BOLD signal tuning to interaural level and time differences in human auditory cortex

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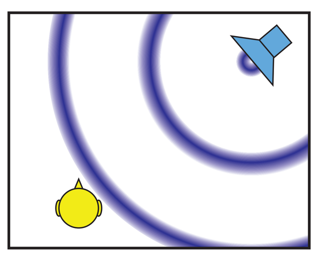
Cortical tuning to auditory space

Interaural time & level differences (ITD & ILD): key binaural cues for localizing sound, separating signal (e.g., speech) from noise.

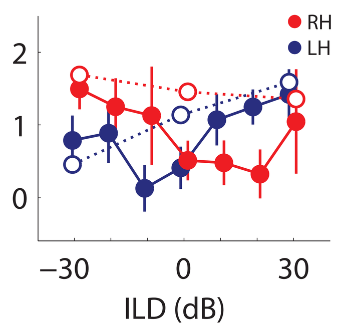


Representation of ITD & ILD in AC poorly understood.

Mammalian AC neurons broadly tuned to contralateral auditory space (Phillips & Irvine 1981; Reale & Brugge 1990; Stecker & Middlebrooks 2003; Werner-Reiss & Groh 2008).

Evidence for (Krumbholz et al. 2005; von Kriegstein et al. 2008; Stecker & McLaughlin 2010) and against (Woldorff et al. 1999; Zimmer et al. 2006) contralateral bias in BOLD fMRI response in human AC.

Tuning of fMRI responses in human AC to ILD appear non-monotonic, but overall biased to favor contralateral ear. Relative to monotic response (open symbols), both hemispheres (red for RH, blue for LH) show significant reductions for moderate ipsilateral ILD values. [Stecker and McLaughlin, ASA 2012



Questions

Is the BOLD signal contralaterally tuned to ILD & ITD in human AC?

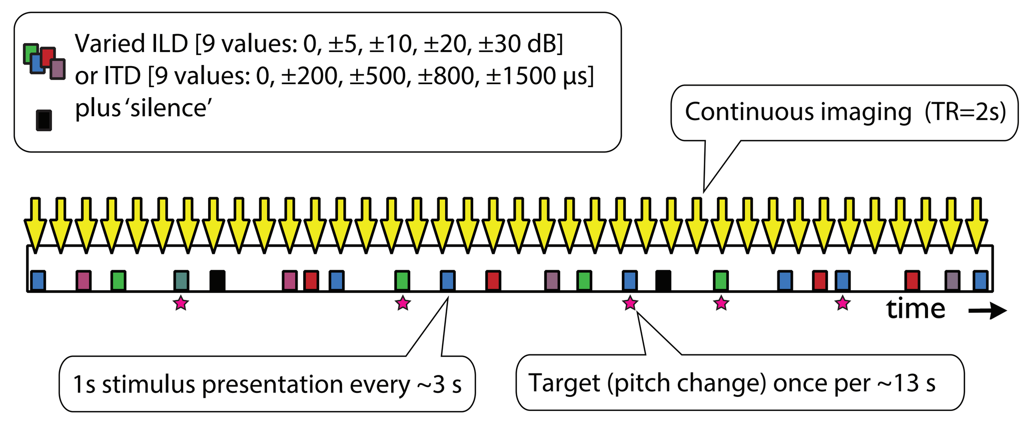
Does tuning in either hemisphere show more contralateral bias (hemispheric asymmetry)?

Is auditory space preferentially processed in posterior AC regions?

Are ILD and ITD represented jointly or separately in AC?

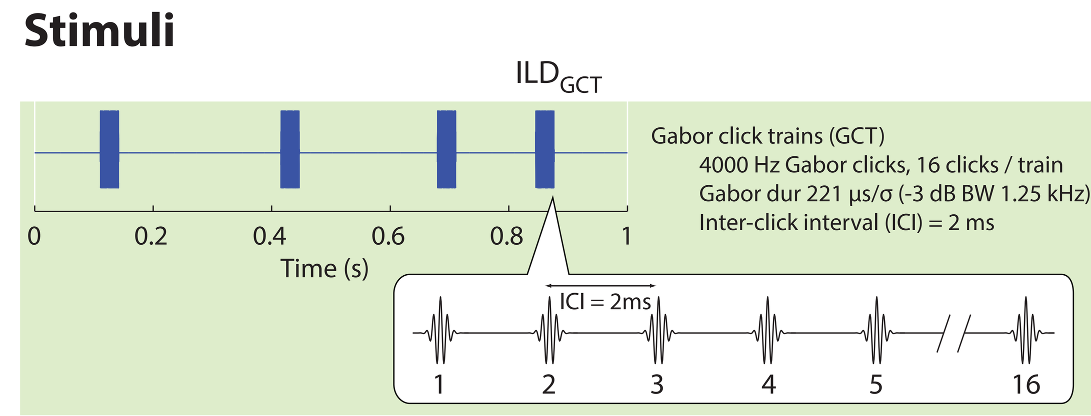
How does stimulus history affect tuning?

