Information in Spoken Language

A quantitative approach

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LOT winterschool 2006

Introduction

Speech is a communication channel

- Communication channels have a bandwidth
- A communication channel should be efficient
- Efficiency can be achieved on several levels:
- Encoding
- Compression (acoustic, phoneme, word)
- Fault tolerance
- In short: Spend effort and bandwidth according to communicative importance

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Efficiency: Efficiency

Effort vs Bits

- For recognition, words and phonemes should be as distinct as possible
- Distinction is determined by:
- Duration: longer means more time to recognize
- Loudness: Dynamic range should be large
- Spectal width: Use whole available spectrum
- Articulation: Precise, consistent articulation
- All of these cost more effort
- For speaking, making distinctions is difficult

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- Assume importance are just lexical bits
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Efficient speech is a testable hypothesis

- A correlation between Reduction (compression) and Bit-load
- Two hypotheses:
- *Smooth signal redundancy hypothesis* [Aylett and Turk(2005)]
- → Prosody structure implements compression
- *Phoneme level reduction*
- → Compression at the lowest levels, down to the phoneme

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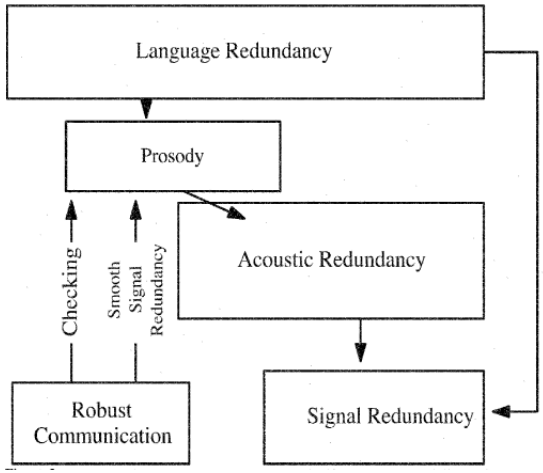

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- Redundancy in the language affects prosody
- Prosody *reduces* redundant articulation
- Determine the distribution of lexical information over prosodic and non-prosodic features

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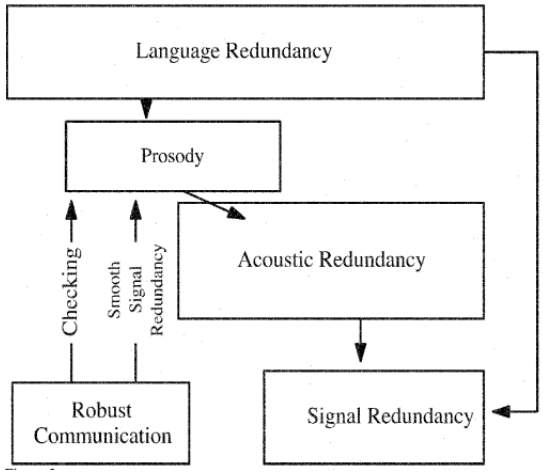

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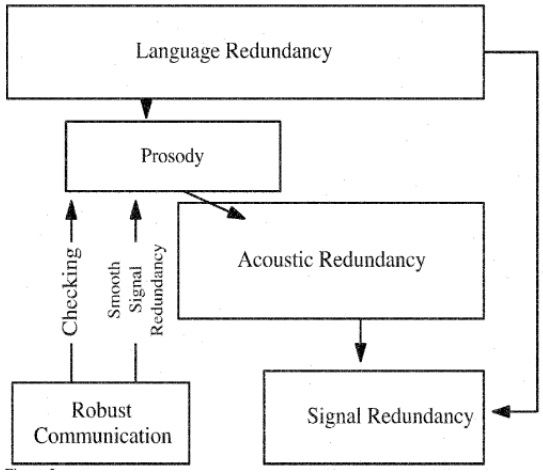

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Vowel inventories

At the lowest level, speech is encoded in phonemic segments. Phonemes are the first candidate for compression

- Efficient use of available perceptual/articulatory space
- In vowel formant (F_1/F_2) space:
- Distribute vowels to be far apart
- Spread them evenly
- Use complex articulations only if space is full
- Start with corner vowels /i a u/
- Construct symmetric systems
- If full, start to use *quantity* (duration), *diphthongs*, *nasalization*

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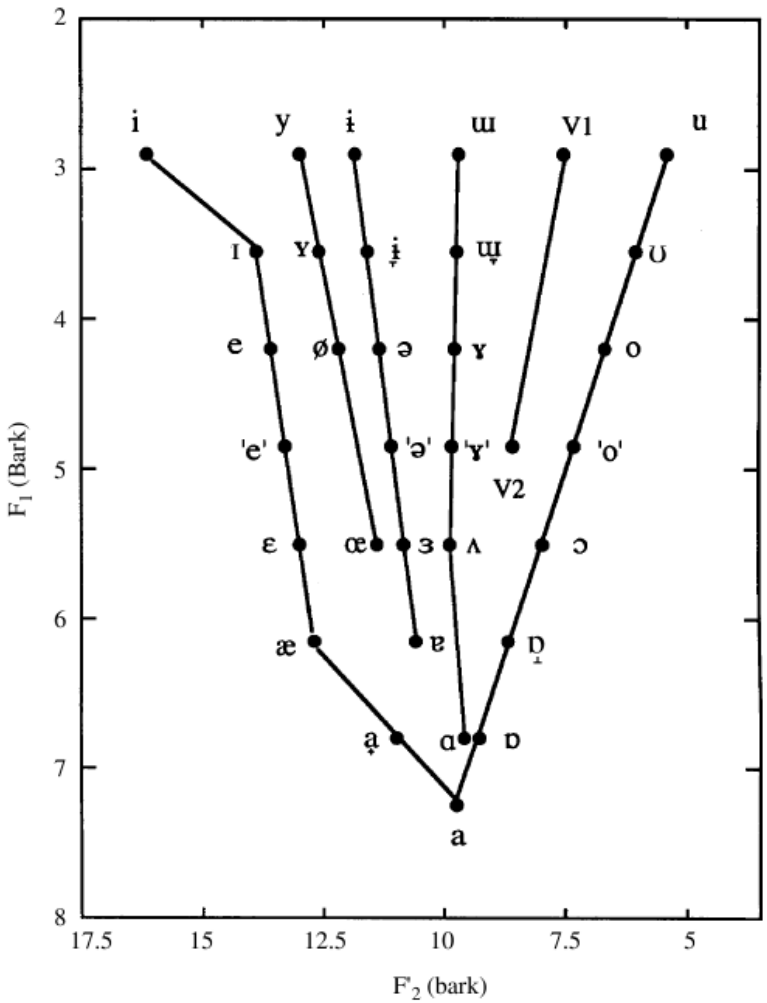

Acoustic vowel space

- Acoustic properties of all monotphthongs
- Probably no language has them all
- Distinguishing them all is "difficult"
- Both in *speaking* and *hearing*

[de Boer(2000)] [Schwartz et al.(1997)Schwartz, Boë, Vallée, and Abry]

