Mapping human auditory cortex according to BOLD fMRI response to click-train stimuli varying in presentation rate and binaural-level configuration

Susan A. McLaughlin and G. Christopher Stecker
Dept of Speech and Hearing Sciences
University of Washington

UNIVERSITY OF WASHINGTON

Background

Multiple markers approach to differentiating auditory cortical (AC) fields physiologically (e.g., Bizley *et al.* 2005, Stecker *et al.* 2005, Harrington *et al.* 2008)
Binaural level, rate sensitivity: key dimensions for characterizing AC neurons (Kitzes 2008, Wang *et al.* 2008)
Goal: use BOLD response to presentation rate and binaural level to differentiate AC fields in human neuroimaging

Objective

Measure sensitivity of AC BOLD (blood-oxygen-level-dependent) response to rate and binaural level characteristics
Binary variation of presentation rate, parametric variation of average binaural level (ABL) , interaural level difference (ILD)

Stimulus presentation

4000 Hz (carrier frequency) Gabor click trains, 3-ms interclick interval (ICI)
Train presentation rate: 5 trains of 32 clicks ("slow", 🐢) or 40 trains of 4 clicks ("fast",🐇) per sec
Level assigned independently at each ear [55-85 dB SPL or silent (-10 dB)]
Presented via piezo insert earphones (Sensimetrics) in ear defenders
Task: detect rare (once per ~13s) presentation of 2-ms ICI by button press

Block Design

12-second blocks present rate x binaural level combination
Silent blocks (-10 dB SPL to each ear) occur every 4th block
Image acquired at end of each block (sparse acquisition)
3 runs of 57 blocks per subject

Imaging Methods

BOLD echoplanar imaging (Philips, 3 Tesla)
Sparse imaging (TR = 12s, one frame per block)
32 slices (4.5 mm), 3mm x 3mm in-plane resolution

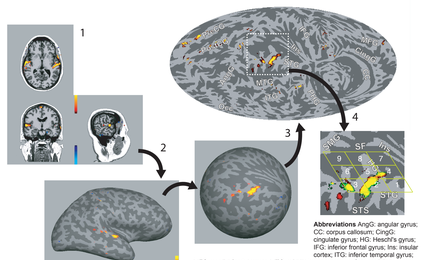
Binaural Level & Rate Combinations

Right-ear level (dB SPL)

Left-ear level (dB SPL)	-10	55	60	65	70	75	80	85
85	🐢				🐢			
80								
75								
70	🐢							🐢
65								
60								
55								
-10	+	🐢				🐢		🐢

Binaural level combinations presented to subjects. Shading illustrates sequences used for testing sensitivity to ABL (shades of blue) and ILD (red to green). Icons (tortoise/hare) represent slow and fast presentation rate. Silent (-10 dB SPL in each ear) blocks indicated by "+".

Analytical Methods



Abbreviations AngG: angular gyrus; CC: corpus callosum; CingG: cingulate gyrus; HG: Heschl's gyrus; IFG: inferior frontal gyrus; Ins: insular cortex; ITG: inferior temporal gyrus; MFG: medial frontal gyrus; MTG: middle temporal gyrus; Occ: occipital cortex; PHG: parahippocampal gyrus; PostCG: postcentral gyrus; PreCG: precentral gyrus; SF: Sylvian fissure; SMG: supramarginal gyrus; STG: superior temporal gyrus; STS: superior temporal sulcus. Right hemisphere depicted.

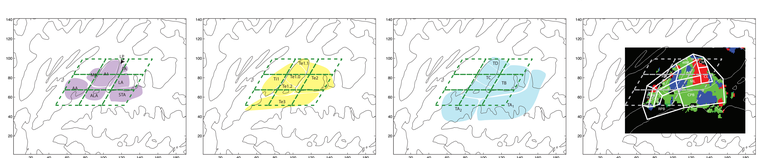
1) 3-D functional preprocessing with FSL
Motion correction, high-pass filtering (100s)

2) Cortical surface extraction using Freesurfer
Between-subject alignment via sphere
At left, light gray: positive curvature (gyri), dark gray: negative curvature (sulci)

3) Projection to equal-area map (Mollweide)
Center on HG x STG, STG on equator
1x1mm grid, 3x3 mm (FWHM) smoothing

