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Structure and Function of the Auditory and Vestibular Systems
(Fall 2014)

Auditory Cortex (2)

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Outline

Lecture 1: Anatomy of auditory thalamus and cortex
   a) Subdivisions of medial geniculate body (MGB)
   b) Multiple fields of auditory cortex
   c) Thalamo-cortial and cortico-cortical connections

Lecture 2: Tonotopic organization and stimulus selectivity
   a) Tonotopic organization of auditory cortex
   b) Firing patterns and tuning to preferred stimulus

Lecture 3: Temporal processing
   a) Temporal-to-rate transformation in A1
   b) Temporal-to-rate transformation outside A1

Lecture 4: Spectral, intensity and spatial processing
   a) Spectral processing
   b) Intensity processing
   c) Spatial processing

Lecture 5: Complex sound processing
   a) Pitch and harmonicity processing
   b) Vocalization processing
The Notion of Tonotopic Organization in Auditory Cortex

(and the history behind it)
Overall organization of auditory cortex

Cat
Imig and Reale (1980)

Primates
Morel and Kaas (1992)
First demonstration of tonotopic organization of auditory cortex (evoked potential, anesthetized cat) at Hopkins! During World War II

Fig. 4. Expt. 2/1/41: right cortex; left cochlea; stimulation of nerve fibers at 6 mm. (basal turn) and 14 mm. (middle turn) from basal end. Note that there are two response areas for the 14 mm. point. See text p. 320 and p. 327. Labels identify sulci. 2 1/2 X.
Evidence of tonotopical organization of A1 and a less organized secondary field (evoked potential, anesthetized cat)

Fig. 5. Expt. 2/5/41; right cortex; left cochlea; nerve fibers stimulated at 1.5, 4, 6, 8, 14 and 19 mm. from the basal end of the spiral. See text p. 321. 2½ X.
Lack of an orderly organization in A1 (single-unit recording, unanesthetized cat, data pooled from multiple animals)

20 years later, on the other side of the Atlantic

Is auditory cortex tonotopically organized?

Evans and Whitfield (1965)
Lack of an orderly organization in A1 (single-unit recording, unanesthetized cat, data pooled from multiple animals)

Similar observation at Hopkins

“Standard cortex”

Suprasylvian sulcus

Goldstein et al. (1970), Neural Encoding Lab, BME, JHU
Is there a columnar organization in auditory cortex?

Abeles and Goldstein (1970)
How reliable are anatomical landmarks?

Merzenich et al. (1975)
Tonotopic organization confirmed once more by a Hopkins graduate 30 years later!
(multi-unit recording, anesthetized cat, single animal mapping)

Merzenich et al. (1975)
Systematic changes of CF across primary auditory cortex (A1)

Merzenich et al. (1975)
Tonotopic organization in marmoset A1 (multi-unit, anesthetized)
Tonotopic organization in auditory cortex (single-unit, awake marmoset)

Bendor and Wang (2005)
Tonotopic organization in awake macaque monkey

A Recording Locations monkey L

B Recording Locations monkey M

C CF map monkey L

D CF map monkey M
Tonotopic organization found across all mammals

Wang and Walker (2012)
Is mouse A1 tonotopically organized? [2-photon imaging]

Bandyopadhyay et al. (2010), Rothschild et al. (2010)

Chen et al. (2011)
Yes, even mouse A1 is tonotopically organized [multi-unit mapping]

Guo et al. (2012)
“Why are Evans et al. and our single track penetrations so out of agreement with the orderly representation of the cochlea within AI reported by Merzenich et al.? First and foremost in our view is the different anesthetic state. There is no question that the sorts of anesthetics Merzenich et al. used render many cortical units unresponsive to sound. Further the effect is probably selective so that units with more indirect input pathways are more likely to be affected.” (p.190)

What have we learnt from the old debate?

- Anesthetized
- MGB input
- Multi-unit
- Near threshold
- Single hemisphere

Unanesthetized
Cortical response
Single-unit
Supra-threshold stimulus
Averaging across hemispheres
“In this chapter and elsewhere, we have stressed the diversity of the neural coding properties of the units in the auditory cortex. This diversity makes the cortex a difficult region to study and makes it especially unattractive to those who like their science in neat packages. Let us hope that new studies, new techniques, and new findings will move us out of what will someday be called the early phases (or even the dark ages) of neuroscientific study of the cortex.”


In 1995, Wang lab was established to reinitiate the research into the auditory cortex at Hopkins (20 years after the above publication)
What would Hubel and Wiesel do if they were to begin their research career again today?

“My first choice if starting anew would be to explore the cortical processing of auditory information. There must be secrets to unearth in exploring the neural basis of our perception of language, music, and voice.”

