

Decoding of vocalized sentences, melodies, and emotions in the left and right perisylvian cortex of healthy adults

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Background

- Certain types of **auditory information** are processed in homotopic regions:¹⁻⁴
 - sentences in the left hemisphere (LH)**
 - vocal emotions and melodies in the right hemisphere (RH)**
- These homotopic substrates are physically bilateral, but are not functionally interchangeable, even despite the many similarities shared by these information types
- A recent multivariate fMRI study¹ found that activation in **auditory region A4** showed a hemispheric dissociation in the processing of speech (left A4) and melodies (right A4)
- We used a similar **multivariate decoding** approach to map activation to distinct sentences, melodies, and vocal emotions

Research Questions

- We compared the brain response to each information type (sentences, melodies, vocal emotions) using an **unsupervised classification approach** to rigorously examine brain areas that process each distinct information type even when the input stimulus contained overlapping information (all spoken sentences)
- We aimed to understand the **degree of participation of brain areas in the ‘dominant’ and ‘non-dominant’ hemisphere** for each information type

Participants

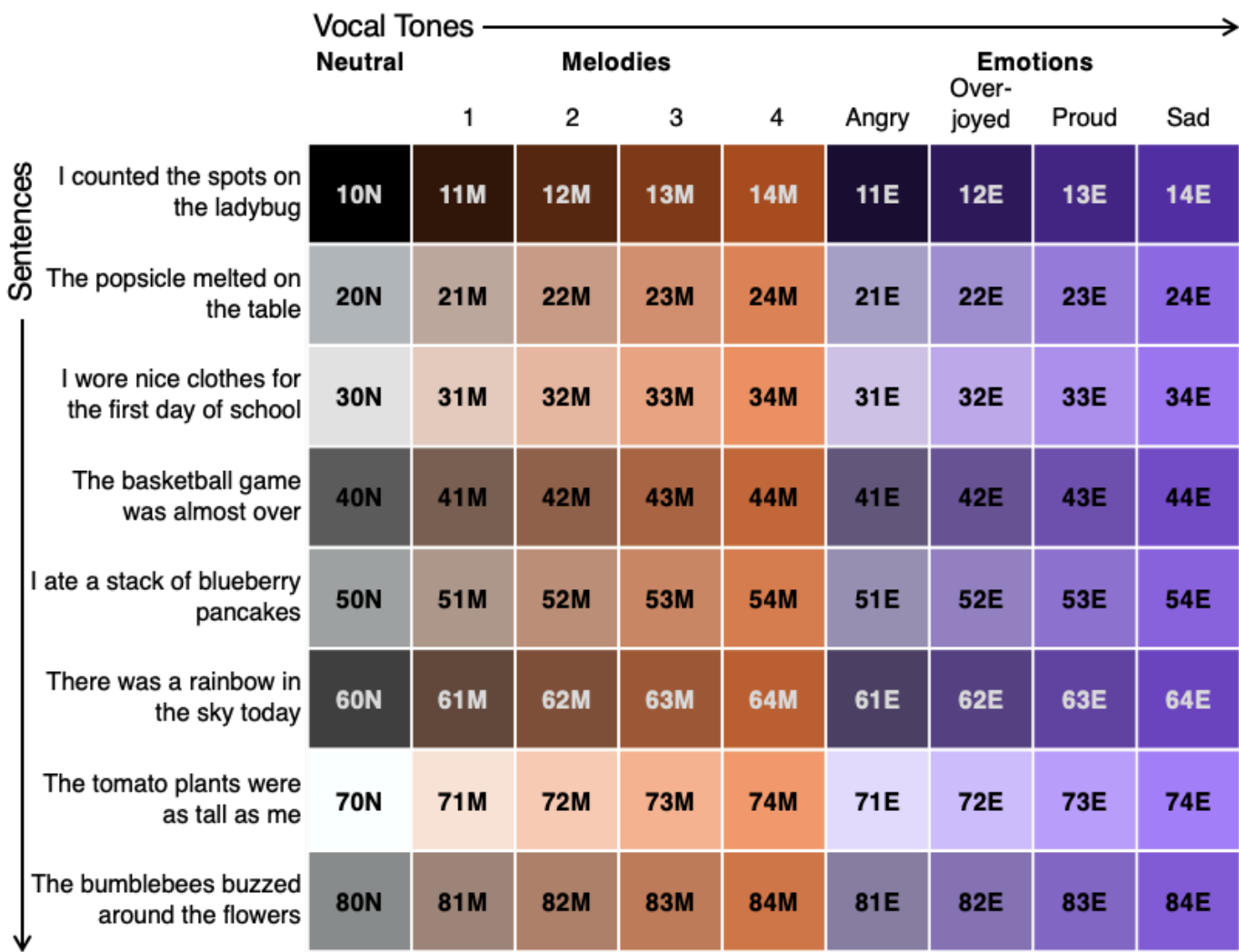
Participants were recruited through the University of Pittsburgh’s online system that connects local residents interested in participating in research with research studies they may be eligible for via email.

Table 1. Participant Demographics

N	Age (years)	N Female	N Right-Handed	Race
10	19-27 (mean=22.5, std. dev.=4.7)	5	10	8 White 2 Black/African American

fMRI Experiment

Figure 1. fMRI Task Presentation for MVPA Analysis



Stimulus Corpus

Eight ten-syllables sentences (Fig.1, rows) delivered in **nine vocal tones** by a female speaker:

- neutral** (Fig.1 column 1)
- 4 melodies** (Fig.1 columns 2-4) sung a capella
- 4 emotions** (Fig.1 columns 5-9): angry, overjoyed, proud, sad

Presentation & Task

Participants heard **each sentence 30 times**, in six runs balanced across information type:

- each neutral x 6** (Fig.1 white cells)
- each melody x 24** (Fig.1 orange cells)
- each emotion x 24** (Fig.1 purple cells)

