonics of the partials.
3. The interval patterns are formed from the summation of subharmonics (cf. Terhardt's virtual pitch)
4. The sieve computes the pattern-strength of these subharmonics of the partials.
5. This representation contains both overtone & undertone series (i.e. more than pure spectral overlap).

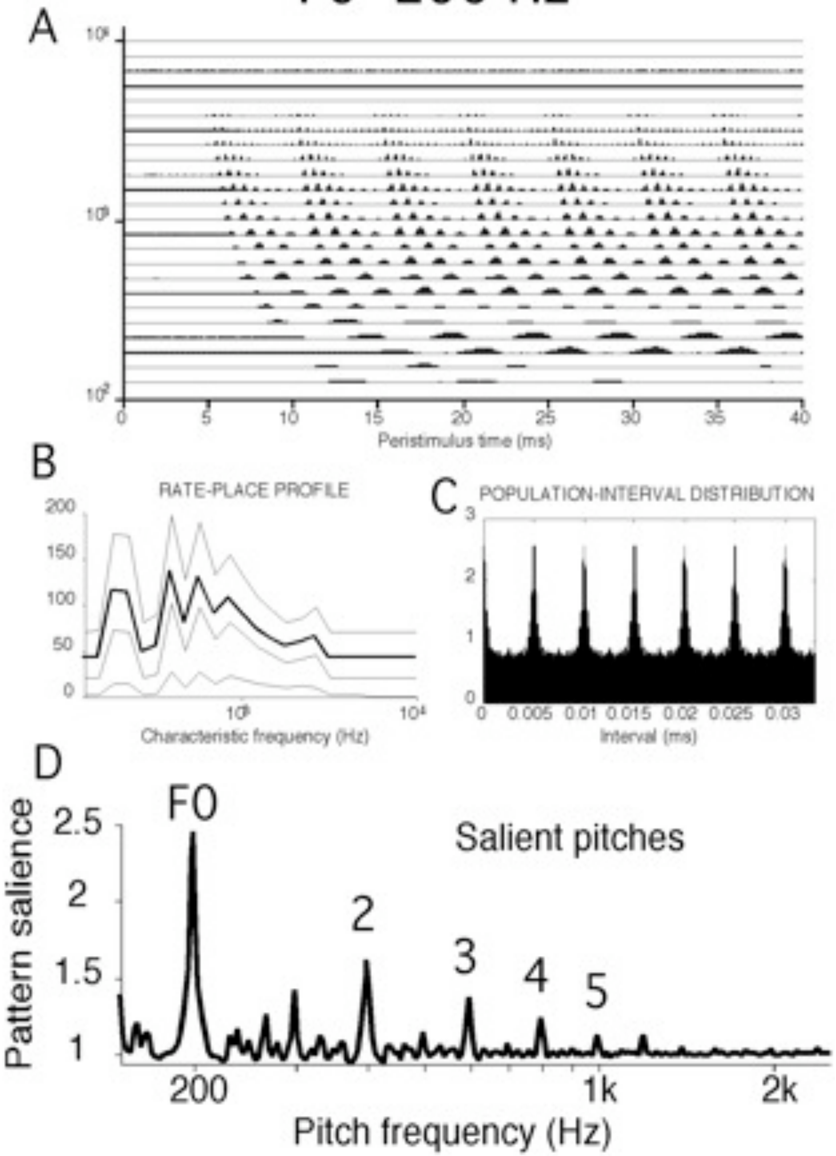
Harmonic resolution

Resolvability of partials (Plomp, 1976)

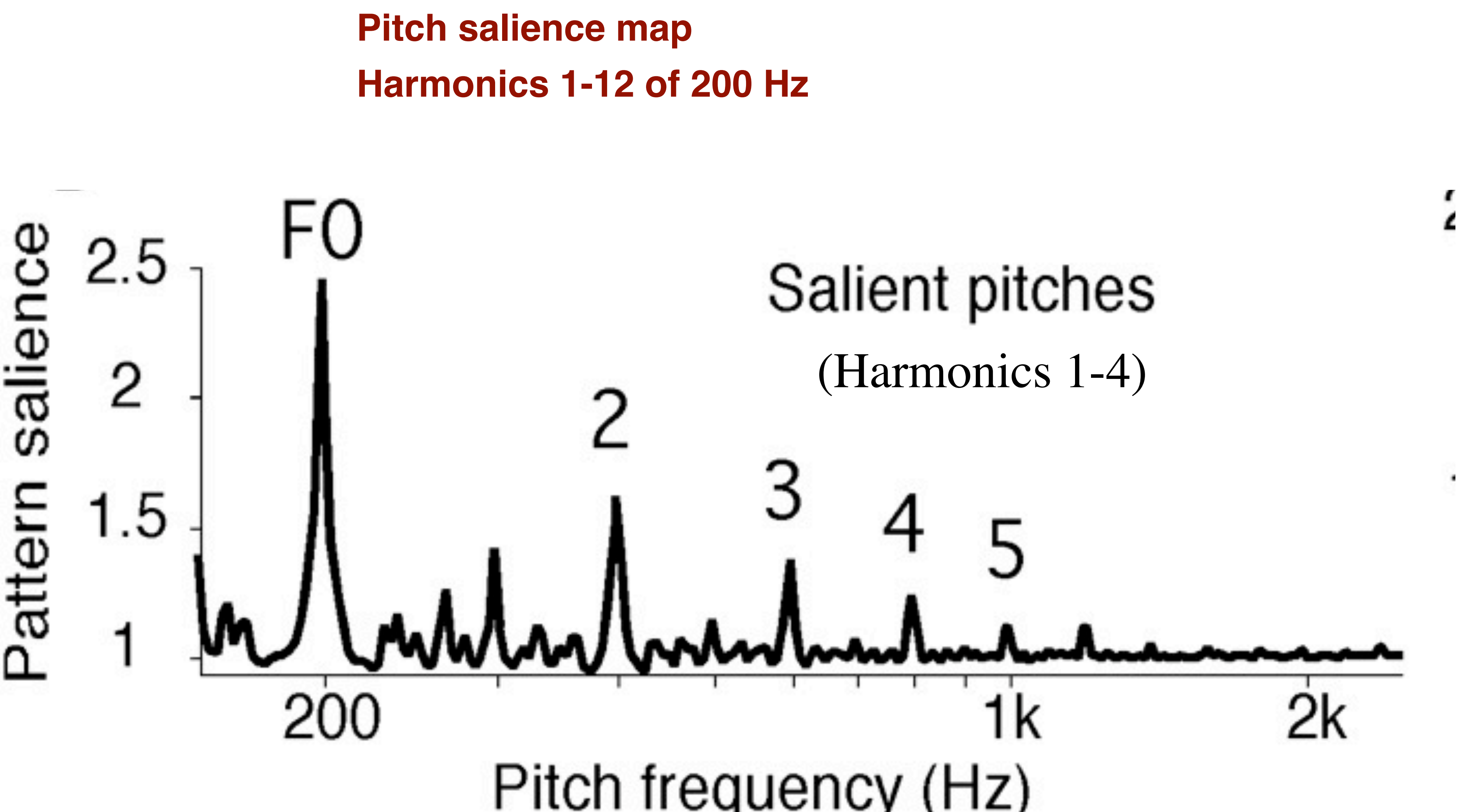


Harmonic complexes (n=1-12)

F0=200 Hz



Step 4: Those pitches with saliences > 1.3 should be audible.



