fMRI of Macaque Auditory Cortex in Awake and in Anesthetized Animals

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INTRODUCTION

Functional magnetic resonance imaging (fMRI) of the non-human primate auditory cortex was unavailable.

1. Can auditory cortex be reliably imaged in noisy high-field scanners, including of awake animals?
2. How well can auditory cortex be functionally tessellated?

SOME BENEFITS:

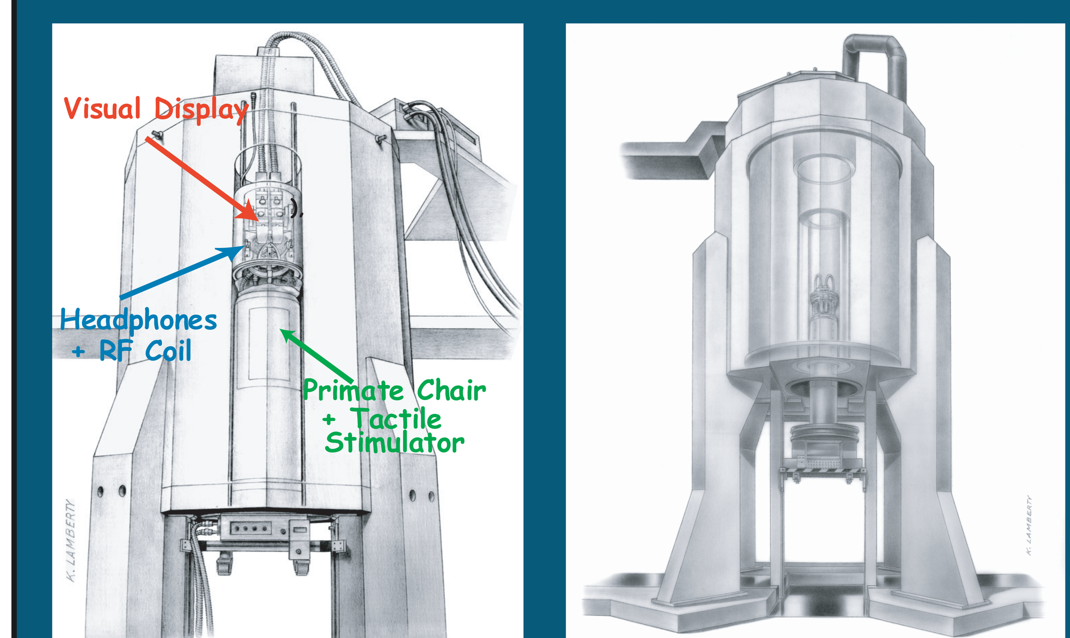
Localized fields implicate the source of activity in auditory cortex, including from multisensory input.

Functional properties can be revealed from fields with limited neurophysiological evidence, to extend our knowledge and guide further neurophysiology.

This non-invasive technique will allow comparative experiments between humans and monkeys.

METHODS

1. Imaging at high magnetic fields



4.7 Tesla scanner   7 Tesla scanner

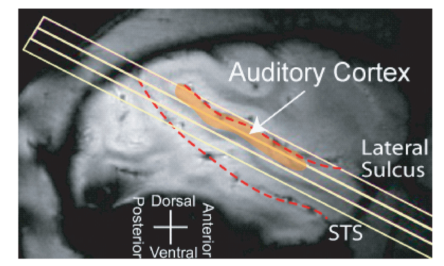
- **AWAKE ANIMAL IMAGING:** Imaging this macaque monkey was in the larger bore of the 7-Tesla magnet. The monkey completed visual fixation trials that assisted him in maintaining minimal body movement, as measured by body sensors . Only correctly completed trials were analyzed to reduce motion artifacts (see Panel 3).
- **ANESTHETIZED ANIMAL IMAGING:** Imaging was at 4.7 and 7 Tesla. Anesthesia was maintained with remifentanil (0.5-2 µg/kg/min). Muscle relaxation with mivacurium chloride (5 mg/kg/h).

