Towards Radar-Driven Speech Therapy: Multimodal Training with Ultrasound, Audio, and Radar for Unimodal Phonetic Segment Classification

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Introduction

- Phonetic segment classification (consonants such as /k/, /g/, /t/, /d/, /s/, /z/ or vowels such as /a/, /e/, /i/, /o/) is essential for speech therapy and linguistics.
- Audio-only models fail in noisy conditions and with similar phonemes.
- Ultrasound Tongue Imaging (UTI) provides articulatory detail but is costly and impractical.
- mmWave radar enables contactless, privacy-preserving sensing of articulators and vocal-fold vibrations.
- USRadioAI: trains with audio + UTI + radar, but deploys radar-only at inference.

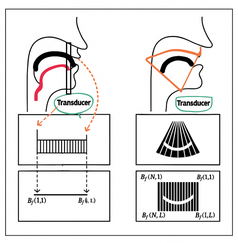
Problem Definition & Objectives

Research Question

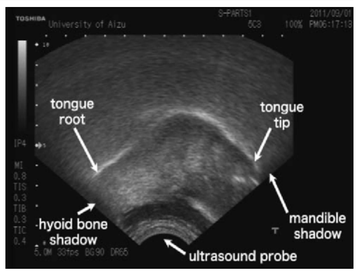
Can radar alone support reliable speech analysis, while leveraging multimodal supervision during training?

- **Assess** UTI and radar classification power independently
- **Train** unimodal vs. multimodal deep learning models
- **Develop** a **radar-only inference** system guided by multimodal knowledge

Preliminary Studies: Ultrasound Tongue Imaging



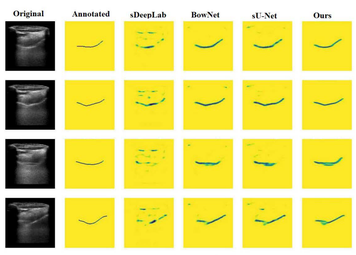
(a) Tongue imaging setup



(b) Example UTI frame

Akgul et al., 2000

Preliminary Studies: UTI in Speech Processing



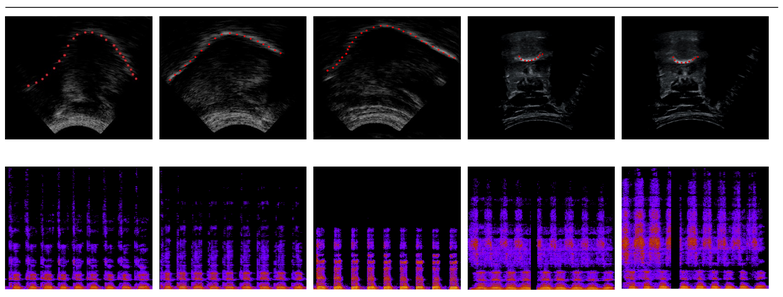
(a) Tongue contour extraction (ours)

(b) Lip + UTI fusion

- **Tongue contours** provide direct articulatory motion cues
- **Lip–UTI fusion** integrates external + internal articulators
- Demonstrates UTI's role in detailed phonetic representation

Ribeiro et al., 2021

Preliminary: Audio + Ultrasound Tongue Imaging



- **Joint UTI + Audio training (MMNet)** achieves 91% accuracy, outperforming unimodal baselines.
- **Audio-only inference (M1)** reaches 81% accuracy, enabling practical, device-free deployment without UTI.

Aytutuldu et al., 2024

References

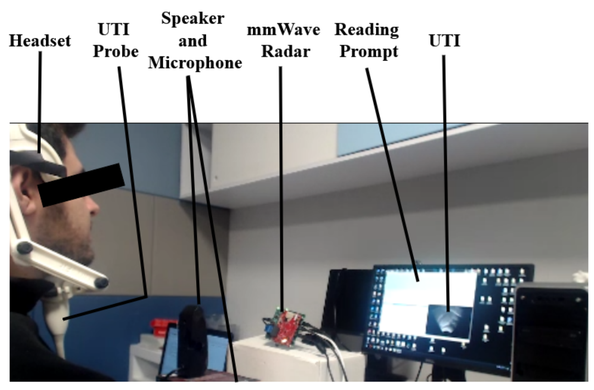
[1] Y.S. Akgul, C. Kambhamettu, and M. Stone. A task-specific contour tracker for ultrasound. In *Proceedings IEEE Workshop on Mathematical Methods in Biomedical Image Analysis. MMBIA-2000 (Cat. No.PR00737)*, pages 135–142, 2000.