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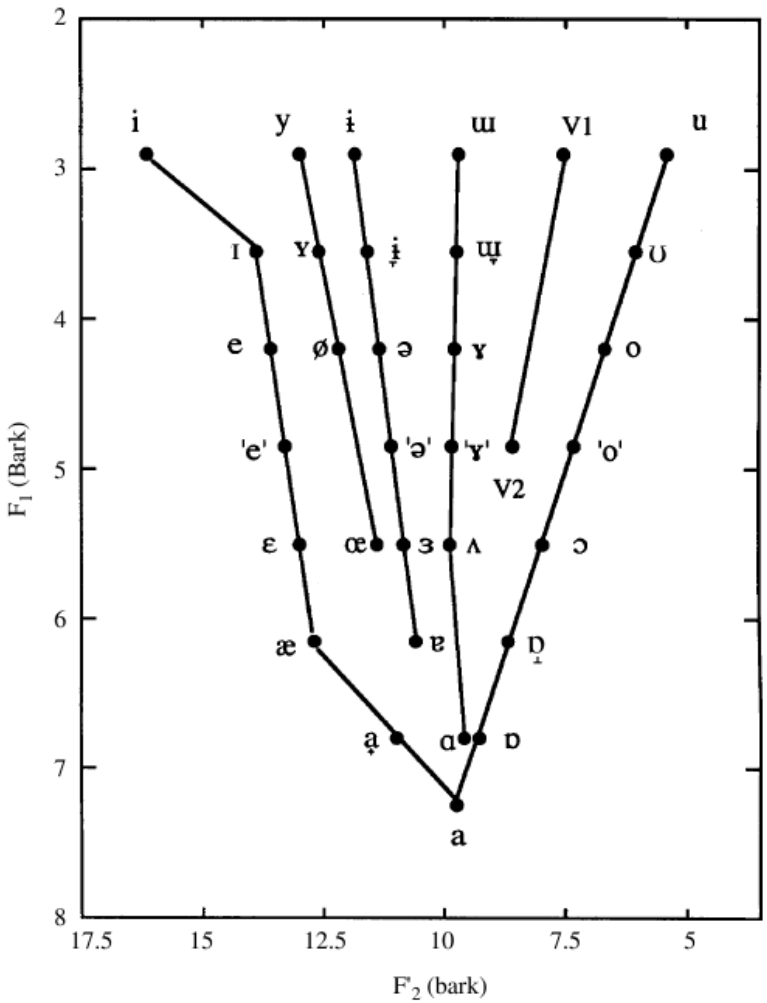

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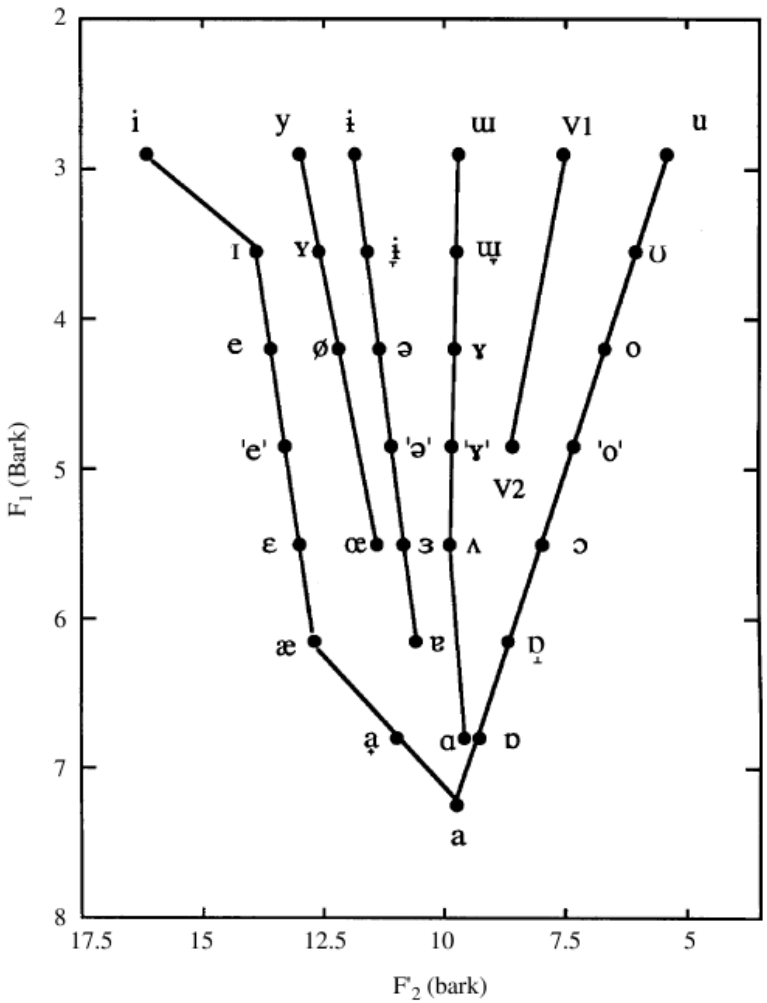

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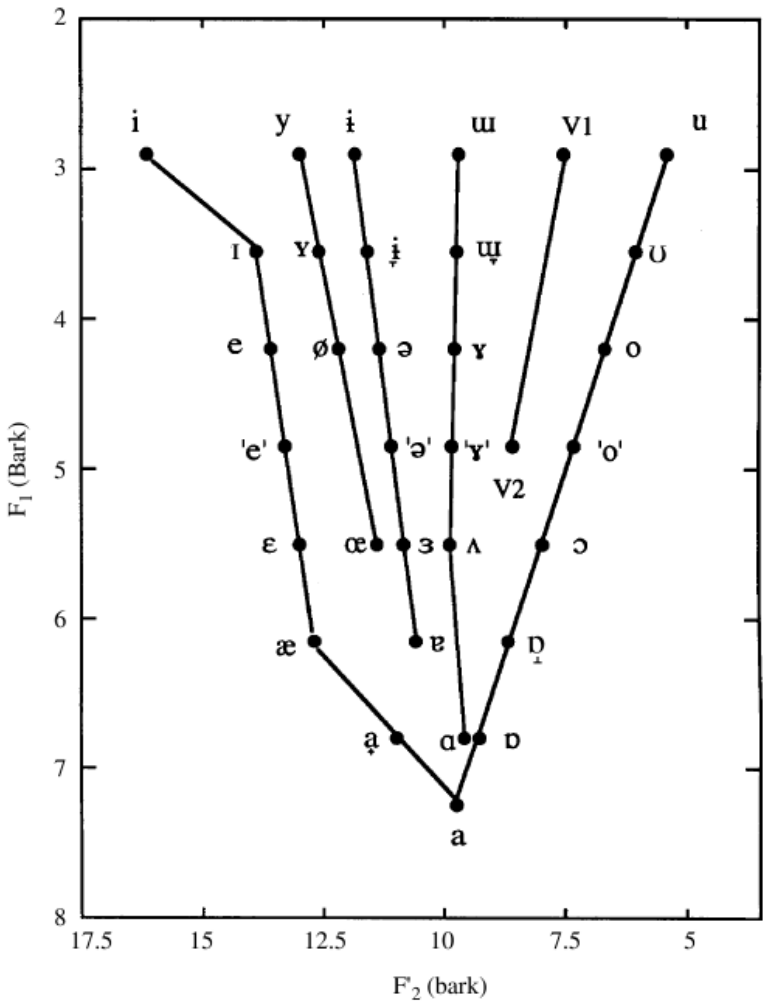