Experimental design

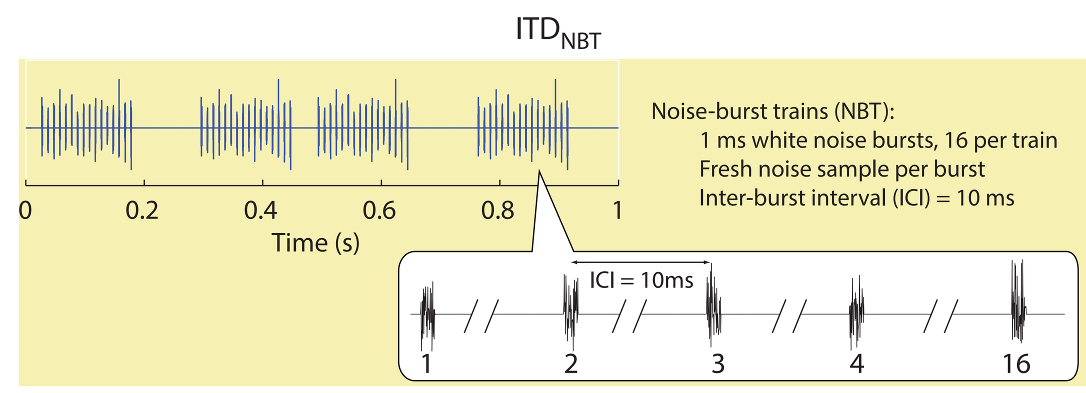


Subjects: 10 per condition (18-35 yo, right handed,normal-hearing).
Stimuli: Presented via piezo insert earphones (Sensimetrics S14) in ear defenders. Four different conditions: 1) ILDS in Gabor click trains (GCT); ITDs in 2) Gabor click trains (GCT), 3) noise-burst trains (NBT), and 4) low-pass noise (LPN).
Design: Event-related continuous carryover (Aguirre 2007): each stimulus presented before and after every other -- test both "direct" effect of binaural cue modulation, and "stimulus history" effect according to value of previous cue.
Task: press button in response to infrequent pitch change.
Preliminary analysis: little tuning to ITD_{GCT} and ITD_{LPN}-- results reported herein only for ILD_{GCT} and ITD_{NBT}.

Stimuli



Gabor click trains (GCT)
4000 Hz Gabor clicks, 16 clicks / train
Gabor dur 221 μs/σ (-3 dB BW 1.25 kHz)
Inter-click interval (ICI) = 2 ms

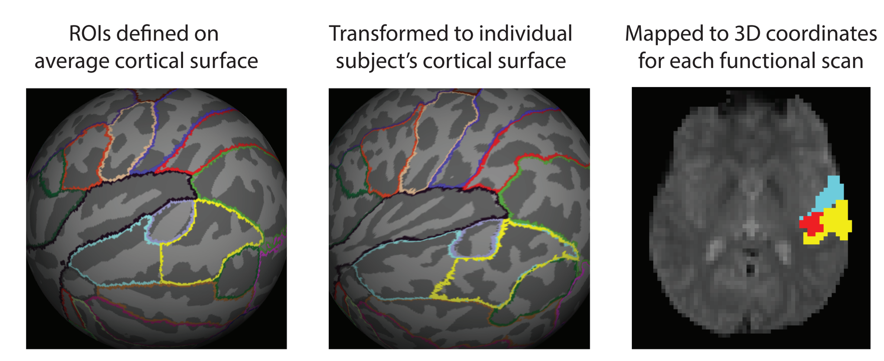


Noise-burst trains (NBT):
1 ms white noise bursts, 16 per train
Fresh noise sample per burst
Inter-burst interval (ICI) = 10 ms