IMAGING:
High resolution (0.5 - 1.5 mm, pixel dimentions, 2mm slices). External RF-coils.
FUNCTIONAL IMAGES: GE-EPI, multisegment, typically: TE = 16 ms, TR = 10 sec, (sparse imaging, volume in 1.5 secs, see Panel 2).
ANATOMICAL IMAGES: MDEFT or FLASH sequences, acquired in register with functional images.
SCANNERS: Brucker Medical, Inc. Germany.
SCANNER NOISE: 4.7 Tesla measured at 105 dB SPL, 7 Tesla at 100 dB.

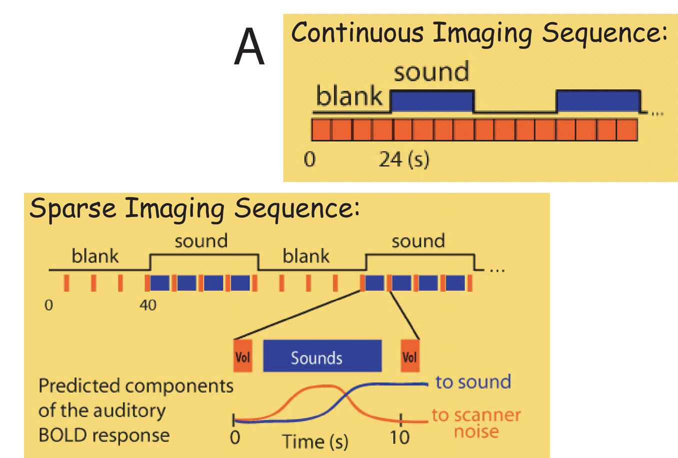
SENSORY STIMULATION:
AUDITORY: (custrom designed electrodynamic headphones, MR Confon). Sounds were tones or noise (band-pass or broadband), with 50 ms duration, presented 8 per sec., 100 dB SPL (continuous imaging) or 70-85 dB (sparse imaging, see Panels 2 and 3).
VISUAL: AVOTEC Silent Vision system with custom infrared eyetracker.
TACTILE: Custom rotating brush, stimulating palm or foot.