Four catch trials per run: button-press to each one-back identical repeat

References

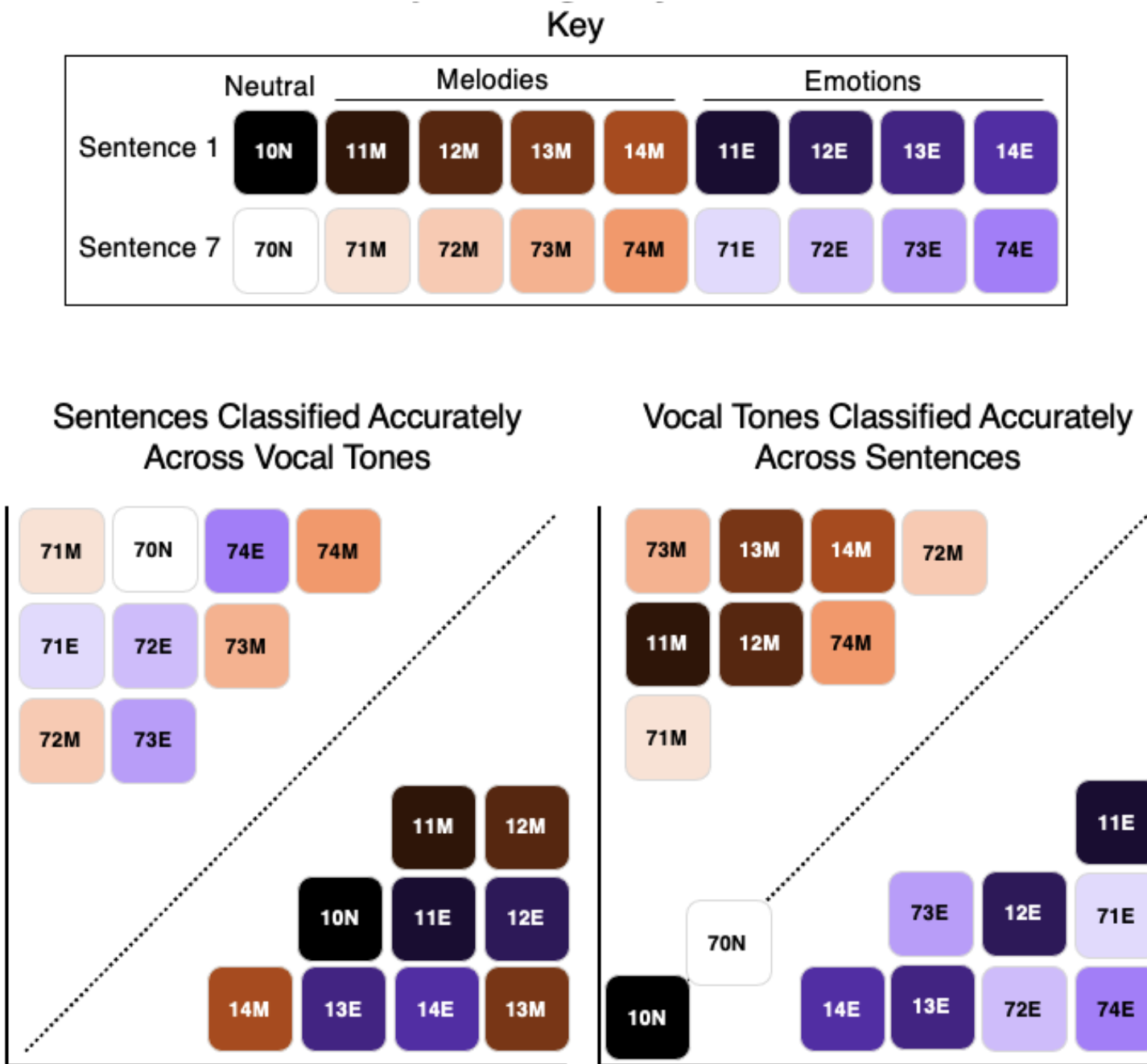
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Acknowledgments

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Whole-Brain Classification Analysis

Figure 2. Schematic of Simplified Classification Example



First-Level GLMs

Two first-level general linear models (GLMs) for each participant:
a. instances of **each sentence (8)**
b. Instances of **each vocal tone (9)**

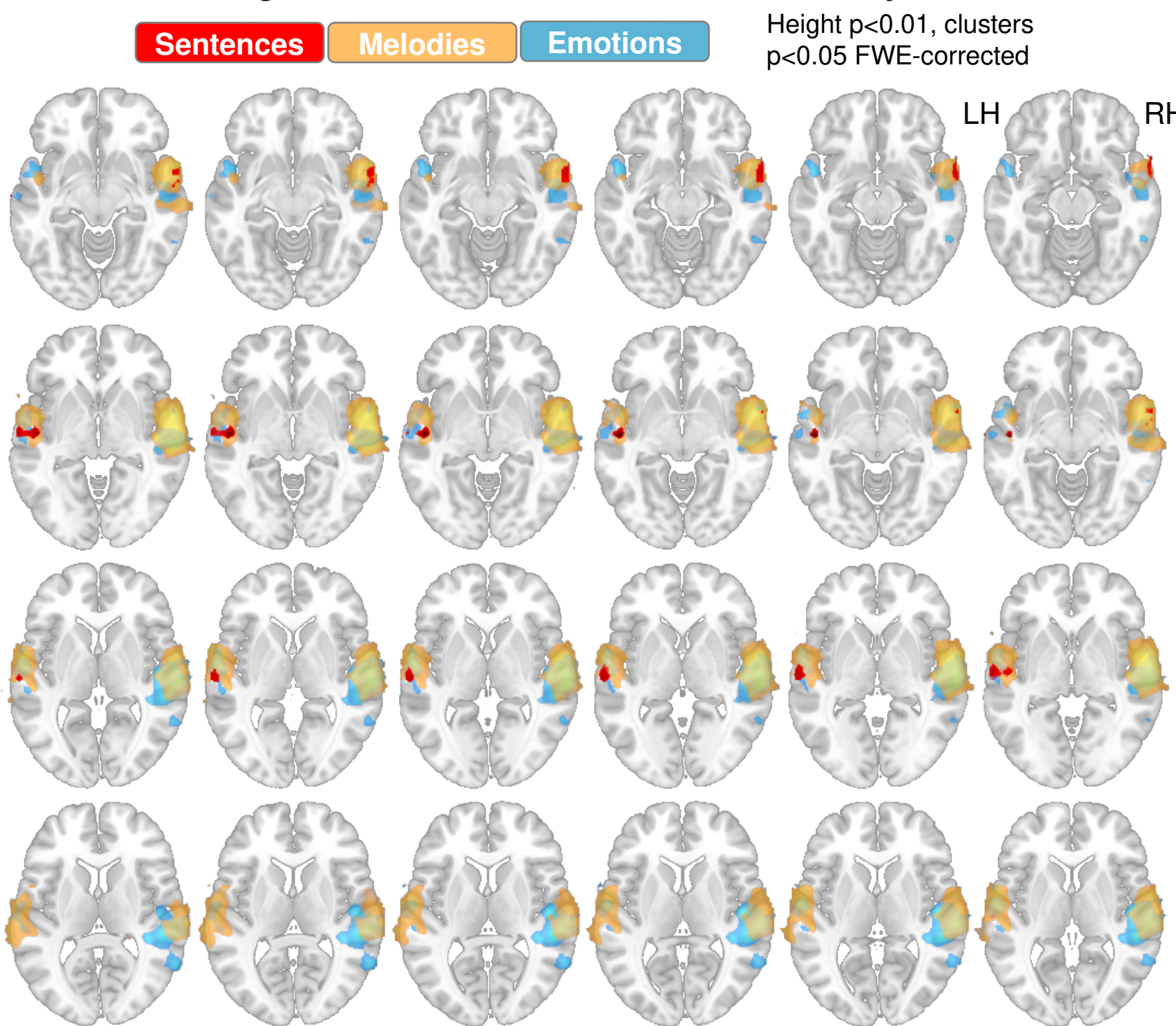
Whole-Brain Decoding

Three whole-brain decoding analyses run on unsmoothed, native-space beta maps
a. **all sentence labels**
b. **all emotion and neutral labels**
c. **all melody and neutral labels**

Group Analysis

A second-level GLM was run on normalized, smoothed accuracy maps to determine where classification-minus-chance values were > zero

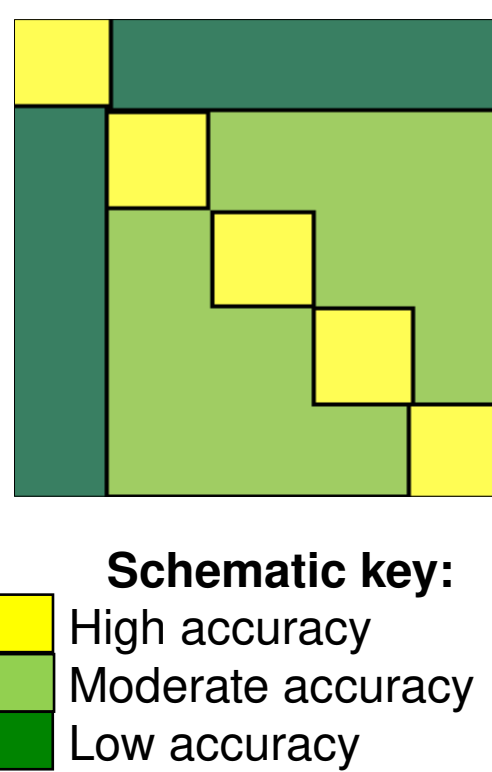
Figure 3. Whole-Brain Classification Analysis



