Neural Correlates of Auditory Distance Perception and of Auditory Distance Cues

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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 [1].
- Our previous studies involving direct-to-reverberant energy ratio (DRR) and the interaural level difference (ILD) cues identified planum temporale (PT) and superior temporal gyrus (STG) as auditory cortical areas important for processing distance independent of intensity cue and of binaural cues relevant for directional hearing [2-3].
- 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 or DRR.
- To examine this, we conducted behavioral and neuroimaging experiments in a virtual reverberant environment. We combined univariate and multivariate pattern analysis (MVPA) on the fMRI 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 2 subjects excluded for not following instructions).

Stimuli:

- Three types of stimuli created by manipulating a non-individualized BRIRsimulated in virtual reverberant environment [2, 4] (Fig. 1A):
  1. **Congruent** - ILD & DRR varying congruently,
  2. **Incongruent** - ILD & DRR varying incongruently and
  3. **ILD-only** - ILD varying, DRR fixed.
- The auditory stimuli were 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 stimulus consisted of a sequence of 14 300-ms noise bursts with SOA 500 ms.
- Each trial consisted of a stimulus presentation 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.

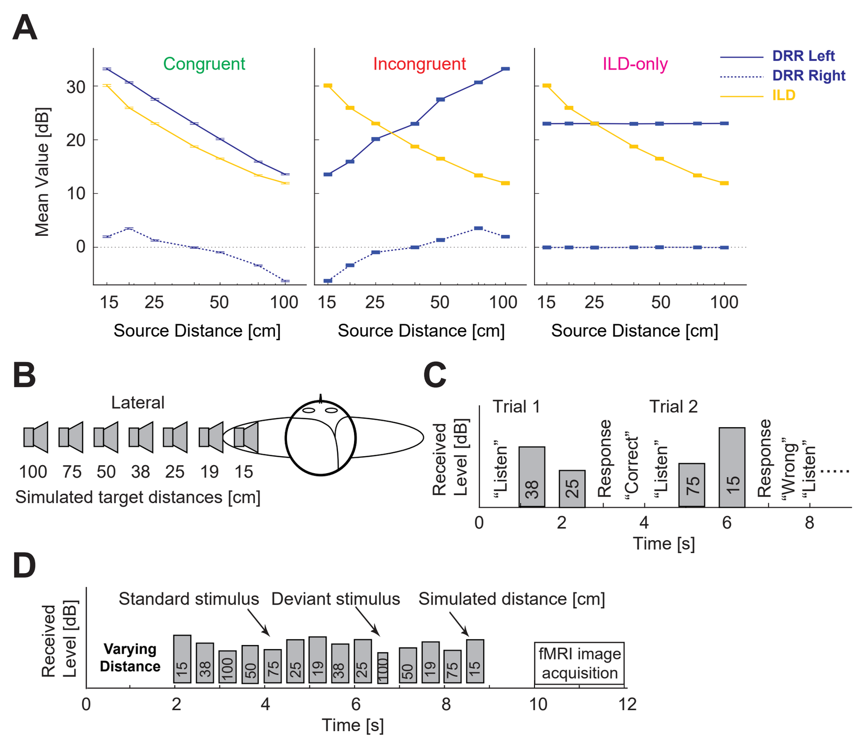

Fig.1 Experimental setup & stimuli. A) Cue manipulation in different conditions. B) Simulated stimulus locations. C) Temporal sequence of trials in behavioral experiment. D) Timing of stimuli & image acquisition during one trial in fMRI experiment.

Data analysis:

Behavior

- d' used to evaluate discrimination performance. [2,5]
- Repeated-measures ANOVA used to compare conditions. [6]

fMRI univariate

- The functional data analyses were conducted using Freesurfer 5.3. and FSL.

fMRI multivariate (MVPA)

- Data preprocessed in native space without smoothing and per session.
- Data fed into a general-linear model with conditions as explanatory variables.
- Split half correlation analysis was done on fMRI data using COSMOMVPA. [10]

