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ECR KOLLOQUIUM
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Analyzing the spectrum with functional data analysis

Rasmus Puggaard-Rode

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We have the tools to statistically model spectral shape directly, and doing so forgoes some of the problems with other methods of describing the spectrum

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Roadmap

- The case: Danish /t/ releases
- Analyzing aperiodic spectra
  - FDA as an alternative
- Two corpus studies
  - Affrication in Modern Standard Danish
    - Function-on-scalar regression
  - Affrication in traditional Jutland Danish varieties
    - Functional principal component analysis
- General discussion

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Danish /t/ releases

- Modern Standard Danish has an aspiration-based laryngeal contrast in stops
  - Unaspirated /b d g/
  - Aspirated /p t k/
- /t/ is saliently affricated
  - Aspirated stop? Affricated stop? Affricate?
- Transcription strategies
  - [d̥ˢ] (Basbøll 1969, 2005; Grønnum 1998)
  - [d̥ˢʰ] (Petersen 1983)
  - [d̥ˢh] (Brink & Lund 1975)
  - [tsʰ] (Basbøll & Wagner 1985)
  - [tˢ] (Grønnum 1998, 2005)
  - [ts] (Schachtenhaufen 2022)

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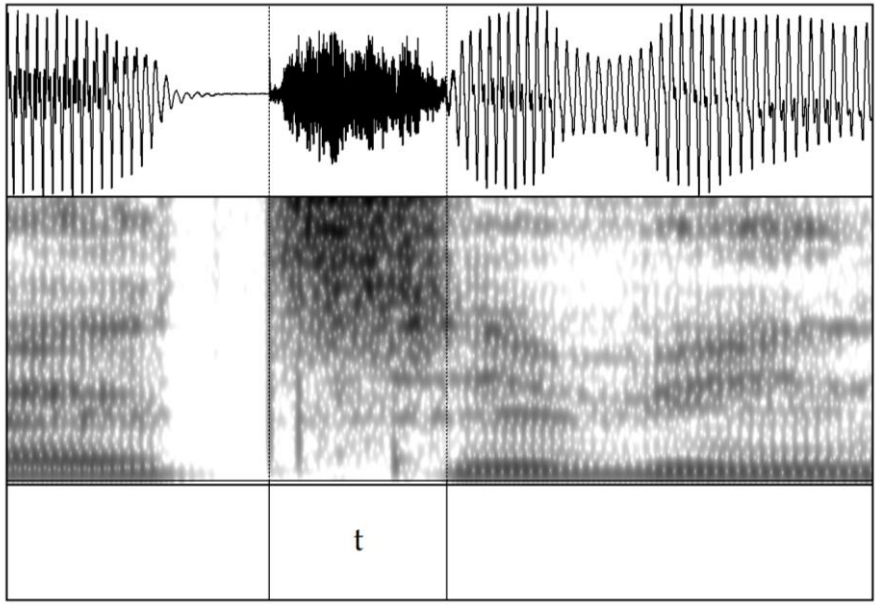

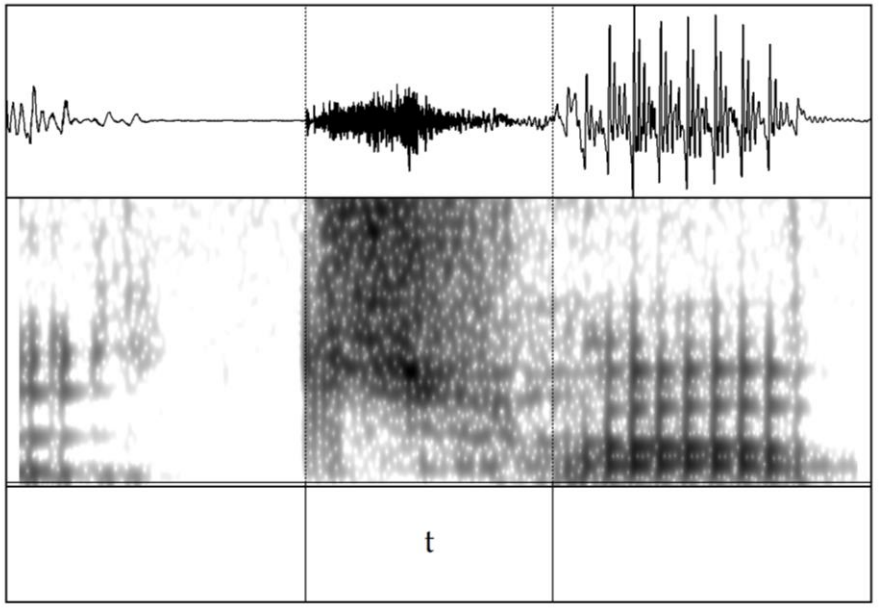

Grønnum (2009)

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Danish /t/ releases

- Fischer-Jørgensen (1954, 1972)
  - /t/ releases contain both affrication and aspiration proper
  - The affrication spectrum is similar to the /s/ spectrum
  - Superimposing /t/ aspiration on /p k/ will lead listeners to perceive the sound as /t/

- Brink & Lund (1975)
  - /t/ affrication was widespread in mid-19C in Copenhagen
  - In mid-20C it was exceptionless in Copenhagen

