Age of L2 Onset Modulates Left MTG Specialization for L1 Lexical Tones

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Background

Lexical Intonation

In Mandarin Chinese, four lexical tones are used to convey semantic information:

Tone 1: High pitch and level
Tone 2: Rising from mid- to high-pitch
Tone 3: Falling from mid- to low-pitch and then rising to high-pitch.
Tone 4: Falling from high- to low-pitch

Example: "mā" (ma1) means "mother" while "mǎ" (ma3) means "horse"

Image credit: sinosplice.com
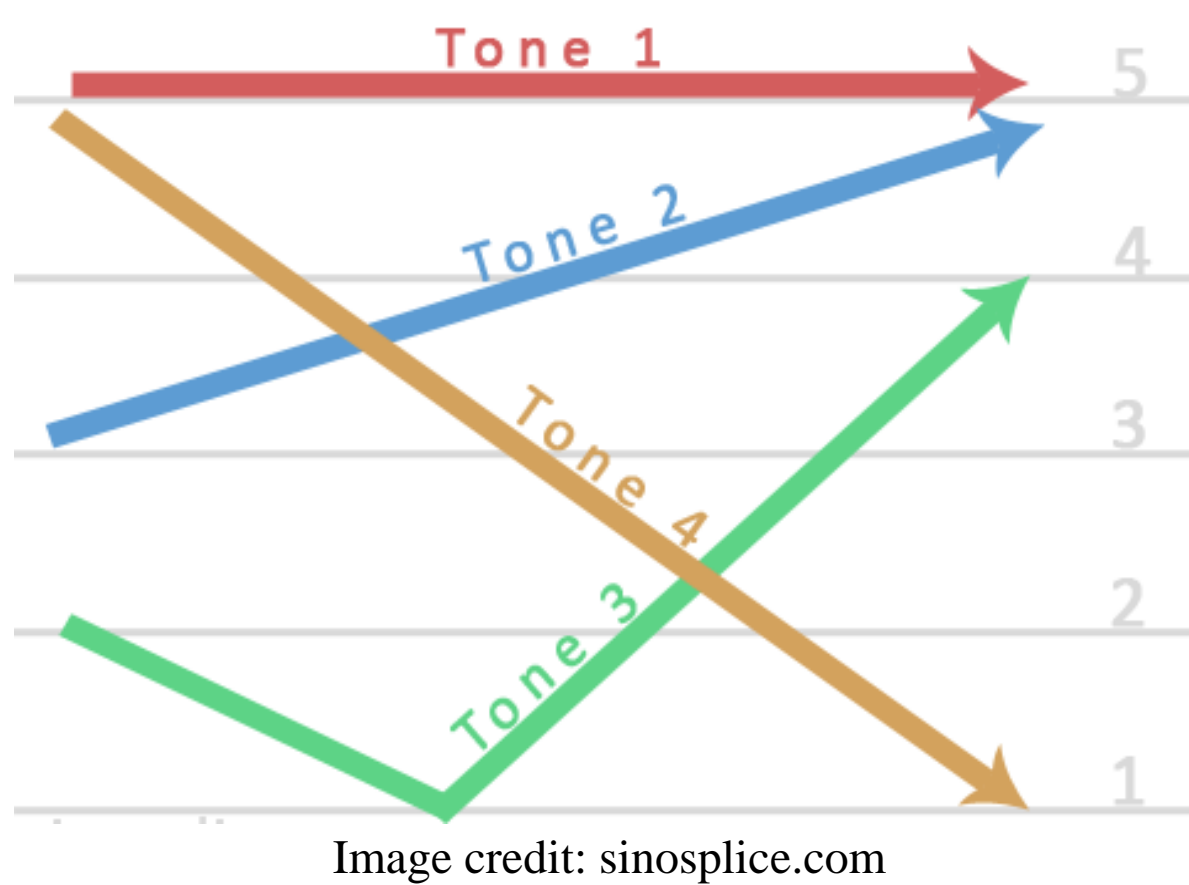
Lexical Tone Categorization

Categorical perception is the ability of humans to perceive continuous changes in a signal as discrete groups.

