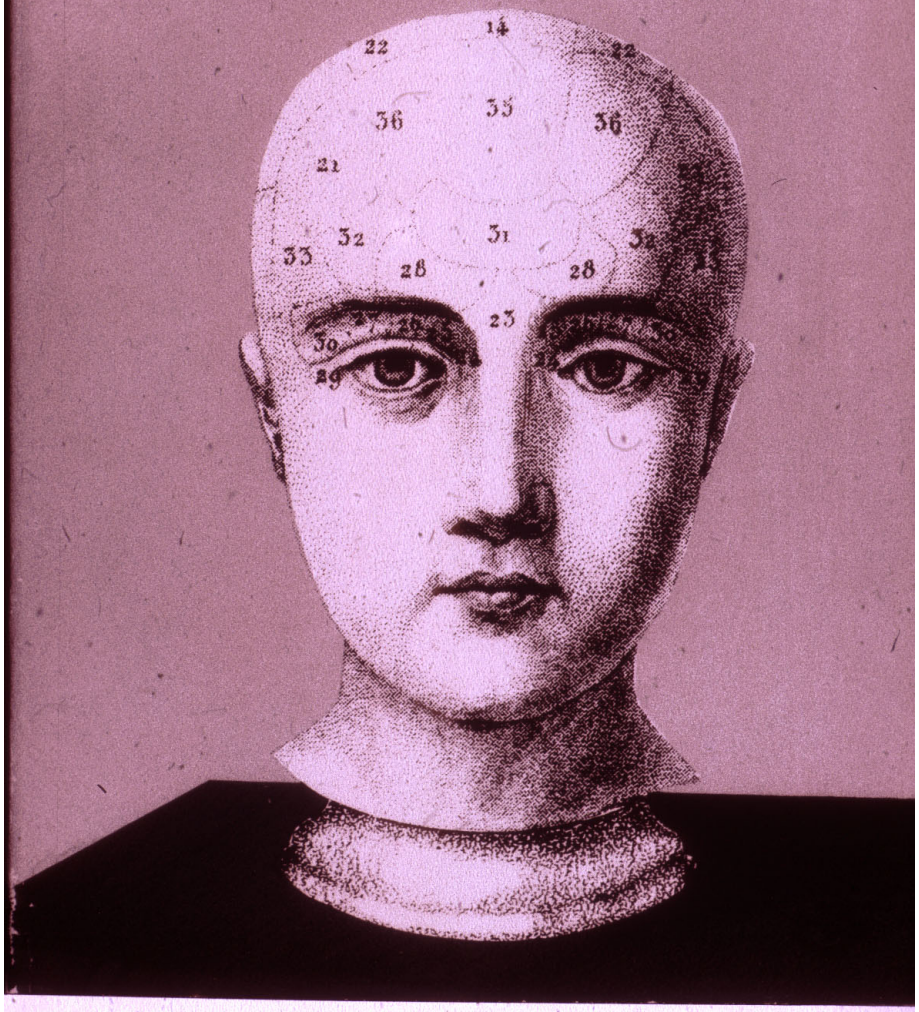
ABRALIN AO VIVO
30 June 2021

Where Did Language Come from? Precursor Mechanisms In Nonhuman Primates

Josef P. Rauschecker, PhD
Department of Neuroscience
Georgetown University
Washington, DC, USA

THE MODULARITY OF MIND

Jerry A. Fodor



Cambridge, MA: MIT Press (1983)

“The trouble with language is that there are no animal models.”

Francis Crick

“The trouble with language is that there are no animal models.”

Francis Crick

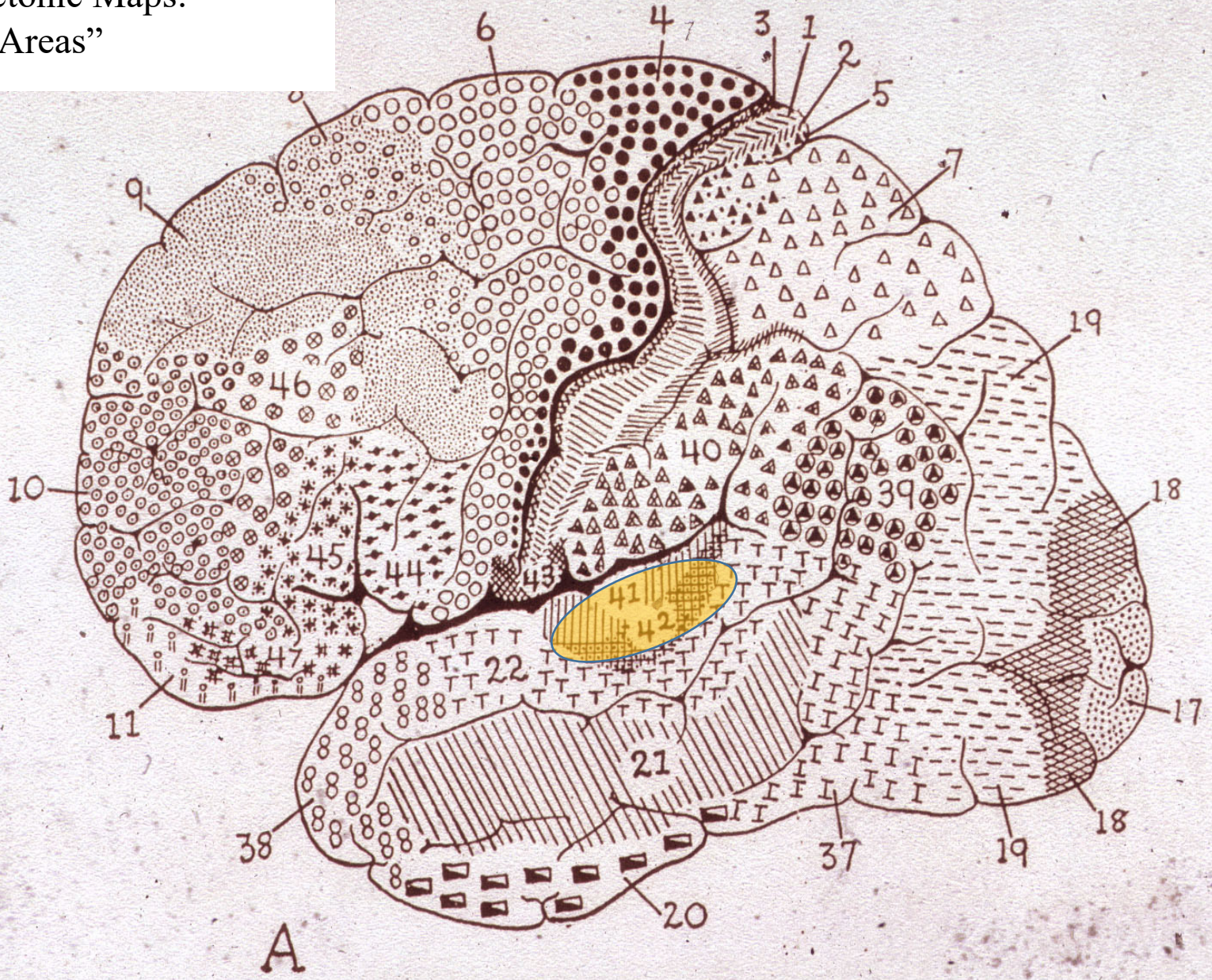
What would Darwin say?

Darwin CR (1871) The descent of man, and selection in relation to sex. London: Murray

Language consists of multiple discrete components (or subsystems) that emerged one at a time and, together, form the human language system.

Korbinian Brodmann (1909): *"Vergleichende Lokalisationslehre der Großhirnrinde"*

Cytoarchitectonic Maps:
"Brodmann Areas"



Korbinian Brodmann (1909): *"Vergleichende Lokalisationslehre der Großhirnrinde"*

Cytoarchitectonic Maps:
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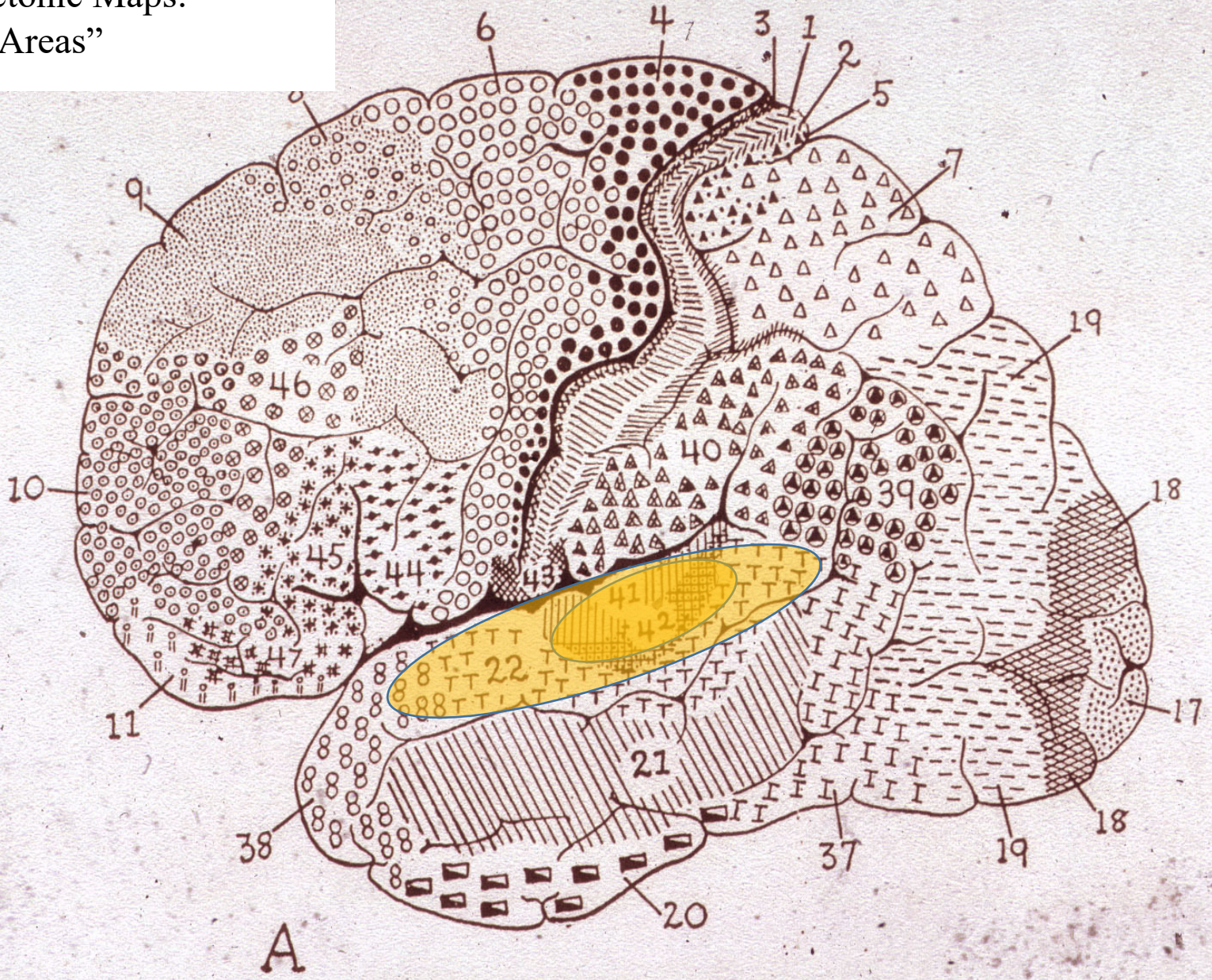

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Cytoarchitectonic Maps:
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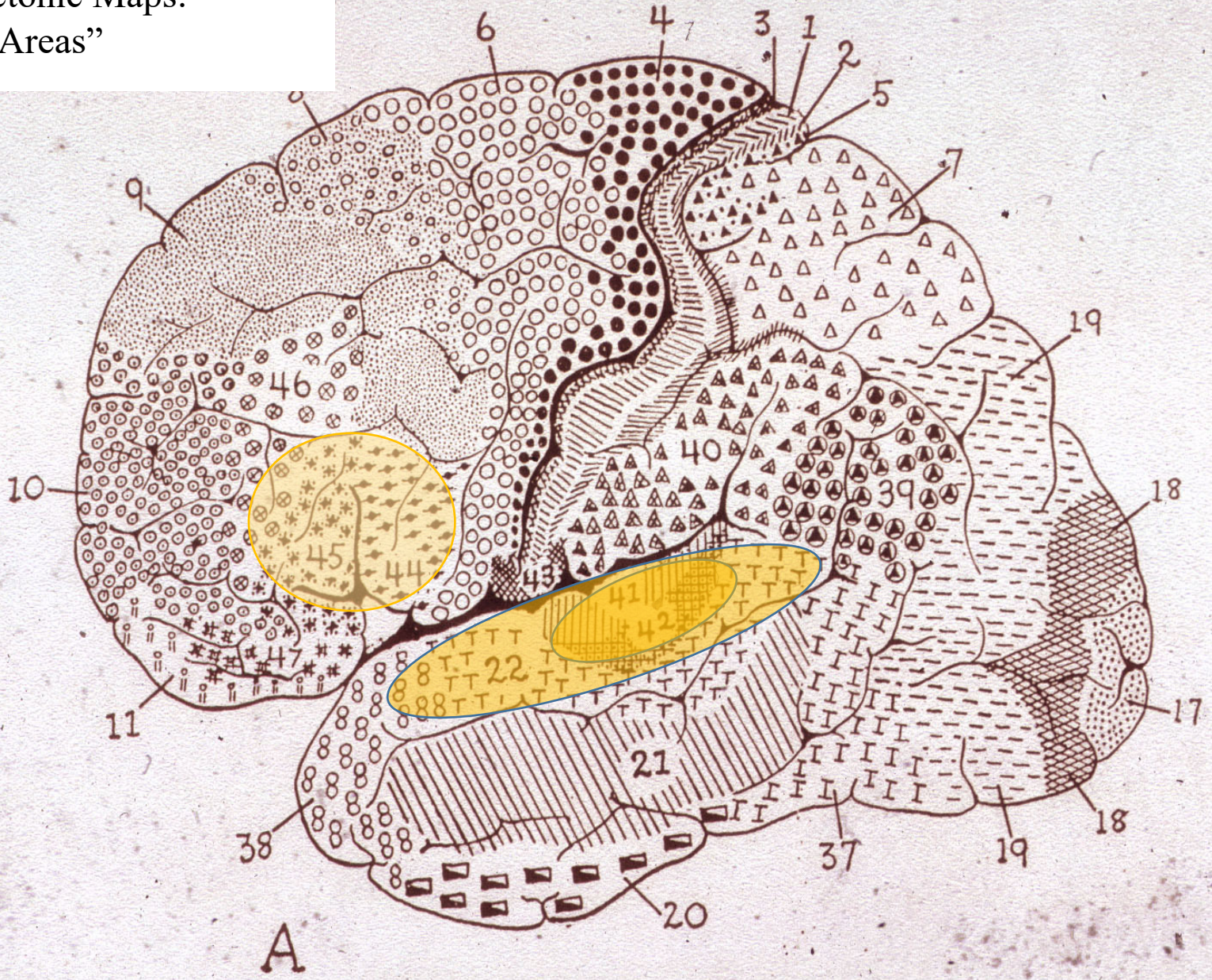
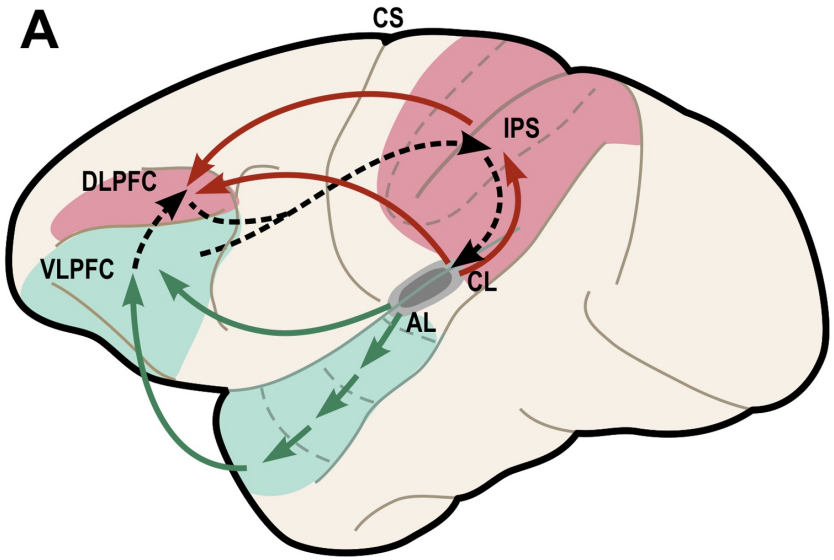
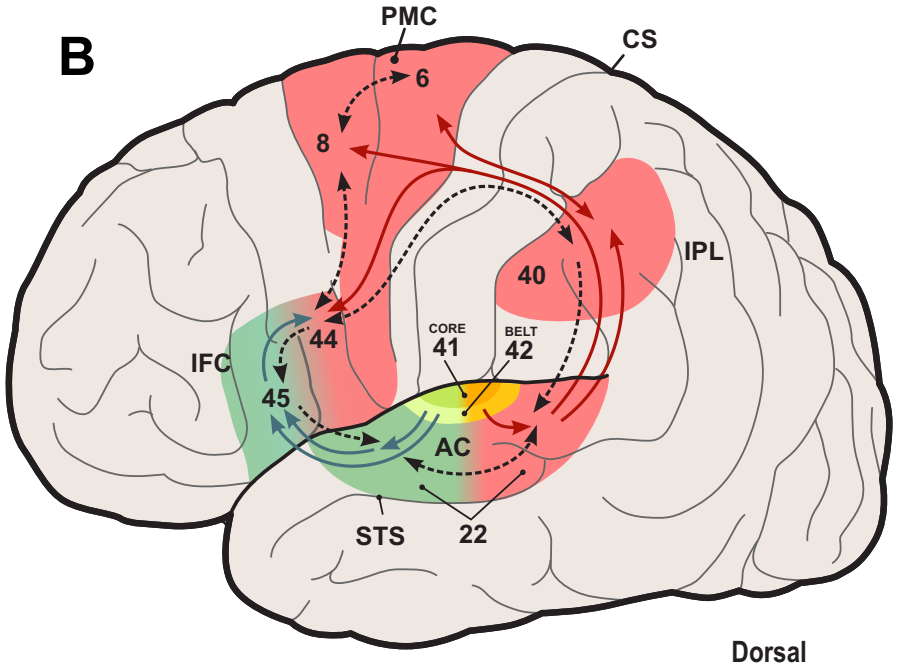
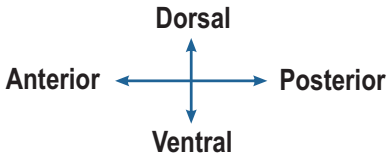


Dual-Stream Model of Auditory Processing

Neurophysiology and Neuroanatomy in Rhesus Monkeys
Rauschecker, 1997, 1998;
Rauschecker & Tian, *PNAS*, 2000





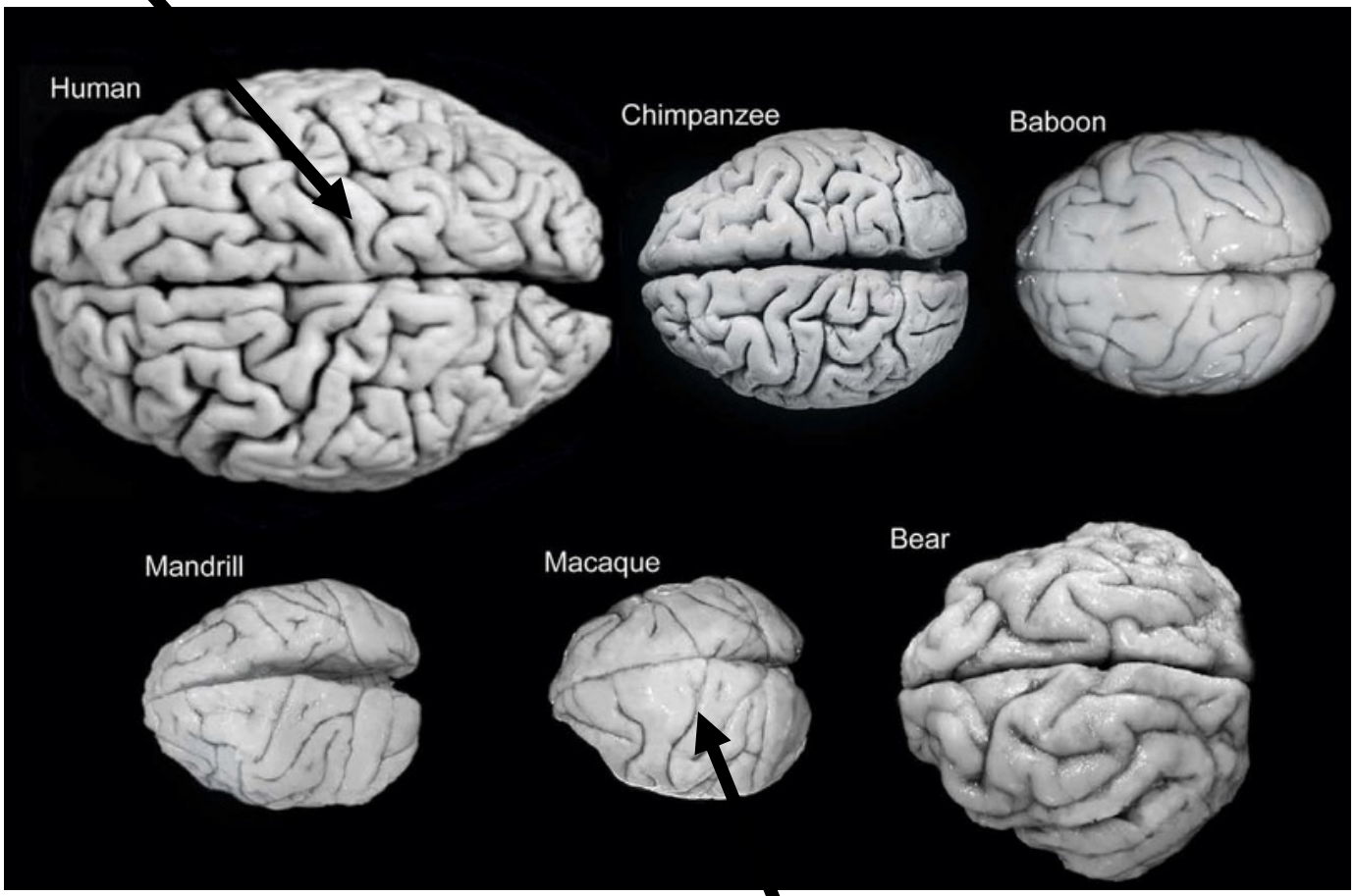


Neuroimaging in Humans (and Monkeys)
Rauschecker & Scott, Nature Neurosci., 2009;
Bornkessel et al., TICS, 2015

Adult rhesus macaque

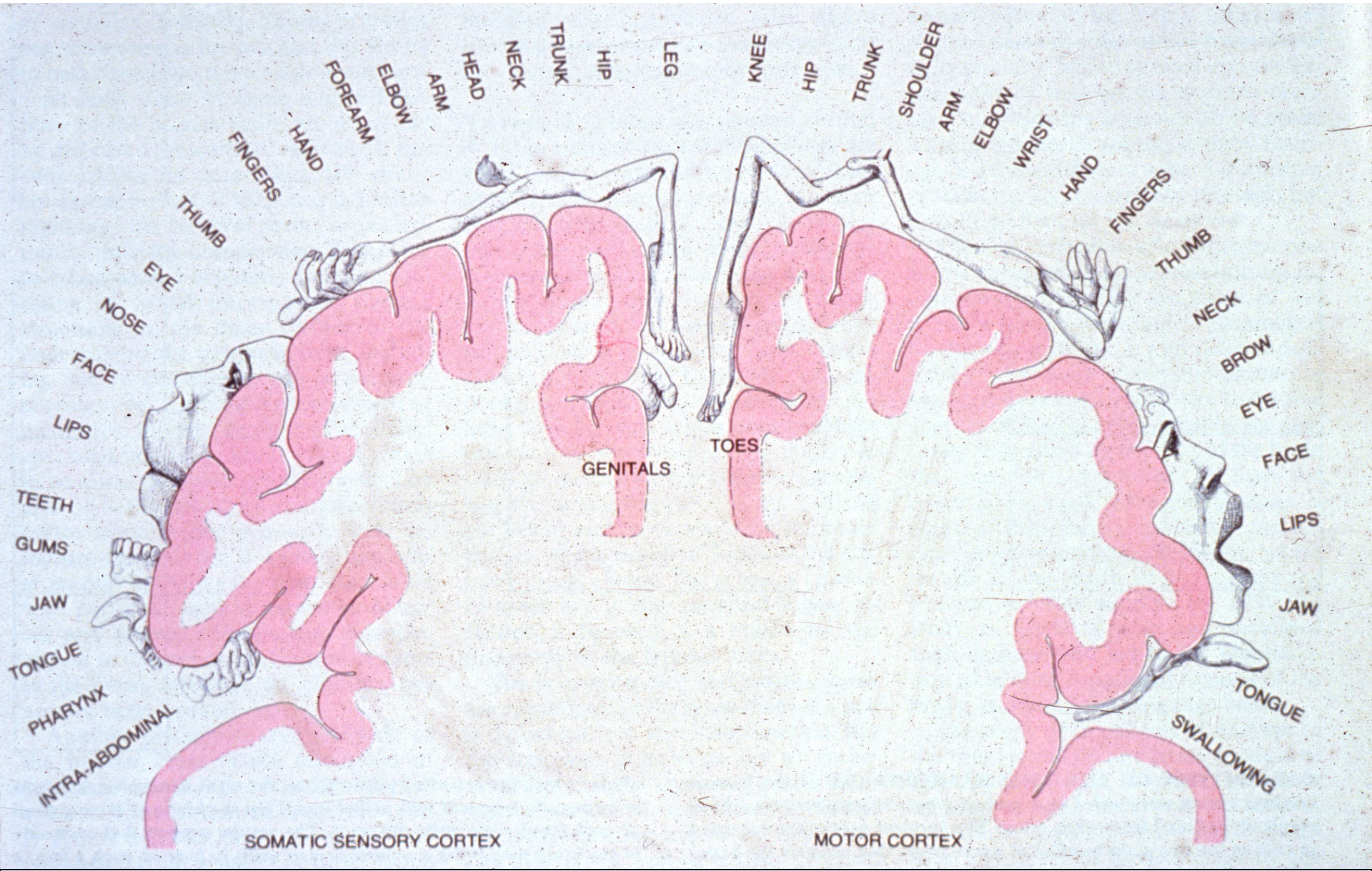
Relative Brain sizes

Human



Javier Defelipe (2011)

