Learning the Neural Organization of Speech Perception from Behavioral Responses: A Deep Learning Approach

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Abstract

Categorical perception (CP) is a neural process of detecting phonetic categories in sound.

and is measured using response time (RT). The cognitive processes involved in mapping neural activities to behavioral response are stochastic and further compounded by individuality and variations. This thesis presents a data-driven approach and develops parameter optimized models to understand the relationship between cognitive events and behavioral response (e.g., RT). We introduce convolutional neural networks (CNN) to learn the representation from EEG recordings. In addition, we develop parameter optimized and interpretable models in decoding CP using two representations: 1) spatial-spectral topomaps and 2) evoked response potentials (ERP). We adopt state-of-the-art class discriminative visualization (GradCAM) tools to gain insights (as oppose to theblack box models) and building interpretable models. In addition, we develop a diverse set of models to account for the stochasticity and individual variations. We adopted weighted saliency scores of all models to quantify the learned representations effectiveness and utility in decoding CP manifested through behavioral response. Empirical analysis reveals that the γ band and early ($\sim 0-200ms$) and late ($\sim 300-500ms$) right hemisphere IFG engagement is critical in determining individuals RT. Our observations are consistent with prior findings, further validating the efficacy of our data-driven approach and optimized interpretable models.

1. Introduction

Categorical perception (CP) of speech is a cogntive process of grouping sounds into small phonetic categories (**?**). CP of speech is a complex process reflecting individuals' ability to perceive sound and can be measured using response time (RT). The cognitive processes involved in mapping neural activities to behavioral responses can be decoded through in-depth analysis of neurophysiological recordings such as EEG. Decoding categorical perception (CP) from EEG recordings involves analyzing spatial-spectral-temporal properties that define the underlying cognitive functions (**???**)]. The spatial, spectral, and temporal aspects explain *'where'* in the brain, the type of operation (i.e., memory, attention) and *'when'* in time the neural activities occurs.

While hypothesis-driven analysis is being widely used in decoding CP, but the multivariate approach based on machine learning (ML) algorithms have been gaining momentum. For example, the ML-based approach reported in (**??**) show promising results in determining contributing factors in age-related hearing loss. In another work reported in (**?**) used an ML-based apporach to decode functional connectivity patterns in CP. The mentioned studies uses classical ML, such as support vector machines (SVM) [(**?**)] with stability selections [(**?**)] to model cognitive processes involved in CP. The feature selection process provides a limited interpretation of the causal relationship between neural activities and behavioral responses.

This thesis presents a data-driven approach and develops parameter optimized models to understand the relationship between cognitive events and behavioral responses (e.g., RT). We introduce convolutional neural networks (CNN) to learn the relevant features from EEG recordings using two representations: 1) spatial-spectral topomaps and 2) Event Related Potentials (ERP) to model the spatial-spectral and temporal properties of CP. In addition, we develop a diverse set of deep CNN models to account for the stochasticity and individual variations. We have used bootstrap averaging of trials to generate ERPs in both spatial-spectral and temporal data generation. We utilize bootstrapping process as a data augmentation step to generate a larger number of samples to improve the generalization of CNN models. We

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use Bayesian hyperparameter optimization algorithm Tree-structured Parzen Estimator (TPE) [(**?**)] to find best performing spatial-spectral and temporal CNN models, respectively. We have selected ten best performing spatial-spectral and temporal CNNs separately to analyze behavioral responses in relation to CP.

In deep learning (DL), model interpretation is still a challenge as these models contain millions of parameters and therefore are extremely difficult to interpret. Convolution Neural Networks (CNNs) are the only models in the DL arena, where insight into feature importance allocations is possible. The visual interpretation of models are achieved through class discriminative feature visualization techniques like Class Activation Maps [(**?**)], GradCAM [(**?**)], CNN-fixation [(**?**)] and EigenCAM [(**?**)]. Studies like (**???**) shows that GradCAM does capture feature importance allocation by CNNs from data and therefore could be used to infer spatial-spectral-temporal properties underlying a cognitive event. Despite the successes in visual interpretation, it begs the question *"Are class discriminative feature visualizations alone enough to capture patterns dictating cognitive events from EEG data?"* To address this, we propose quantification of learned spatial-spectral-temporal representation from EEG data by CNN models.

