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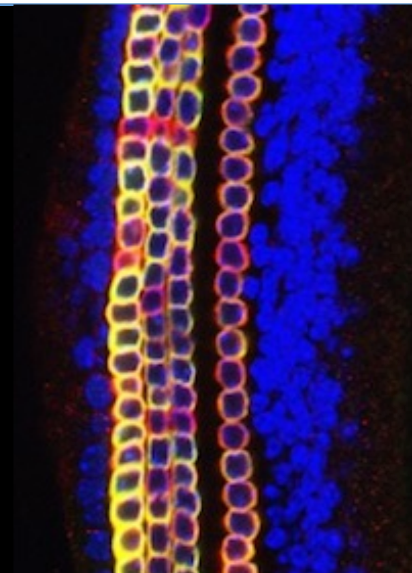


Physics of Hearing: From Neurobiology to Information Theory and Back

Summer 2017

Tutorial: Cortical pathway organization for encoding frequency, timing and location of sound

Heather Read

Department of Psychological Sciences,

Behavioral Neuroscience

Department of Biomedical Engineering

University of Connecticut

Talk Outline

1. ***Sound Frequency*** audibility in human other mammals

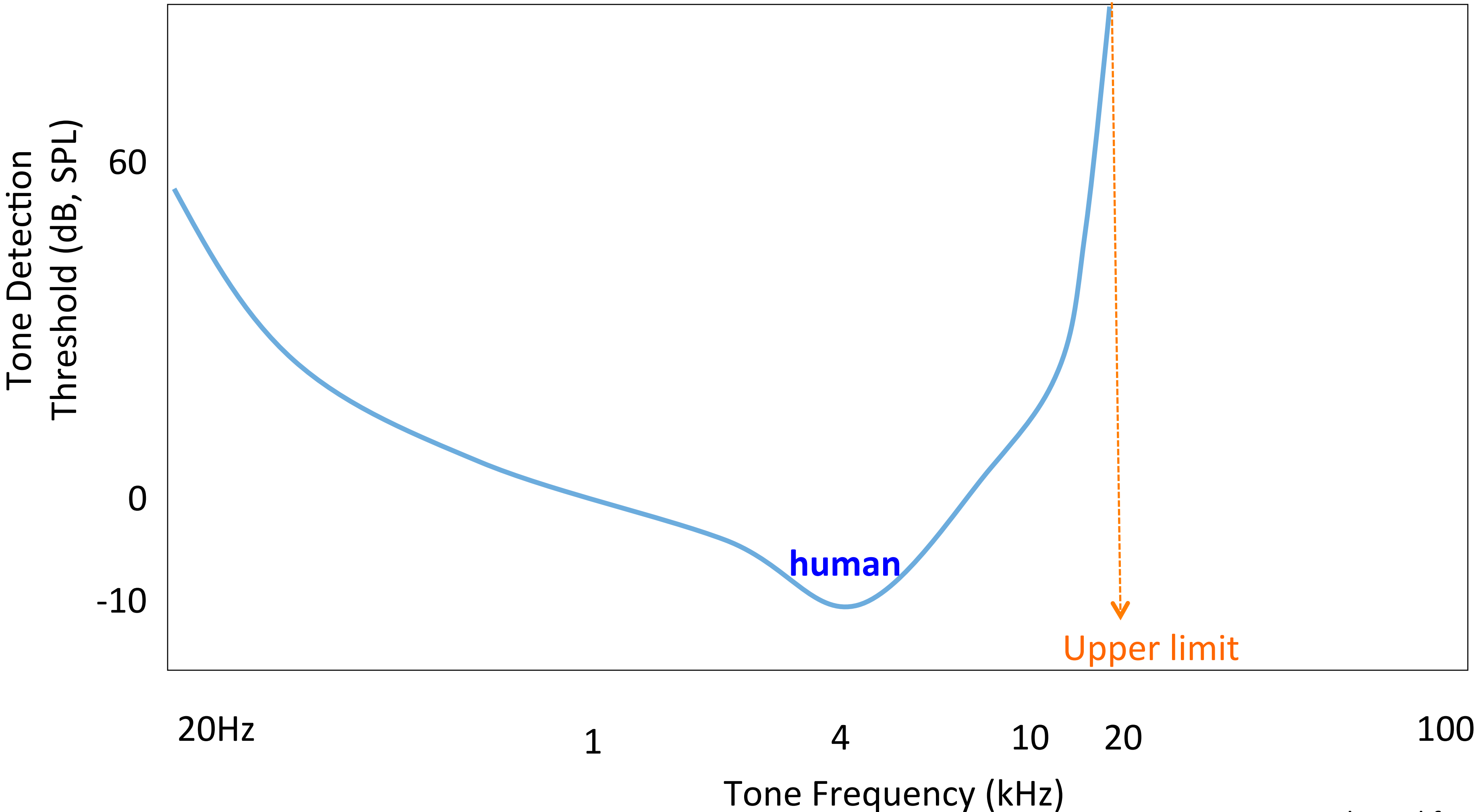
2. ***Cochleotopy*** in ascending primary auditory pathway

3. ***Cochleotopic*** sound processing streams in Inferior Colliculus

4. ***Cochleotopic*** auditory cortices

5. ***Parallel*** ascending thalamocortical pathways to primary and non-primary cortex

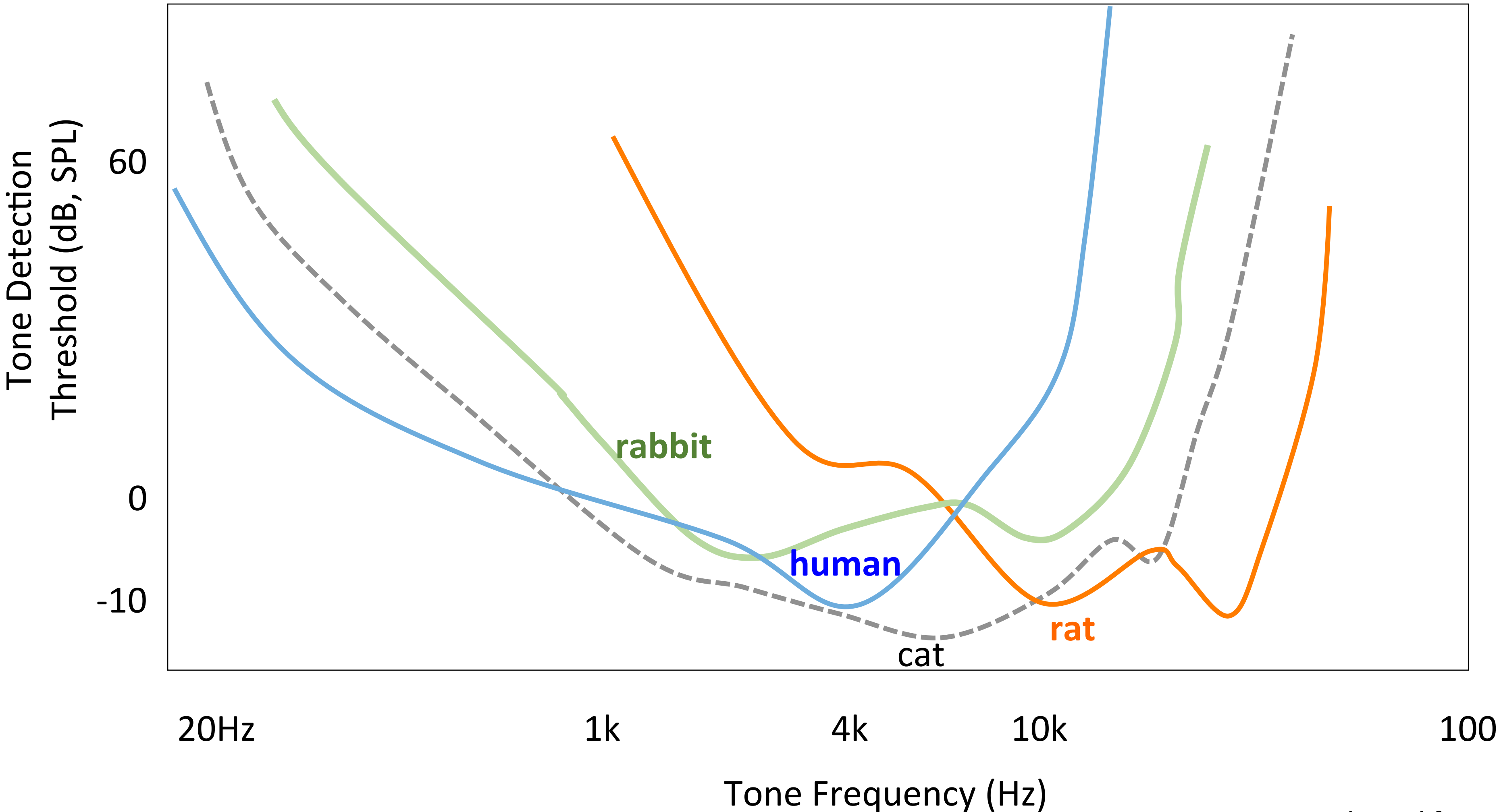
Audible sound frequency range in humans



Adapted from,
Gleich Otto and Strutz Jürgen (2012).

Heffner et al., Hearing Res. 1985, 1994
Koay, Heffner, Heffner, Hearing Res. 2002
Heffner, Anatomical Records, 2004

Audible sound frequency range varies in mammals



Adapted from,
Gleich Otto and Strutz Jürgen, 2012)

Heffner et al., Hearing Res. 1985, 1994
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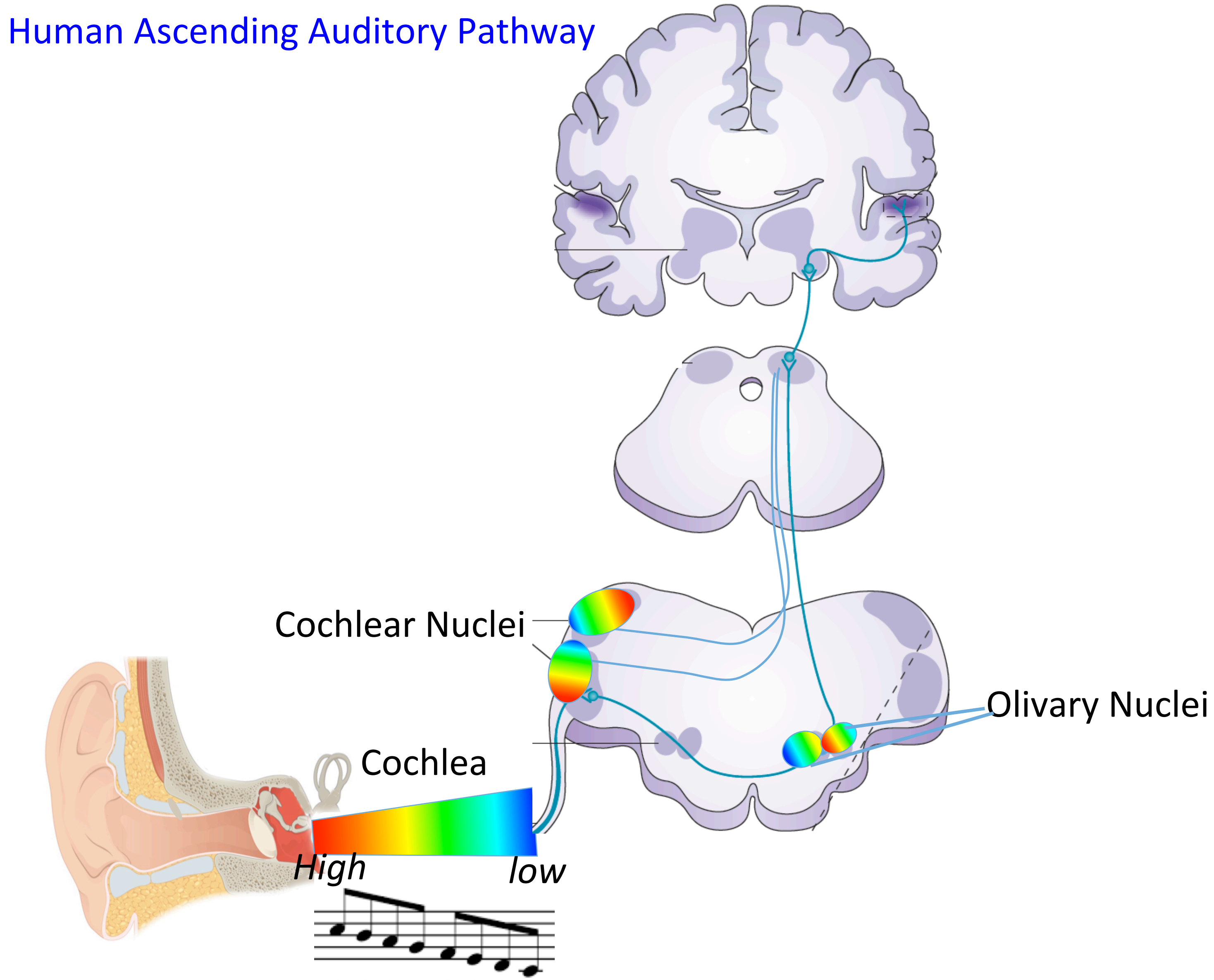
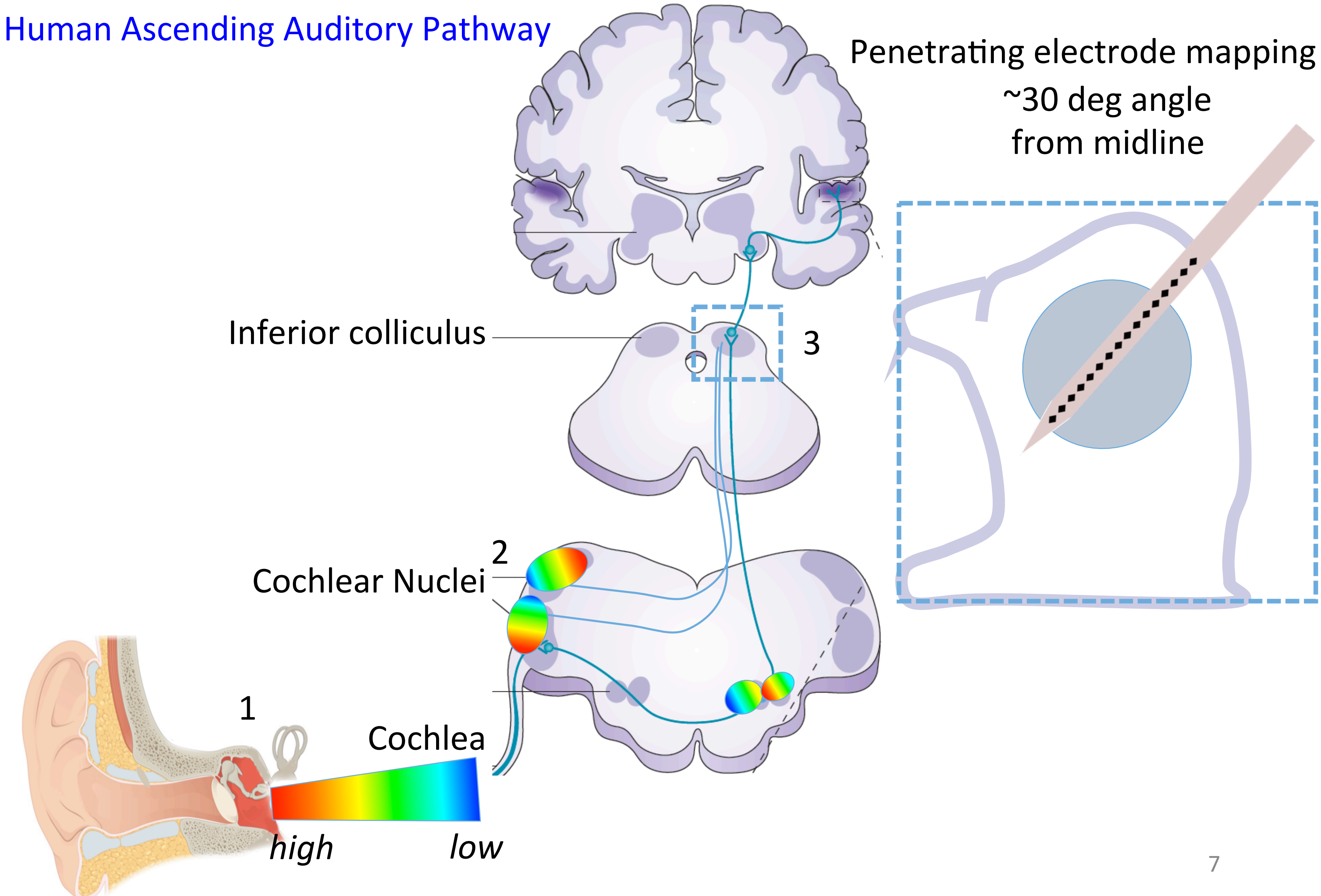
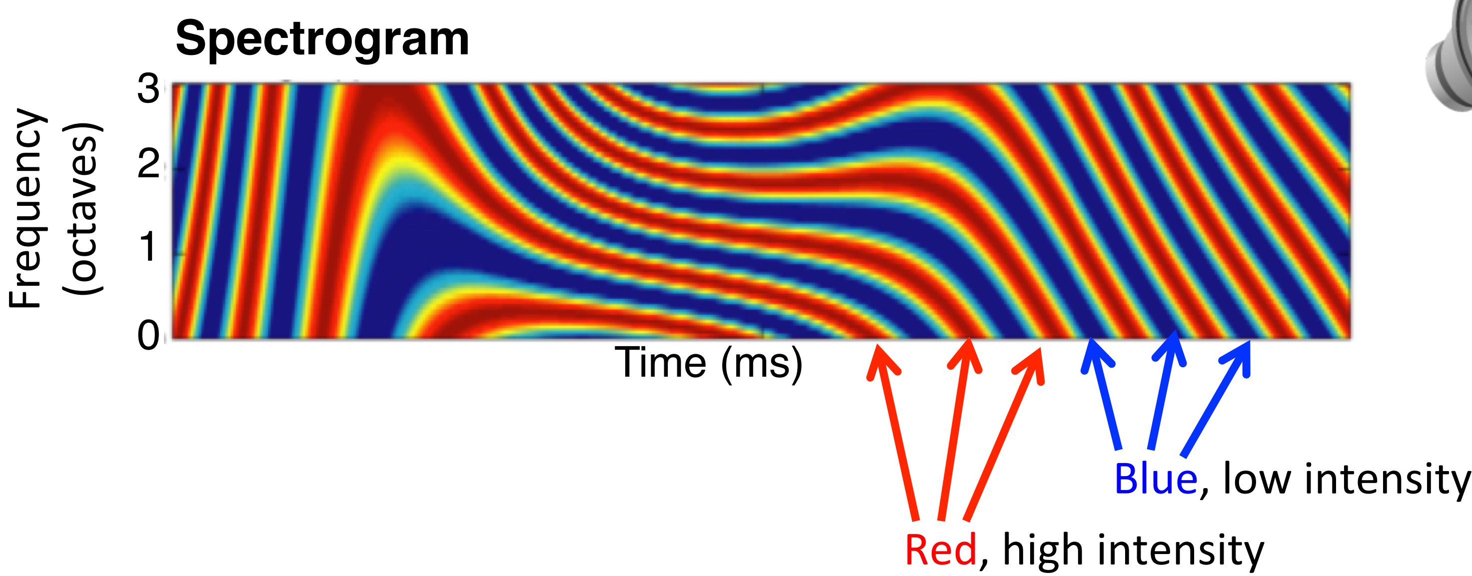
Background: Organization of ascending pathways



Inferior colliculus (IC) is a minimum of 3 synapses away from the cochlea.