Results

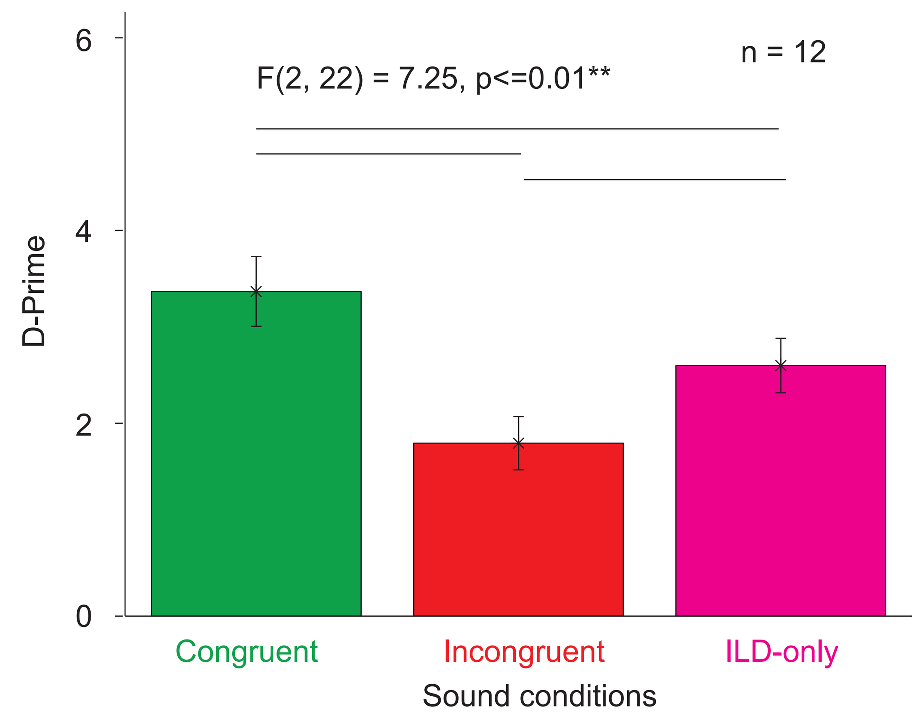

Fig.2 Discrimination task performance across different sound conditions.

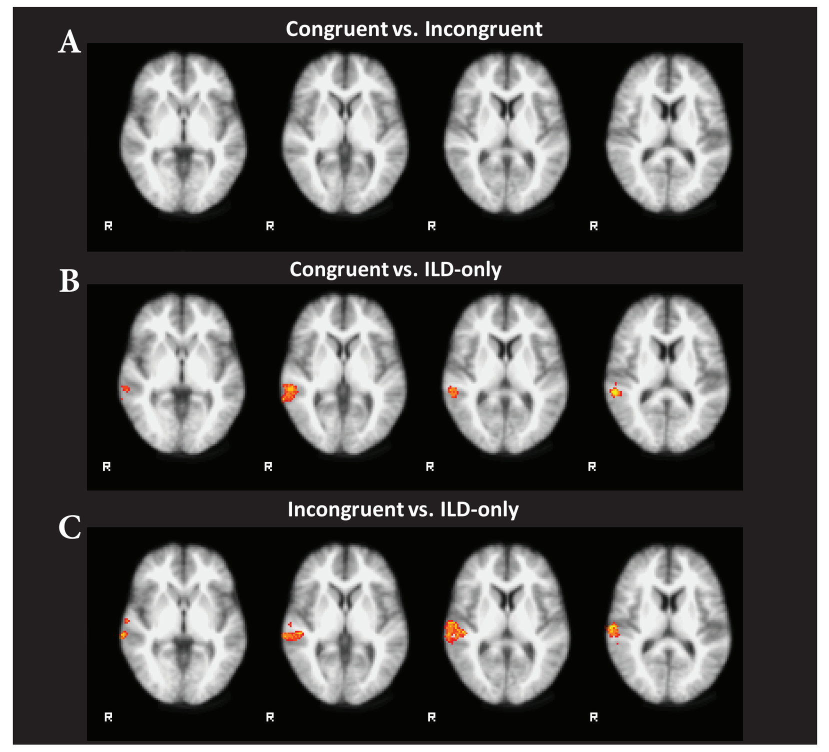

Fig.3 Volume-based fMRI analysis of activations across different sound condition contrasts. (Slices: 19-22)

Behavioral Experiment (Fig. 2):

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

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

- There was no significant differece in the activations for the contrast Congruent vs Incongruent (Fig.3.A).
- For the other 2 contrasts a significant activation cluster was formed in the right hemisphere contralateral to the stimulus direction (Fig.3.B&C)..