Macaque



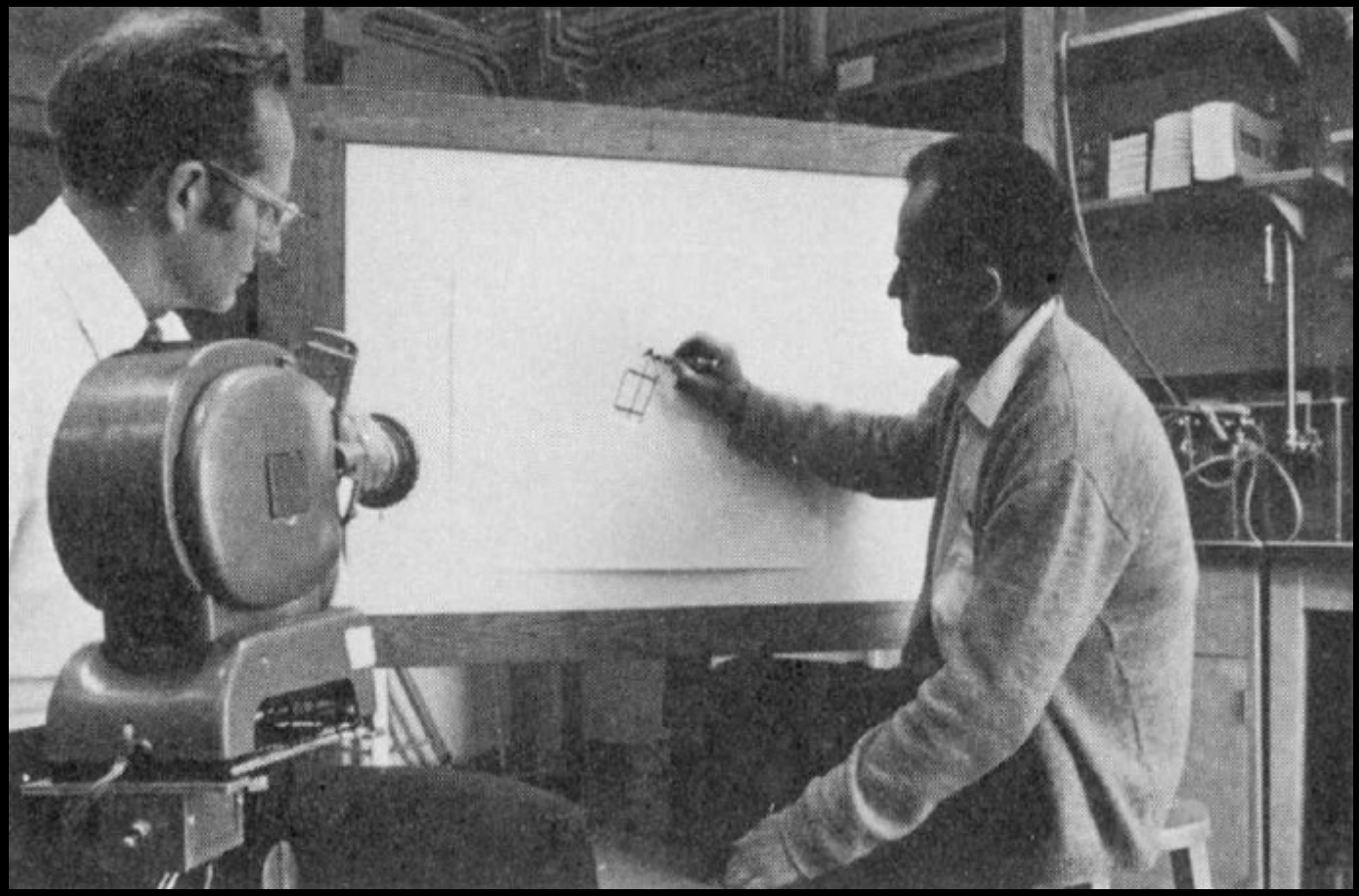
"Homunculus": Somatomotor Cortex

Wilder G. Penfield (1959)

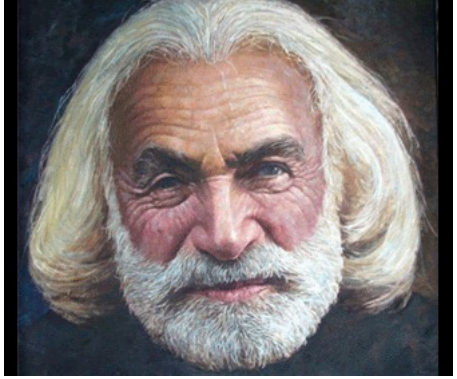
D. Hubel
1926-2013

T. Wiesel
*3-6-1924

Functional Architecture of Visual Cortex



Nobel Prize for Medicine/Physiology 1981

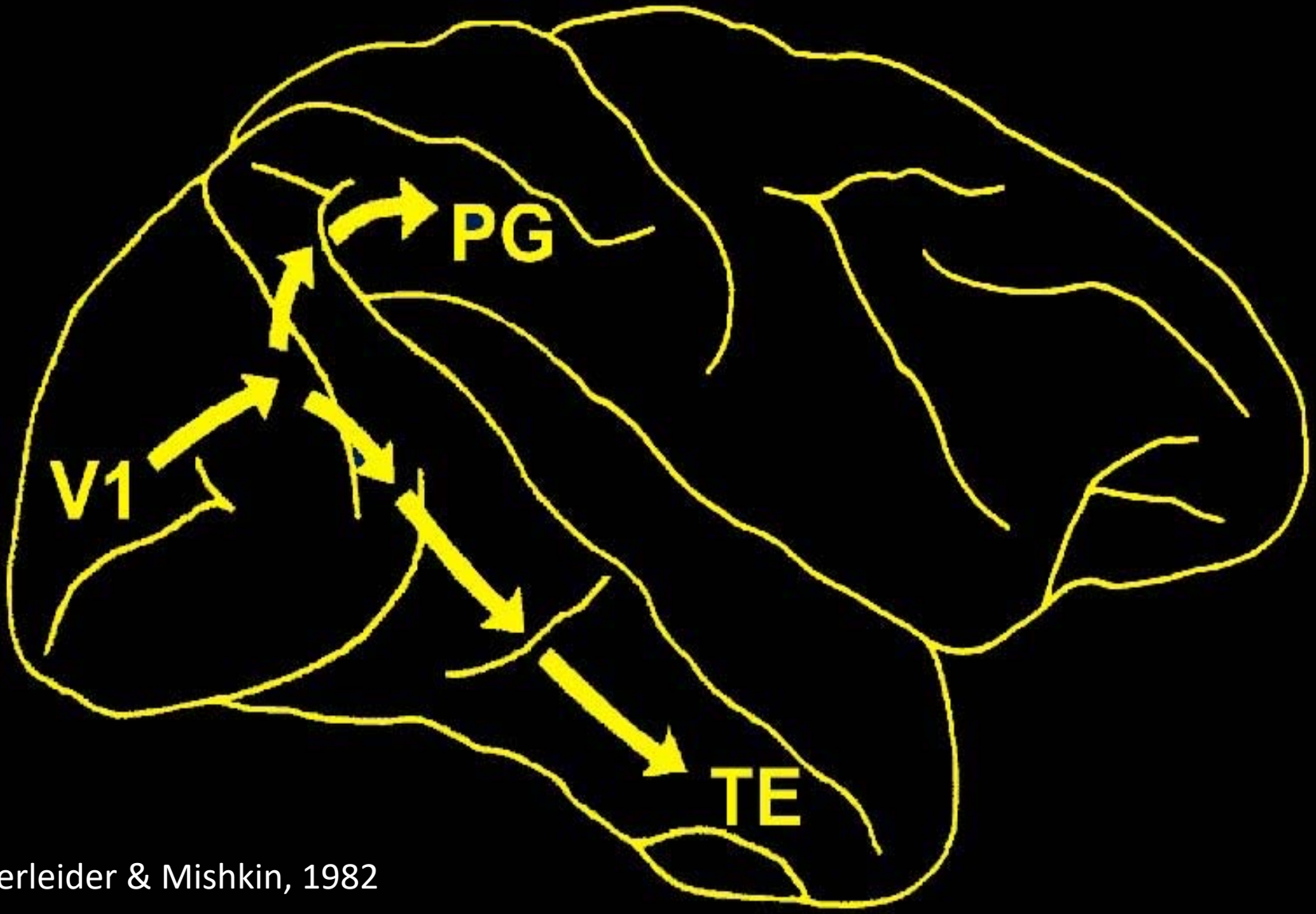


Karl Pribram
*1919-2015

Leslie Ungerleider
1946-2020

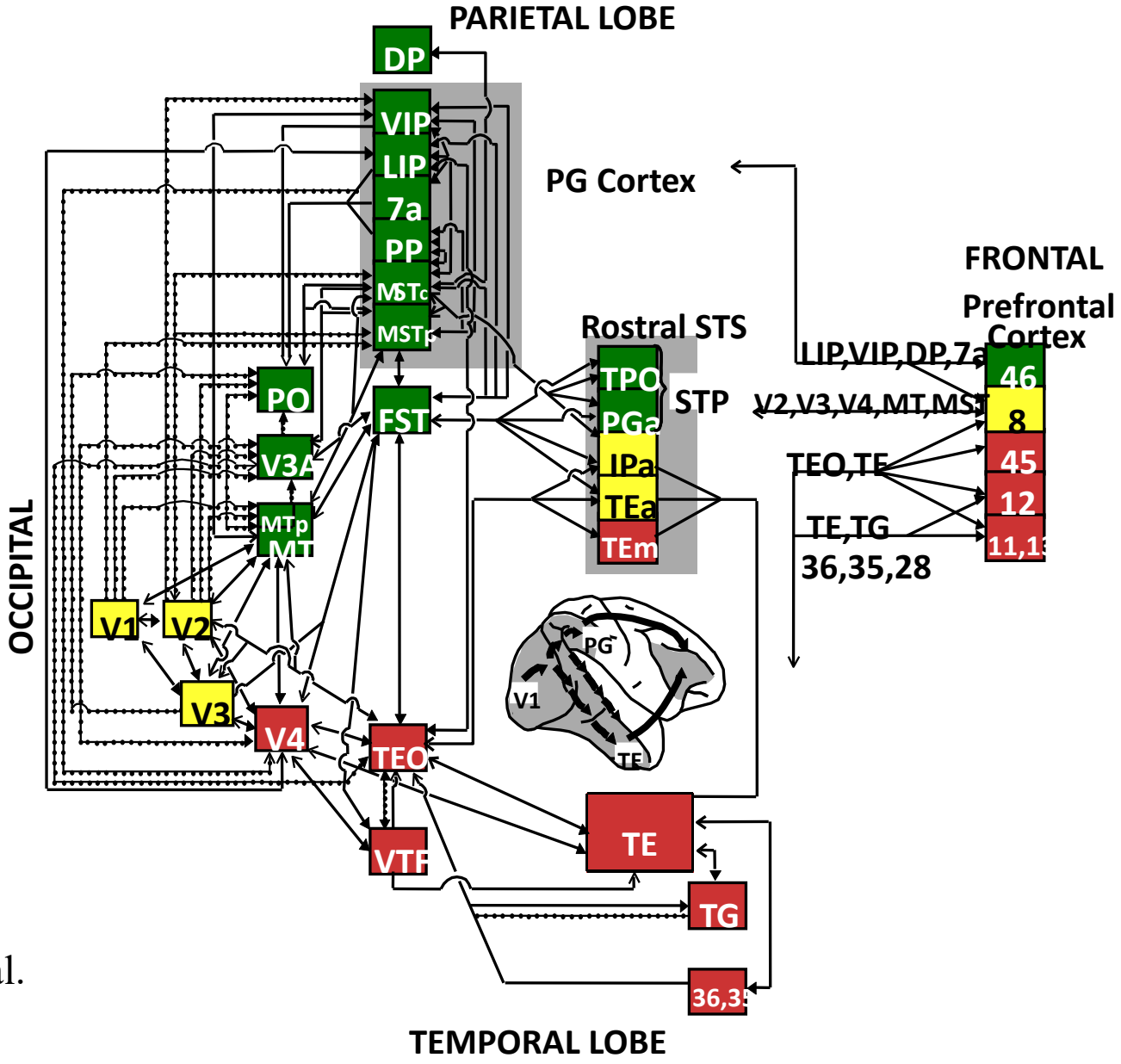
Mort Mishkin
*12-13-1926

Two Cortical Visual Systems: What versus Where



Ungerleider & Mishkin, 1982

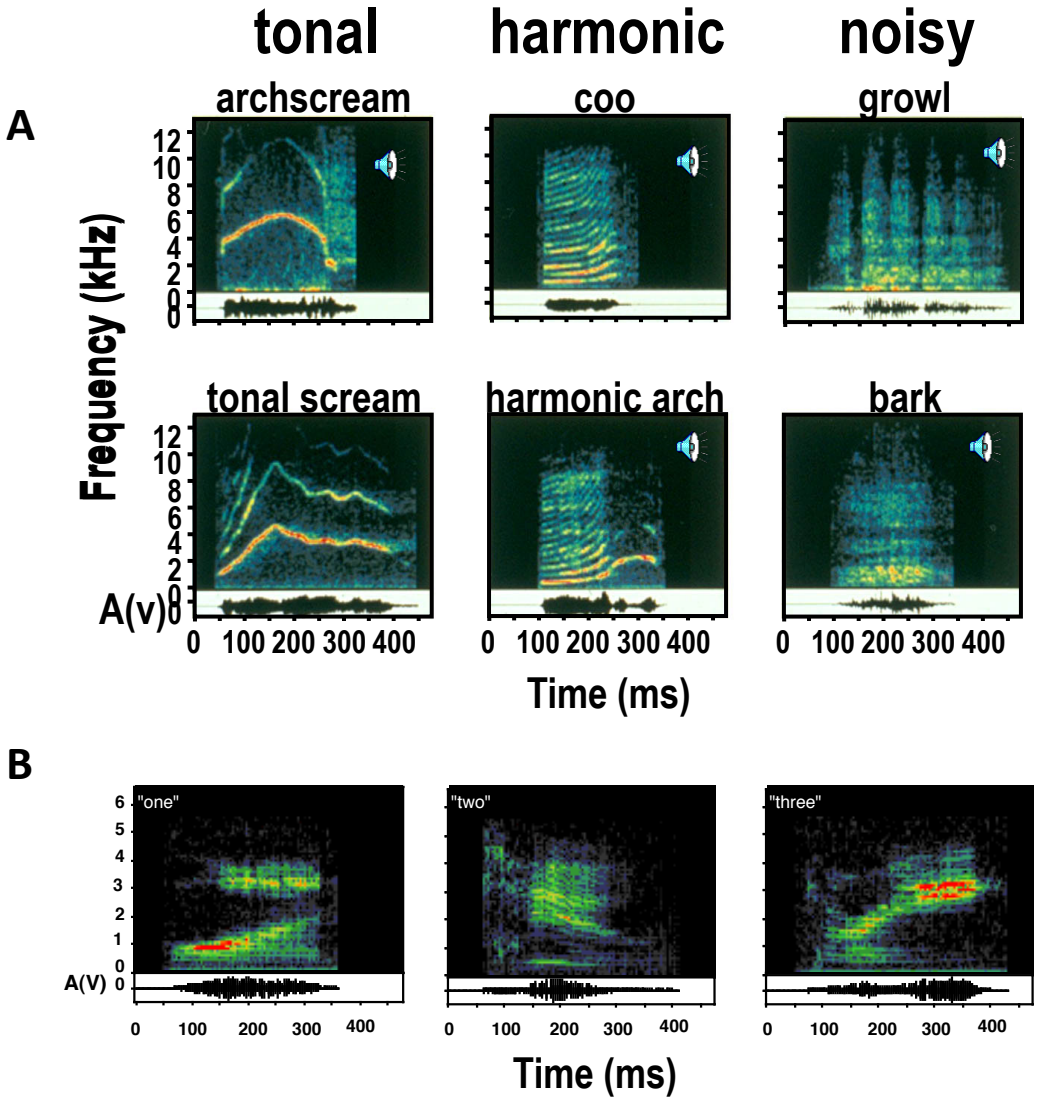
Visual Cortex



Ungerleider et al.

