Neural Correlates of Auditory Distance Perception with Congruent and Incongruent Cues

Keerthi Doreswamy[a,b], Jyrki Ahveninen[a], Samantha Huang[a], Stephanie Rossi[a], Norbert Kopco[a,b,c]

[a] *Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Harvard Medical School/Massachusetts General Hospital, Charlestown, MA, 02129, USA*

[b] *Institute of Computer Science, P. J. Safarik University, Kosice, 04001, Slovakia*

[c] *Hearing Research Center, Boston University, Boston, MA, 02215, USA*

Introduction

- Perceiving the sound source distance is of key value in many everyday activities.
- Even though auditory distance perception is a critical component of spatial hearing, it has received substantially less attention than the directional sound localization.
- Hence the psychoacoustics of distance perception and its neuronal correlates are poorly understood [10].
- Our previous studies used direct-to-reverberant energy ratio (DRR) and the interaural level difference (ILD) cues to simulate distance. They identified planum temporale (PT) & superior temporal gyrus (STG) as auditory cortical areas important for processing distance independent of intensity cue and of binaural cues relevant for directional hearing [1-2].
- However, it is not clear whether the previously identified areas represent the distance percept *per se* or one of the intensity independent acoustic cues ILD and/or DRR.
- To examine this, we conducted behavioral and neuroimaging experiments in a virtual reverberant environment, using multivariate pattern analysis (MVPA) to analyze the data.

Objectives

- For stimuli varying in distance along the interaural axis, manipulate the availability of DRR and ILD cues so that DRR is either unavailable (constant) or incongruent with ILD.
- Examine behaviorally how sensitivity to distance varies for the stimuli containing different types of cues.
- Use fMRI to identify brain areas sensitive to distance percept (as opposed to individual cues) and to the DRR cues.

Hypotheses and predictions:

- Behavioral experiment: DRR and ILD both contribute to distance perception. → Distance sensitivity with congruent cues will be better than that with ILD-only cue, which will be better than that with DRR and ILD cues incongruent.
- Neuroimaging experiment: both the individual acoustic cues and distance percept are neurally encoded, possibly in overlapping distributed neural representations.

→ Activations related to distance percept and to DRR cue will be visible either in univariate or in multivariate analysis of the fMRI data.

Methods

Subjects:

- 13 naive subjects with normal hearing participated in the behavioral experiment. 1 subject excluded (for not following instructions).
- 15 right-handed individuals with self-reported normal hearing participated in the imaging experiment (data from 1 run in 1 subject excluded for not following instructions).

Stimuli:

- Three types of stimuli simulated in virtual reverberant environment [1, 3] (Fig. 1A):
  - ILD & DRR varying congruently,
  - ILD & DRR varying incongruently and
  - ILD varying, DRR fixed.
- The auditory stimuli were 300-ms broadband noise bursts varying in distance (15–100 cm) on the left-hand side along the interaural axis. (Fig. 1B)
- In behavioral experiment, stimulus level roved on each presentation.
- In fMRI experiment, stimulus presentation level fixed, congruent with ILD.

Behavioral experiment (Fig. 1C):

- Distance discrimination task for all stimulus distance pairs presented in random order:
  - 2 to 3 runs of 84 trials (4 for each distance pair) for each stimulus type,
  - feedback provided in congruent and ILD-only conditions, not in incongruent condition.

fMRI experiment (Fig. 1D):

- Each trial consisted of a sequence of 14 noise bursts with SOA 500 ms followed by image acquisition (listener's task was to detect a duration deviant).
- Experimental run contained 96 trials and each subject performed 2 runs.
- Whole-head fMRI was acquired at 3T using a 32-channel coil.
- To circumvent response contamination by scanner noise, we used a sparse-sampling gradient-echo BOLD sequence.
- T1-weighted anatomical images were obtained using a multi-echo MPRAGE pulse sequence.

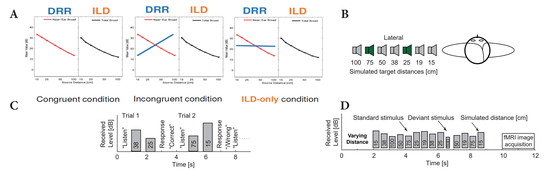

Fig.1 Experimental setup and stimuli. A) Cue manipulation in different conditions. B) Simulated stimulus locations. C) Temporal sequence of trials in behavioral experiment. D) Timing of stimuli and image acquisition during one trial in fMRI experiment.