Region of Interest Confusion Matrix Analysis

- 32 10mm-radius spheres across left and right perisylvian cortices symmetrically in native space
- Confusion matrices extracted for each ROI using classification parameters from whole-brain analyses
- Mean accuracies were compared between categories and regions

Figure 4. Confusion Matrix Schematic



Example - Column 1:

- How often the stimuli were classified as neutral (yellow), versus when they were melody 1, 2, 3, or 4 (dark green)

Example - Column 2:

- How often the stimuli were classified as melody 1 when they were neutral (dark green), versus melody 1 (yellow), versus melody 2-4 (light green)

Figure 5. ROIs with significant decoding accuracy

Four LH regions and six RH regions had decoding accuracies significantly above chance for one or more categories

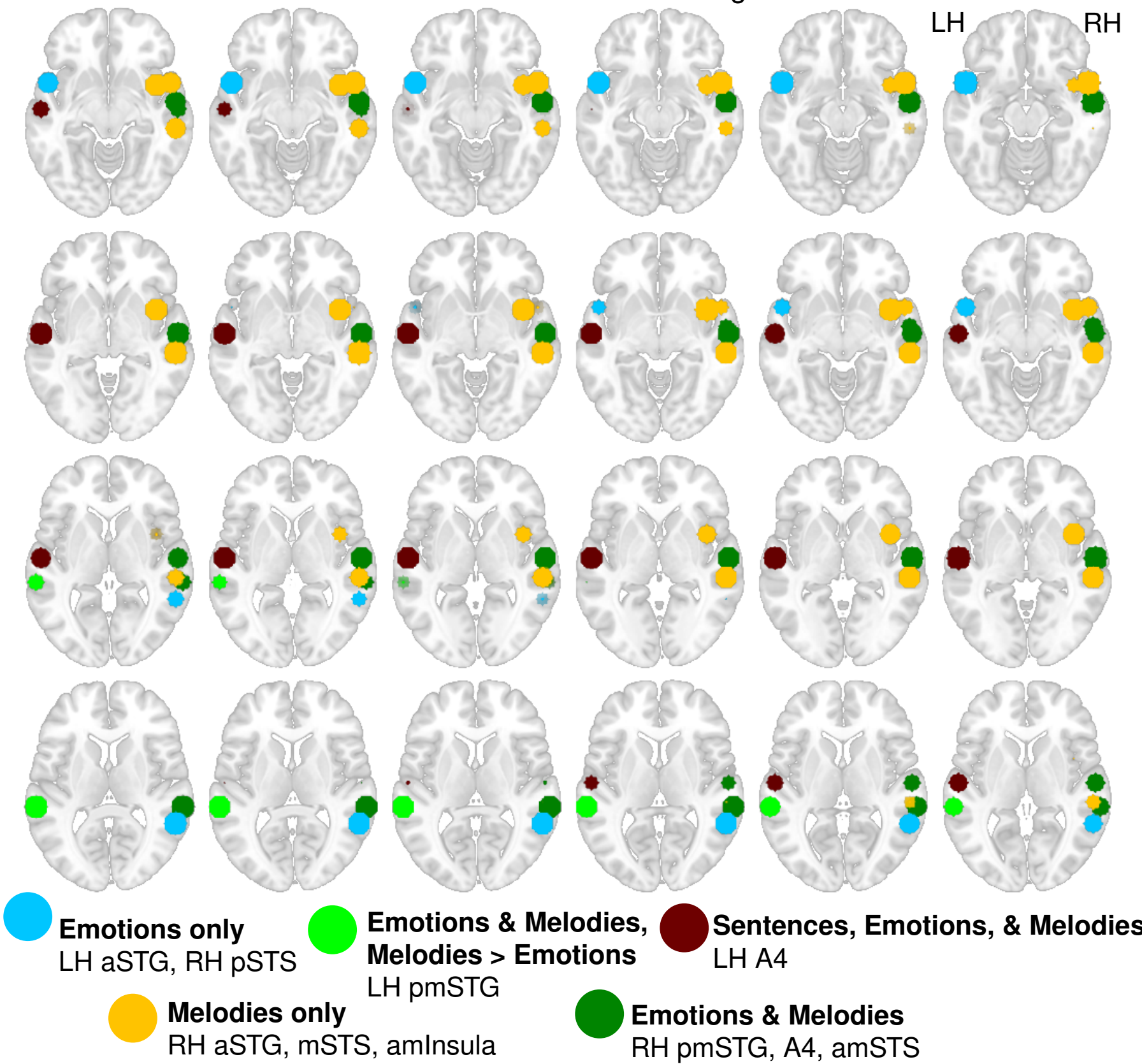
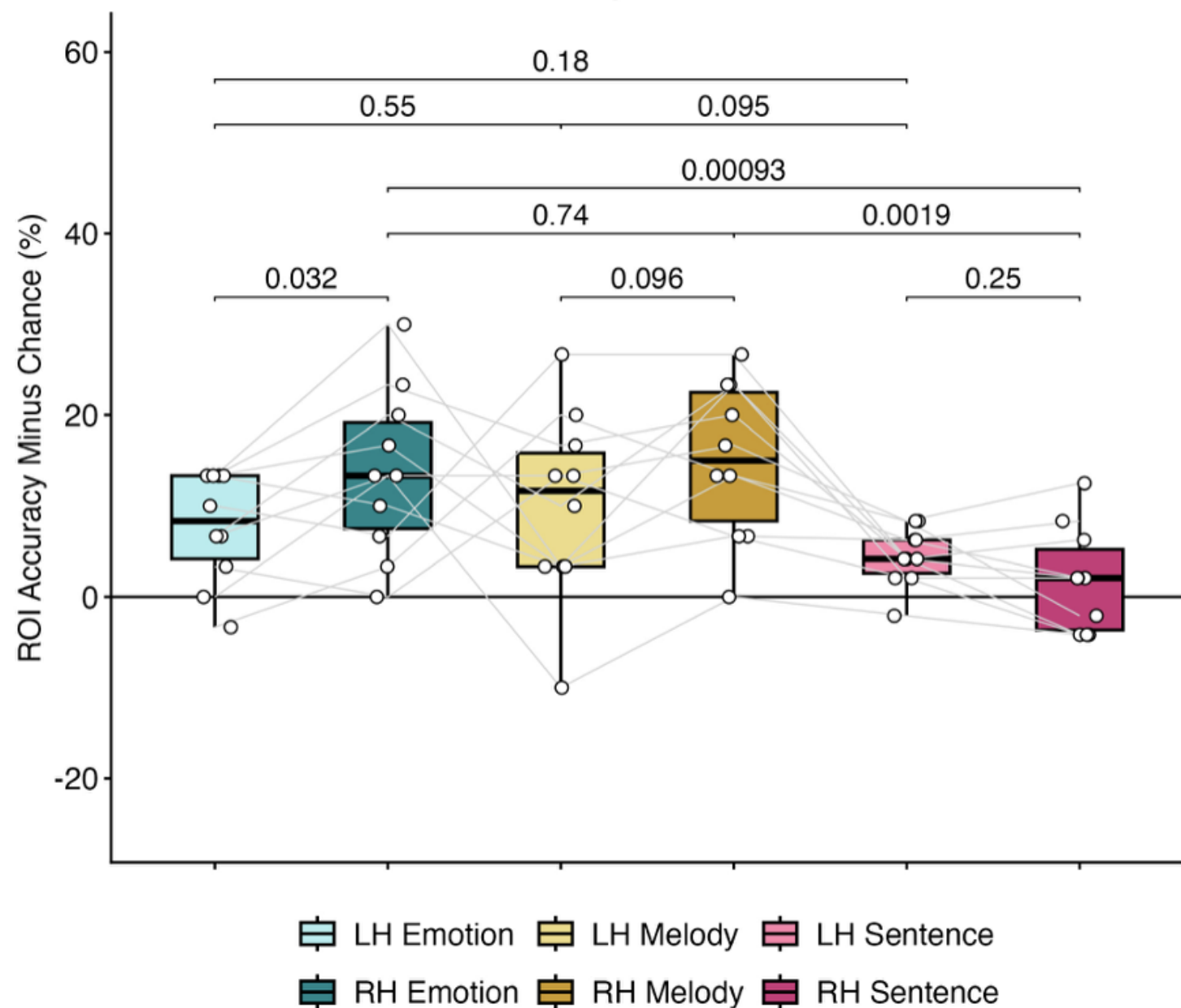