Plomp & Levelt (1965) Dissonance of pure tone dyads

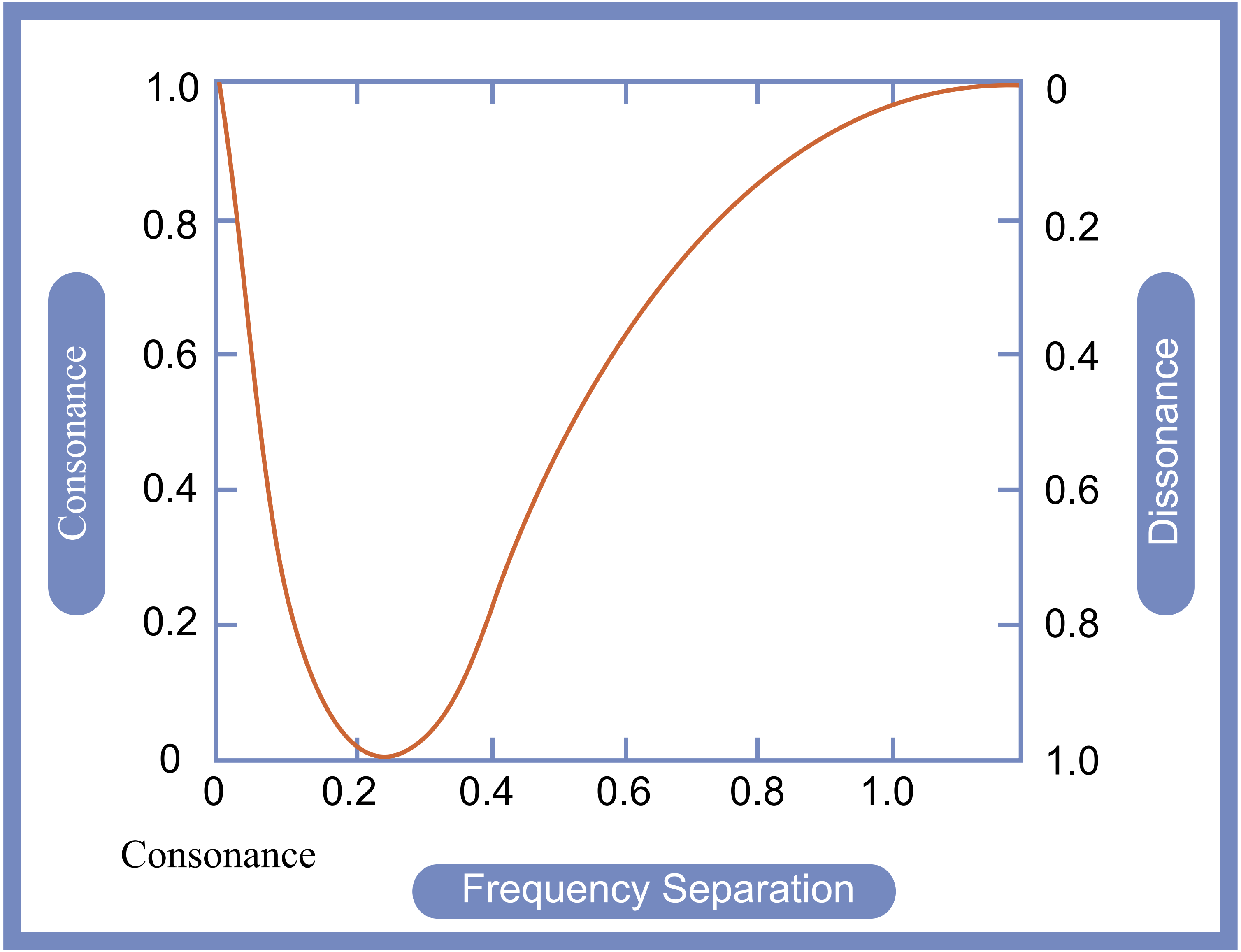
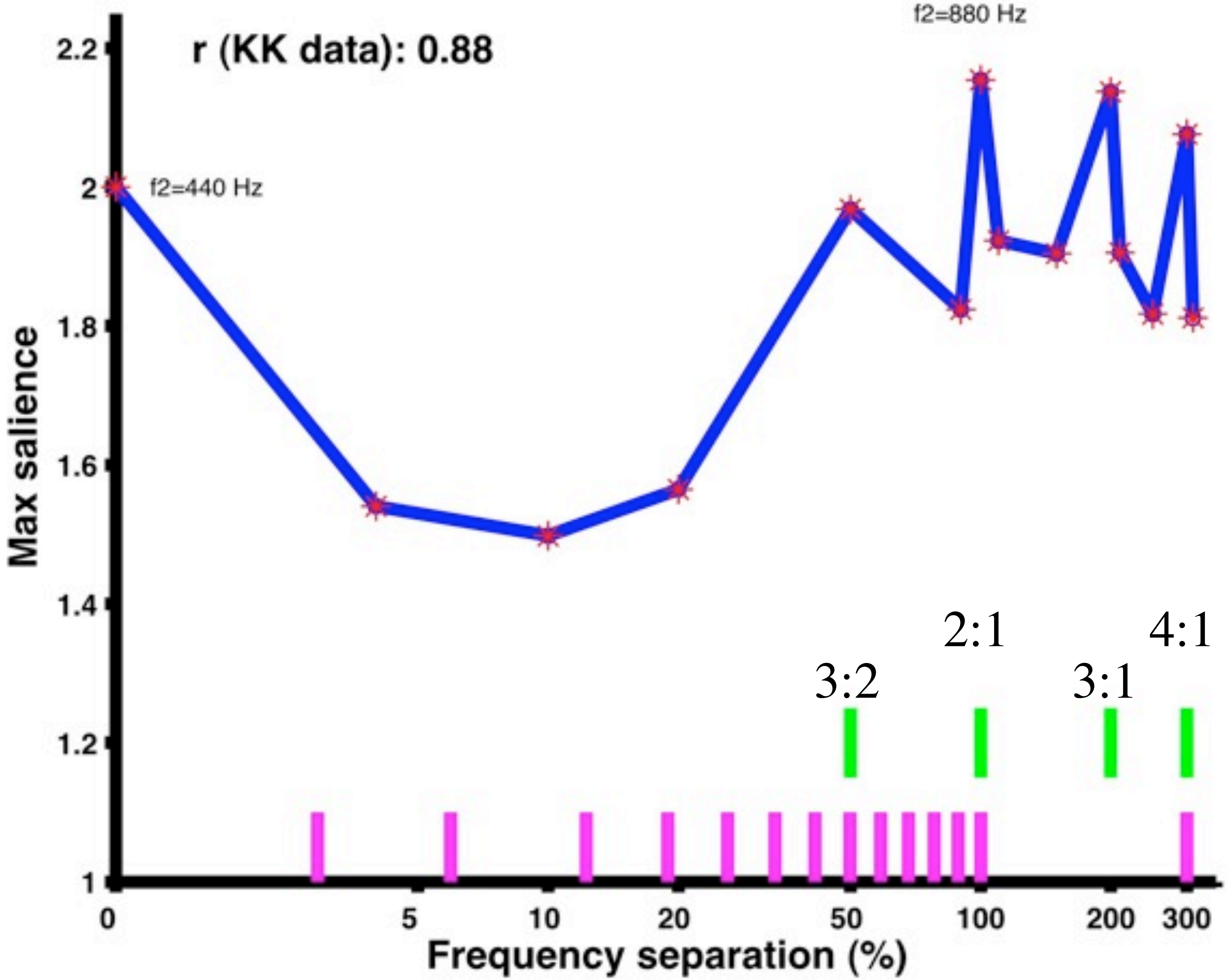


Figure by MIT OpenCourseWare.

Kameoka & Kuragawa, 1969a, Pure tone ratings
Japanese audio engineers, "sunda/nigotta" (clearness/turbidity)

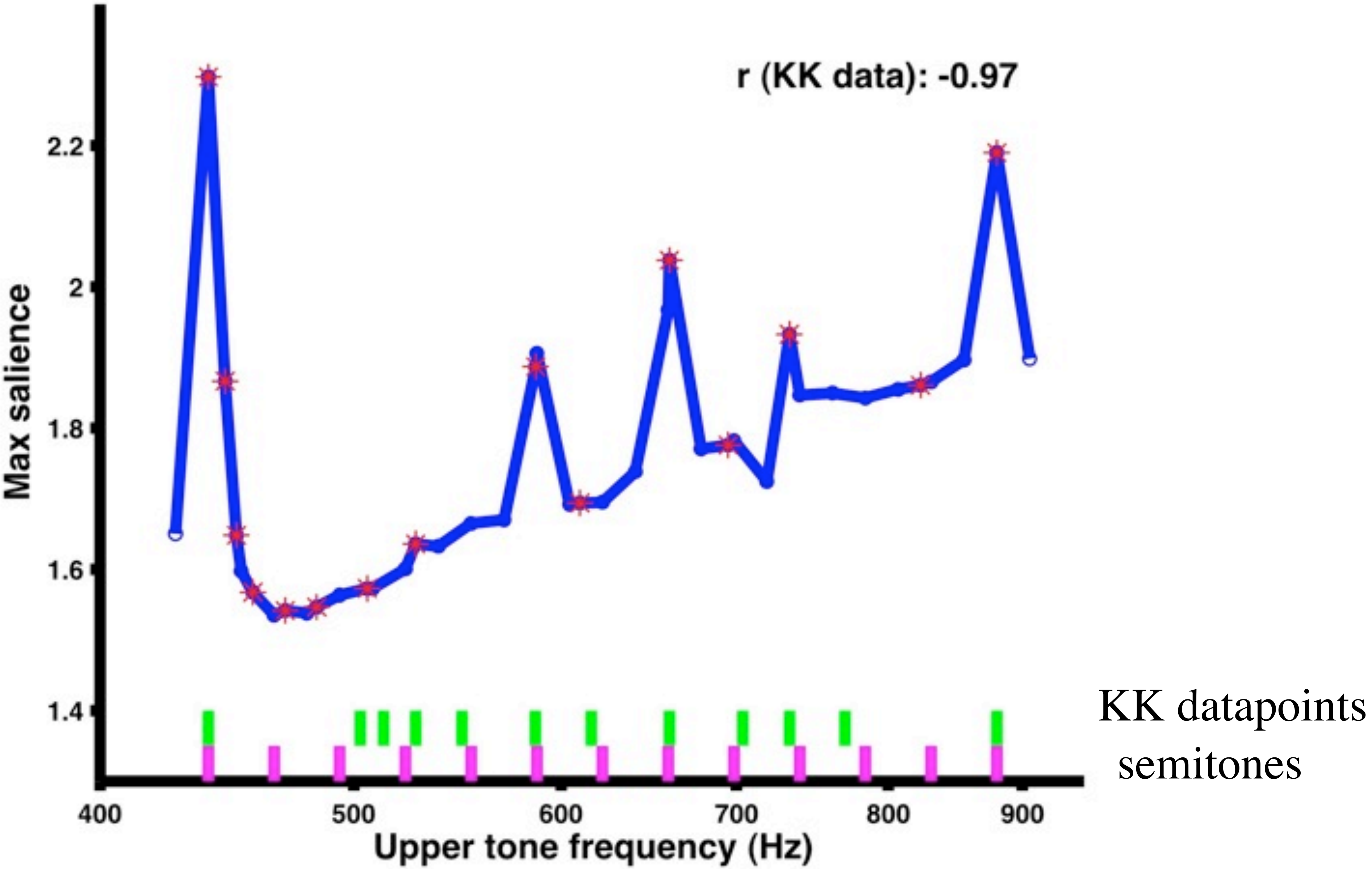
Image removed due to copyright restrictions. Kameoka, A., and M. Kuriyagawa. "Consonance Theory Consonance of Dyads." *J Acoust Soc Am* 45 (1969): 1451-1459.