TECHNIQUES AND RESULTS

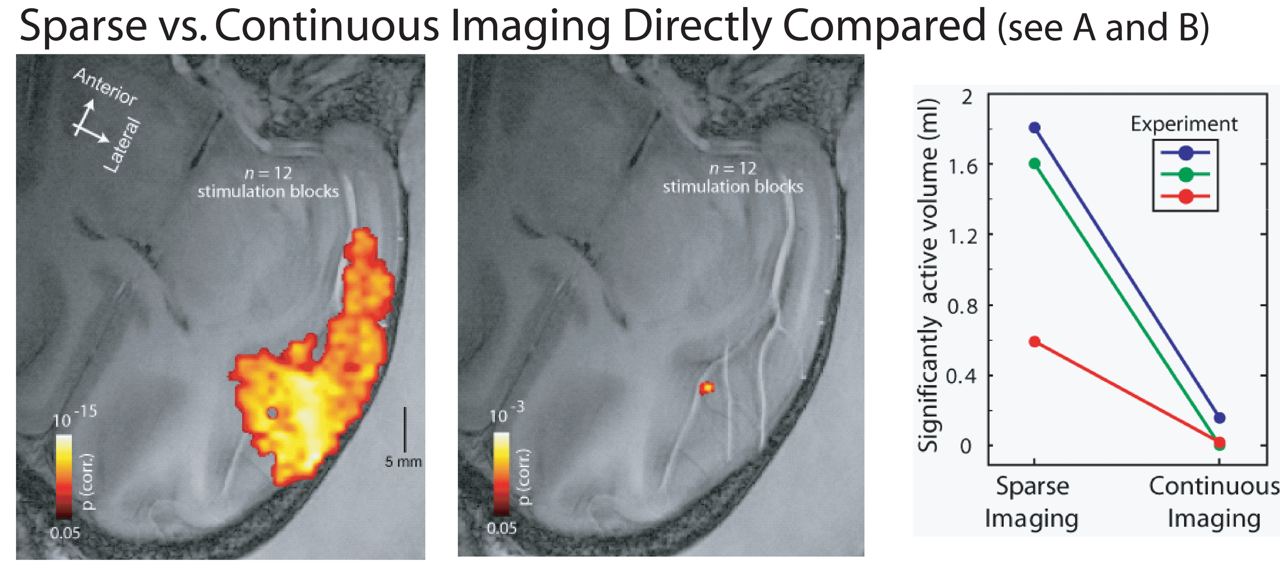
2. Optimizing Auditory Cortex Imaging



Imaging slices were aligned with the lateral sulcus to obtain a slice of activity over auditory cortex on the (superior temporal plane).



Sparse vs. Continuous Imaging Directly Compared (see A and B)



Acoustical stimulation (broad-band noise, 100 dB) during sparse imaging (left) elicited more activity than continuous imaging (middle), where stimulation competes with the scanner noise. We directly compared the two imaging paradigms in 3 experiments (right).

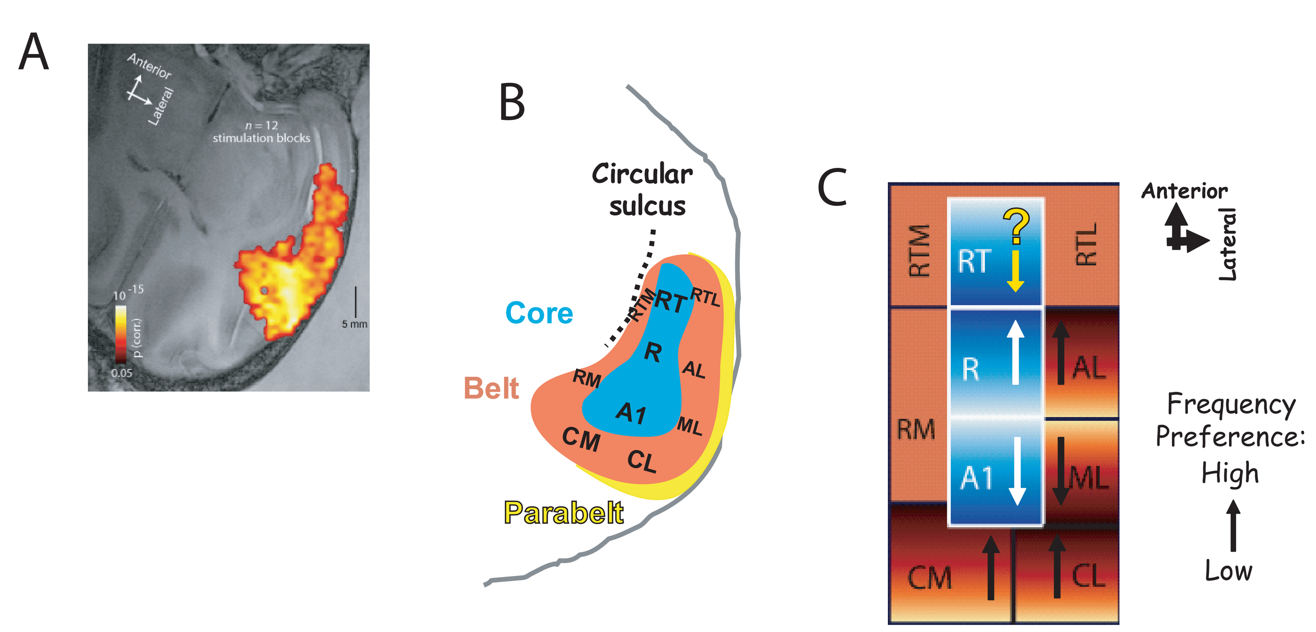
3. Strategies for revealing many fields

PRIMARY GOAL:
Activate most of auditory cortex AND preserve functional specificity.