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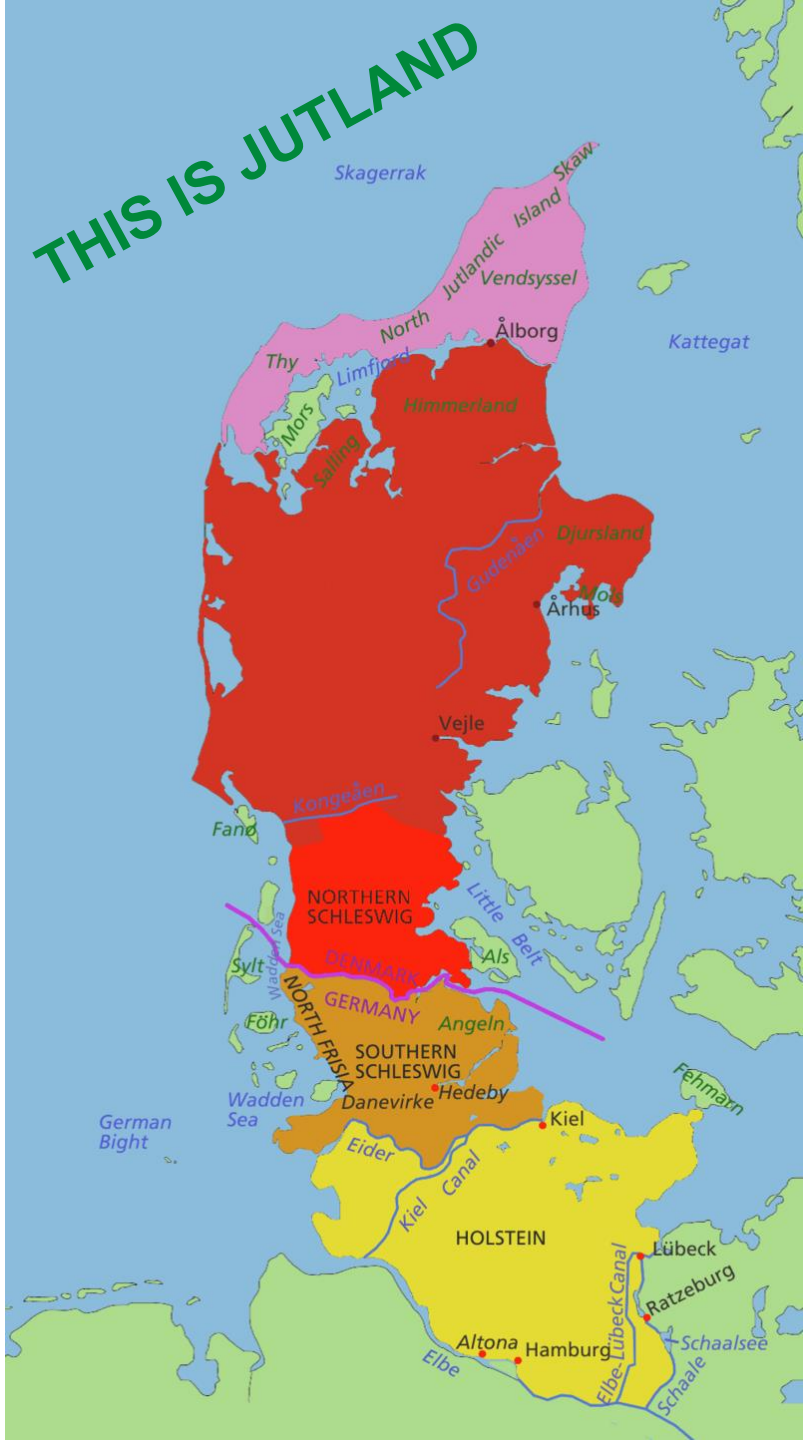
Variation

- Not all varieties have saliently affricated /t/
- **But** it's a complete mystery which varieties lack it
  - Missing from
    - 'All dialects' (Brink & Lund 1975)
    - High and formal styles (Grønnum 2005)
    - Northern Jutlandic (Petersen 2009)
    - Western Jutlandic (Petersen et al. 2021)
    - All Jutland varieties except Eastern Jutlandic (Heger 1981)
- The sociolinguistic situation of Danish dialects is complex, but these traditional varieties are presumably (nearly) extinct (Pedersen 2003; but see also Maegaard & Monka 2019)



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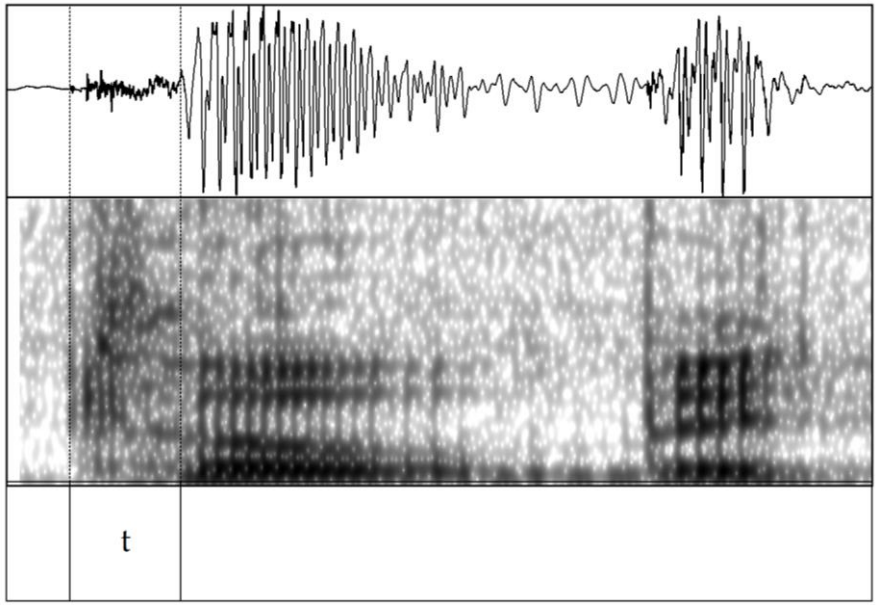