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Vowel inventories

number of vowels	Vowel system and number of occurrences (UPSID)				
3	 14				
4	 14	 5	 4	 2	
5	 97	 3			
6	 26	 12	 12	 4	
7	 23	 6	 5	 4	 3
8	 6	 3	 3	 2	
9	 7	 7	 3		

Distribution of vowels versus inventory size over languages

- 5 vowel inventory is most popular (100 languages)
- For every size, the most even distribution is overwhelmingly chosen

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Languages try to optimize vowel spaces

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Word length: Number of phonemes

$I = -log_2(frequency)$	R	N	Token Count
$-log_2(TF)$	0.300	69,501	>10 (CELEX)
$-log_2(TF)$	0.186	259,984	>10 (TNC)
$-log_2(TF \cdot IDF)$	0.319	259,984	>10 (TNC)
$-log_2(TF) - CD$	0.379	259,984	>10 (TNC)
$-log_2(TF)$	0.686	11,337	all (IFA, usage)

TF: Term Frequency, $TF \cdot IDF$: TF time Inverse Document Frequency,

CD: Context Distinctiveness [Van Son(2003)][Ordelman(2002)]

An efficient coding of words would make high-frequency words short and low frequency words long

- The correlation is rather high in the small CELEX wordlist
- The TNC (350 Mword) shows the correlation increases with context
- On a token basis, ie word occurences, almost half the variance in length is explained

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R (N) for Read and Spontaneous speech

Style	all	$l \leq 10$	$l > 10$
Read	0.720 (*29,269*)	0.428 (*14,739*)	0.489 (*14,530*)
Spontaneous	0.609 (*11,348*)	0.180 (*5,832*)	0.484 (*5,516*)

Correlation between $-\log_2()$ CELEX word frequencies and word duration

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- High frequency words tend to be shorter, both in phonemes and duration
- There is a large distinction between *Function* and *Content* words
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Phoneme reduction

Efficient speech would also mean that redundant phonemes are reduced

- Less informative phonemes should be:
  - Shorter
  - Weaker (= less loud)
  - Spectrally reduced
  - Leads to less distinctive sound segments
  - Vowels: Less contrast in F_1/F_2 formants
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Efficient speech would also mean that redundant phonemes are reduced

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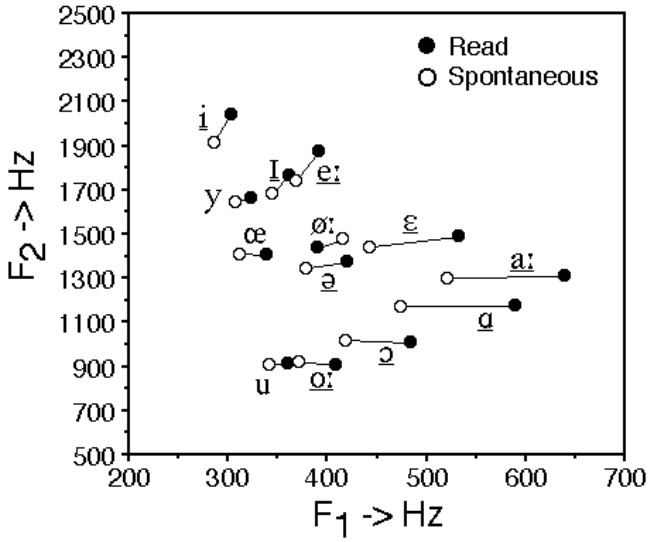

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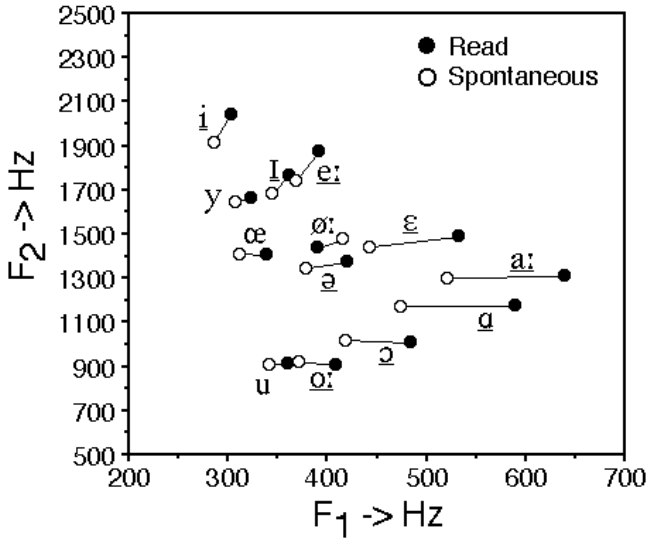

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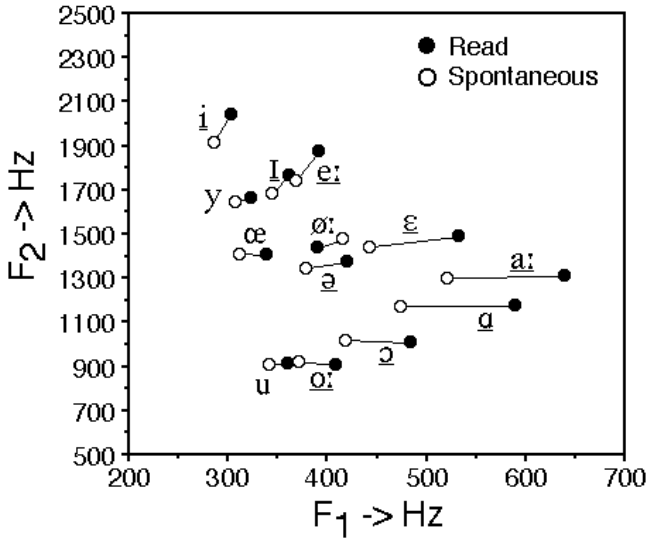

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$$I''(phon|onset, w) = -\log_2 \frac{TokenCount(onset + phon) + D(w)}{TokenCount(onset + \star) + D(w)}$$

$D(w) = (TF(w) \cdot 2^{CD(w)} - TF(w)) \cdot TotalCount$
$CD(w) = KL(LocalDistr(w), GlobalDistr)$

$TF(w)$: Term frequency of w

Focus on direct context of w: $LocalDistr(w)$

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Prosodic and structural factors determine reduction