Many auditory fields are active over such a broad region (A).
Anatomy suggests there could be 10 functional fields here (B, based on Kaas & Hackett, 2000).

The challenge is to obtain broad activity & preserve functional specificity:

1. At moderate sound levels neuronal specificity for sound features deteriorates.
2. Neurophysiology outside of primary auditory cortex (the 'core' fields A1 and R) is limited.
3. The belt (non-primary cortex) does not respond well to simple sounds like tones.



Initial strategies and assumptions based on the available data (C):

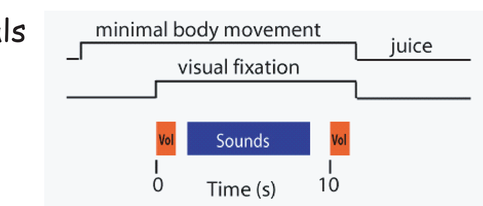
1. Tonotopy (selectivity for sound frequencies) should be a prominent property of many fields. (C) schematizes what is known neurophysiologically.

2. Core fields should preferentially respond to simple sounds like tones, but belt fields to more complex sounds (e.g., band-pass noise, see black arrows in C).

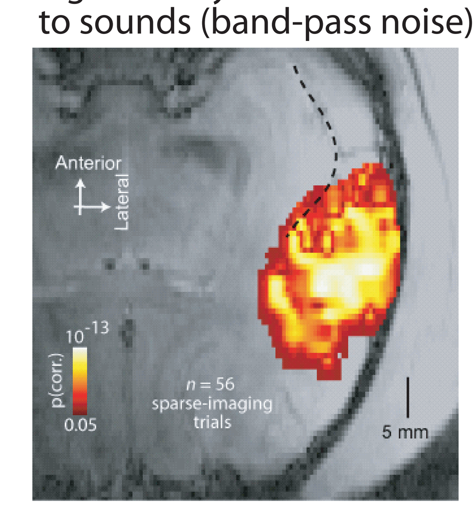
3. Functional Tesselation of Auditory Cortex

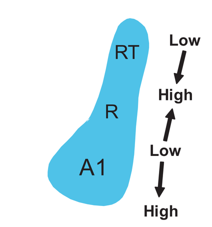
A. Behaving animal imaging at 7-Tesla

Only correctly completed trials were analyzed:



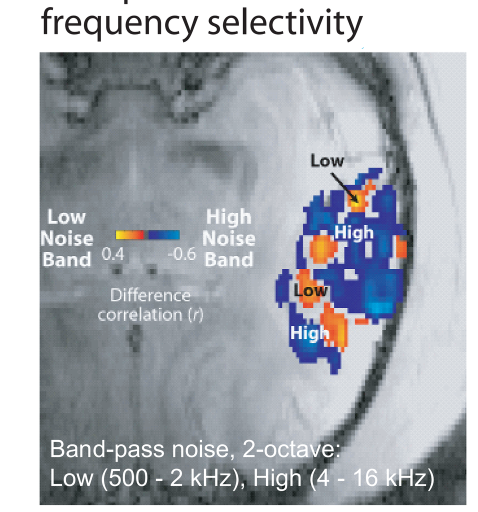
Significantly active voxels to sounds (band-pass noise)





Prediction: Two sounds with different frequency content will elicit multiple alternations of frequency selectivity, at least over the core.

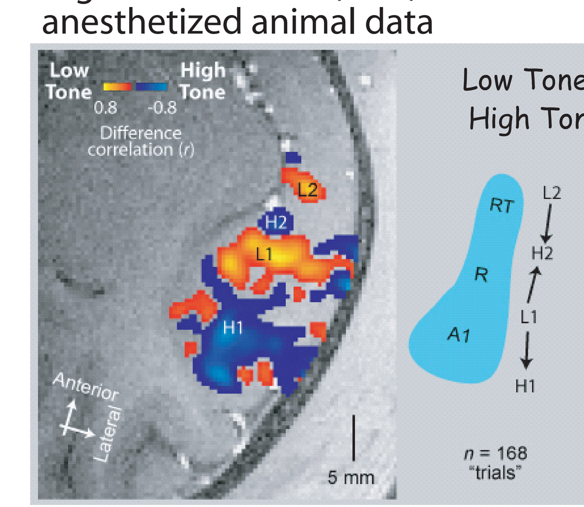
Multiple alternations of frequency selectivity