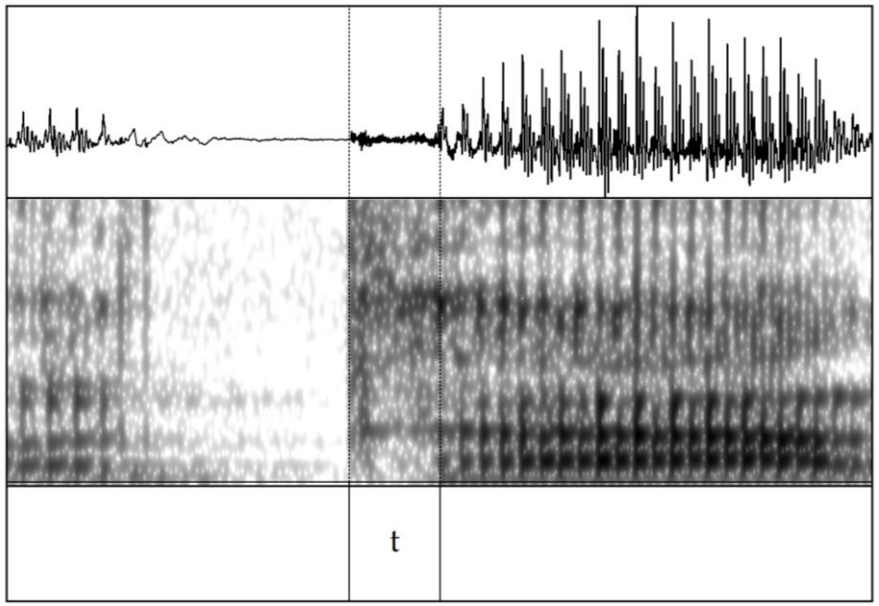

DS (1971–1976)

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Who cares?

- These are unresolved issues in a very well-described language
  - But too often they're treated as solved

- How much does fine phonetic detail vary?
- What governs variation in fine phonetic detail?

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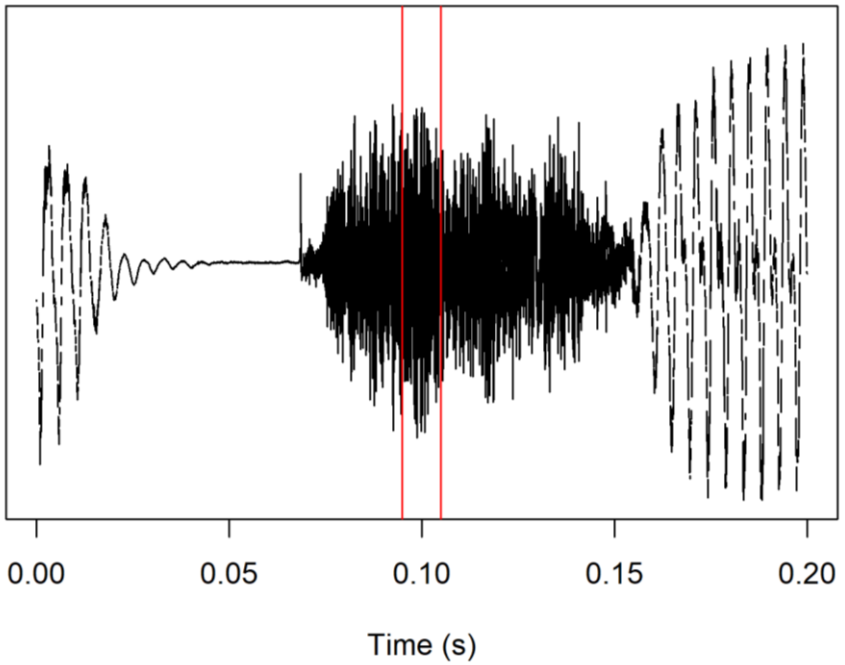
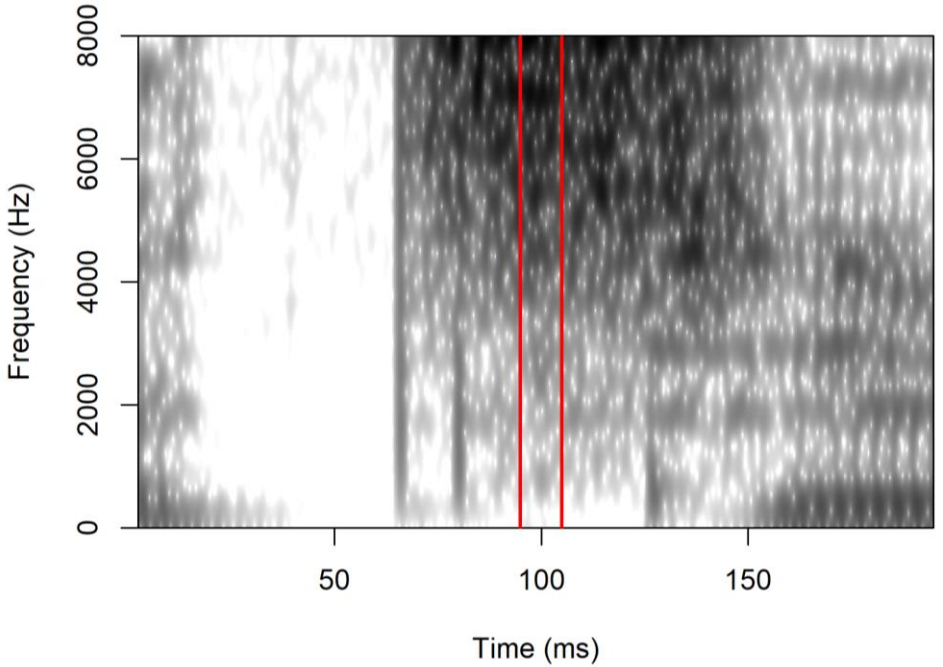
RQ1: How do spectral characteristics vary over time in Modern Standard Danish /t/ releases, and how are they affected by phonetic context?

RQ2: How do spectral characteristics of /t/ releases vary geographically in traditional dialects of Jutland?

