BEHAVIORAL & NEURAL CORRELATES OF SPEECH MOTOR SEQUENCE LEARNING

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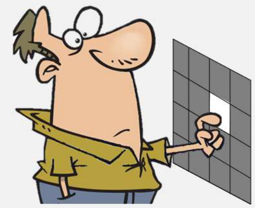
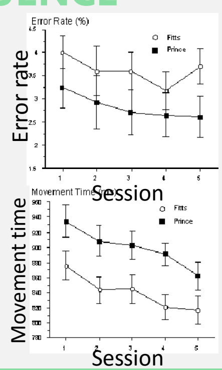
MOTOR LEARNING



MOTOR SEQUENCE LEARNING

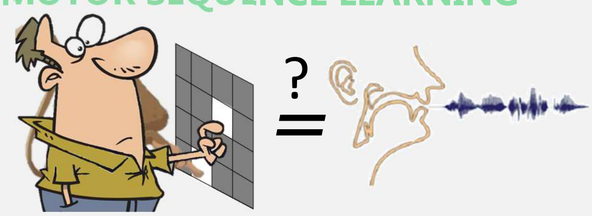


↓ in error rate

↓ in time to make movement

Kabbash. & Buxton. (1995). *Proceedings of CHI'95*, 273-279.

NON-SPEECH V. SPEECH MOTOR SEQUENCE LEARNING



Question: Can we find analogous behavioral evidence for speech motor sequence learning?

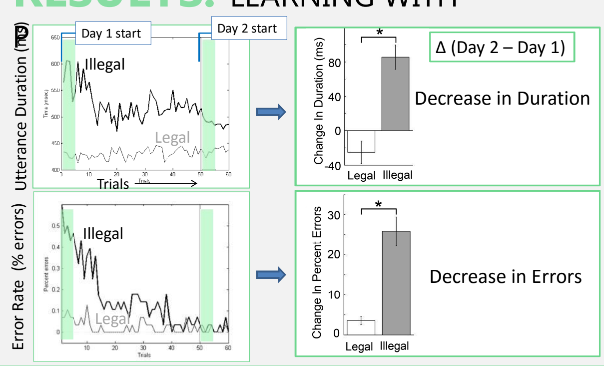
PARADIGM: PRACTICE

1. **LEGAL**
   - e.g. FREMP
   - **Legal** consonant clusters in English
2. **ILLEGAL**
   - e.g. FSEFK
   - **Illegal** (or highly infrequent) consonant clusters in English
     - i.e. novel subsyllabic sequences

15 sequences (pseudowords) per condition
60 repetitions per sequence over 2 days

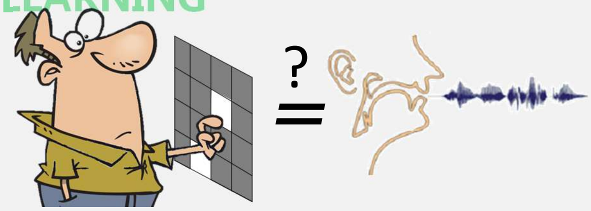
16 participants (9 F, mean 25.6 years)

RESULTS: LEARNING WITH



* $p_{FWE} < 0.05$, error bars show standard error

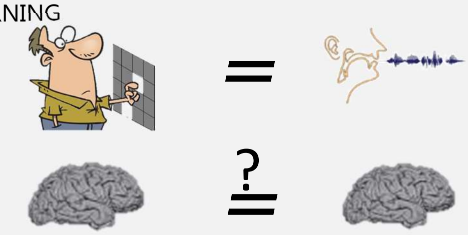
MOTOR SEQUENCE LEARNING



Question: Can we find analogous behavioral evidence for subsyllabic speech motor sequence learning?

YES!

NEURAL CORRELATES OF MOTOR SEQUENCE LEARNING



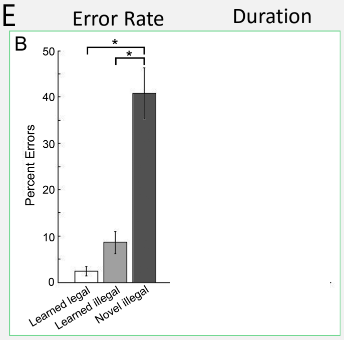
Question: What are the neural correlates of speech motor sequence learning? How do they relate to non-speech motor sequence learning?