Model predictions, est. pitch fusion = maximum salience



Kameoka & Kuragawa, 1969a, Complex tone ratings (diff. scale)

Model predictions, est. pitch fusion = maximum salience

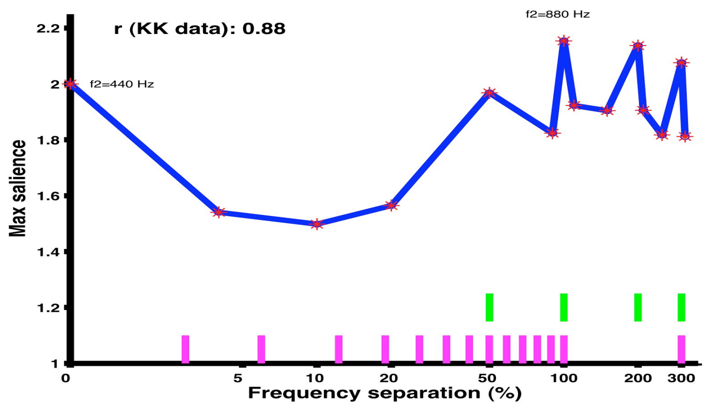


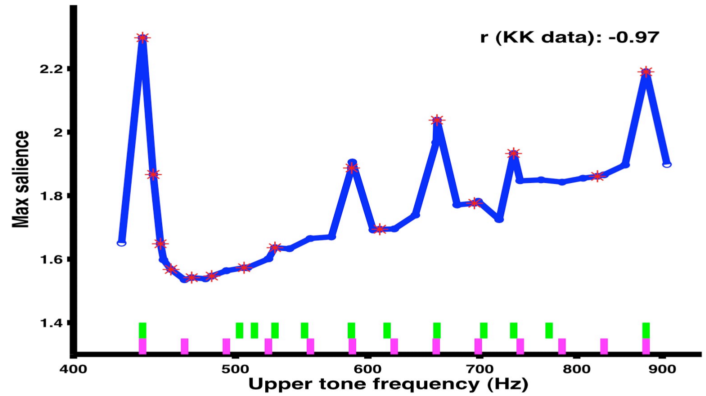
Estimated consonance of pure & complex tone dyads

Kameoka & Kureagawa psychophysical data

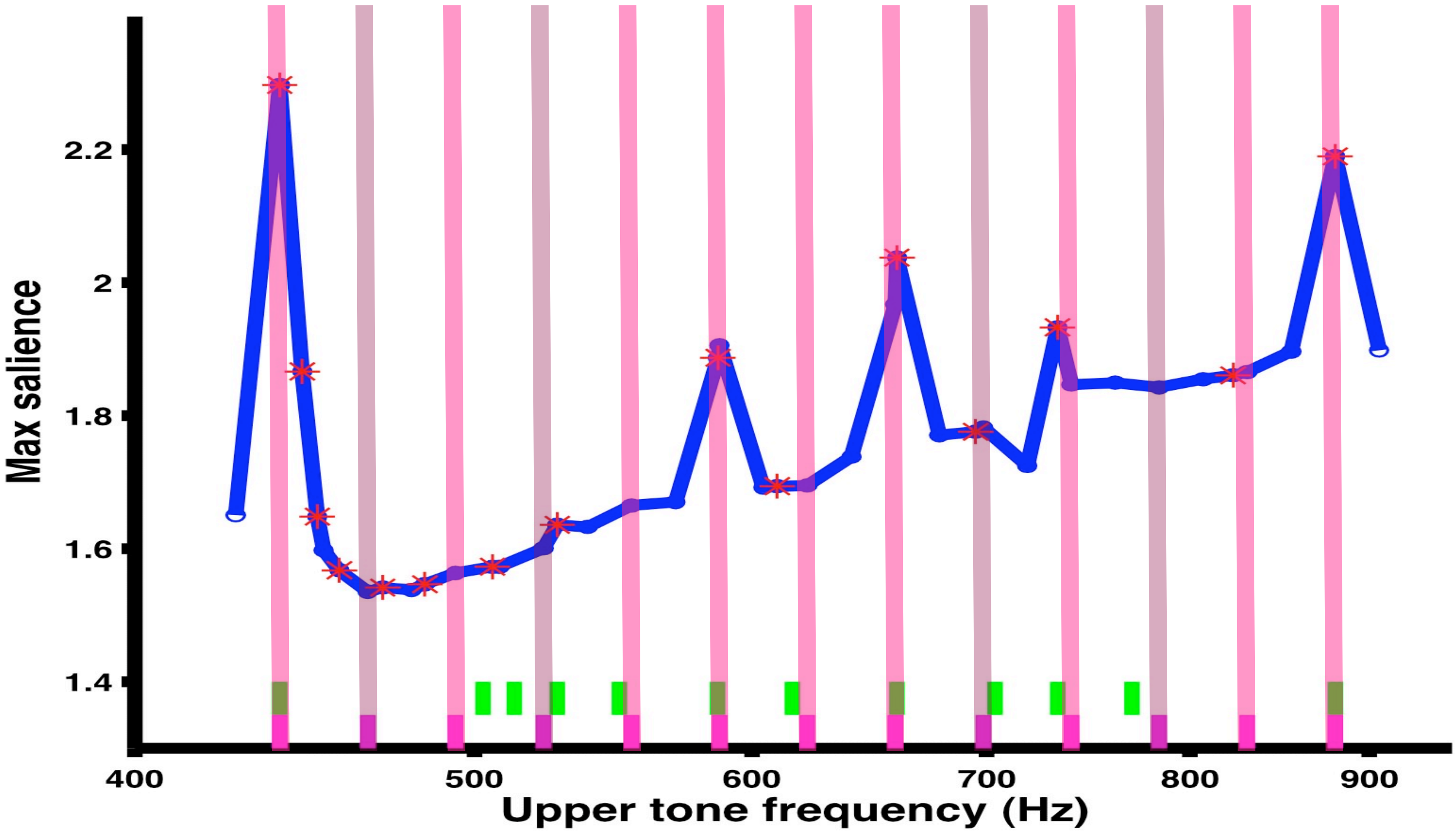
Image removed due to copyright restrictions. Kameoka, A., and M. Kuriyagawa. "Consonance Theory Consonance of Dyads." *J Acoust Soc Am* 45 (1969): 1451-1459.

Temporal pitch multiplicity model





Designing a scale system - 12 equally tempered notes/oct.