[2] Ilhan Aytutuldu, Yakup Genc, and Yusuf Sinan Akgul. Audio-only phonetic segment classification using embeddings learned from audio and ultrasound tongue imaging data. *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, 2024.

[3] Ribeiro M., Eshky Aciel, Richmond Korin, and Renals S. Speaker-independent Classification of Phonetic Segments from Raw Ultrasound in Child Speech. *IEEE International Conference on Acoustics, Speech, and Signal Processing*, 2019.

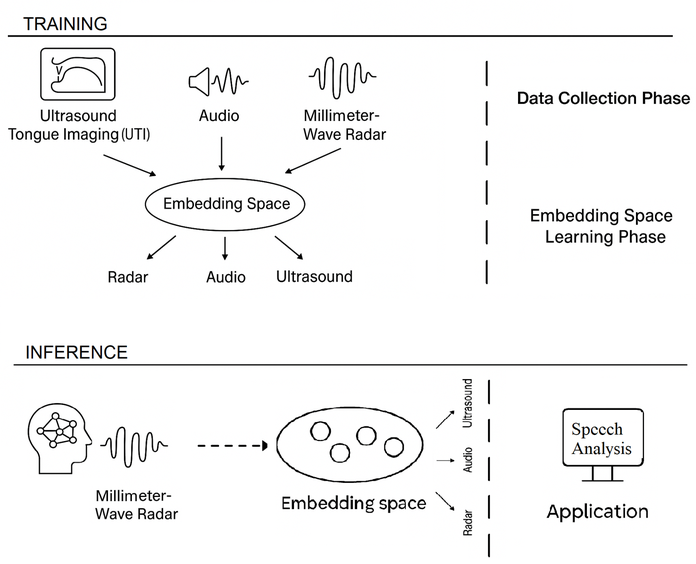
Dataset & Acquisition

- **Participants:** Six native speakers (2F / 4M), ages 18–65
- **Speech Material:** 2,400 utterances of four consonants (/d/, /g/, /k/, /t/)
- **Sensing Modalities:**
  - TI IWR1843 **mmWave radar**
  - Shure Beta 58A **microphone** (48 kHz)
  - **Ultrasound Tongue Imaging (UTI)** device
- **Synchronization:** Achieved via audible ping



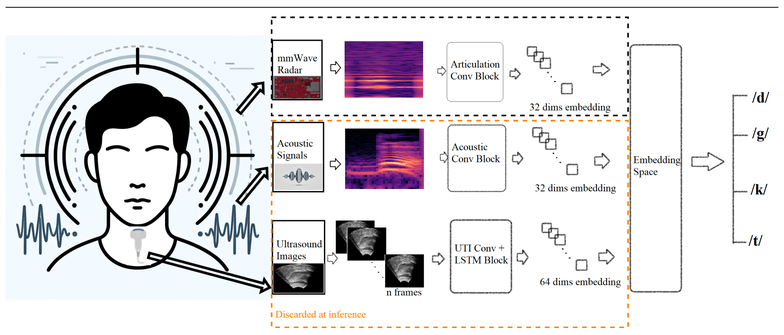
Experimental data collection setup

System Schema



- **Input:** Audio, UTI, and radar signals
- **Training:** Multimodal learning across all three
- **Inference:** Radar-only operation for practicality

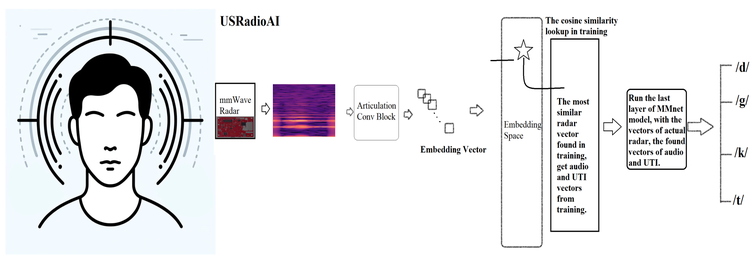
Multimodal Architecture Overview



- Parallel networks process UTI, audio, and radar
- Shared embedding aligns articulatory and acoustic cues
- Enables robust phonetic classification