Processing of Complex Sounds: Monkey Neurophysiology

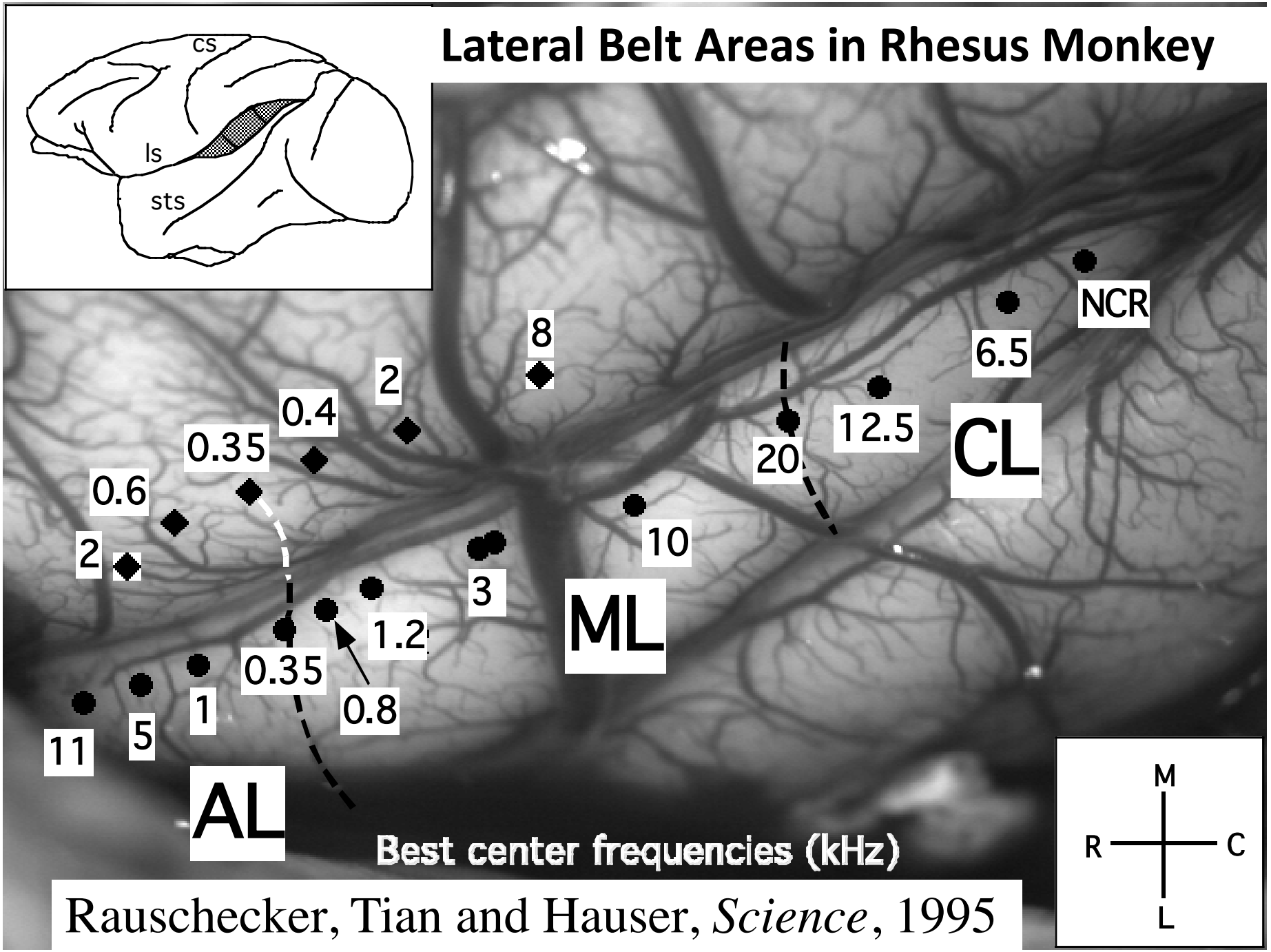
Species-Specific Communication Sounds



Monkey Calls

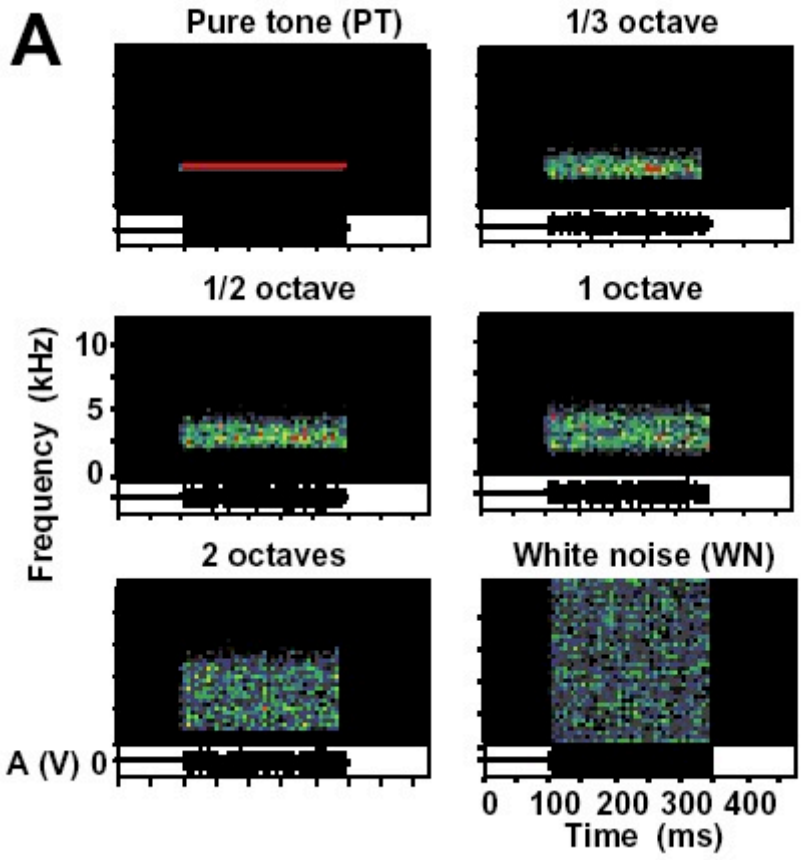
Human Speech

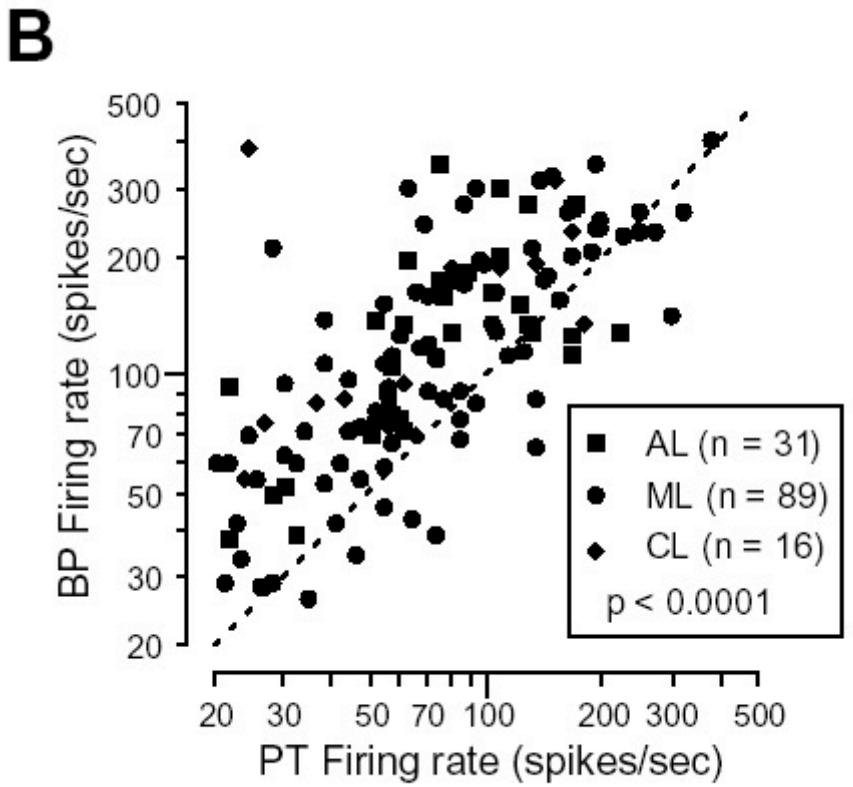
Lateral Belt Areas in Rhesus Monkey



Rauschecker, Tian and Hauser, *Science*, 1995

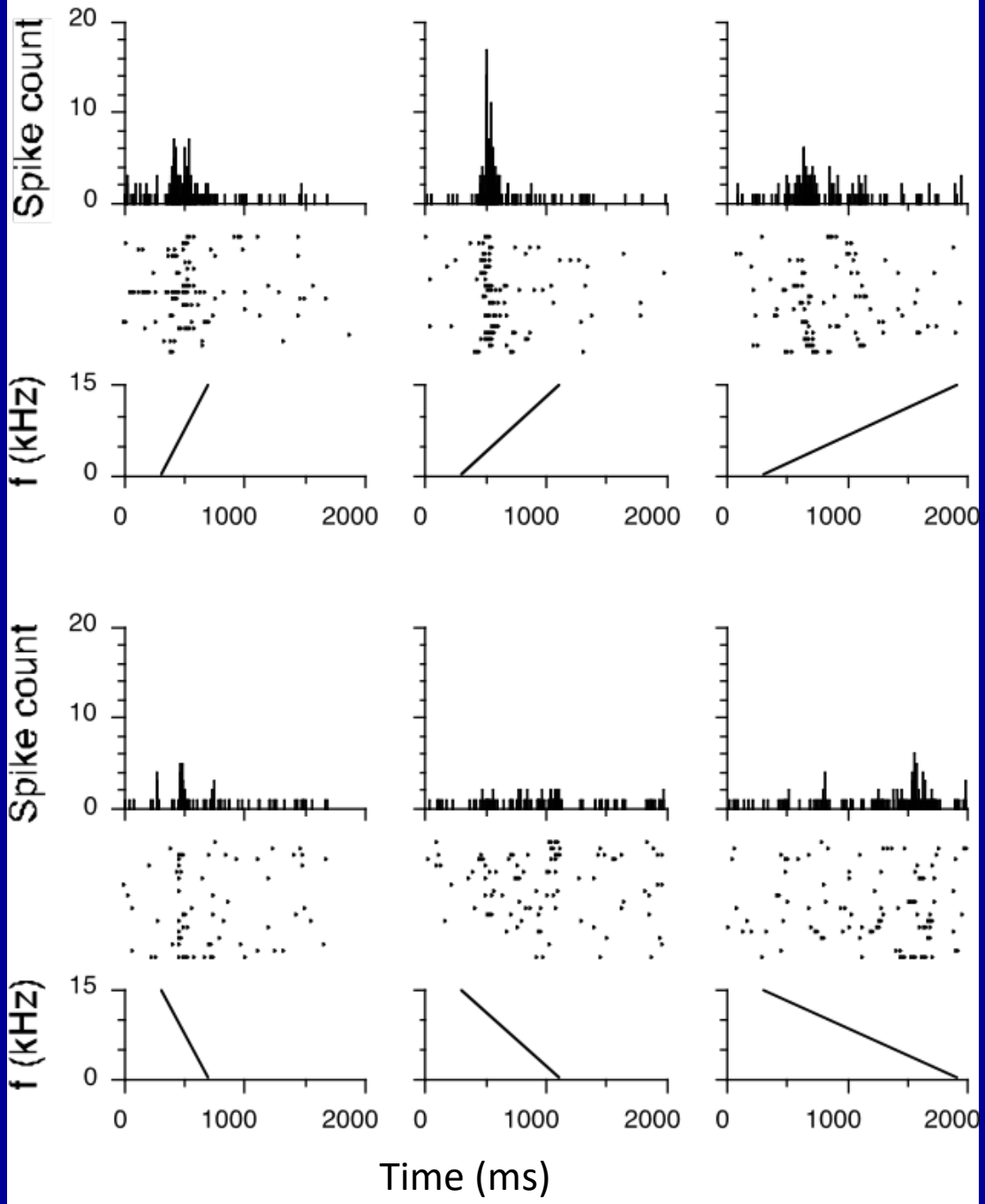
Band-Pass Tuning





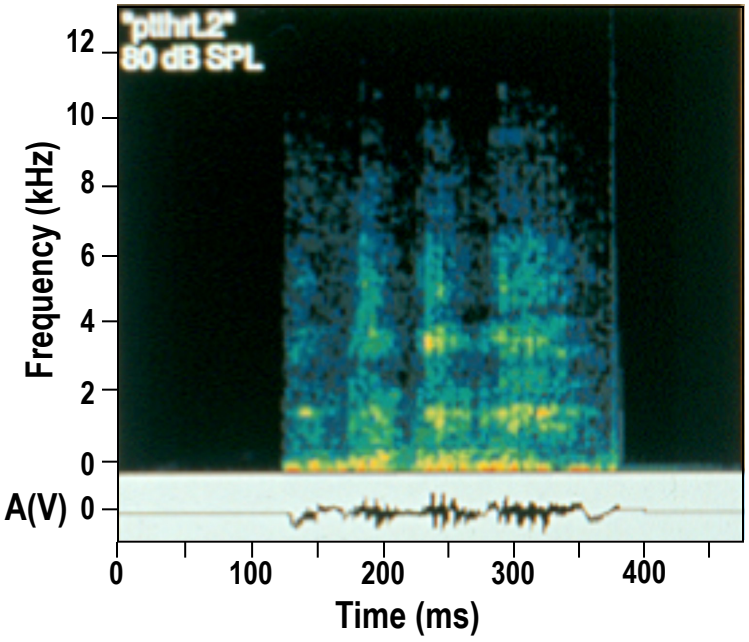
Rauschecker, Tian and Hauser, *Science*, 1995

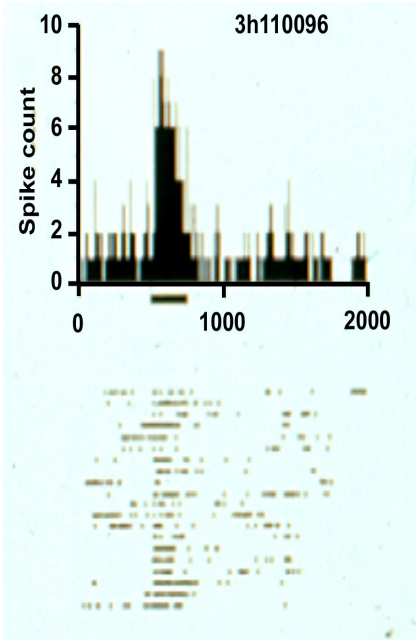
FM Tuning

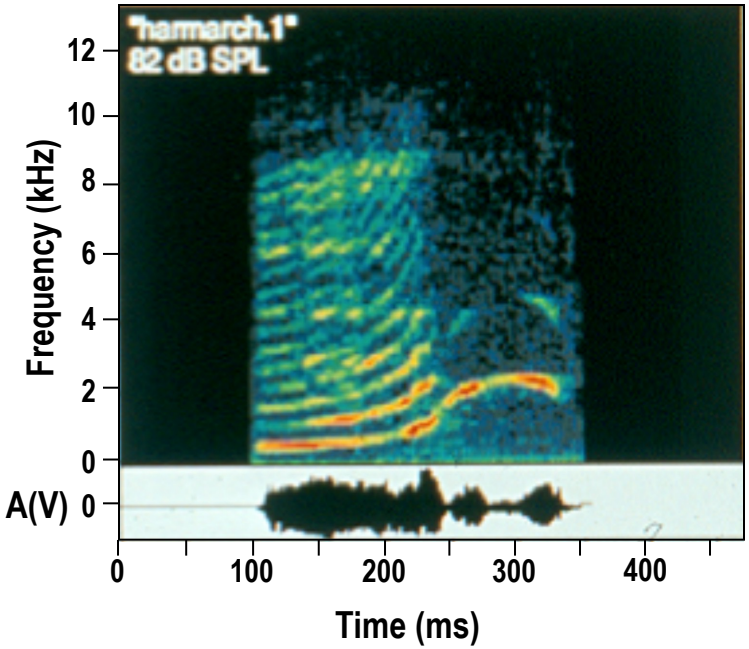


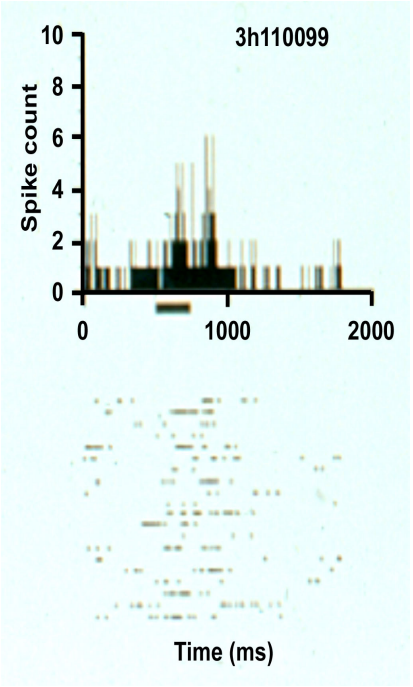
FM up

FM down

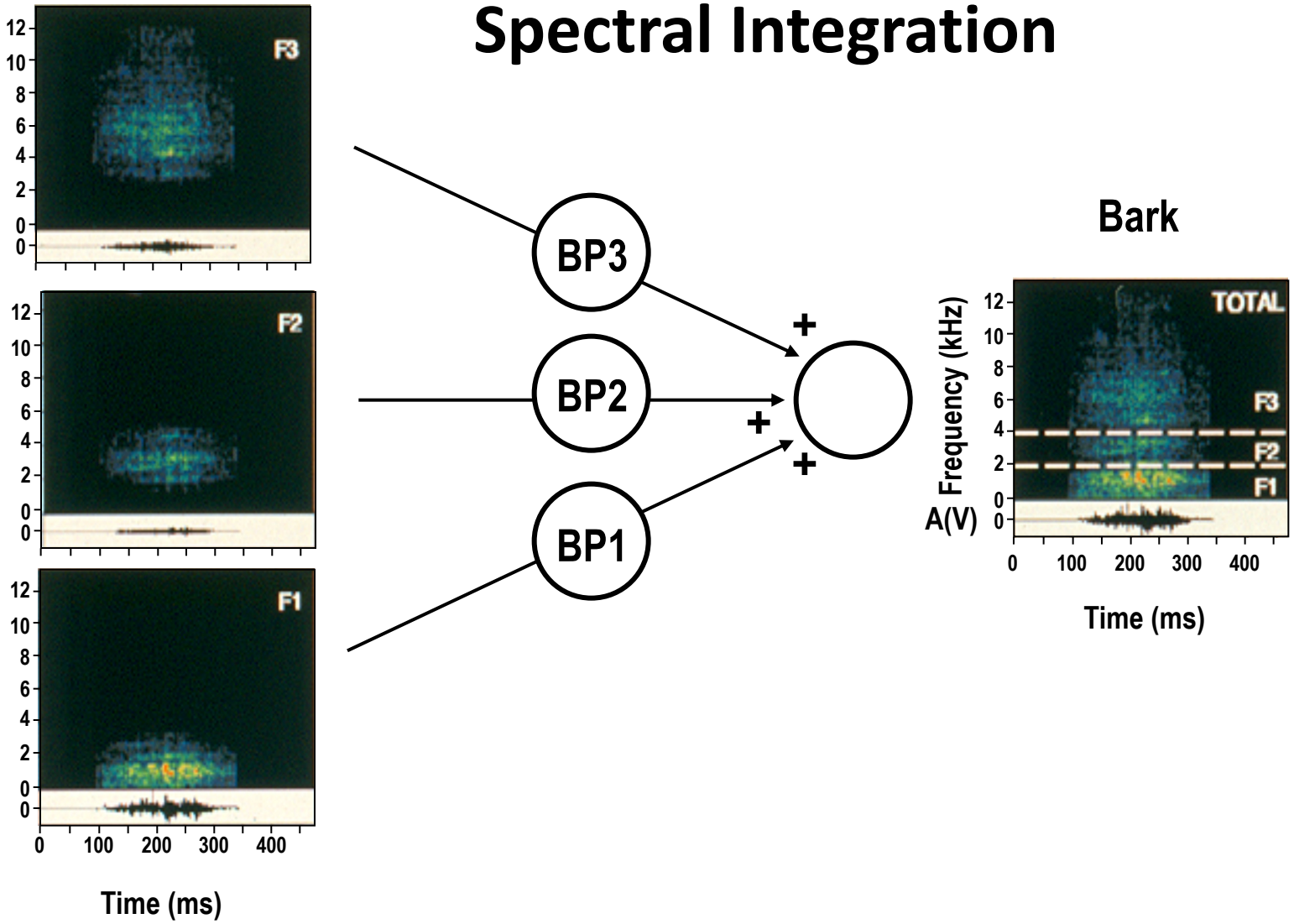

"pilhrt.2"
80 dB SPL
Frequency (kHz)
12
10
8
6
4
2
0
A(V)
0
0
100
200
300
400
Time (ms)


3h110096
Spike count
10
8
6
4
2
0
0
1000
2000

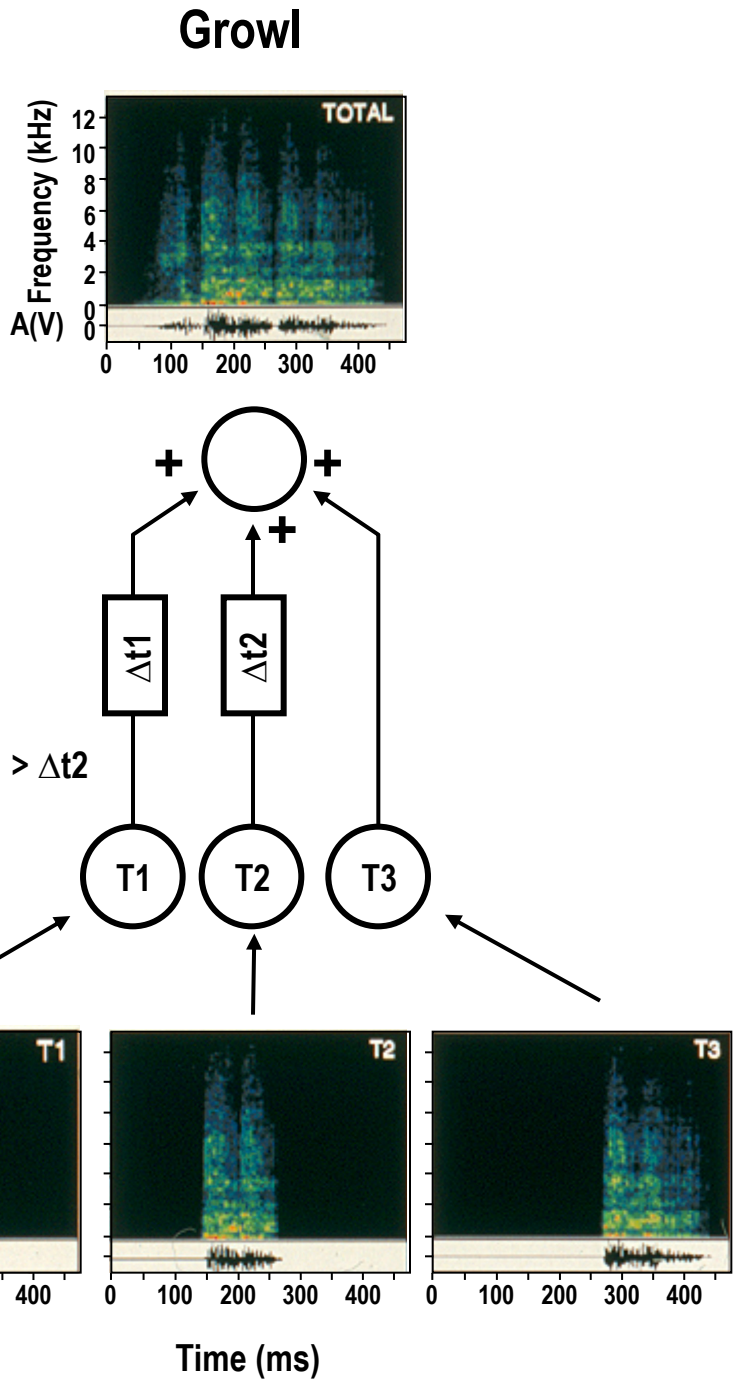

"harmarch.1"
82 dB SPL
Frequency (kHz)
12
10
8
6
4
2
0
A(V)
0
0
100
200
300
400
Time (ms)


3h110099
Spike count
10
8
6
4
2
0
0
1000
2000
Time (ms)

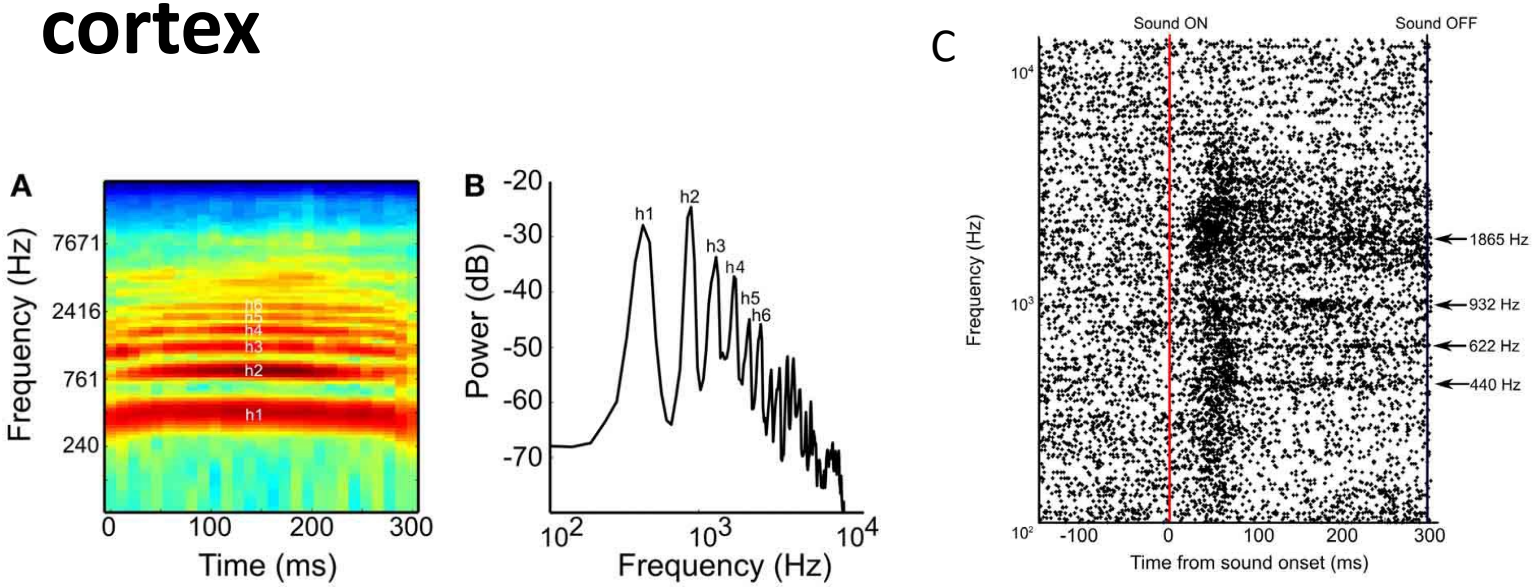
Combination Sensitivity: Spectral Integration



Combination Sensitivity*: Temporal Integration



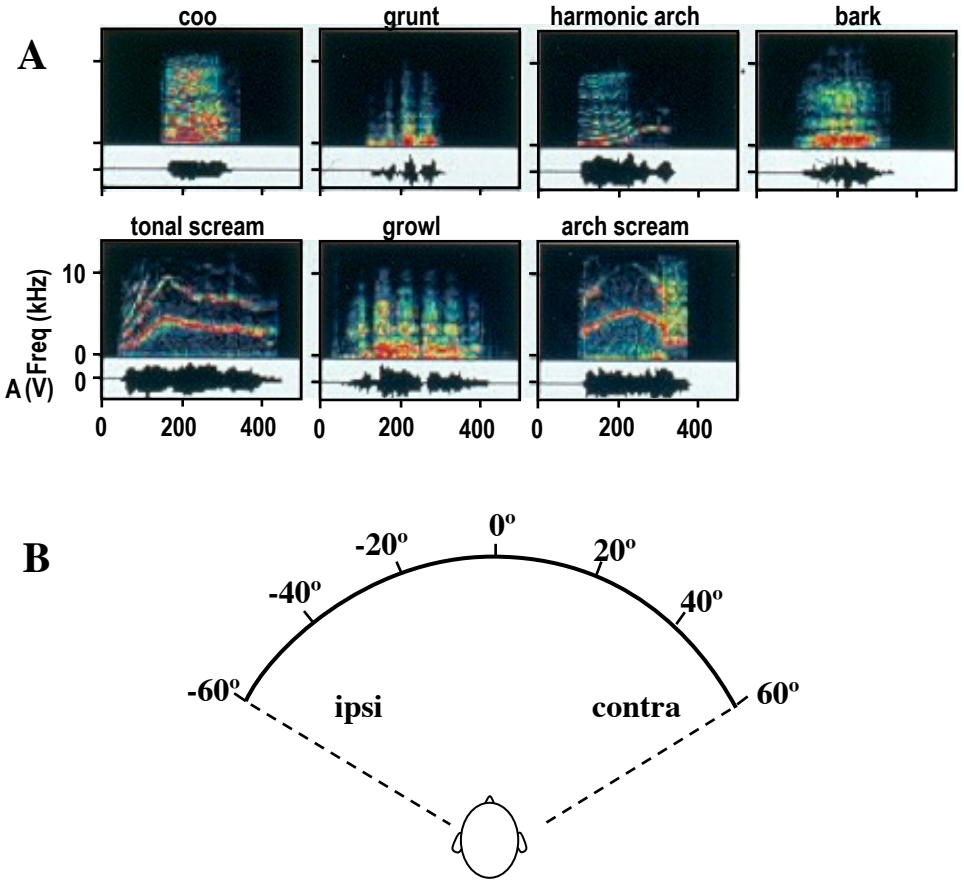
Processing of harmonics in macaque auditory cortex



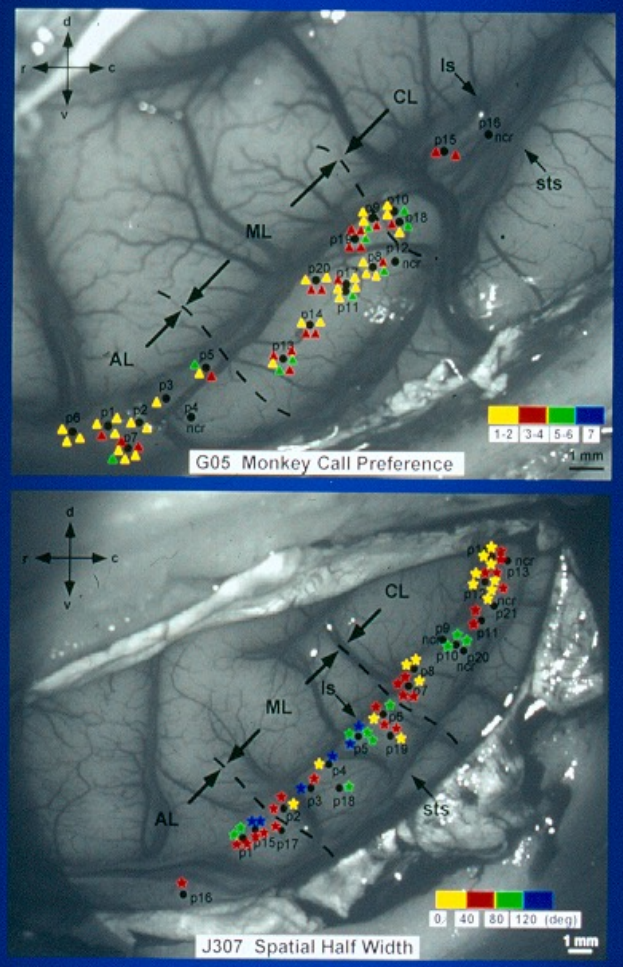
Kikuchi, Y., Horwitz, B., Mishkin, M., and Rauschecker, J.P. (2014) Processing of harmonics in the lateral belt of macaque auditory cortex. Frontiers in Neuroscience 8, 204.