PARADIGM: NEUROIMAGING

1. Learned **LEGAL**
   - e.g. FREMP
   - **Legal** consonant clusters in English
2. Learned **ILLEGAL**
   - e.g. FSEFK
   - **Illegal** (or highly infrequent) consonant clusters in English
3. Novel **ILLEGAL**
   - e.g. TPIPF
   - **Illegal** (or highly infrequent) consonant clusters in English

RESULTS: LEARNING WITH PRACTICE

Error Rate　　Duration



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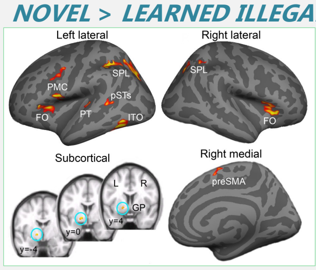
RESULTS: MAIN EFFECT OF LEARNING

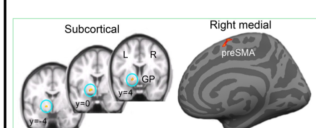
NOVEL > LEARNED ILLEGAL



	Region	Talairach coord x	y	z	t	Size
L	PMC/IFS	-46.4	2.0	38.6	4.15	157 mm^2
	PMC/IFo	-47.5	8.7	9.3	5.89	261 mm^2
	FO	-44.4	26.2	3.3	6.14	212 mm^2
	PT	-44.4	-27.6	3.6	4.12	57 mm^2
	pSTS	-52.3	-40.5	7.4	4.68	100 mm^2
	SPL	-35.9	-40.4	36.1	7.37	361 mm^2
		-27.2	-62.7	26.4	5.34	445 mm^2
	ITO	-48	-53.4	-6.6	8.77	308 mm^2
	GP	-14.8	-38.1	-4.82	4.70	376 mm^3
R	PreSMA	7.5	7.4	53.4	4.14	87 mm^2
	FO	29.3	26.9	0.9	5.70	329 mm^2
	SPL	24.9	-56.3	36.9	5.16	136 mm^2
		29.2	-49.8	40.3	4.68	92 mm^2

Voxel-corrected at $p < 0.001$ (uncorrected)
Cluster-corrected at CWP < 0.05, corrected for 1 subcortical and 2 hemisphere cortical analyses

RESULTS: PRESMA - BASAL GANGLIA LOOP



- Consistently implicated in non-speech motor sequence learning
- **Motor chunk initiation and/or formation**

Contreras-Vidal (1999). *Prog Brain Res*, 121, 261-276. Graybiel (1998). *Neurobiol Learn Mem*, 70, 119-136. Hikosaka et al. (1996). *J Neurophysiol*, 76, 617-621.

SYLLABIC STRUCTURE

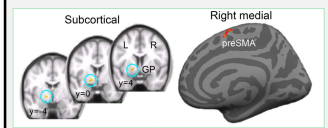
Syllable: GVAZF

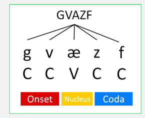
Phonemes: g v æ z f

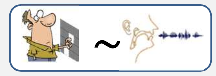
C C V C C

Subsyllabic Constituents (SSCs): Onset | Nucleus | Coda

RESULTS: PRESMA - BASAL GANGLIA LOOP



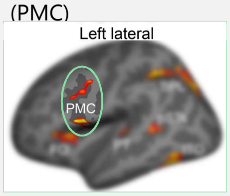


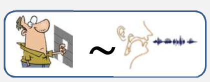


- Consistently implicated in non-speech motor sequence learning
- **Motor chunk initiation and/or formation**
- **In subsyllabic speech motor sequence learning:**
  - *Novel*: Phoneme chunks
  - *Learned*: SSC chunks
  - Fewer chunks = less activity

Contreras-Vidal (1999). *Prog Brain Res*, 121, 261-276. Graybiel (1998). *Neurobiol Learn Mem*, 70, 119-136. Hikosaka et al. (1996). *J Neurophysiol*, 76, 617-621.