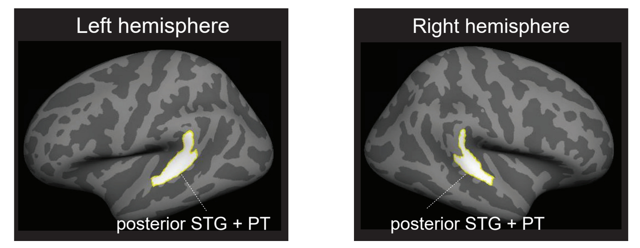

Fig.4 Hypothesis-based region-of-interest (ROI) STG + PT

fMRI MVPA – Split-half correlation analysis in STG + PT ROI (Fig. 4 & 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 e.g., [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 conditions (mean ± SD), t-tests one-tailed:

Congruent vs. Incongruent:

- Left hemisphere: 0.007 ± 0.029 (not signif.),
- **Right hemisphere: 0.017 ± 0.027 , t_{12}=2.225, p=0.023*,**
- **Combined hemispheres: 0.013 ± 0.022, t_{12}=2.198, p=0.024*.**

Congruent vs. ILD-only

- **Left hemisphere: 0.028 ± 0.044, t_{12}=2.254, p=0.021*,**
- Right hemisphere: 0.011 ± 0.044 (not signif.),
- **Combined hemispheres: 0.020 ± 0.036, t_{12}=2.007, p=0.033*.**

Incongruent vs. ILD-only :

- Left hemisphere: -0.011 ± 0.047, (not signif).
- Right hemisphere: -0.000 ± 0.036, (not signif).
- Combined hemispheres: -0.005 ± 0.039 (not signif).

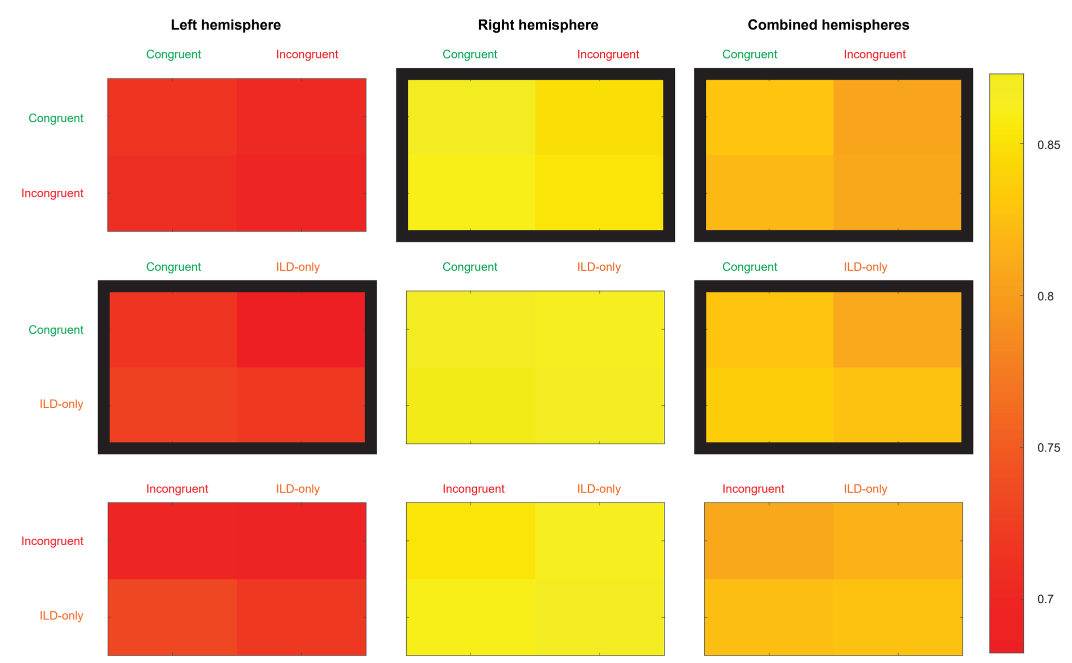

Fig.5 Average split-half correlation across subjects for the different contrast (n= 13). Black outline indicates contrasts with significant correlation differences.

Conclusions & Discussion

Behavioral results:

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

Imaging results:

- Suggests that the auditory cortex ROI encompassing the PT and STG encodes both the DRR distance cue and the distance percepts.
- While the cue encoding is non-distributed, detectable by univariate analysis, the percepts are encoded in a distributed network detectable only by multivariate analysis.
- **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.**
- **The nature of distributed representation of percpets and the form of cue-percept overlap needs further investigation.**

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