Aperiodic spectra





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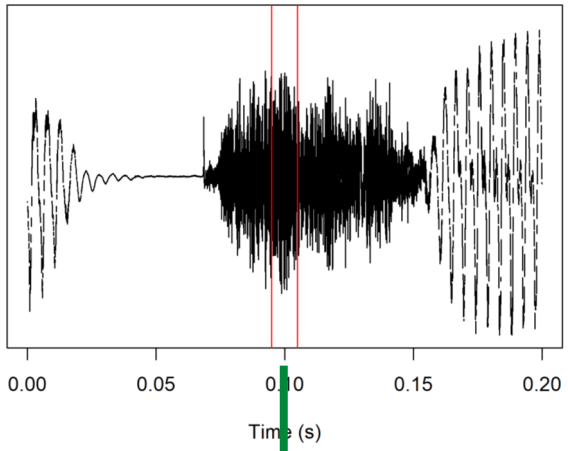
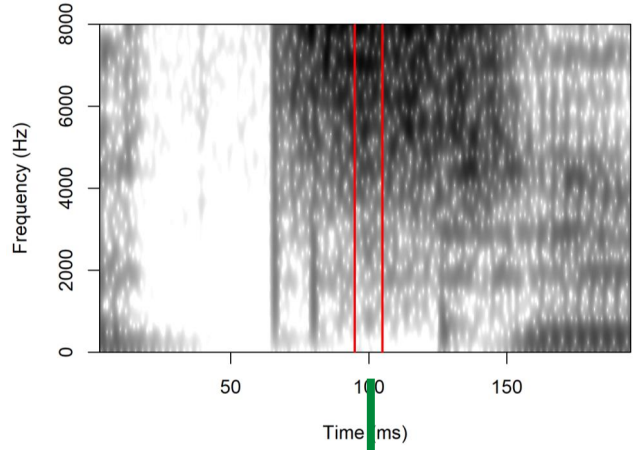
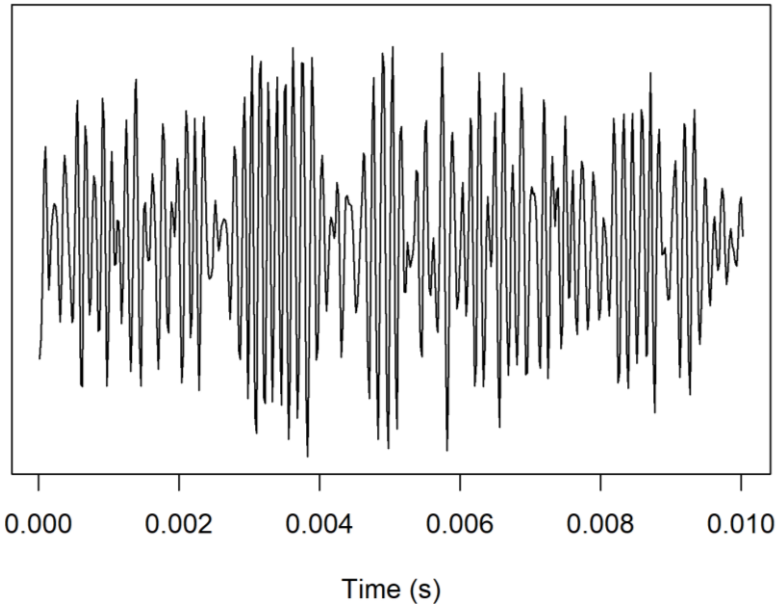
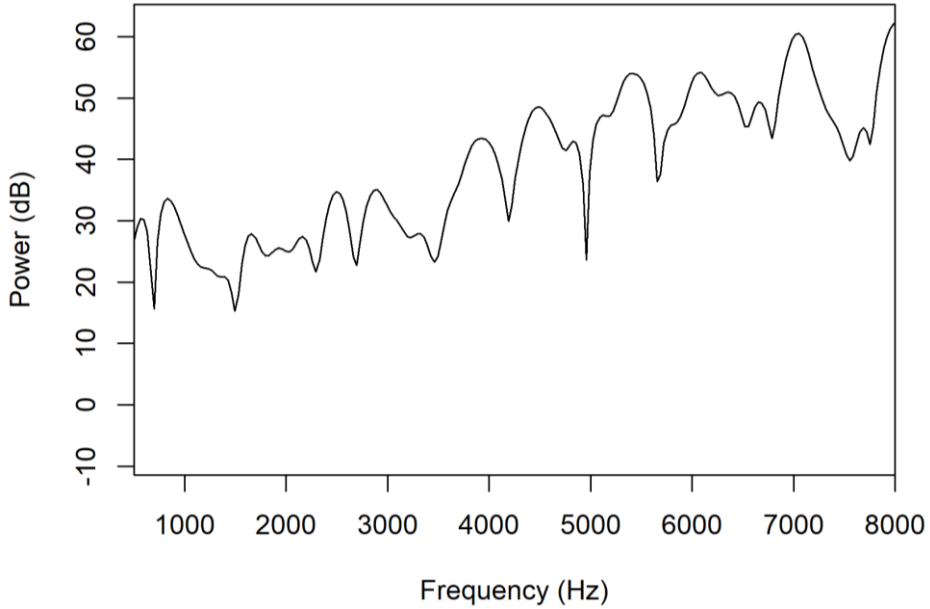
Aperiodic spectra









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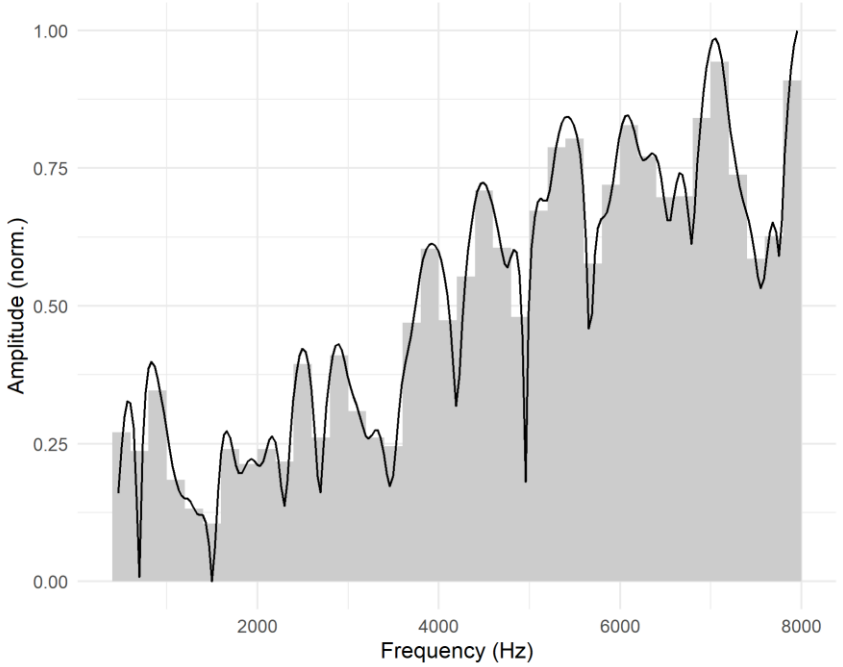
Spectral moments