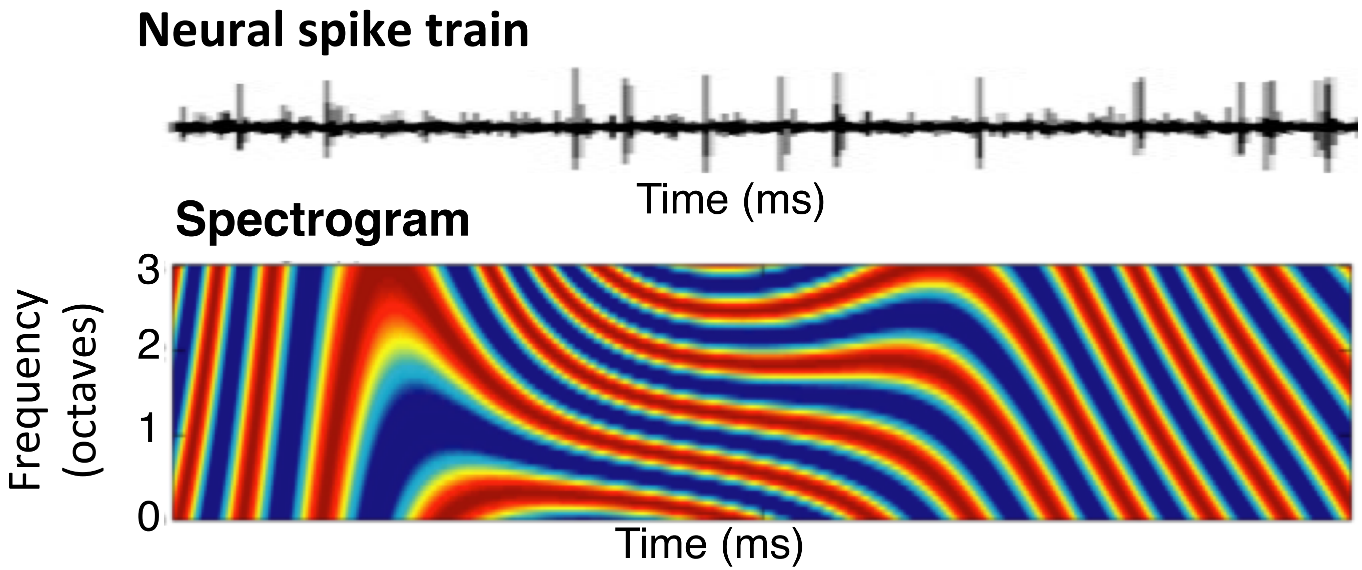


"Dynamic moving ripple" sounds probe large range of spectral temporal neuronal responses



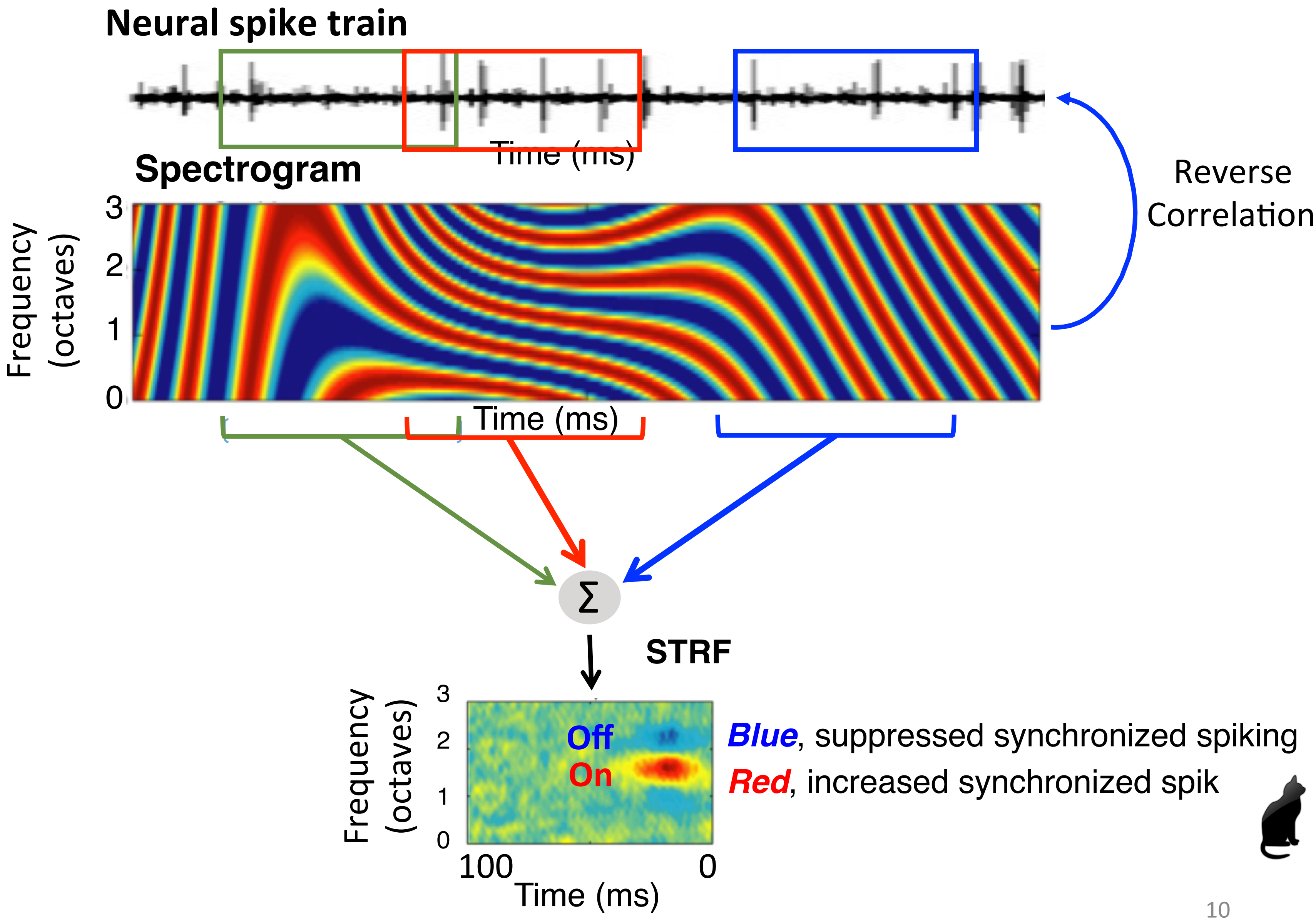
Escabi & Schreiner 2002

Probe neuronal spectral temporal response fields (STRF) with "*dynamic moving ripple*" sounds



Escabi & Schreiner 2002

Probe neuronal spectral temporal response fields (STRF) with "*dynamic moving ripple*" sounds



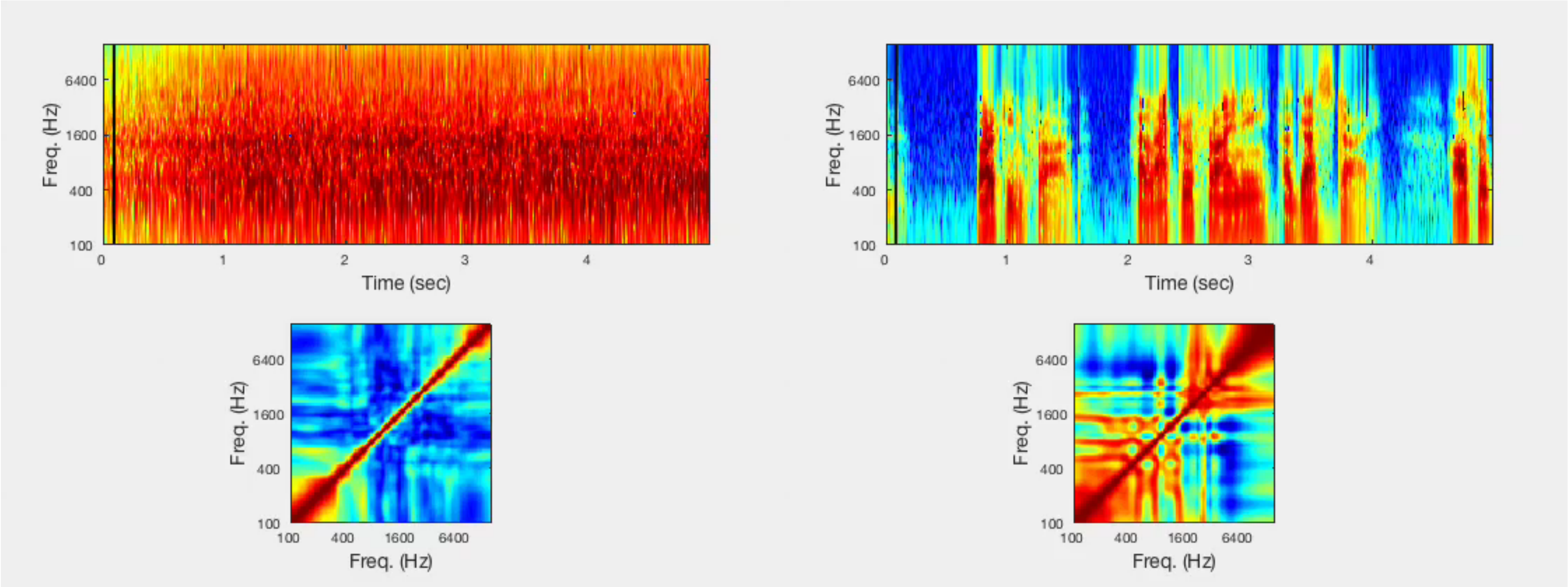
Blue, suppressed synchronized spiking
Red, increased synchronized spik

Escabi & Schreiner 2002

Natural sounds differ in short-term correlation statistics

Running Water

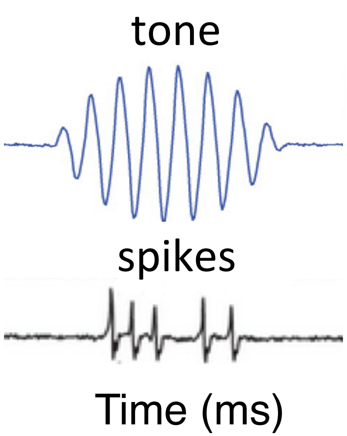
Speech

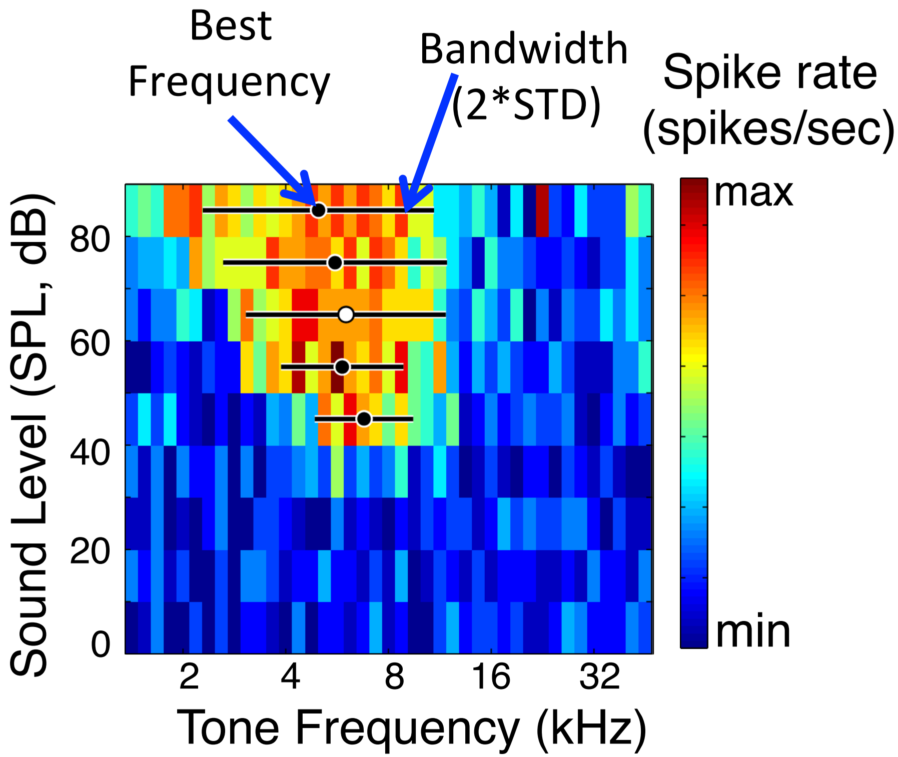


Water and backgrounds sounds are typically stationary

Speech and vocalizations are nonstationary

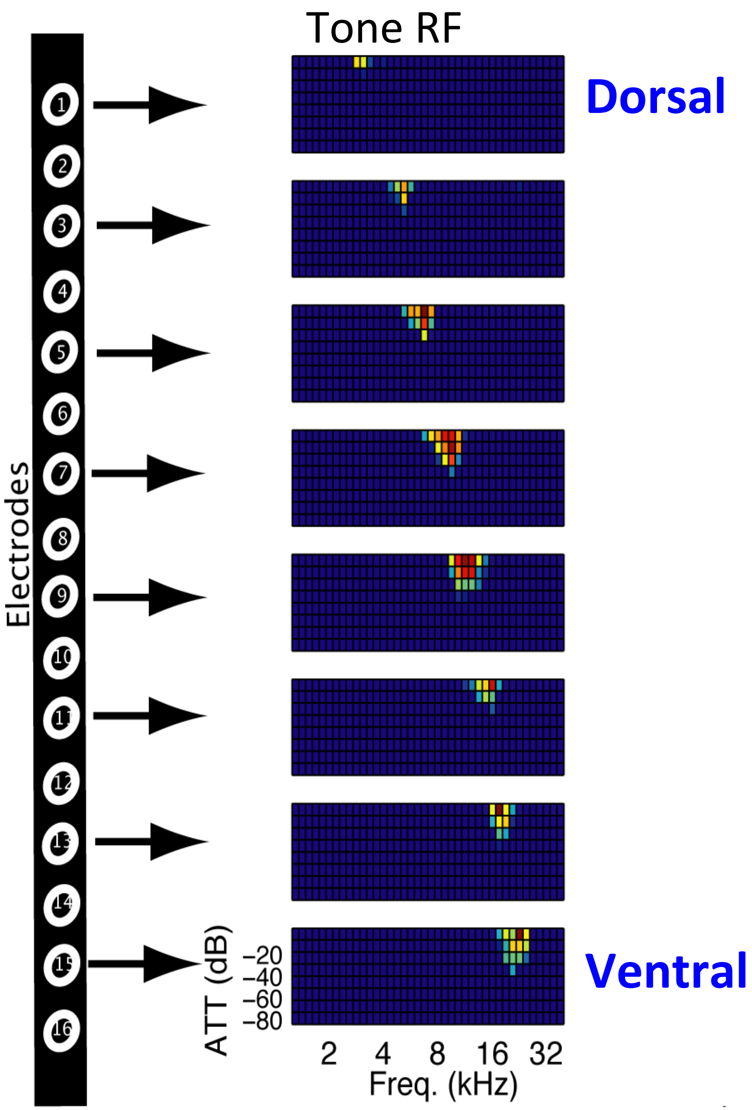
Spike rate responses to brief tone sounds to probe intensity-frequency response fields

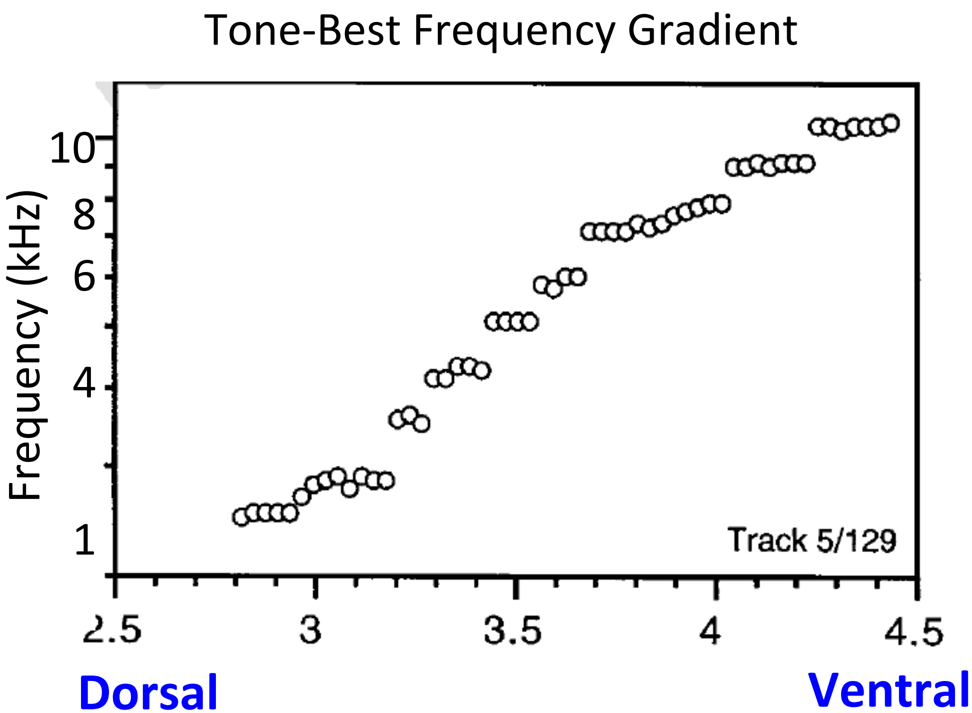




Storace, Higgins and Read,
J Comp. Neurol. 2011

Tone Receptive Field (RF) mapping confirms low-to-high frequency gradient in dorsal-to-ventral dimension of Inferior Colliculus



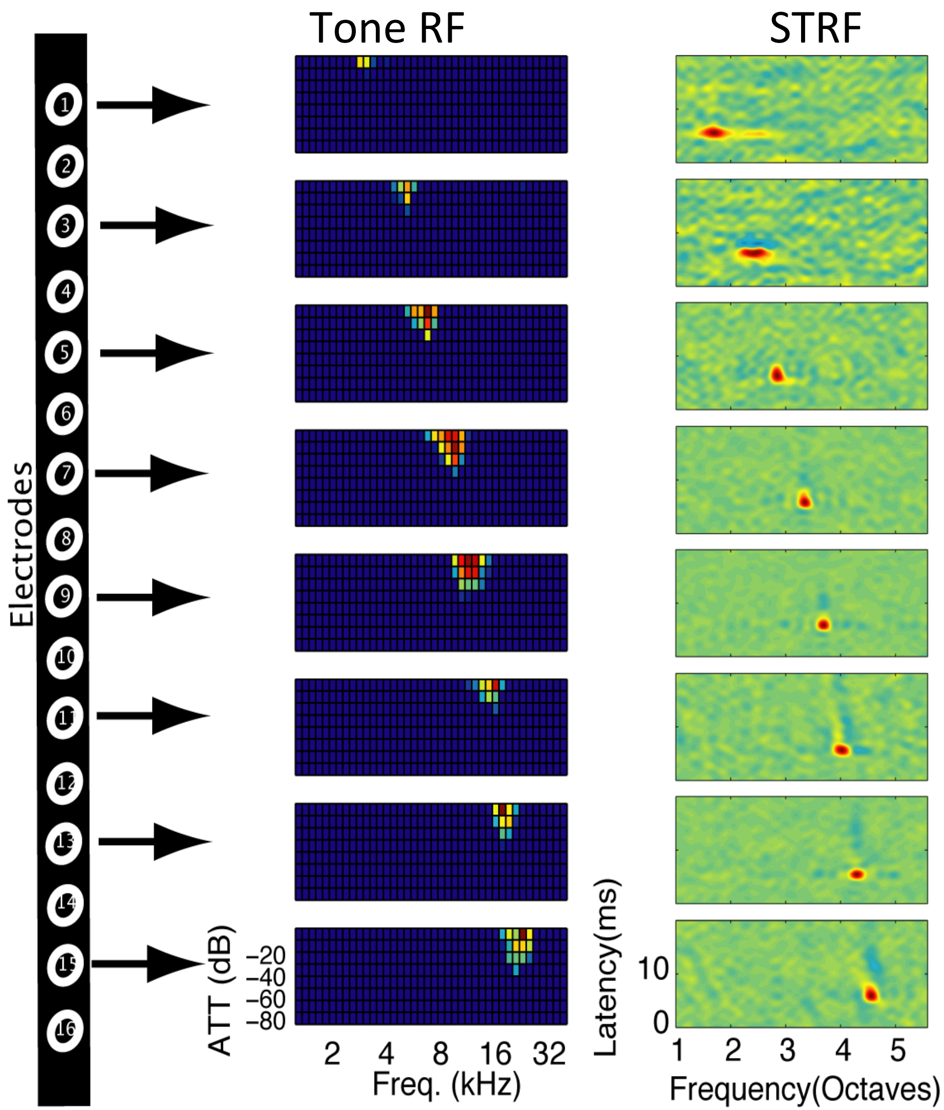


Schreiner and Langner, Nature 1997

Physiologic shifts in BF align to IC neuron dendrites and input from the cochlear nucleus.