Figure 6. Confusion Matrix Results in Area A4 Accuracy Minus Chance



Conclusions

- Left A4 was a key region for sentence processing, but also for vocal tones
- There was no region that processed sentences that did not also process one or both vocal tone categories
- We identified additional areas, mostly in the RH, that processed both vocal tone categories, or selectively processed either melodies or emotions
- These findings show that **lateralization is not binary and that regions in the dominant/non-dominant hemisphere can process different dimensions of information that occur simultaneously**

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Abstract

- We examined three types of auditory information processing that are typically lateralized—sentence processing to the left hemisphere (LH), and vocal emotion and melody processing to the right hemisphere (RH)—to understand the degree of participation and overlap among involved regions in both hemispheres.
- A female speaker recorded each of eight ten-syllables sentences in four emotions (angry, overjoyed, proud, and sad), four melodies sung a capella, and in a neutral tone. In an fMRI experiment, ten healthy, right-handed, English-monolingual adults (5 female, average age 22.5) heard each sentence 30 times, each emotion 24 times, each melody 24 times, and each neutral sentence 6 times (in six runs balanced across information type). On four additional catch trials per run, participants heard a one-back identical repeat and responded via button-press.
- Two first-level general linear models (GLMs) modeled the instances of each sentence and of each vocal tone, respectively, for each participant. Three whole-brain decoding analyses were performed on the two resulting sets of unsmoothed, native-space beta maps: one classifier was trained/tested on all sentence labels, a second was trained/tested on all emotion and neutral labels, and a third was trained/tested on all melody and neutral labels. For group analysis, a second-level GLM was run on normalized, smoothed accuracy maps to determine where the group's classification-minus-chance (AMC) values were significantly above zero. Finally, a region-of-interest (ROI) analysis was performed using 32 10mm-radius spheres spread symmetrically across left and right perisylvian cortices. Confusion matrices were extracted for each ROI in native space using the classification parameters from whole-brain analyses, and then compared mean accuracies between categories and between regions for all participants.
- Whole-brain classification maps revealed one small cluster in left hemisphere (LH) region A4, with accuracy-minus-chance (AMC) values that survived voxelwise but not cluster-level correction. Results for melodies and emotions were both robust, spanning much of the temporal lobe with a concentration in anterior and middle areas. In the ROI analysis, sentences across vocal tones were only classifiable in LH A4. Vocal tone was classifiable across all sentences in LH A4, RH A4, anterior-middle STS and bilateral posterior-middle STG. Melody was classifiable in LH posterior-middle STG and emotion-only was classified in LH STG, RH posterior STS, RH middle STS and RH anterior-middle insula. Among the regions identified for both emotions and melodies, only LH posterior-middle STG showed a mean difference, in favor of melodies. Among all regions with AMC values greater than zero, the only hemispheric differences were in anterior-middle and middle STS, which were greater in the RH than LH for melodies.
- In summary, left A4 was a key region for sentence processing, but also for vocal tone processing. There was no region that processed sentences that did not also process one or both vocal tone categories. We identified additional areas, mostly in the RH, that processed both vocal tone categories, or selectively processed either melodies or emotions. These findings show that lateralization is not binary and that regions in the dominant/non-dominant hemisphere can process different dimensions of information that occur simultaneously.