See also: Norman-Haignere, Kanwisher, McDermott and Conway (2019) Nature Neuroscience

Functional Specialization



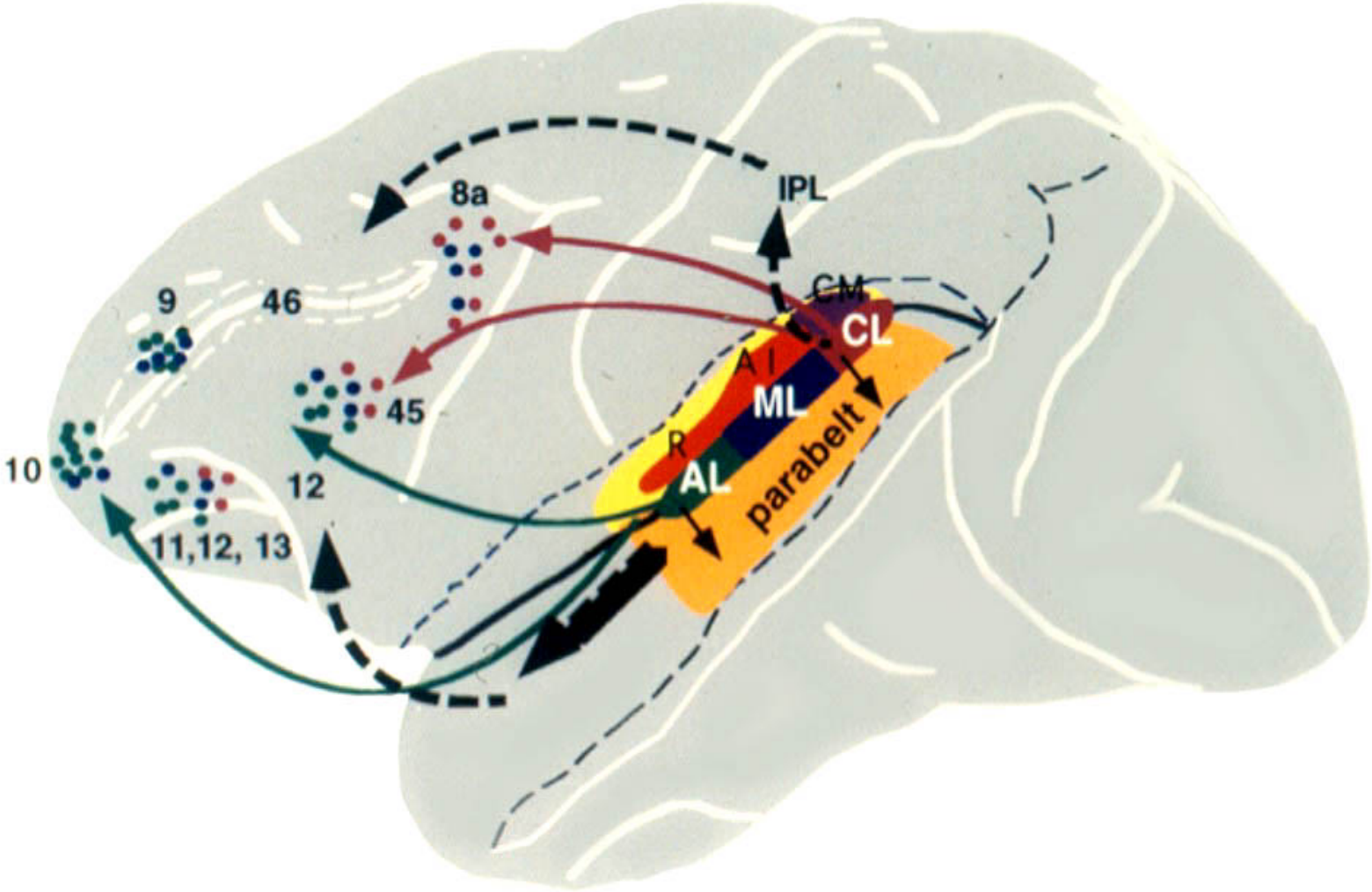
Monkey Call Preference: AL



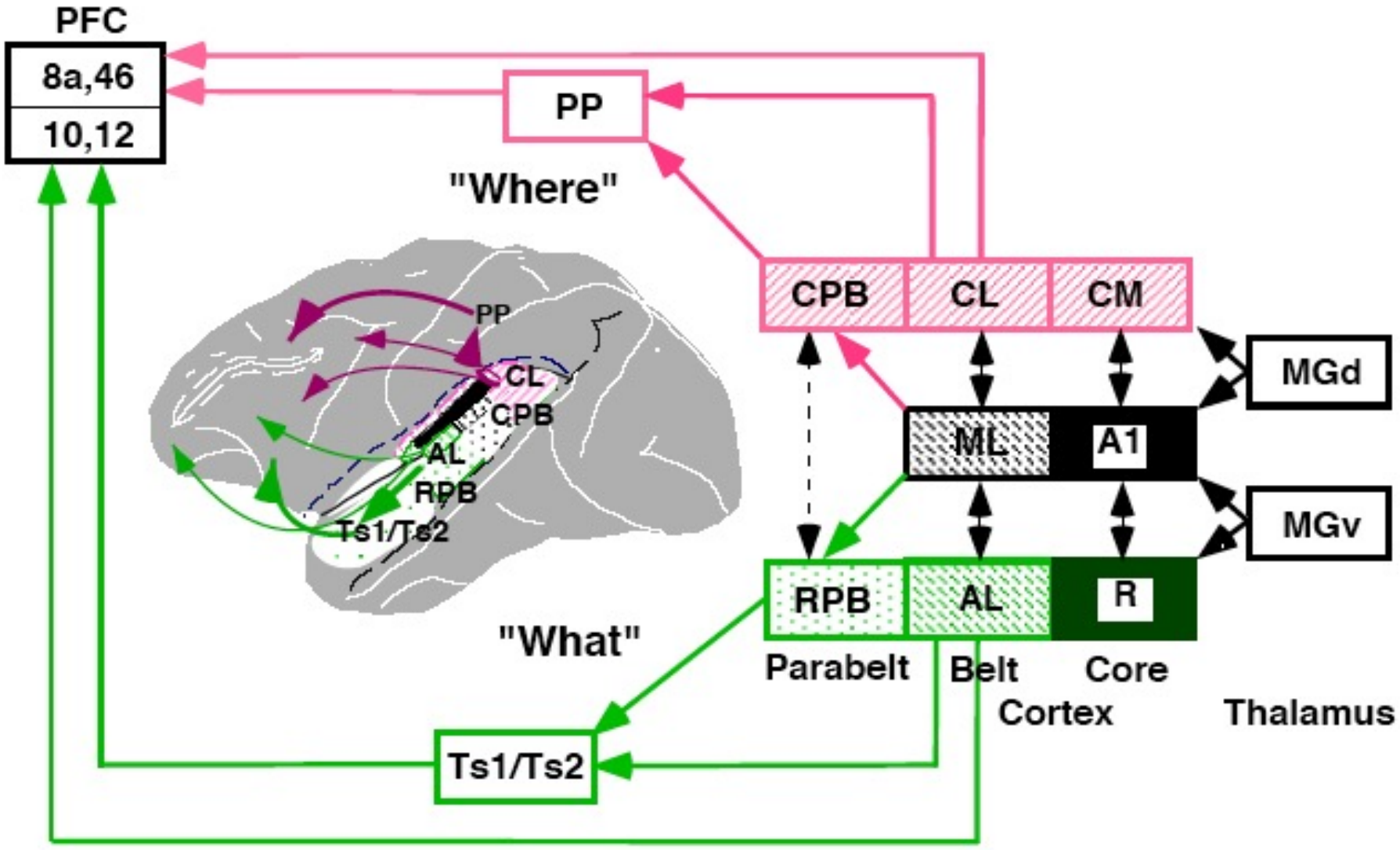
Spatial Tuning: CL

Tian, Reser, Durham, Kustov, Rauschecker, *Science*, 2001

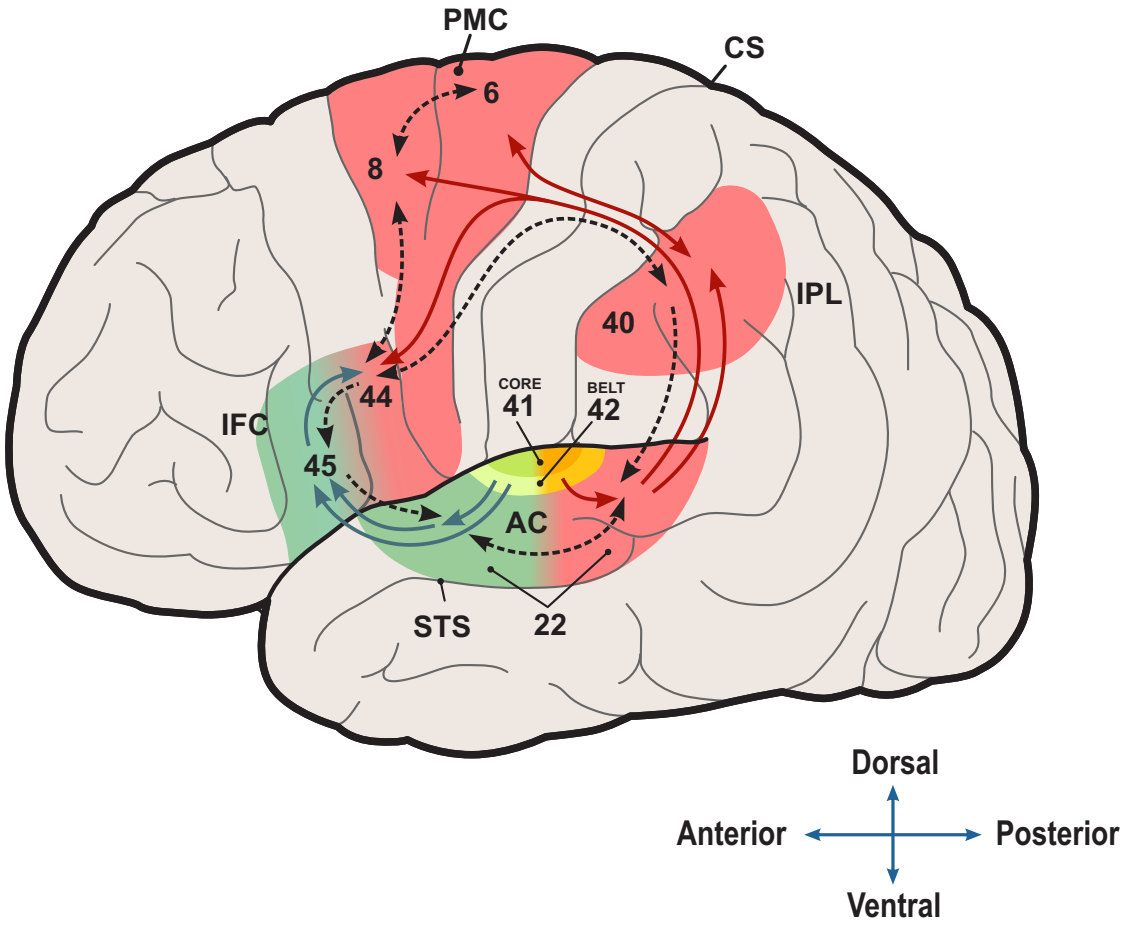
Auditory Connections With Prefrontal Cortex



Romanski, Tian, Fritz, Mishkin, Goldman-Rakic, Rauschecker, *Nature Neurosci.,* 1999



expanded from Rauschecker and Tian, *PNAS*, 2000



Dorsal Stream:

Sensorimotor Integration and Control

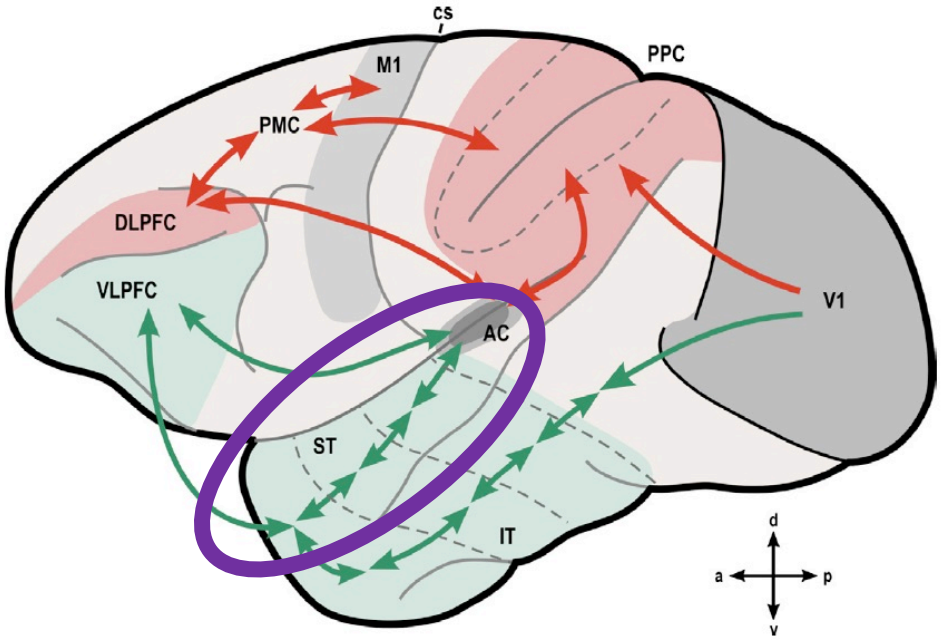
Ventral Stream:

Hierarchical Processing and Object Identification

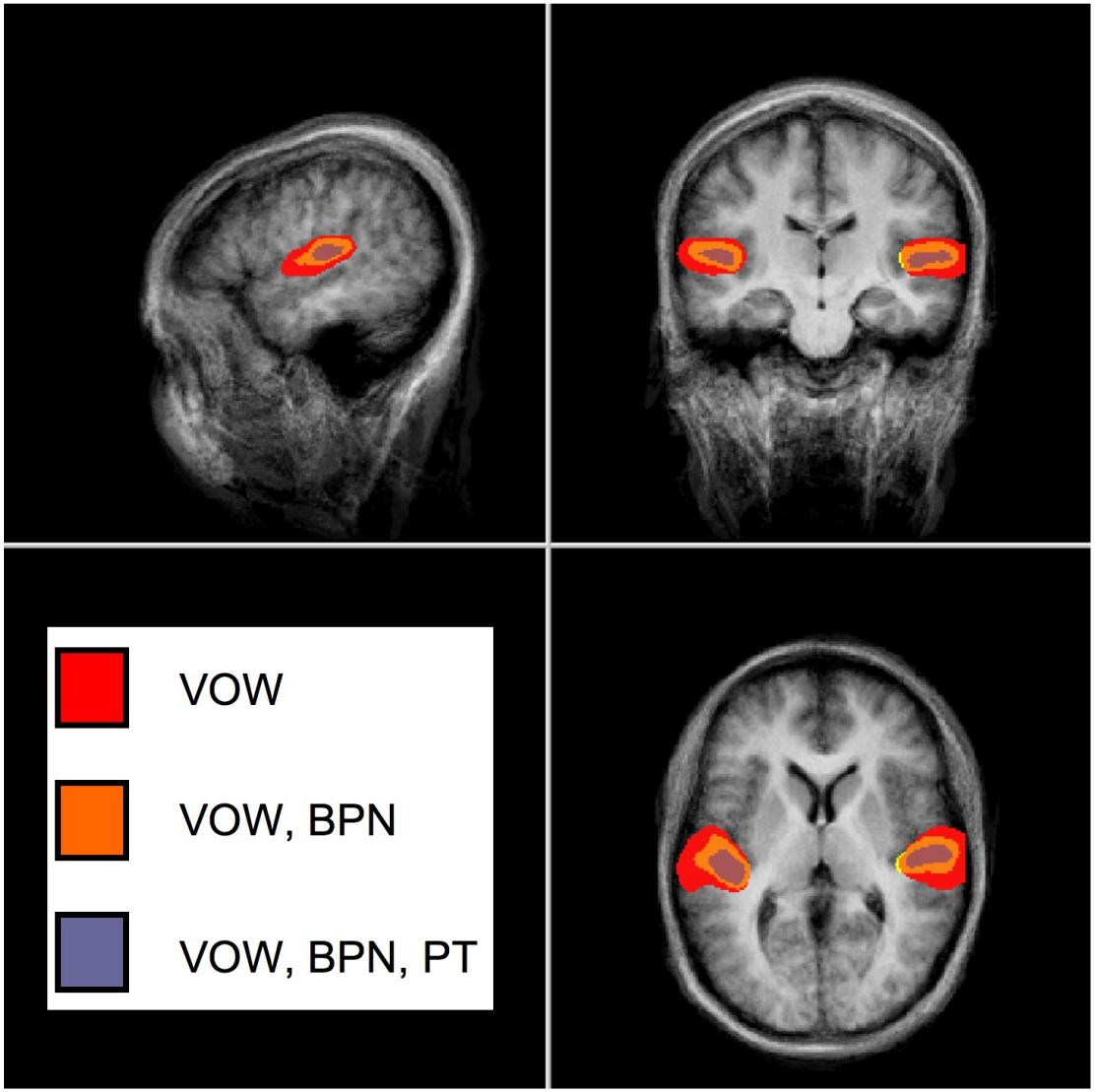
Rauschecker and Scott, *Nature Neuroscience* (2009);
Rauschecker, *Hearing Research* (2011);
Bornkessel-Schlesewsky, Schlesewsky, Small, Rauschecker, *TICS* (2015)

Auditory Processing Streams in Humans: Spoken Language

Representation of complex sounds in the ventral stream: Auditory object recognition



Auditory Core, Belt, Parabelt in Humans

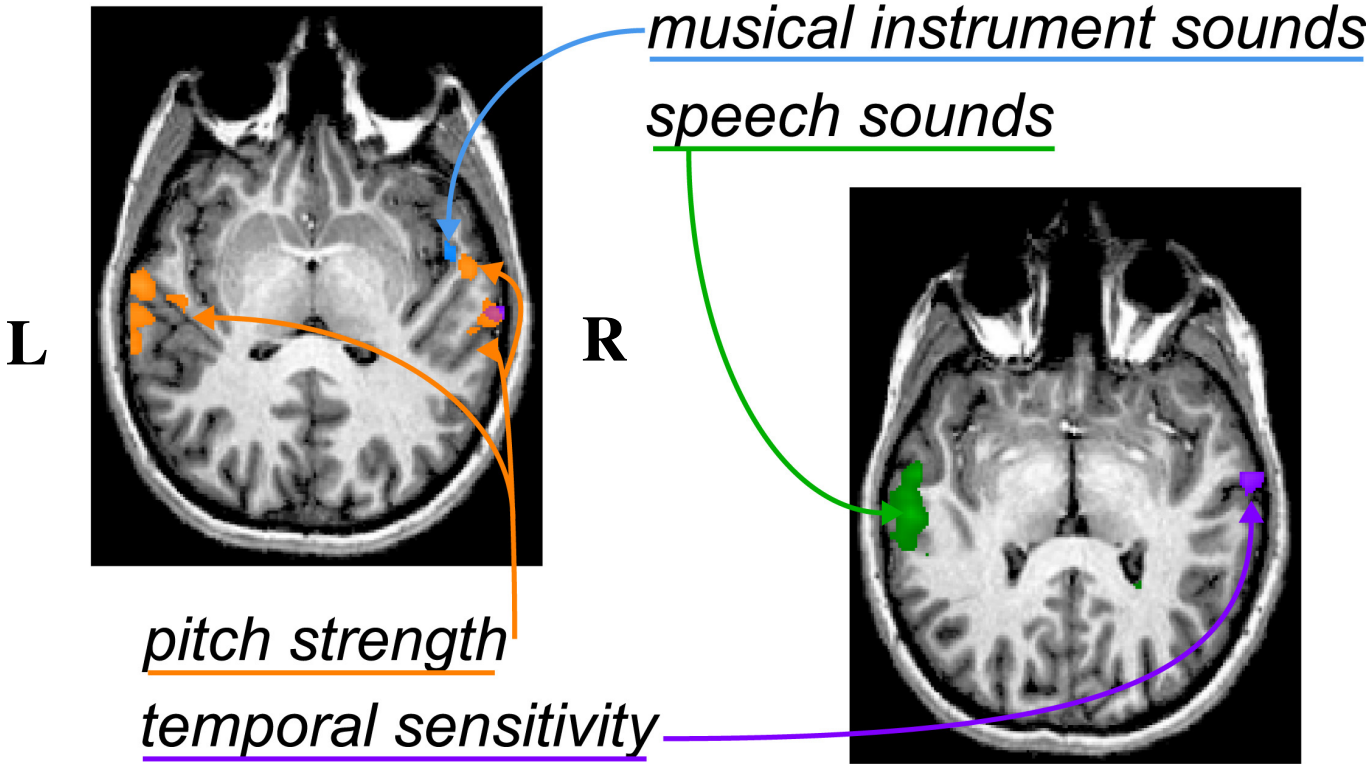


Chevillet, Riesenhuber, Rauschecker, *J. Neurosci*. (2011)

Ventral Stream: Auditory "Objects"

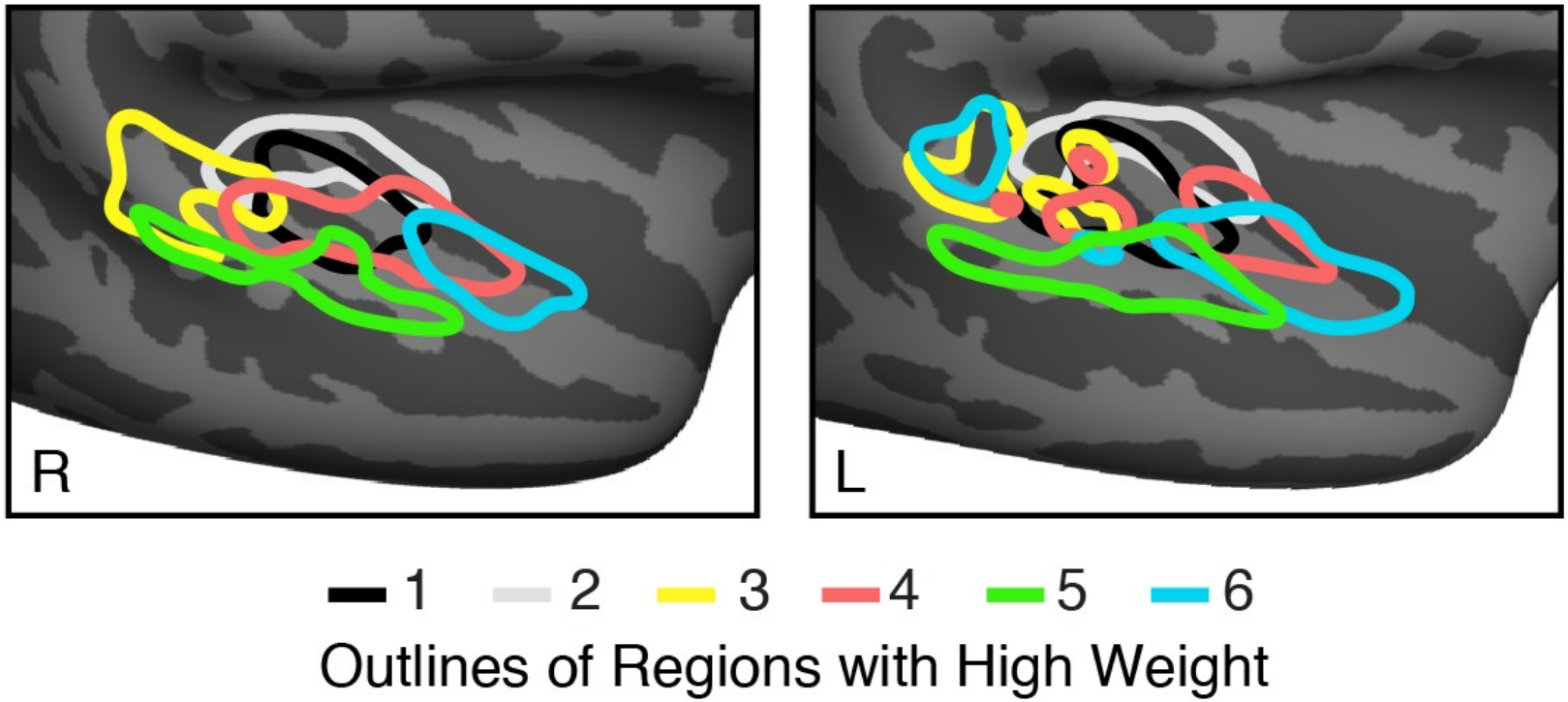
Leaver and Rauschecker, *J. Neurosci.* (2010)

Auditory cortex responses to
sound category and acoustic features:

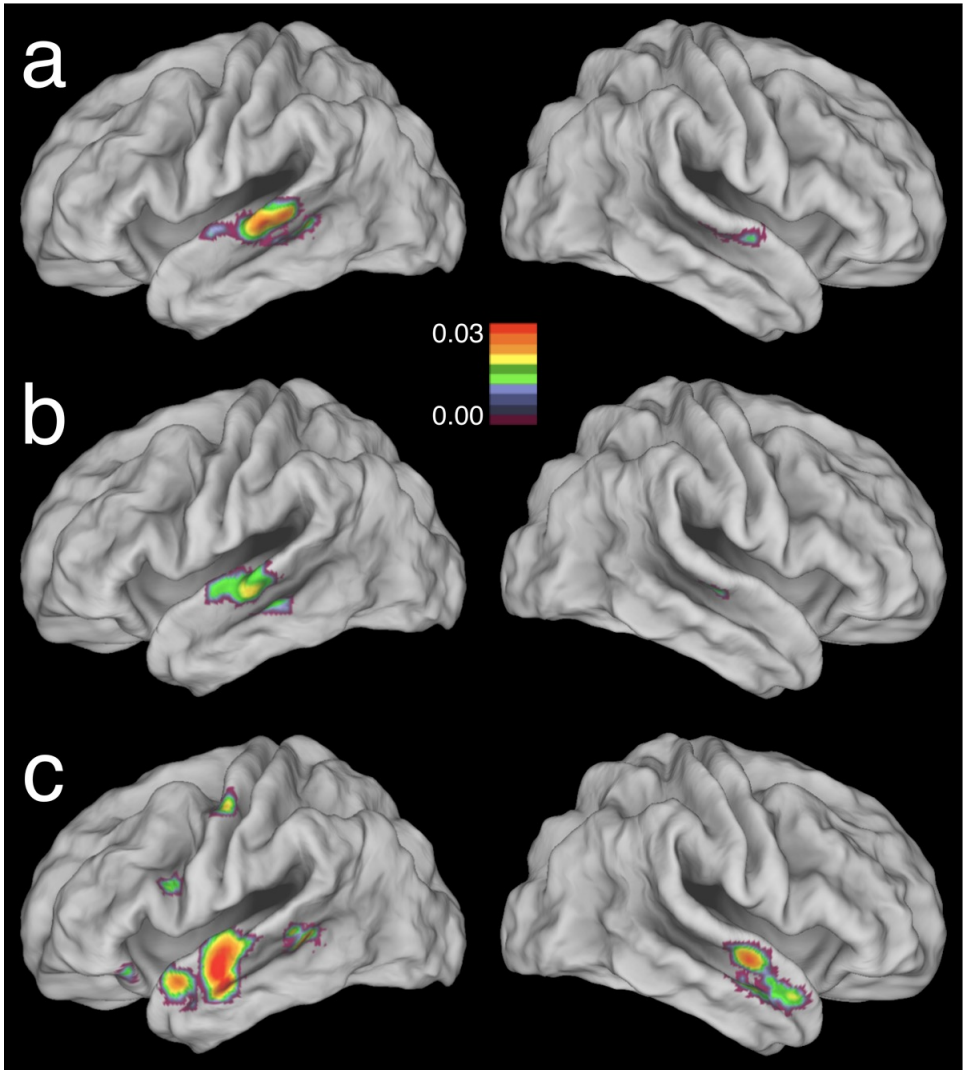


Distinct Cortical Regions for Music and Speech

Norman-Haignere, Kanwisher, McDermott, *Neuron* (2015)