diatonic scale

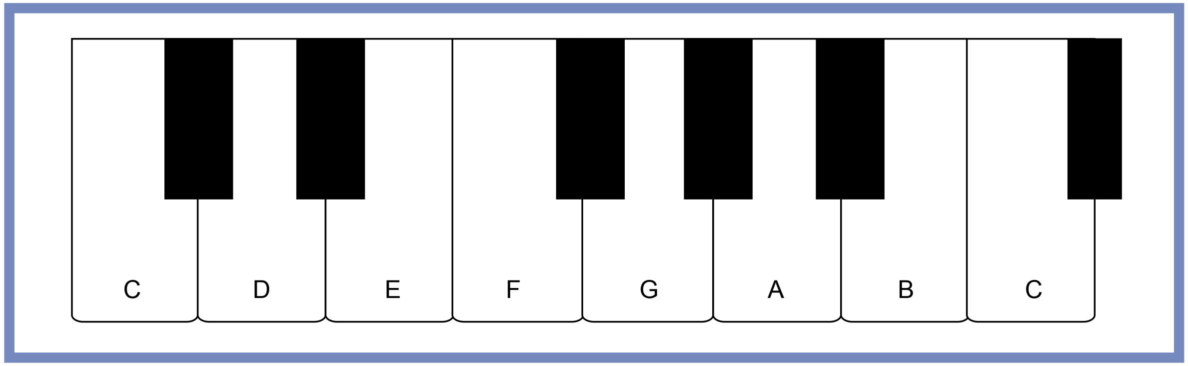
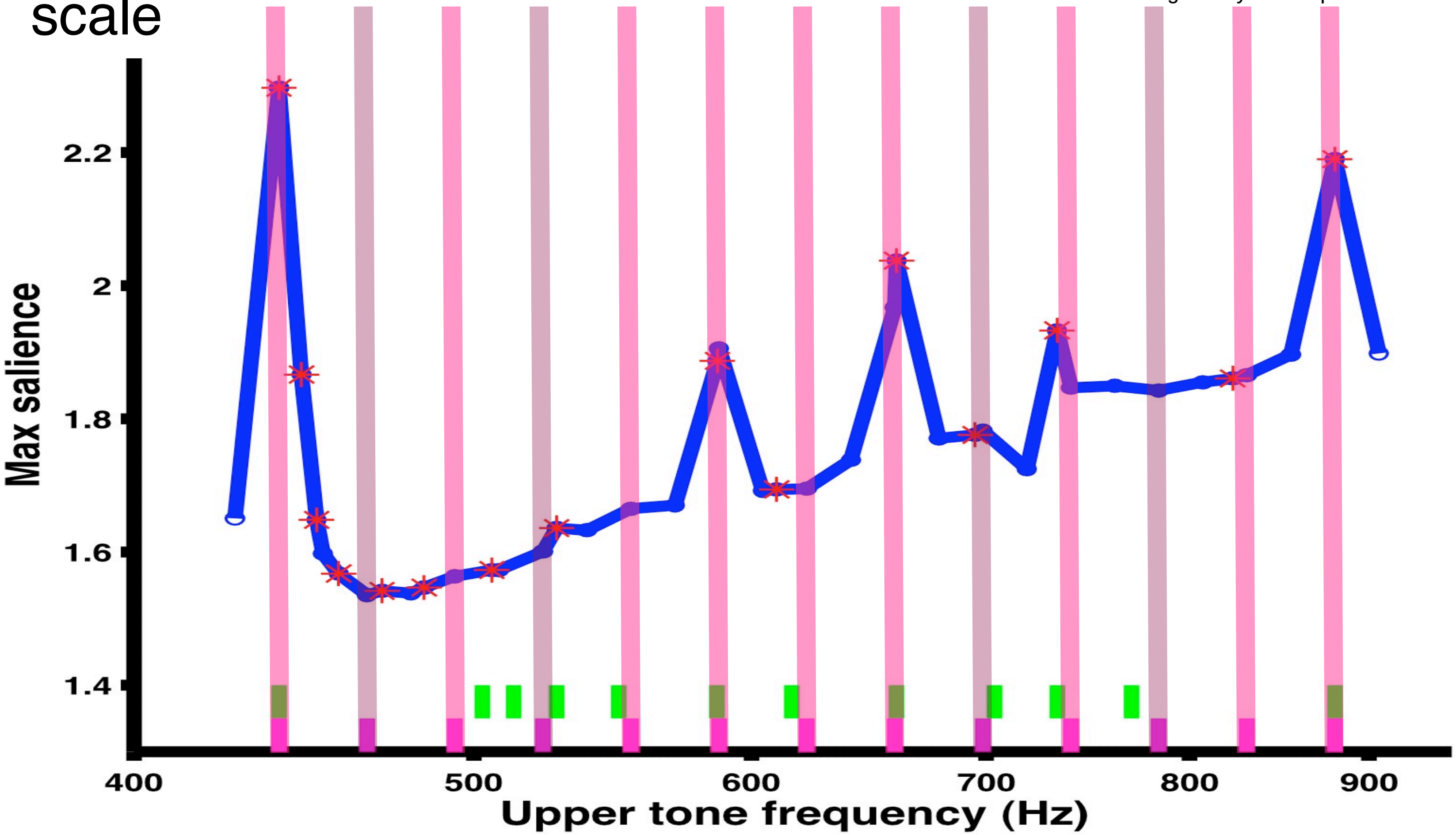
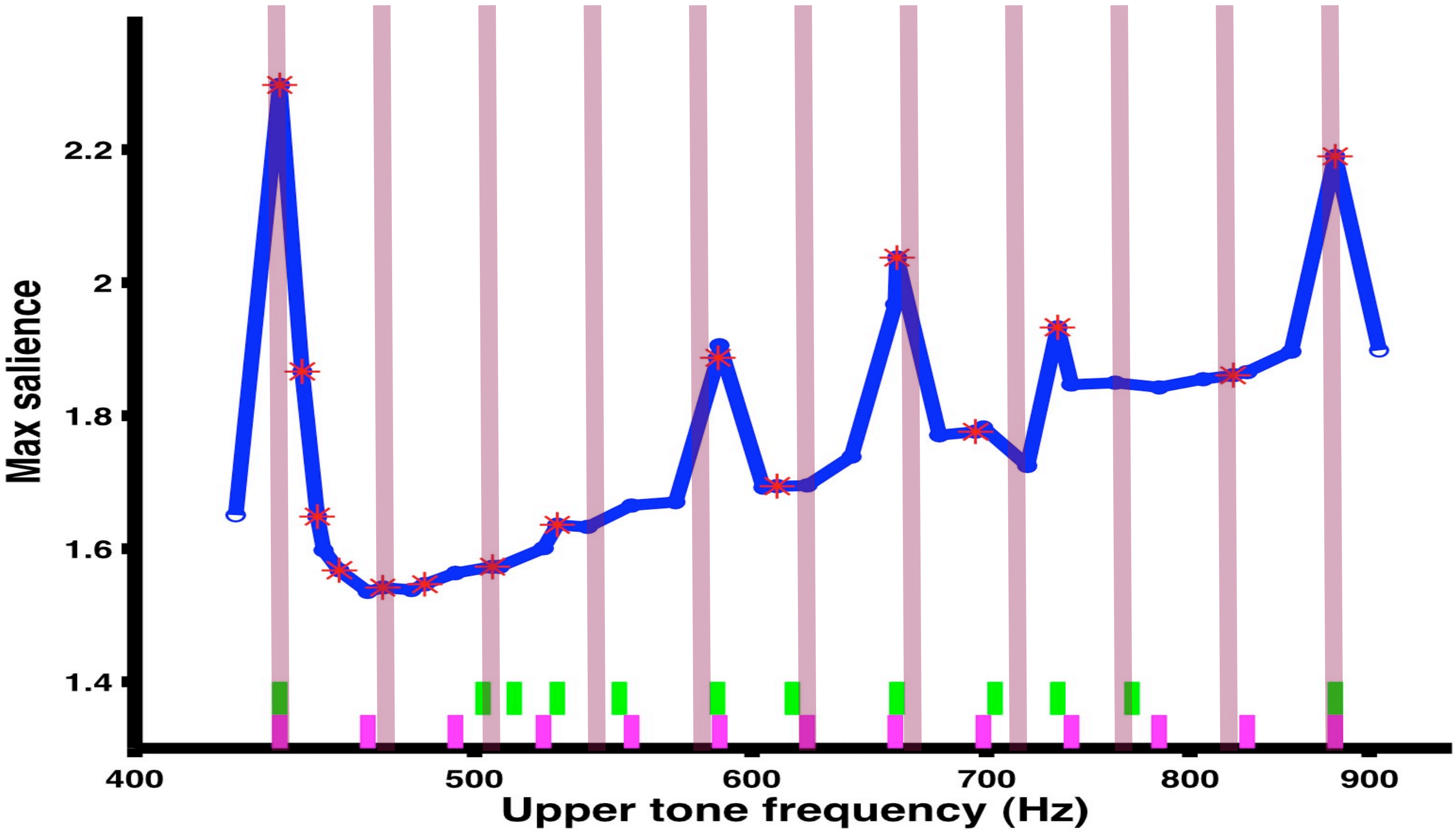