Version 2 or 3

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	Vocal Tones		Melodies				Emotions			
	Neutral		1	2	3	4	Angry	Overjoyed	Proud	Sad
Sentences	I counted the spots on the ladybug	10N	11M	12M	13M	14M	11E	12E	13E	14E
	The popsicle melted on the table	20N	21M	22M	23M	24M	21E	22E	23E	24E
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	There was a rainbow in the sky today	60N	61M	62M	63M	64M	61E	62E	63E	64E
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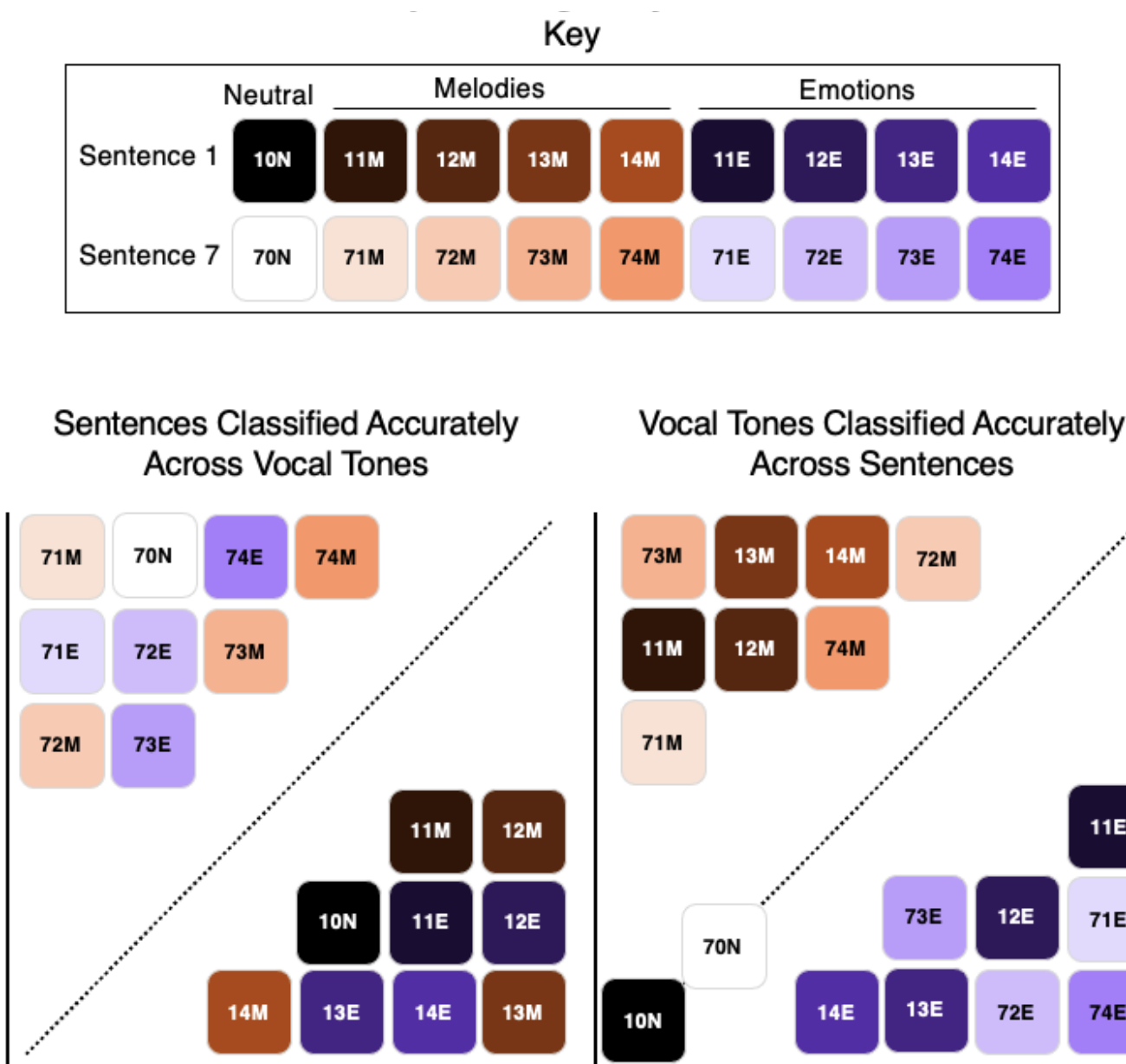
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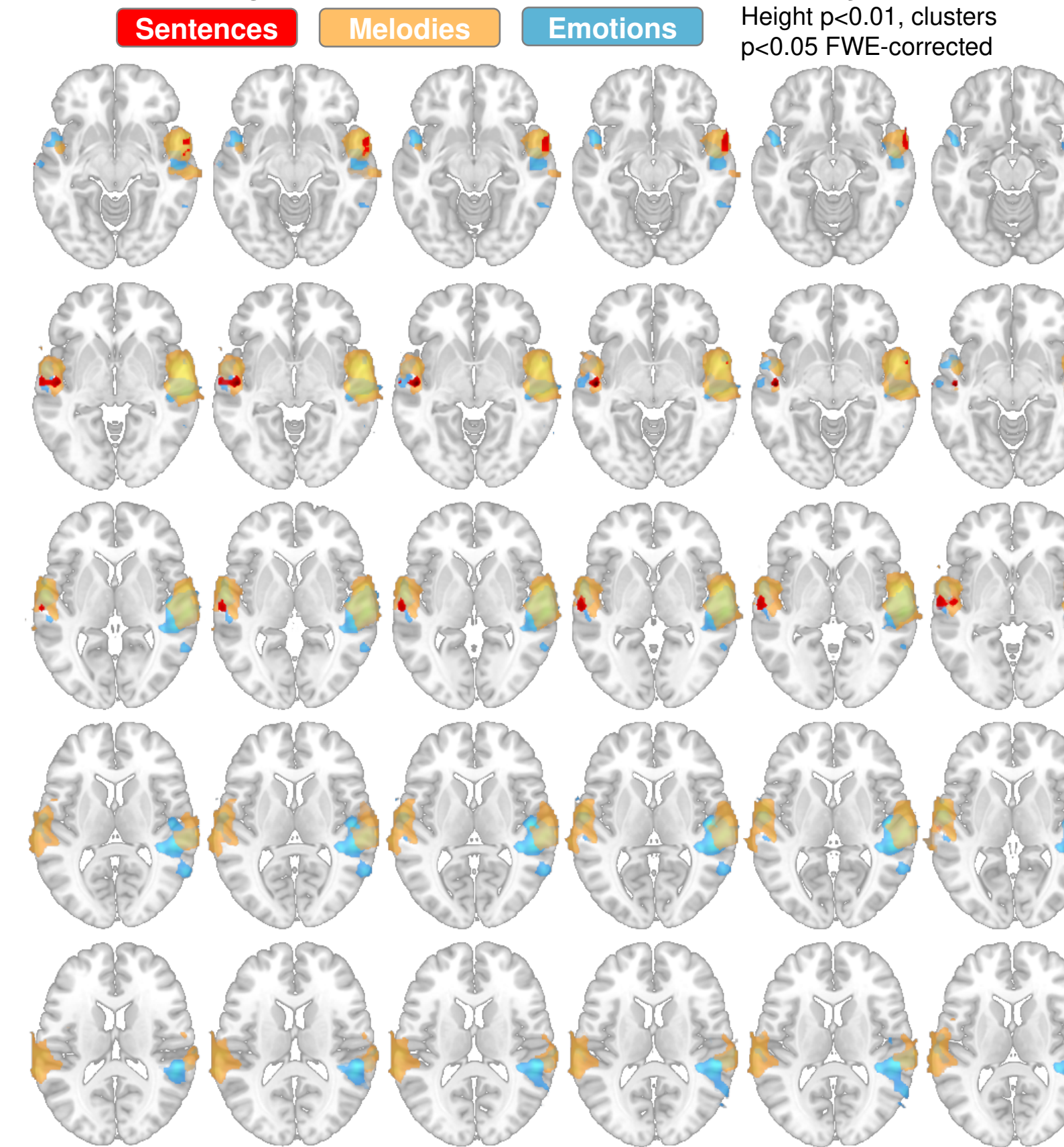
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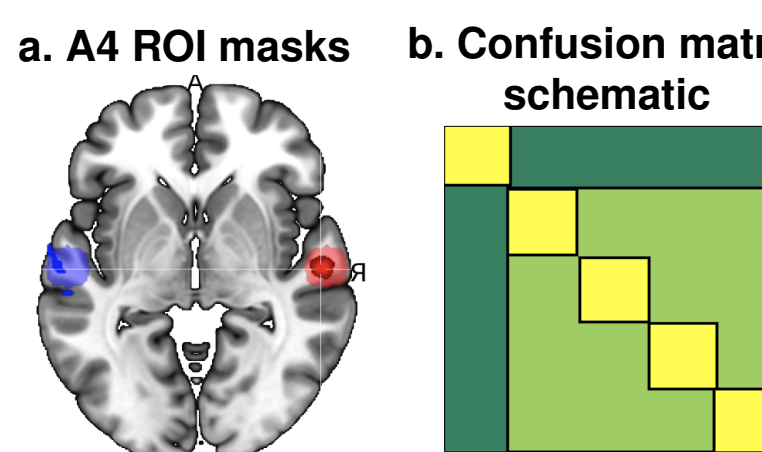
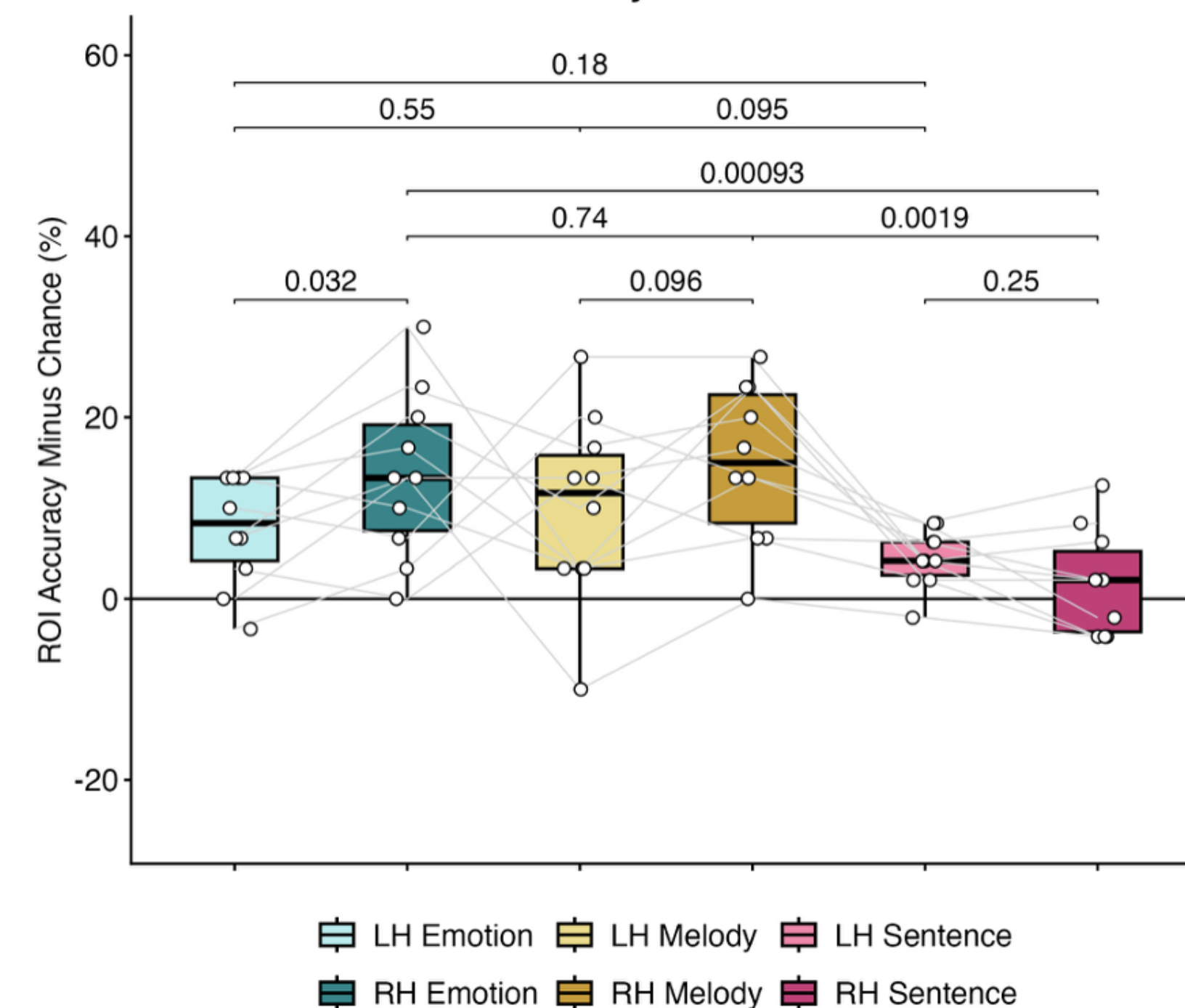