- Chinese lexical tones are perceived categorically
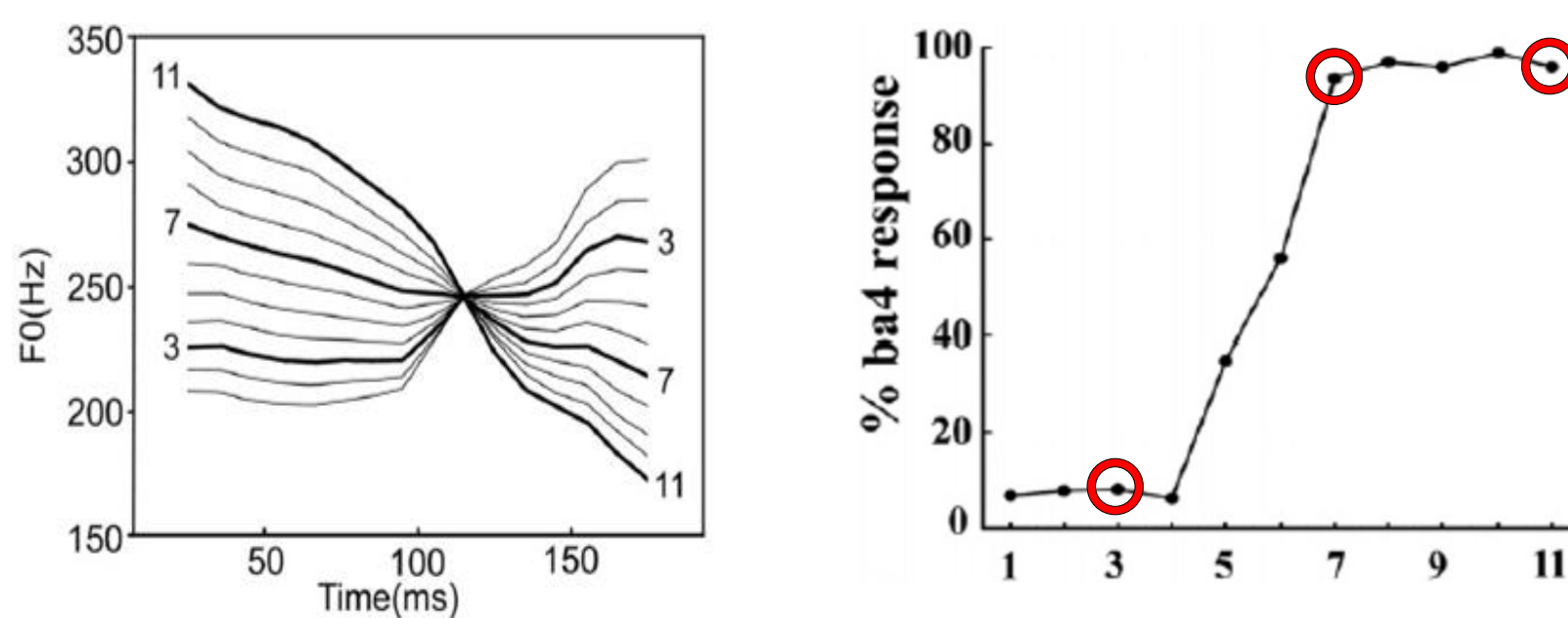- Manipulation of pitch contours can be used to test categorization of Rising and Falling tones.

Figure 1. Tone contours of the continuum from /ba1/ to /ba4/. Contours 3, 7 and 11 are marked with thick lines. doi:10.1371/journal.pone.0020963.g001

graphs: Xi and colleagues (2010)