Rodriguez, Read and Escabi, J Neurophys, 2010

Dynamic moving ripple and *tone* receptive fields same low-to-high best frequency gradient direction



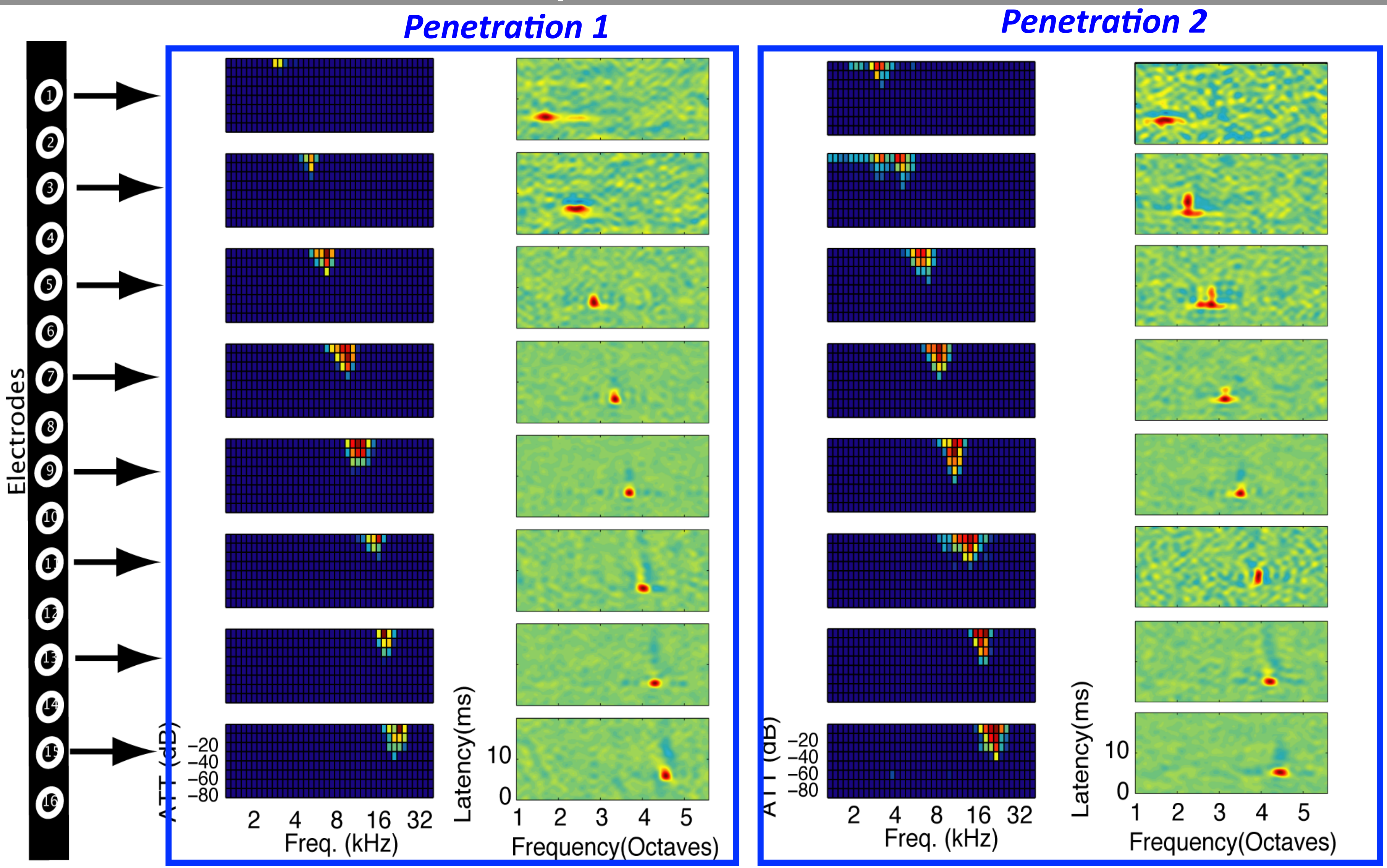
***Significance*:**

Best frequency responses and the gradient direction are stable properties observed with many sounds in IC.

Modified from

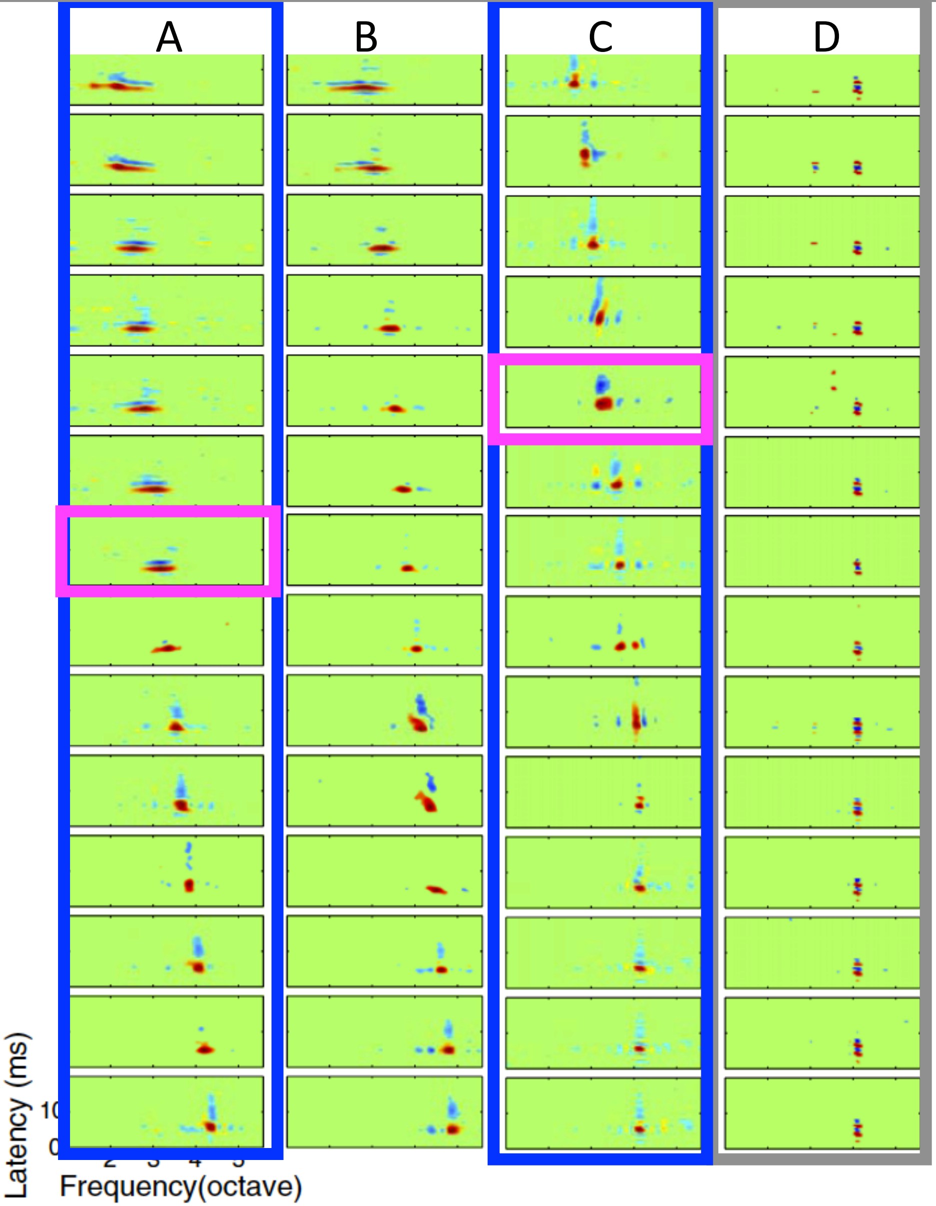
Rodriguez, Read and Escabi, J Neurophys, 2010

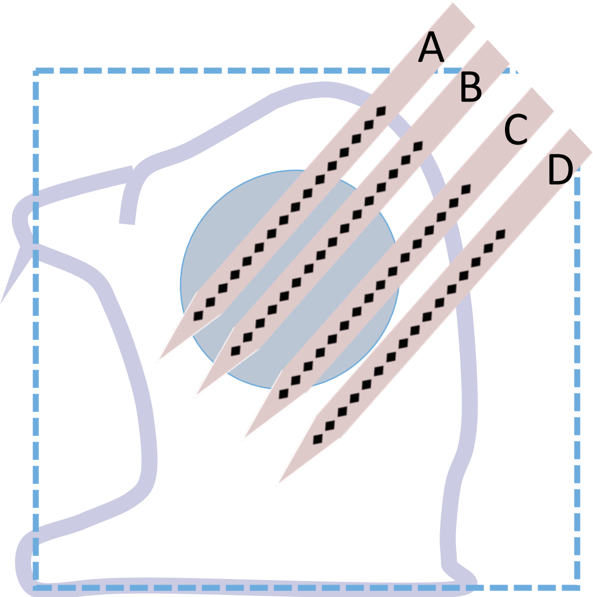
Same low-to-high frequency gradient direction for all dorso-ventral electrode penetrations in Inferior Colliculus



Modified from
Rodriguez, Read and Escabi, J Neurophys, 2010

STRF properties vary across penetrations and within frequency layers





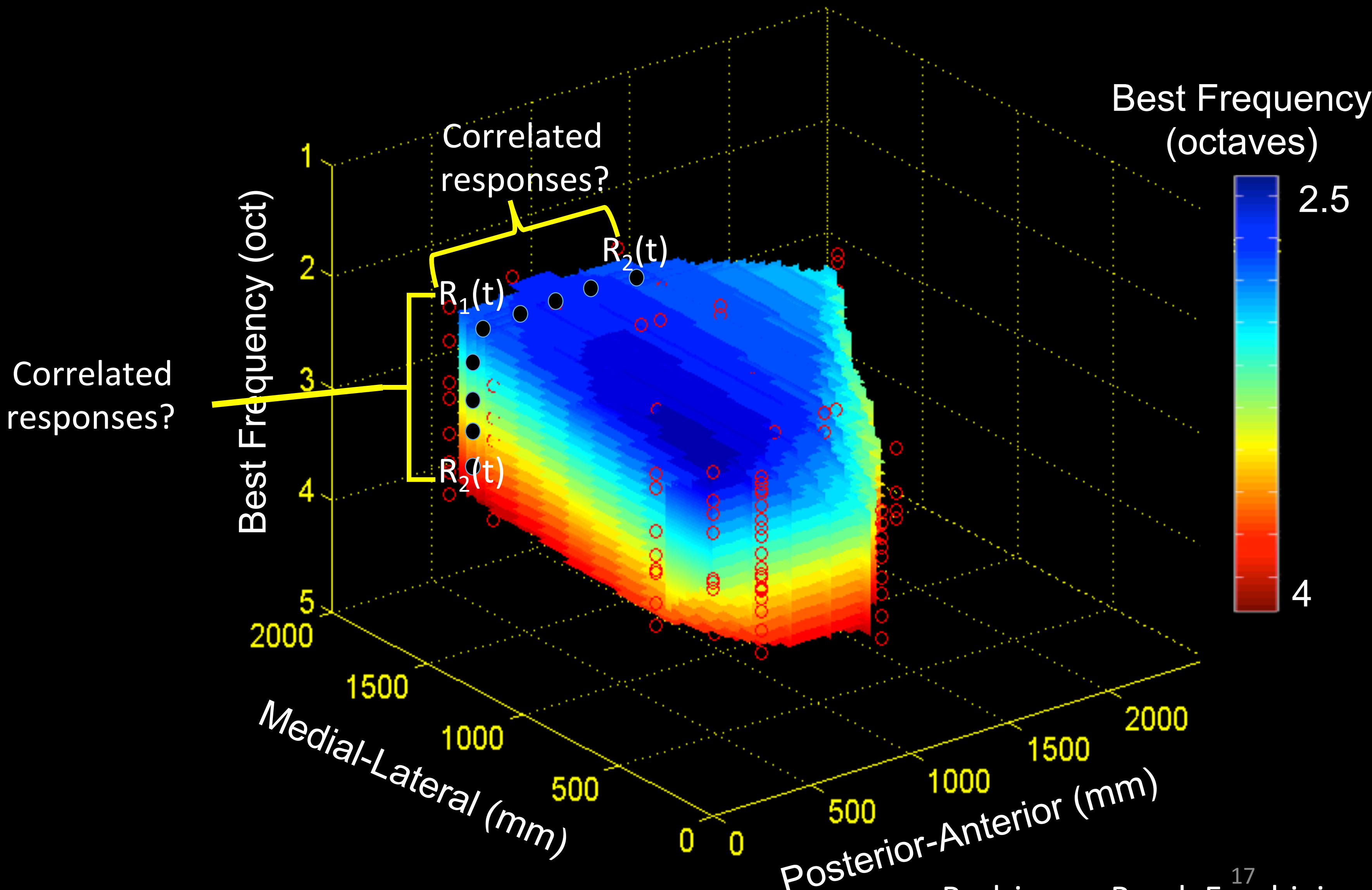
Penetration D:
STRF's don't change outside Central IC

Penetrations A and C:
Same low-to-high best frequency (BF) gradient

....but STRF shape is changing.

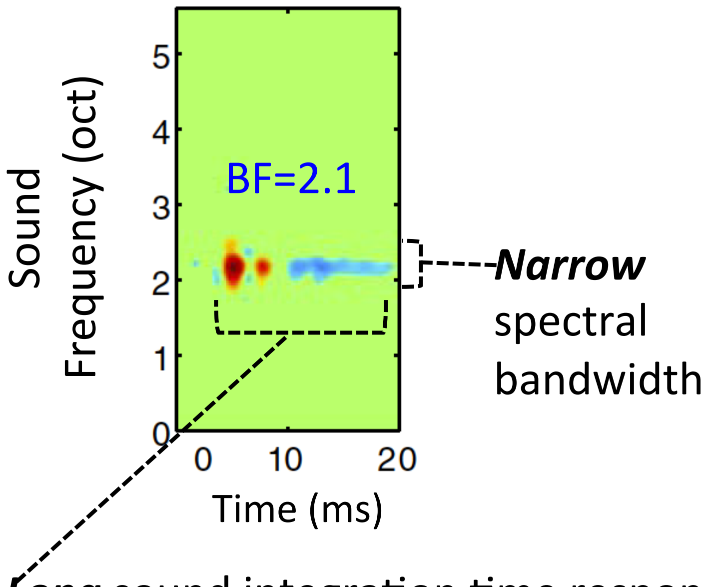
Modified from
Rodriguez, Read and Escabi, J Neurophys, 2010

Laminar organization when STRF best frequency (BF) is rendered in 3-dimensions



Rodriguez, Read, Escabi, in p

Variation in STRF spectral and temporal properties for neurons with same best frequency (BF)

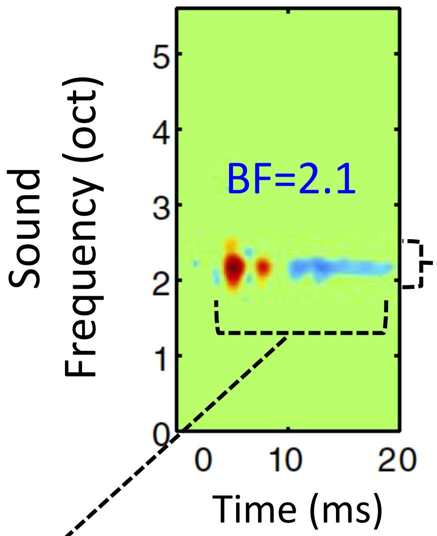


Long sound integration time responds to
Slow sound modulation frequencies

Cat

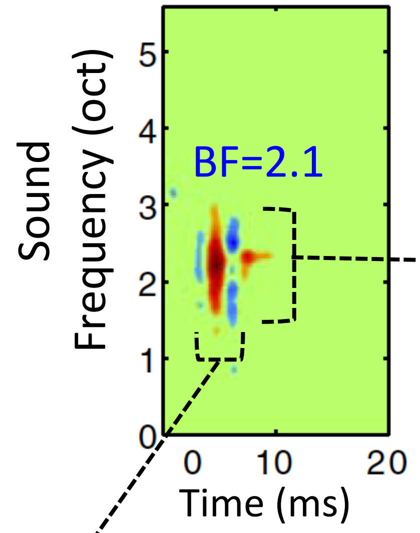
Rodriguez, Read and Escabi
J Neurophys, 2010

IC neurons with matched Best Frequency (BF) can vary in other spectral and temporal properties evident in the STRF



High *(cycles/oct)*
Frequency modulation sensitivity

Slow *(cycles/sec)*
time modulation sensitivity



Low *(cycles/oct)*
Frequency modulation sensitivity

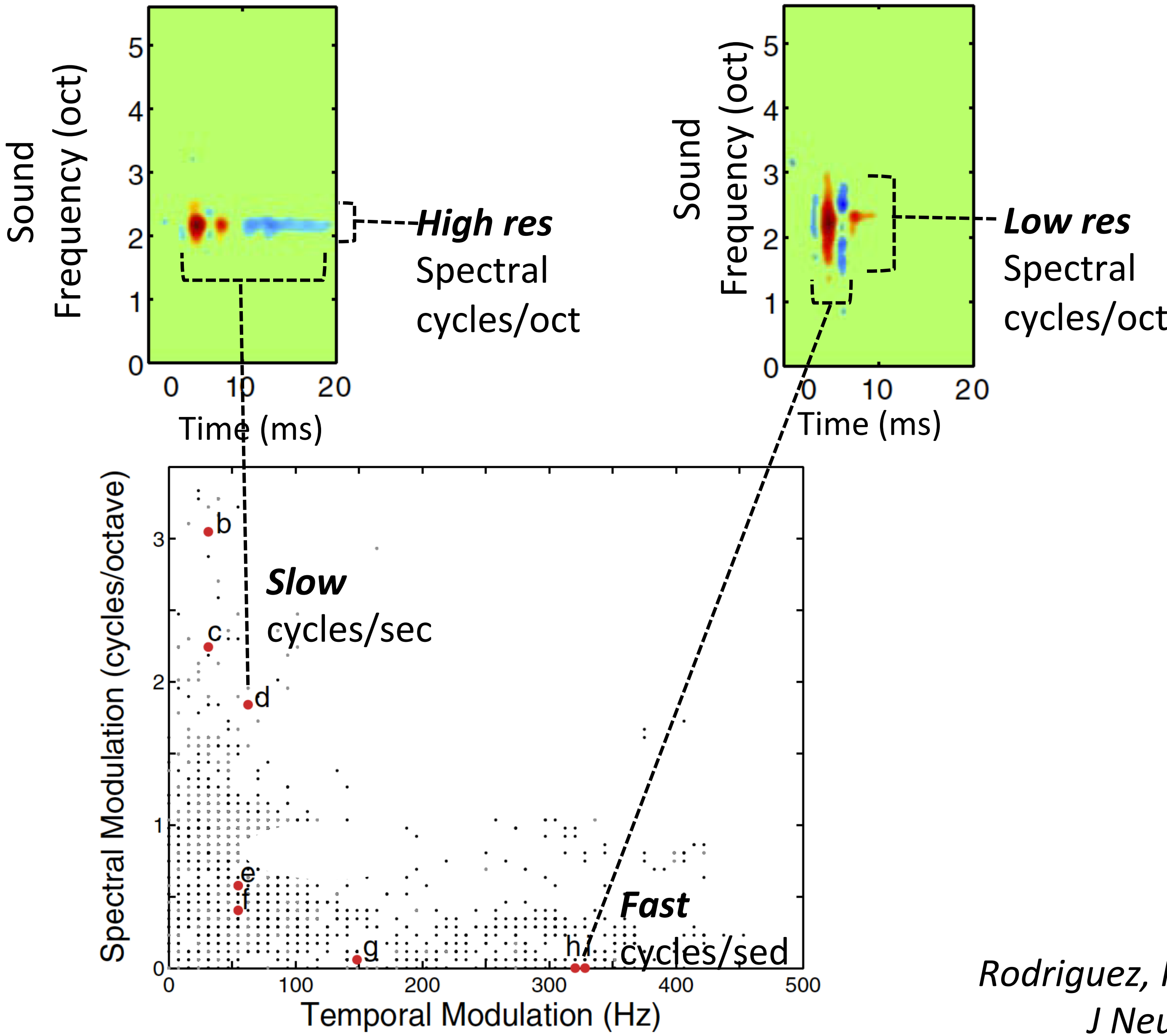
Fast *(cycles/sec)*
time modulation sensitivity

1. STRFs recorded from same frequency layer but different electrode positions
2. Best Frequency (BF) similar yet STRF very different!!!