Phoneme and Word Recognition in the Auditory Ventral Stream



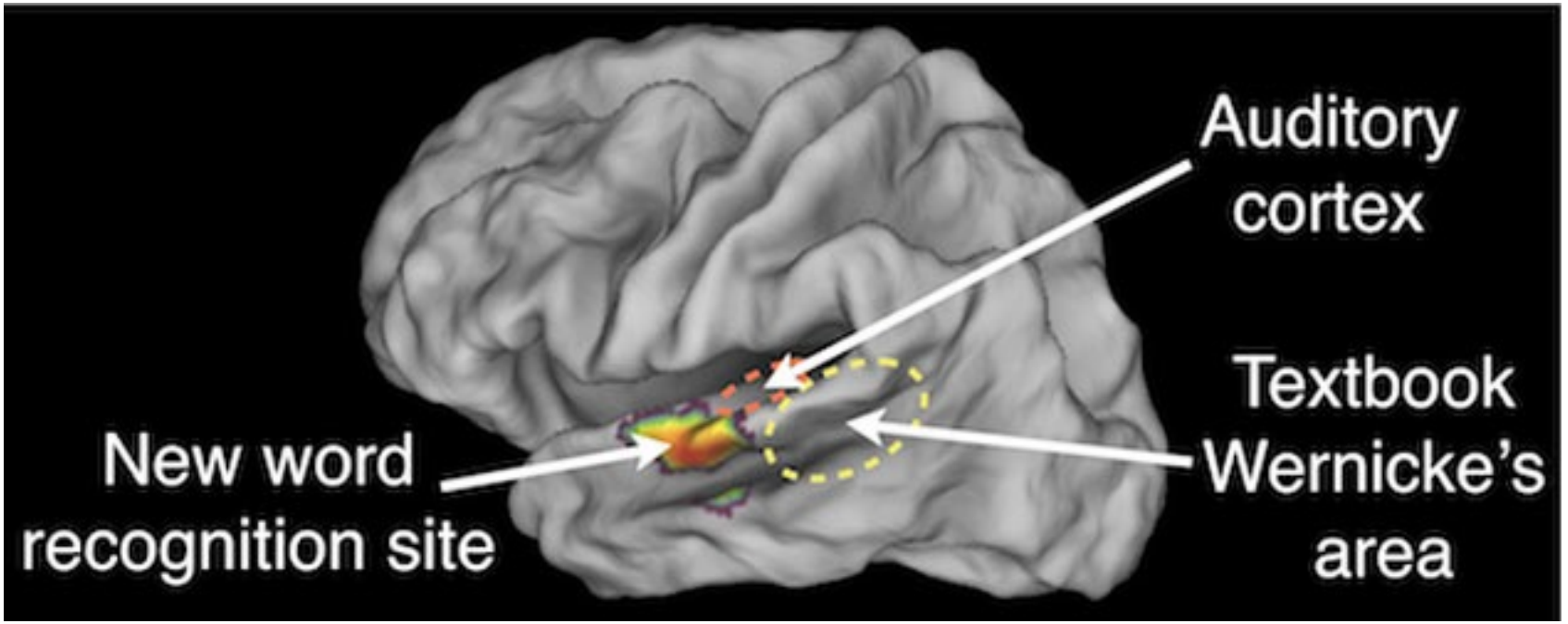
Phonemes

Words

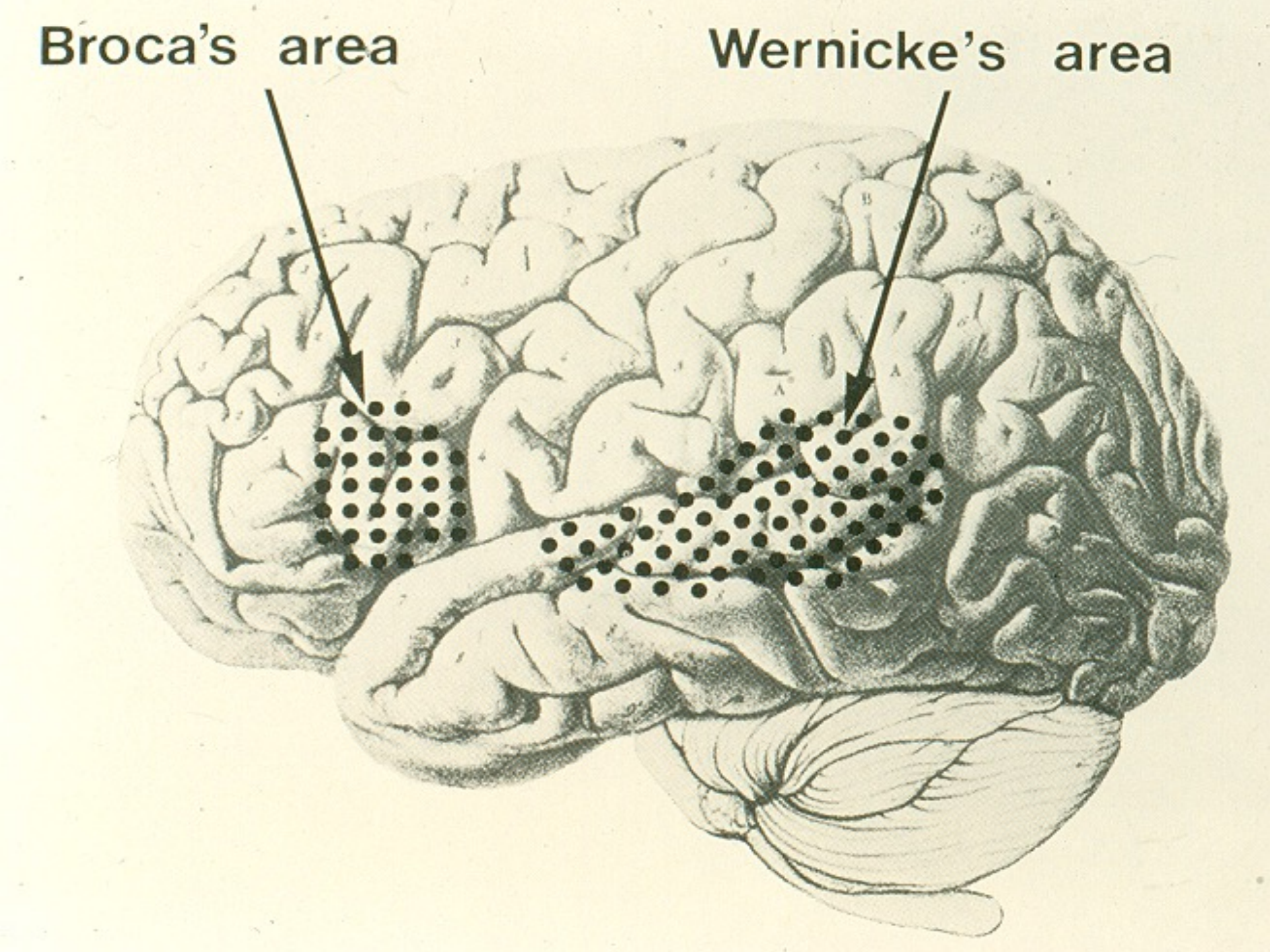
Phrases

DeWitt & Rauschecker *PNAS* (2012)

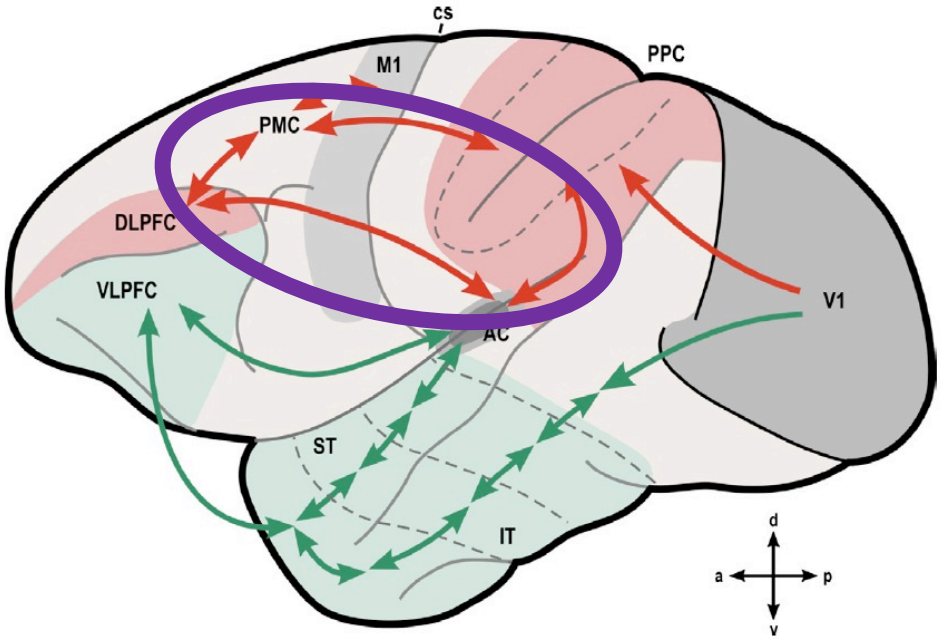
“Wernicke’s area” re-located



DeWitt & Rauschecker, PNAS (2012)

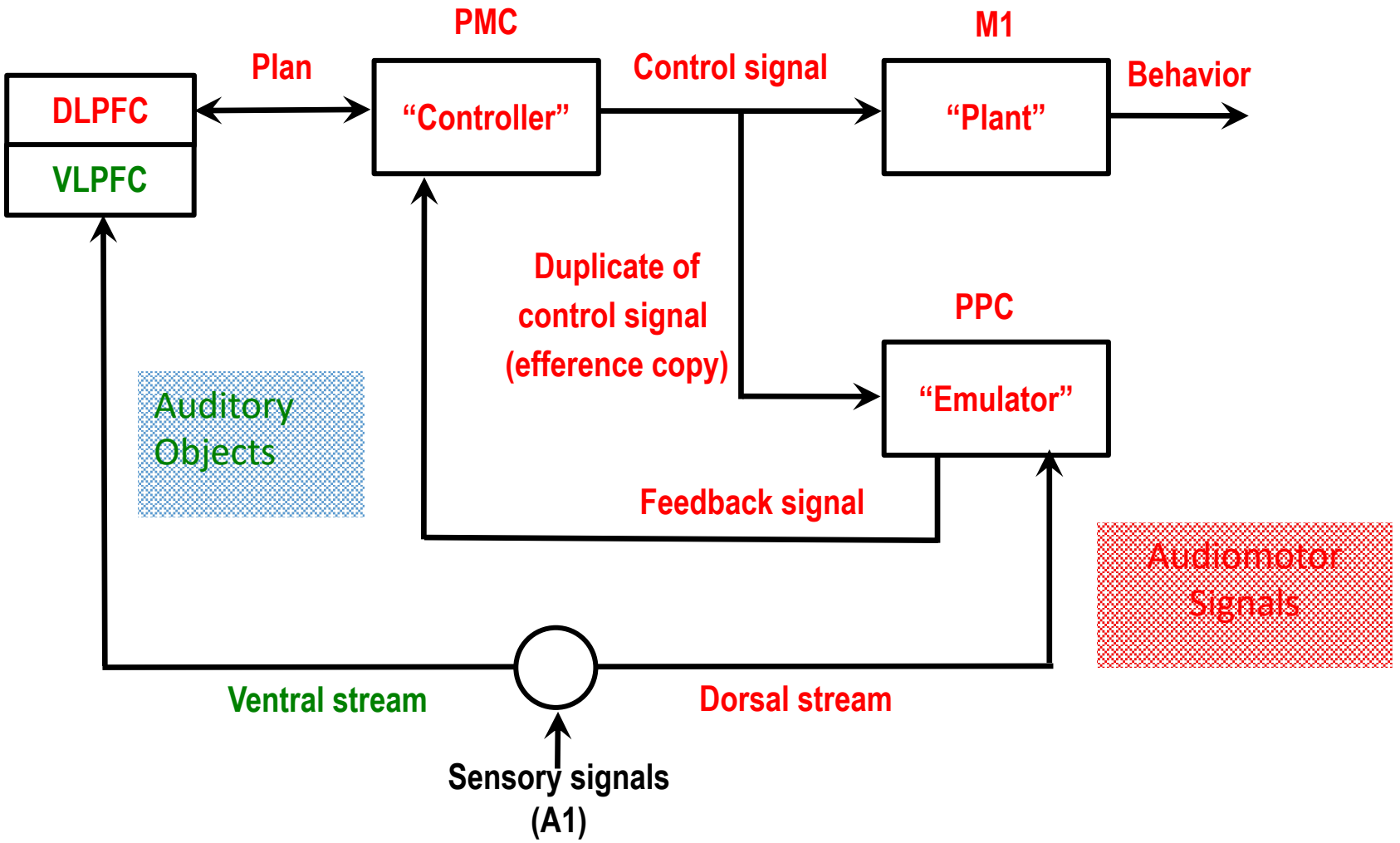

Broca's area
Wernicke's area

Audiomotor integration in the dorsal stream



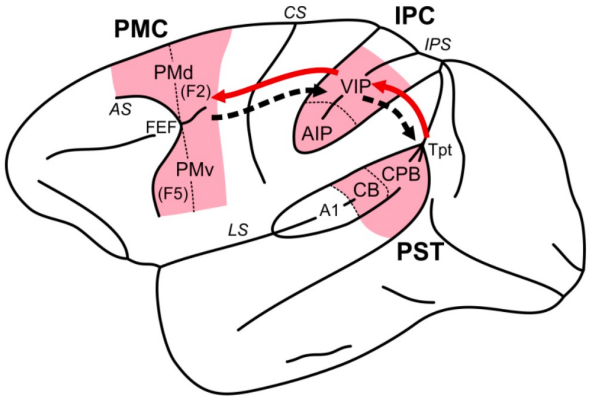
Jimmy, 2 months old

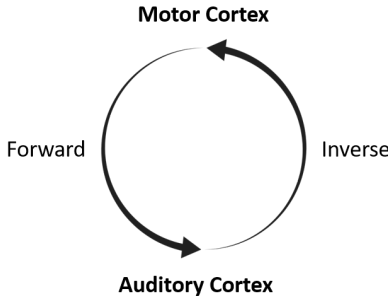
Internal Models



Rauschecker, *European J. Neuro.*, 2015

Audiomotor integration in the dorsal stream: Internal models





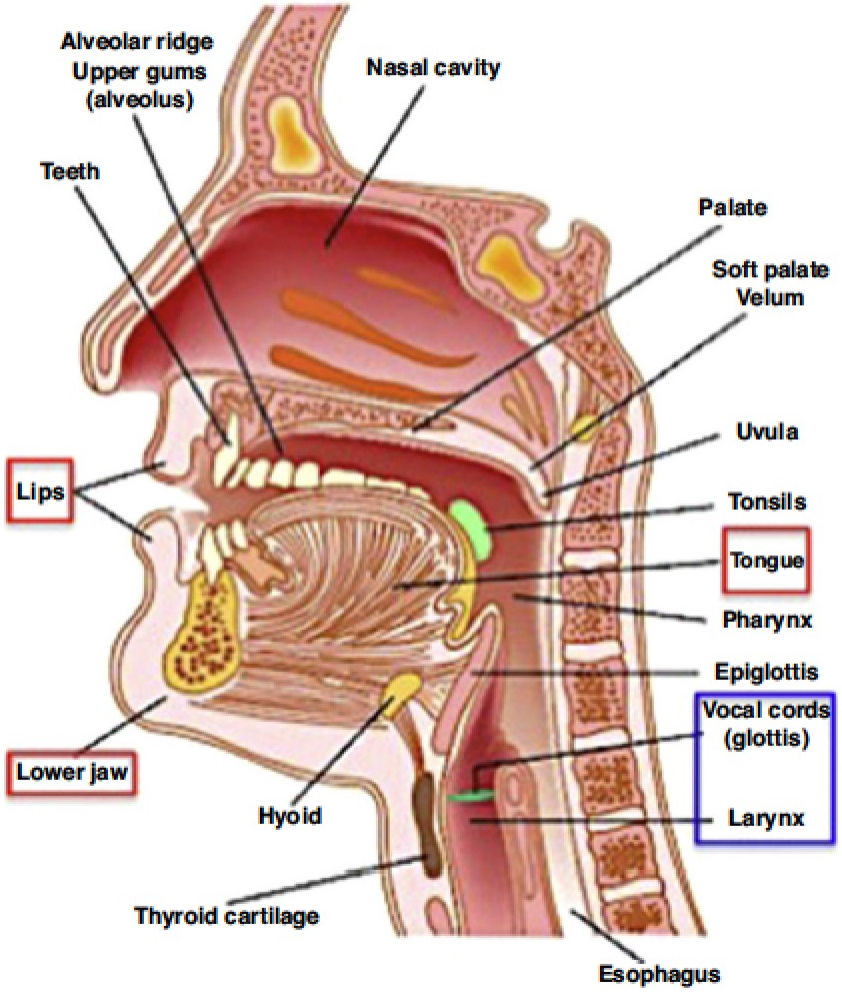
- Forward model

Motor commands (MC) ⇢ Predicted sensory consequences (AC)

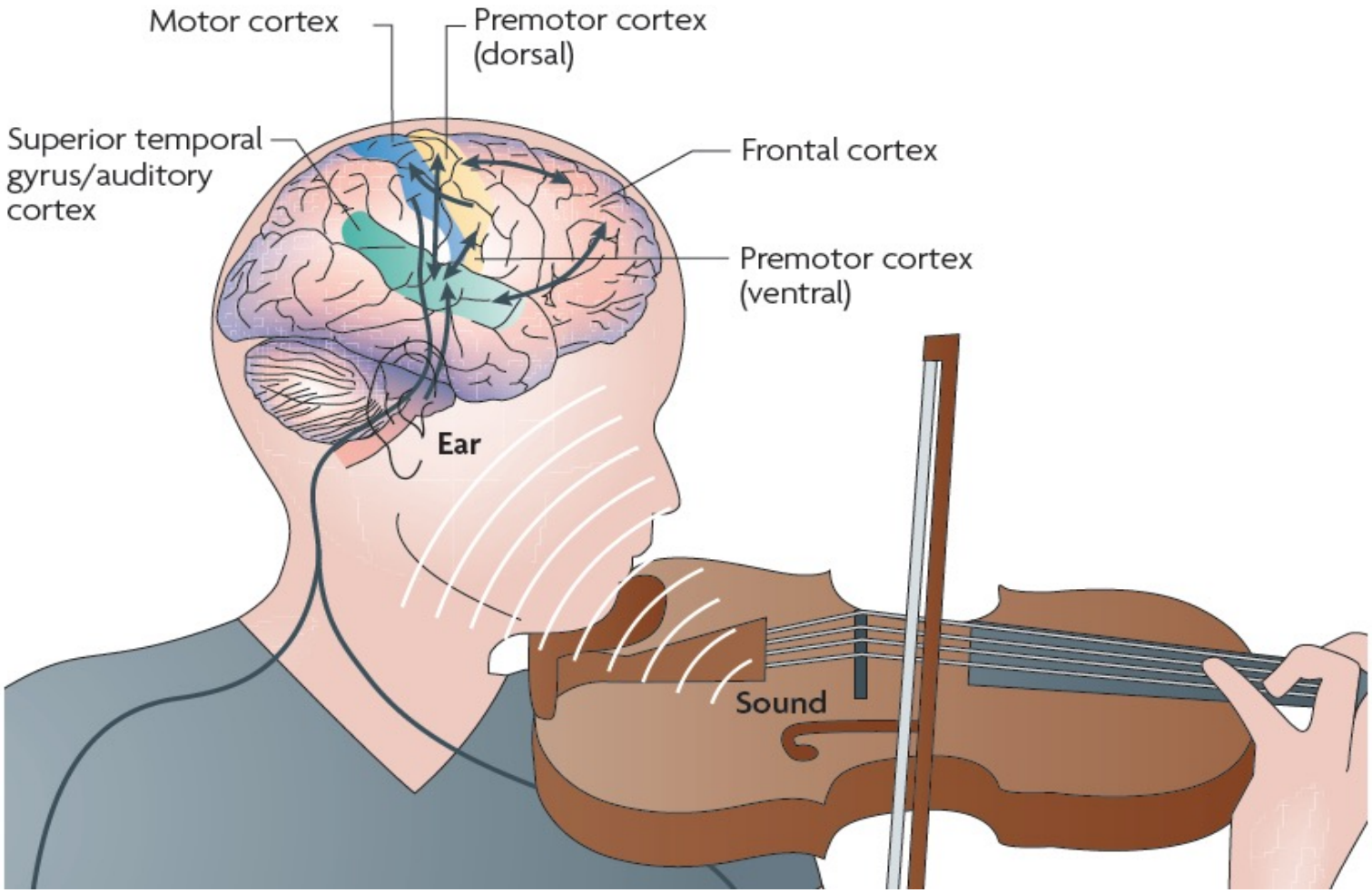
- Inverse model

Desired sensory consequences (AC) → Motor commands (MC)

Supralaryngeal Articulators

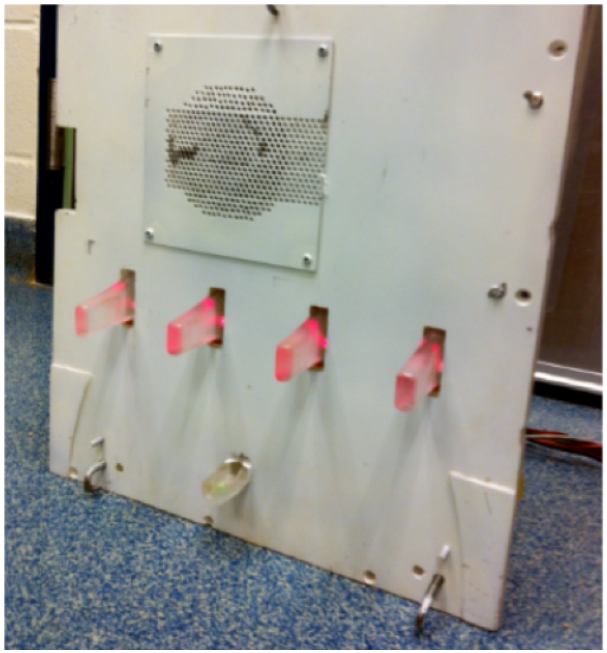


Audiomotor Integration

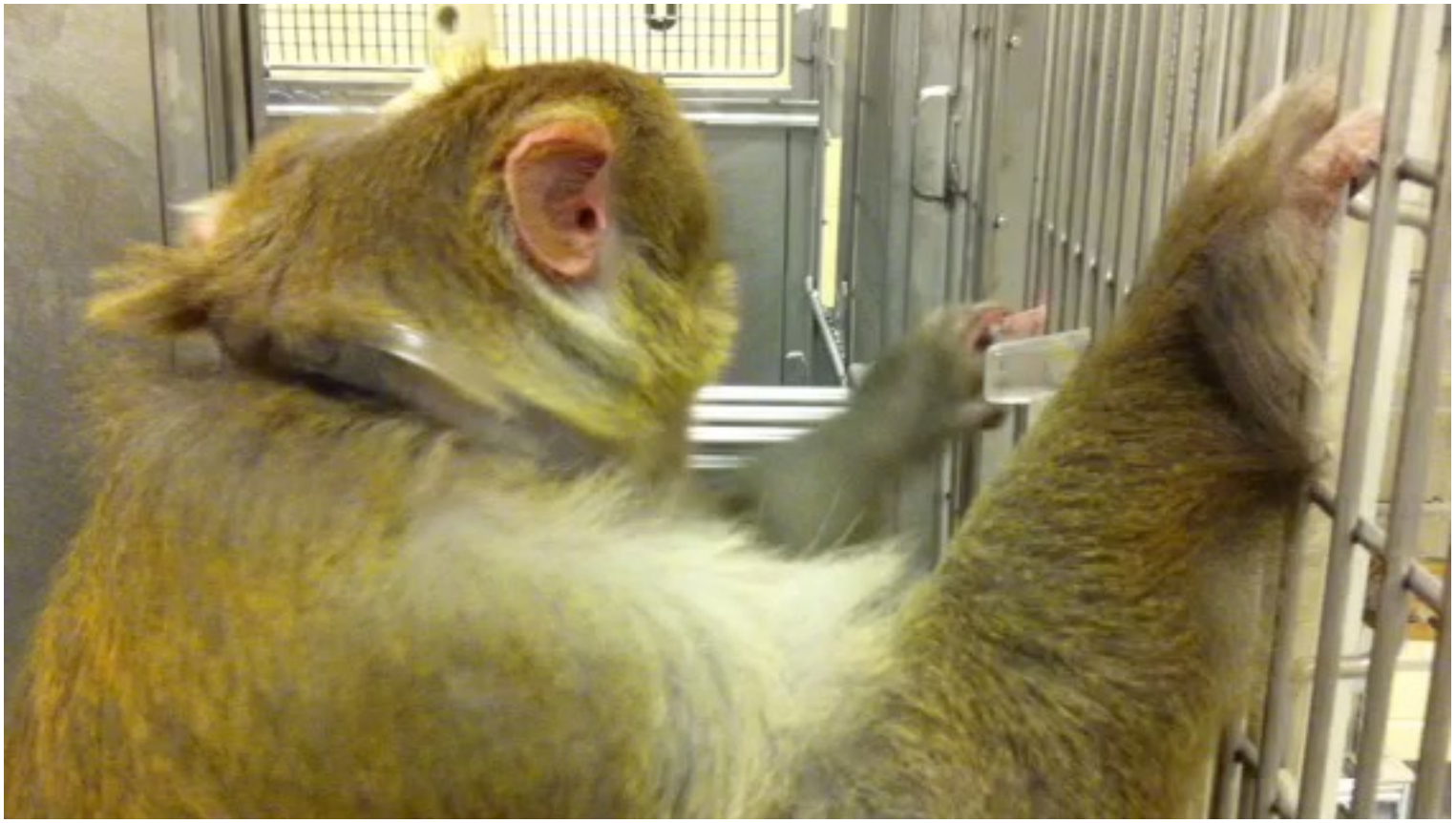


Zatorre et al. (2007)

Behavioral training of monkeys

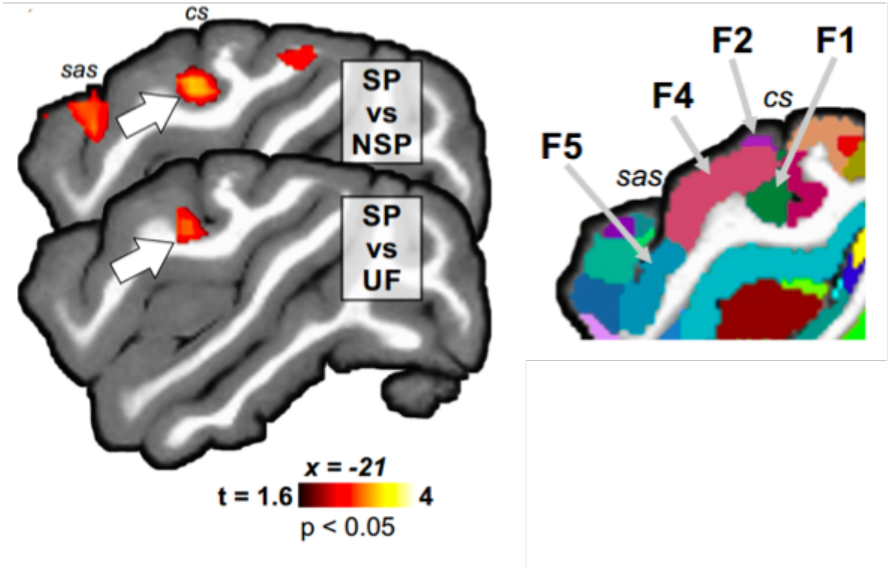


“Monkey piano” (Ramon)