Lexical Tone Processing

*Tone contrasts that contain **linguistically**-relevant differences are processed differently than contrasts which only differ **acoustically***
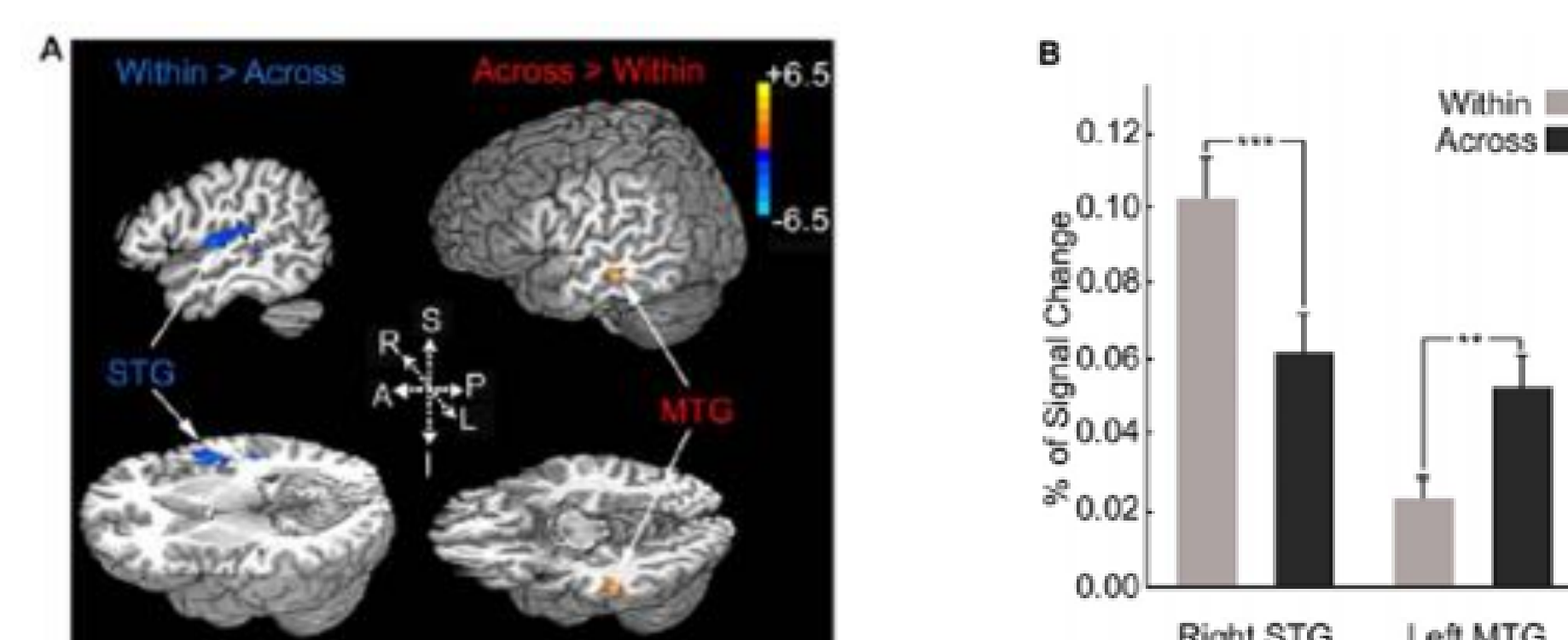
- Mismatch Negativity (MMN) evoked by Standard+Deviant tone contrasts in an oddball task (Xi et al., 2010)
- MMN is lateralized by category relationship (Across or Within)
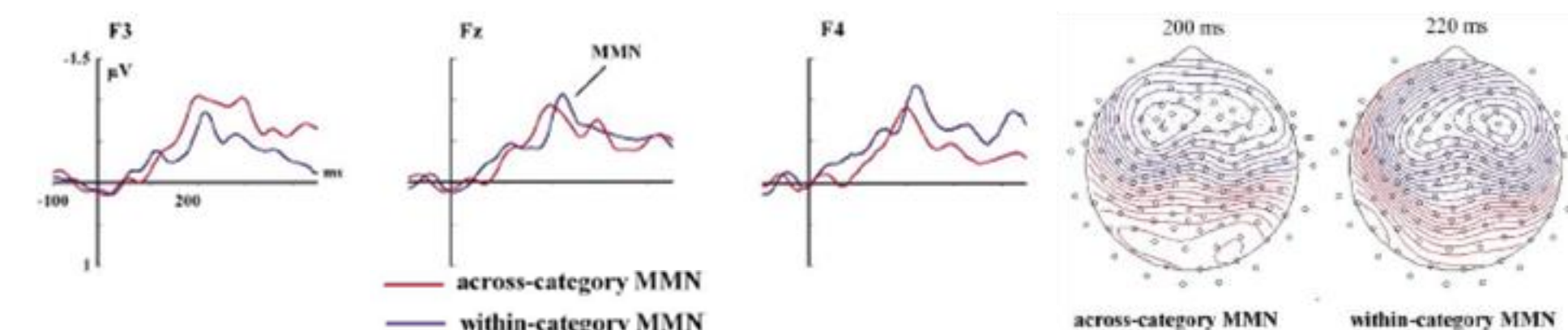
Left-lateralized MMN for Across-category contrasts and right-lateralized for Within-category contrasts. No significant difference in timing.