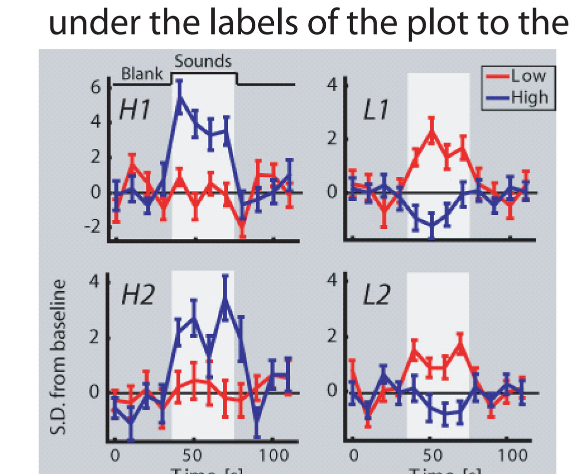
B. Tones are expected to reveal frequency selectivity over the core.

High vs. low tones (core): anesthetized animal data

Low Tone (500 Hz)
High Tone (8 kHz)



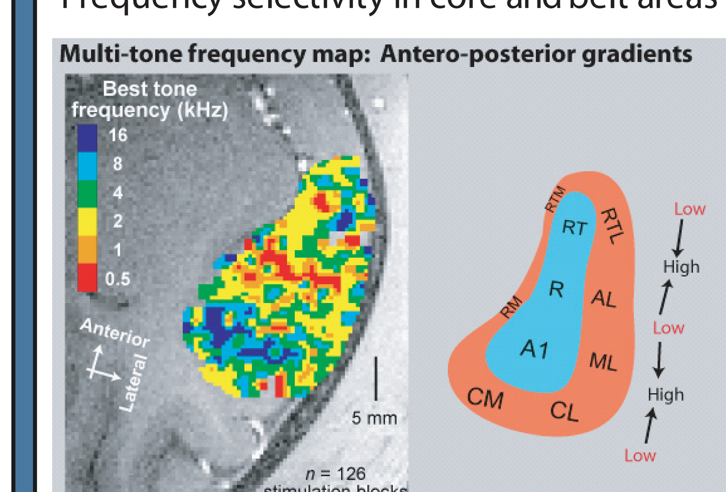
Timecourse of voxel cluster under the labels of the plot to the left



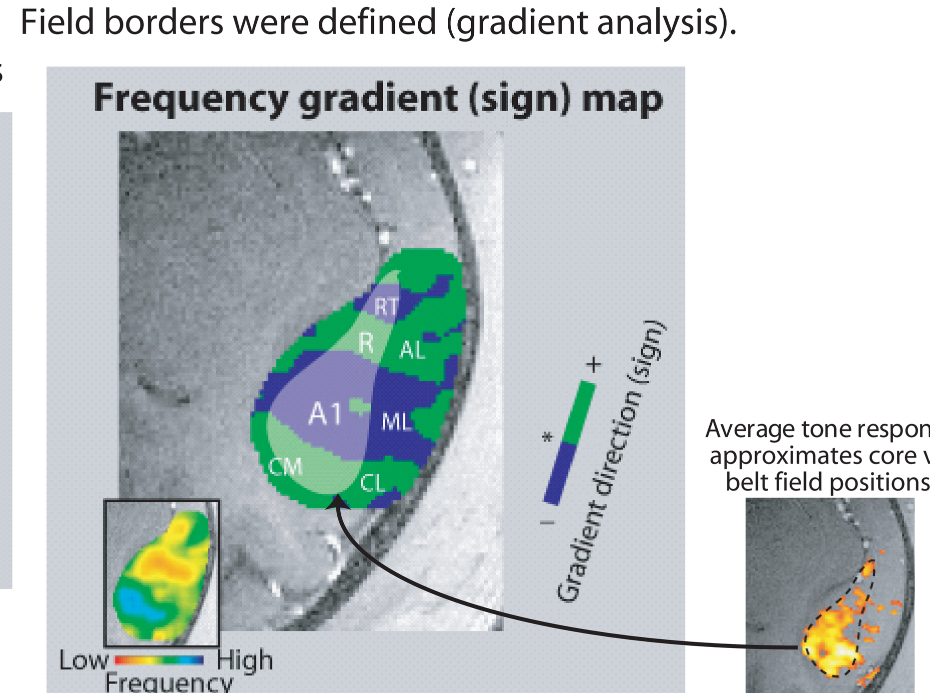
This pattern of alternating frequency selectivity regions was reliably observed: from posterior to anterior (high, low, high, low), consistent with these regions emanating from at least the core fields.