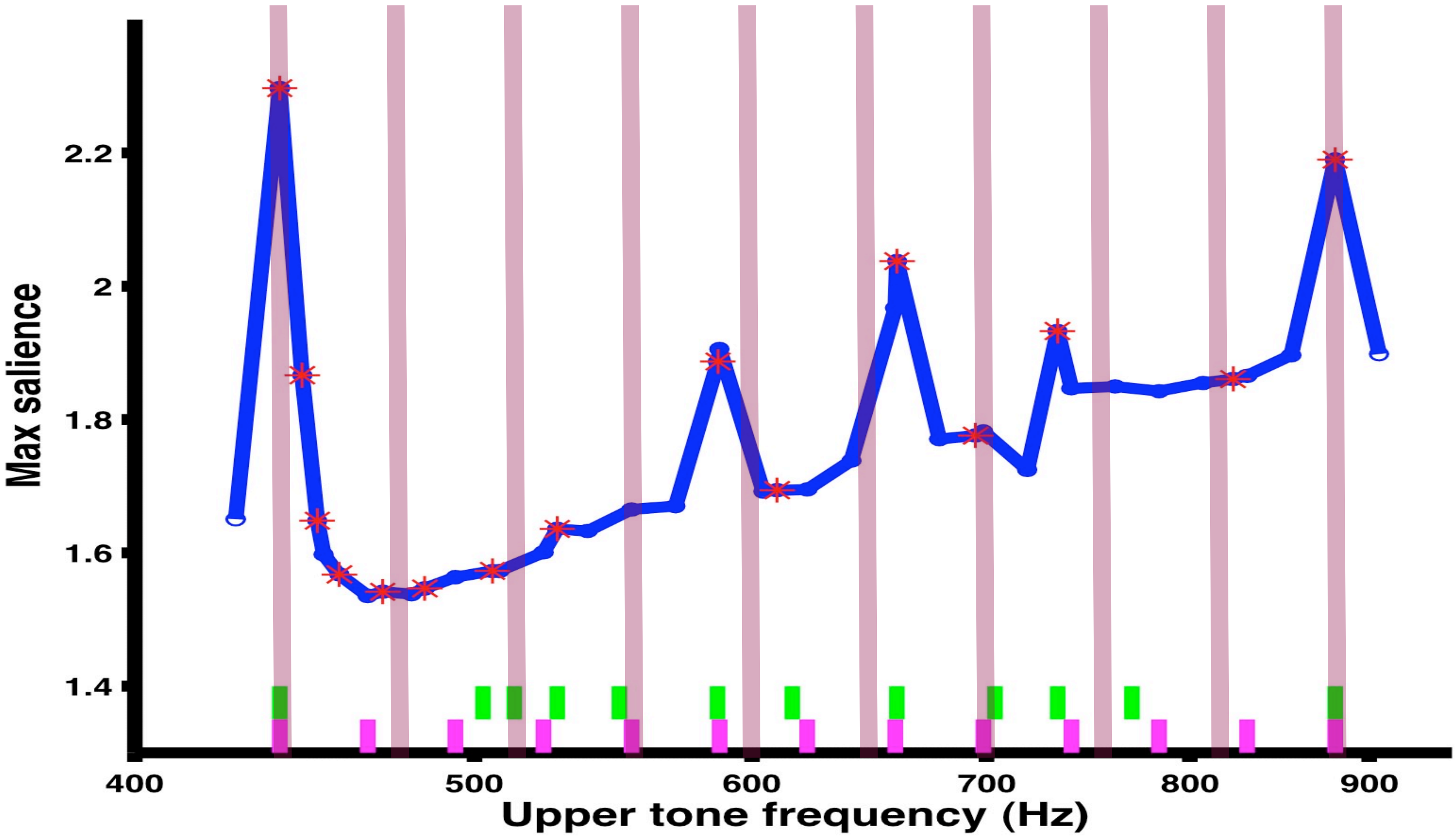
Figure by MIT OpenCourseWare.



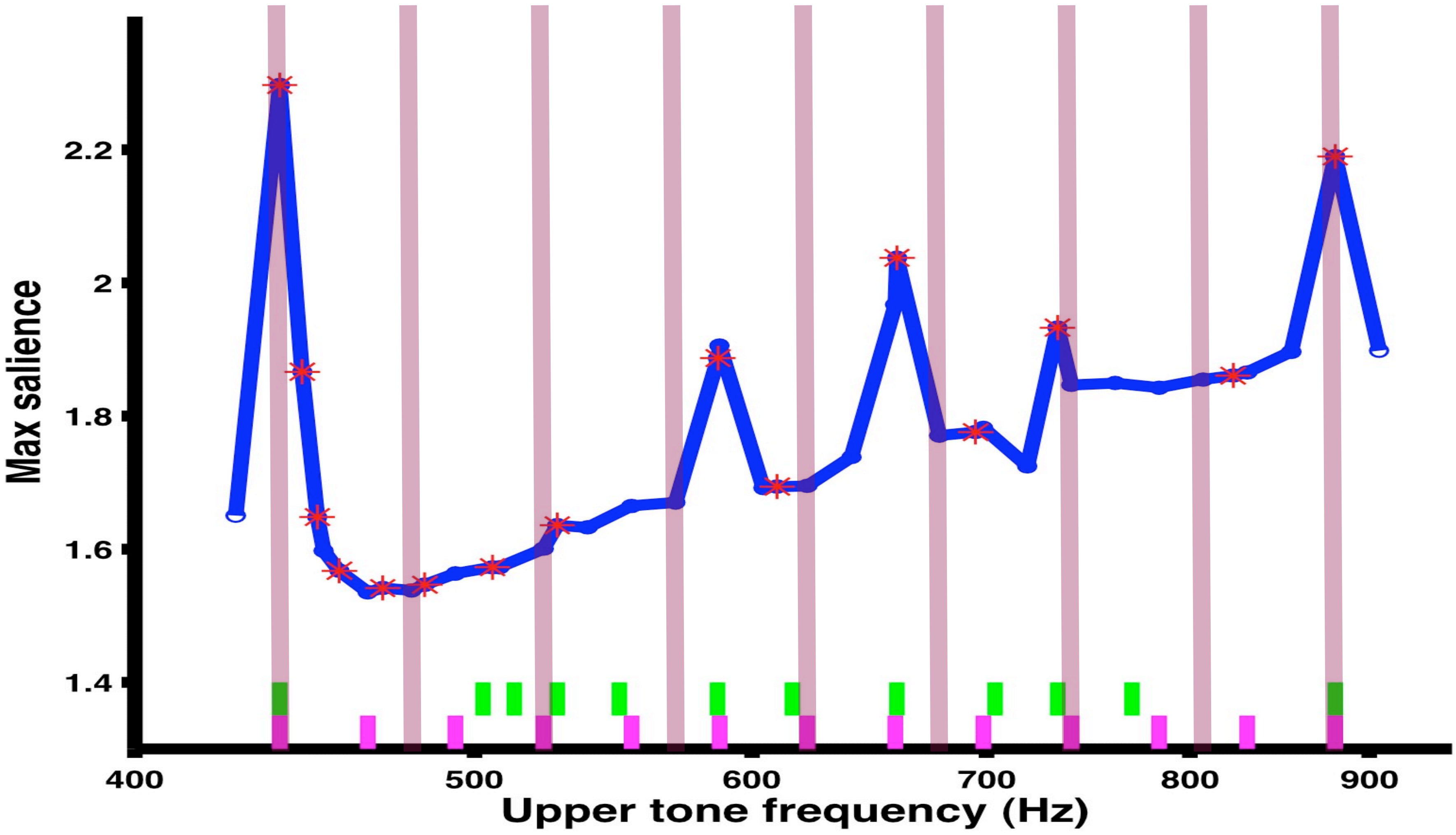
Designing a scale system - 10 equally tempered notes/oct.



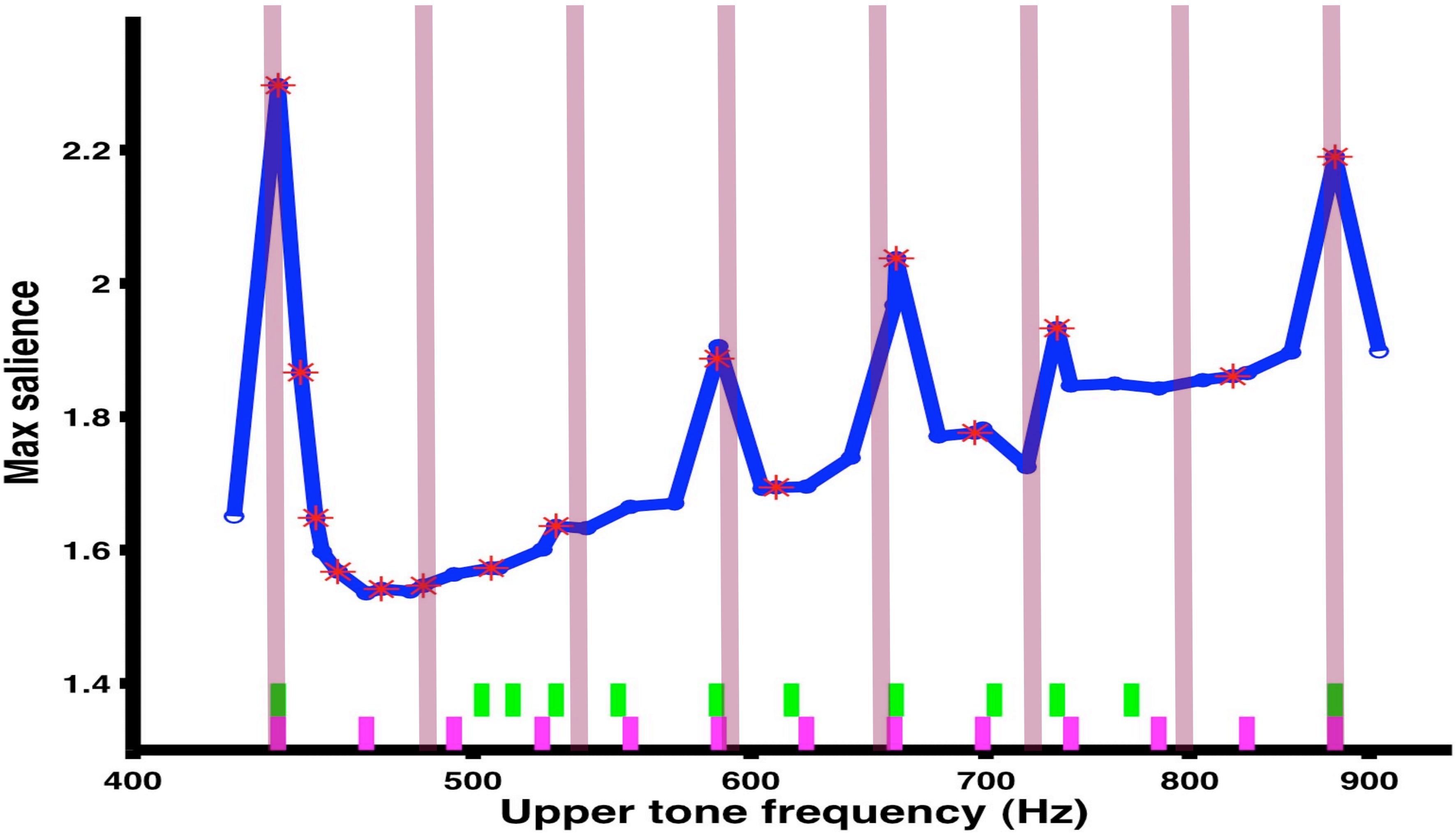
Designing a scale system - 9 equally tempered notes/oct.