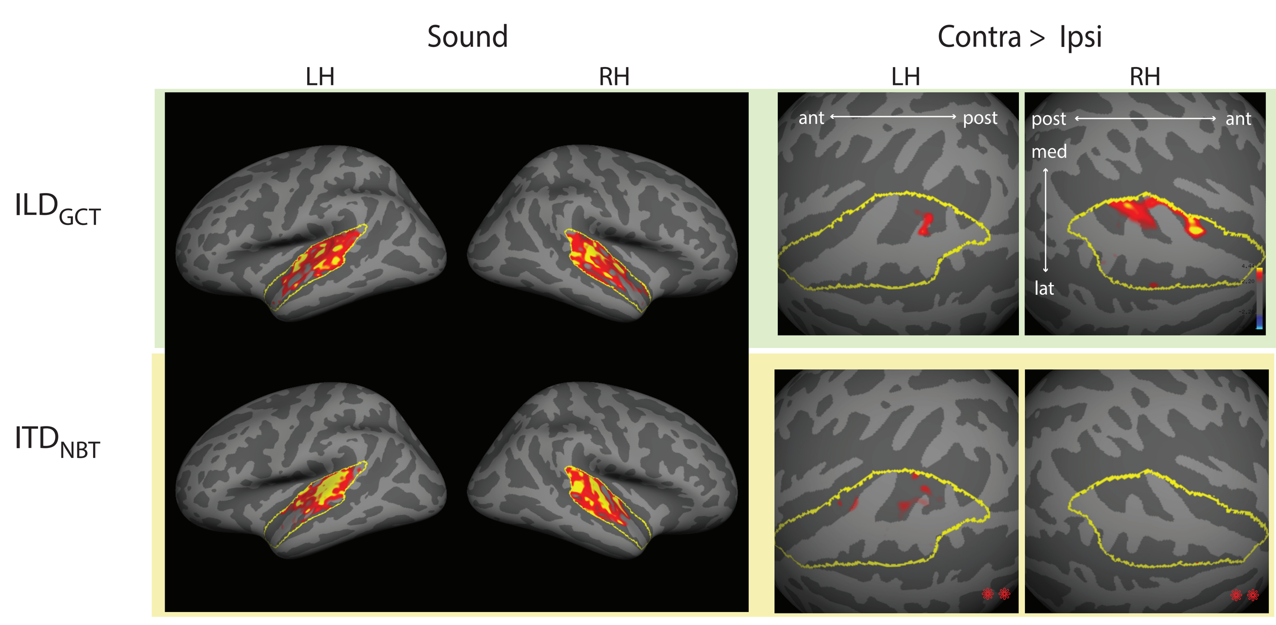
Imaging & analysis

Echo-planar imaging: 3T (Philips), TR=2s, 42 3-mm slices, 2.75 x 2.75-mm in-plane resolution
Pre-processing: motion correction, .01 Hz high pass filtering, ICA-based denoising in MELODIC (FSL)
Univariate general linear model (GLM) analysis in FEAT (FSL)
For region of interest (ROI) analyses, beta weights averaged across sound-responsive (z>2.3, uncorr) voxels in each ROI

ROIs defined using Freesurfer following Desikan et al. (2006)
HG: Heschl's gyrus (red)
aSTG: Anterior half of Superior Temporal Gyrus, excluding HG (cyan)
pSTG: Posterior half of Superior Temporal Gyrus excluding HG (yellow)
AC: Auditory cortex (HG plus STG)



Results, direct effects : clear contralateral tuning to ILD in both hemispheres; more modest tuning to ITD, only in left hemisphere