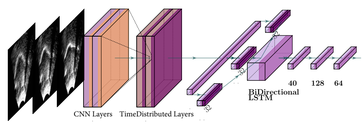
Radar-Only Inference

- **Input:** Radar signals processed into embeddings
- **Comparison:** Radar embeddings are matched against **multimodal reference embeddings** using cosine similarity
- **Advantages:** Lightweight, device-free, and privacy-preserving speech analysis

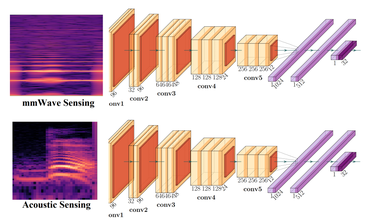


Joint Embedding (MMnet)

- **Two sub-networks** project into a shared embedding space:
  - (a) **UTI:** Spatio-temporal CNN + BiLSTM → 64-D embedding
  - (b) **Radar/Audio:** CNN stacks on spectrograms → 32-D embedding
- **Training:** All modalities are aligned in a common embedding space
- **Inference:** Radar-only, guided by multimodal supervision

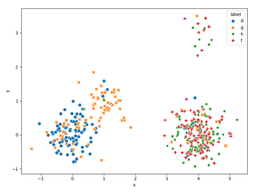


(a) UTI subnetwork

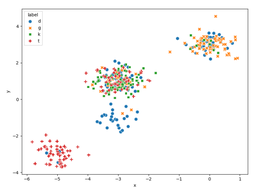


(b) Radar/Audio subnetwork

Unimodal Results: Radar vs. Audio



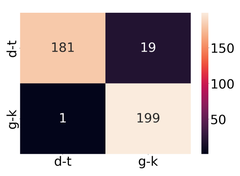
Radar: Strong in **voiced** sounds (/d/, /g/)

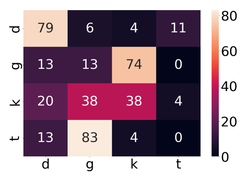


Audio: Strong in **voiceless** sounds (/t/, /k/)

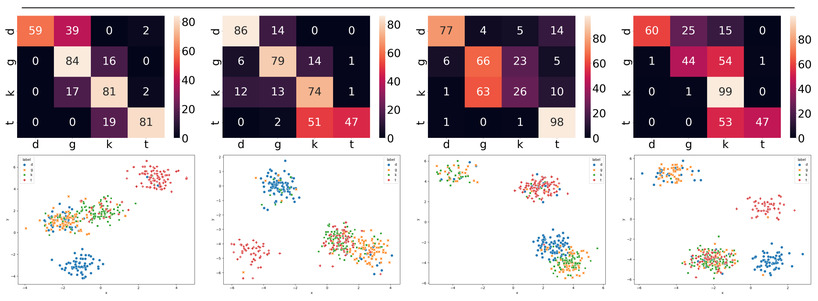
Unimodal Results: UTI

- UTI-only classification
- **2-class:** Velar (/k/, /g/) vs. Alveolar (/t/, /d/) → clear separation
- **4-class:** Harder to distinguish similar tongue positions





Multimodal Fusion Performance



MMNet USRadioAI Audio+UTI Radar+UTI

Test Accuracy	Model	Training			Inference		
		UTI	Audio	mmWave	UTI	Audio	mmWave
0.33	US	+			+		
0.57	Radar			+			+
0.58	Audio		+			+	
0.60	RadioAudio		+	+		+	+
0.62	RadioUS	+		+	+		+
0.67	AudioUS	+	+		+	+	
0.71	USRadioAI	+	+	+			+
0.76	MMnet	+	+	+	+	+	+

Conclusion and Future Work

MMNet vs. USRadioAI

- **MMNet:** 76% accuracy (UTI + Audio + Radar) → highest performance, but low practicality
- **USRadioAI:** 71% accuracy (radar-only inference) → practical, cost-effective, easy deployment
- Tradeoff: small accuracy drop ↔ major usability gain

Future Work

- Clinical validation on speaker-dependent & pathological speech
- Extend to paralinguistic tasks (emotion, prosody, fluency)
- **Dual-radar setup:** track face + vocal folds simultaneously

Acknowledgment

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