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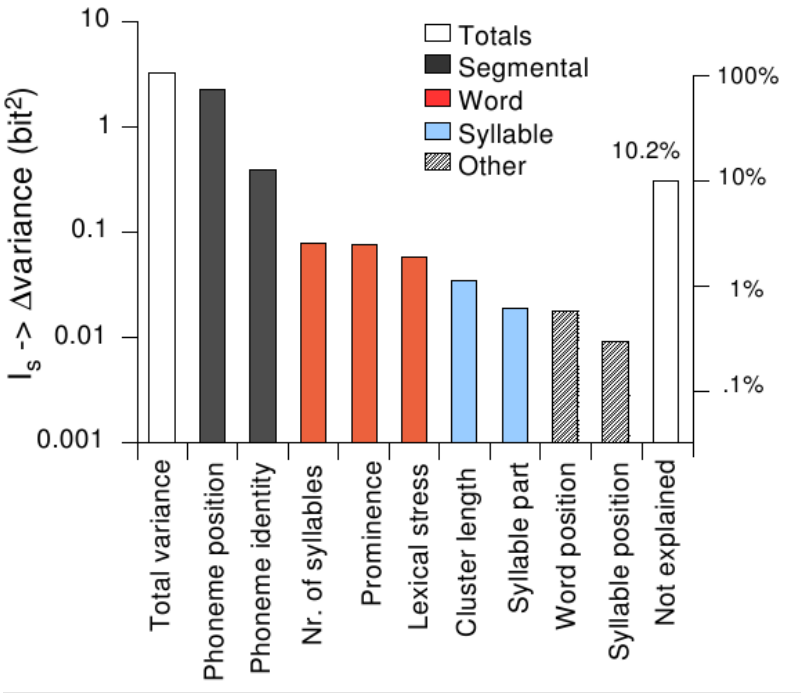

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Explained variance of I''

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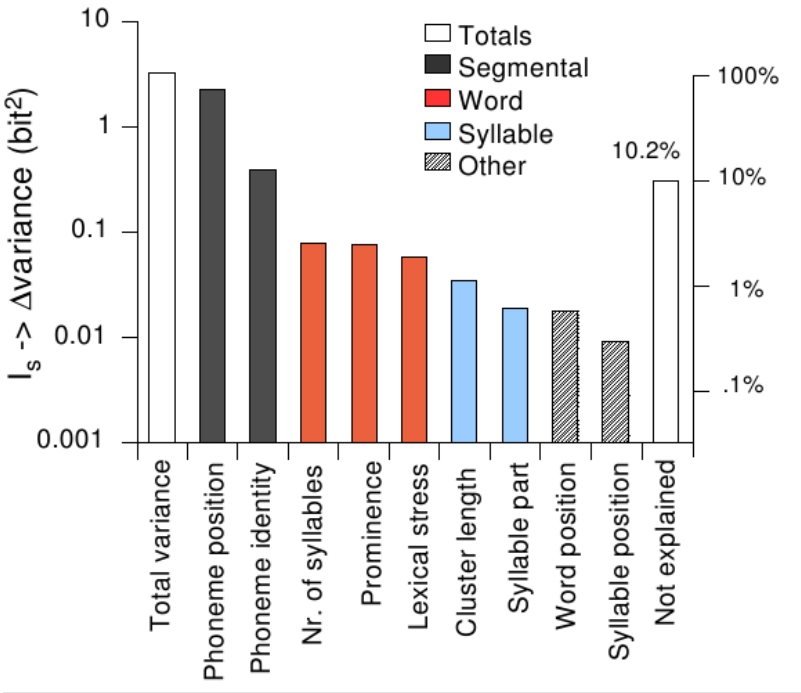

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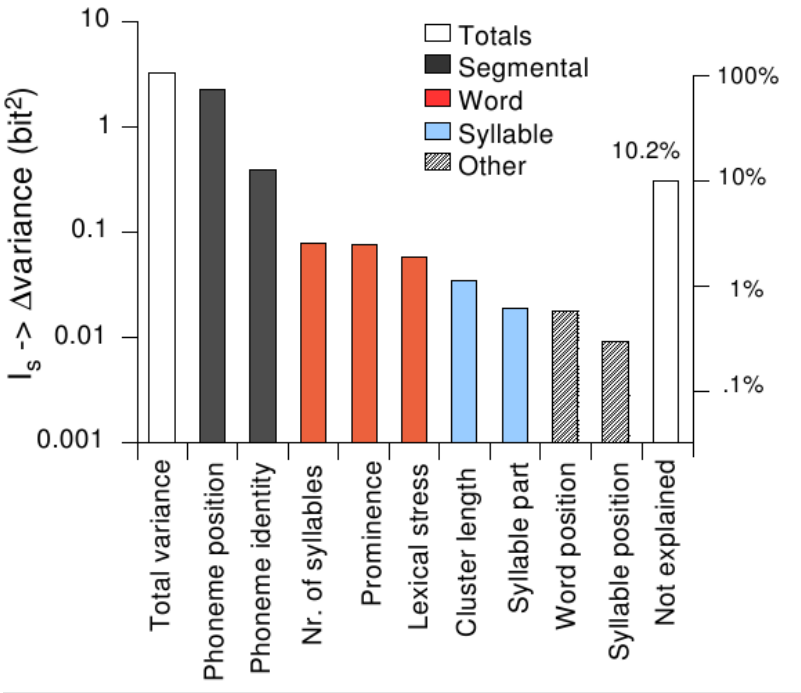

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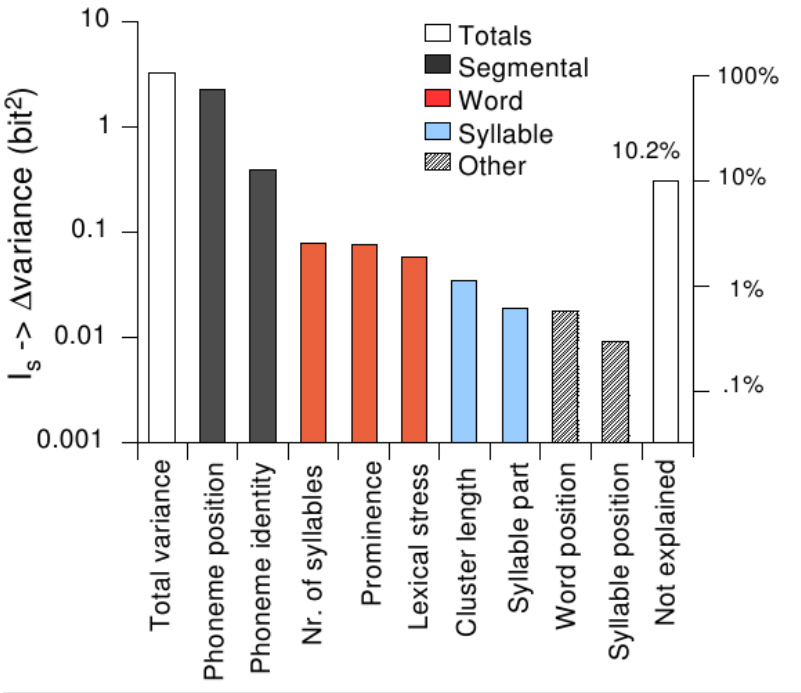

