Neural Pathways of Vocal Pitch Modulation: An ongoing fMRI Study

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ABSTRACT ***Humans' ability to voluntarily control pitch*** *is central to language function. This research investigates the neural mechanisms of vocal pitch control using* ***functional MRI****, focusing on two experimental approaches. The first examines neural circuits involved in* ***pitch modulation*** *during* ***speech repetition tasks,*** *comparing full speech rehearsal to* ***humming prosodic patterns****. The second aims to differentiate* ***pitch-specific pathways*** *from general speech networks by analyzing neural responses to speech repetition under* ***Altered Auditory Feedback*** *(AAF) with perturbations in* ***fundamental frequency*** *(F0) and the* ***first formant*** *(F1). Early findings suggest the existence of* ***two anatomically distinct pathways*** *in the* ***premotor cortex****: one pitch-related and the other articulation-related. These insights have implications for understanding vocal pitch in communication and potential clinical interventions.*

Introduction

Pitch plays an essential role in communication

Not only for **conveying information** but also for expressing **emotions** and **social signals**. It is also extensively used in **singing** (musical expression).

Recent studies emphasize that **pitch and prosody** are deeply integrated with **syntax, semantics, phonological rhythm,** and **pragmatic meaning**.

Humans show a unique ability to control pitch

Humans exhibit an **unparalleled capacity** for controlling pitch, which may have links to the **evolution of language and singing** (Fitch, 2016).

While nonhuman primates possess vocal tracts capable of producing a wide range of sounds (Boë et al., 2019), they lack the necessary **neural mechanisms** to control these sounds for **speech** (Fitch, 2016).

Hypothesis for two functionally distinct speech coordination areas in premotor cortex

Dichter et al. (2018) showed that bilateral **dorsal laryngeal motor cortex** (dLMC) selectively encode **produced pitch** but not non-laryngeal articulatory movements by high-density intracranial recordings.

Hickok et al. (2022) proposed **two distinct regions** in the **precentral gyrus** (main motivation of this research):

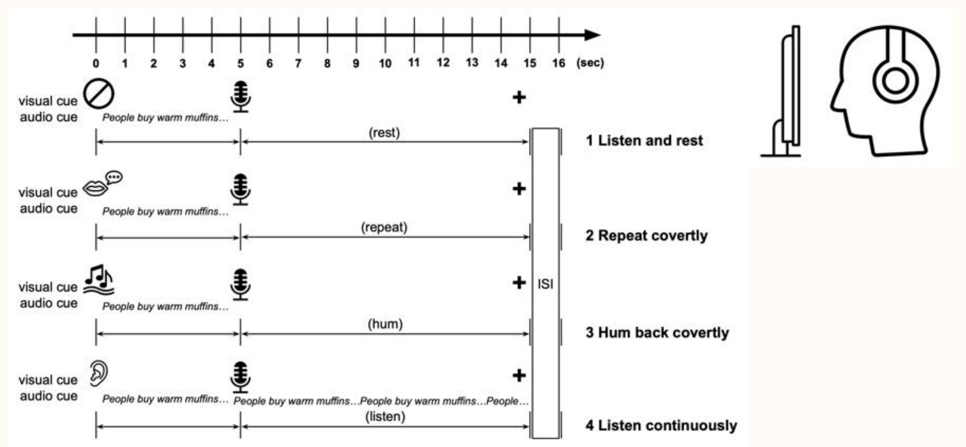
dorsal precentral speech coordination area (**dPCSA**)	**ventral** precentral speech coordination area (**vPCSA**)
auditory-weighted sensorimotor control	**somatosensory**-weighted sensorimotor control
prosodic, pitch-related, laryngeal effector	**syllabic, phonetic**-related, supralaryngeal effector

RQ: Are there distinct neural pathways for pitch modulation vs supralaryngeal articulation? Can we differentiate them?

Experiment 1
Repetition of Prosodic Patterns

TL;DR You listen to sentences and either **repeat** them or **hum** their prosodic patterns in the scanner. This will allow us to break down the **auditory-motor network** into distinct sub-networks for **pitch control** and (supralaryngeal) **articulatory movements**.

Paradigm



Each run = 25 trials (1 dummy + 3 cond × 8 trials) = 7 min. → Each session = 8 runs = 1 hr.

Each session has 64 trials per condition (**Blocked**)

Stimuli

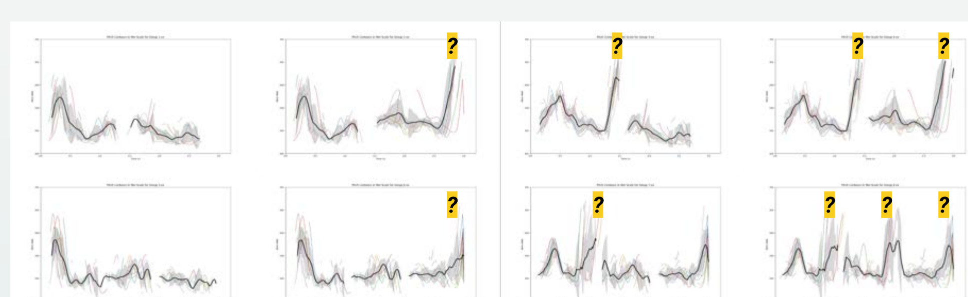
64 Machine-generated **sentence-level** speech sounds of 3–3.5 s duration with **maximized prosodic variability & phonetic variability**