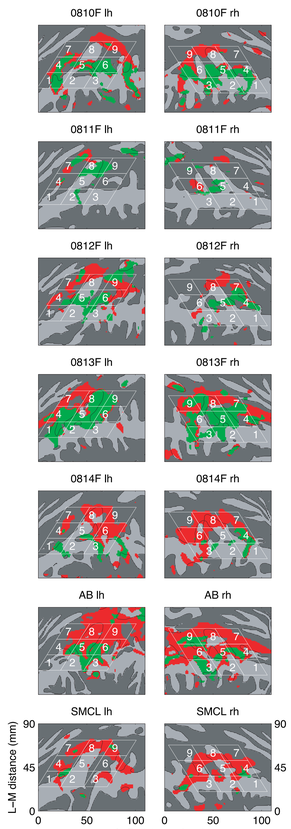
4) Definition of 9 regions of interest
3 x 3 oblique arrangement
Oriented along HG (L-M), STG (A-P)
ROI 1 = anterolateral, ROI 9 = posteromedial

5) Statistical analyses in MATLAB
ANOVA contrasts (1 df)
Percent signal change
Parametric average response



Rough comparison of analytical ROIs (3x3 oblique grid) to parcellation models of human AC. Left to right: based on anatomical observations of Rivier and Clark (1997, violet), Morosan et al. (2001, yellow), and von Economo and Koskinas (1925, blue). Far right: based on comparison of tonotopic organization of AC BOLD responses in Human (Woods et al., in press; red=high frequency, blue = low frequency) and Macaque AC (Kayser et al. 2007). Solid gray line: contour of 0 cortical curvature. Left hemispheres depicted.

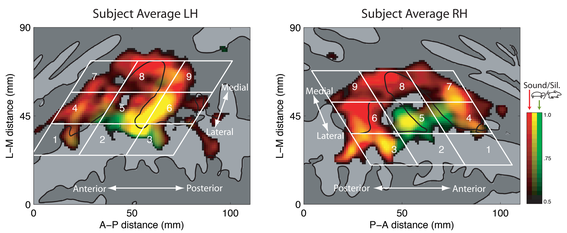
Distinguishing AC Regions by Sensitivity to Presentation Rate



Individual F-contrast maps. Green indicates significantly greater response to slow vs fast presentation rate ($F > 20$). Red indicates significant overall response ($F>20$) to sound vs silent blocks, but absence of sensitivity to presentation rate. Rows represent individual subjects. Left hemispheres plotted in left column, right hemispheres in right. Grid and labels indicate ROI positions relative to individual anatomy.

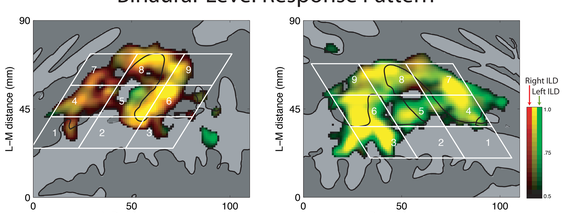
Presentation-Rate Response Pattern

Presentation rate response pattern. Color values plot % signal change, averaged across subjects, for slow vs fast (green), and sound vs silence (red). Labels, grid indicate ROI positions. Left and right panels plot left and right AC, respectively.



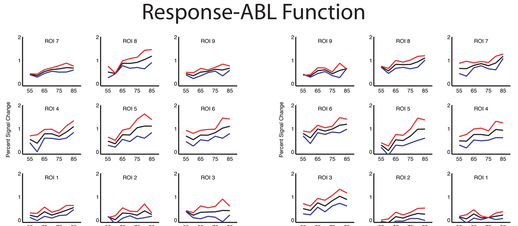
Binaural-Level Response Pattern

Binaural response pattern. Color values plot % signal change, averaged across subjects, for ILD favoring left ear presentation vs silence (green), and ILD favoring right ear presentation vs silence (red). Formatting identical to presentation rate response plot above.