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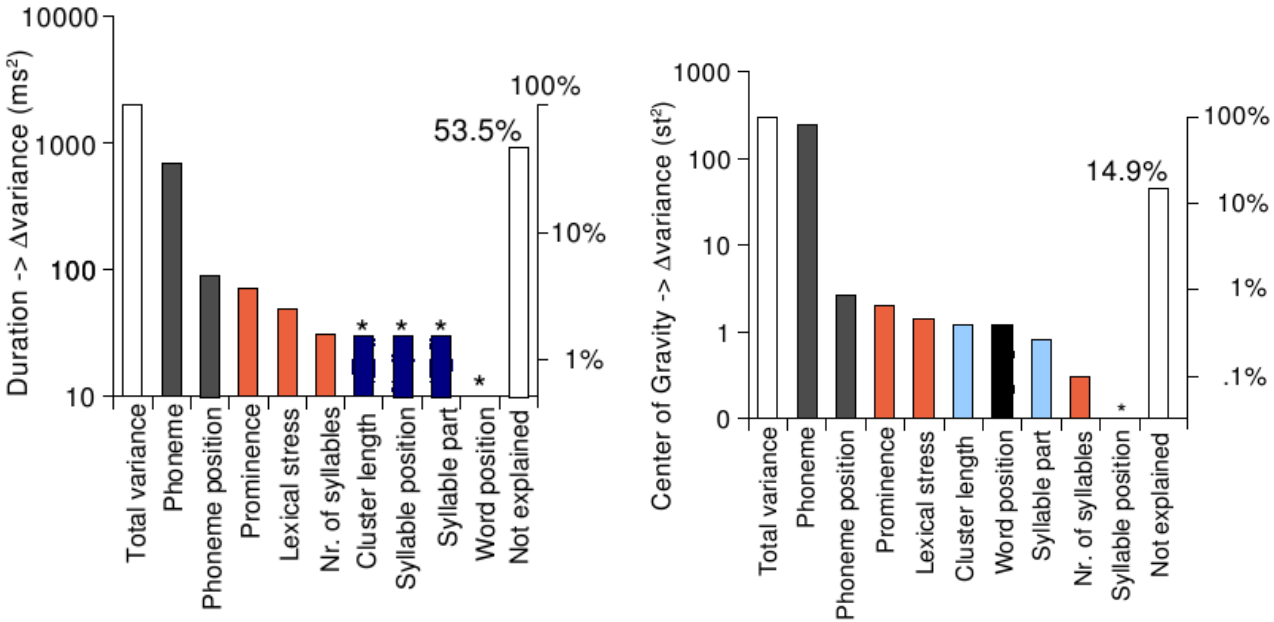

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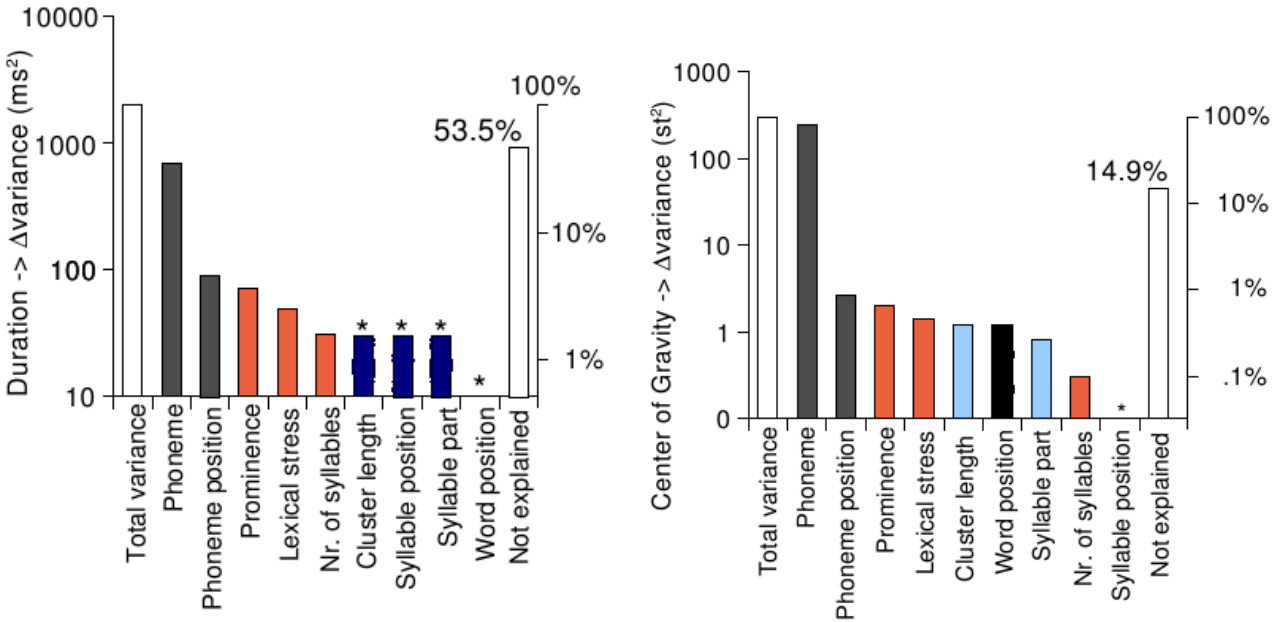

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Information structure, ie, prosody, can account for a lot of the efficiency

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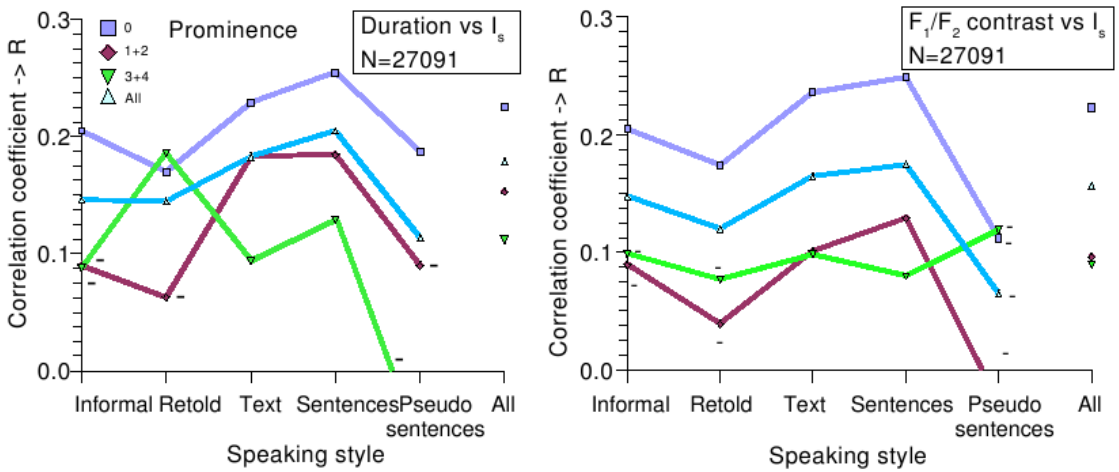