p<.05, FDR corr in AC, except where ** then p<.01, uncorr

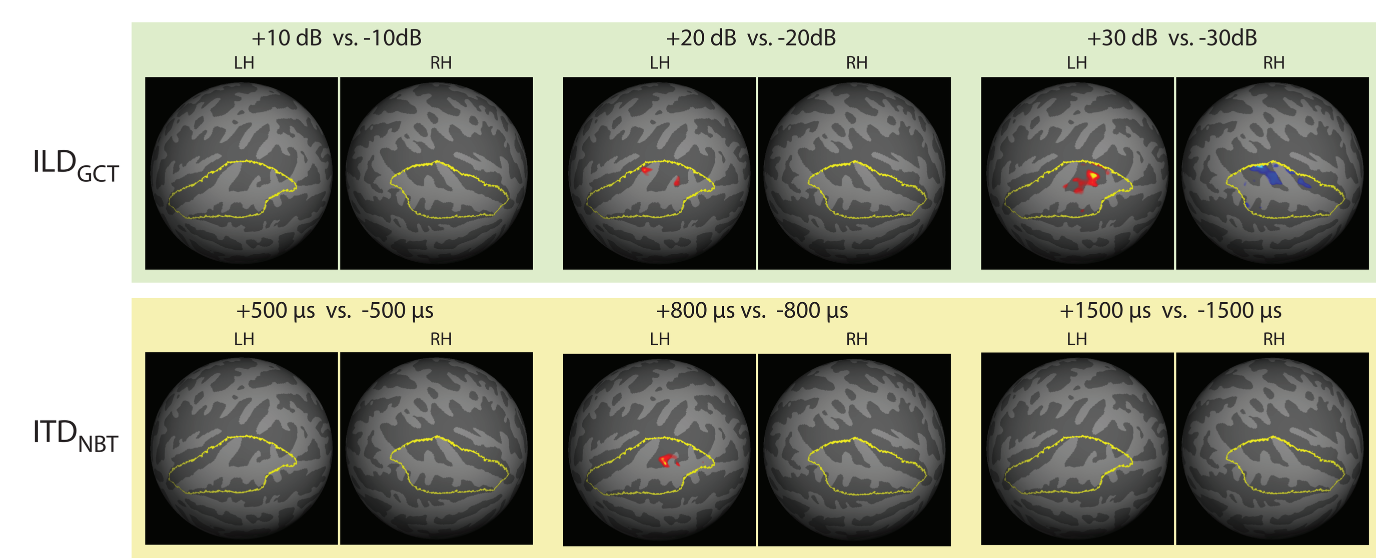
Maps of contralateral vs. ipsilateral stimulation show tuning in both hemispheres to contralateral ILD_{GCT} sound, little difference in response to contralateral vs. ipsilateral ITD_{NBT} sound in either hemisphere.

Voxel-wise maps displayed on FSaverage (Freesurfer). Responses masked by AC ROI (outlined in yellow), and FDR corrected within AC at p < .05 (except where noted).

Far left: Response to all sound conditions.

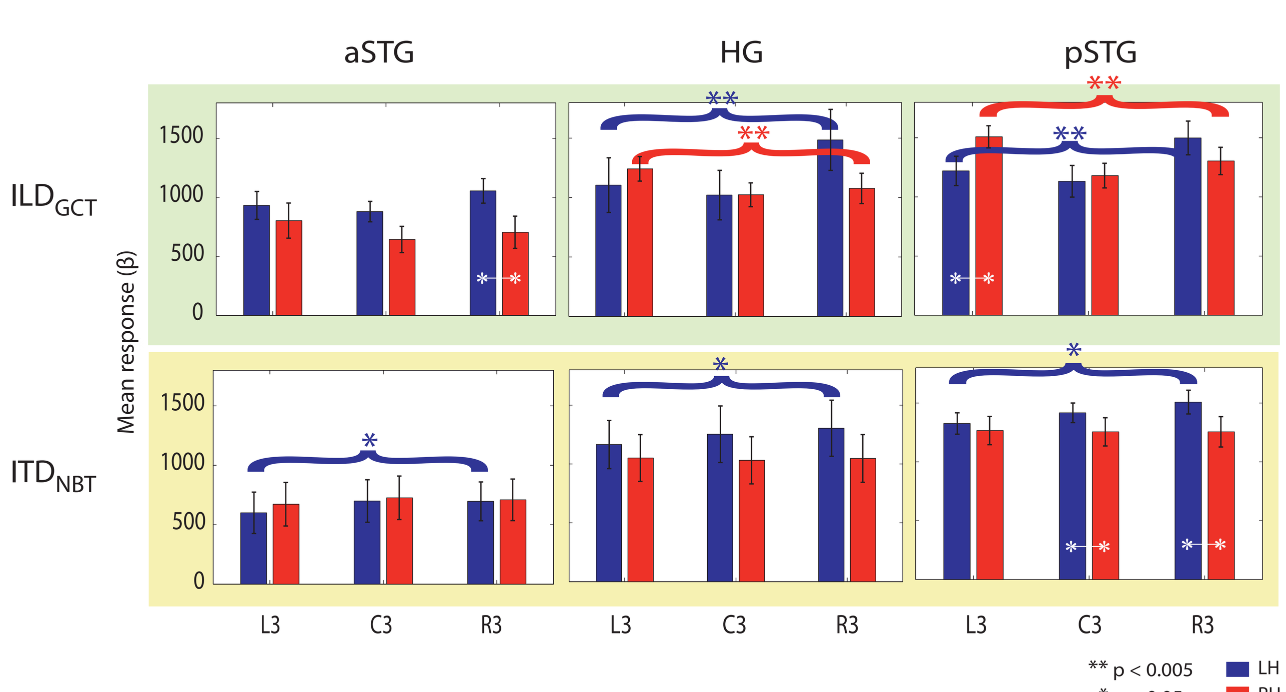
Near left: Red/yellow voxels are those in which response to contralateral sound is greater than to ipsilateral sound. Blue voxels are those which respond more to ipsi than contra sound. For ILD, "left" is defined as -30, -20, & -10 dB and right as 10, 20, & 30 dB. For ITD, left is defined as -800, -500, & -200 μs, and right as 800, 500, & 200 μs.

