Discovering the perceptual space of natural sounds from similarity judgments

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Introduction

- Understanding multidimensional mental representations has been a longstanding challenge in perceptual & cognitive science
- We explored whether representations derived from machine learning could account for human similarity judgments in the domain of audition
- We collected a dataset of human similarity judgments for sound textures and asked:
  1. **How well can representations from contemporary auditory models predict these human judgments?**
  2. **How many dimensions are needed to account for this perceptual space?**

Sound similarity experiment

- Triplet odd-one-out task (Hebart et al. 2020)
- On each trial, participants (N=213) listened to three sounds and chose the odd-one-out
- Implicitly indicates which pair of sounds was the most similar within the triplet
- Stimuli: 1,080 unique two-second excerpts of natural sound textures drawn from YouTube soundtracks (AudioSet)
- We collected judgments for 38,332 triplets

Noise ceiling

- We collected judgments from 20 participants for 180 randomly chosen triplets
- Measured average consistency of choices for each triplet across participants, yielding a noise ceiling of 68.47%
- Provides an upper bound on best possible performance achievable by any model given the variability across participants

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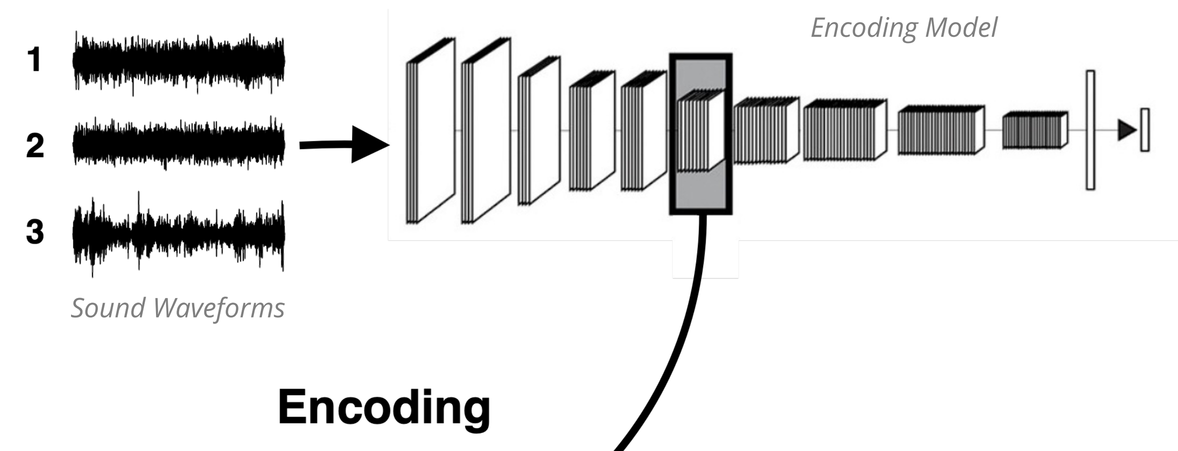
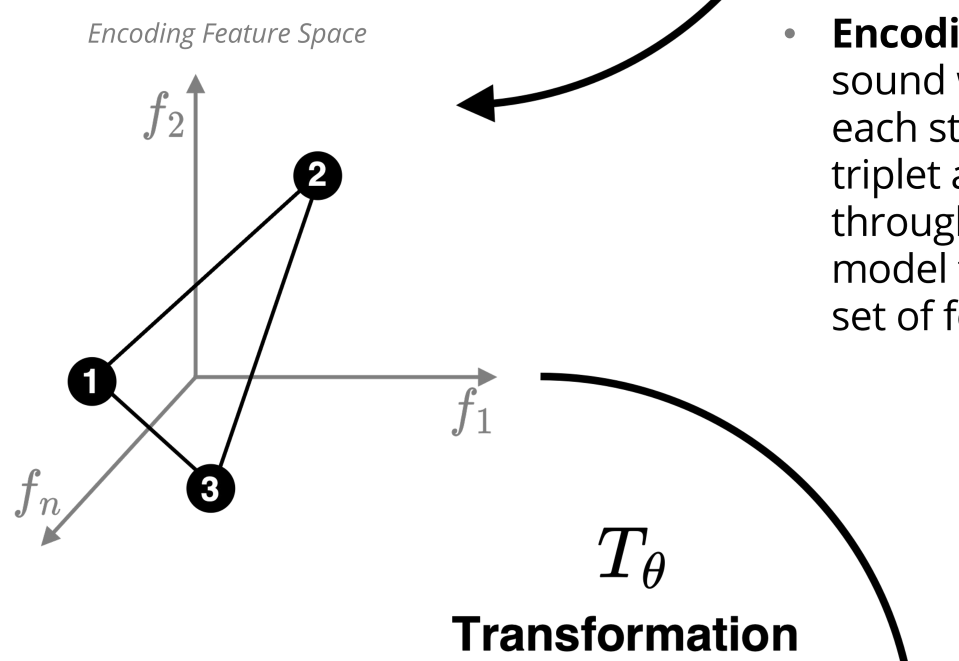
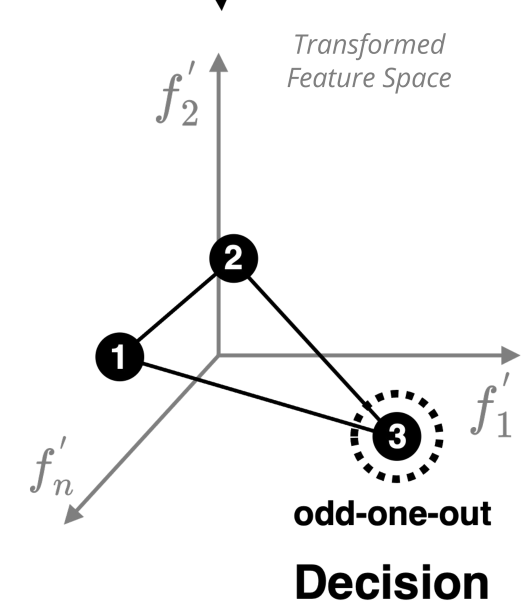
Similarity modeling framework