Data analysis:

Behavior

- A model based on signal detection theory was used to evaluate the performance of the discrimination task. [1, 4]
- Statistical comparisons of the behavioral data were done using repeated-measure ANOVAs using CLEAVE software. [5]

fMRI univariate

- Cortical surface reconstructions and standard-space co-registrations of each subject's anatomical data [6] and the functional data analyses were conducted using Freesurfer 5.3.

fMRI multivariate (MVPA)

- Data were preprocessed in native space without smoothing and per session.
- Preprocessed data were fed into a general-linear model (GLM) with the task conditions as explanatory variables.
- Split half correlation analysis was done on fMRI data using COSMOMVPA. [9]

Results

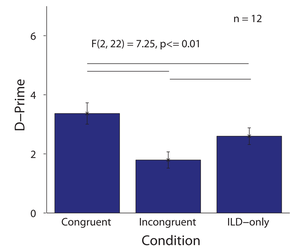

Fig.2 Discrimination task performance across different sound conditions.

Behavioral Experiment (Fig. 2):

- Performance is significantly different in the 3 conditions, confirming the hypothesis that both cues contribute to distance judgments.

fMRI univariate surface-based analysis (Fig. 3):

- Activations are similar across the 3 conditions. Contrasts between conditions do not identify a clear area that would correspond to distance percept (Congruent vs. Incongruent) or DRR (Incongruent vs. ILD-only).

fMRI Region-of-interest analysis in posterior STG + Planum Temporale (Fig. 4):

- No significant difference, but a trend towards significance in the left-hemisphere.

fMRI MVPA – Split-half correlation analysis in STG + PT ROI (Fig. 5):

This analysis tests the hypothesis that the correlation between pattern vectors, obtained from the % signal changes of each voxel in our ROI, are more consistent across the same-condition run pairs [Run-1 Congruent, Run-2 Congruent] and [Run-1 Incongruent, Run-2 Incongruent] than across the different-condition run pairs [Run-1 Congruent, Run-2 Incongruent] and [Run-1 Incongruent, Run-2 Congruent].

An average difference in z-transformed correlations between same and different-condition correlations:

- Left hemisphere: 0.022 ± 0.059 (mean ± SD), right hemisphere: 0.020 ± 0.031, (difference not significant)
- Value of the average difference: 0.021 ± 0.038 (mean ± SD), t(13) = 2.085, **p = 0.028*** (one-tailed).

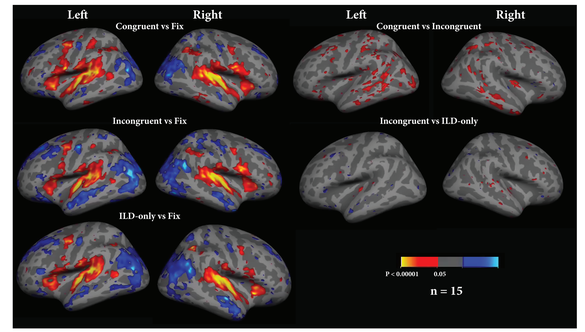

Fig.3 Results of the fMRI experiment presented on inflated cortical surface for different contrasts between conditions.

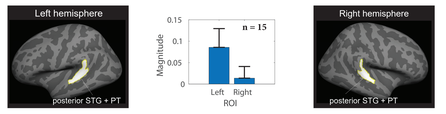

Fig.4 Hypothesis-based region-of-interest (ROI) analysis of posterior nonprimary auditory cortex activations for the Congruent-vs-Incongruent contrast.

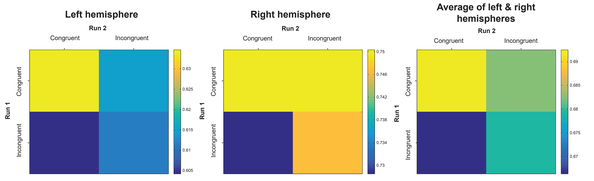

Fig.5 Average split-half correlation across subjects for the Congruent-vs-Incongruent contrast (n= 14).

Conclusions & Discussion

Behavioral results:

- Performance with incongruent ILD & DRR worse than with congruent or ILD-only cues → simulated distance percepts are based on both cues.

Imaging results:

- No significant effects in fMRI univariate contrast between congruent vs incongruent cue stimuli → areas identified in previous studies [1-2] likely encoded cues.
- Split-half correlation (MVPA) analysis of activation pattern in the auditory cortex ROI encompassing the PT and STG differed depending on cue congruency → distance percepts encoded in a distributed interconnected network that might overlap with individual cue representations [8].
- MVPA result not hemisphere-specific → perceptual representation more bilateral than the cue representations [1].
- Overall, these results are consistent with the hypothesis that the PT and STG is a spatial computational hub representing the spatial percepts as well as the acoustic cues.
- Future steps: volume-based univariate analysis and more sensitive searchlight-based MVPA.

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