Same stimuli adapted for fMRI procedure (Zhang et al, 2011):
Dissociation and laterality of Across/Within contrasts confirmed
Localized to left MTG (Across) and right STG (Within)

- Dyslexia is reflected in both behavioral measures and modulation of the MMN (Zhang et al, 2012).

References

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Questions

Can localized effects from linguistically and acoustically-driven processing of lexical tones be observed more economically and less invasively?

- fMRI is expensive, difficult for children, and unsuitable for some patients
- Functional near-infrared spectroscopy (fNIRS) is relatively inexpensive, robust against motion, safe for surgical implants

Are individual differences in normal, native Chinese speakers associated with processing differences for lexical tones?

Methods

Participants: 25 native speakers of Chinese in Beijing, college and graduate students, right-handed
Task: Participants passively listen to a stream of syllables on headphones while watching a silent nature film.

Stream (based on Minagawa-Kawai et al, 2003)**:**
Block types (16 syllables, 20 sec):
- Standard (Tone contour #7)
- Within (50% T7 + 50% T11, random sequence)
- Across (50% T7 + 50% T3, random sequence)

Blocks alternate between Standard and Deviant (Within or Across):
- 10 of each (Standard and Deviant)
- 20 sec rest blocks in between

After 10 Standard blocks and 10 Deviant blocks, Deviant type switches:
- 10 Standard / 10 Within followed by 10 Standard / 10 Across
- Deviant-type order counter-balanced between subjects

Total 26:40 (m:s): 20 Standard, 10 Within, 10 Across, 40 rest blocks

Behavioral Data

Tone Identification Task

All participants judged 11 tone contours as Rising or Falling tones (10 repetitions per contour, randomly ordered).

- T3 and T11 are uniformly categorized
- Notable increase in uncertainty for T7 (compared to Xi et al, 2010 depicted to the left)
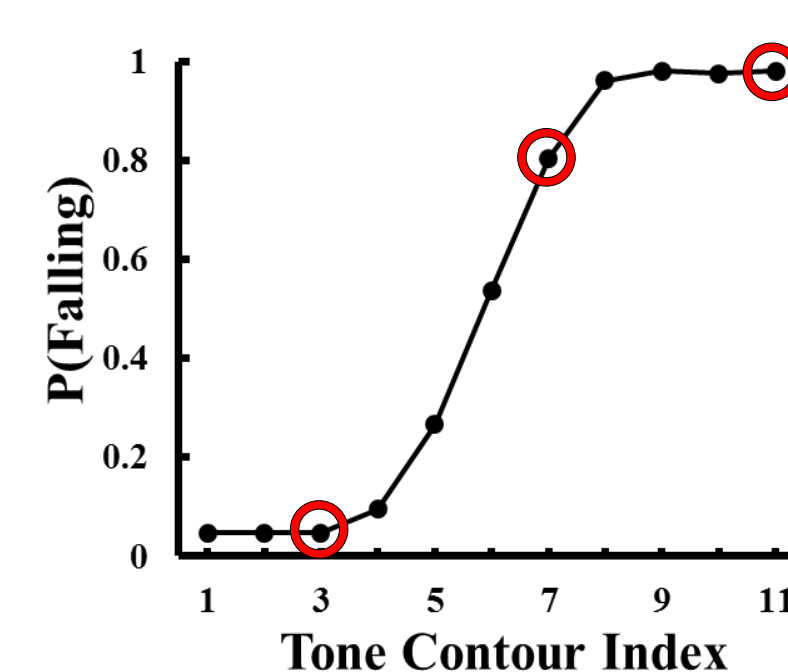
Language History Questionnaire

All participants completed a Language History Questionnaire (Li et al, 2006) to assess relevant biographical factors.