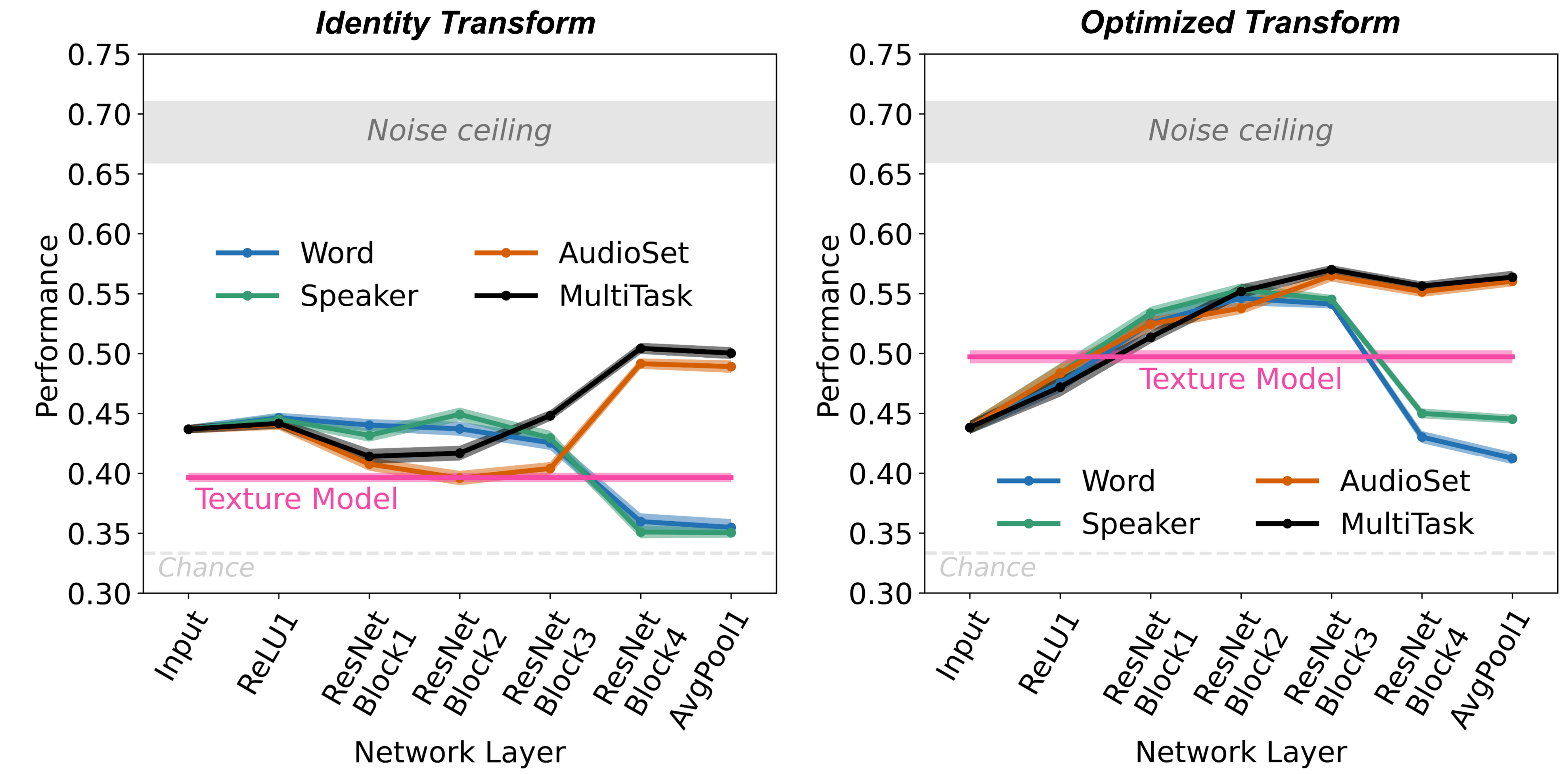


- **Encoding** stage: the sound waveforms for each stimulus within a triplet are passed through an encoding model to generate a set of feature vectors
- **Transformation** stage: feature vectors from the encoding stage are transformed into a new feature space where the odd-one-out decision can be made
- **Decision** stage: the distance between all pairs of stimuli within a triplet is computed in the transformed feature space and the odd-one-out is selected as the stimulus not contained in the minimum-distance pair



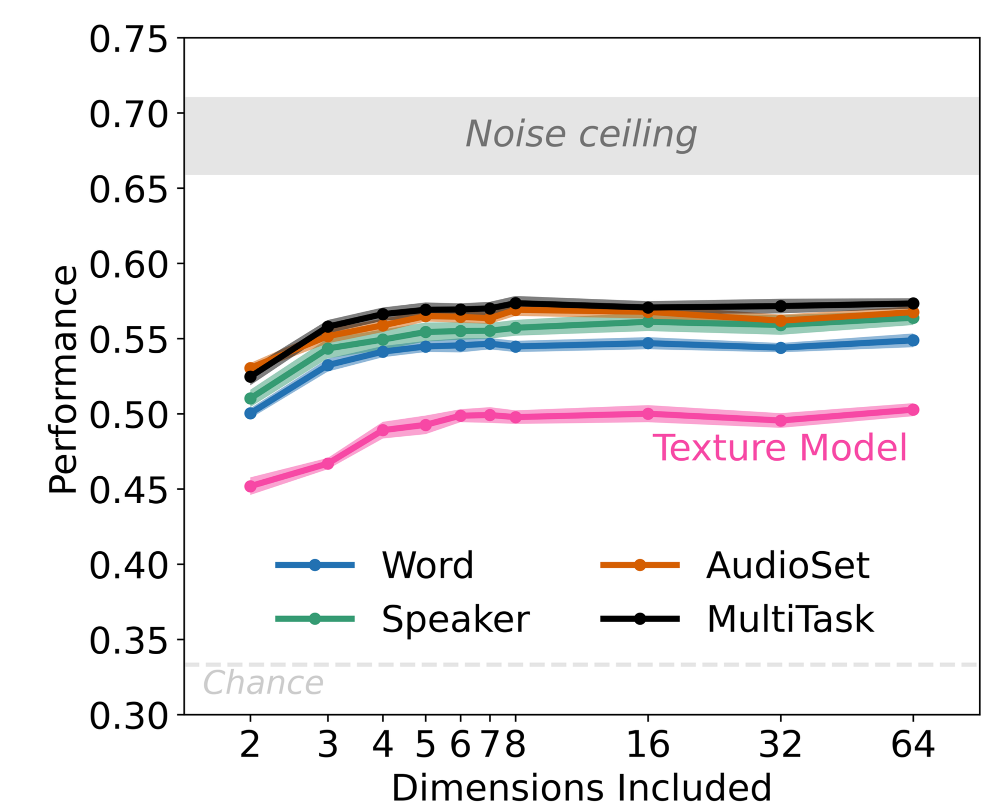
Model performance

- Learned linear transformations were critical to predicting judgments on held-out sounds:
  - an identity transform yielded average performance of 43%
  - the learned transforms yielded performance of 51%, averaged across all stages of all models
- The best-performing stages of the trained neural networks also substantially outperformed the texture model
- Strong dependence on task neural networks were trained on: late stages of models trained to recognize words and speakers produced worse predictions than late stages of models trained on the AudioSet environmental sound recognition task
  - Plausibly explained by these tasks requiring model to be invariant to background noise, perhaps by throwing out information related to textures
- Sizeable gap remained between the best model performance and the noise ceiling