- Treating the spectrum as a probability distribution, and deriving moments from it (Forrest et al. 1988)



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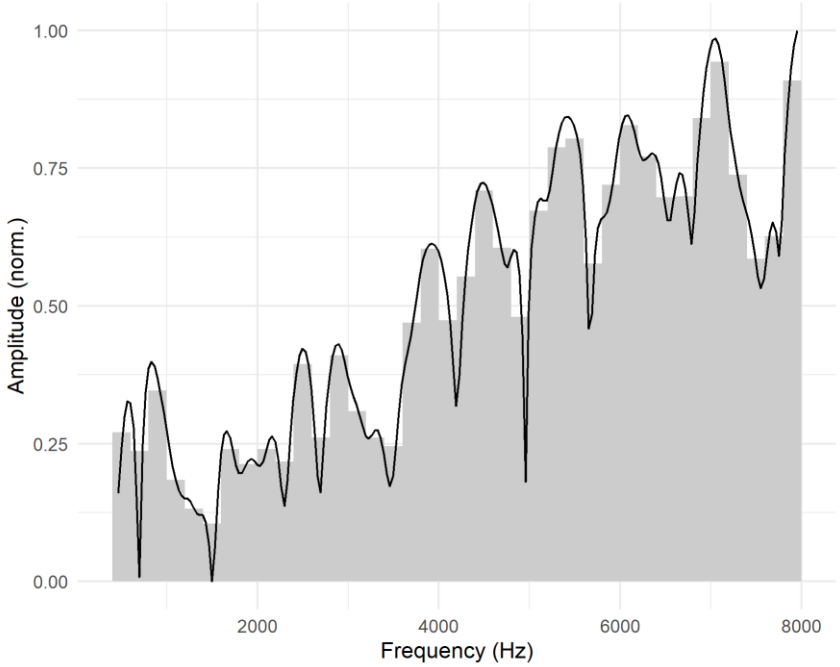
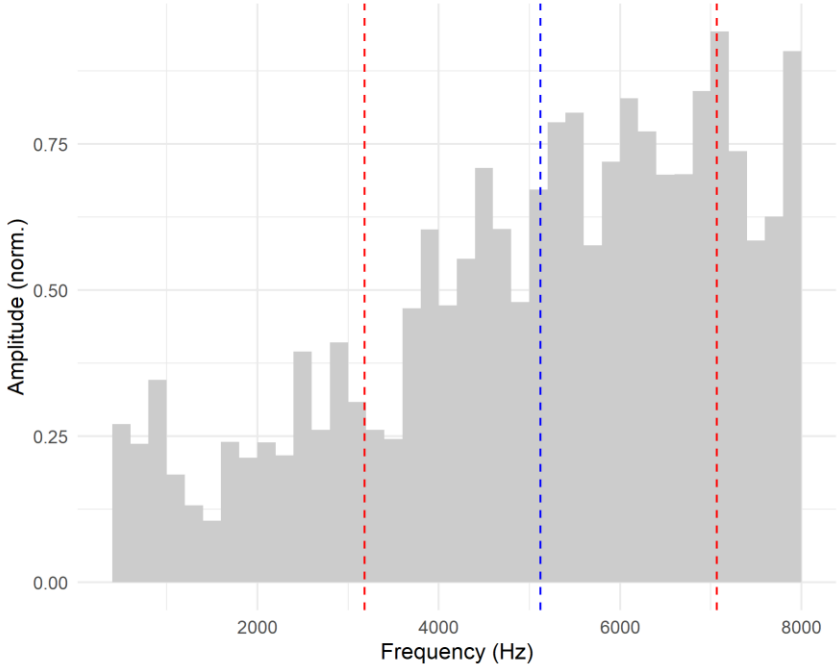
Spectral moments

- Treating the spectrum as a probability distribution, and deriving moments from it (Forrest et al. 1988)
  - Centroid frequency, or **center of gravity**
    - 5,124 Hz
  - Standard deviation
    - 1,941 Hz
  - Skewness
    - -1.2
  - Kurtosis
    - 1.36





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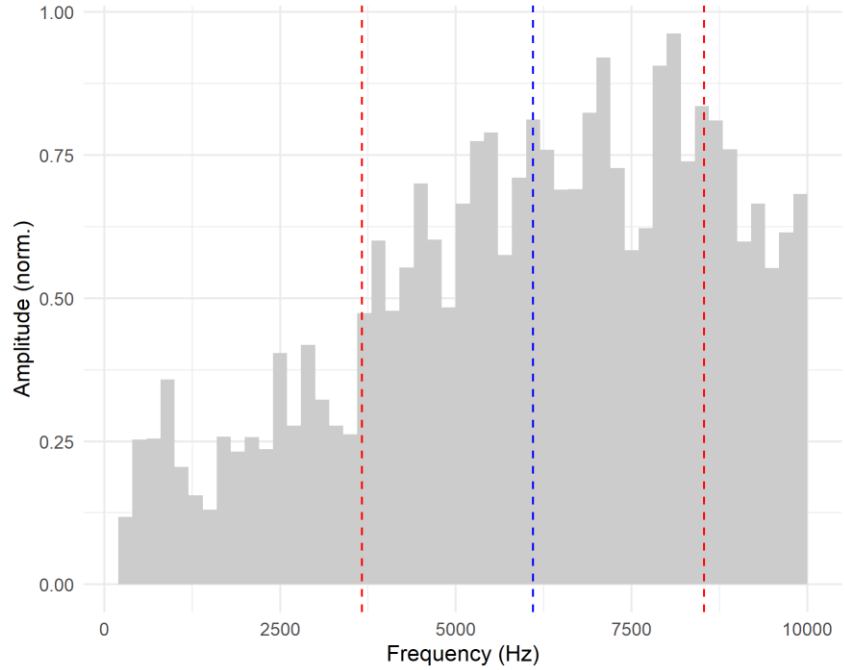
Spectral moments