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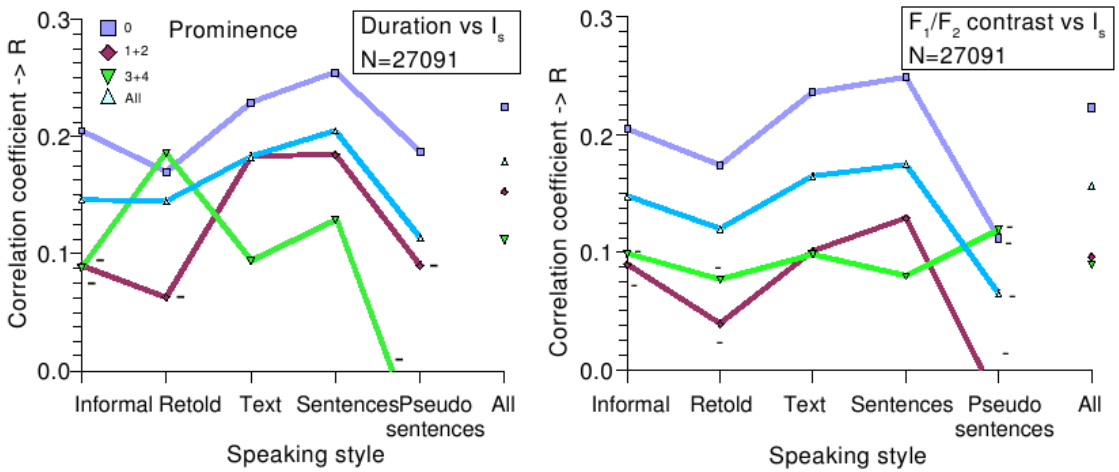

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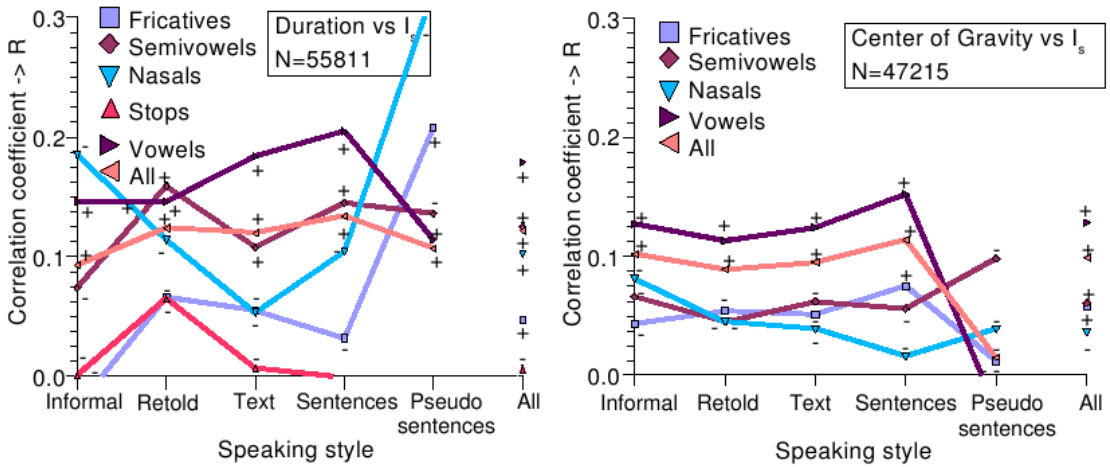

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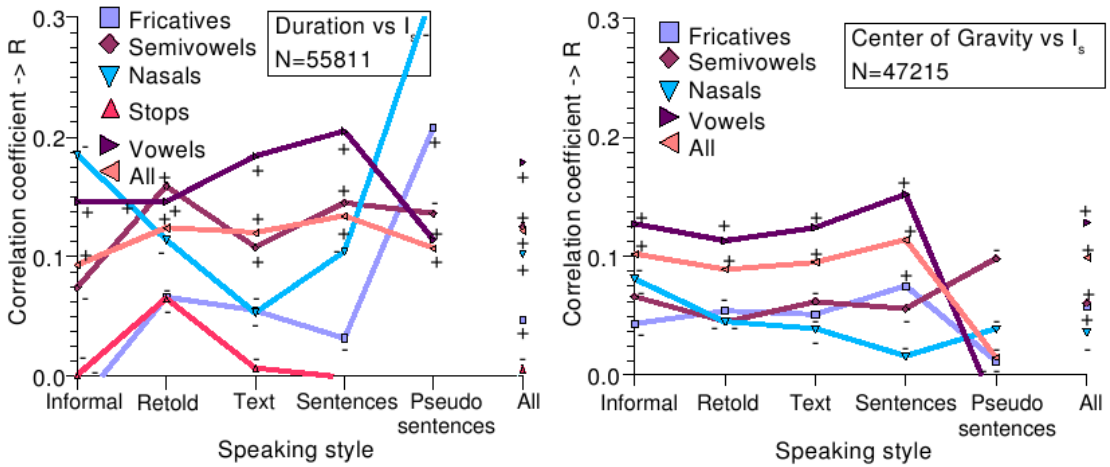

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Model duration and spectral reduction of intervocalic consonants in US English

- Remove all prosodic variation and focus on three factors:
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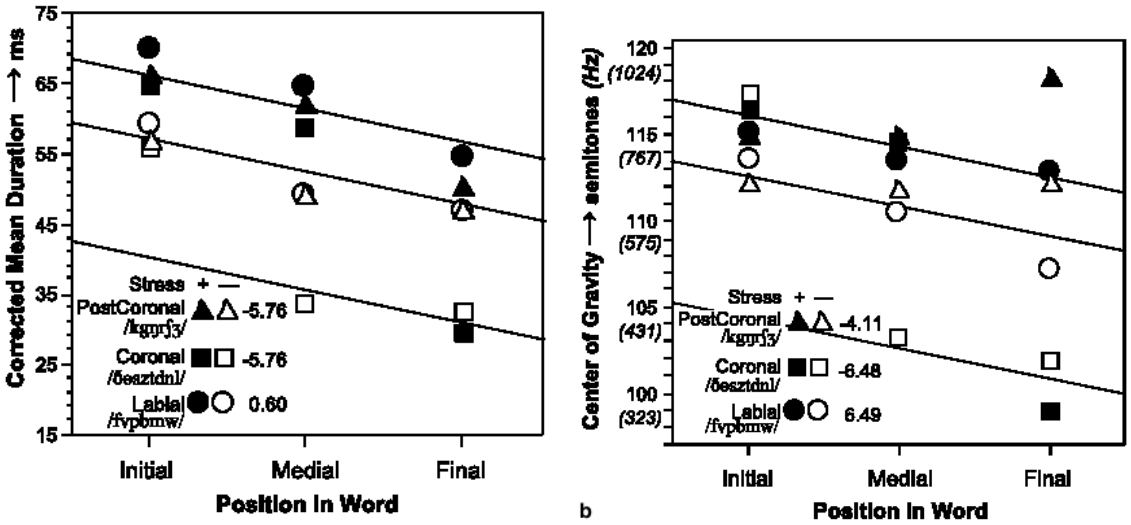