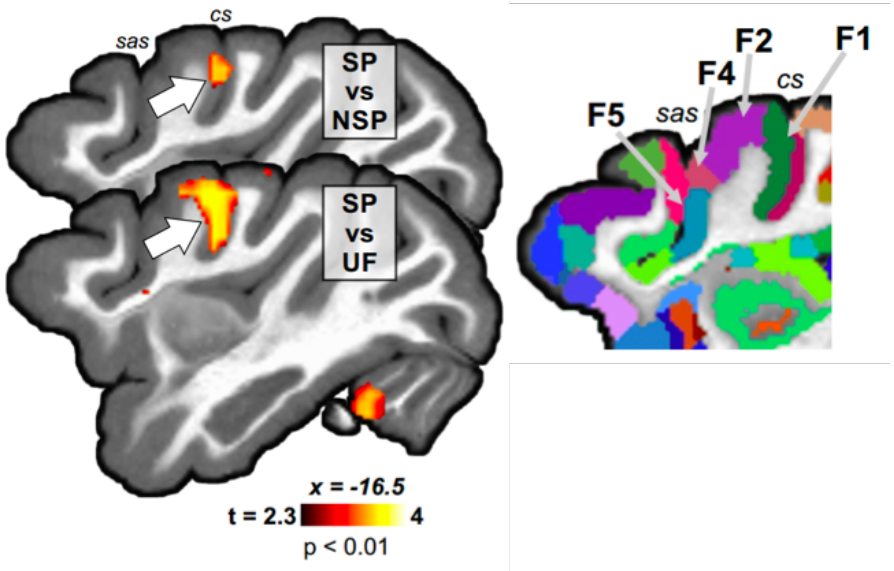


Selective representation of self-produced sound sequences

Monkey D

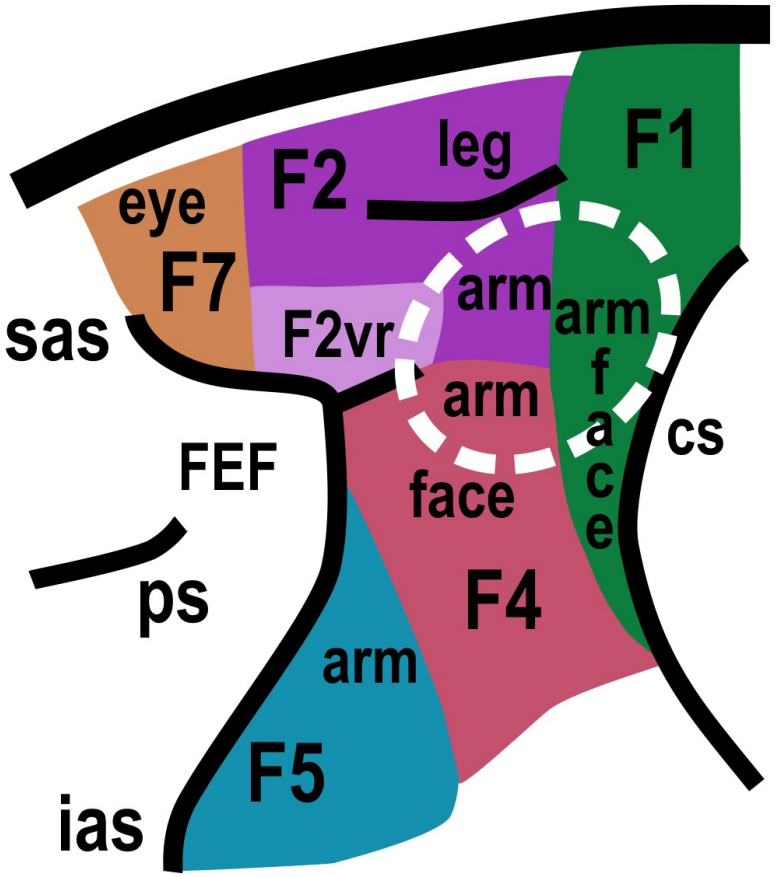


Monkey R



Auditory representation in motor cortex

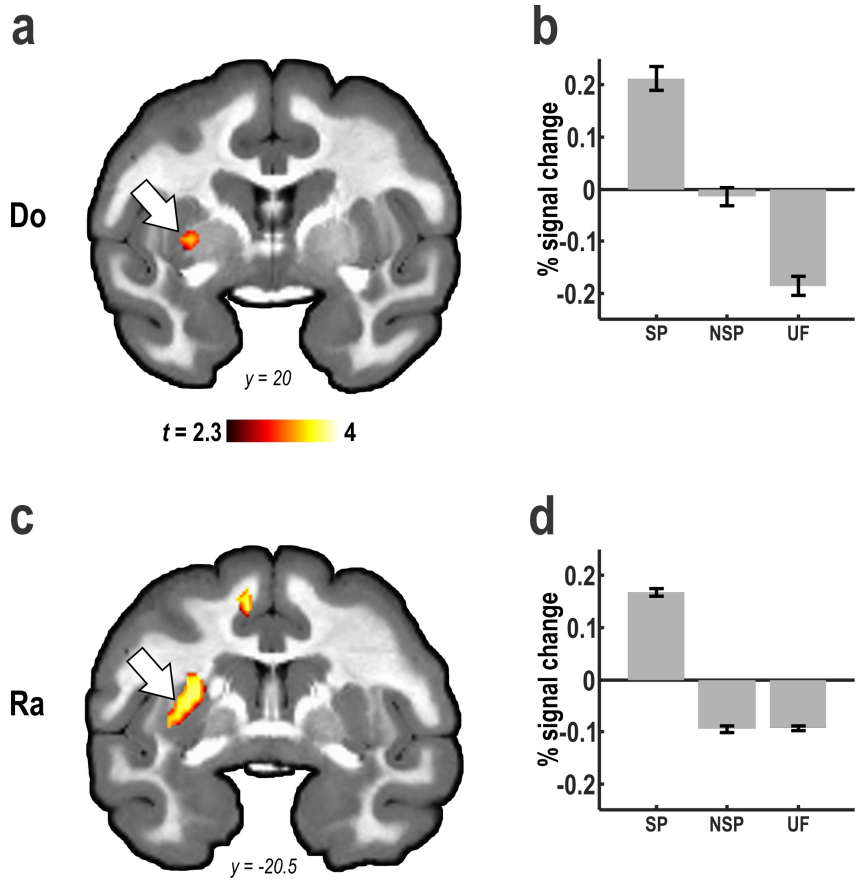
Archakov, DeWitt, Kusmierek, Ortiz, Cui, VanMeter, Sams, Jääskeläinen, Rauschecker, PNAS (2020)



Matelli & Luppino, 2001

Basal Ganglia (Putamen)

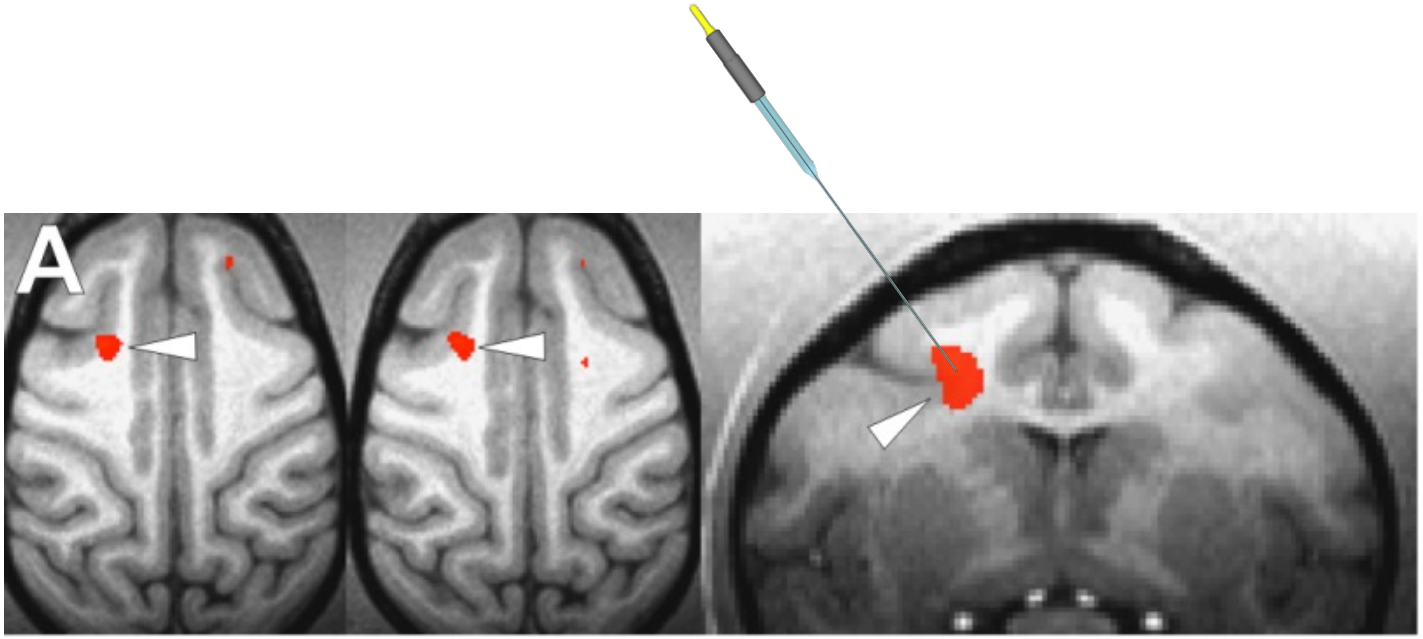
Learning of sequences



Archakov, DeWitt, Kusmierek, Ortiz, Cui, VanMeter, Sams, Jääskeläinen, Rauschecker, PNAS (2020)

Activation of monkey (pre)motor cortex by sounds of self-produced sequences

dPMC
(F2)



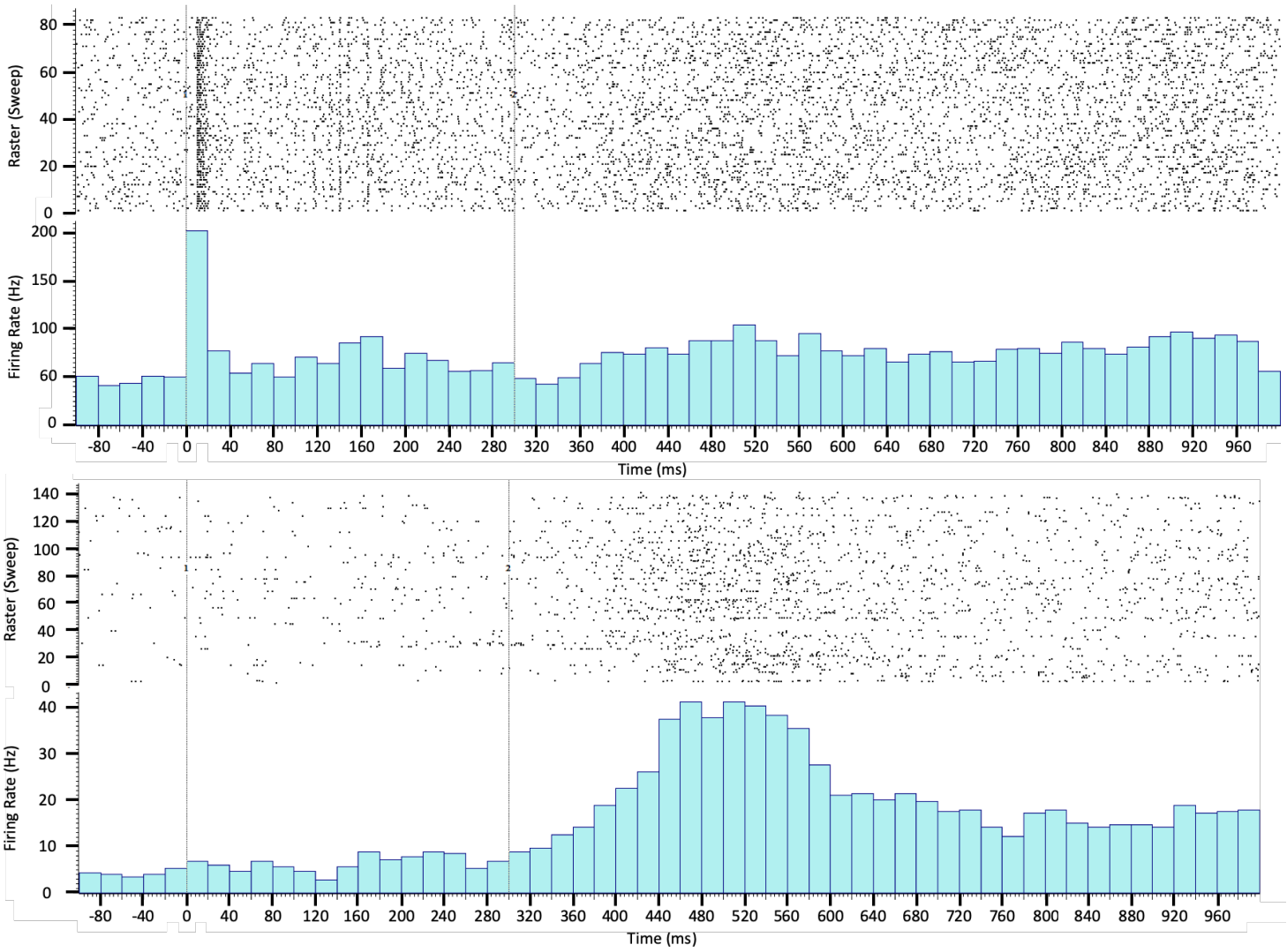
Archakov, DeWitt, Kusmierek, Ortiz, Cui, VanMeter, Sams, Jääskeläinen, Rauschecker, PNAS (2020)

Mechanisms of auditory-motor integration: Single-unit data

Electrophysiological response of a motor cortex neuron to listening to an auditory sequence that the monkey has been trained to produce

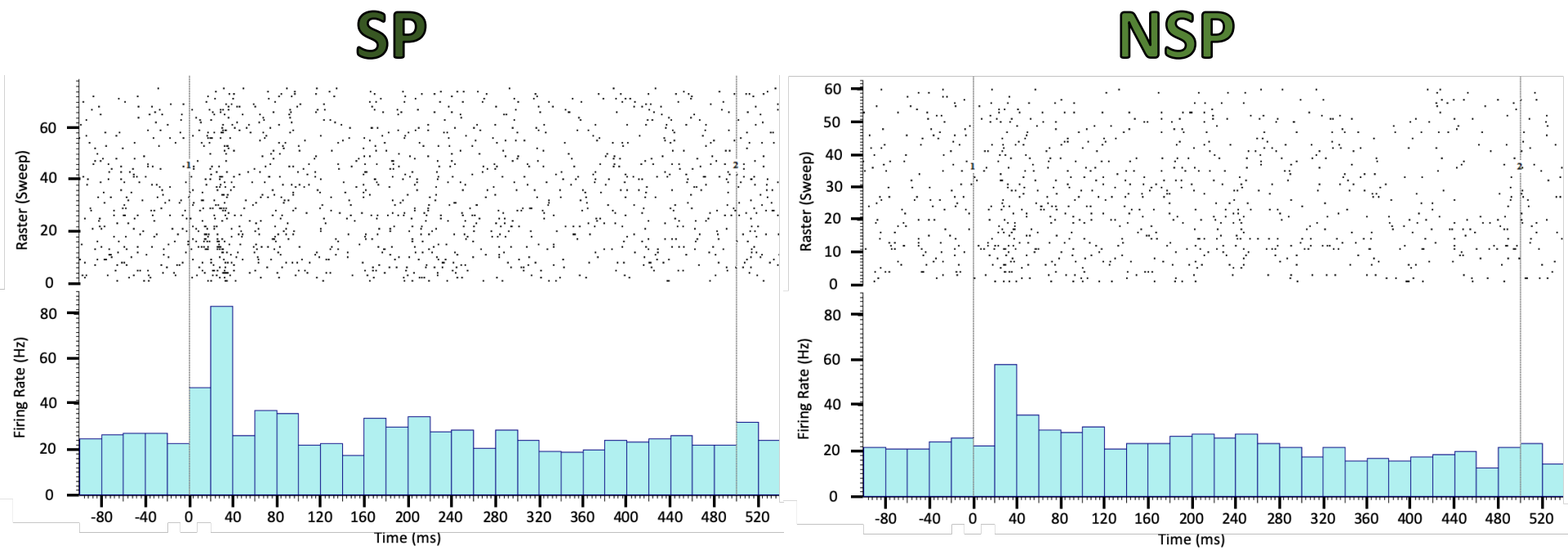
(Jessica Jacobs et al., unpublished data)

Auditory and motor responses in M1



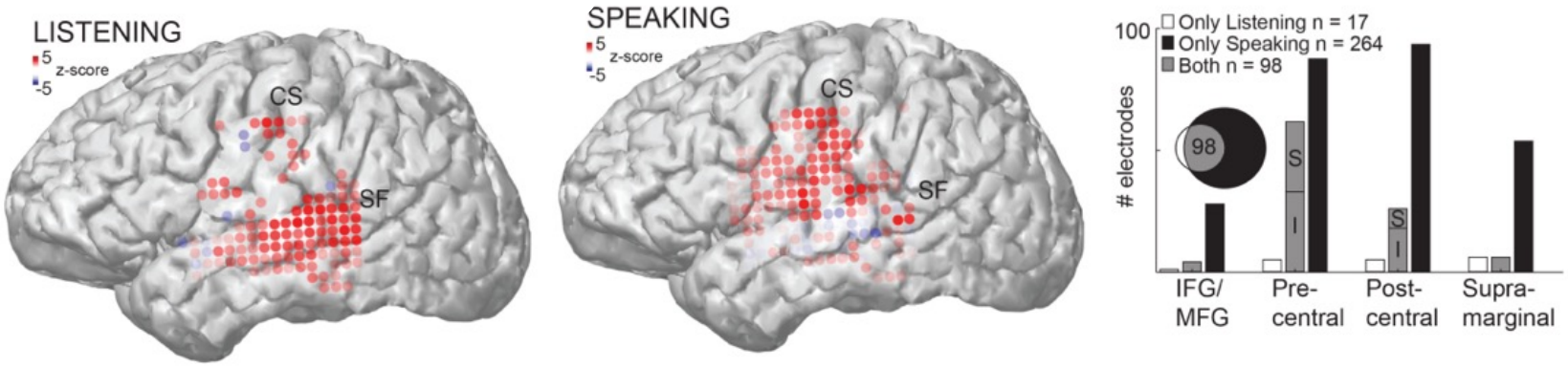
(Jessica Jacobs et al., unpublished data)

Selective auditory responses in PMC



(Jessica Jacobs et al., unpublished data)

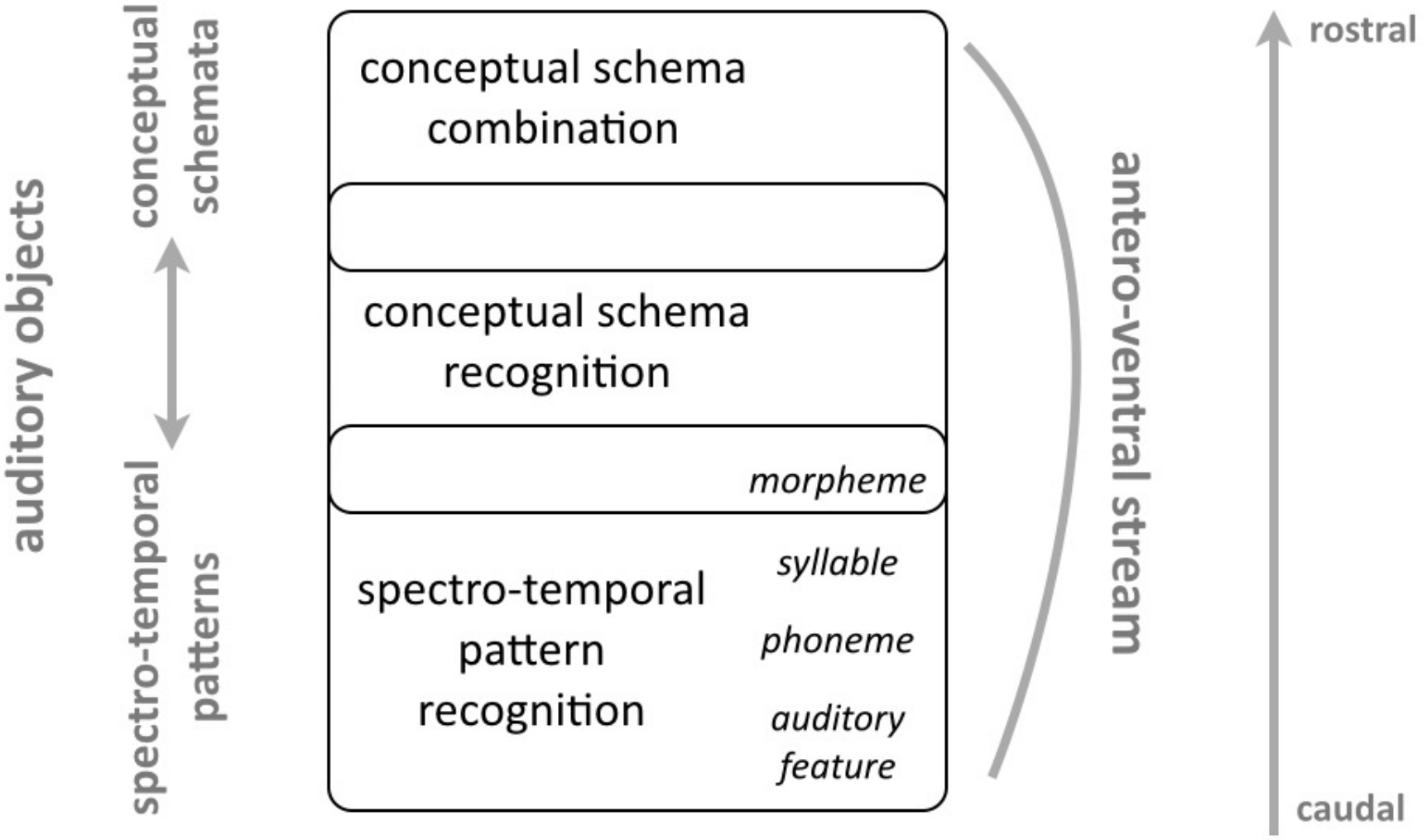
Human motor cortex is activated during speech perception and production



Cheung, Hamilton, Johnson and Chang (2016) eLife

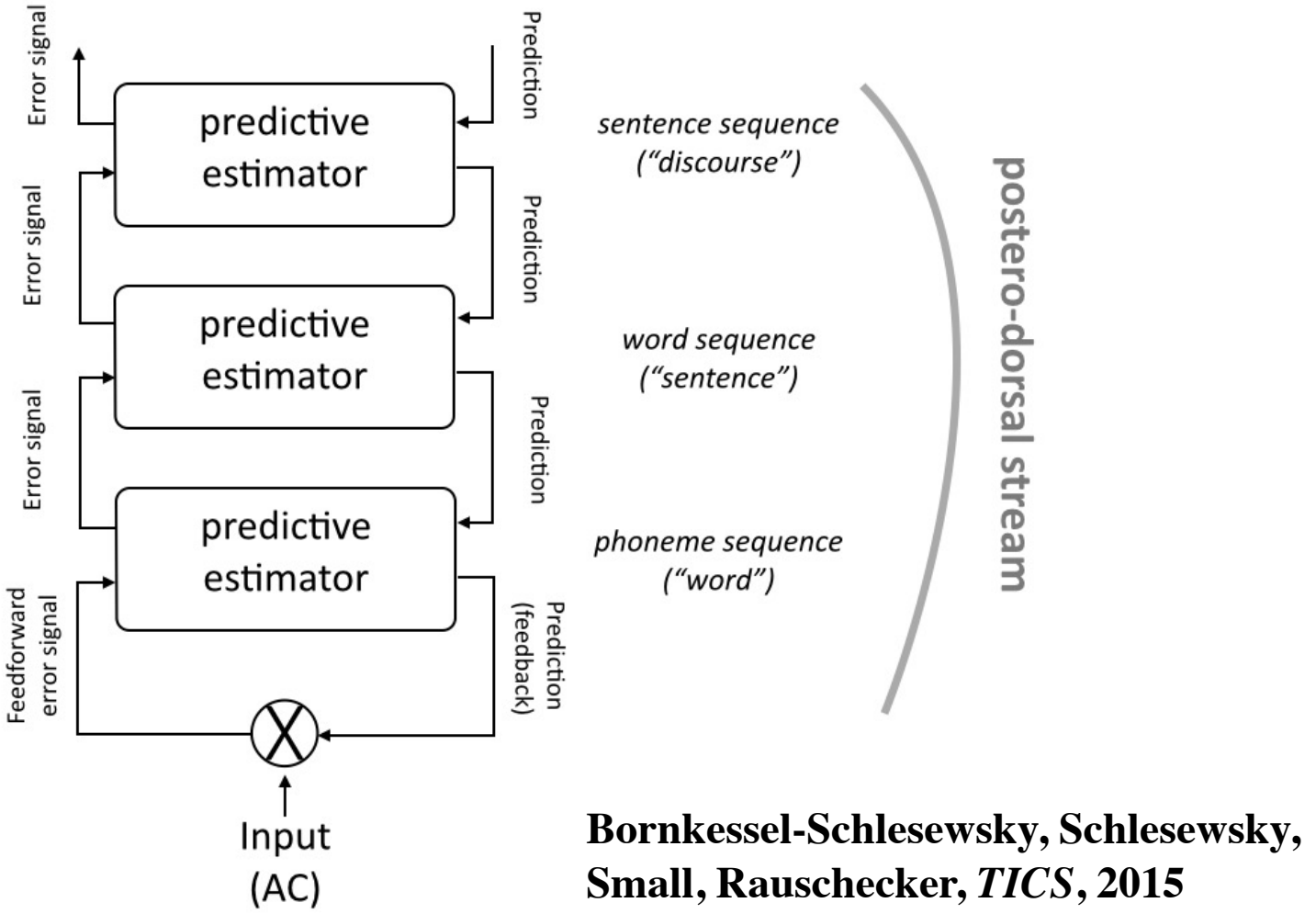
Neurobiological roots of language in primate audition: common computational properties