Right: Comparisons between response to leftward and rightward sound at +/- 10, +/- 20, and +/- 30 dB for ILD stimuli, and at +/- 500, +/- 800, and +/- 1500 μs for ITD stimuli. Red/yellow voxels = greater response to rightward stimulation. Blue voxels = greater response to leftward stimulation.



p < .05, FDR corr in AC

Pairwise maps show contralateral tuning in both hemispheres at 30dB, only in LH at 20 dB for ILD_{GCT}, contralateral tuning in LH at 800 μs for ITD_{NBT}.

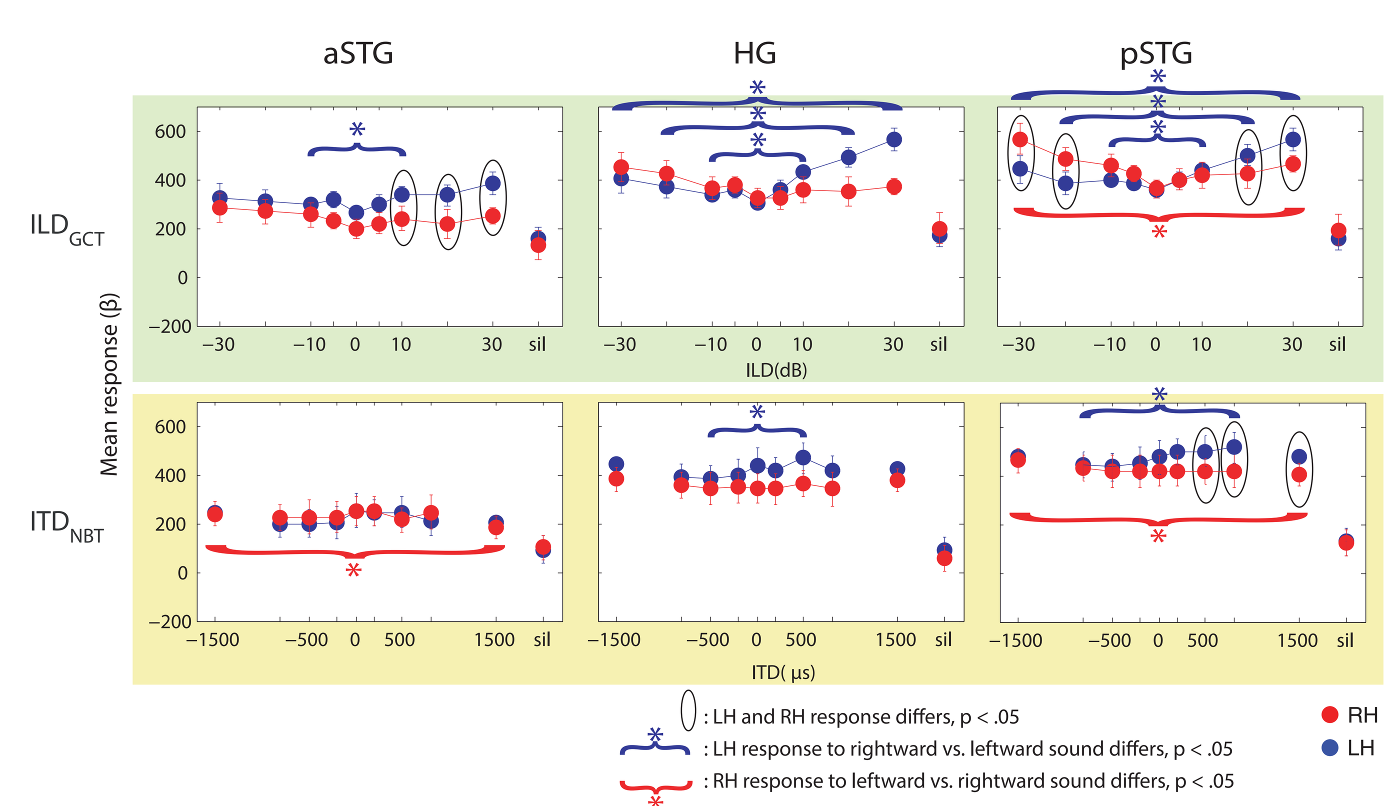


Hemifield-level contrasts show robust contralateral tuning (non-monotonic) in pSTG & HG for ILD_{GCT} stimulation, contralateral tuning in LH in all ROIs (more monotonic?) for ITD_{NBT} stimuli.