- Subsequent studies have not given consistent results about which moments are useful
  (Stoel-Gammon et al. 1994; Shadle & Mair 1996)
- Spectral moments are highly dependent on how the spectrum is filtered
  - Our spectrum was filtered at 500–8,000 Hz
  - If we'd chosen 300–10,000 Hz instead
    - COG would be ~1,000 Hz higher
    - SD would be ~500 Hz higher



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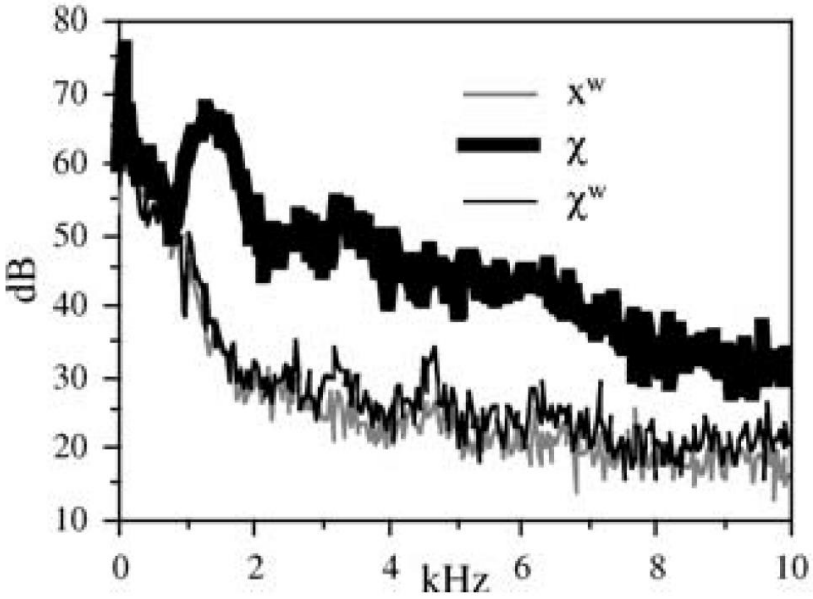
  - If we'd chosen 300–10,000 Hz instead
    - COG would be ~1,000 Hz higher
    - SD would be ~500 Hz higher
- Higher moments are often ignored, and **COG alone says little about spectral shape**
  - [χ χ^w] have roughly identical COG in Montana Salish

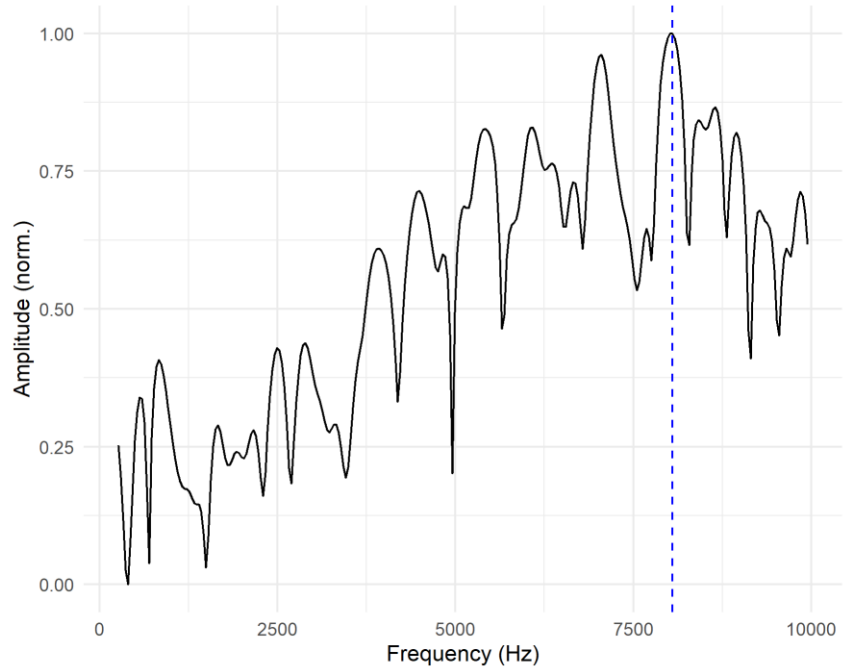


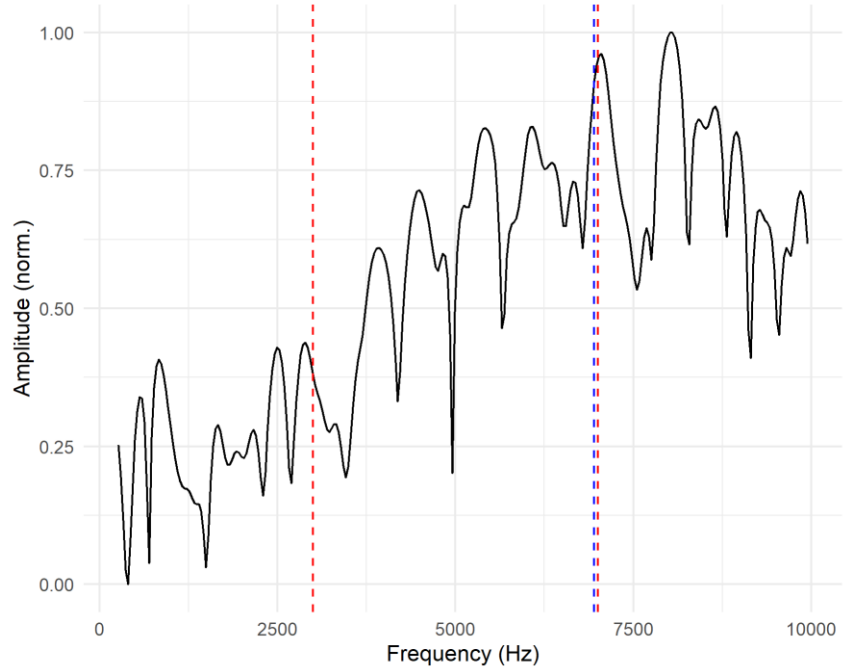
Gordon et al. (2002)