Antero-ventral stream in language processing



Bornkessel-Schlesewsky, Schlesewsky, Small, Rauschecker, *TICS*, 2015

Postero-dorsal stream in language processing



Bornkessel-Schlesewsky, Schlesewsky, Small, Rauschecker, *TICS*, 2015

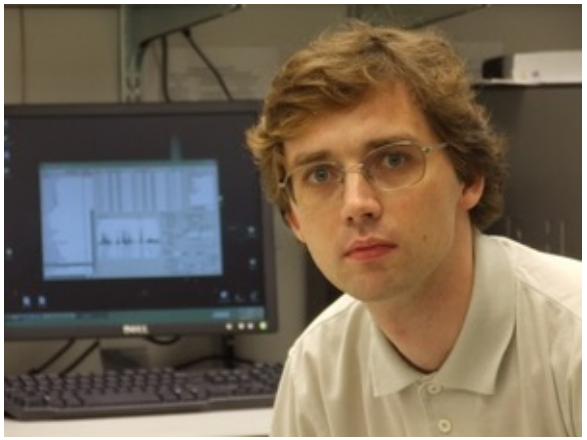
Neurophysiology Team

Denis Archakov

Josie Ding

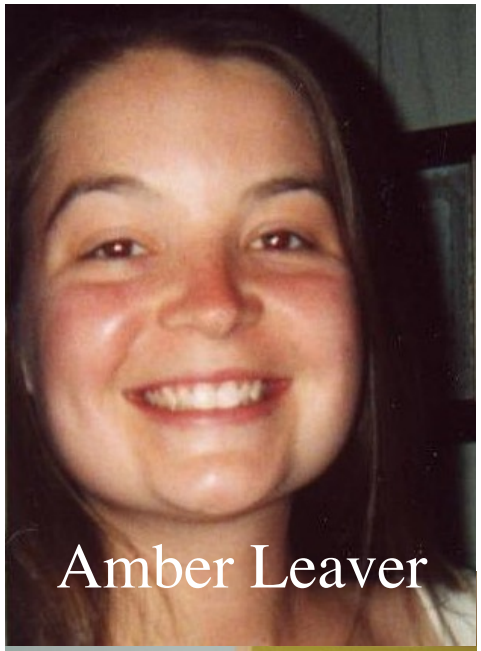
Michael Ortiz

Jess Jacobs

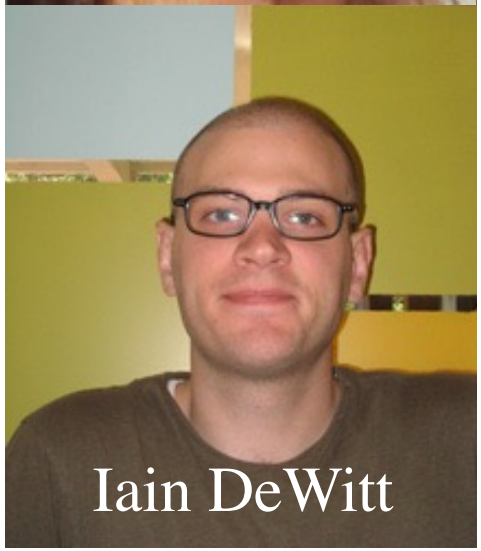


Pawel Kusmierek

Georgetown MRI Team


Amber Leaver

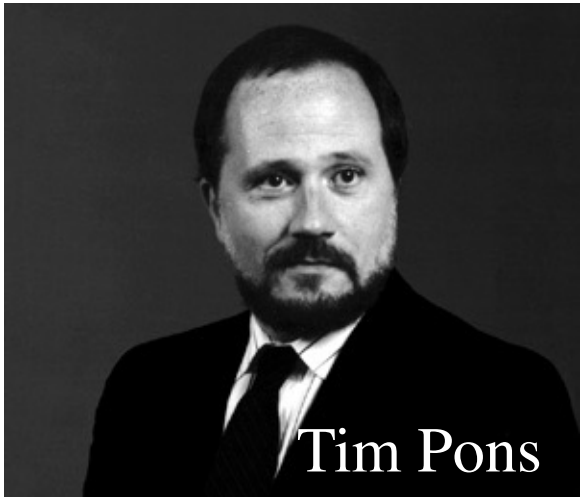

John Van Meter

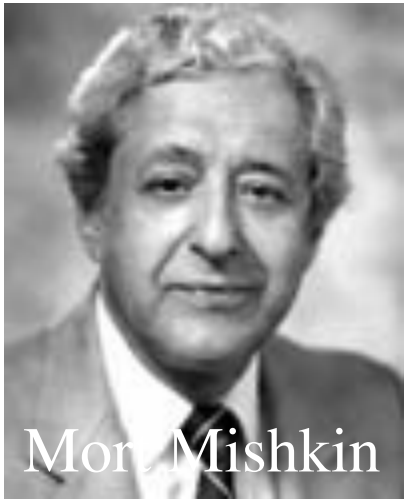

Iain DeWitt


Mark Chevillet

Former Collaborators


Biao Tian


Tim Pons


Mort Mishkin


Liz Romanski

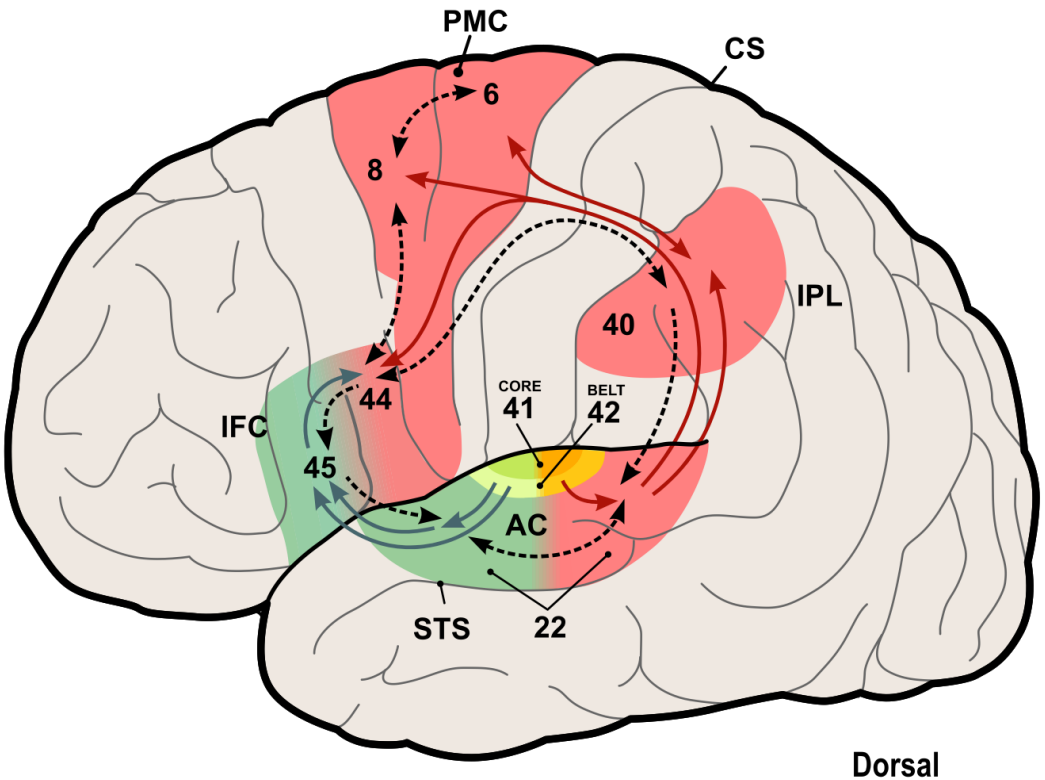

J. Fritz


Pat Goldman

FUNDING

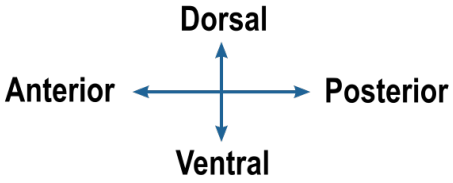
NIH (NIDCD)
NIH (NINDS)
NSF (PIRE)
Alexander-von-Humboldt Foundation

Auditory Processing Streams



Auditory Dorsal Stream:
Sensori-Motor Processing, Dynamic Control and Optimal State Estimation

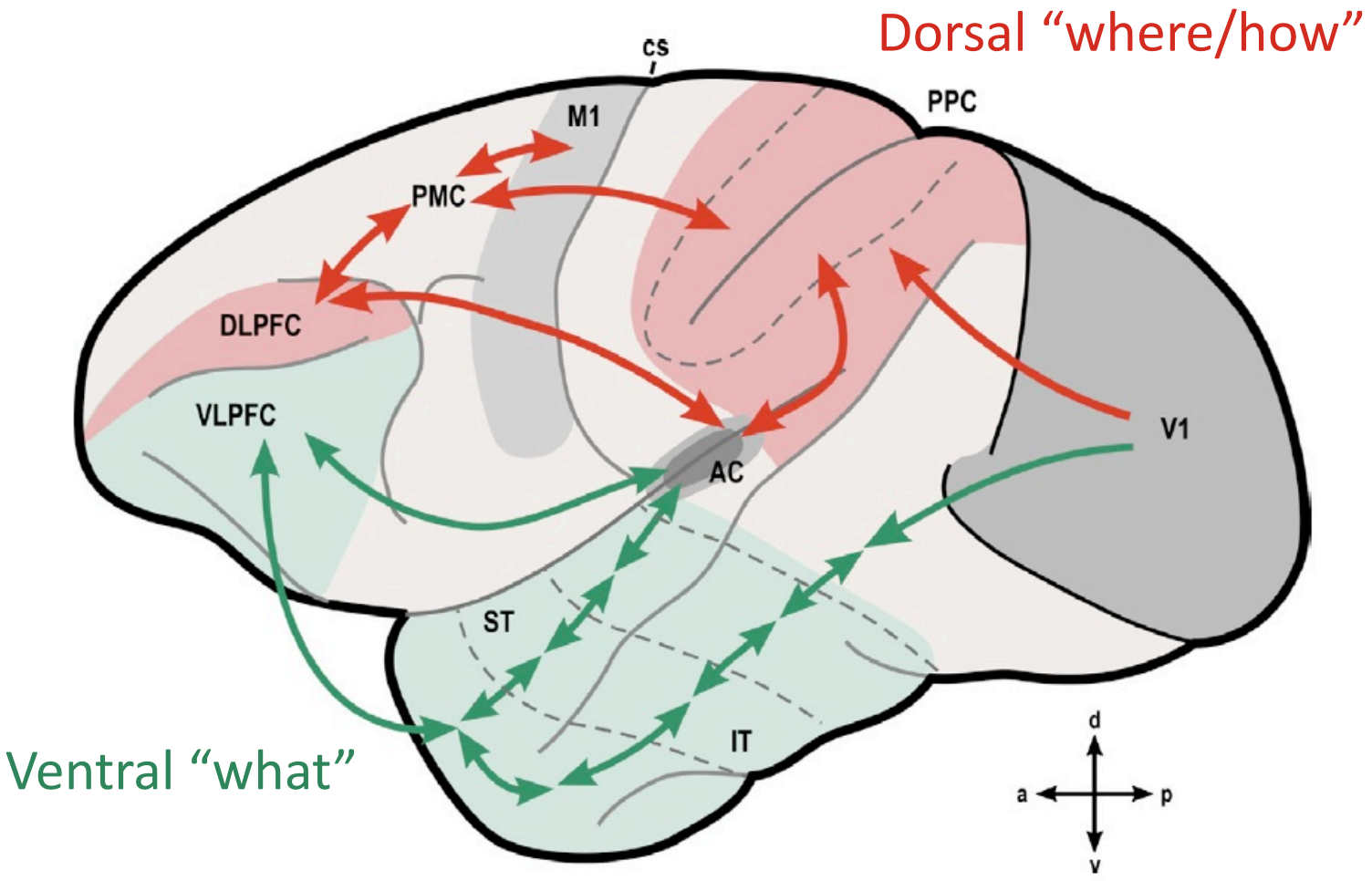
Auditory Ventral Stream:
Hierarchical Processing, Object Identification



Rauschecker and Scott, *Nature Neuroscience* (2009)

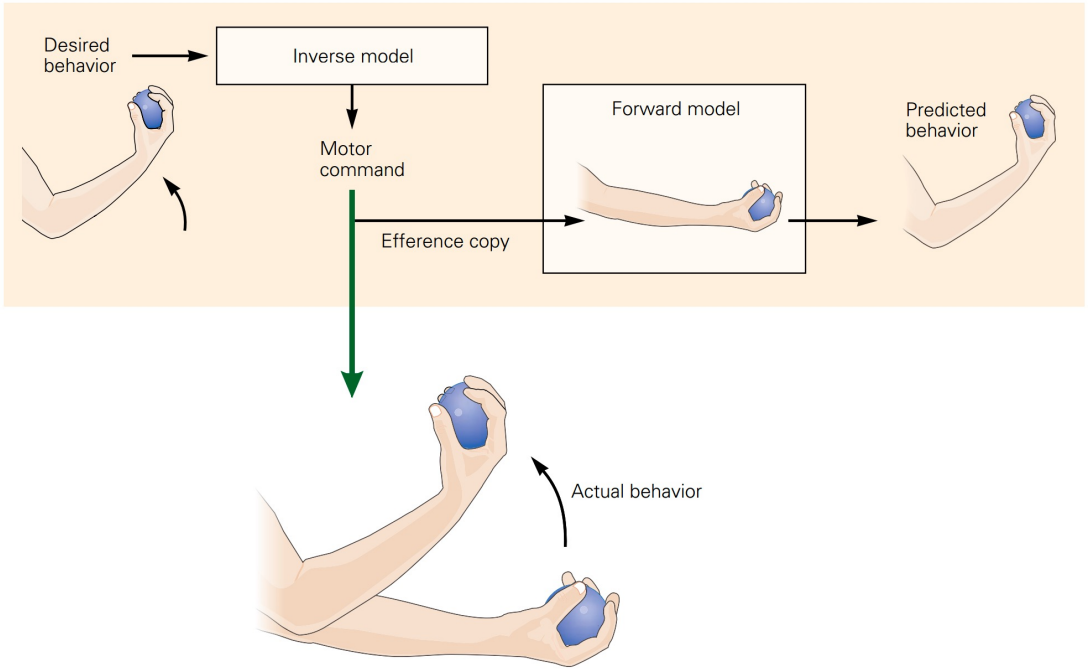
Real-Time MRI of Song

Dual processing pathways



Rauschecker 2014, EJN

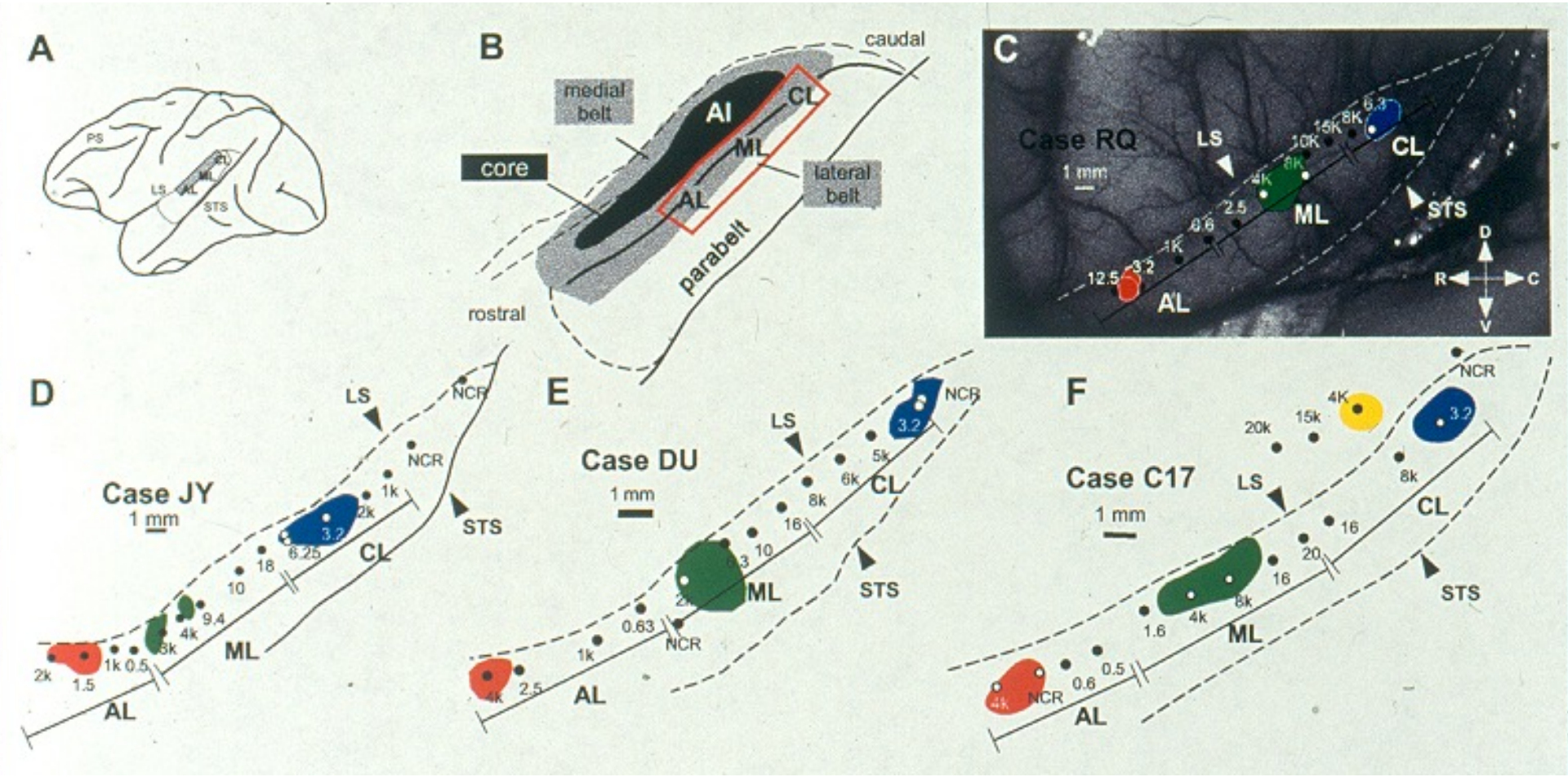
Internal models



- Internal models relate motor commands to expected sensations
- Forward models
  - Motor commands → predicted sensory consequences
- Inverse models
  - Desired sensory consequences → motor commands
- Mismatch results in error signal and on-line correction

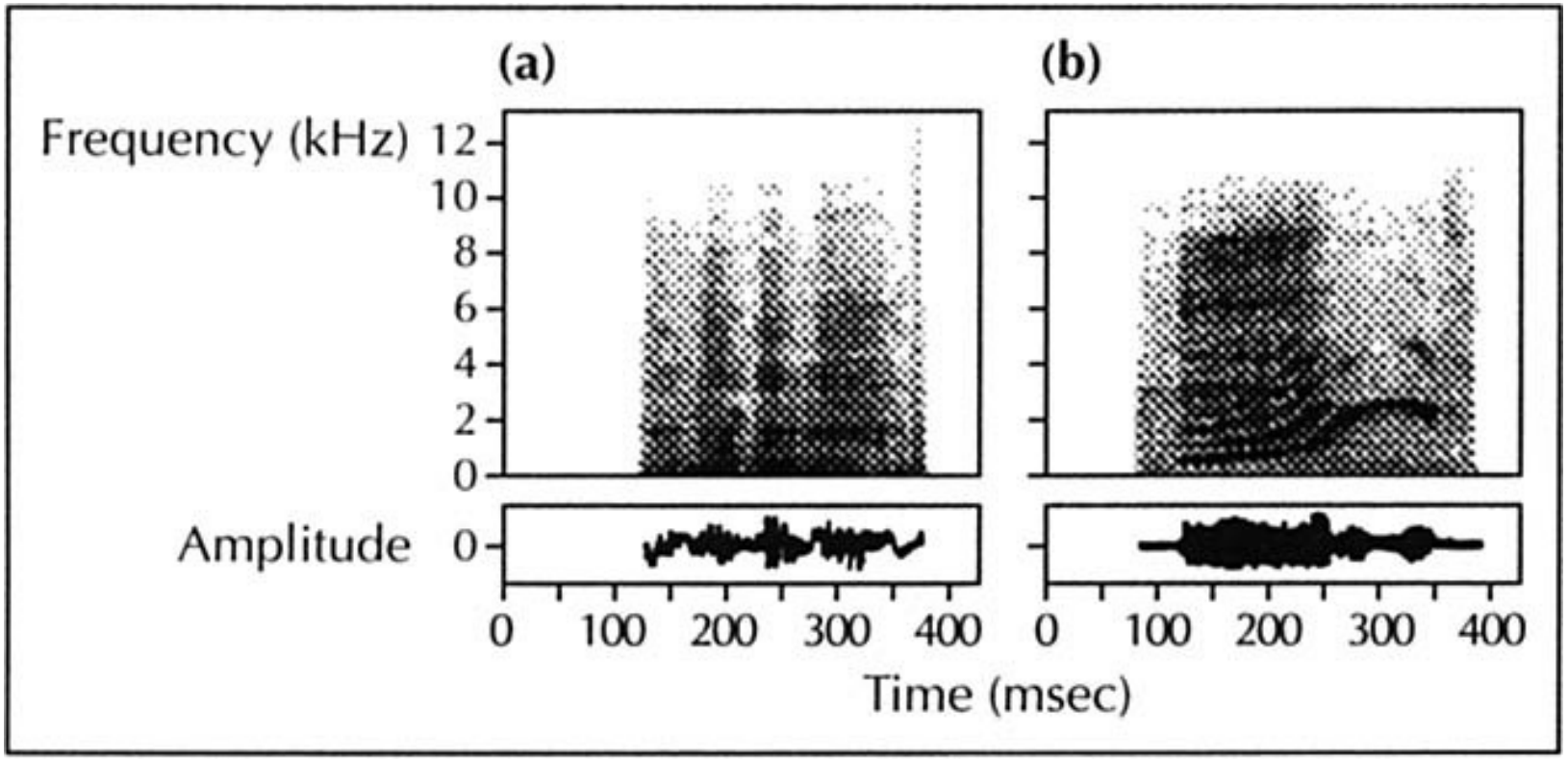
E. R. Kandel, et al., *Principles of Neural Science* (2000)

Romanski, Tian, Fritz, Mishkin, Goldman-Rakic, Rauschecker, *Nature Neurosci.*, 1999



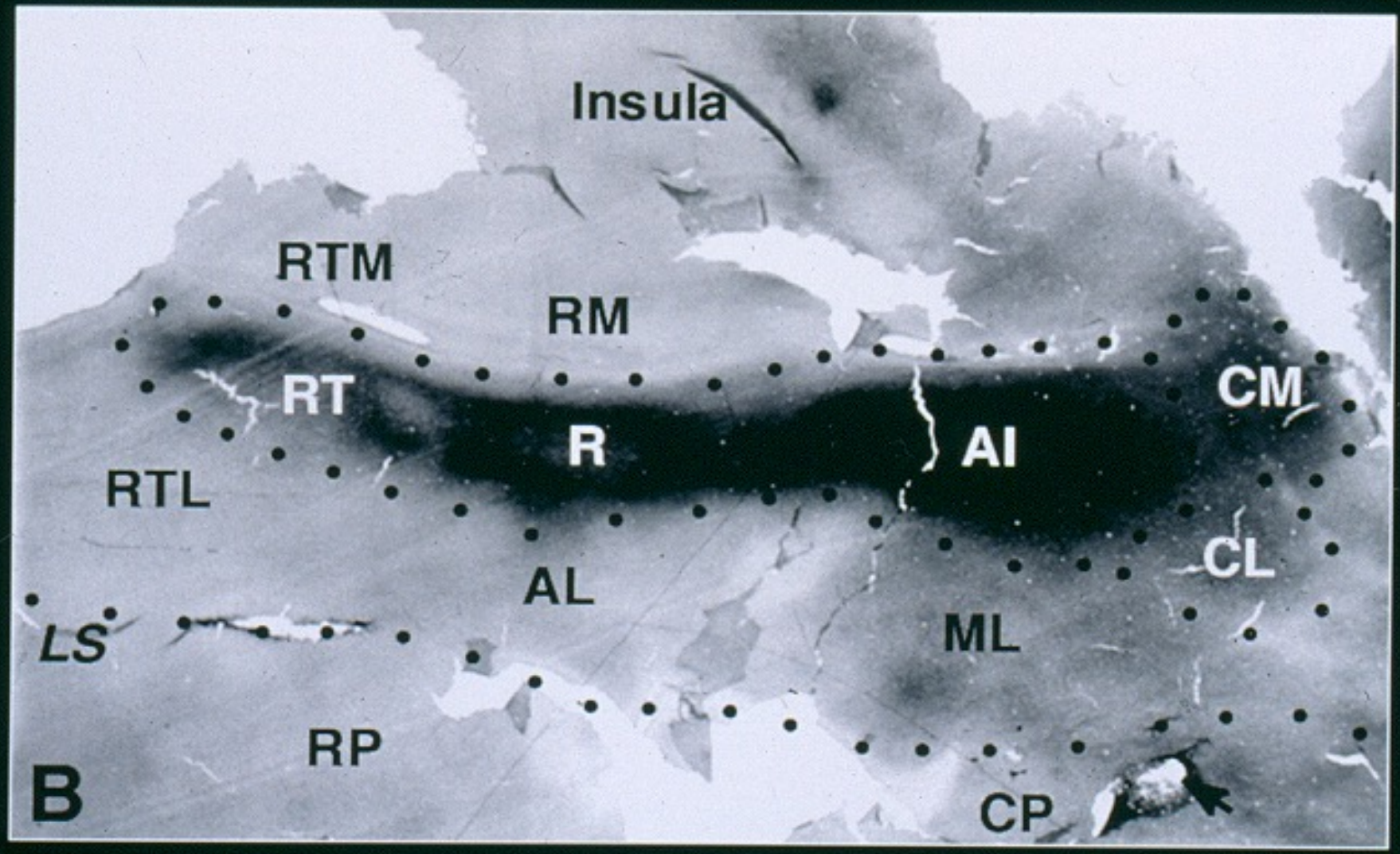
Asking the auditory cortex the right question

Recordings in different parts of the cortex are beginning to reveal how animal communication calls are analyzed by the brain.