Labial	*People buy warm muffins, after morning meetings.*
Coronal	*Teachers instruct subjects, through engaging lessons.*
Dorsal	*Kangaroos carry young, hopping across grasslands.*
Nasal	*Mountain meets horizon, in misty morning light.*
Stop	*Octopus attacked ships, during big ship attack.*
Fricative	*Fossil features findings, beneath the surface earth.*
Lateral	*Uncle helped little girl, telling lovely stories.*
Rhotic	*Mirror reflects bright light, under rare auroras.*

Analyzed with **eng-to-ipa panphon** & **Praat**

Pattern 1	*People buy warm muffins, after morning meetings.*
Pattern 2	*People buy warm muffins, after morning meetings?*
Pattern 3	*People buy warm muffins? after morning meetings.*
Pattern 4	*People buy warm muffins? after morning meetings?*
Pattern 5	*Baby makes mess, with messy hands, in warm bedroom.*
Pattern 6	*Baby makes mess, with messy hands, in warm bedroom?*
Pattern 7	*Baby makes mess? with messy hands, in warm bedroom?*
Pattern 8	*Baby makes mess? with messy hands? in warm bedroom?*

Written with **GPT-4o** Text-to-Speech by **Google TTS**



Data Analysis

Auditory-motor network is identified by the conjunction of **[listen > repeat]** and **[repeat > rest]**

Pre-processing (fmriprep) / GLM (AFNI)

To do: **Representational Similarity Analysis** (RSA)

Expected Outcomes

Repetition Pathway: **vPCSA + dPCSA**
Humming Pathway: **only dPCSA**

Prosodic variability correlates with the **dPCSA**
Phonetic variability correlates with the **vPCSA**

within-subject comparison

Experiment 2
Altered Auditory Feedback: F0 vs F1

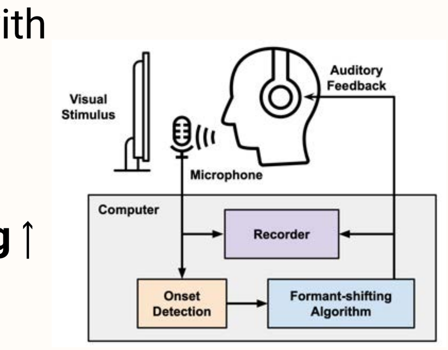
TL;DR While reading words on a screen, your voice is **altered in real time**, with either **pitch** (F0) or **vowel quality** (F1) manipulated and **fed back to your ears**. This will help us find the regions responsible for **pitch control** (source) and **vowel production** (filter).

Experimental Setup

MR-safe audio equipment with active **noise-cancellation** system (Optoacoustics)

EPI sequence modified to reduce noise: **Echo Spacing** ↑ (final noise level ≈ 65 dB)

Pitch/Formant-shifting algorithm ***Audapter*** (Cai et al., 2008; Tourville et al., 2013)



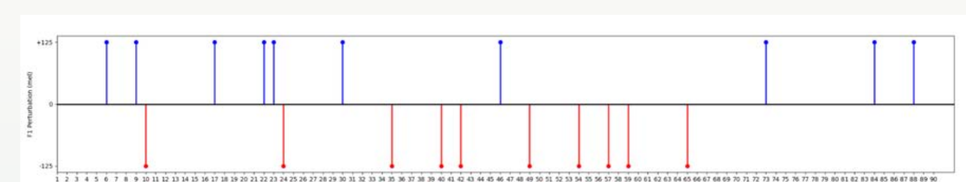
Paradigm

Following Niziolek (2021) F1 AAF Paradigm

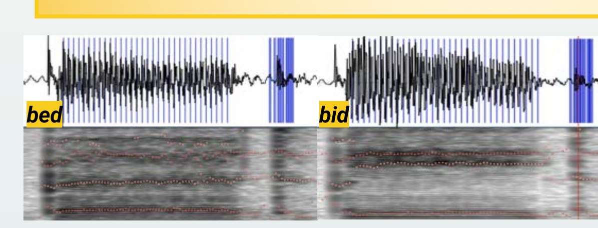
Visual stimuli: 3 English words -ɛd: *bed, dead, head*

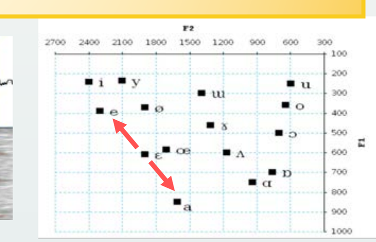
F0 perturbation ±6% / **F1 perturbation** 125 mel (45°)
⅙ up-shift + ⅙ down-shift + ⅔ control
total 90 trials per run (= 6 min) / total 8 runs
(**Rapid jittered event-related design**)

Visual feedback (colored dots) indicating whether vowel duration was too short, enough, or too long



A **formant** is a peak in the speech frequency spectrum, representing **resonant frequencies** in the vocal tract. Shifting F1 can change **vowel perception**; for example, shifting F1 up in ***bed*** /bɛd/ makes it sound like ***bad*** /bæd/, and shifting it down makes it sound like ***bid*** /bɪd/.