English Proficiency histogram

AOEE histogram

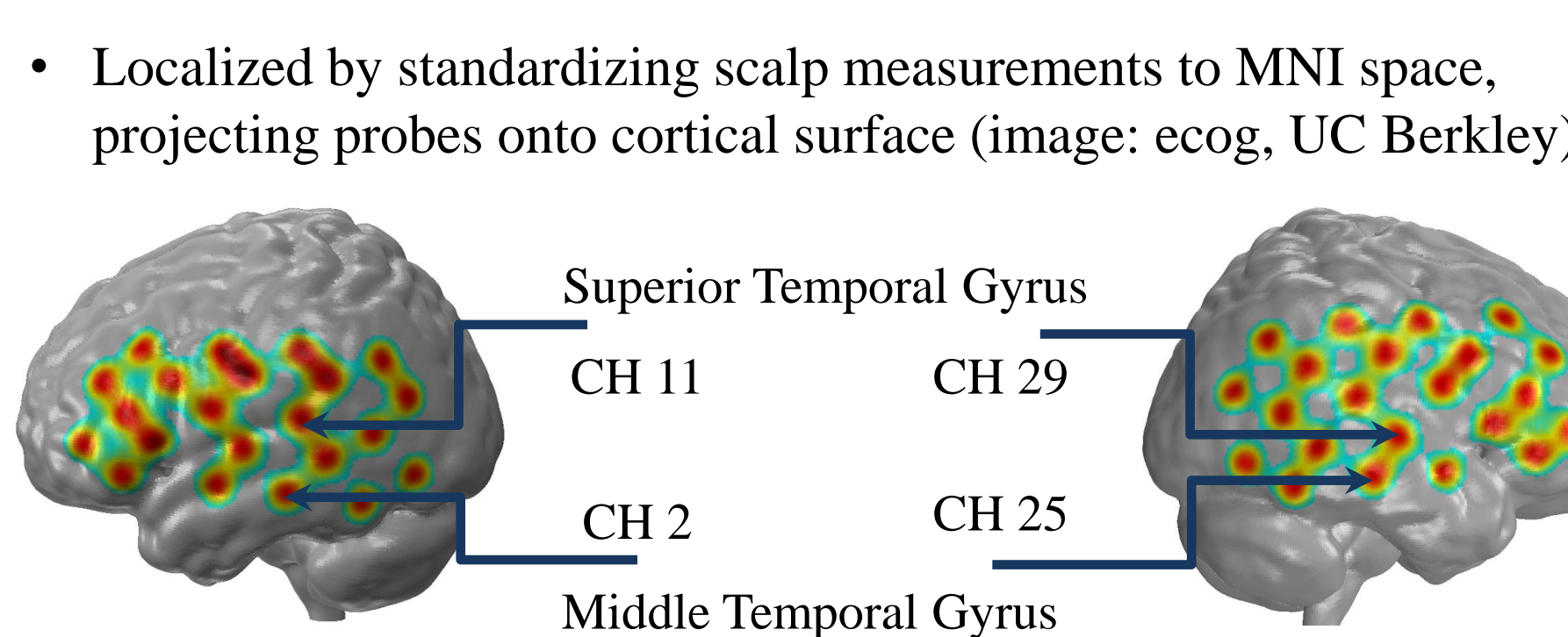| Measure	Mean	SD
Age	22.3y	2.6
Chinese Proficiency	7 / 7	-
English Proficiency	3.6 / 7	0.87
Age of Earliest English Exposure (AOEE)	11.9 y	1.71
P(T3=Falling)	0.04	0.13
P(T7=Falling)	0.81	0.23
P(T11=Falling)	0.98	0.04
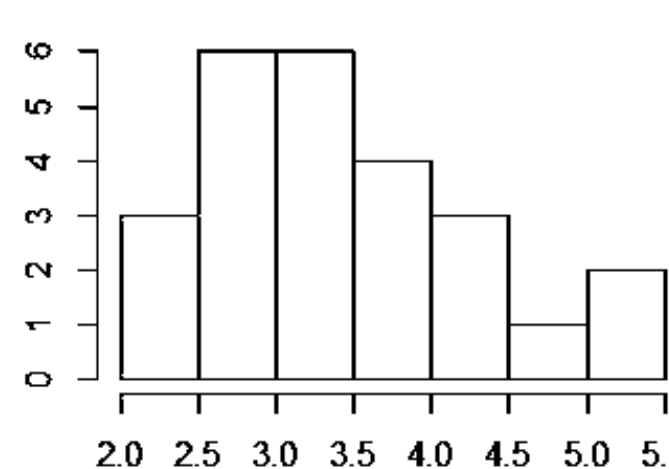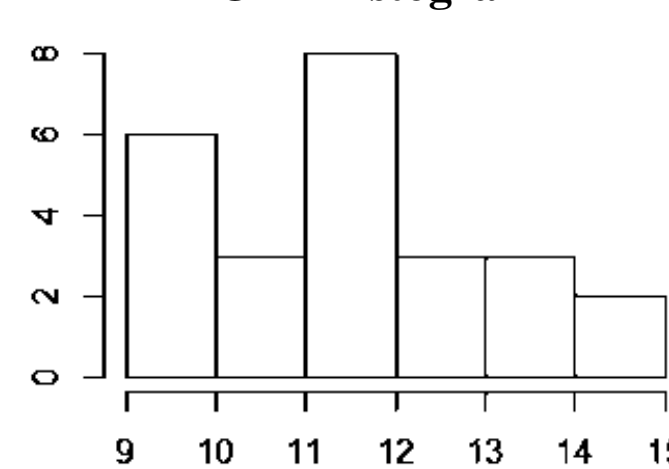
fNIRS Device