Peak frequency

- Peak frequency (Jongman et al. 2000)
  - 8,050 Hz

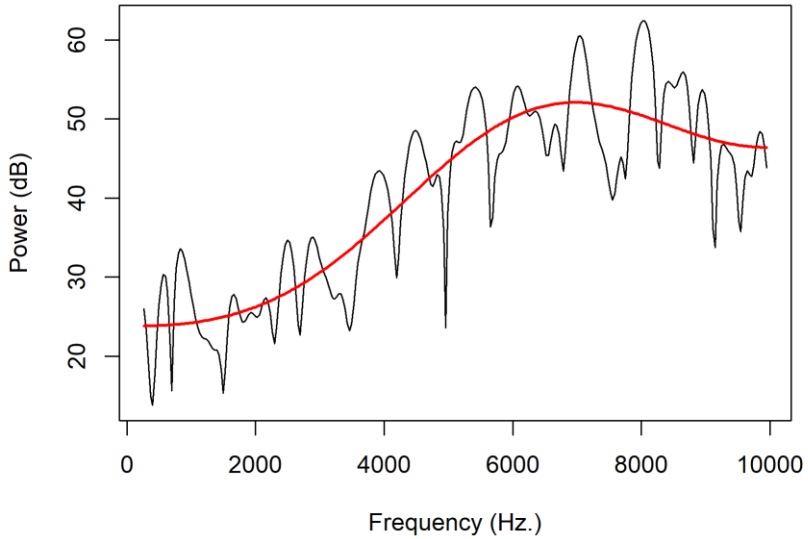
- Mid-frequency spectral peak
  (Koenig et al. 2013; Chodroff & Wilson 2022)
  - 6,952 Hz





DCT coefficients

- Smoothing aperiodic spectra with four DCTs usually retains gross spectral shape (Bunnell et al. 2004; Harrington 2010; Spinu & Lilley 2016; Jannedy and Weirich 2017; Kokkelmans 2021)
  - DCT coefficients then tell us something about
    - Mean (k0)
    - Slope (k1)
    - Curvature (k2)
    - Amplitude at higher frequencies (k3)



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We need to operationalize RQ1 and RQ2, but we are now lost in the garden of forking paths

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Functional data analysis

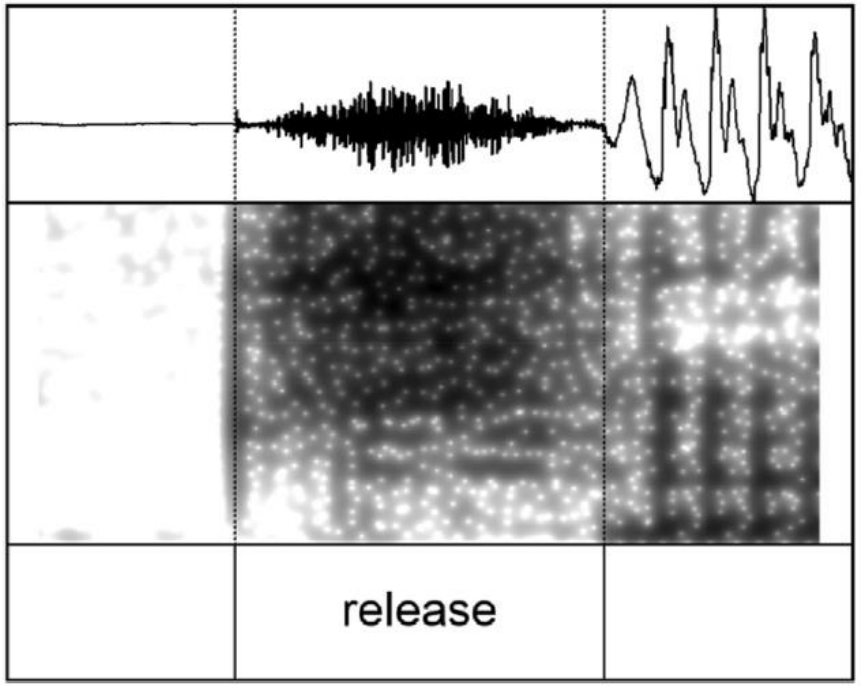
- Extensions of statistical methods for functional data (Ramsay & Silverman 2005; Kokoszka & Reimherr 2017)
  - Functional PCA (Gubian et al. 2015)
  - Functional regression models (Greven & Scheipl 2017; Pouplier et al. 2017)

- Often applied to time series data *Y(t)*
  - But should work just as well for spectral data *A(f)*

RQ1: Materials

- Monologs from DanPASS corpus (Grønnum 2009)
  - ~3 hours of speech, 18 speakers (5F/13M)
  - 850 /t/ tokens
    - Mean VOT: 79 ms (stressed), 68 ms (unstressed)

- Each stop split into 20 normalized time steps
  - Multitaper spectra generated in R for each of these
  - Frequency range 500–10,000 Hz



Puggaard-Rode (2022)

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Function-on-scalar regression

- Modeled with **function-on-scalar** models fitted with `refund::pffr` (Bauer et al. 2018; Goldsmith et al. 2021)
  - Wrapper for `mgcv` functions, so won't be totally unfamiliar for GAMM users (Wood 2017)
  - Allows problems to be formalized as functional regression

- GAMM: amplitude ~ frequency × time ☹
- FOSR: spectrum ~ time ☺

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Function-on-scalar regression