Data Analysis

Behavioral data to be first analyzed to confirm the **compensation** phenomena under AAF of F0 and F1

ROI to be localized using GLM (AFNI)

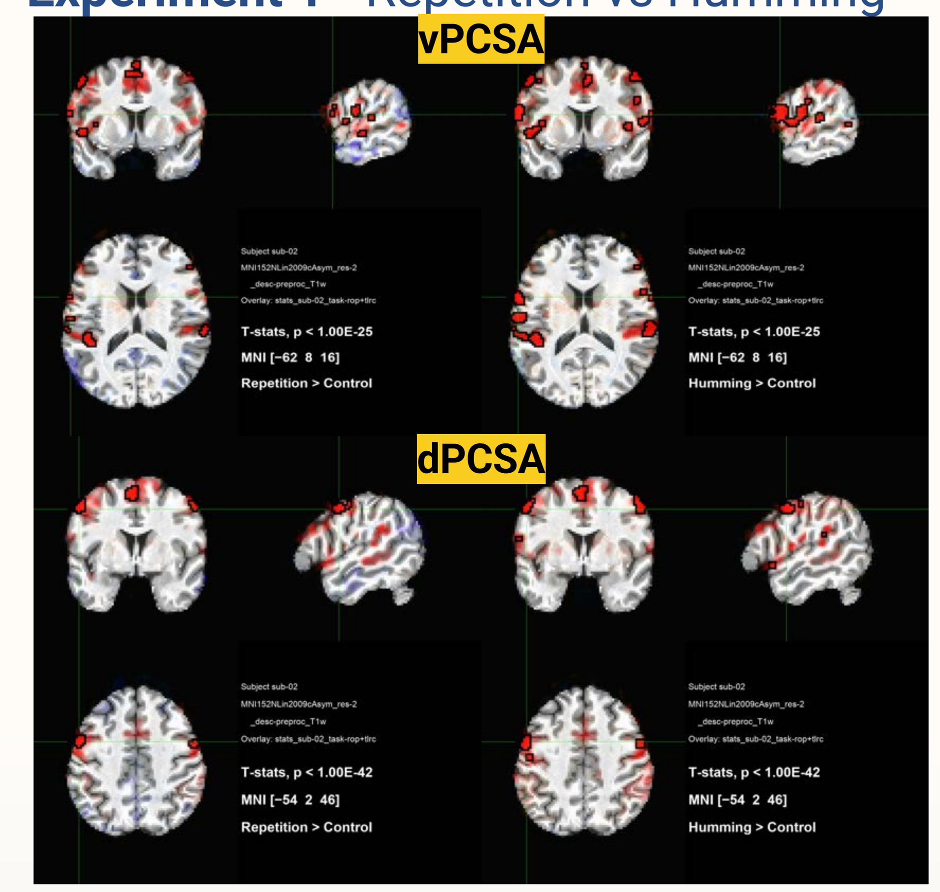
Expected Outcomes

F0 shift preferentially activate the **dPCSA** region
F1 shift preferentially activate the **vPCSA** region

Using the **same participant pool** for both experiments will enable a **within-subject comparison**, which strengthens our claims regarding the functional roles of these regions.

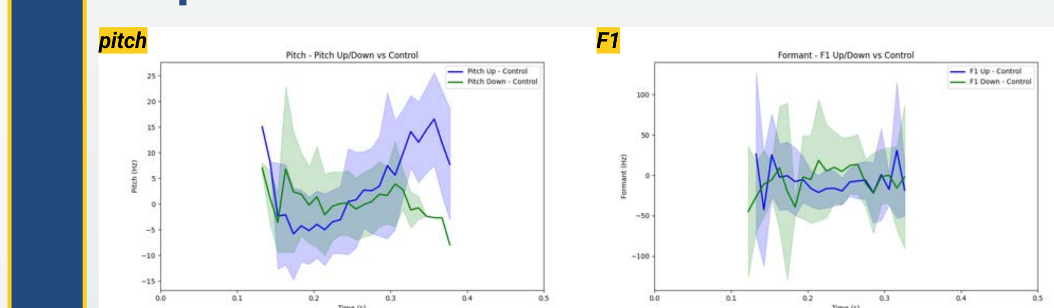
Results

Experiment 1 Repetition vs Humming



- **Localized** the regions we believe correspond to the **vPCSA** and **dPCSA**. (Individual level)
- The **humming condition** showed **stronger activation** in the **vPCSA**. (⊥ Our hypothesis)
- **Little to no difference** observed in the **dPCSA**.

Experiment 2 AAF F0 vs F1



- The **behavioral data is insufficient** to confirm a replicable **compensatory response** at this stage.

Next Steps

- Revise Experiment 1 to **reduce the vPCSA load** during the **humming condition**.
- Collect **more behavioral data** and further fine-tune the Experiment 2 paradigm.

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