Hitachi ETG-4000 fNIRS System
- Bilateral probe arrays with 3x5 configuration, 22 channels per side
- Temporal, inferior parietal, and prefrontal coverage
- Measures relative changes in oxygenated and deoxygenated hemoglobin on cortical surface

- Localized by standardizing scalp measurements to MNI space, projecting probes onto cortical surface (image: ecog, UC Berkley)
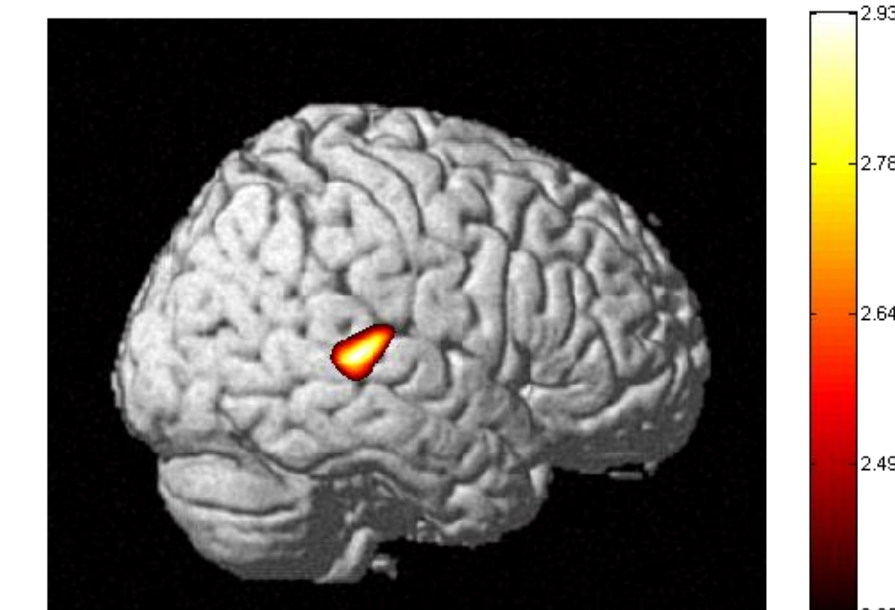