Group avearge beta-weights for aSTG, HG, and pSTG ROIs; error bars are standard error of the mean (S.E.M.) across subjects. Blue bars/points = LH responses; red bars/points = RH responses. Significance levels shown at p<.005 (**) and p<.05 (*).

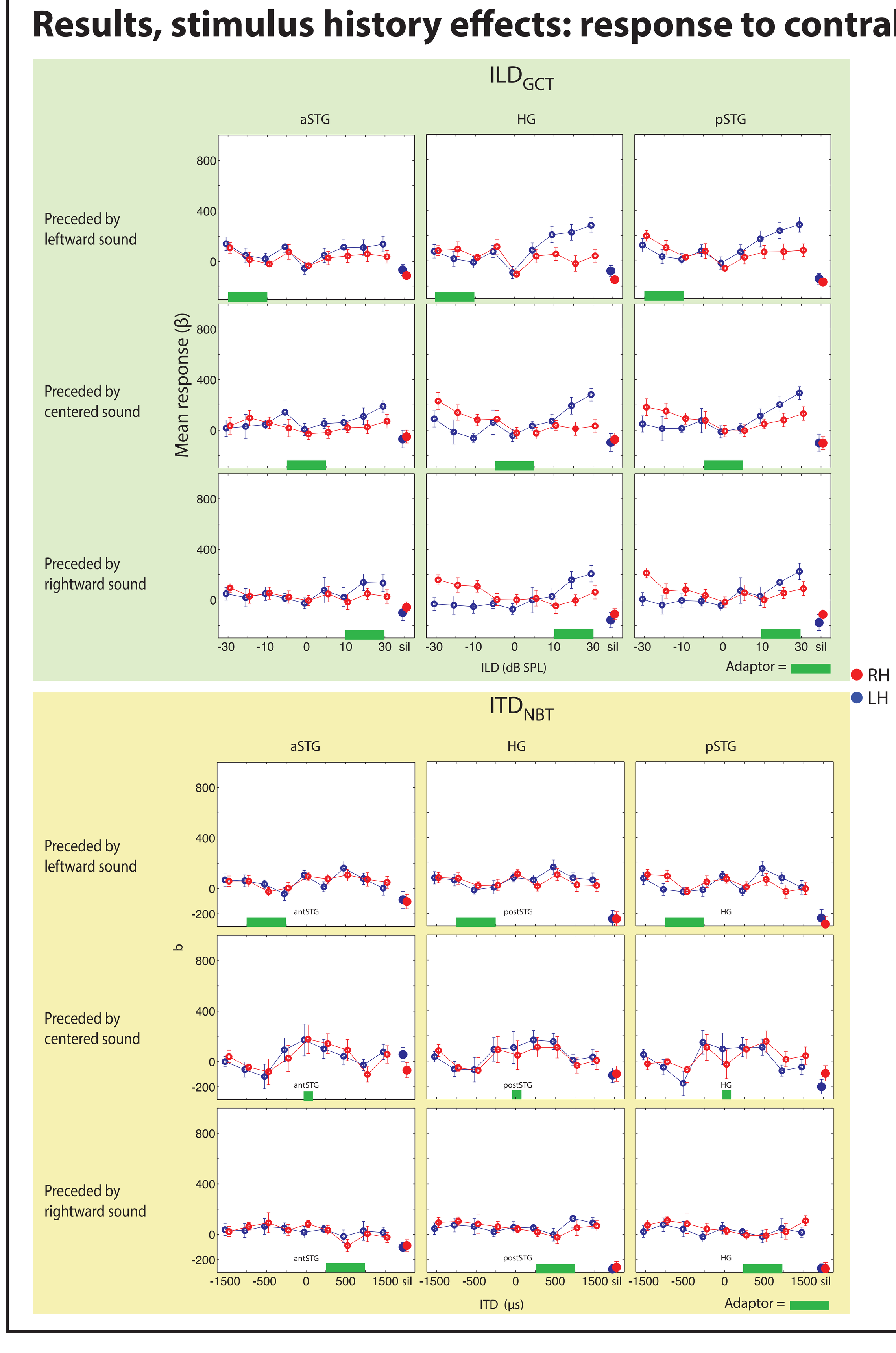
Left: Group average response to leftward (L3), centered (C3), and rightward (R3) 'hemifield-level' sound. L3 and R3 as defined above. For ILD, C3 is defined as -5, 0, & 5 dB for ILD, and for ITD as -200, 0, & 200 μs. White lines extending across LH and RH bars indicate significant differences between RH vs. LH responses at a given hemifield level. Horizontal braces extending across hemifield conditions indicate significant differences within a hemisphere between responses to L3 vs. R3 stimulation.