C. Multiple tones surprisingly also activated belt regions, allowing the functional tesselation of many core and belt fields.

Frequency selectivity in core and belt areas



Field borders were defined (gradient analysis).



References

Kaas, J & Hackett, TA (2000) Subdivisions of auditory cortex and processing streams in primates. PNAS, 97: 11793-9.
Kayser, C, Petkov, CI, Augath, M & Logothetis NK (2005) Integration of touch and sound in auditory cortex. Neuron 48: 373-84.

Acknowledgements

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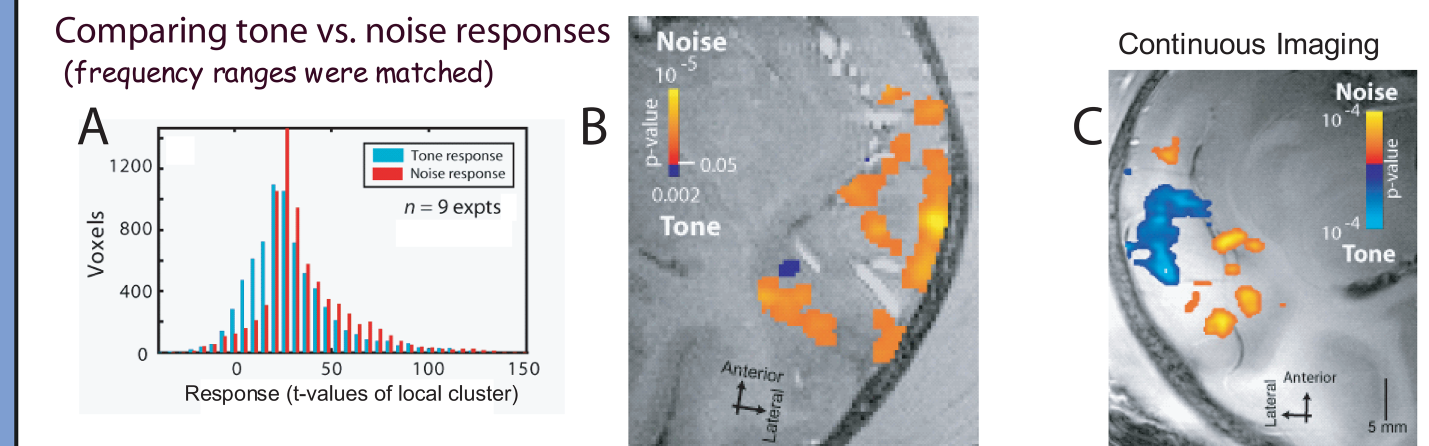
4. Hierarchical processing: core vs. belt