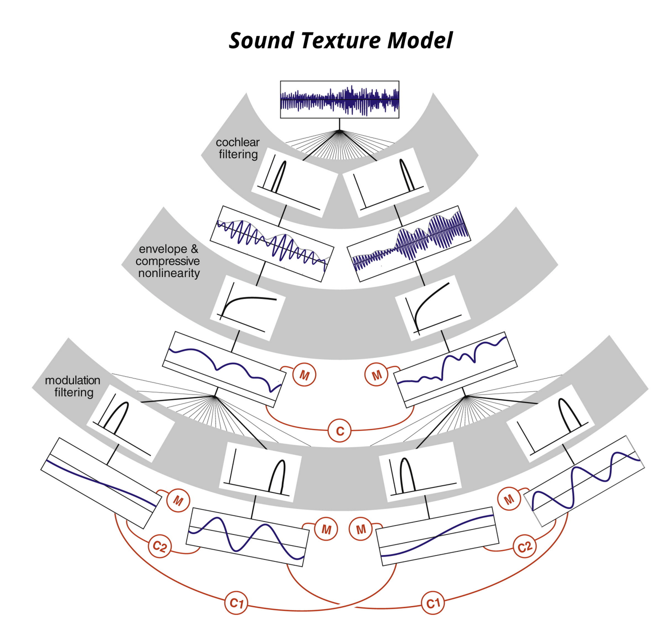
Low-dimensional projections

- For each model, we used the representation from the best-performing stage and learned a linear projection to a low-dimensional feature space, varying the number of dimensions included
- All models reached their peak performance with a surprisingly low number of dimensions
- This result is surprising since many dimensions are needed to synthesize perceptually realistic textures (Feather & McDermott 2018)
- Raises the possibility that similarity judgments tap into a representation that is impoverished relative to that used for discrimination tasks or realism judgments

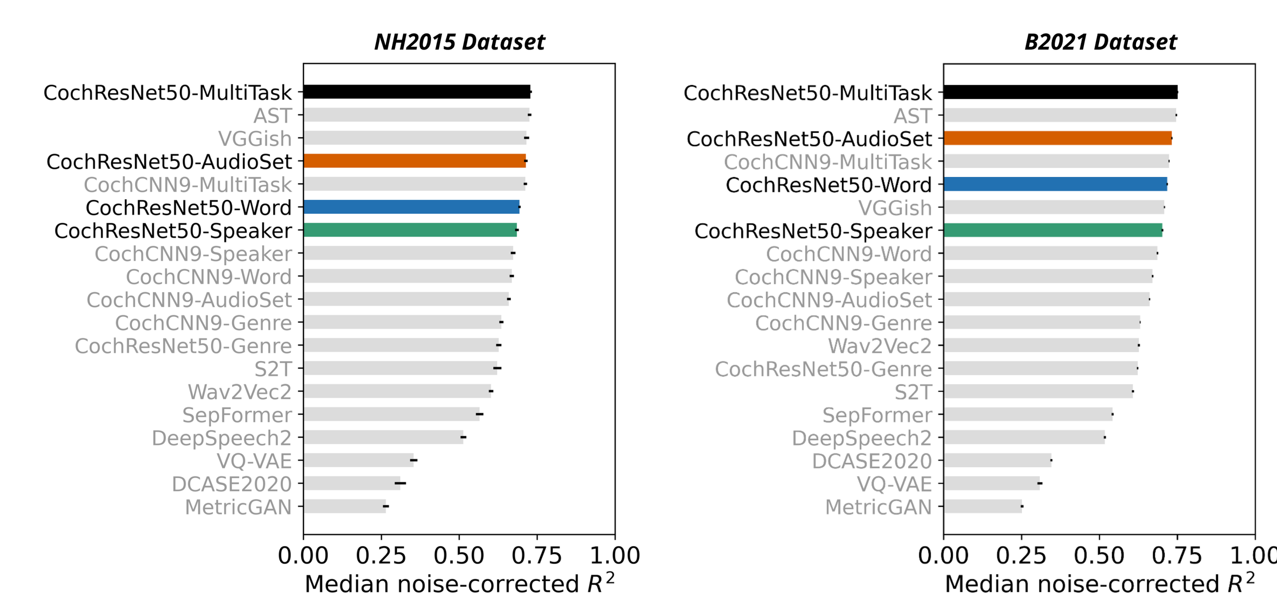


Encoding models

- We evaluated representations from two distinct classes of encoding models:
  1. standard sound ***texture model*** (McDermott & Simoncelli 2011)
  2. convolutional neural network models previously shown to effectively predict neural responses to natural sounds (Tuckute et al. 2023)
- Networks were trained to perform either word recognition ("***Word***"), speaker identification ("***Speaker***"), or background sound recognition ("***AudioSet***") tasks individually, or to perform all three tasks simultaneously ("***MultiTask***")
- We found little effect of network architecture and thus present results for a single ResNet50 architecture with a cochleagram front end ("CochResNet50")



McDermott & Simoncelli 2011



Adapted from Tuckute et al. 2023

Conclusions

- We collected similarity judgments for natural sounds and assessed how well representations from auditory models could predict these judgments
- Linear transformations of model representations substantially improved performance, but a sizeable gap remained between the best model's performance and the noise ceiling, indicating that current models fail to fully capture human sound similarity
- Peak model performance could be achieved with surprisingly low-dimensional representations
- Future work is needed to understand what aspects of perception these dimensions capture and what additional dimensions must be added to improve human-model alignment and close the gap with the noise ceiling