Cat

Rodriguez, Read, Escabi., J Neurophys, 2010

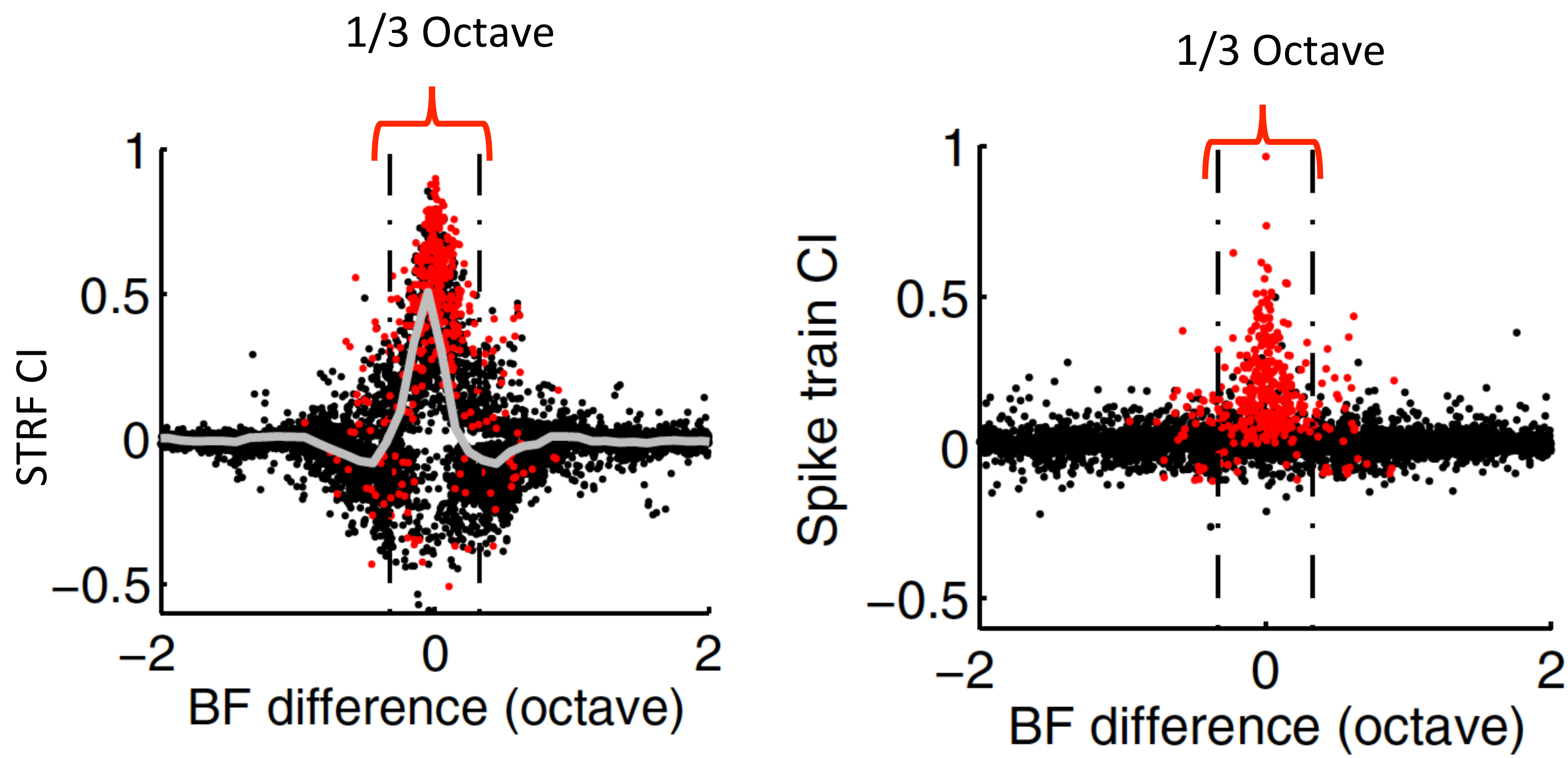
The population of STRFs demonstrates "trade-offs", possibly reflects optimal processing of different acoustic features in IC



Cat

Rodriguez, Read, Escabi., J Neurophys, 2010

Significant correlations between neuron pairs with < 1/3 octave separation for Best Frequency



****Red dot*** significant correlations $p < 0.0001$

STRF correlations higher than spike train

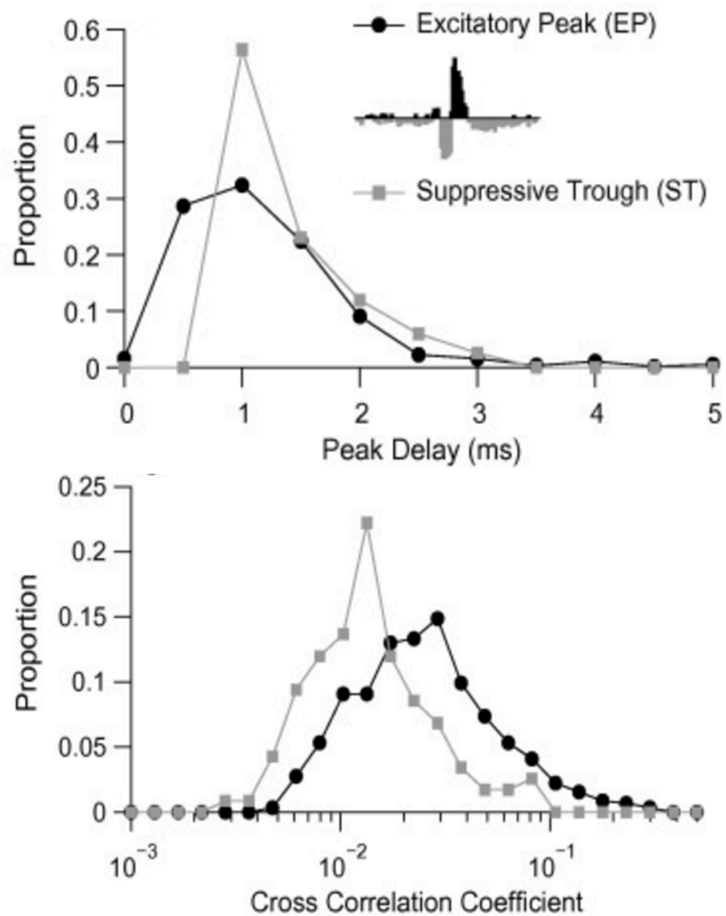
STRF and spike train correlations are both ~1/3 octave

Cat

Chen, Read and Escabi

J Neuroscience, 2012

Higher correlations between STRF excitatory peak for pairs of neurons in IC



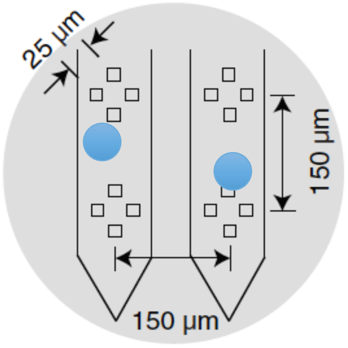
Cat

Antencio, Shen, Schreiner, Neuroscience, 2016

Examine response correlations as a function of proximity within Inferior Colliculus

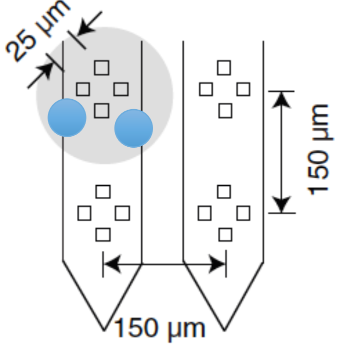
Adjacent Tetrodes

(≥ 150 µm)

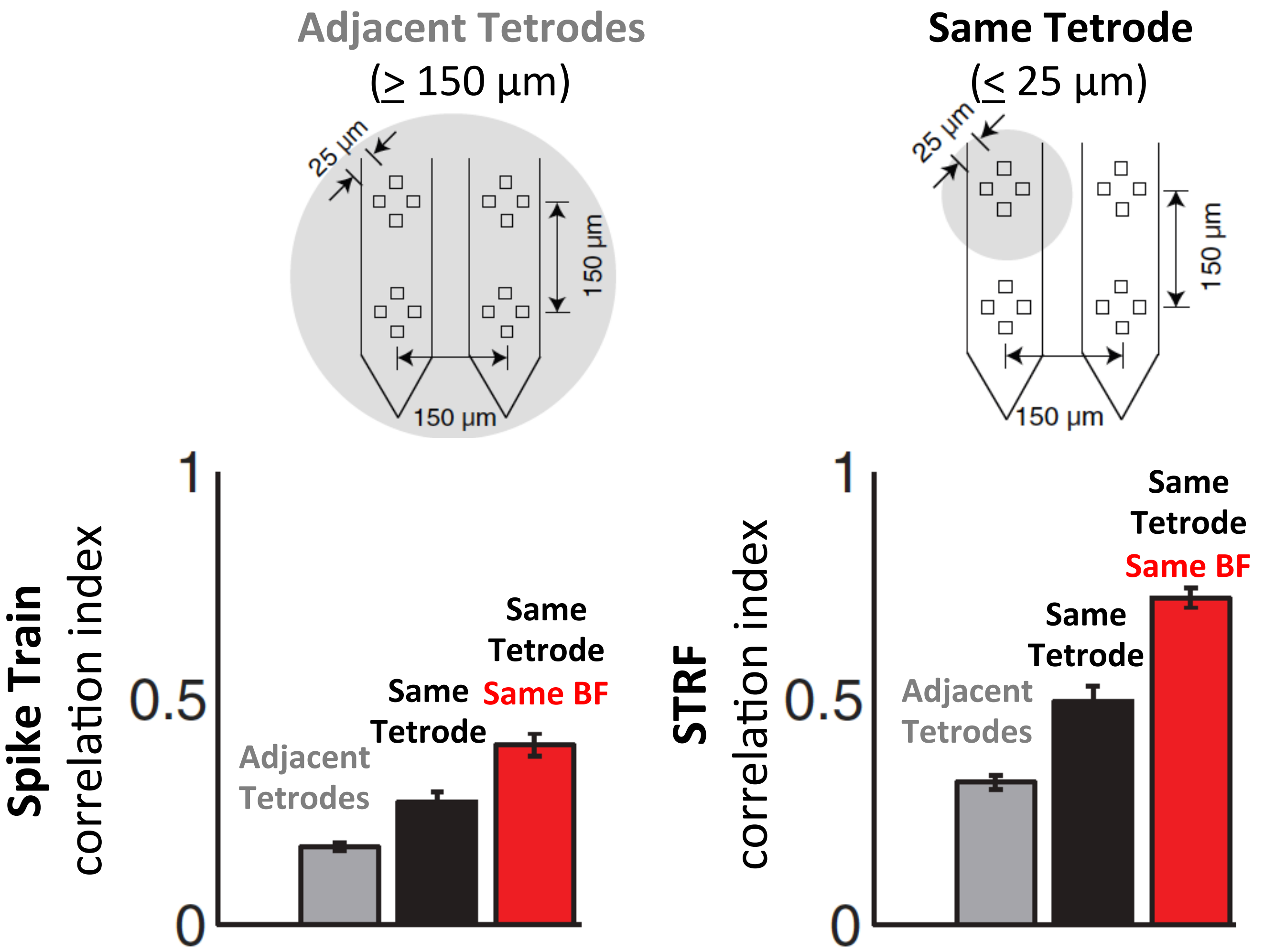


Same Tetrode

(≤ 25 µm)

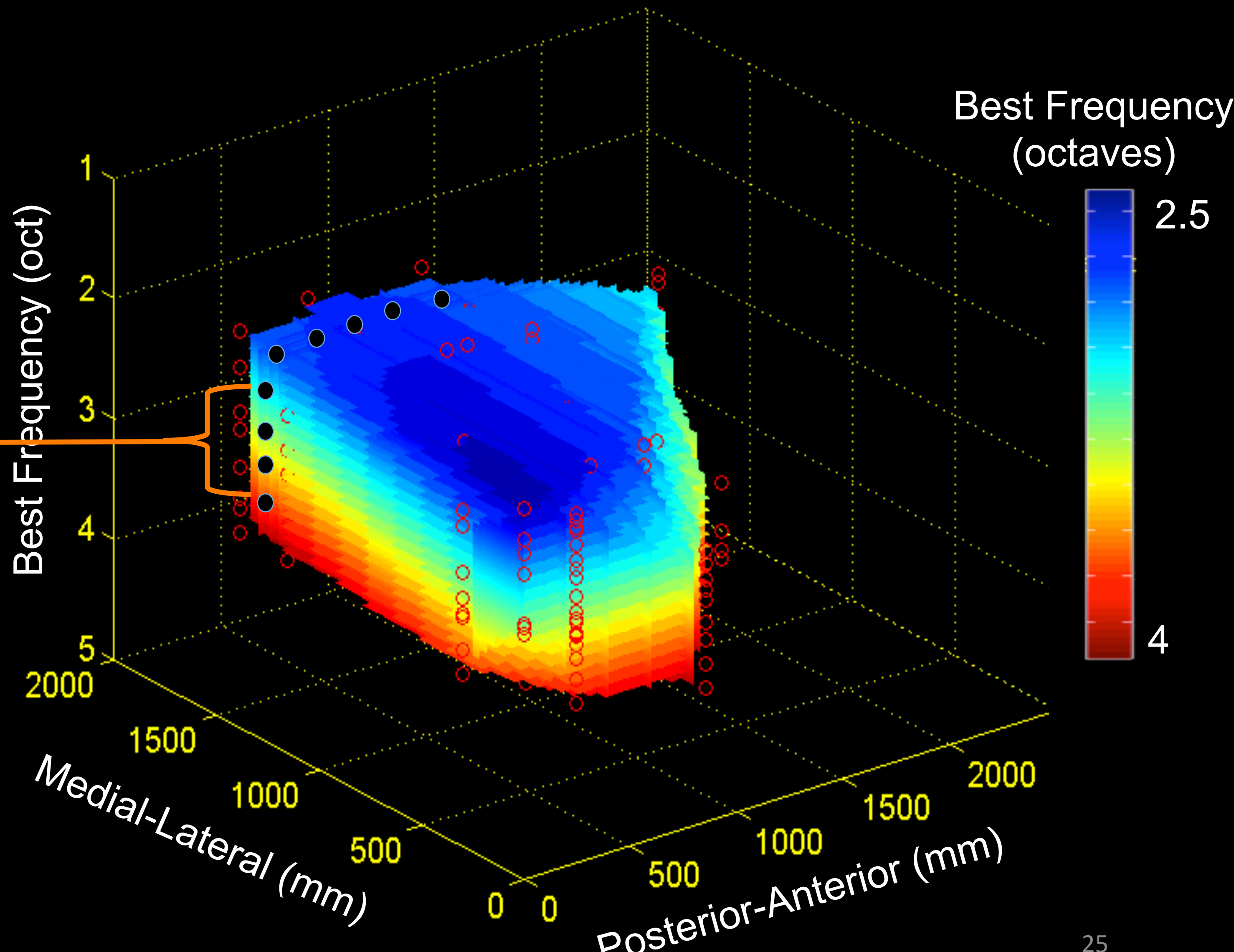


Spike train and Receptive field (STRF) correlations highest for neighboring neuron pairs with same Best Frequency (BF)



Chen, Rodriguez, Read and Escabi
Frontiers Neural Circuits, 2012

Significance

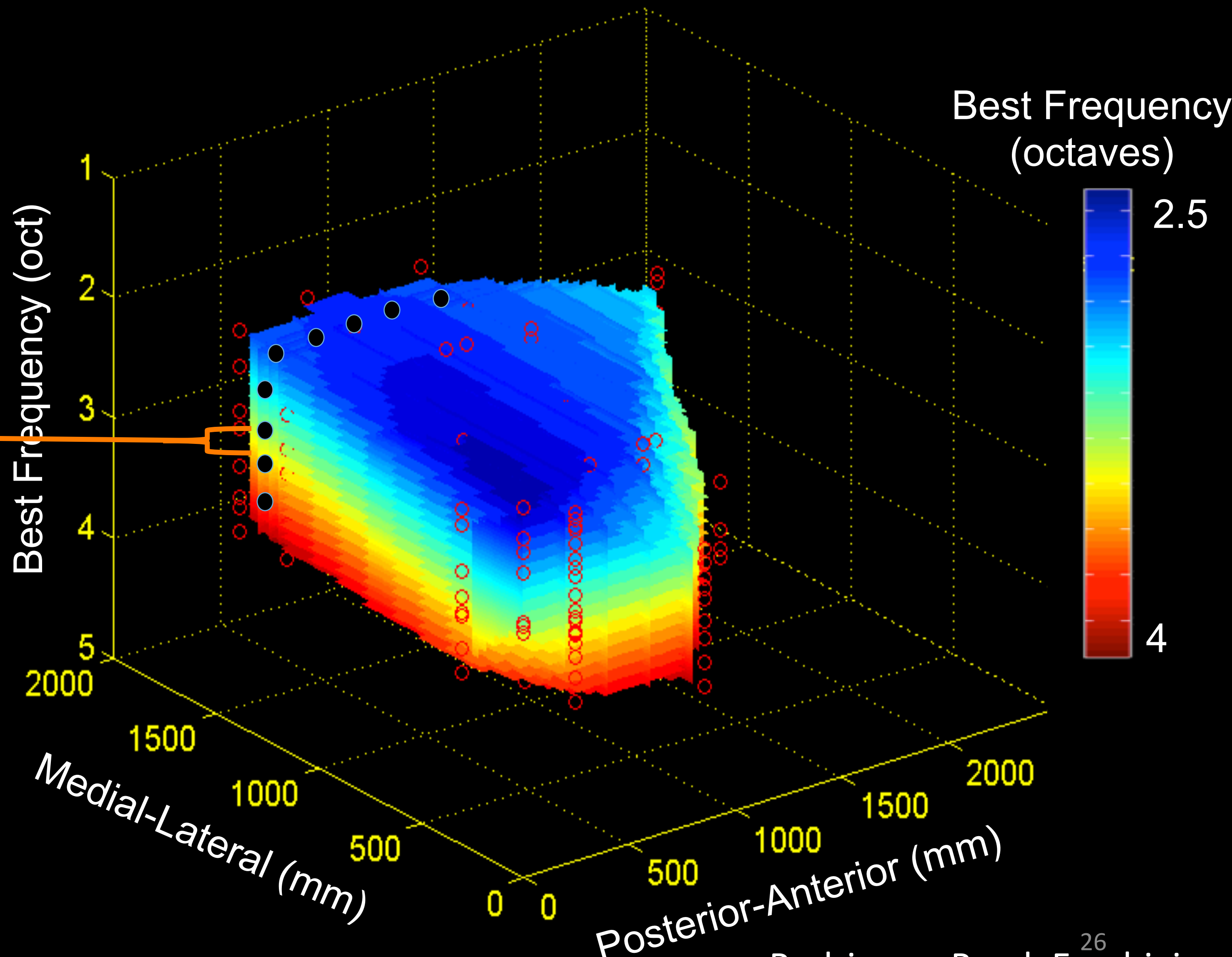


Minimal Correlations
Far apart and >1/3 octave

Rodriguez, Read, Escabi, in p

Significance

Maximal Correlations nearby <1/3 octave



Rodriguez, Read, Escabi, in p

Significance of spatial and 1/3 octave limits for correlated output

1) Consistent with *sparse* correlated neuronal spike output.

2) Potential neural mechanism for *grouping sound features* within perceptual limits such as critical bandwidth (cat frequency perception: Pickles, 1975).

3) Neurons must be nearby [25-150 µm] to have highly correlated spike time output

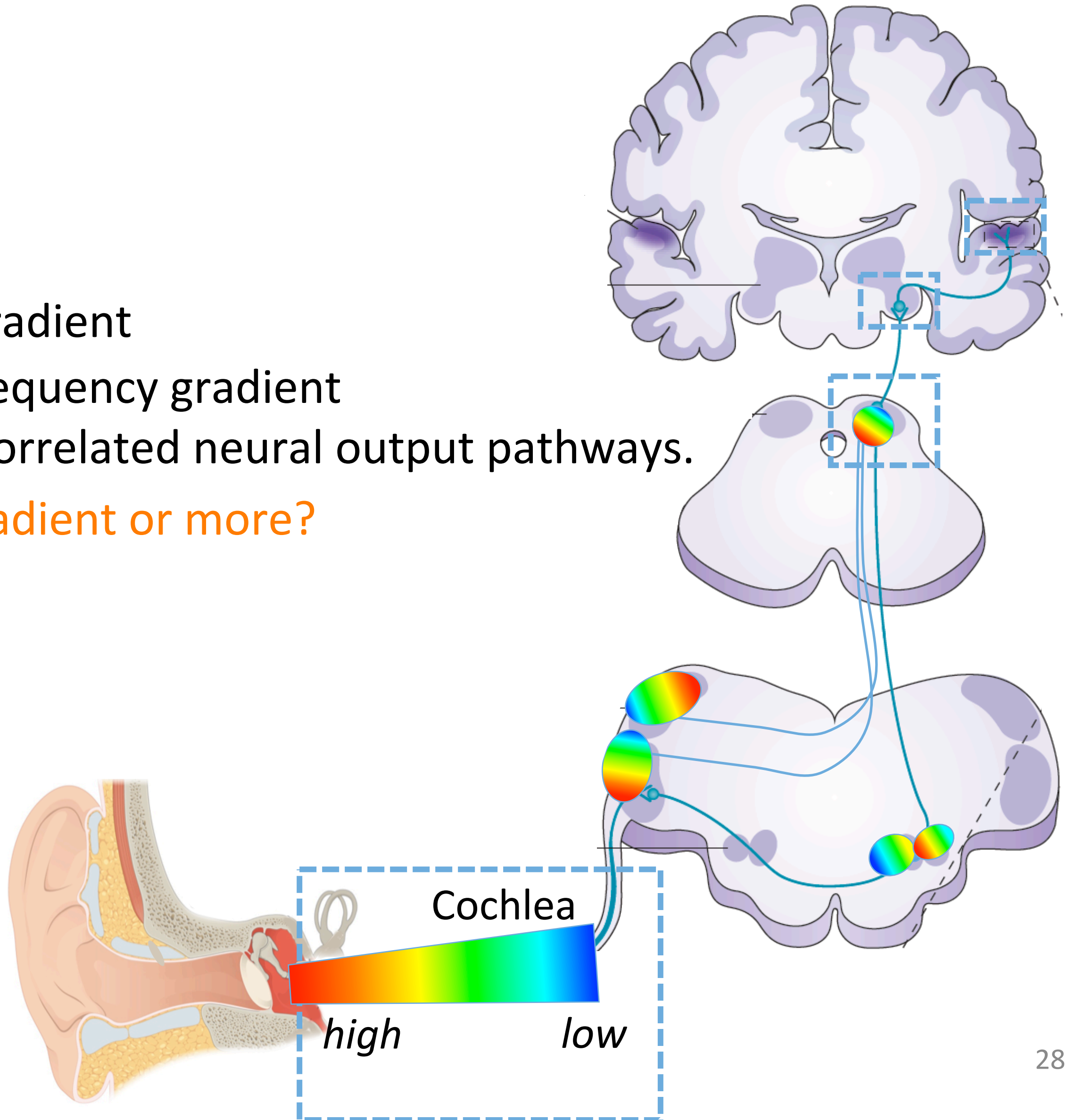
4) Inferior Colliculus output pathways are highly parallel!!