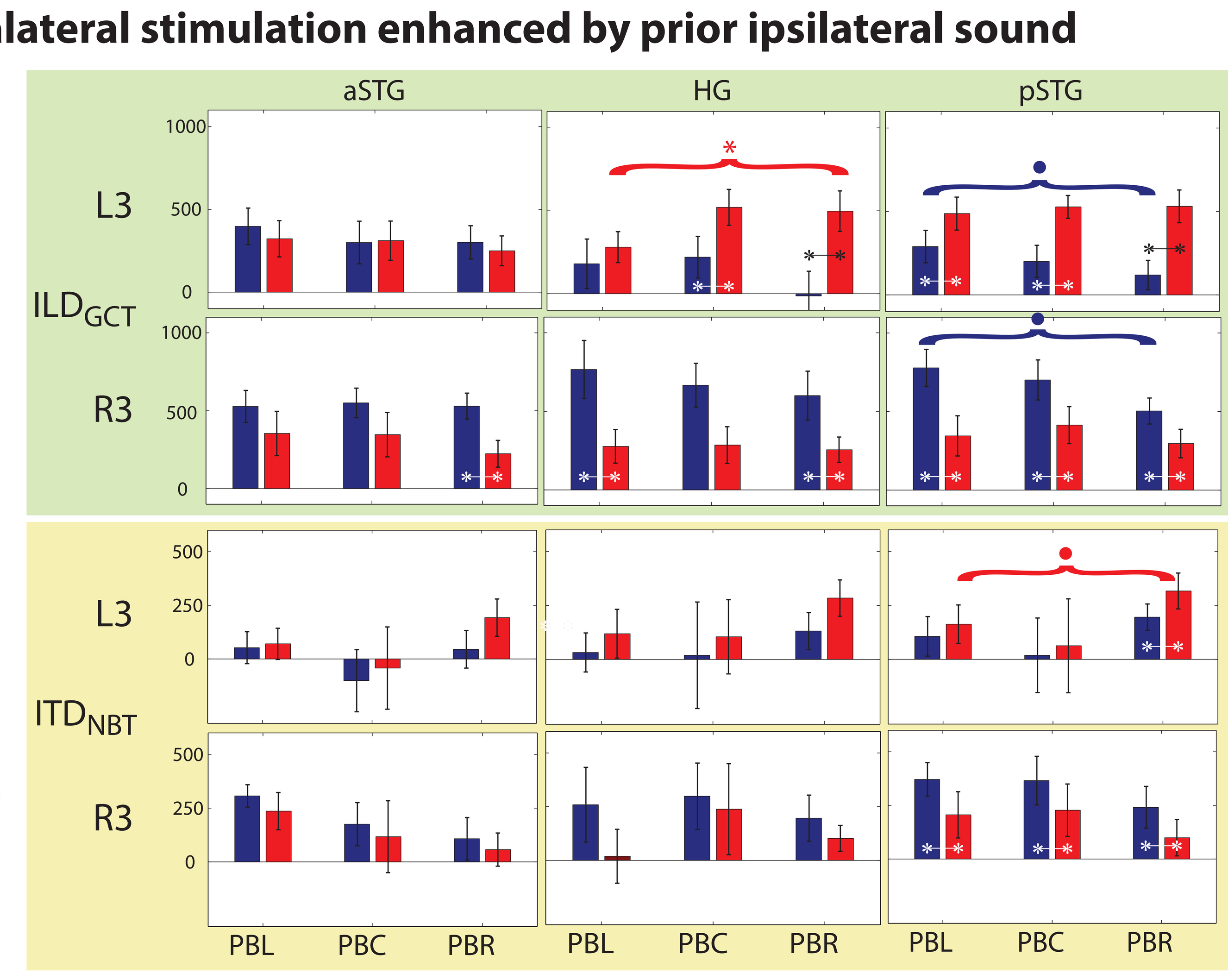
Right: Binaural level-response functions. Sounds coming from the left side of auditory space represented as negative values, and sounds from the right as positive values. Responses to 1500 μs are separated off because it is not a physiologically plausible stimulus. Indicated on response functions are significant pariwise contrasts. Ellipses encircling LH and RH points indicate significant difference between LH vs. RH responses to stimulation at a given binaural cue level. Upward horizontal braces extending across matched cue values in left and right hemifields indicate significant difference in LH response to rightward vs. leftward stimulation. Downward horizontal braces indicate significant difference in RH response to leftward vs. rightward stimulation .