Superior Temporal Gyrus
CH 11
CH 29
CH 2
CH 25
Middle Temporal Gyrus

Acknowledgements

fNIRS Results

Analysis 1: Statistical Parametric Mapping

- Optode location on cortex estimated using NFRI function (Singh et al, 2005)
- Oxygenated hemoglobin interpolated between optodes by NIRS-SPM (Ye et al, 2009)
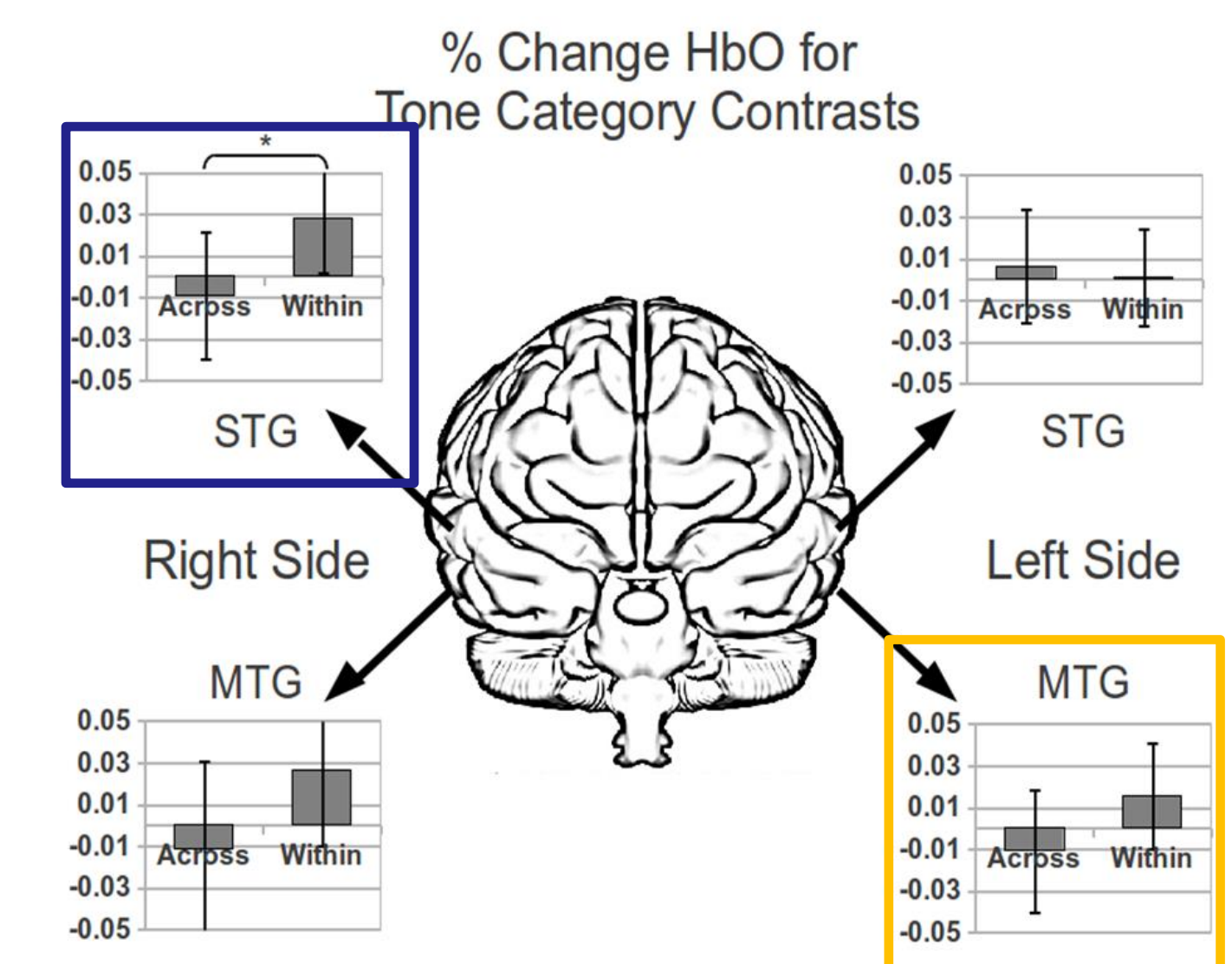

Results
- Only significant contrast: Within - Standard
- Localization in right STG roughly consistent with Zhang et al (2011)
- Why no Across Category effect?