General Conclusions

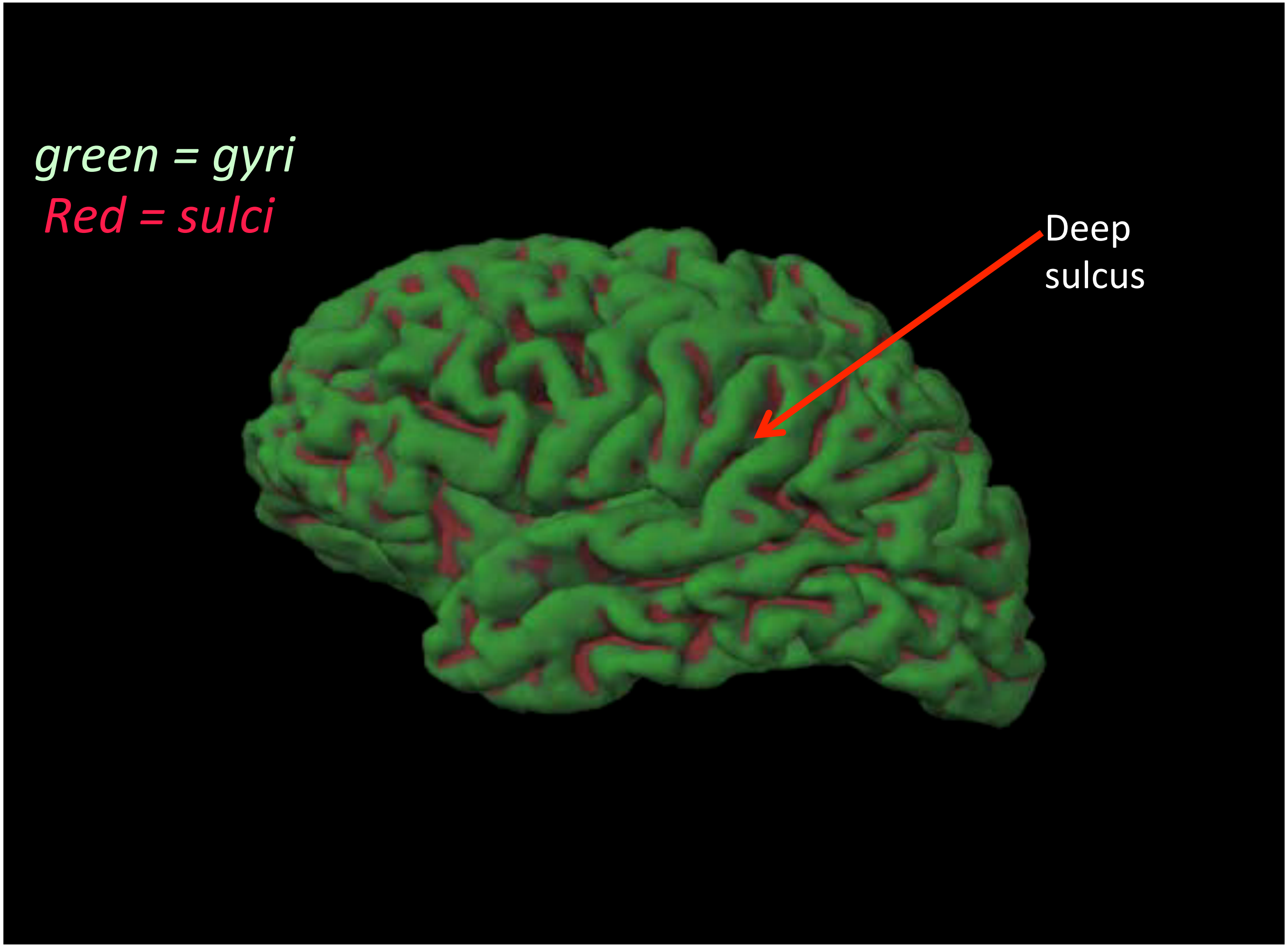
1. Cochlea -one frequency gradient

2. Inferior Colliculus –one frequency gradient
but many "sparse" parallel correlated neural output pathways.

3. Cortex - one frequency gradient or more?

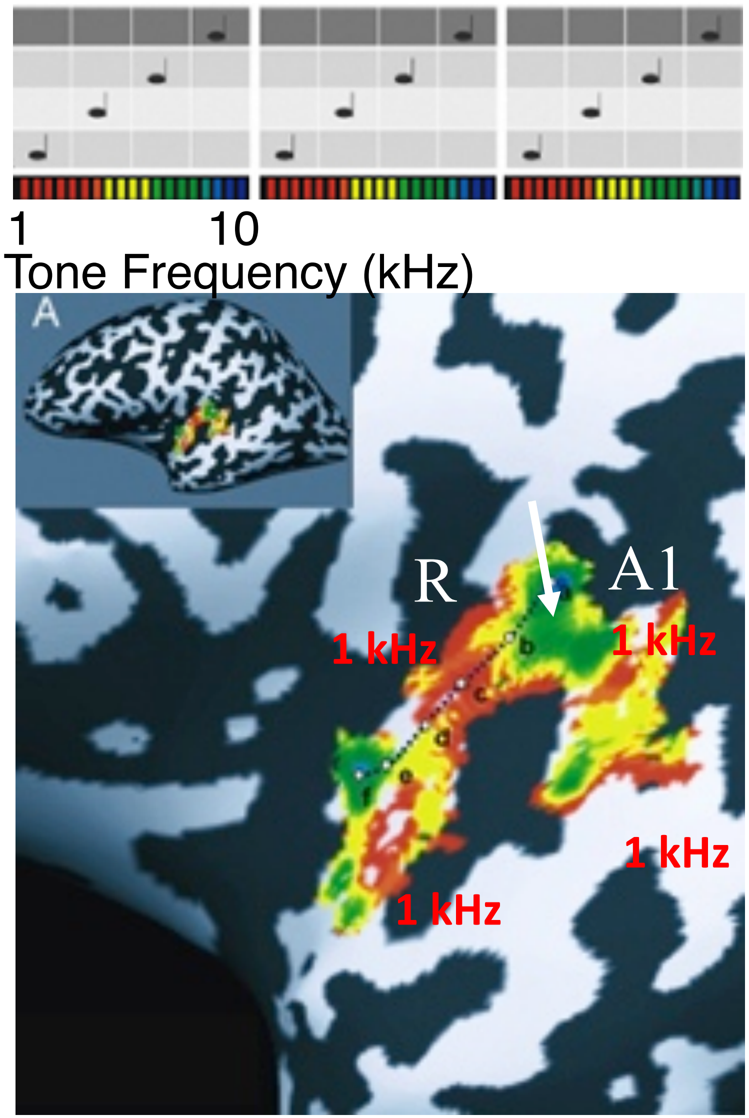


Flattening magnetic resonance image (MRI) reveals human auditory cortex in deep sulci



Marty Sereno, UCSD
http://www.cogsci.ucsd.edu/~sereno/

Flattened functional magnetic resonance image (fMRI) tone responses in human brain

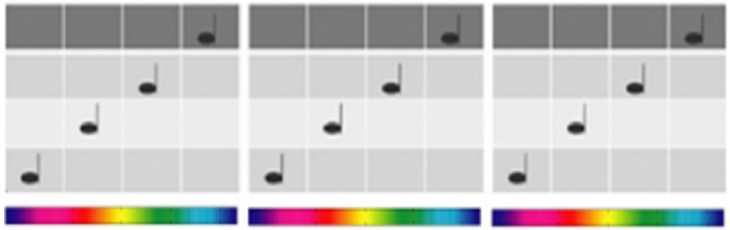


Four “low frequency” areas sensitive to 1 kHz tones

Primary (A1) and Rostral (R) fields share border responding to high (arrow) tone frequency

Forminsano et al., Nature 2003

Optical imaging of intrinsic metabolic tone responses in rat brain

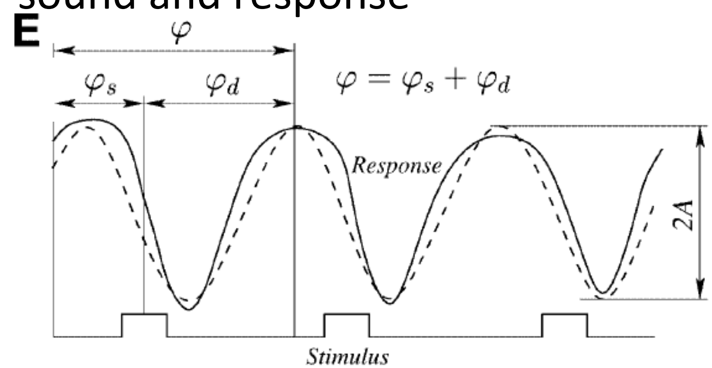


2 32
Tone Frequency (kHz)

1. Surgically expose surface of temporal cortex
2. Play continuous sound sequence
3. Measure light reflectance change (ΔR) known to be associated with oxygenation of hemoglobin

Dalsa CCD camera
30 frames/sec

4. Compute phase delay between sound and response



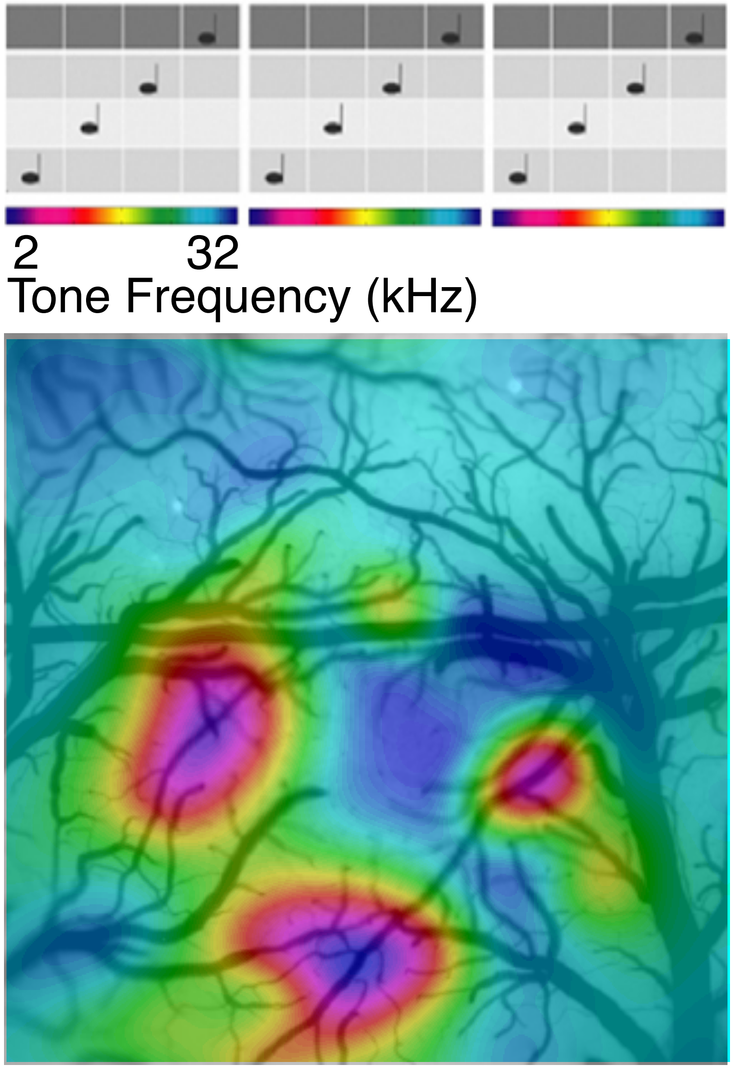
Phase ϕ time when response reaches maximum relative to a reference point (Q_s, stim; Q_d, hemodynamic delay)

Kalatsky Stryker, Neuron 2003
Kalatsky et al., PNAS 2005

Optical image of intrinsic metabolic tone responses in rat brain

2 32
Tone Frequency (kHz)

Dorsal

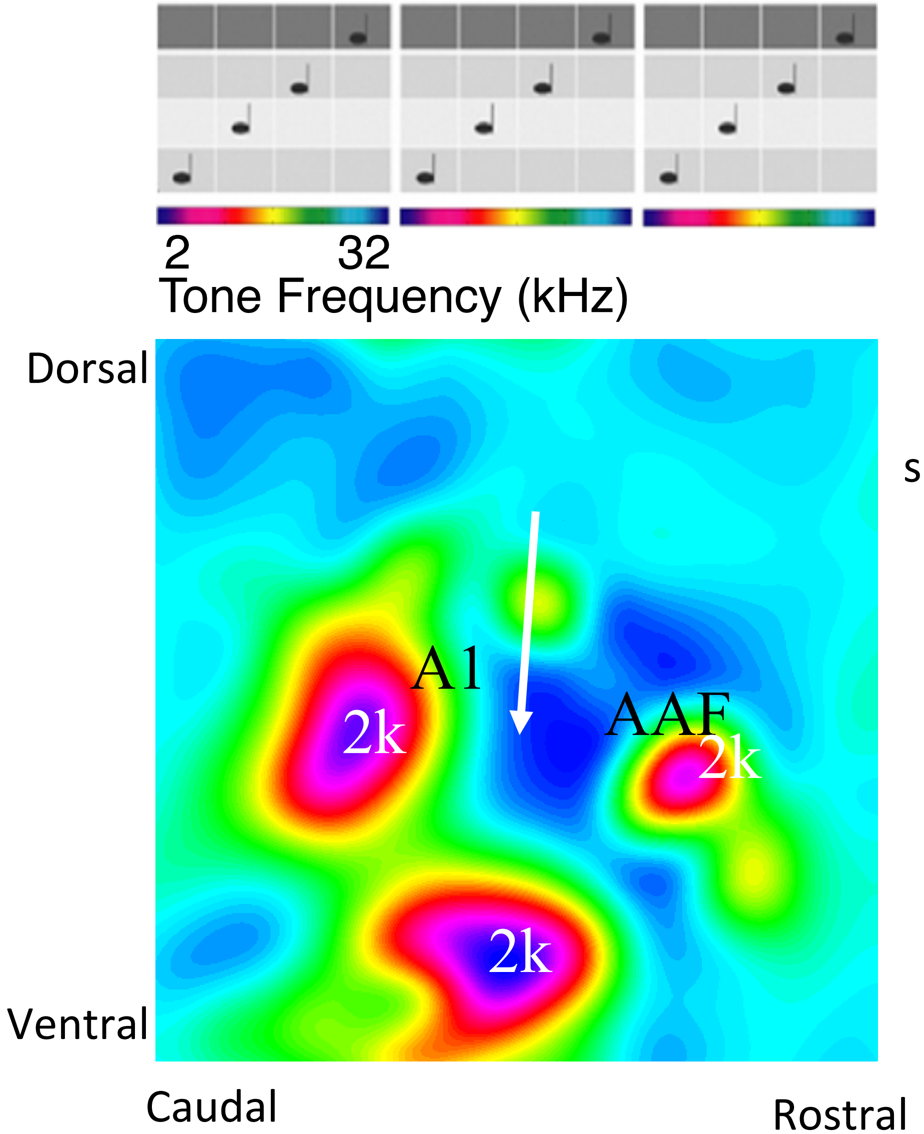


Ventral

Caudal Rostral

Read lab,
Higgins et al., J Neurosci 2010

Optical image of intrinsic metabolic tone responses in rat brain

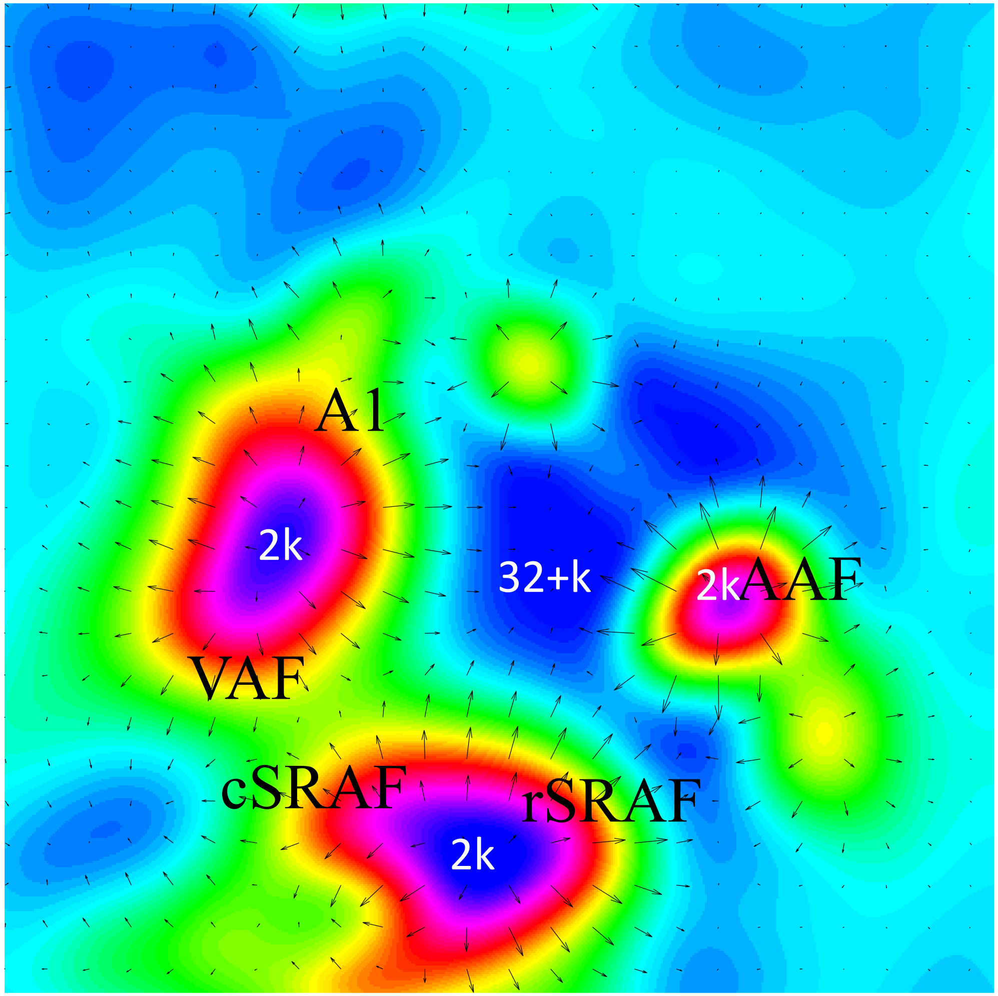


Three "low frequency" areas sensitive to ***2 kHz*** tones Multiple Areas:

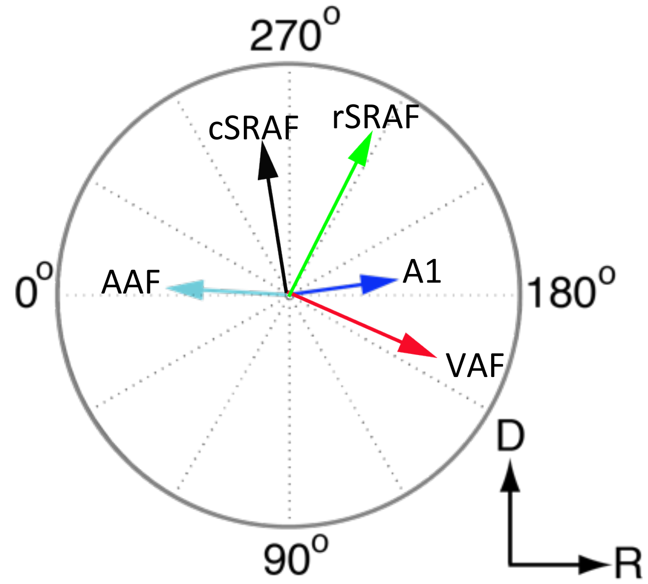
Primary (A1) and Anterior (AAF) fields share border responding to high (arrow) tone frequency

