Using ultrasound articulatory signals to investigate the phonetic motivations of English /æ/ tensing

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uOttawa
/æ/ in North American English (Labov et al., 2006)
Zeller (1997) reported that younger, but not older, speakers from the Milwaukee area merged /æɡ/ with /ejg/ (e.g., hag=Haig)

Labov, Ash, and Boberg (2006) reported the same merger for some speakers in Wisconsin, Minnesota, and central Canada; they also noted that /æ/ tended to be higher before /ɡ/ than before /d/ over a somewhat wider area
A linguistic problem: Raising of /æ/ before /g/ (2)

- Bauer and Parker (2008), Benson et al. (2011): speakers from Eau Claire, Wisconsin, raised /æg/
- Bauer and Parker’s ultrasound data show that tongue body is raised in /æg/ but still distinct from other front vowels.
- Wassink (2015) concluded that /æg/ and /ɛg/ were raised in Seattle.

![Figure 5](image)

A linguistic problem: Raising of /æ/ before /g/ (3)

- Purnell (2008), using x-ray data, found that, after /æ/, Wisconsin subjects articulated /g/ more fronted than /k/ and with more forward lip position.
Potential phonetic motivations for pre-velar raising

- Palatal-induced upgliding has occurred other times in the history of English, mostly before voiced stops and fricatives (and mostly not before voiceless stops).
  - Palatal [ç] conditioned upgliding in Middle English, e.g. OE eahta [æðxta] > *[æçtə] > ME eight [aiçt]
  - /g/ = [ʒ], /ŋ/ = [ŋ], /ʃ/, and /ʒ/, as in bag, hang, cash, and azure, respectively, condition upglides in various American dialects (see, e.g., Kurath and McDavid 1961; Hartman 1969; Thomas 2001)

- Hyperarticulation before voiceless obstruents?
  - There is some evidence that vowels can show more extreme articulations before voiceless obstruents than elsewhere (e.g., Wolf 1978; Summers 1987; Moreton 2008)
  - For low vowels, this means that F1 values are higher before voiceless obstruents than before voiced obstruents (so that the vowel reaches a lower position before voiceless obstruents).
/æ/ raising in other contexts

/æ/ raising before nasals is widespread in North American English.

Apparent phonetic motivation: Nasalization has a strong effect on F1 in low vowels, altering their perceived height (and may also raise F2; Krakow et al. 1988)

Raising in other contexts (e.g., before anterior voiceless fricatives) attributable to an earlier lengthening event.
Speaker 1: acoustic raising+fronting and tongue raising+fronting
Speaker 3: acoustic raising + fronting only
Selection of single representative image from target segment
Selection of single representative image from target segment
Tongue surface contour tracing
Purnell (2008): Pellet trajectories from XRMB database (Westbury, 1994)

Tongue Pellet Trajectories for /æɡ/ and /æk/ for Select Tokens and Speakers

a. PVR-Affected Speaker WID14

Coda Voicing
- -k
- -g

American Speech
Published by Duke University Press
Time-varying signals from PCA of XRMB data (Story, 2007; Story and Bunton, 2013)

Fig. 7 Audio waveforms (upper), time-varying coefficients (middle), and formant contours (bottom) based on the production of four vowels by a male talker. Note the time-varying coefficients are continuous throughout the entire 3.6 s duration; the lines are thickened during the portions of time where sound is present.
EigenTongues decomposition (Hueber et al., 2007)

- Principal component analysis of vocal tract images (Hueber et al. 2007 for ultrasound; Carignan et al. 2013 for MRI)
- Principal Component loadings remapped onto original spatial location
- A video becomes a matrix of PC scores
- http://phon.wordpress.ncsu.edu
Acoustic/articulatory vowel plots

F1_frequency
F2_frequency

AE1, EY1, AW1, EH1, IY1, IH1, AY1, AA1, OW1, OY1, UW1, AH1, UH1, L, ER1
Acoustic/articulatory vowel plots

PCA Data collection Articulatory signals

BEEB
BIB
BABE
BEB
BAB
BOB
BUB
BOBE
BUHB
BOOB
BAUB
BIBE
BOIB
BURB
BULB

PC1_score
PC2_score
PC loadings heatmaps (first nine PCs for one speaker)
Ultrasound image acquisition (at NCSU and uOttawa)

- Terason t3000
- 8MC3 microconvex array
- Ultraspeech software (Hueber et al., 2007)
- Articulate Instruments probe stabilization headset
- 120 monosyllabic words, randomized and repeated 3 times
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Pilot: 21 speakers (overlaid on ANAE /æ/ map; Labov et al. 2006)
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Time-varying articulatory signals from ultrasound

Quantified images $\rightarrow$ articulatory signal with sampling rate $=$ system frame rate

- Deriving time-series data from measured tongue contour tracings (Falahati, 2013)
- PCs and rotated PCs over time
- Linear Discriminant Analysis of PC scores over time (Pouplier and Hoole, 2013)
- Acoustically-inspired linear combinations of PCs over time...
**Acoustic diagonal (Z2-Z1)**

Standardized F2 — standardized F1 (Z2-Z1) = designed to match the front diagonal of the acoustic vowel space (Labov et al., 2013)
Articulatory diagonal (art.Z2Z1)

Audio segmented using P2FA (Yuan and Liberman, 2008) and vowel/approximant formants measured at 7ms intervals

Linear regression for each speaker’s front diagonal vowels [a æ e ej i]:
(Z2-Z1 ∼ PC1 + … + PC20)