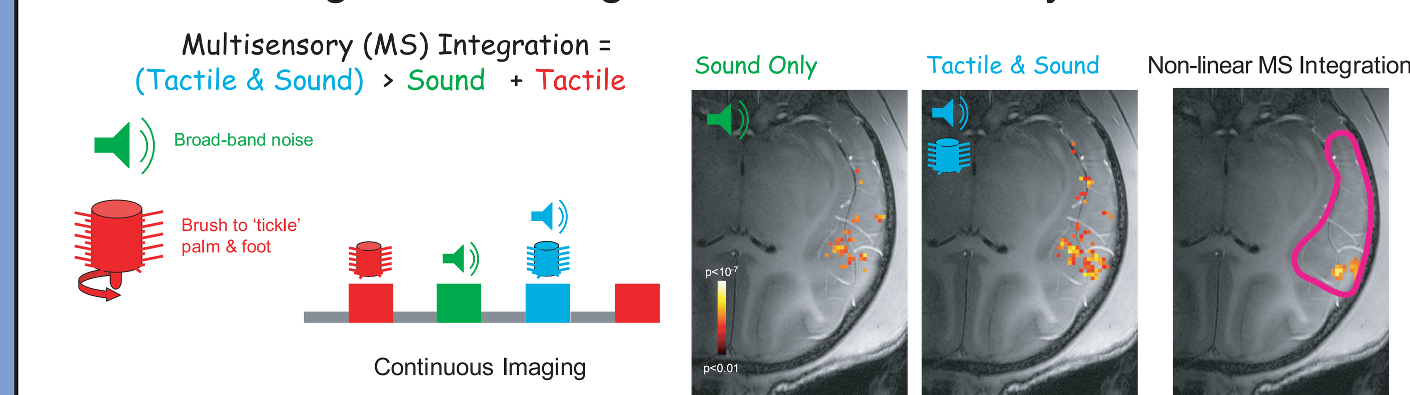
Comparing tone vs. noise responses (frequency ranges were matched)

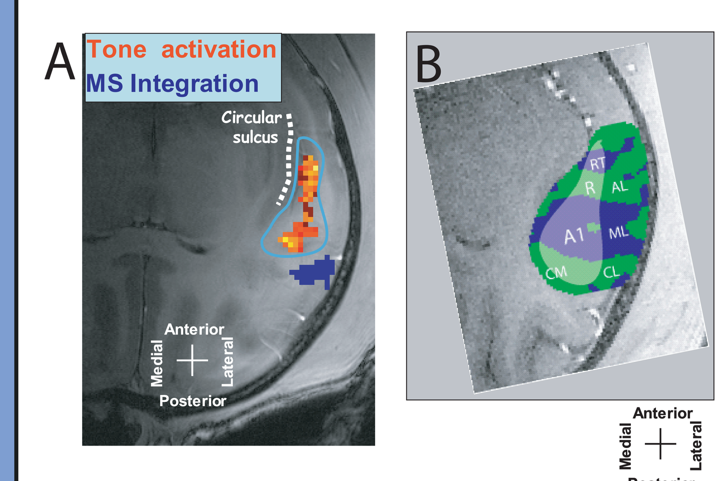


Auditory cortex responded more to noise than bands of tones (A) in the auditory belt (B). This is evidence of heirarchical processing in auditory cortex (note that frequency ranges were matched). With sparse imaging the core didn't show a preference either for tones or noise. With continuous imaging the auditory core responded more to tones, and noise responses surrounded these (C).

5. Integration of Touch in the Caudal Belt:

The strength of knowing the involved auditory functional fields.





Integration of touch and sound stimulation was observed in auditory cortex (above).

Activity to tones suggests that the caudal belt is involved (A to left).

Localized functional fields leave no question that the caudal belt is involved (B to left), in particular field CL and parts of field CM in this example.

Integration of Touch and Sound in Auditory Cortex: see Poster 388.6 or Kayser et al., 2005

CONCLUSIONS

Tones activated belt fields with fMRI, allowing the functional tesselation of auditory cortex.

Multiple auditory fields were revealed and borders defined.

We obtained evidence for hierarchical processing in auditory cortex.

Caudal belt fields integrate touch information.