Read lab,
Higgins et al., J Neurosci 2010

Tone frequency response gradients define multiple fields

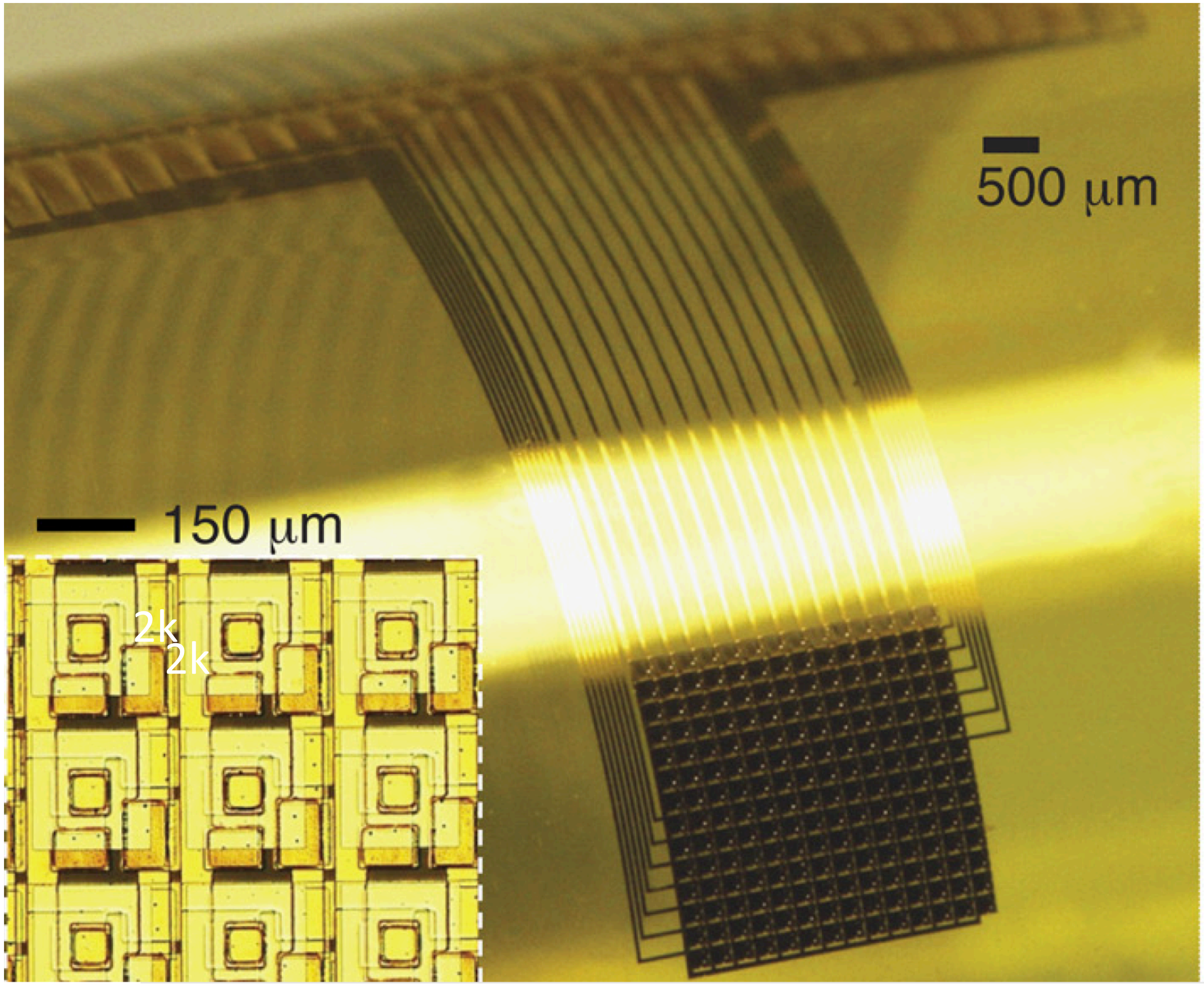


Frequency gradients



Read lab,
Higgins et al., J Neurosci 2010

Cochleotopy evident electrocorticography (ECoG) surface local field potentials if using high density surface electrode arrays



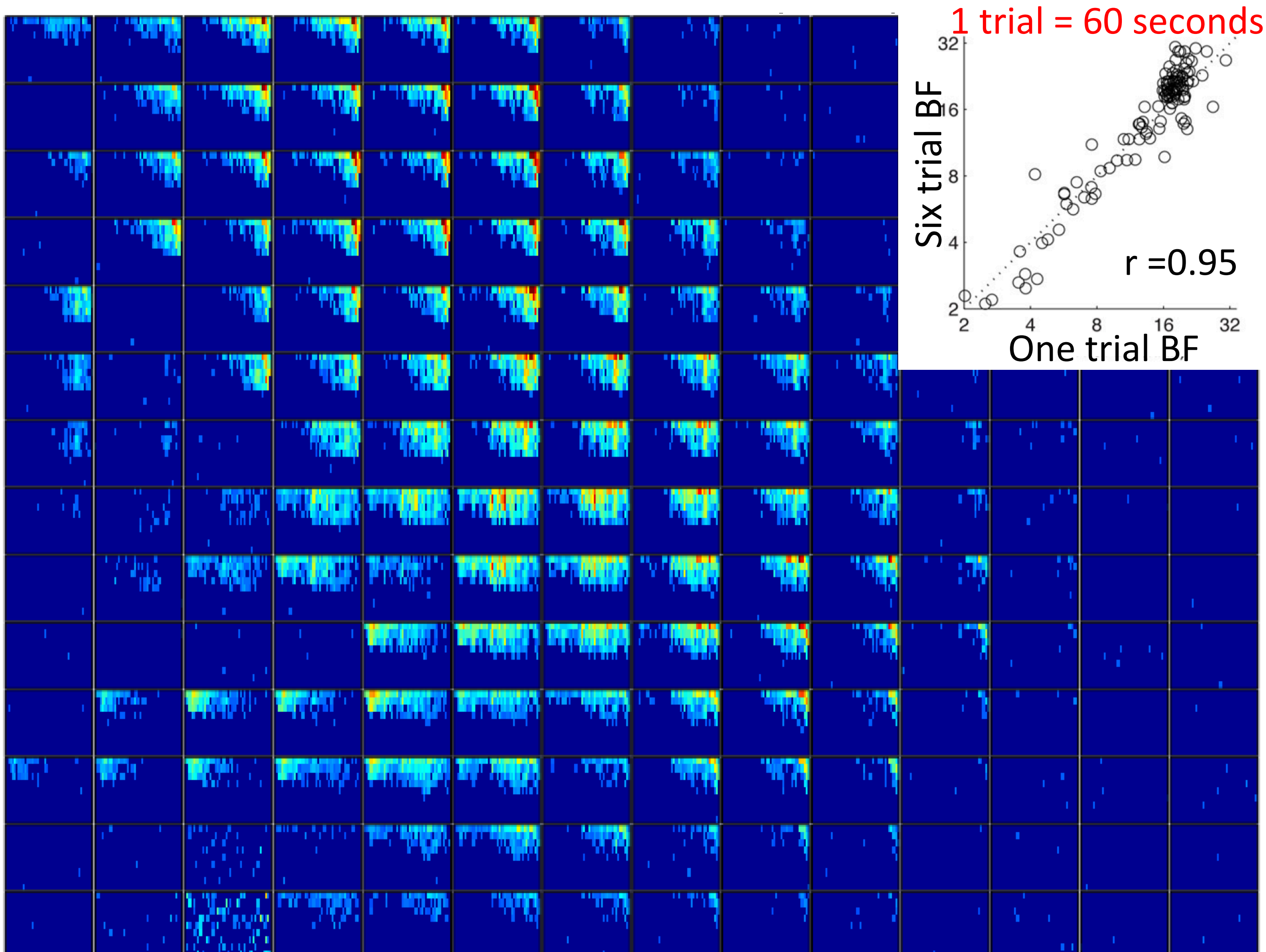
14 x 14 array

196 electrodes

150 µm spacing

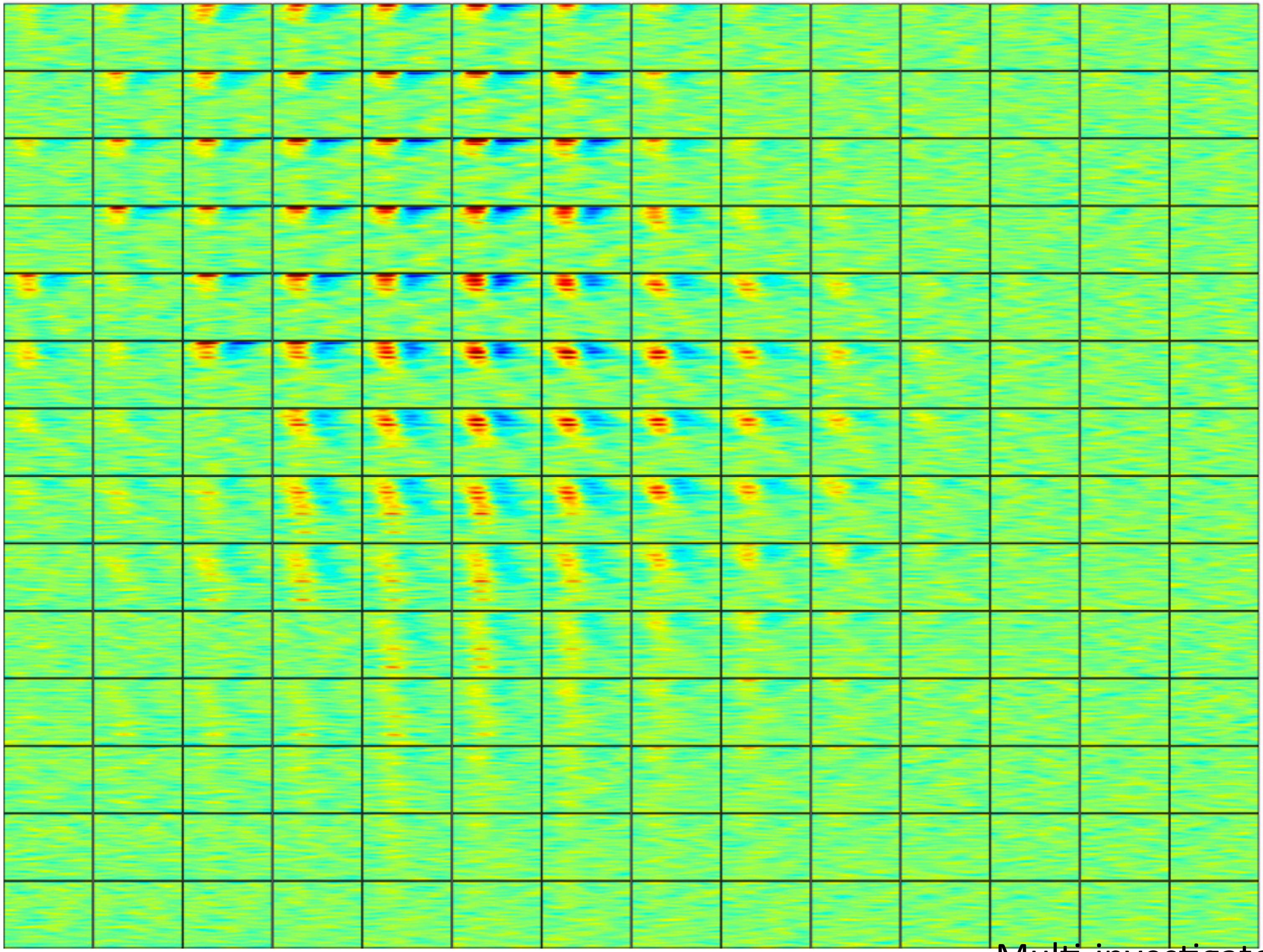
Multi-investigator team
Escabi, Read, Viventi et al., 2014

Wide-field micro-ECoG brain mapping of *tone* responses with single trial taking 60 seconds total



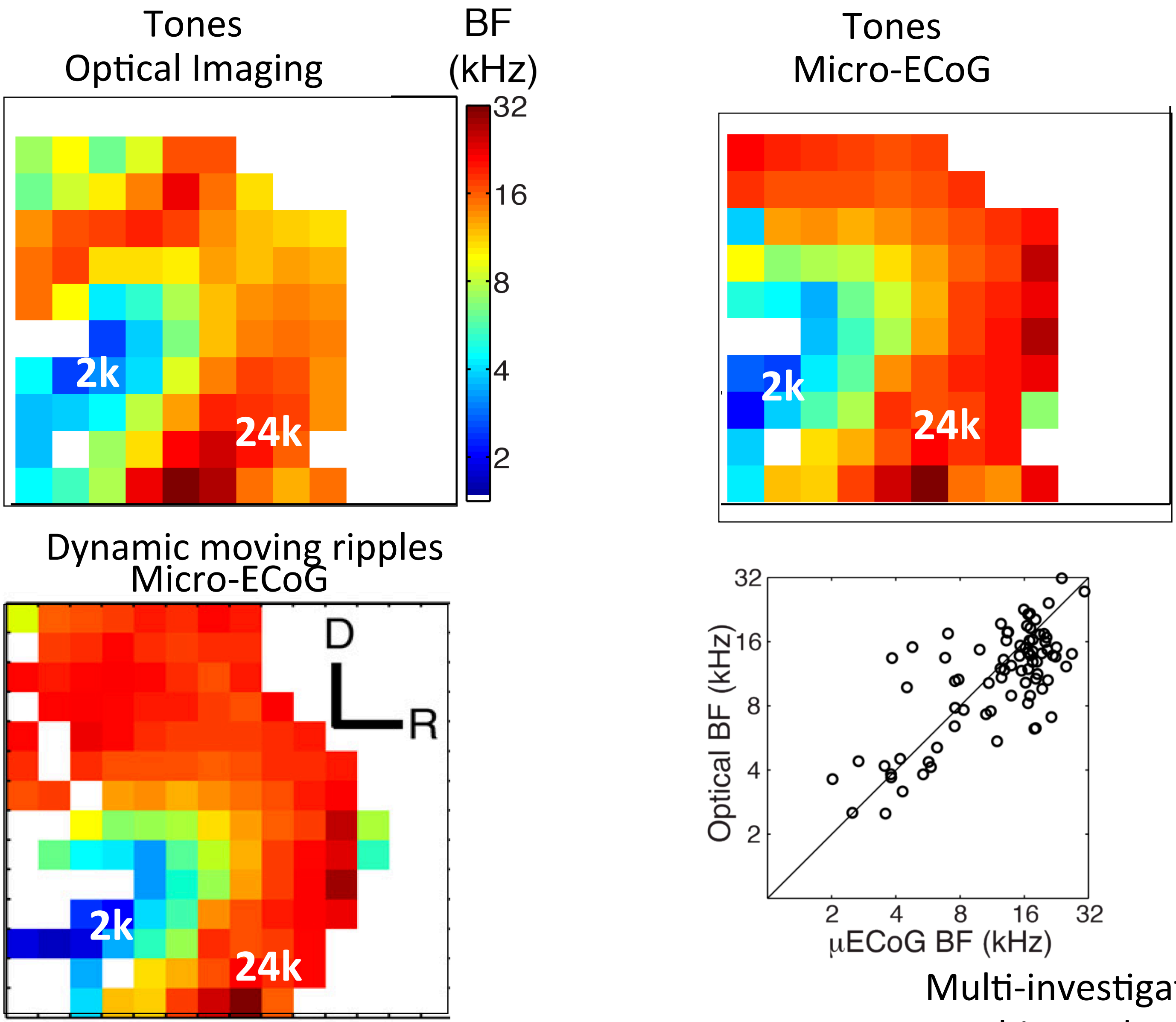
Multi-investigator team
Escabi, Read et al., 2014

Wide-field micro-ECoG brain mapping of *dynamic moving ripple* STRF



Multi-investigator team
Escabi, Read et al., 2014

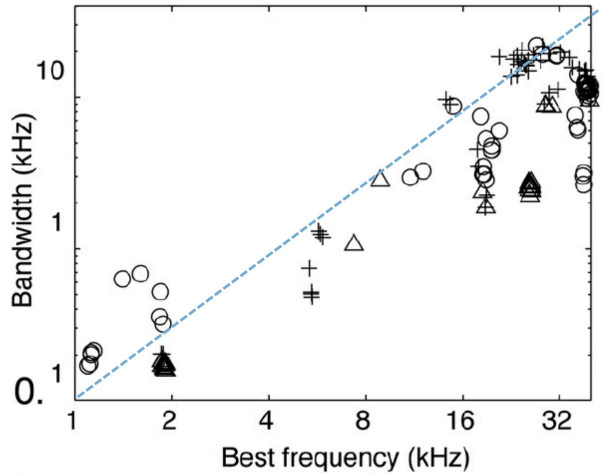
Micro-ECoG and Optical wide-field brain maps are correlated

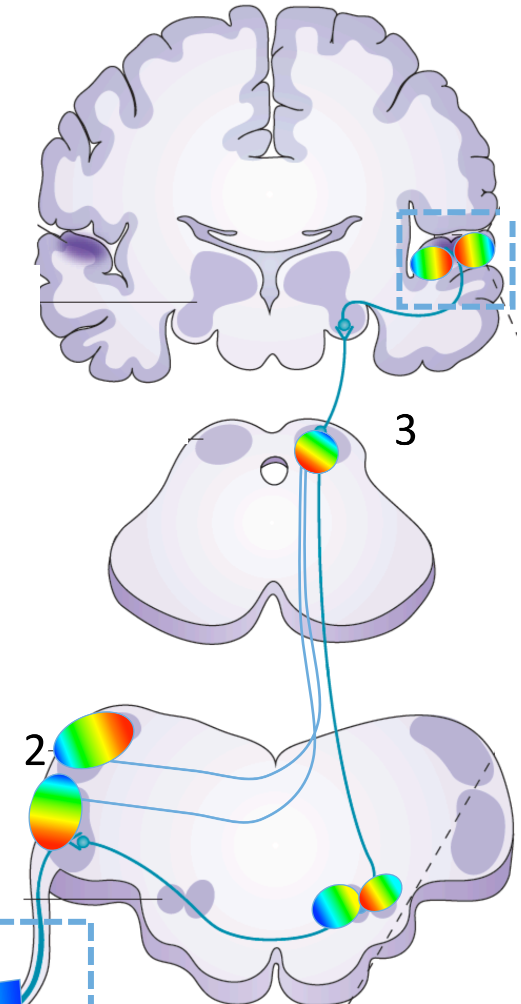


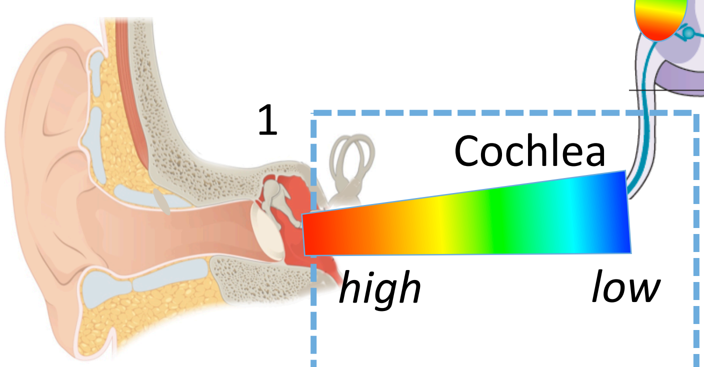
Multi-investigator team
Escabi, Read et al., 2014