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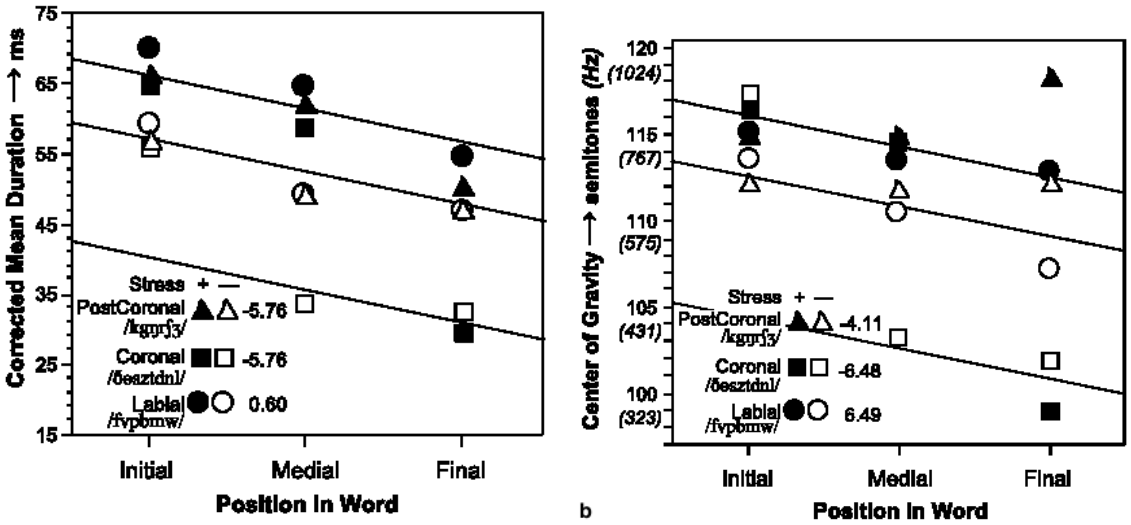

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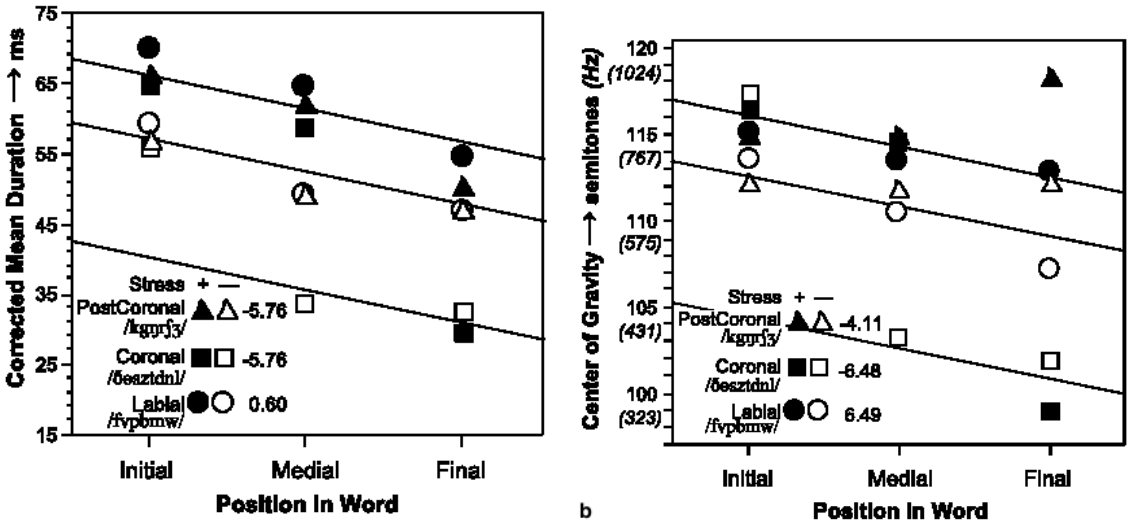

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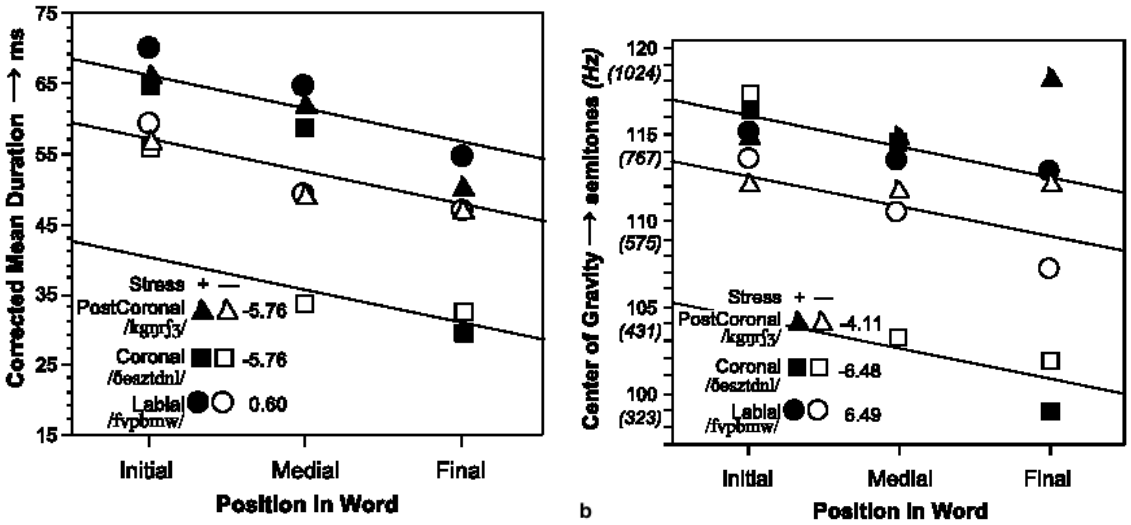