20 coefficients used to make a linear weighted combination of the PCs that approximates Z2-Z1

Second set of linear regressions using only F1 (to examine relationship between tongue position, nasalization, and F1)

Speaker: nov03
(Broadway, NC; 1992, M)
Articulatory diagonal (art.Z2Z1): heatmaps

Speaker: nov01  
(Vancouver, WA; 1976, M)

Speaker: nov03  
(Broadway, NC; 1992, M)

Speaker: nov04  
(Olympia, WA; 1982, M)

Speaker: nov07  
(Arlington, TX; 1992, M)

Speaker: nov11  
(Wilmington, NC; 1986, M)

Speaker: nov12  
(Fargo, ND; 1981, M)
Alveolar signal (LDA with [t d n s z]): "sag"
Velar signal (LDA with [k ɡ ɲ]): “sag”
Front diagonal (art.Z2Z1) articulatory signal: “ban”
\(/\text{æ}/\) tensing before nasals

- pre-nasal tensing for all speakers except UK and Newfoundland (Wilmington, NC example)
- widespread pre-\(/m\) \(/n/\) tensing involves peak aligned \(\approx\) with vowel nucleus
- pre-\(/\text{ŋ}/\) tensing involves tongue raising aligned to end of vowel (anticipating following velar)
- 16/20 North Americans: pre-\(/\text{ŋ}/\) tenser than pre-\(/\text{g}/\), both acoustically and articulatorily (cf. Baker et al. 2008)
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F1 vs. Lingual F1 in vowels before /m/ and /b/
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Change in F1 and Lingual F1 in pre-nasal position: /a/

![Graph showing the change in F1 and Lingual F1 in pre-nasal position for different regions.]
Change in F1 and Lingual F1 in pre-nasal position: /æ/

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Ultrasound articulatory signals and /æ/ tensing
Change in F1 and Lingual F1 in pre-nasal position: /ε/
Change in F1 and Lingual F1 in pre-nasal position: /ej/
/æ/ tensing: /g/ > /d/

- /g/ > /d/ by end of vowel for all speakers (velar pinch) (Arlington, TX example)
- from 2nd half of vowel for most Mid-Atlantic and Southern speakers (Harrisburg, NC example)
- from 1st half of vowel for most Northern speakers (Olympia, WA example)
- entire vowel for all Ontario speakers (Barrie example)
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/æ/ before velars /k gŋ/: North

nov08: Altoona, WI ("North")

nov12: Fargo, ND ("North")

nov15: Batavia, NY ("North")

nov16: Buffalo, NY ("North")

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/æ/ before velars /k g η/: North (including Northwest)

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/æ/ before velars /k ɡ η/: Canada

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Ultrasound articulatory signals and /æ/ tensing 28/31
/æ/ before velars /k g η/: North Carolina

nov03: Broadway, NC ("South")

nov06: Harrisburg, NC ("South")

nov14: Hickory, NC ("South")

nov11: Wilmington, NC ("South")
/æ/ before velars /k g η/: Misc. South

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Ultrasound articulatory signals and /æ/ tensing
/æ/ before velars /k ɡ ɲ/: Mid-Atlantic and UK

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Ultrasound articulatory signals and /æ/ tensing
/æ/ tensing: Philadelphia

- some /d/ > /ɡ/ for one of the Philadelphia speakers
- ‘bad’ > ‘sad’: tongue gesture similar to /æ/ before /n/ (like two of De Decker and Nycz’s (2012) four New Jersey speakers)
- Anterior voiceless fricatives involve gesture similar to ‘bad’ and almost all of the pre-/m n/ raising we have seen so far.
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Anterior voiceless fricatives involve gesture similar to ‘bad’ and almost all of the pre-/m n/ raising we have seen so far.
Summary: /æ/ raising

- Pre-nasal and Philadelphia tensing: large tongue raising gesture at the vowel nucleus.
- F1 lowering in pre-nasal /æ/ is accounted for by tongue raising.
- Pre-velar /æ/ raising is a matter of timing (because pre-velar vowels end with velar contact).
- The dorsal target appears to more anterior for /g/ than for /k/ for many speakers, but conspicuously not for some, including the one UK speaker and the one Texas speaker.
  - Many of our Upper Midwest and Ontario speakers have pre-/g/ raising and articulatorily distinct /g/ and /k/.
  - Our Northwestern speakers have pre-/g/ raising but articulatorily similar /g/ and /k/.
  - Our North Carolina speakers have distinct /g/ and /k/ but no pre-/g/ raising.
Summary: articulatory signals

- Ultrasound is a *relatively* easy and practical way to collect articulatory data on the scale necessary for variation studies.
- By reducing the labor involved in ultrasound data analysis, articulatory signals make ultrasound data analysis much more flexible and make studying the dynamics of speech production more practical.
- Signals derived from PCs using acoustic data can be used to track linguistically relevant tongue movements (e.g. articulatory movement along the front edge of the vowel space).
- Acoustically-derived signals can also be used to distinguish effects of tongue movement from effects of lips, nasalization, etc.
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Articulatory signals Matlab scripts and polar SSANOVA R script: http://phon.wordpress.ncsu.edu or google “NCSU phonology”


Anteriority of closure: Velar palatalization

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Ultrasound articulatory signals and /æ/ tensing
Anteriority of closure: Velars after /æ/

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Ultrasound articulatory signals and /æ/ tensing
Anteriority of closure: Velars before /i ej ε a/
Anteriority of closure: Velars after /i ej e a/