Cortical (ECoG) STRF bandwidths increase with the cortical site Best Frequency

Primary (A1) and Ventral (VAF) STRF Bandwidths







Escabi, Read et al., 2014

Significance regarding cortical cochleotopies

1) There are multiple cortical fields with cochleotopic organization

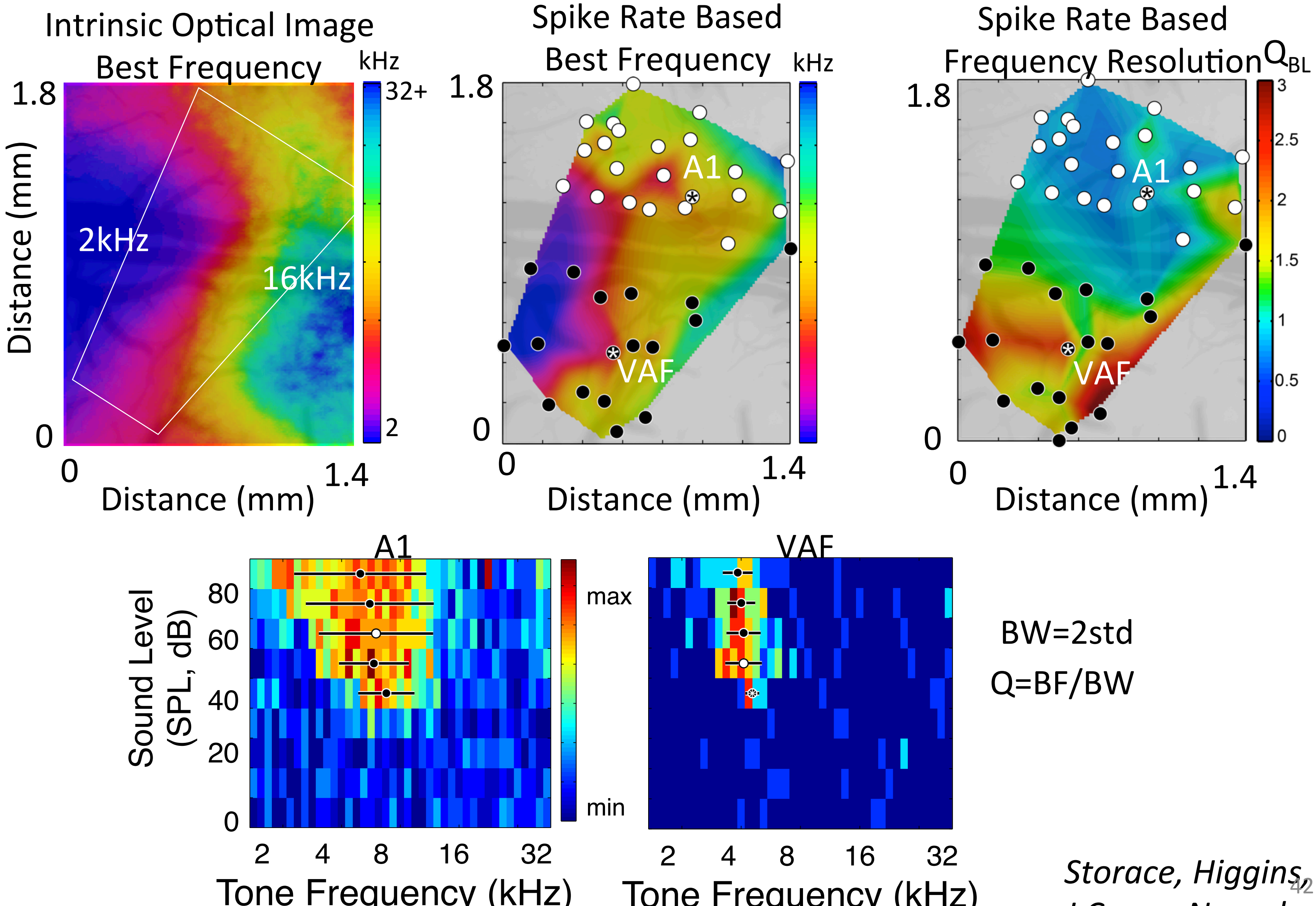
2) Cross-validation with fMRI, Optical, Multi-unit, ECoG and anatomy indicates a robust response topographhly akin to retinotopy in visual cortices (aka, V1, V2, V3..).

3) 150 µm ECoG array spacing sufficient for mapping cochleotopy.

4) Multiple cochleotopies in mammals indicates a highly parallel cortical processing.

Do different cochleotopic cortical fields process sound differently?

Ventral auditory field (VAF) resolves sound frequency better than more dorsal Primary (A1) auditory field.

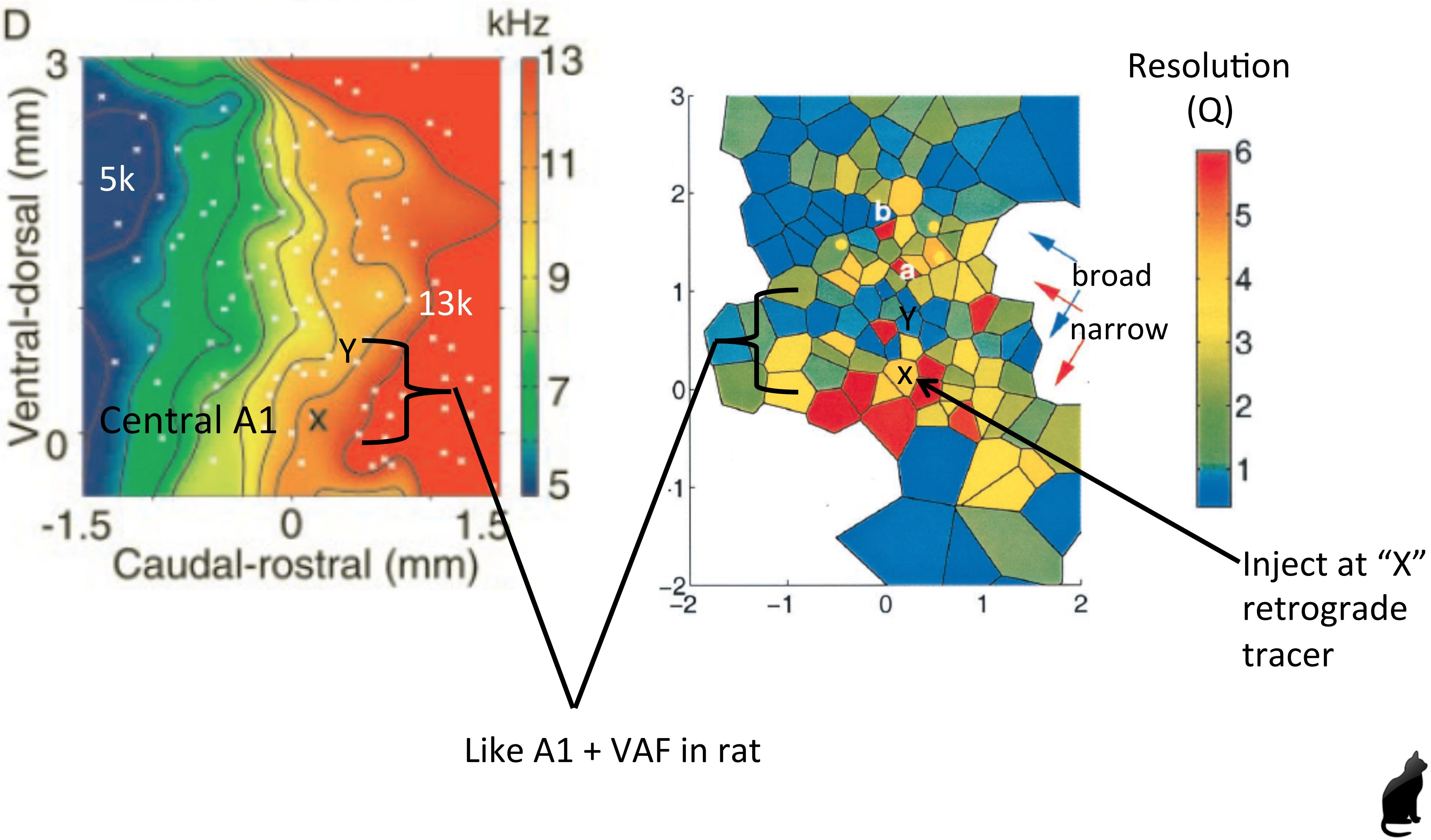


BW=2std

Q=BF/BW

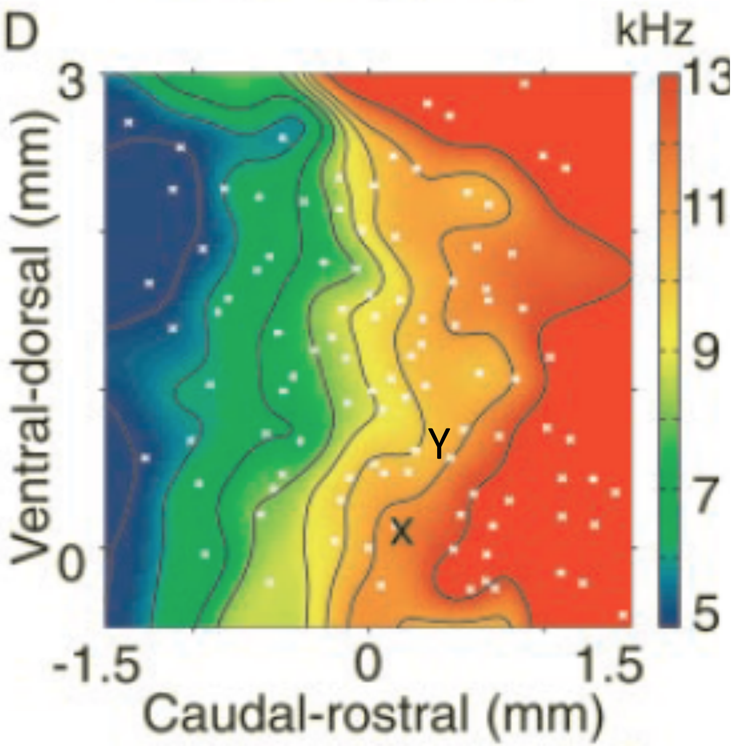
Storace, Higgins, Read, J Comp. Neurology 2011

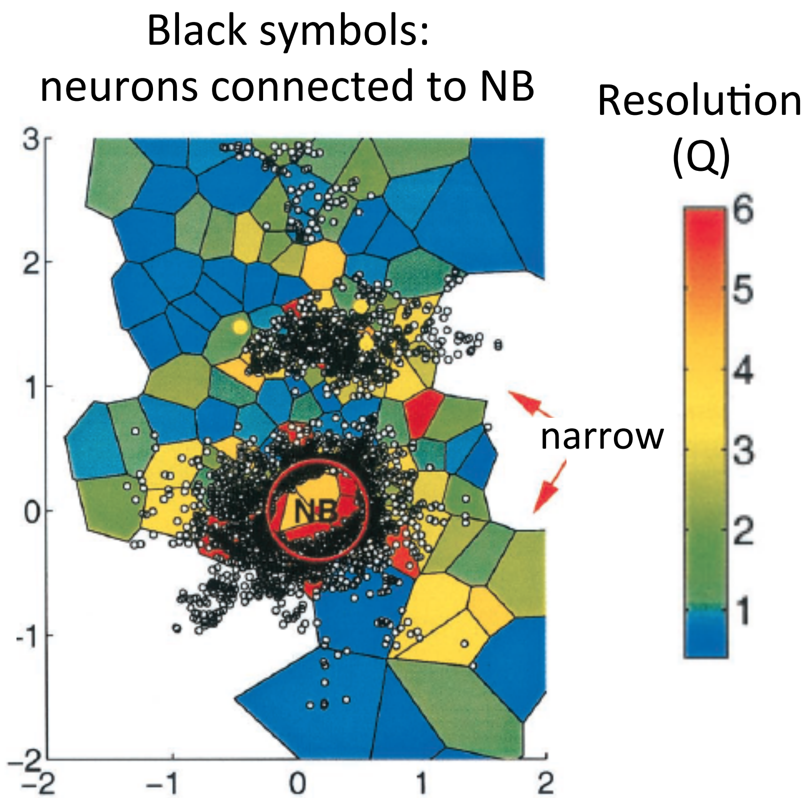
Similar phenomenon observed in cat which has alternating domains with neurons having broad and narrow bandwidths



Read et al., PNAS, 2001

Retrograde tracers label high density of cortico-cortical connections between narrowband regions



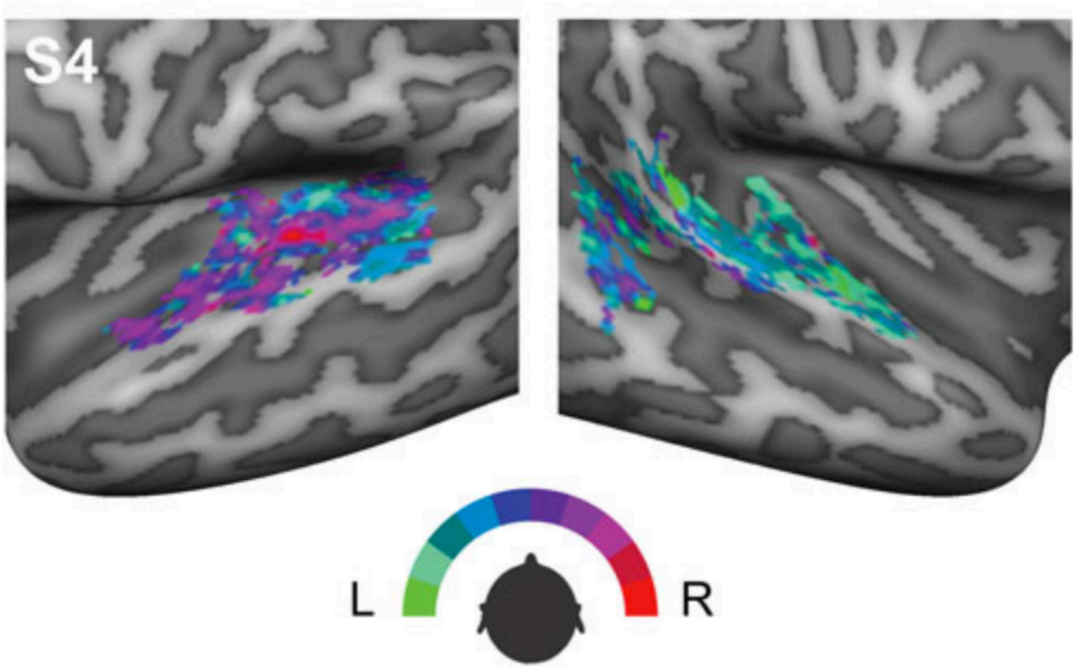


***Significance:** spectral resolution differs across regions and determines cortical network connectivity*

Read et al., PNAS, 2001

Virtual sound position fMRI: Each acoustic hemifield activates contralateral cortex in humans

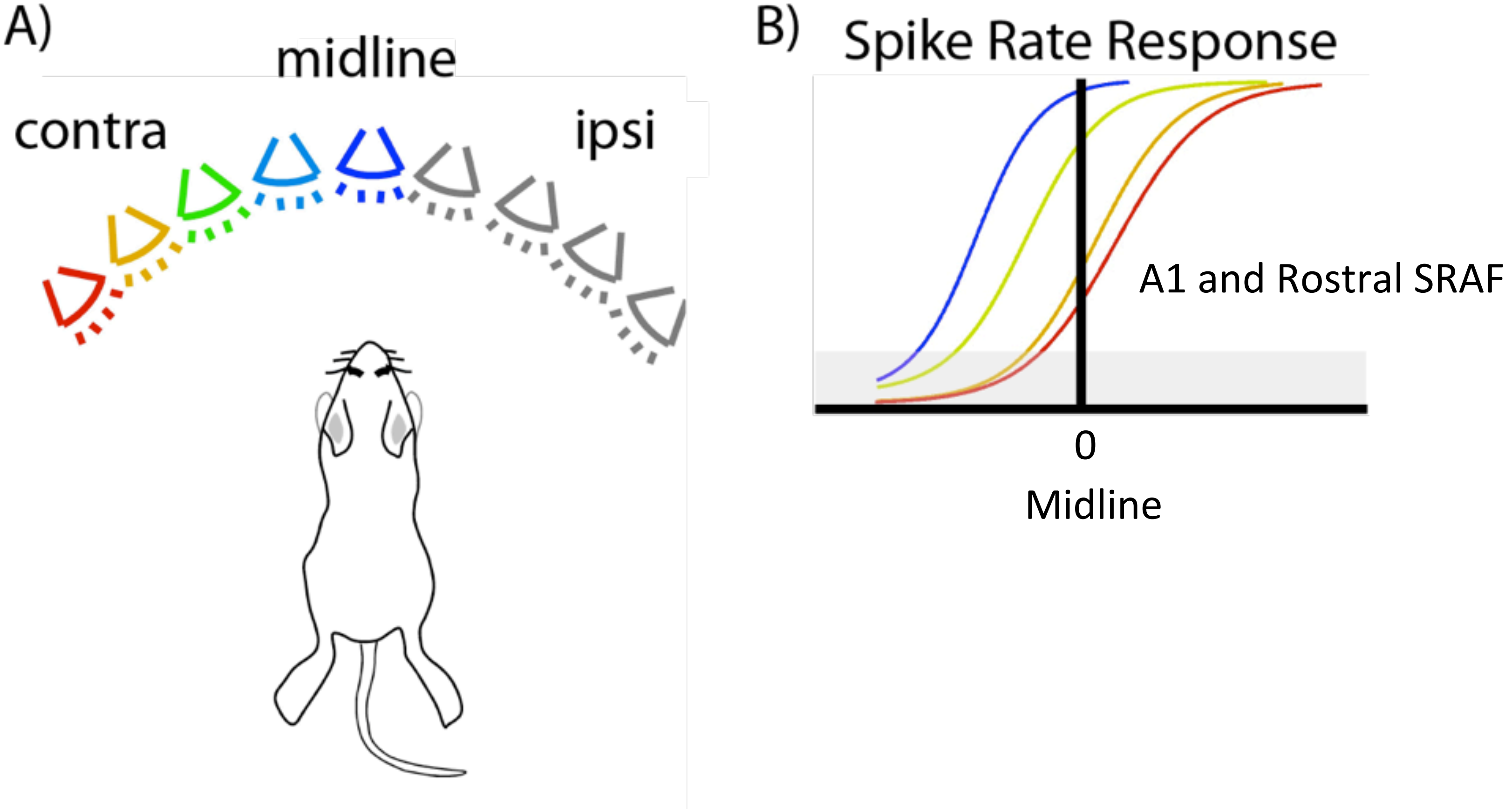
Heschl's Gyrus



Human
Formisano lab
Derey et al., Cerebral Cortex, 2016

Cat
Stecker et al., PLoS Biol, 2005

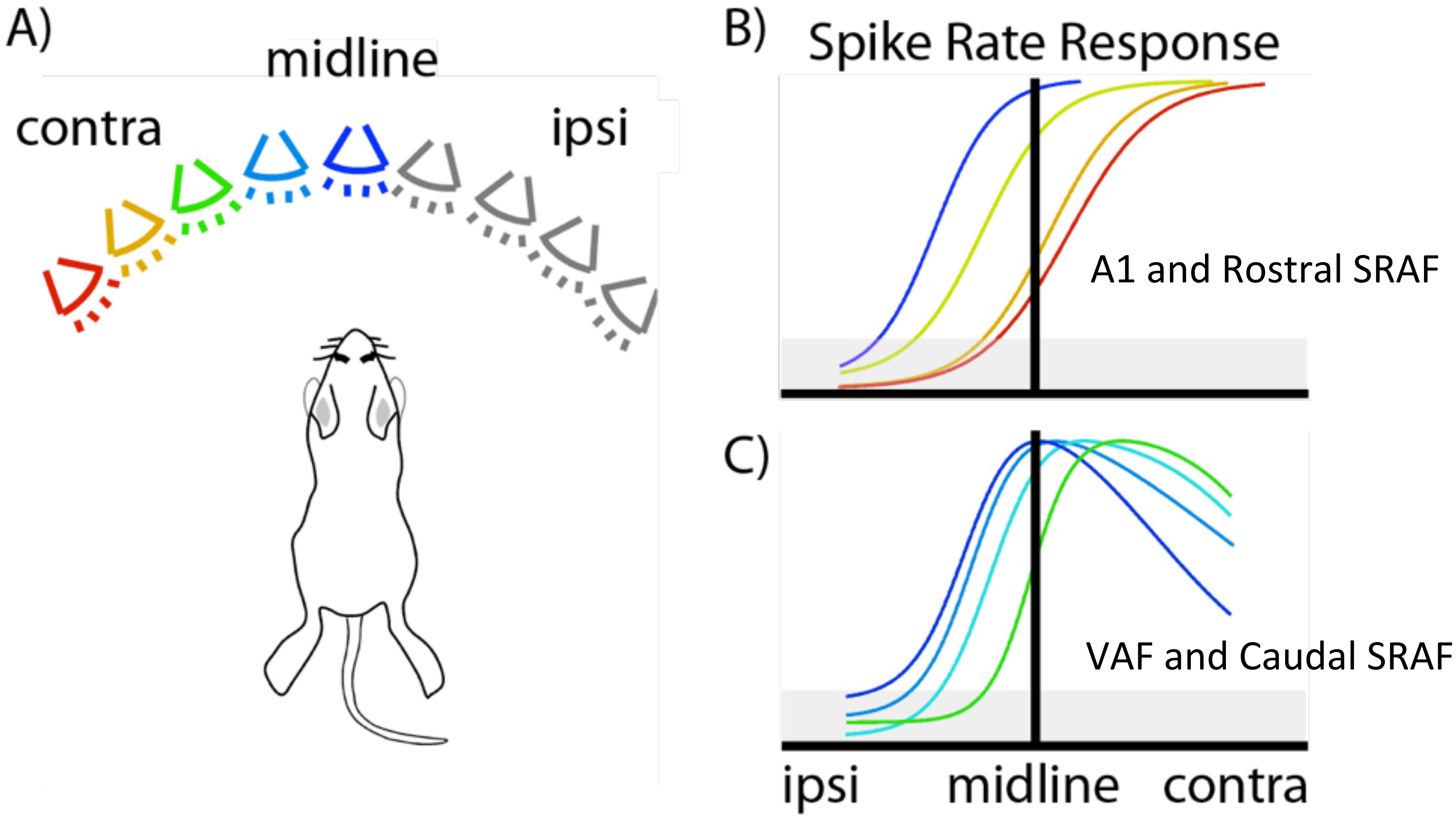
Virtual sound position responses: Each acoustic hemifield activates contralateral cortex in rats