Table 2. Accuracies between Information types in ROIs with decoding accuracy above zero

	Region	Condition for which Decoding Accuracy > Zero (one-sample t-test)	Statistical Test	Interpretation
Left	A4	Sentences, Melodies, Emotions	Repeated-Measures ANOVA F(2,9)=1.477, p=0.255	No mean difference in left A4 decoding of Sentences, Melodies, and Emotions
	pmSTG	Melodies, Emotions	Paired Samples t-test t(9)=2.478, p=0.035	Greater decoding accuracy for Melodies than Emotions in left pmSTG
	aSTG	Emotions	--	Emotions-only decoding in left aSTG
Right	A4	Melodies, Emotions	Paired Samples t-test t(9)=0.386, p=0.708	No mean difference in right A4 decoding of Melodies and Emotions
	amSTS	Melodies, Emotions	Paired Samples t-test t(9)=1.941, p=0.084	No mean difference in right amSTS decoding of Melodies and Emotions
	pmSTG	Melodies, Emotions	Paired Samples t-test t(9)=0.147, p=0.886	No mean difference in right pmSTG decoding of Melodies and Emotions
	amInsula	Melodies	--	Melodies-only decoding in right amInsula
	aSTG	Melodies	--	Melodies-only decoding in right aSTG
	mSTS	Melodies	--	Melodies-only decoding in right mSTS
	pSTS	Emotions	--	Emotions-only decoding in right pSTS

Figure 5. Confusion Matrix Results in Area A4 Accuracy Minus Chance



References

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- Certain auditory functions are organized in homotopic regions:¹⁻⁴
 - sentence processing** in the **left hemisphere (LH)**
 - and **vocal emotional and melody processing** in the **right hemisphere (RH)**
- These homotopic substrates that are physically bilateral, but are not functionally interchangeable (i.e., cannot compensate for the other side effectively after injury)
- There are striking similarities but also key differences in the consistent features of the information structure and brain organization of these auditory functions (Table 1)
- A recent multivariate fMRI study¹ found that activation in **auditory region A4** showed a hemispheric dissociation in the processing of speech (left A4) and melodies (right A4)
- Here we used a similar **multivariate decoding** approach to map the neural response to sentences, melodies, and vocal emotions

Table 1. Overview of some important similarities and differences in the consistent features of auditory sentences, melodies, and vocal emotions

Consistent features:	Sentences	Melodies	Emotions
High temporal variation	yes	no	no
High spectral variation	no	yes	yes
Vocally produced	yes	no (sometimes lyrics)	yes
Direct ties to lexicon	yes	no (sometimes lyrics)	yes (e.g., discrete labels)
Hierarchical, systematically ordered components	yes (e.g. words in phrases)	yes (e.g., notes in harmonies)	no
Unfold over time	yes	yes	yes
Engage perisylvian regions	yes	yes	yes
Impaired after unilateral injury	yes (LH)	inconclusive	yes (RH)

Research Questions

- We compared the brain response to each information type (sentences, melodies, vocal emotions) using an **unsupervised classification approach** to rigorously examine brain areas that process each distinct information type even when the input stimulus contains overlapping information (all spoken sentences)
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fMRI Experiment & Classification Analysis

Figure 1. fMRI Task Presentation for MVPA Analysis.

a. Schematic of Stimulus Variance Across Sentences and Vocal Tones

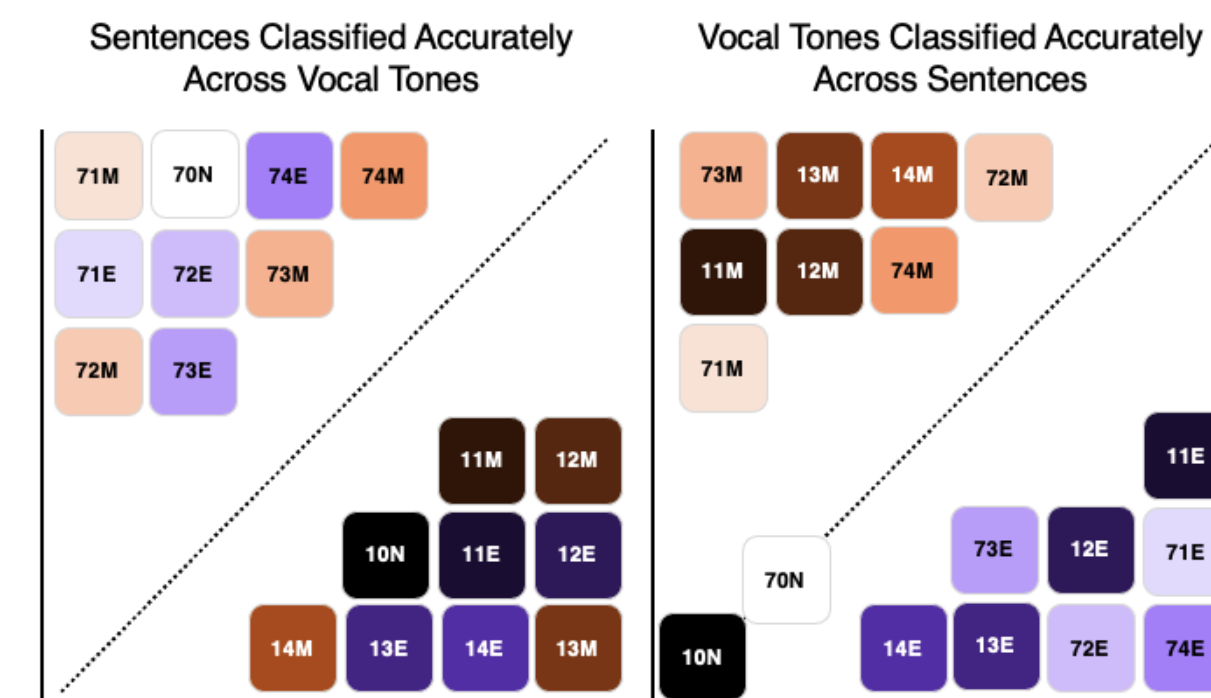
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		Neutral		Melodies				Emotions		
			1	2	3	4	Angry	Over-joyed	Proud	Sad
Sentences	I counted the spots on the ladybug	10N	11M	12M	13M	14M	11E	12E	13E	14E
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	I wore nice clothes for the first day of school	30N	31M	32M	33M	34M	31E	32E	33E	34E
	The basketball game was almost over	40N	41M	42M	43M	44M	41E	42E	43E	44E
	I ate a stack of blueberry pancakes	50N	51M	52M	53M	54M	51E	52E	53E	54E
	There was a rainbow in the sky today	60N	61M	62M	63M	64M	61E	62E	63E	64E
	The tomato plants were as tall as me	70N	71M	72M	73M	74M	71E	72E	73E	74E
	The bumblebees buzzed around the flowers	80N	81M	82M	83M	84M	81E	82E	83E	84E