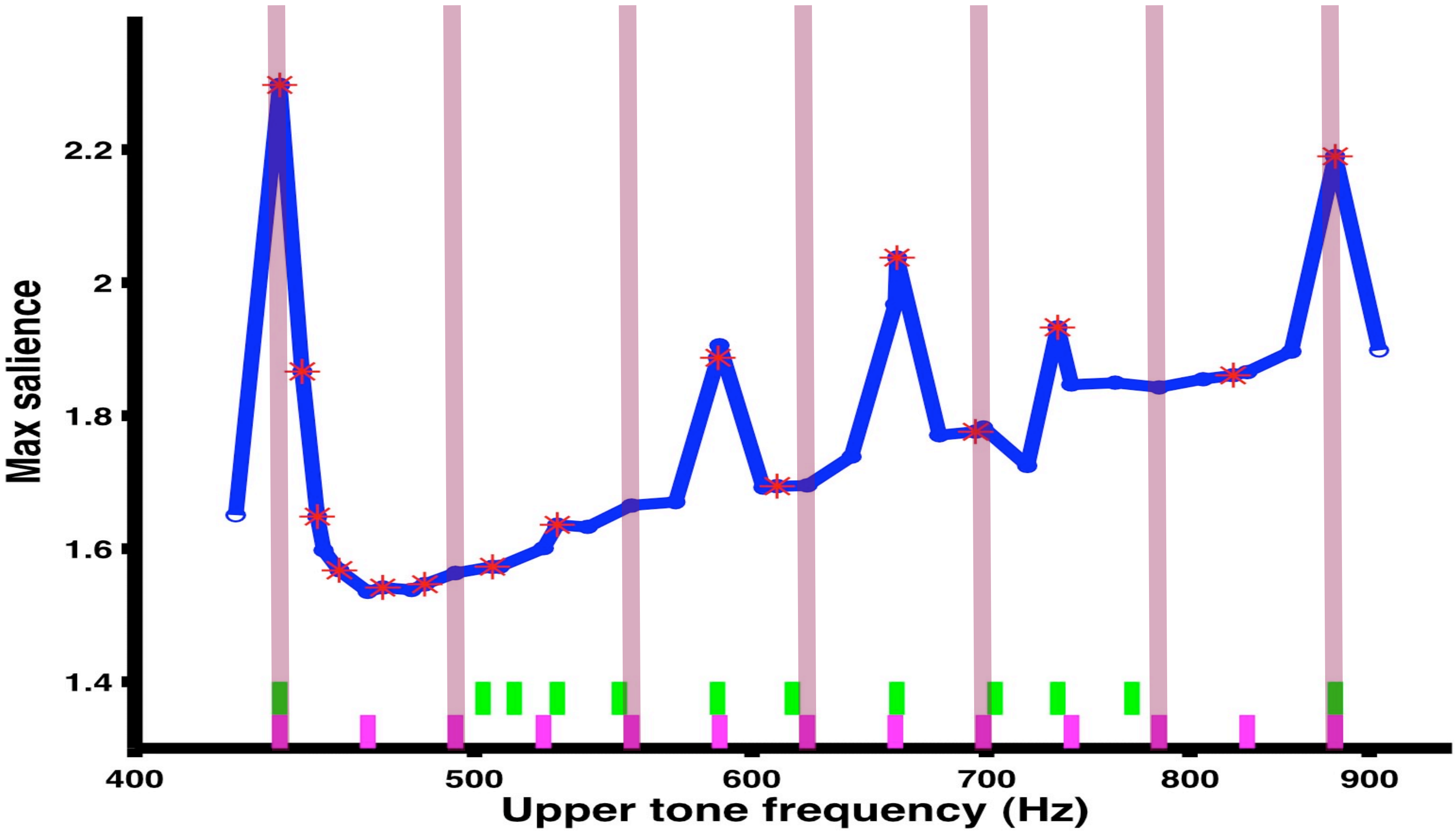
Designing a scale system - 8 equally tempered notes/oct.



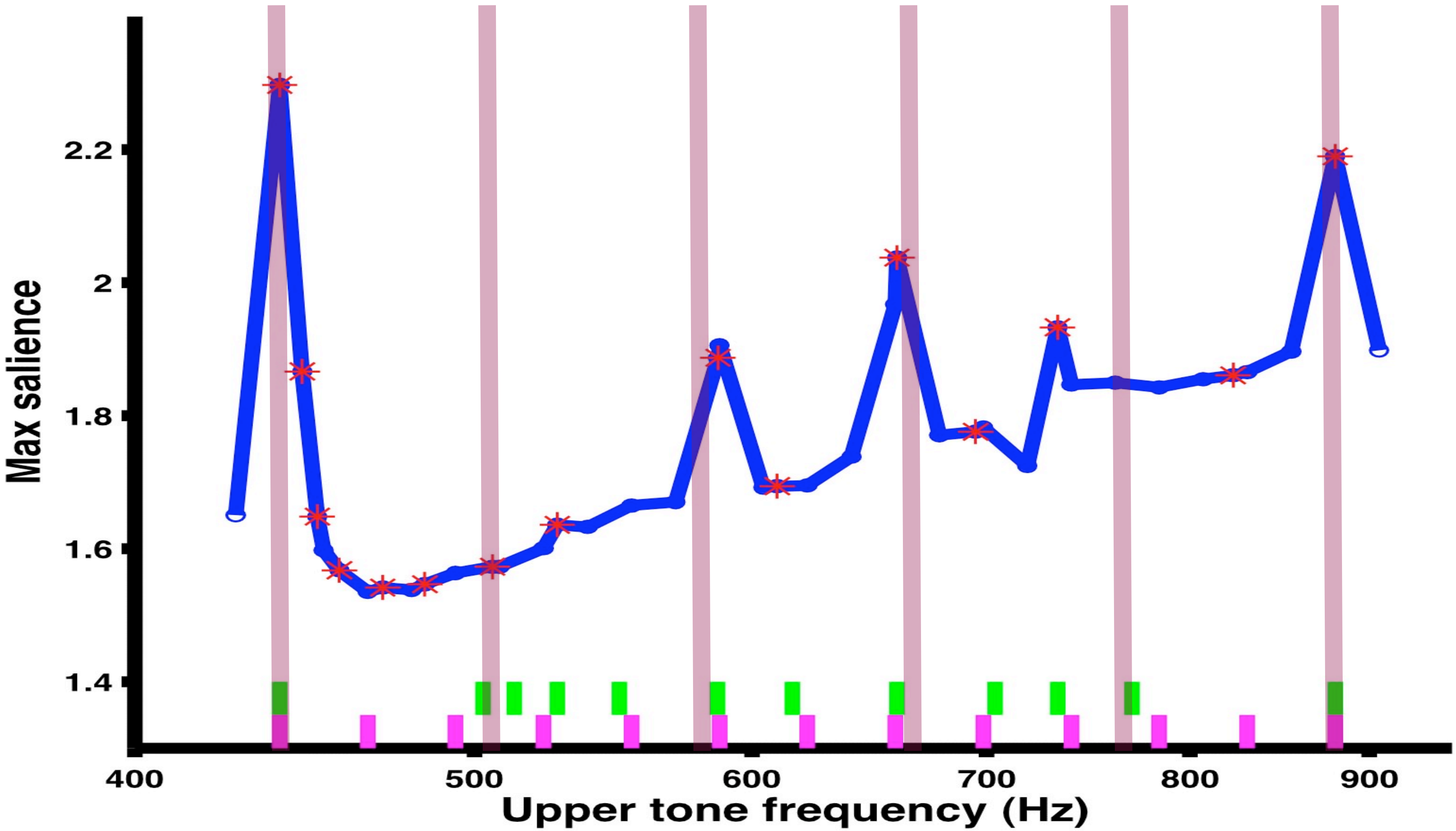
Designing a scale system - 7 equally tempered notes/oct.



Designing a scale system - 6 equally tempered notes/oct.



Designing a scale system - 5 equally tempered notes/oct.