© Current Biology 1995, Vol 5 No 10

Parvalbumin

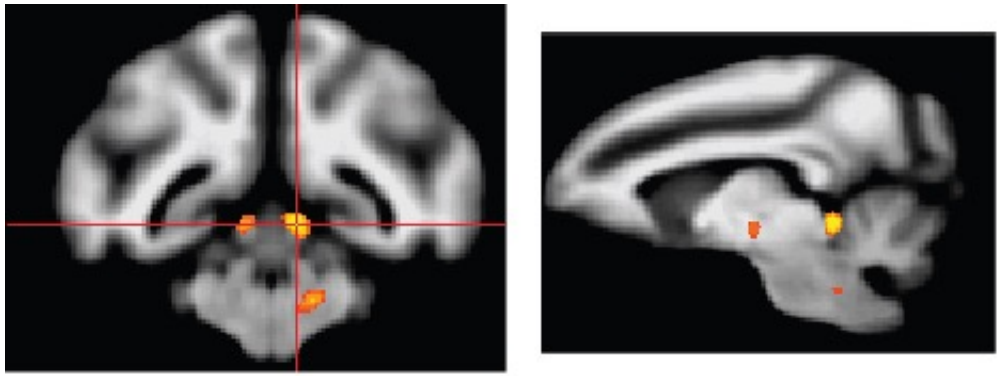


from Hackett, Stepniewska, and Kaas (1998)

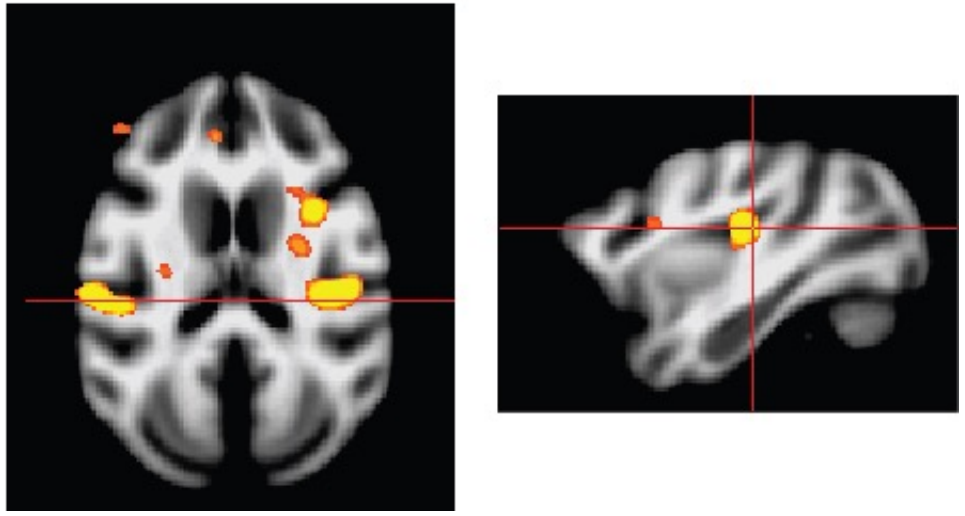
FMRI Activation During Listening to Sequences: Self-produced (SP) and non-self-produced (NSP) vs. silence

Auditory areas

Inferior colliculus

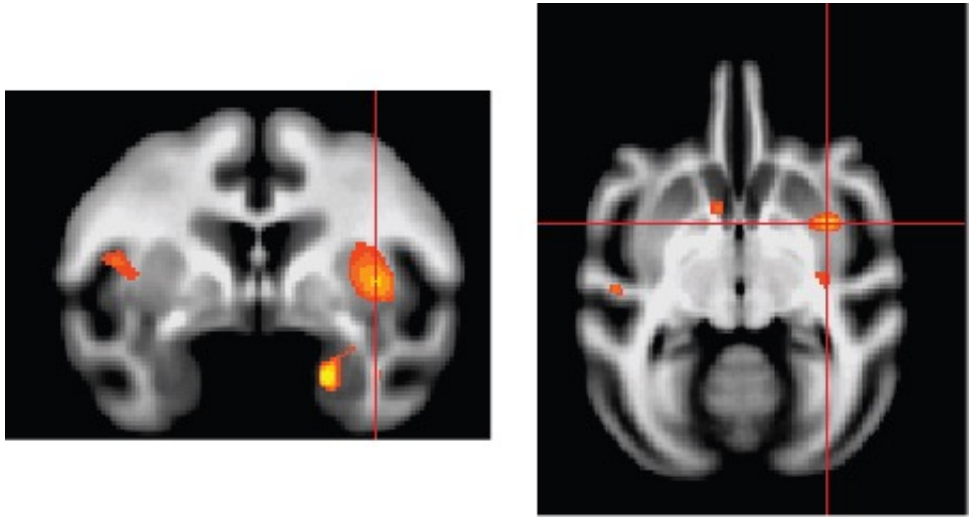


Auditory cortex



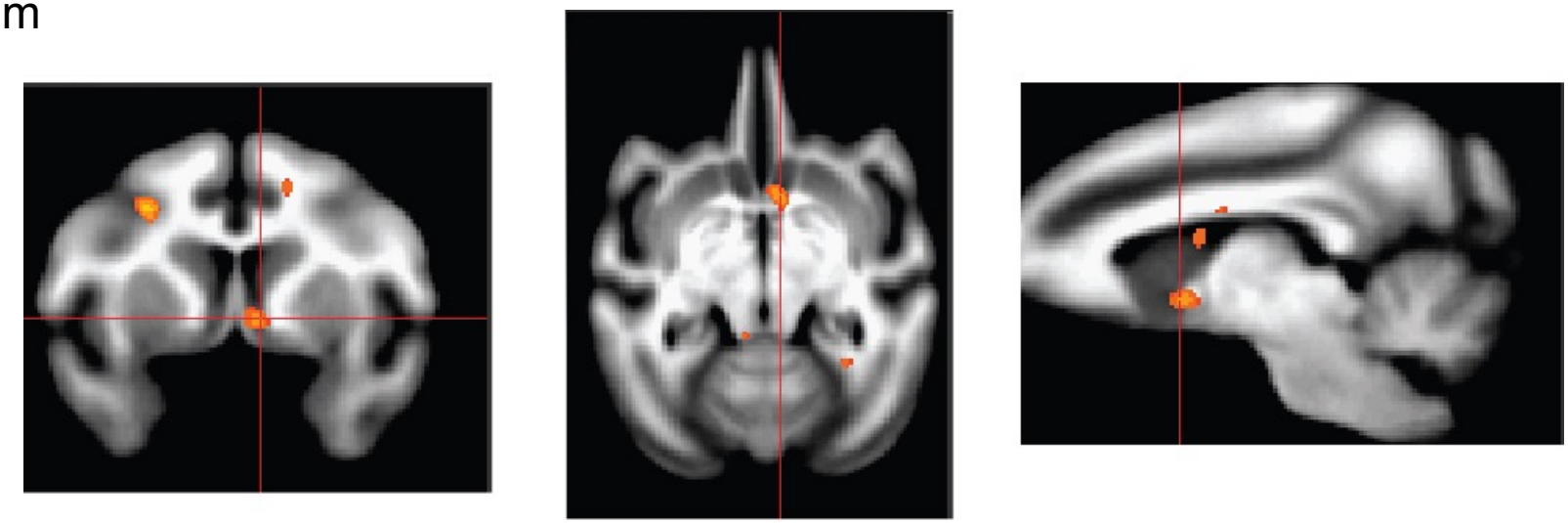
Basal ganglia

Putamen



SP and NSP vs silence

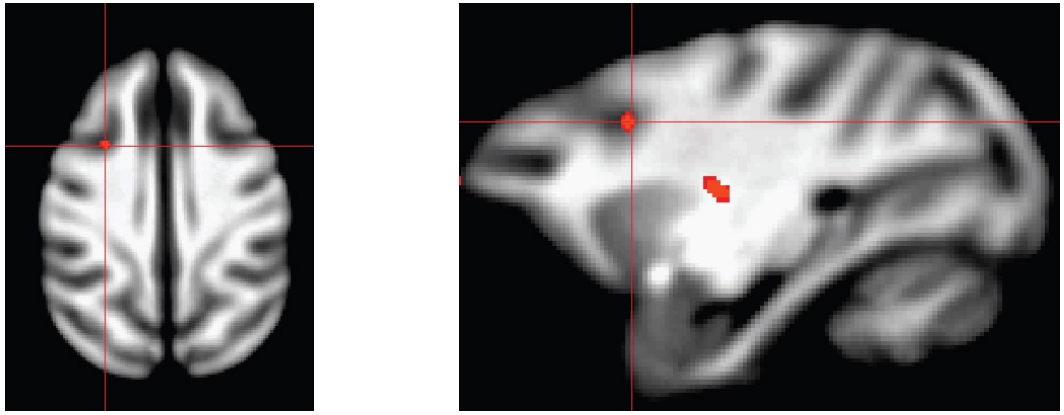
Pallidum



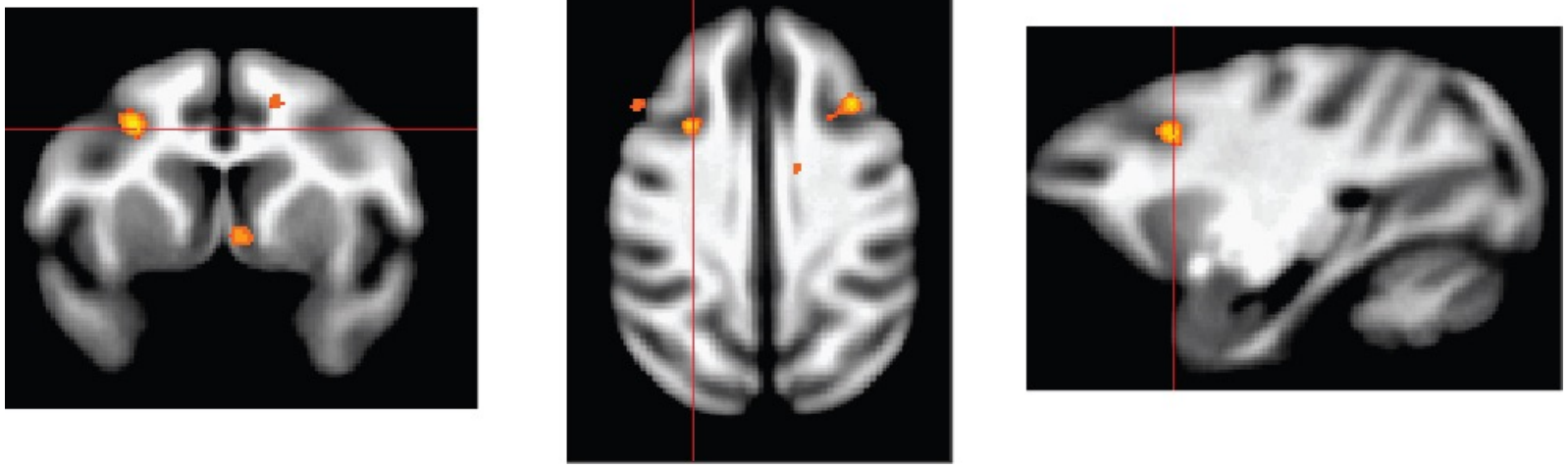
SP vs NSP

Premotor area F2

SP vs silence

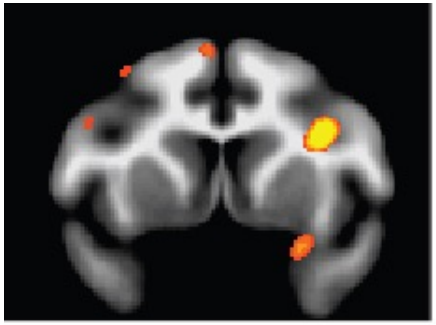


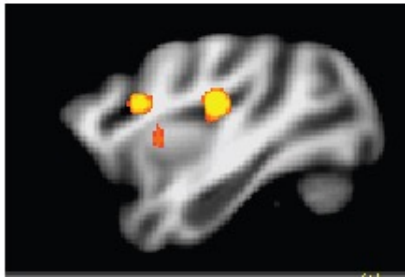
SP vs NSP



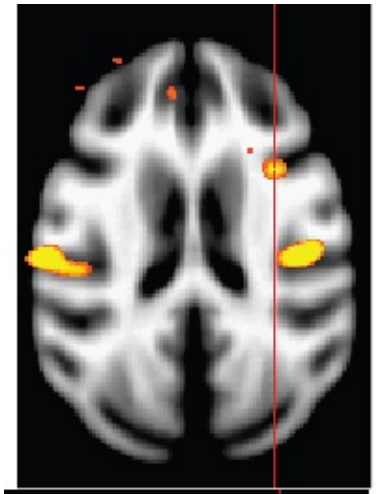
Premotor area F5

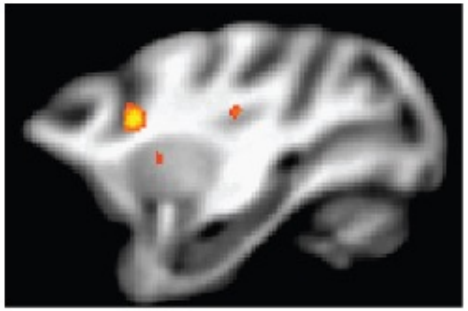
SP and NSP vs baseline



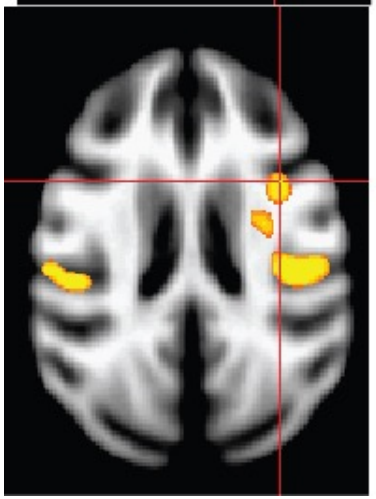


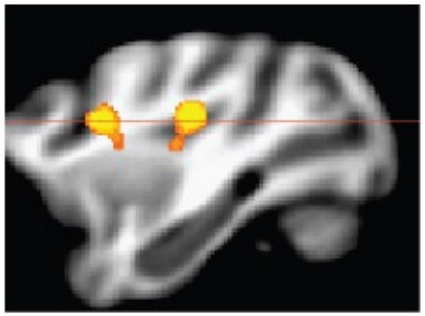
SP





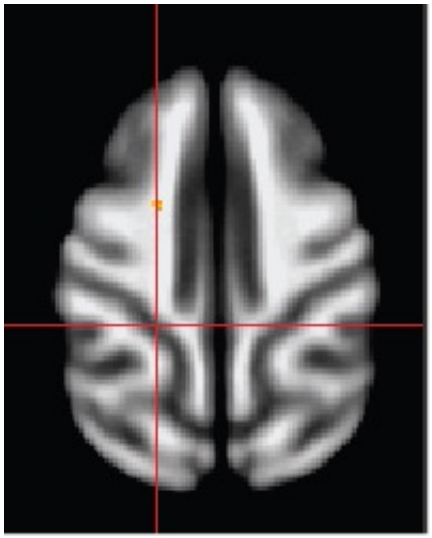
NSP

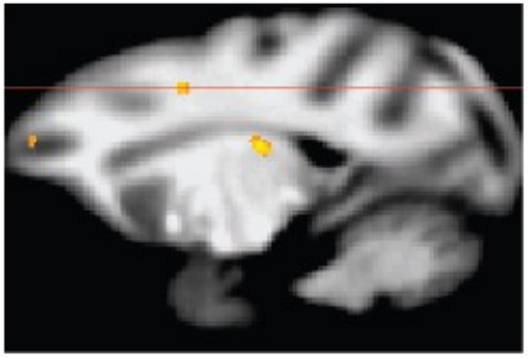




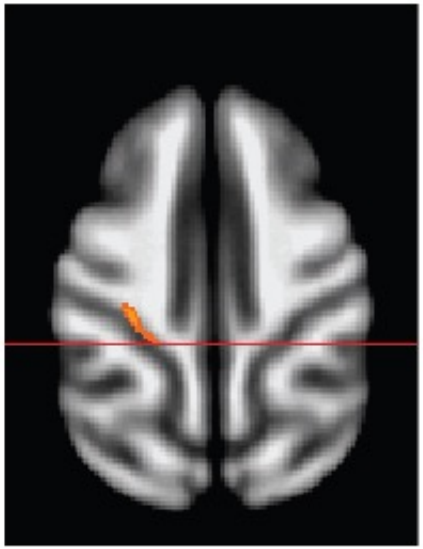
Ventral inferior parietal area (VIP)

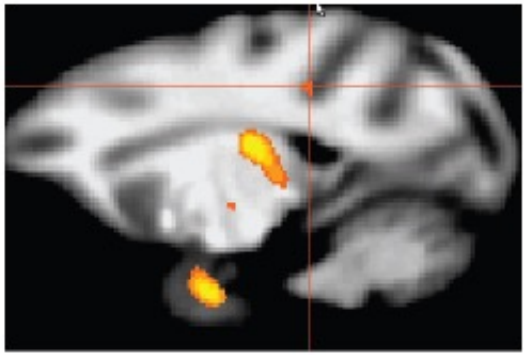
SP





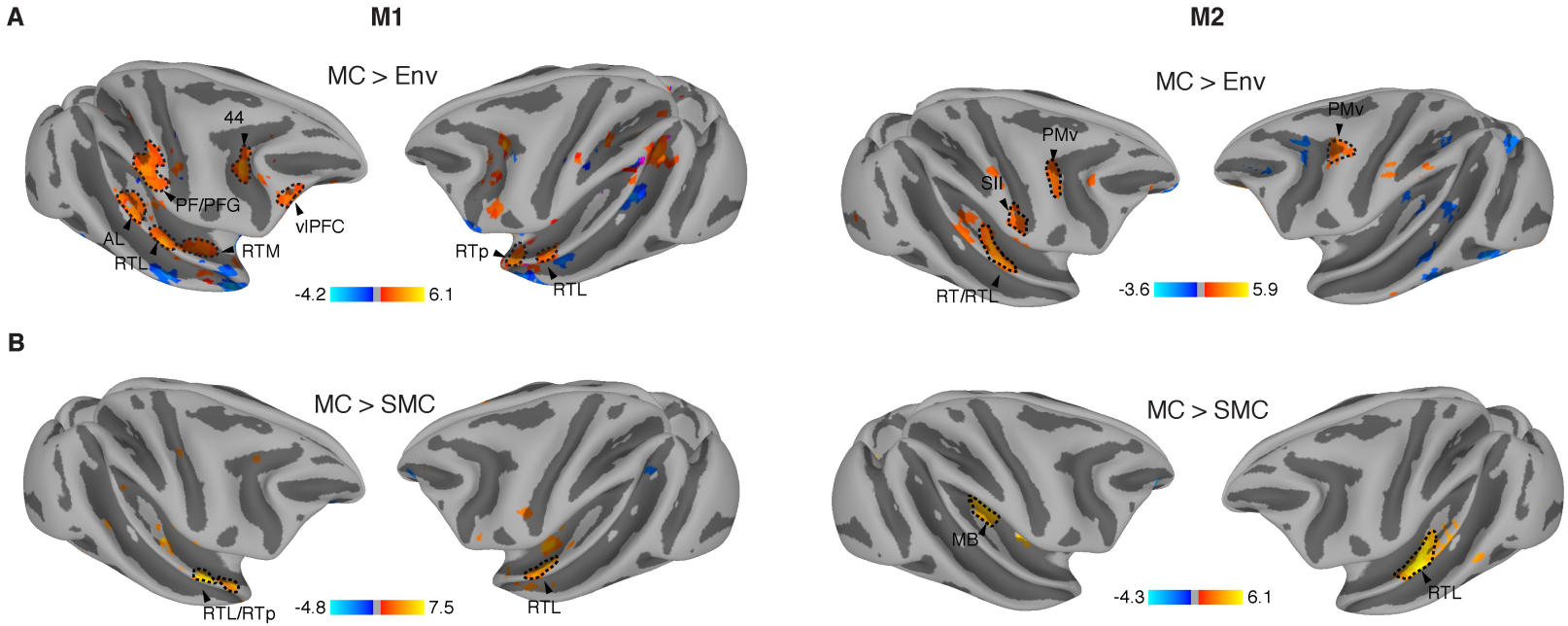
NSP





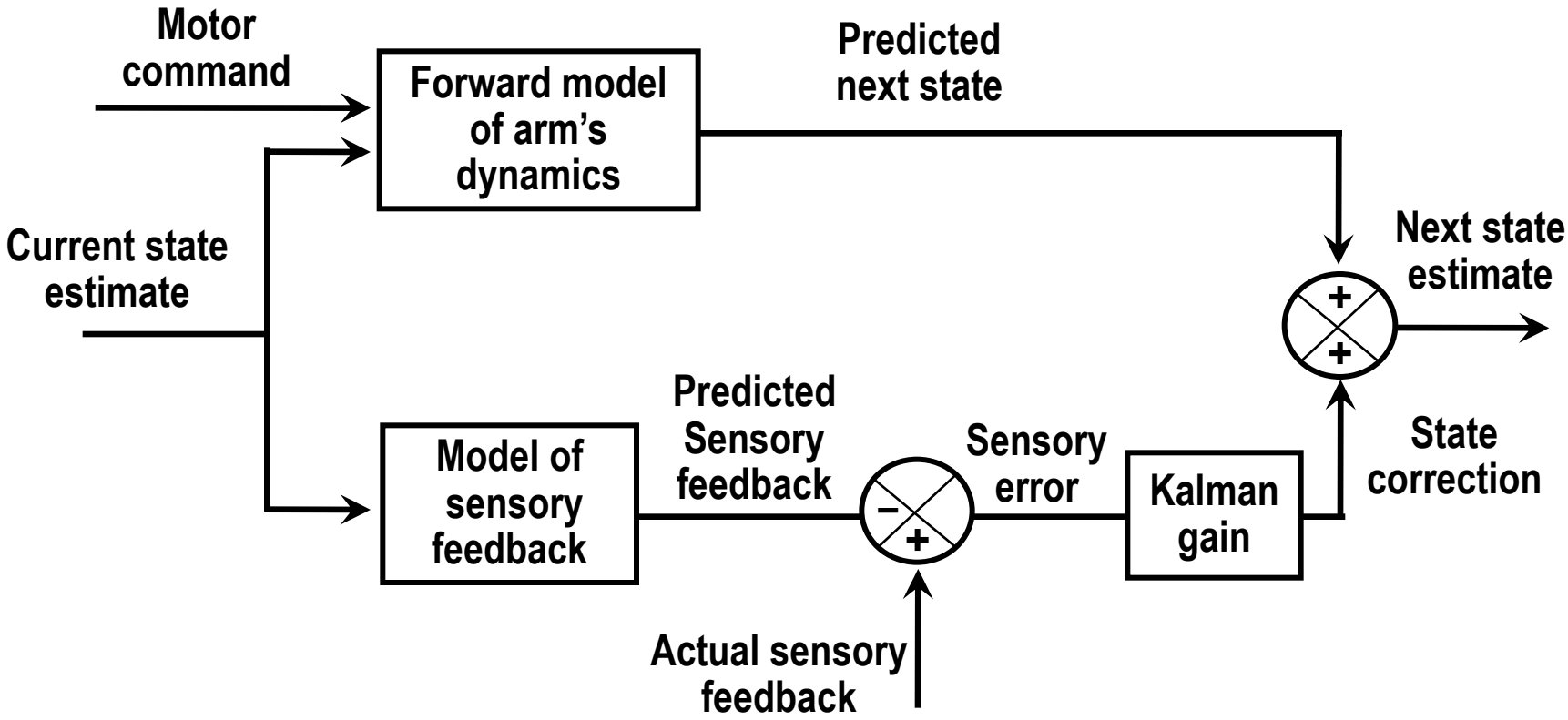
Vocalization-processing network in the macaque brain

Ortiz-Rios, Kuśmierek, DeWitt, Archakov, Azevedo, Sams, Jääskeläinen, Keliris, Rauschecker (2015)



An Internal Model for Sensorimotor Integration

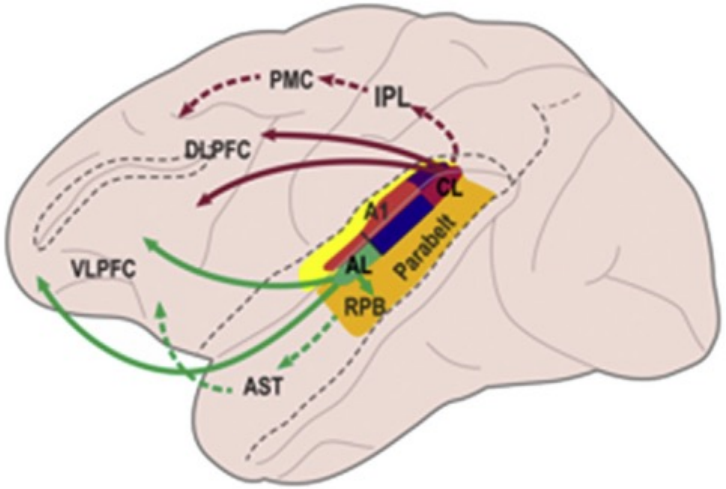
Daniel M. Wolpert,* Zoubin Ghahramani, Michael I. Jordan



Science • Vol 269 • 29 September 1995

Auditory dorsal stream is specialized for temporal processing of stimuli

- **Short response latencies in caudal belt** (Kusmierek & Rauschecker, 2014; Camalier et al., 2012)
- **High temporal precision of responses in caudal belt** (Kusmierek & Rauschecker, 2014)



Rauschecker, *Cortex* (2018)
Where, When, and How:
Are they all sensorimotor?