b. Experimental Design

Trial	Run 1A	Run 1B	Run 2A	Run 2B	Run 3A	Run 3B
1	20N	70E	12E	82M	31M	94E
2	82M	50N	64M	84E	54M	10N
3	11E	83M	73E	41M	43E	21E
4	61M	34E	30N	50N	REPEAT 43E	84M
5	54E	REPEAT 34E	12M	63M	60N	32M
6	REPEAT 54E	60N	54E	83E	24M	70N
7	30N	54M	43M	24M	82E	13E
8	22E	20N	60N	71E	73M	83M
9	73M	43M	82E	REPEAT 71E	11E	51E
10	REPEAT 73M	51E	24E	62M	42E	41M
11	13E	70N	61M	20N	80N	30N
12	44M	22E	54M	52E	33E	83E
13	50N	11M	40N	32M	63M	REPEAT 83E
14	63E	82E	11E	14E	50N	22M
15	31M	74M	REPEAT 11E	72E	84E	72E
16	10N	30N	31M	44M	42E	REPEAT 72E
17	42E	12M	74E	REPEAT 44M	20N	53M
18	64M	REPEAT 12M	52M	10N	51M	14M
19	84E	44E	10N	21E	REPEAT 51M	60N
20	70N	61E	63E	53E	14E	24E
21	21M	53M	22M	11M	34M	52M
22	REPEAT 21M	81M	REPEAT 22M	73M	70N	12E
23	31E	41E	60N	80N	82M	14E
24	14M	34M	81E	22E	23E	64M
25	53E	80N	44E	13E	31E	REPEAT 64M
26	13M	22M	23M	40N	81M	20N
27	72E	52E	32E	53M	62M	13M
28	60N	41M	REPEAT 32E	REPEAT 53M	71E	71M
29	23M	REPEAT 41M	80N	42E	10N	63E
30	81E	24E	71M	72M	54E	52E
31	REPEAT 81E	62M	14M	51M	23M	80N
32	52M	71E	23E	64E	62E	41E
33	74E	60M	31E	40N	33M	33M
34	40N	10N	74M	21M	12M	REPEAT 33M
35	84M	83E	81M	33E	53E	50N
36	32E	14E	51E	13M	74E	44M
37	64E	24M	20N	60N	11M	32E
38	72M	62E	33M	84E	REPEAT 11M	61M
39	43E	REPEAT 62E	42M	34M	72M	30N
40	51M	32M	62E	61E	61E	40N
41	21E	40N	83M	70N	74M	81E
42	80N	12E	REPEAT 83M	41E	22E	34E
43	43M	71M	43E	84M	REPEAT 22E	21M
44	32M	33E	70N	30N	43M	73E

c. Classification Example Using Only Two Sentences

	Neutral					Melodies					Emotions				
Sentence 1	10N	11M	12M	13M	14M	11E	12E	13E	14E						
Sentence 7	70N	71M	72M	73M	74M	71E	72E	73E	74E						



Stimulus Corpus

- Eight ten-syllables sentences** (Fig.1a, row labels) delivered in **nine vocal tones** by a female speaker:
- neutral** (Fig.1a col. 1)
 - four melodies** (Fig.1a col. 2-4) sung a capella
 - four emotions** (Fig.1a col. 5-9): angry, overjoyed, proud, sad

Presentation & Task

- Participants heard **each sentence 30 times**, in six runs balanced across information type (Fig.1b):
- each neutral sentence 6 times** (Fig.1b white cells)
 - each melody 24 times** (Fig.1b orange cells)
 - each emotion 24 times** (Fig.1b purple cells)
- Four catch trials** per run: participants responded via button-press to each one-back identical repeat (Fig.1b "REPEAT")

First-Level GLMs

- Two first-level general linear models (GLMs) for each participant:
- instances of **each sentence (8 categories)**
 - Instances of **each vocal tone (9 categories)**

Whole-Brain Decoding

- Three whole-brain decoding analyses** run on the two resulting sets of unsmoothed, native-space beta maps (Fig.1c shows a scaled-down schematic of this classification; the real version used all 8 sentences):
- trained/tested on **all sentence labels**
 - trained/tested on **all emotion and neutral labels**
 - trained/tested on **all melody and neutral labels**

Group Analysis

For group analysis: a second-level GLM was run on normalized, smoothed accuracy maps to determine where the group's classification-minus-chance (AMC) values were reliably > zero

ROI Analysis

Region-of-interest (ROI) analysis:

- 32 10mm-radius spheres spread symmetrically across left and right perisylvian cortices
- Confusion matrices** extracted for each ROI in native space using classification parameters from whole-brain analyses:
 - mean accuracies compared between categories and regions for all participants

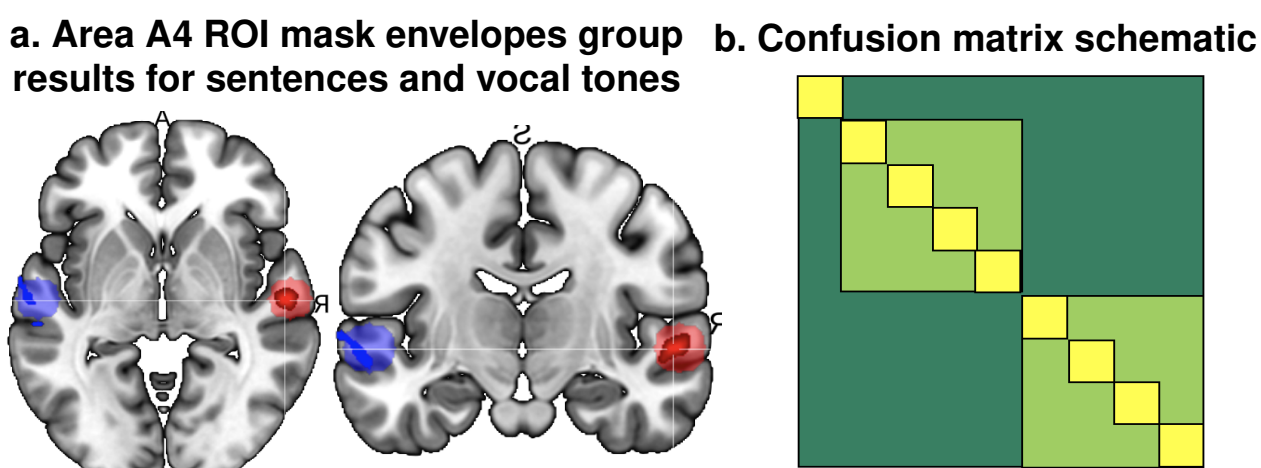


Figure 2. ROI Confusion Matrix Analysis. The area A4 ROI masks for individual analyses also envelopes the most consistent areas of classification at the group level (a). Confusion matrices were extracted for each ROI, revealing how often all other labeled stimuli (e.g., melodies 1-4, emotions 1-4) were confused for being a given labeled stimulus (e.g., neutral, in column 1). This was done for vocal tones, and separately for sentences (e.g., how often sentences 2-8 were confused for being sentence 1, in column 1). This schematic shows the most dramatic difference possible between the three vocal tone categories (b).