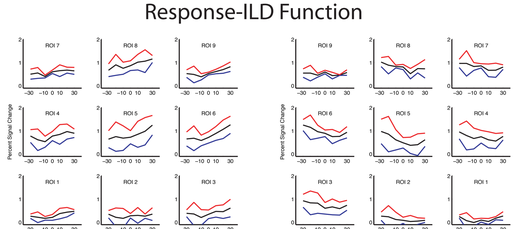
Response-ABL Function

Response-ABL functions. Lines plot percent signal change as a function of ABL for fast (blue), slow (red), and combined (black) presentation rates. Panels correspond to ROIs located in left (left panels) and right (right panels) AC. Note variation in overall response magnitude, sensitivity to rate and ABL.



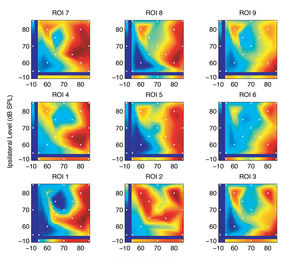
Response-ILD Function

Response-ILD functions. Lines plot percent signal change as a function of ILD. Formatting identical to Response-ABL function, above. Note variation in ILD response profile between ROIs. Also note exaggerated sensitivity to rate at some ILD values.



Level-Response Area

Level-response area (LRA). Color (blue to red) plots normalized signal change in the left hemisphere (slow presentation rate only) Axes indicate stimulation level in the contralateral / right (x-axis) and ipsilateral / left (y-axis) ears. White dots indicate tested level combinations; other values cubic-spline interpolates. Dark blue bars separate responses to monotic stimulation (one ear at -10 dB) from rest of plot.



Discussion

1) Variation in sensitivity to presentation rate across AC
-Overall advantage of slow vs fast rate; strongest in lateral HG (ROI 5, possibly ALA/Te1.2)
-Consistent with prior studies showing lateral HG sensitivity to rate (Schonwiesner *et al.* 2005), periodicity/pitch (Patterson *et al.* 2002), spectrotemporal complexity (Hall and Plack 2008)

2) Variation in binaural level sensitivity across AC
-May relate to different binaural interaction types (EE / E0 / EI)
-AC regions differ in strength of preference for contralateral ear
-LRA can potentially discriminate EI-type ILD tuning from E0-type contralateral drive

2) ROI Determination
-Match size/shape to responses (avoid averaging smaller-scale structures)
-Alignment with functional markers of microanatomy rather than gyral structure
-Accounting for individual variation

3) Pattern recognition to generate candidate ROI based on consistency of response tuning.

4) Role of carrier frequency
-Expect to activate different regions of AC (e.g., low-frequency A1)
-Shift in binaural sensitivity? (change in slope, shift to ITD?)

References

Bizley JK, Nodal FR, Nelken I, and King AJ (2005) *Cereb. Cortex.* 15(10):1637-53
von Economo C and Koskinas GN (1925) *Atlas of Cytoarchitectonics of the Adult Human Cerebral Cortex*
Hall DA and Plack CJ (2009) *Cereb. Cortex* 19:576-85
Harrington IA, Stecker, GC Macpherson EA, and Middlebrooks JC (2008) *Hear Res.* 240(1-2):22-41
Kayser C, Petkov CI, Augath M, and Logothetis NK (2007) *J Neurosci.* 27(8): 1824-35.
Kitzes (2008) *Hear Res.* 238(1-2):68-76
Morosan P, Rademacher J, Schleicher A, Amunts K, Schormann T, and Zilles K (2001) *NeuroImage* 13(4):684-701
Patterson RD, Uppenkamp S, Johnsrude IS, and Griffiths TD (2002) *Neuron* 36:767-76
Rivier F and Clarke S (1997) *Neuroimage* 6(4):288-304
Schonwiesner M, Rubsamen R, and von Cramen DY (2005) *Eur J Neurosci.* 22:1521-1528
Stecker GC, Harrington IA, Macpherson EA, and Middlebrooks JC (2005) *J Neurophysiol.* 94(2):1267-80
Wang X, Lu T, Bendor D, Bartlett E (2008) *Neuroscience* 157(2):484-94
Woods DL, Stecker GC, Rinne T, Herron TJ, Cate AD, Yund EW, Liao I, and Kang XJ (in press) *PLoS Biology*

Acknowledgments

The authors thank Jeff Stevenson and Jenee O'Brien for assistance with scanner configuration and data collection. Work supported by NSF IOB-0630338 and University of Washington.

email: smcl@u.washington.edu, cstecker@u.washington.edu
http://faculty.washington.edu/cstecker