Analysis 2: Baseline Mixed Effects Model

Peak oxygenated hemoglobin (HbO) levels are recorded for each block and entered into a linear model for 4 ROI channels (Kovelman et al, 2008)

$$\log(\text{PeakHbO}) \sim \text{Subject} + \text{Condition} + \text{Counterbalance}$$

- Fixed effects: Condition (Block Type), Counterbalance (Block Order)
- Random effect: Subject (individual variation in baseline HbO level)

% Change HbO for Tone Category Contrasts

Results
- Significant W>A effect in right STG (see Analysis 1)
- No significant effects in left MTG or STG

Analysis 3: Biographical Mixed Effects Model

AOEE and English Proficiency are correlates of the Across-Within effect in left MTG but not right STG

ROI	AOEE (R²)	Eng. Prof. (R²)
Left MTG	0.13, p=0.08	0.13, p=0.08
Right STG	0.05, p=0.28	1E-6, p=0.996

$$\log(\text{PeakHbO}) \sim \text{Subject} + \text{Condition} + \text{Counterbalance} + T3 + T7 + T11 + \text{AOEE} + \text{EngProf} + (\text{All 2- and 3-way interactions})$$

Models at each channel are pared down:
1. removing non-significant interactions
2. removing non-significant main effects (except Counterbalance)
To maximize statistical power and reduce effects of colinearity.

Across > Within Category
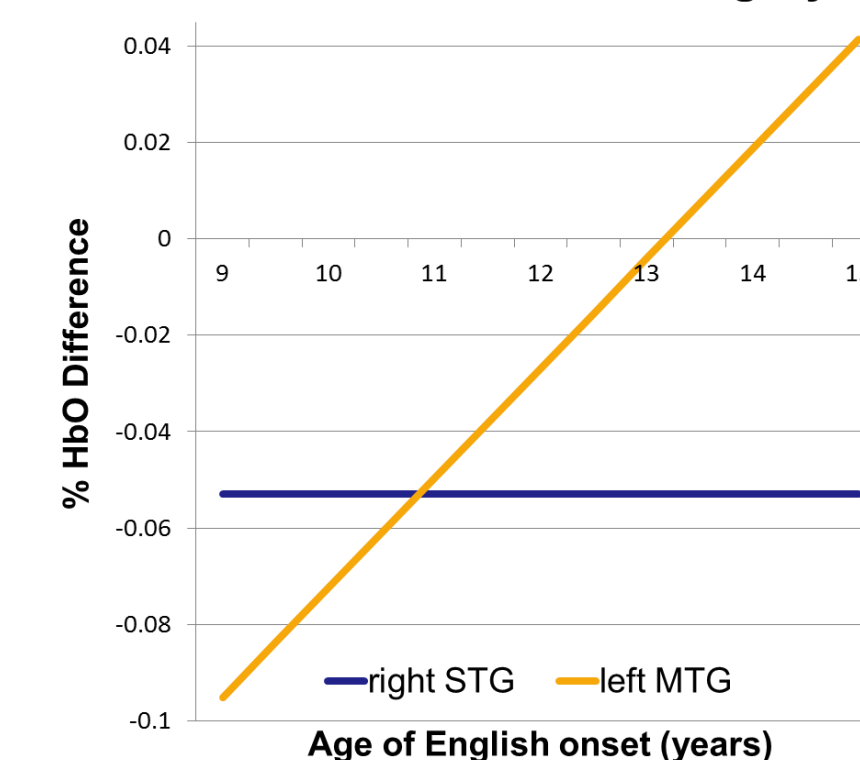
Results
- AOEE is a significant predictor in left MTG but *not* right STG
- English Proficiency accounts for less variance than AOEE (removed from both models)
- Uncertainty in T7 judgment not a significant predictor in either ROI

Discussion

Analyses 1 and 2 agree
- Effect of Within-Category (acoustic) processing in right STG
- No overall effect of Across-Category (linguistic) processing... *but why not?*

Individual Differences (Analysis 3)
- Categorical perception behavior (participants' T3,7,11 ratings) did not clearly explain activity in left MTG or right STG
- History of English learning seems correlated with Across-Category effect in MTG
- AOEE > 13y estimated as threshold for A>W in left MTG

Left MTG linguistic processing varies with L2 experience
- Less lMTG activity is recruited for Across category condition
- lMTG appears less specialized (or less entrenched) in L1-Chinese lexical tone categories for earlier learners of English