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PostCor	22% *2.21*	32% *1.65*	32% *1.66*	22% *2.18*	29% *1.79*	24% *2.05*
	Stressed Word Medial			Unstressed Word Medial		
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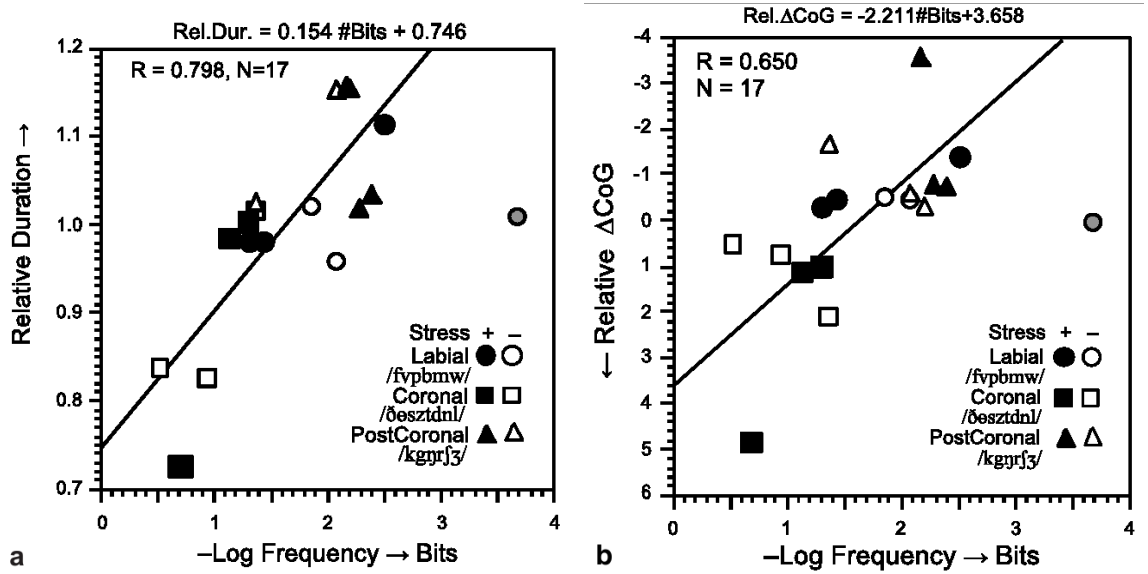
Coronal consonants are very frequent in unstressed/word-final position, C_1: intervocalic, C_N: clusters (based on US English CELEX word list)

- Strong: All word initial and stressed word medial
- Weak: Unstressed word medial and all word final
- Weak labials or Post-coronals contribute ≥ 2 bits
- Weak coronals contribute < 1 bit

[Van Son and Van Santen(2005)]

Stress and Position



Correlate variation (reduction) versus information content

- Most dots lie on a straight line
- Special behavior of weak coronals /sztdnl/ understandable
- Consonant reduction explainable from information content

[Van Son and Van Santen(2005)]

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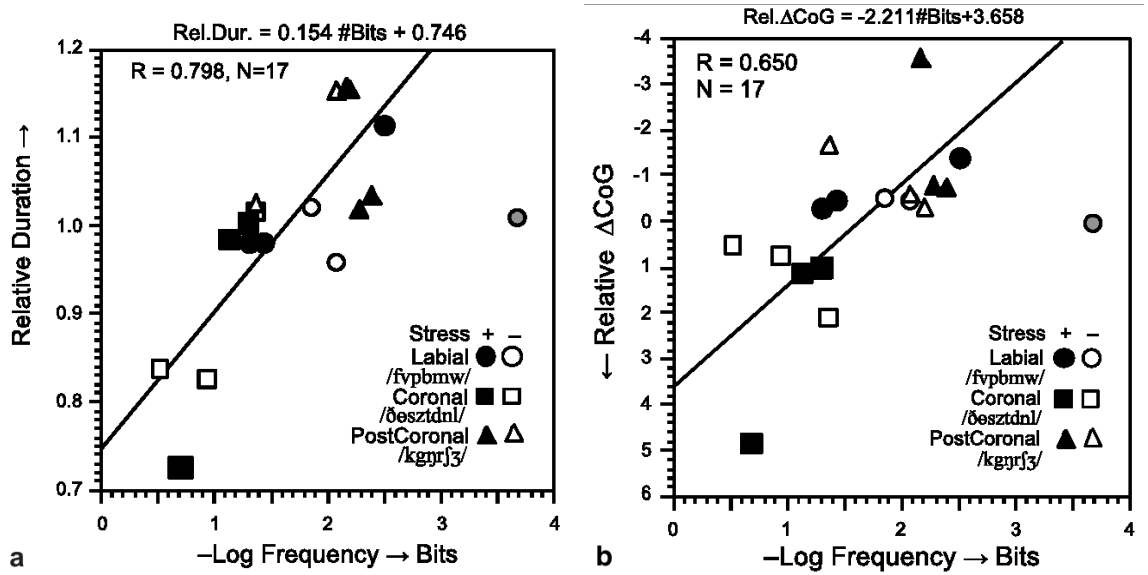

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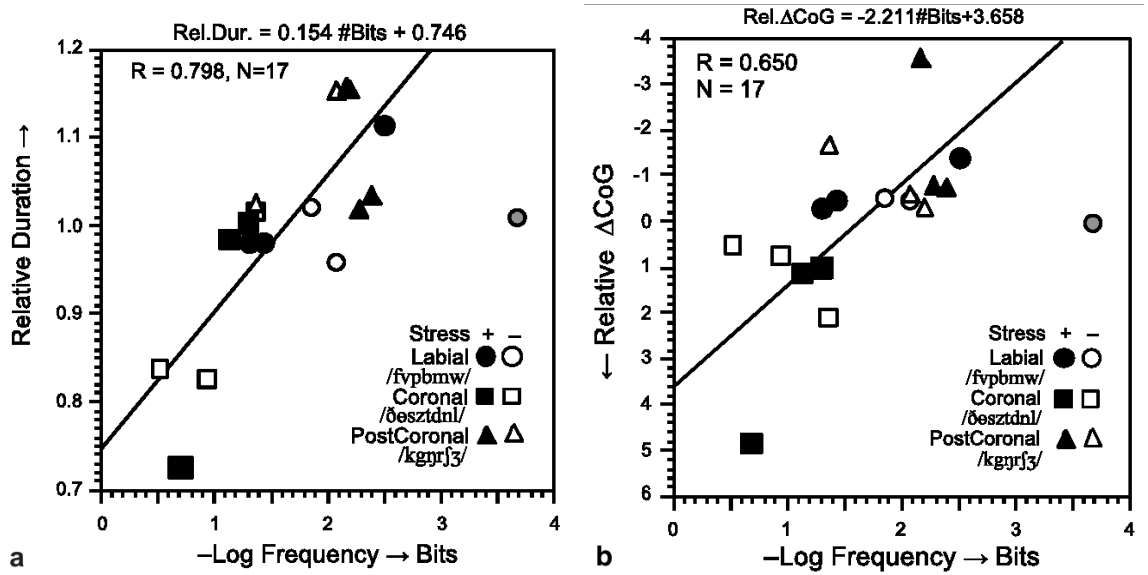

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Stress and Position: Conclusion

Again, phoneme reduction seems to be correlated to the information content

- This time, information structure cannot explain this
- There is efficiency beyond the information structure
- On the whole, speech seems to be efficiently organized
- Do speakers actually attend to efficiency?
- Unlikely, efficiency might result from speakers being listeners too
- If things are obvious for the speaker, they tend to be obvious for the listener
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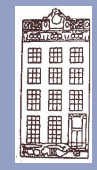

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