Receptive fields in "B" similar to Formisano and Stecker receptive fields

Read lab
Higgins et al., 2010

Azimuth response fields form an "acoustic fovea" with tuning to midline observed in non-primary cortex of rat

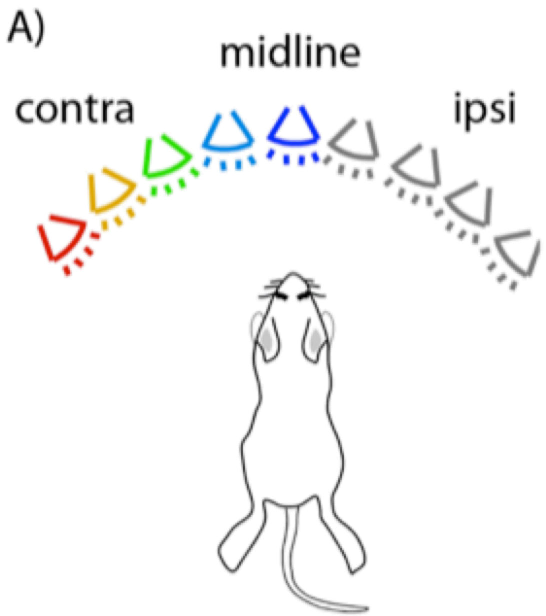


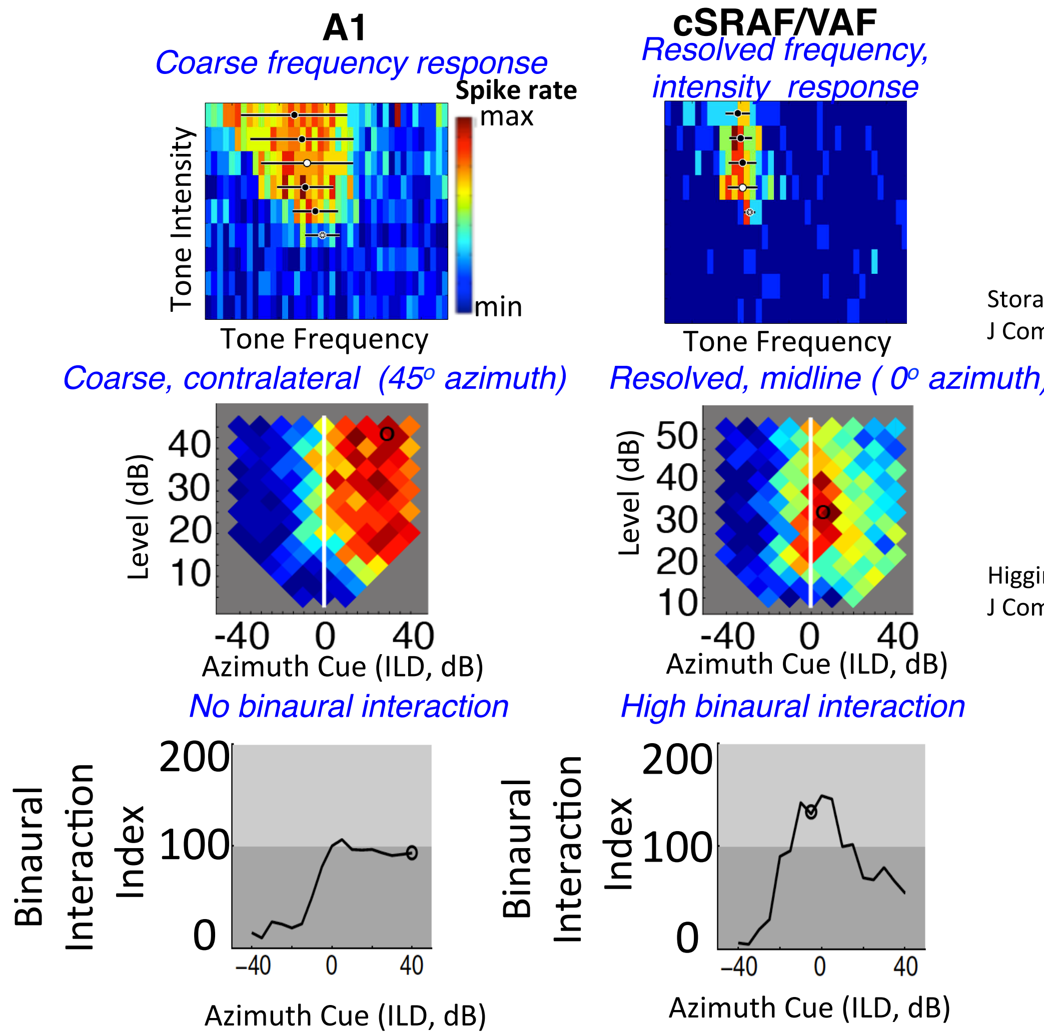
Receptive fields in "C" similar to Semple and Kitzes in cat.

Spatially "tuned" VAF and SRAF responses only with low sound levels.

Read lab
Higgins et al., 2010

Ventral non-primary cortex better at resolving sound frequency and azimuth and responds





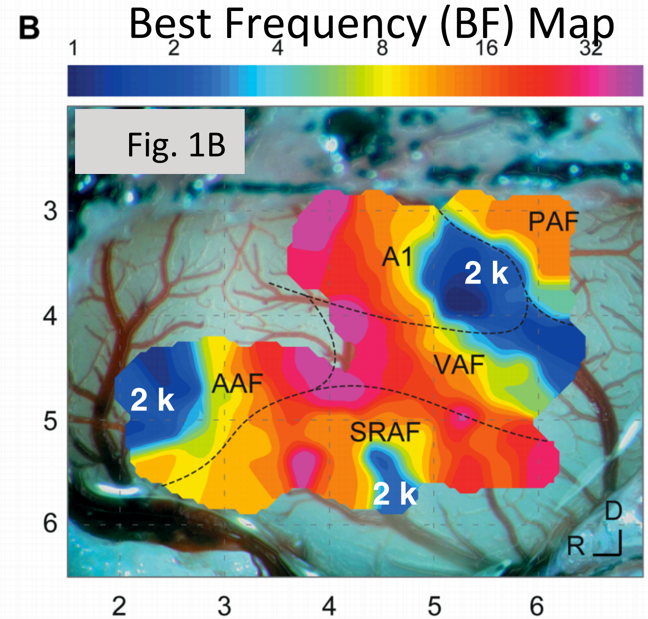
Storace et al., J Comp. Neurol. 2011

Higgins et al., J Comp. Neurol. 2010

$$\mathrm{BII} = \frac{R(\mathrm{SPL_c}, \mathrm{SPL_i})}{\mathrm{R}(\mathrm{SPL_c}) + R(\mathrm{SPL_i})} \times 100$$

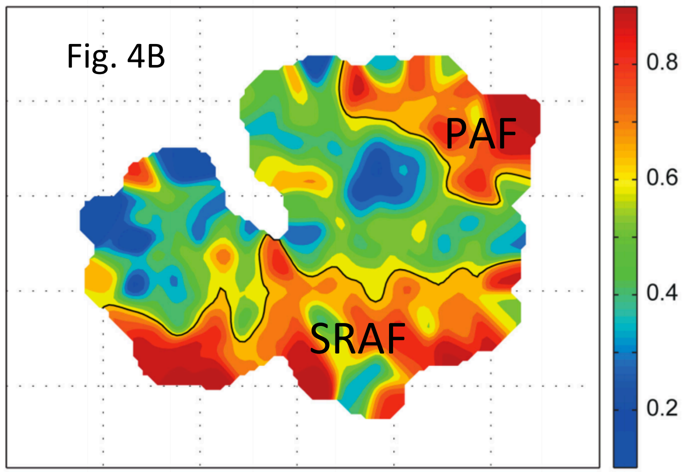
Stimulus-specific adaptation prominent in non-primary auditory cortex (PAF and SRAF)

Smoothed Spike Rate
Best Frequency (BF) Map



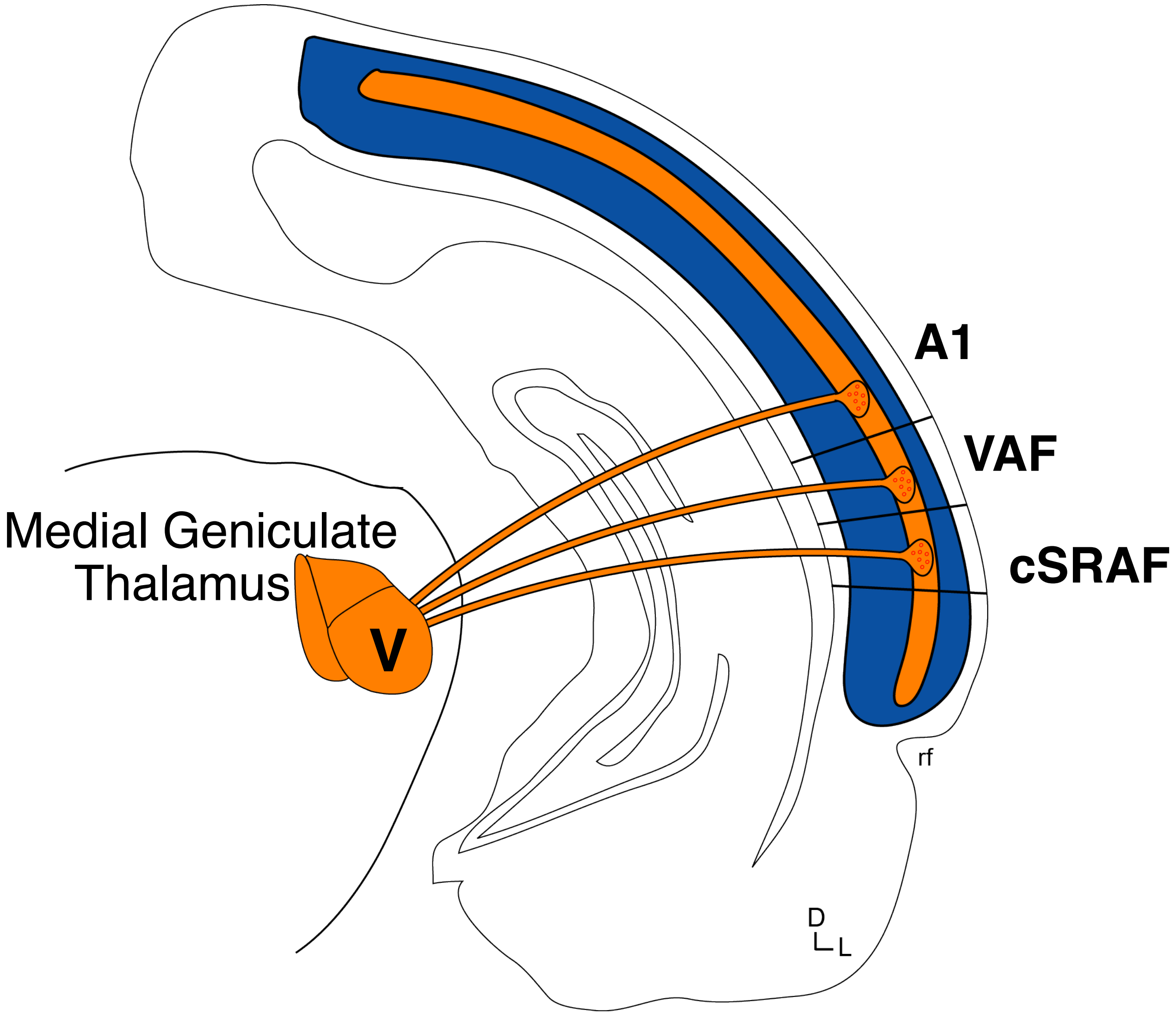
Rostral Caudal

Stimulus Specific Adaptation (SSA)



Nieto-Diego Malmierca PLOS 2016

"Single inherited cochleotopy concept"
ventral (V) division thalamus common source of cochleotopy



Kaas, Hackett,
Weinberger
Schreiner, Winer

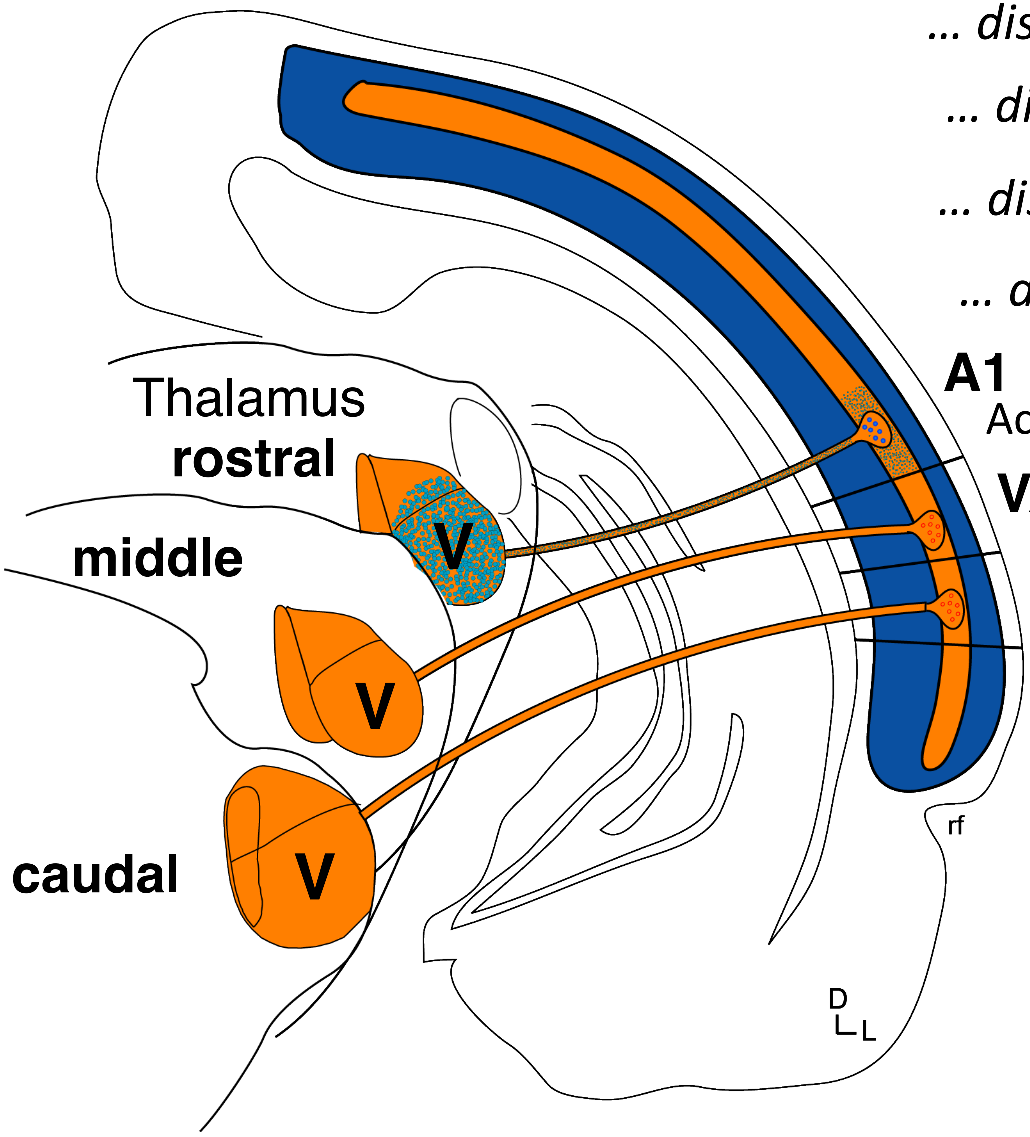
New Conceptual Framework: Multiple parallel pathways afford simultaneous distinct sound processing ability

… distinct spectral processing bandwidths

… distinct stimulus-specific adaptation

… distinct azimuth tuning, acoustic fovea

… distinct thalamic pathways



Time processing differences on Friday

Read lab,
Storace et al. J. Comp Neurol, 2010, 2011
Storace et al., J Neurosci., 2012

The End

Thanks!

to laboratory members, collaborators, funders

Current graduate Students on project

Ahmad Osman (Biomed. Engineering, PhD)
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Mike Jacobs (Biomedical Engineering, PhD)

Integrative organismal systems

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Doug Storace (Behavioral Neuroscience, PhD)
Chen Chen (Electrical Engineering, PhD)
Francisco Rodriguez (Biomedical Engineering, PhD)

Collaborators

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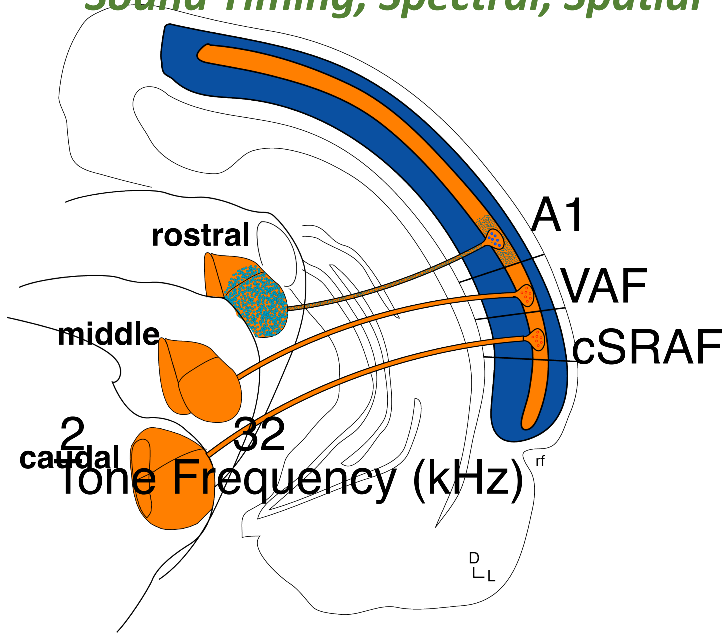
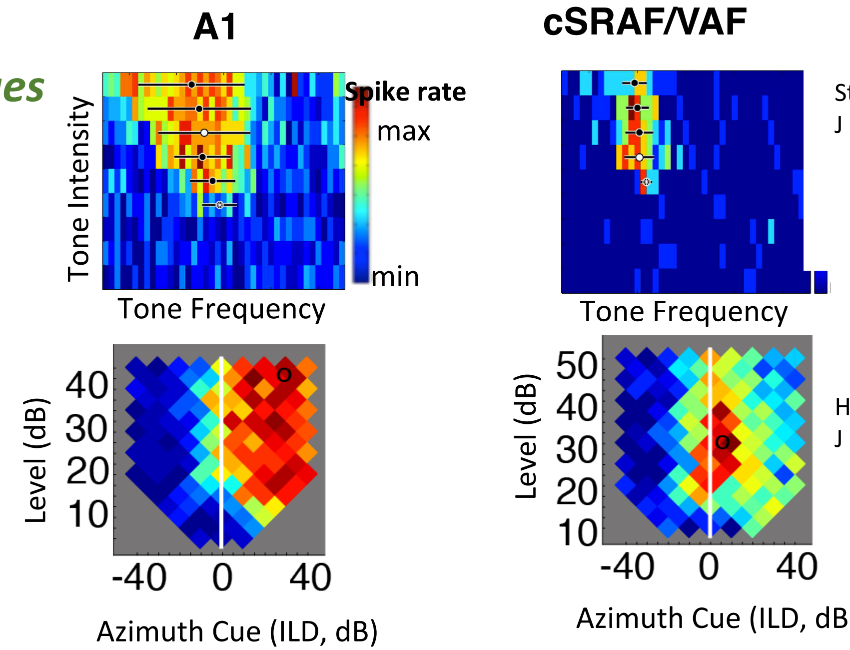
Ian Stevenson, University of Connecticut
Jon Vivente, Duke University

Parallel Paths Discriminate: Sound Timing, Spectral, Spatial Cues





Storace et al., J Comp. Neurol. 2011

Higgins et al., J Comp. Neurol. 2010