Neural coding of pitch fusion

Covaries with roughness models; many parallels. Both explain basic consonance of complex harmonic tones quite well

Responsible interval information probably exists at least up to the level of the midbrain (IC) -- work by Greenberg (FFR)

Interval models parallel spectral pattern approaches

- (e.g. Terhardt's subharmonics, Parncutt)

Pitch competition and stability leads to a theory of tonal stability and higher levels of tension-relaxation.

Fusion is similar to Stumpf's theory

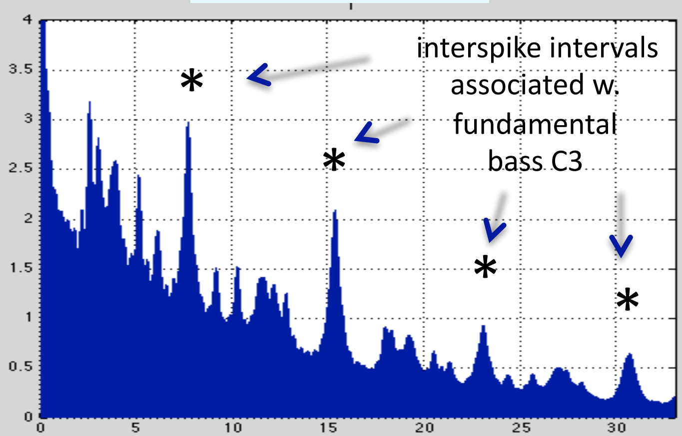
Based in part on undertone series; may be related to Riemann's theory of harmonic dualism

Estimated pitch-stability of major and minor triads

Simulated interval distributions

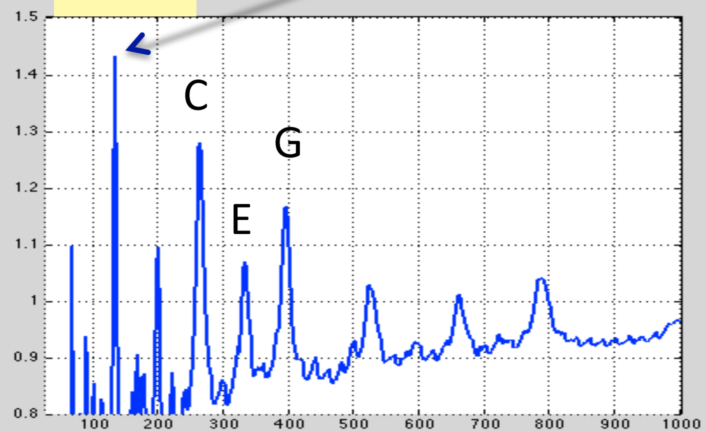
Estimated saliences of pitches
(pitch stability, unity, fusion)

C-Major triad

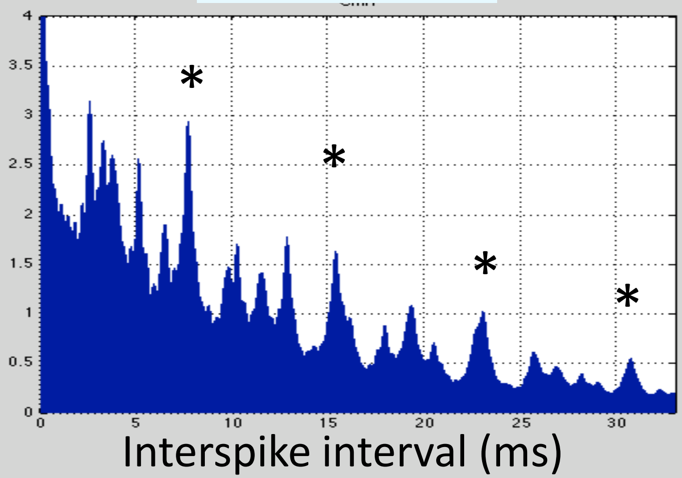


1.43

fundamental bass: C3

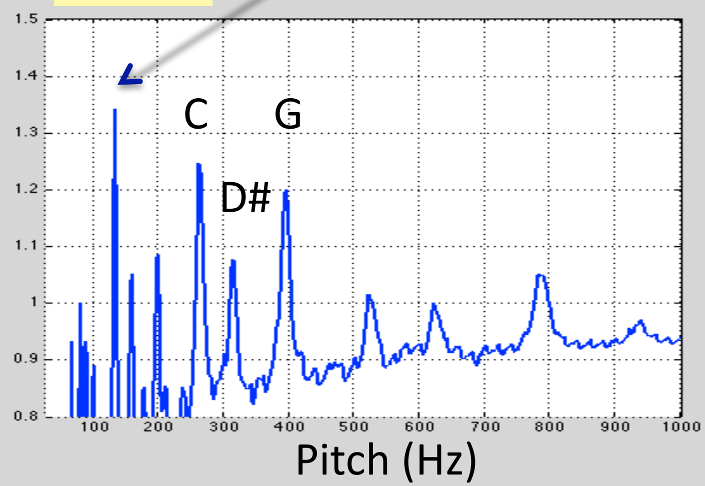


C-Minor triad



1.34

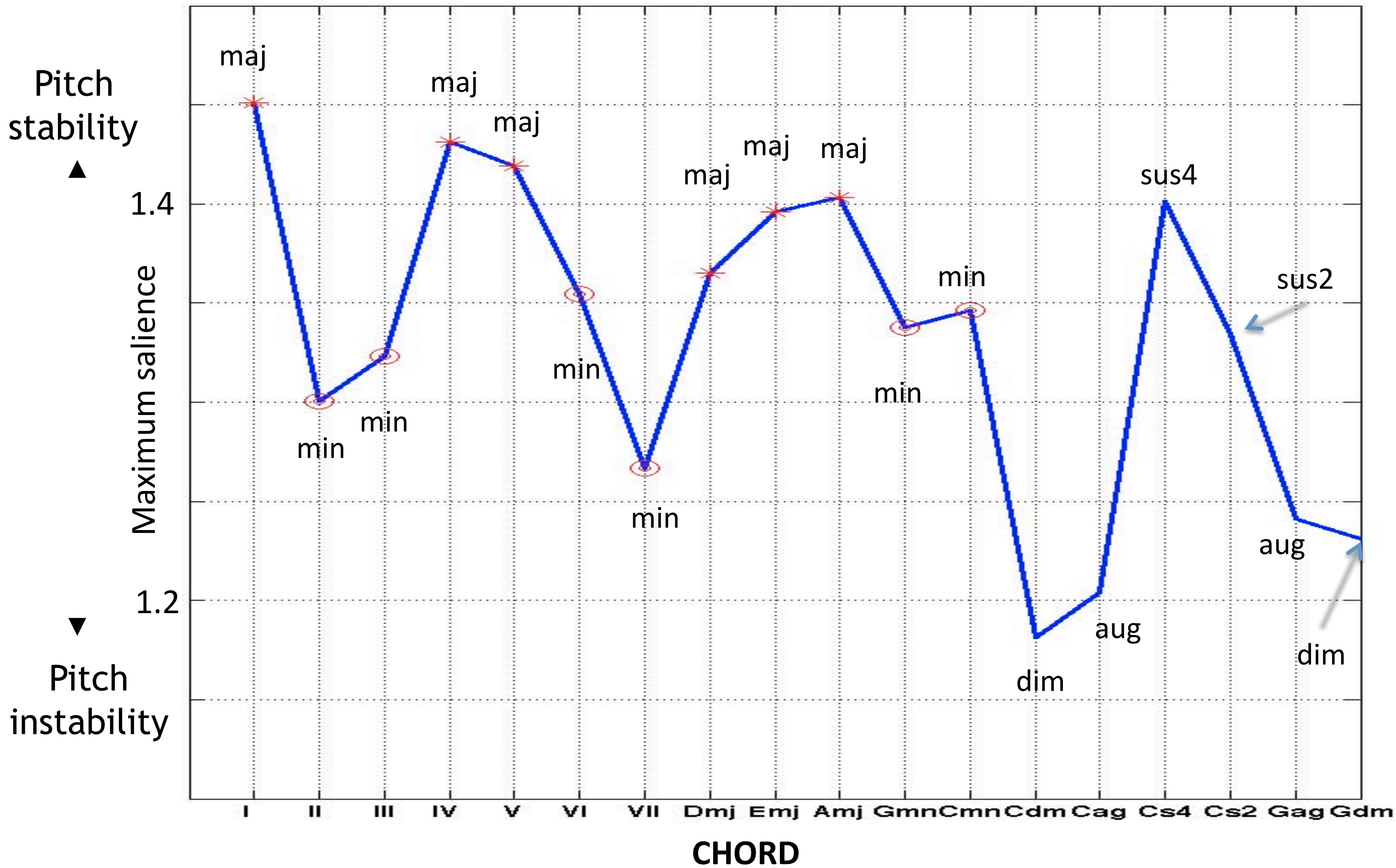
fundamental bass: C3



Estimated pitch-stability of triads of all scale degrees

Preliminary results: Maj > Sus4 > Min > Sus2 >> Aug > Dim

Simulation: 24 CF's, 72 fibers,
1/n harmonic amplitudes
72 dB SPL



Chord progressions, "cadences"