RESULTS: LATERAL PREMOTOR CORTEX (PMC)

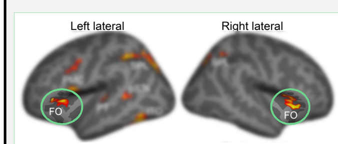


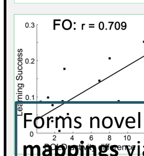


- Adjacent to motor representations of larynx, lips, and tongue
- Hypothesized to store **mental syllabary**
  - **Frequently used feed-forward speech motor programs**
- *Learned sequence* uses fewer chunks (SSCs v phonemes) and therefore fewer motor programs
- In **non-speech** motor sequence learning studies
  - In *novel* > *learned* contrasts, **dorsal** premotor areas (adjacent to **hand** motor representations)

Grabinski et al. (2012). *HBM,* 33, 2306-2321. Guenther (2006). *J Commun Disord* , 39, 5, 350-365. Tourville & Guenther (2011). *Lang Cog Proc*, 25, 952-981.

RESULTS: FRONTAL OPERCULUM / ANTERIOR INSULA (FO)





Implicated in:

- Correcting speech movements based on **auditory feedback**
- Learning to perceive and produce **novel phonemes**
- **Phonological** processing during reading and listening

Forms novel **orthography-motor & auditory-motor mappings** via **phonological** representations

Christoffels et al. (2007). *HBM*, 28, 9, 868-879. Dogil, et al. (2002). *J Neurolinguistics*. 15, 59-90. Golestani & Pallier (2007). *Cerebral Cortex*, 17, 4, 929-934. Golestani & Zatorre (2004). *NeuroImage*. 21, 494-506. Price (1998). *TICS,* 2, 8, 281-288

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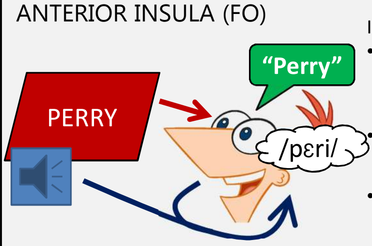

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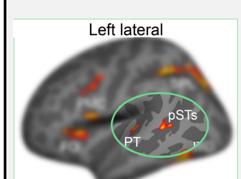
RESULTS: PLANUM TEMPORALE (PT) & POSTERIOR SUPERIOR TEMPORAL SULCUS (pSTs)



- Implicated in auditory-phonology conversion
- Implicated in correcting speech movements based on **auditory feedback** (DIVA/SFC models)
- Greater activity in *novel* over *learned* may reflect:
  - ↑ errors or
  - ↑ attention to auditory feedback

Gow (2012). *Brain Lang* 121, 273-288. *Guenther* (2006). *J Commun Disord* 39, 5, 350-365. Hickok (2012). *Nat Rev Neurosci*, 13, 135-145. Turkeltaub et al. (2003). *Nat Neurosci* 6, 6, 767-773. Turkeltaub, et al. (2010). *Brain Lang* 114, 1, 1-15

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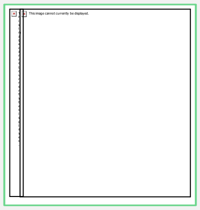


- Positive correlation with white matter anisotropy
  - ↑ WM integrity, ↑ learning success
  - Suggests **neuroanatomy mitigates learning ability**
  - Underlying learning success:
    - Ability to **adjust motor program based on auditory feedback**, OR
    - Ability to **map between phonological and articulartory representations**

Guenther (2006). *J Commun Disord*, 39, 5, 350-365. Hickok (2012). *Nat Rev Neurosci*, 13, 135-145. Parker Jones (2013). *J Neurosci*, 33, 6, 2376-2387

THE BOTTOM LINE…

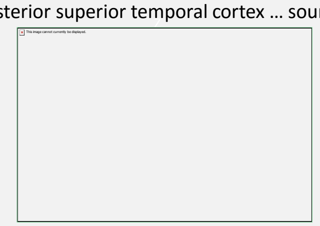
Similar mechanisms may be used, but…

Different **modalities** → different **neural correlates**
- Different end articulators
- Different feedback mechanisms

SPEECH MOTOR SEQUENCE LEARNING IN PEOPLE WHO STUTTER

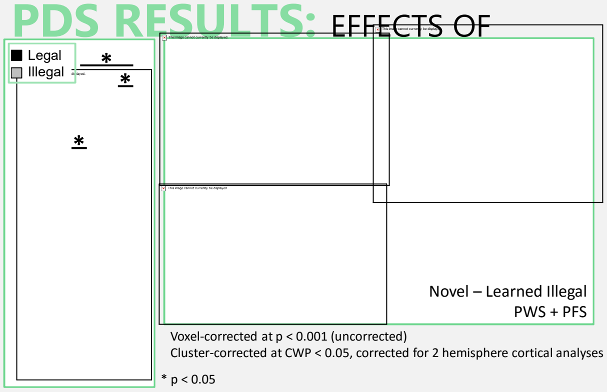
WHY PERSISTENT DEVELOPMENTAL STUTTERING?

