THE REPRESENTATION OF SYLLABIC FRAME STRUCTURES AND PHONOLOGICAL CONTENT IN THE BRAIN

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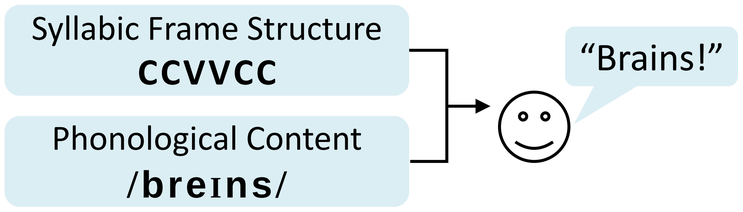
Background

- The **slot/filler** theory (Shattuck-Huffnagel,1979) and the **frame/content** theory (MacNeilage, 1998) both posit that:
  - The phonological content of a speech utterance is represented **in parallel** with its structure and timing



- For instance, Spoonerisms (or exchange errors) occur when two phonemes in different syllables, but in the same syllable position exchange places
  - e.g. "**d**ear old **qu**een" → "**qu**eer old **d**ean"
  - Suggests that phonemes and their syllable position information are represented separately at some processing stage
- These theories have been implemented in several influential models of speech (GODIVA, WEAVER++, Coupled Oscillator)
- **However, a neural basis of the syllabic frame is largely unexplored.**
- Previous work (Peeva et al., 2010) showed a syllabic representation in the ventral premotor cortex, but did not differentiate between representations of a syllabic frame and a full syllable (with phonological content)

Methods

- *Subjects*: 17 American English speaking subjects
- *Stimuli & Paradigm*
  - **FMRI repetition suppression (fMRI-RS) paradigm**
    - BOLD response **decreases across repeated presentations of stimulus** in a region that processes that stimulus

Buckner et al., (2011) *J Neurophysiol.* 105, 5, 2322-45. Fischl et al. (2002) *Cereb Cortex.* 14, 1, 11-22. Guenther et al. (2006) *Brain Lang.* 96, 280-301. Hazeltine et al. (1998) *TICS.* 1, 3, 163-169. Koch et al. (2007) *Exp Brain Res.* 179, 291-299. Levelt & Wheeldon (1994) *Cognition.* 50, 239-269. MacNeilage (1998) *Beh Brain Sci.* 21, 499-511. O'Reilly et al. (2010) *Cereb Cortex.* 20 (4): 953-965. Peeva et al. (2010) *NeuroImage.* 50, 628-638. Shattuck-Huffnagel (1979) In *Sentence Processing: Psycholinguistic studies presented to Merrill Garrett.* Hillsdale, NJ: Erlbaum. Stoodley & Schmahmann (2009) *NeuroImage.* 15, 44, 489-501. Tourville et al. (2008) *NeuroImage.* 39, 3, 1429-1443. Tourville & Guenther (2003) *Boston University Technical Report CAS/CNS-03-022.* Boston, MA: Boston University.

4 speaking conditions varying by how often each type of speech representation – syllabic frame, phoneme, or complete syllable – was repeated between pairs of pseudowords

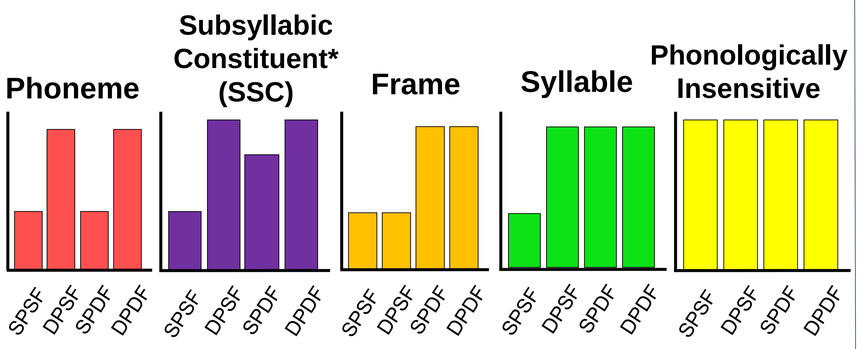
SPSF	DPSF	SPDF	DFDF
Same phonemes **Same** frames	**Different** phonemes **Same** frames	**Same** phonemes **Different** frames	**Different** phonemes **Different** frames
TWAI	FAS	RAUD	DEEF
TWAI	REEN	DRAU	GLAI
TWAI	FAS	RAUD	DEEF
TWAI	REEN	DRAU	GLAI
TWAI	FAS	RAUD	DEEF
TWAI	REEN	DRAU	GLAI

time ↓

- Auditory & orthographic presentations of each target pseudoword (0.7 & 1.5 s)
- Blocks consisted of 6 trials followed by a 3 s pause

- *fMRI acquisition*
  - Siemens Trio Tim 3T, 32 channel head coil
  - TR: 2.5 s, 41 slices, Skip: 25%, 200mm coverage
  - Voxel size: 3.1 x 3.1 x 3.0 mm
- *fMRI analysis*
  - Functional volumes realigned to subject's anatomical volume, corrected for slice acquisition timing, and first level model estimated with **SPM8**.
  - ROI parcellation: cortical (surface-based speech-focused, Tourville & Guenther, 2003), subcortical (Fischl et al., 2002), and cerebellar (Diedrichsen, 2001)
  - Contrast values – *1st half of block vs. baseline (silent fixation)* for each speaking condition – extracted and averaged across each ROI using **REX** (http://web.mit.edu/swg/rex)
    - Normalized by average activity across each ROI