sequences of chords

tension & relaxation instability-stability

One of the self-conscious aims of 20th c. "atonal" music (e.g. Schoenberg) is the avoidance of tonal centers and expectations

http://www.musictheory.net/load.php?id=55

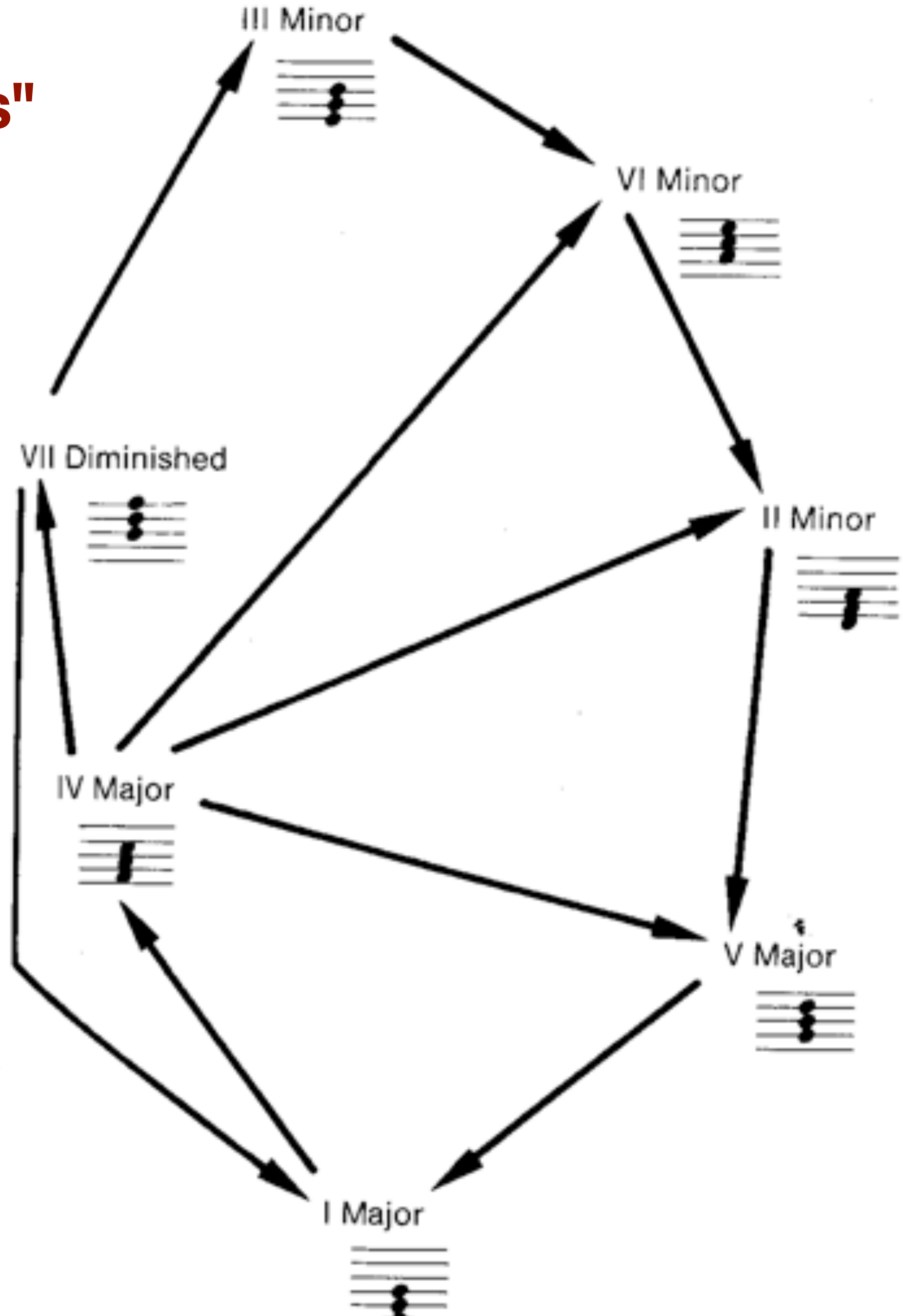
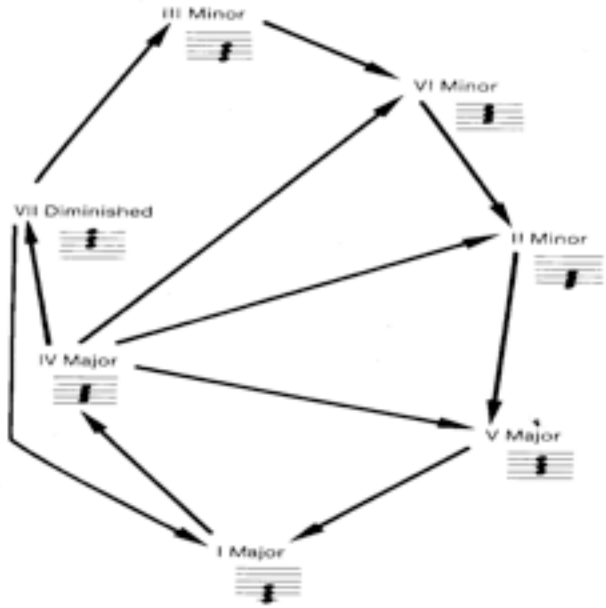
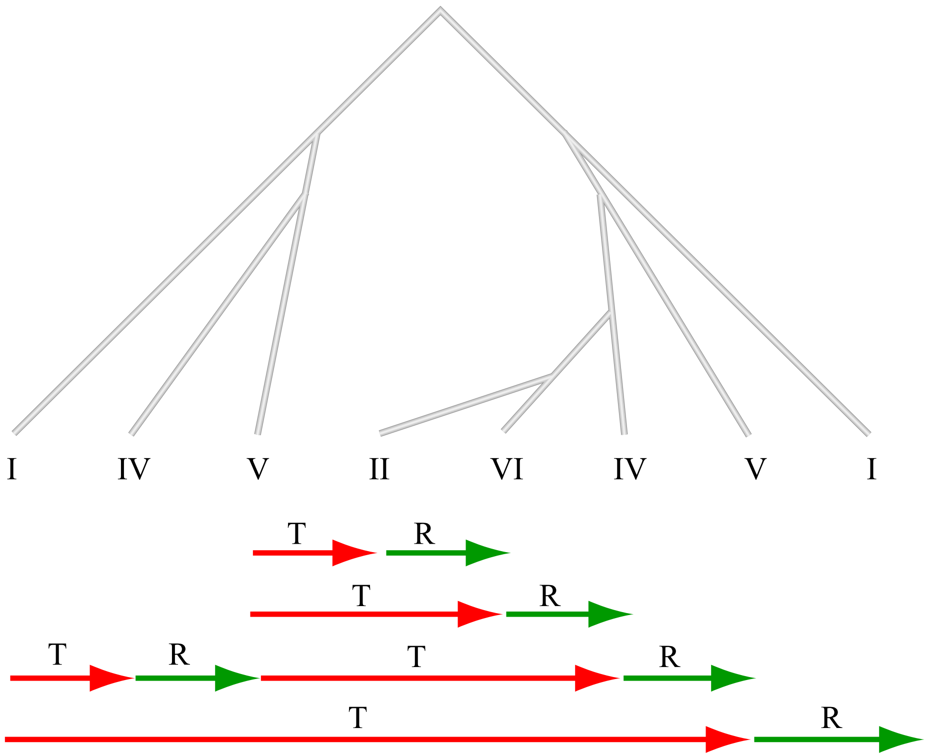


Figure 10.7
Chord progressions. The movement tendencies among the seven triads (c
of major scales is illustrated. Chord movement often starts at I, moves to a
returns to I by way of V. Alternatively, the chord progression may retu
VII (adapted from Zuckerkandl 1959).

Tonal hierarchies





Tonal hierarchy of chords. The tree diagram indicates the relative hierarchical importance among the chord degrees. The horizontal arrows show the conventional listener interpretation of tension (T) and release (R).

Figure by MIT OpenCourseWare.

Main Points re: consonance

- Early experiments with strings (Greeks)
- Psychophysics of consonance
  - Meanings of "consonance" and "dissonance"
  - Euphonious, "pleasant" vs. jarring, unpleasant
  - Smooth, well-defined, unified vs. rough, buzzy, unsettled
- Beating & roughness (Helmholtz), fusion (Stumpf)
- Neural correlates of roughness (cochlear filtering)
  - Periodicities below the range of the pitch mechanism
  - Population-wide fluctuations in discharge rates
- Neural correlates of tonal fusion (pitch)
- Consonance in music - where does it lead?
  - Tuning systems and scales
  - Instability-Stability (tension-resolution)

Reading/assignment for next meetings

- Scales and tuning systems

  History, basic psychophysics, scales and tuning systems, role in music theory. Relations between auditory and cultural factors

Handel chapter on musical grammars -- deals with melody & harmony

Reading: Deutsch, Burns chapter on intervals & scales

HST.725 Music Perception and Cognition
Spring 2009