- **Speech disorder:** First develops around the age of 3, as children are beginning to produce complex speech sequences
- **Speech sequencing disorder:** People who stutter (PWS) show (speech) motor sequence learning deficits
- Brain areas most implicated in stuttering, e.g., basal ganglia, preSMA, posterior superior temporal cortex … sound familiar?



*Smits-Bandstra & De Nil (2009). *Clin Linguist Phon*, 23, 1, 38-57. Buddhe et al. (2014). *Brain Lang*, 139, 99-107. Chang et al. (2010). *NeuroImage*, 46, 1, 201-212.

PDS RESULTS: EFFECTS OF

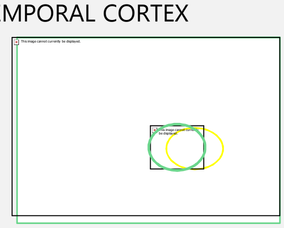


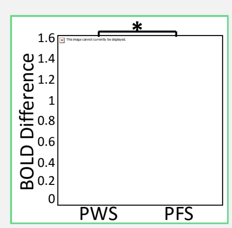
Voxel-corrected at $p < 0.001$ (uncorrected)
Cluster-corrected at CWP < 0.05, corrected for 2 hemisphere cortical analyses

* $p < 0.05$

14 PWS (SSI range: 13-43, mean: 24), 14 PFS

RESULTS: POSTERIOR SUPERIOR TEMPORAL CORTEX





↑PWS activity in pSTg

Chang et al. (2009). *NeuroImage*, 46, 201-212. Luc et al. (2008). *Brain Lang*, 107, 114-123. Watkins et al. (2008). *Brain*, 131, 50-59.

*$p_{FDR} < 0.05$

MANY THANKS TO:

FRANK GUENTHER
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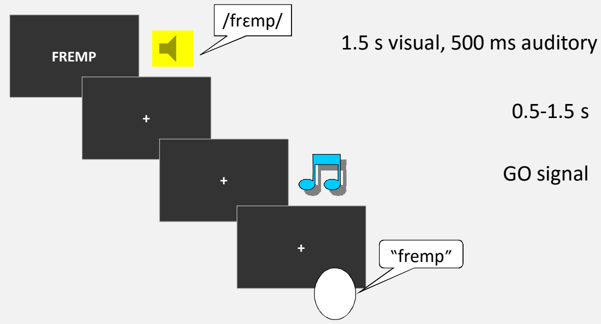
ELISA GOLFINOPOLOUS
ALFONSO NIETO CASTAÑÓN
ANNA OH
JASON TOURVILLE

THANK YOU.

PARADIGM: PRACTICE



SPEECH MOTOR SEQUENCE LEARNING (FMRI): SPEECH STIMULI

Legal					
BLERK	FREMP	KRENGTH	TRALP	GWEFTH	SPRIDTH
BRALK	GLANCH	PLARTH	THRIMF	TWERVE	SWARF
DRALF	GRALVE	PRENGE	DWILM	THWILB	SKELN
FLISK	KLELTH	SHRIDTH	KWANST	SPLERST	STISP
Illegal					
FSEFK	VTHASHP	SHTAZG	BVIMPF	TVITP	PTACHST
FSHIKP	ZVEKCH	VBIMK	BZINSCH	BDANGT	TBASTF
FTHAMCH	FPESCH	VGAMSH	GVAZF	DKEDV	TGITK
FZICHB	FTEBSCH	ZBAPK	KVACHK	GBESB	TPIPF
VSEPSH	SHKEVT	ZDEBG	TFIPSHCH	KPESHCH	ZGEKF

LEARNED ILLEGAL VERSUS *NOVEL ILLEGAL*

1.	VGAMSH	*Novel*
2.	VSEPSH	
3.	FTEBSHCH	*Learned*
4.	VTHASHP	

SONORITY HIERARCHY

Sonority Index	Sound
10	[a]
9	[e o]
8	[i u]
7	[r]
6	[l]
5	[m n]
4	[s]
3	[v z ð]
2	[f Ɵ]
1	[b d g]
0.5	[p t k]