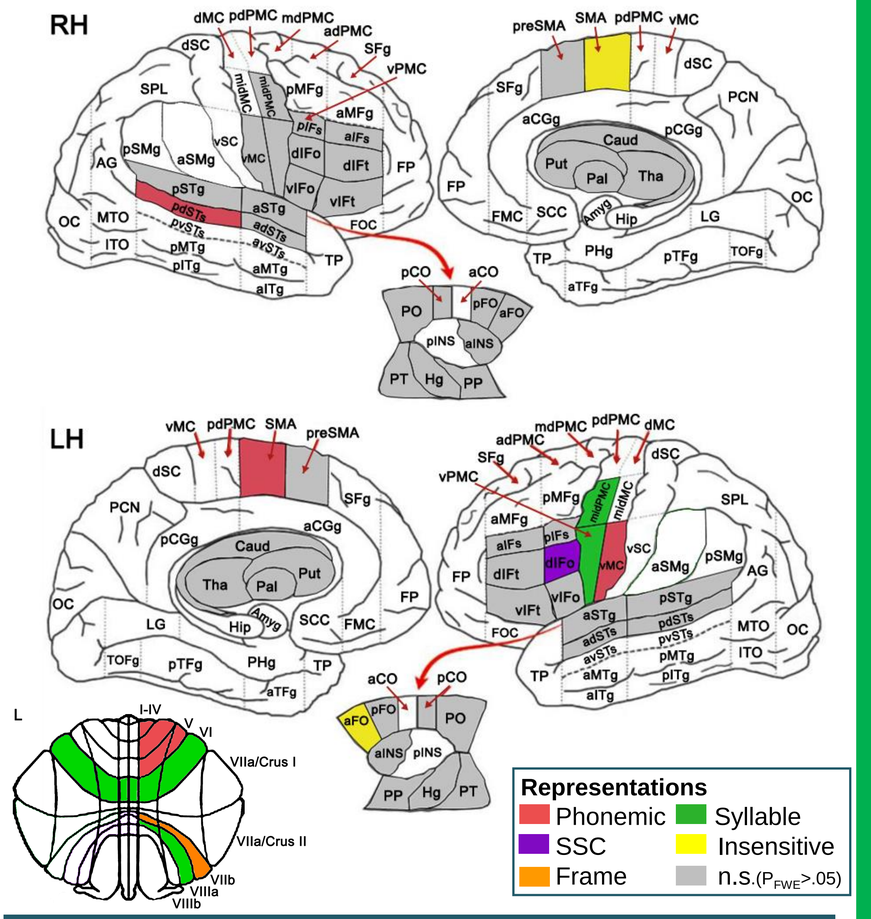
5 hypothesized patterns of across-condition fMRI-RS



*Here, SSCs refer to onset, nucleus, and coda subsyllabic constituents

- *Across-condition pattern matching within ROIs* (Peeva et al., 2010)
  - *A priori* models defined by BOLD activity comparisons across conditions
  - Model fit quantified by conjunction test comparing the 4 speaking conditions based on 5 predicted patterns of repetition suppression at each speech production ROI
  - Significance threshold of $P_{FWE} < 0.05$
    - Where P is derived from distribution of values from Monte Carlo simulation with 10,000 trials

FMRI-RS Pattern Matches



Discussion

Left lateral prefrontal cortex

- Two representations:
  - **Syllable** in middle and ventral premotor cortex
  - **SSC** in posterior inferior frontal gyrus, pars opercularis
  - Both areas hypothesized to store **feedforward motor commands for speech** (Guenther, 2006; Levelt & Wheeldon, 1994)
  - Suggests that either:
    - **SSC** motor programs are used to construct **syllable** motor programs for execution, or
    - **SSC** motor programs are used for utterances in which **syllable** motor programs are not available

Cortico-cerebellar loops

- Functional and anatomical cortico-cerebellar connections (Buckner, et al., 2011; O'Reilly, et al., 2010)
- **Anterior cerebellum, right lobules I-IV & V**
  - Sensorimotor processing (e.g. Stoodley & Schmahmann, 2009)

    Phoneme representation for motor execution & auditory stimulus processing
    - Loop with superior temporal cortex, M1, SMA
- **Lateral cerebellum, bilateral lobule VI & right lobule VIIIa**
  - Language, articulation, and auditory speech feedback processing (e.g. Stoodley & Schmahmann, 2009; Ackermann et al., 1992; Tourville et al.,2008)

    Syllable representation for monitoring & modulating feedforward speech motor programs with auditory feedback
    - Loop with lateral premotor cortex

Cerebellar representation of speech structure and timing

- **Lateral cerebellum, right lobule VIIB**

  Frame representation for millisecond range timing and movement synchronization (Hazeltine, et al., 1998; Koch, et al., 2007) of speech utterances