Binaural level-response functions show non-monotonic tuning to contralateral ILD_{GCT} sound in pSTG more for LH than RH, and only in LH in HG. In response to ITD_{NBT} stimulation, monotonic contralateral tuning is seen in LH in pSTG at 800 μs and in HG at 500 μs. Contralateral tuning is seen in RH pSTG and aSTG at 1500 μs.

Results, stimulus history effects: response to contralateral stimulation enhanced by prior ipsilateral sound





For ILD_{GCT} stimulation, RH in HG responds more to contralateral leftward probe sound when preceded by ipsilateral rightward adaptor, and LH in pSTG shows a trend toward a greater response to rightward (and leftward) probe sound when preceded by ipsilateral leftward adaptor. Likewise, for ITD_{NBT} sound, RH trends toward a greater response to leftward probe sounds that are preceded by rightward than those that are preceded by leftward.

Left: Binaural-level response functions for ILD (top) and ITD (bottom) across stimulus history conditions: preceded by leftward sound (-30, -20, & -10 dB ILD and -800, -500, & -200 μs ITD), preceded by centered sound (-5, 0, 5 dB ILD and 0 μs ITD), and preceded by righward sound (10, 20, & 30 dB ILD and 200, 500, & 800 μs ITD). Green bars show values of adaptor sounds in each condition.

Above: Group average response to leftward (L3) and rightward (R3) 'hemifield-level' sound across stimulus history conditions: PBL (preceded by left), PBC (preceded by centered), and PBR (preceded by right). Stimulus history conditions as defined above. L3 and R3 encompass same values as leftward and rightward sound defined above. White lines extending across LH and RH bars indicate significant differences between RH vs. LH responses at a given hemifield level. Horizontal braces extending across hemifield conditions indicate significant differences within a hemisphere between responses to L3 vs. R3 stimulation.

Discussion

Robust contralateral tuning (non-monotonic) in BOLD response to ILD; modest tuning (more monotomic) in response to ITD. Why?
- Weaker cortical coding for ITD?
- BOLD signal may not capture ITD coding, potentially reliant on:
  - excitatory/inhibitory relationships (McAlpine et al. 2001; Stecker et al. 2005)
  - temporal coding mechanisms (Furakawa & Middlebrooks 2002)
  - distributed code (Stecker et al. 2003; Werner-Reiss & Groh 2008)
- Influences of task/attention on cortical ITD processing

More robust contralateral tuning in LH than RH, consistent with previous neuroimaging (Krumbholz et al. 2005, 2007; Johanson & Hautus 2010) and clinical lesion (Clarke et al. 2000; Spierer et al. 2010) data. Pronounced asymmetry for ITD, more modest for ILD.

ILD and ITD tuning strongest in pSTG and HG; some tuning in aSTG.

Stimulus history effects on ILD and ITD tuning:
- Response to stimulus in contralateral hemifield enhanced when preceded by prior sound in ipsilateral hemispace.

Present results do not provide clear evidence of separate AC processing mechanisms for ILD and ITD; disparities observed may be artifact of weaker BOLD tuning to ITD rather than differential effects of distinct processing mechanisms.

Future directions

Analysis of subcortical data

Other analytical methods tby which to fit voxel response to binarual tuning (e.g., population receptive fields)

Auditory spatial task

Alternative imaging methods that better capture temporal aspects of response (e.g., MEG and EEG)

Binaural processing in patient populations with disorderd cortical processing

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