Torsten Wiesel (Neuron 2012)
The Real Challenges in Auditory Cortex

(The Wild West)
“Attention” Units in the Auditory Cortex

Abstract. In the course of examining single unit responses from the cortex of unrestrained and unanesthetized cats, we have come upon a population of cells that appears to be sensitive to auditory stimuli only if the cat “pays attention” to the sound source. We have described these responses, since they have not been previously reported and since they illustrate an important difference between the information which can be gleaned from experiments of this type and that obtained in the usual “acute” microelectrode experiment.

Cortical units that seem to be sensitive to auditory stimuli only if the subject “pays attention” were encountered in a series of experiments carried out on the auditory cortex of seven cats. The results of these experiments will be described in detail in a subsequent paper. The present paper is devoted to the description of one of these units and to the demonstration of the difference in the responses to stimuli presented in the same and the opposite direction of attention.

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Fig. 2. Schematic drawing of the left auditory cortex of the cat, showing the location of electrode tracks in seven cats. A1, AII, and AEP are the main auditory cortical areas.

Hubel et. al. (Science, 1959)
What makes auditory cortex so difficult to study?

Fig. 1. Response of an auditory cortical unit in cat No. 17. Lower line shows response of a microphone located near the cat’s ear; the deflections seen there were produced by squeaks emitted when a toy mouse was squeezed. The upper line shows the unit responding to the squeaks to which the animal was paying attention; this unit almost never responded to clicks, tones, or noise from a nearby loud-speaker.

The unit responded briskly, for example, to (i) voice, (ii) squeaks emitted by squeezing a toy rubber mouse [Fig. 1], (iii) scratching fingernail on table nearby, (iv) hissing, (v) tapping the table.

Finally, it has proved impossible to discover the stimuli adequate for driving many of our cortical units, a fact we cannot readily explain.

Hubel et. al. (Science, 1959)

Because of anesthesia and non-optimal stimuli

Onset responses to brief sounds (anesthetized rats)

“Binary firing”

DeWeese and Zador (J. Neurosci 2003)

Onset responses to continuous sounds (anesthetized marmosets)

DeCharms and Merzenich (Nature 1996)
Auditory cortex is capable of sustained firing in awake animals

Primary Auditory Cortex
(Stimulus: Tone)

Non-Primary Auditory Cortex
(Stimulus: Noise)

Wang et. al. (Nature, 2005)
Auditory cortex neurons respond to preferred stimuli with sustained firing and adapt quickly to non-preferred stimuli.

Wang et. al (Nature, 2005)
Sustained firing evoked by temporally modulated stimuli

Wang et. al (Nature, 2005)
How responsive is auditory cortex during sleep? (unlike under anesthesia!)

3 simultaneously recorded single-units

Issa and Wang (J. Neurosci 2008)
Auditory cortex is as responsive to sounds during sleep as during awake state

Issa and Wang (2008)
SWS shows less excitation at low sound levels

Issa and Wang (J. Neurosci 2011)
SWS shows less inhibition at high sound levels

Issa and Wang (J. Neurosci 2011)
SWS alters auditory processing across sound levels

Issa and Wang (J. Neurosci 2011)
Firing pattern and stimulus selectivity in auditory cortex of awake monkeys.

Auditory cortex neurons respond to preferred stimuli with sustained firing and adapt quickly to non-preferred stimuli.
“When a sound is heard, a particular population of auditory cortex neurons fire continuously throughout the duration of the sound. Responses of other, less optimally driven neurons fade away quickly after the onset of the sound.” (Wang et al. *Nature* 2005)
From a neuron’s point of view:

Responses of one neuron to entire acoustical parameter space

Acoustic parameter space

Preferred stimulus (sustained firing)

Non-preferred stimuli (onset firing)

Outside RF (no response)

Wang (*Hearing Research*, 2007)
From a neuron’s point of view:

Responses of one neuron to entire acoustical parameter space

Acoustic parameter space

Wang (Hearing Research, 2007)
Increased stimulus selectivity along ascending auditory pathway

Wang (Hearing Research, 2007)
Summary of observations from auditory cortex in awake condition

1) Neurons in auditory cortex are high selective to acoustic stimuli.
   - Each neuron is only responsive to a small region of acoustic
   - As a result, each stimulus only excites a small number of neurons (“spatial sparseness”)

2) Neurons in auditory cortex are also highly responsive (fire plenty of spikes), but only to stimuli they like.
   - “spatial sparseness” does not result in sparse firing (i.e., transient responses)

3) “Selectivity” and “responsiveness” are closely coupled.
   - Stimulus selectivity is a more useful measure than “sparseness” if you want to understand what a neuron actually does.
Suggested readings:

**Tonotopic organization:**


**Firing pattern and stimulus selectivity:**