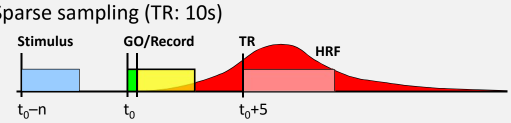
Relational theory of the syllable
e.g. SI(x) ≤ 8

- Minimum sonority difference
- e.g. SI(y) ≤ SI(x) – n
- English: ~ 4 ([s] is an exception)

Selkirk (1984). In *Language Sound Structure* , pp.105-136,

PARADIGM: FMRI

- Siemens 3T Trio Tim, 32 channel head coil
- Functional voxel size: 3.1 x 3.1 x 3 mm
- Sparse sampling (TR: 10s)



- Also collected DTI volume
  - Voxel size: 2mm^3

Hall et al. (1999). *HBM*, 7, 213-233.

ANALYSIS: FMRI 1ST LEVEL

- **Nipype** – interface across neuroimaging analysis software packages
  - **SPM8**: Functional volumes motion-corrected, high-pass filtered, aligned to subject's anatomical volume
  - **RAPIDART**: Errors, intensity- and motion-outliers removed
  - **SPM8**: GLM estimated for each subject
    - Utterance duration regressor included

Ghosh et al. (2010). *OHBM*, Barcelona, Spain.
http://www.fil.ion.ucl.ac.uk/spm/software/spm8. http://www.nitrc.org/projects/rapidart/

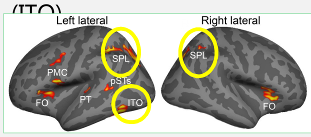
ANALYSIS: FMRI 2ND LEVEL

- Cortical results (**Freesurfer**)
  - Individual contrast volumes projected onto an average brain surface using spherical projection
  - Smoothed: 6mm FWHM
  - T-statistics at each vertex
- Subcortical results (**SPM8**)
  - Individual T1s normalized to MNI152 template (DARTEL)
  - Individual contrast volumes registered
  - Smoothed: 6mm FWHM

- Voxel thresholded at $p < 0.001$ (uncorrected)
- Cluster thresholded at CWP < 0.0167 (corrected for 3 analyses – 2 cortical and 1 subcortical)
  - Calculated with Monte Carlo simulations

Fischl et al. (1999). *HBM*, 8,272-284. Ashburner (2007). *NeuroImage*, 38, 1, 95-113. Klein et al. (2009). *NeuroImage*, 46, 3, 786-802. Hayasaka & Nichols (2003). *NeuroImage*, 20, 2343-2356

RESULTS: SUPERIOR PARIETAL LOBULE (SPL) & INFERIOR TEMPORAL-OCCIPITAL CORTEX (ITO)



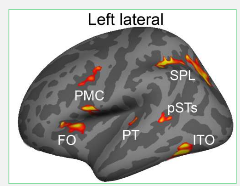
SPL
- Shifting visual attention or shifting between multi-modal stimuli

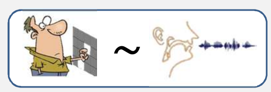
ITO
- Proposed visual word form area

Novel > *learned* implies:
- Greater attention to visual stimulus for *novel*

Coull & Frith (1998). *NeuroImage*. 8, 176-187. McCandliss, et al. (2003). *Trends in Cog Sci*. 7, 7, 293-299. Shomstein & Yantis. (2004). *J Neurosci*. 24, 47, 10702-10706.

RESULTS: INFERIOR FRONTAL SULCUS (IFS)





- Implicated in verbal working memory
- Non-speech motor sequence learning
  - Dorsal lateral prefrontal cortex (dlPFC) consistently implicated
  - Tasks use visual/spatial cues
  - dlPFC also implicated in visual working memory

METHODS: DTI

- Diffusion-weighted images analyzed with FMRIB Diffusion Toolbox
  - Eddy-current and motion corrected
- Diffusion tensors fitted at each voxel (in cortical mask)
- Volumes registered to individual subjects' anatomical volume

- ROIs from *novel > learned illegal* contrast
  - Used voxels 2mm below grey-white boundary
  - Mean FA across voxels within ROI

- For FA-BOLD correlation, LOSO analysis to avoid "voodoo" correlations

Gotts, et al. (2012). *Cog Neurosci* 3, 3-4, 250-259.