Classification Analysis Results

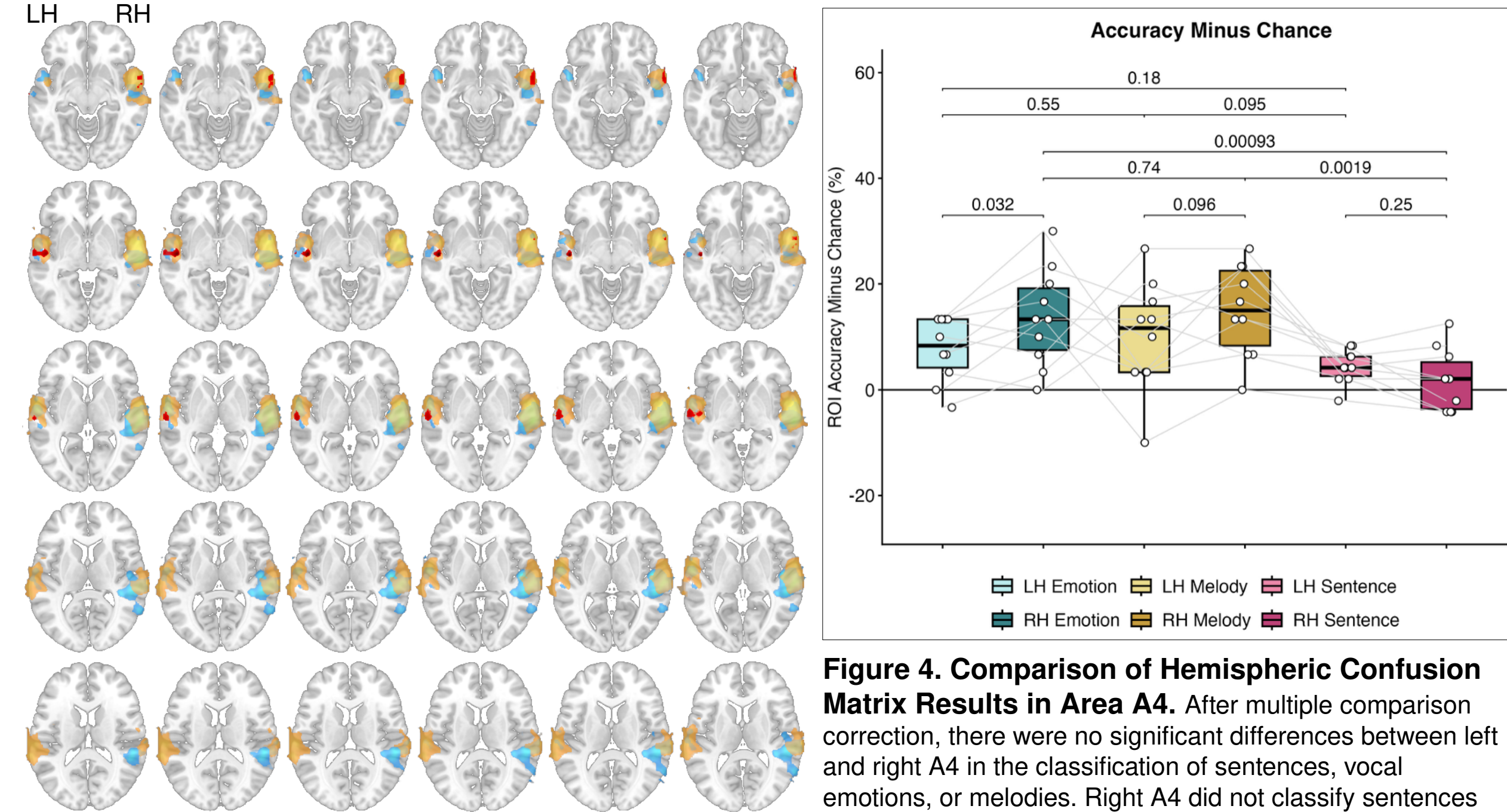


Figure 3. Whole-Brain Classification Analysis.

We found that sentence-level classification (across all vocal tones) was performed in a more inferior right temporal region, and a more superior left temporal region. Vocal emotion classification was right-lateralized, and melody classification was generally bilateral. There were no regions outside of perisylvian cortex, primarily temporal, identified in any of the classification analyses.

Table 3. ROI Analysis Hemispheric Comparisons

ROI	Centroid MNI Coordinates (10-mm or 5-voxel radius)	Accuracy Minus Chance (chance = 1/6 runs = 16.67%) mean (standard deviation)		
		Sentences	Melodies	Emotions
aSTG	+/- 45 -62 35	LH -3.33 (3.14) RH 2.29 (3.98)	LH 7.00 (11.80) RH 12.70 (9.53)	LH 7.67 (7.38) RH 4.00 (5.62)
A4	+/-57 -15 -3	LH 4.37 (3.18) RH 1.87 (5.76)	LH 10.00 (10.40) RH 15.00 (8.64)	LH 7.67 (6.10) RH 13.70 (9.22)
pmSTG	+/-61 -35 9	LH 2.50 (6.27) RH -2.92 (4.07)	LH 12.30 (6.49) RH 10.30 (9.74)	LH 6.00 (5.84) RH 9.67 (10.40)
amSTS	+/-55 -8 -14	LH 2.92 (3.29) RH 1.04 (4.84)	LH 1.33 (7.40) RH 10.70 (5.16)	LH -0.33 (7.11) RH 7.00 (6.18)
mSTS	+/-55 -31 -4	LH 2.08 (4.28) RH -1.46 (3.55)	LH 4.33 (10.70) RH 12.70 (11.00)	LH 2.67 (8.14) RH 4.67 (7.57)
pSTS	+/-55 -49 10	LH 2.29 (4.76) RH -2.08 (6.51)	LH 7.67 (10.70) RH 3.67 (9.36)	LH 1.00 (10.30) RH 9.33 (8.58)
amInsula	+/-39 6 -6	LH -1.46 (2.79) RH -1.46 (2.79)	LH 7.67 (9.44) RH 7.00 (7.28)	LH 0.00 (6.48) RH 3.67 (10.10)

- Highlighting < FDR Benjamini-Hochburg critical value for 32 tests across both hemispheres within each information type.
- Not significant: aSTS, HG/plnsula, Amygdala, IFG pars tri, Rolandic Operc, Dorsal Precentral, SMG, AG, V1/V2

Conclusions & Future Directions

- Left A4 was a key region for sentence processing, but also for vocal tone processing
- There was no region that processed sentences that did not also process one or both vocal tone categories
- We identified additional areas, mostly in the RH, that processed both vocal tone categories, or selectively processed either melodies or emotions
- These findings show that **lateralization is not binary and that regions in the dominant/non-dominant hemisphere can process different dimensions of information that occur simultaneously**