We argue that consistent patterns over multiple models could be considered the neural correlates of CP. To this extent, we have proposed the computation of overall saliency score that allows us to find the prevalent spatial-spectral-temporal patterns consistent over multiple CNN models. We have defined two processes to compute overall saliency scores, 1) averaging of saliency scores across models 2) performance weighted averaging of saliency scores across models. To understand the efficacy of CNN models, we performed mixed model ANOVA analysis on the saliency scores to determine the spatial-spectral-temporal differences in neurological actions that define the RT groups.

We empirically evaluate the CNN models using the CP data obtained from 50 participants. First, we cluster the RTs using Gaussian Mixture Model (GMM). We modeled spatial-spectral-temporal attributes of the neural activities defining three categories of RT (slow, medium, and fast) from EEG data. Employing the proposed process, we observe that early and late engagement in right-hemispheric frontal regions (presumably IFG) is crucial in determining listeners' decision speed. We also find that all three bands (α, β, γ) have active and passive roles while γ band is the most significant in driving listeners' RT. The significance of γ band suggests that auditory CP ability in individuals is the primary predictor of their decision speed. Our findings are coherent with recent and prior studies of brain-behavior function in auditory CP, a validation of our decoding process using CNNs.

The rest of the thesis is organized as follows: in chapter 2, we review existing decoding processes from EEG data using CNNs and the use of machine learning algorithms in decoding auditory CP. Chapter 3 provides a detailed description of our proposed modeling and decoding process, and in chapter 4, we present our modeling and decoding results. Finally, in chapter 5, we discuss our approach's novelty and the findings of the cognitive processing of behavioral responses in categorical speech perception.

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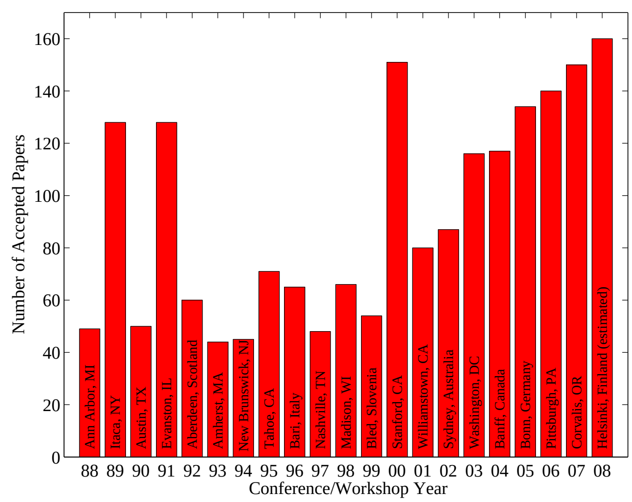

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Algorithm 1 Bubble Sort

Input: data x_i, size m
repeat
  Initialize $noChange = true$.
  for $i = 1$ **to** $m - 1$ **do**
    if $x_i > x_{i+1}$ **then**
      Swap x_i and x_{i+1}
      $noChange = false$
    end if
  end for
until $noChange$ is $true$

Table 1. Classification accuracies for naive Bayes and flexible Bayes on various data sets.

DATA SET	NAIVE	FLEXIBLE	BETTER?
BREAST	95.9± 0.2	96.7± 0.2	√
CLEVELAND	83.3± 0.6	80.0± 0.6	×
GLASS2	61.9± 1.4	83.8± 0.7	√
CREDIT	74.8± 0.5	78.3± 0.6	
HORSE	73.3± 0.9	69.7± 1.0	×
META	67.1± 0.6	76.5± 0.5	√
PIMA	75.1± 0.6	73.9± 0.5	
VEHICLE	44.9± 0.6	61.5± 0.4	√

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