- Model structure
  - The spectrum has a smooth functional intercept
  - Spectral shape can vary smoothly over time
  - For each of the following fixed effects, spectra can vary smoothly over time
    - Speaker sex
    - Following vowel height, roundness, backness
    - Stress
  - By-speaker functional random slopes for each fixed effect
  - Corrected for autocorrelated errors

```
pffr(Y ~ s(timestep, k=16) +
    s(timestep, k=16, by=stressn) +
    s(timestep, k=16, by=sexn) +
    s(timestep, k=16, by=high_vn) +
    s(timestep, k=16, by=back_vn) +
    s(timestep, k=16, by=round_vn) +
    s(speaker, timestep, bs="re") +
   s(speaker, timestep, by=stressn, bs="re") +
   s(speaker, timestep, by=high_vn, bs="re") +
   s(speaker, timestep, by=back_vn, bs="re") +
   s(speaker, timestep, by=round_vn, bs="re"),
data=t_df, ydata=t_y,
bs.yindex = list(bs="ps", k=6, m=c(2,1)),
bs.int = list(bs="ps", k=round(nrow(t_y) / nrow(t_df), 0), m=c(2,1)),
rho = ar1+0.1,
```

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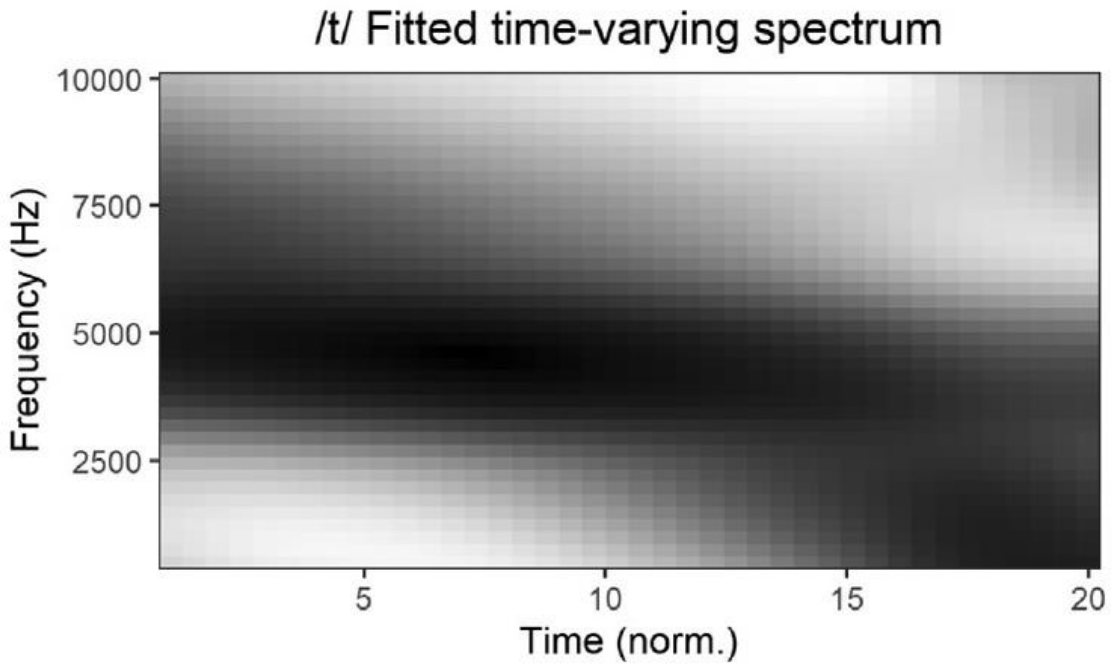
Results



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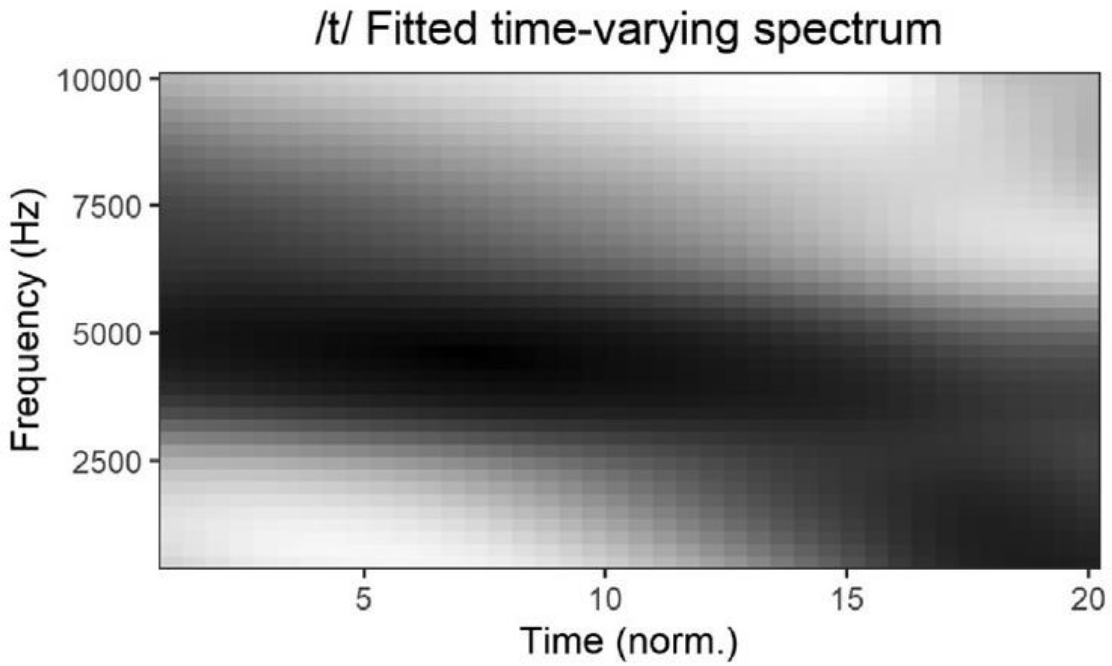
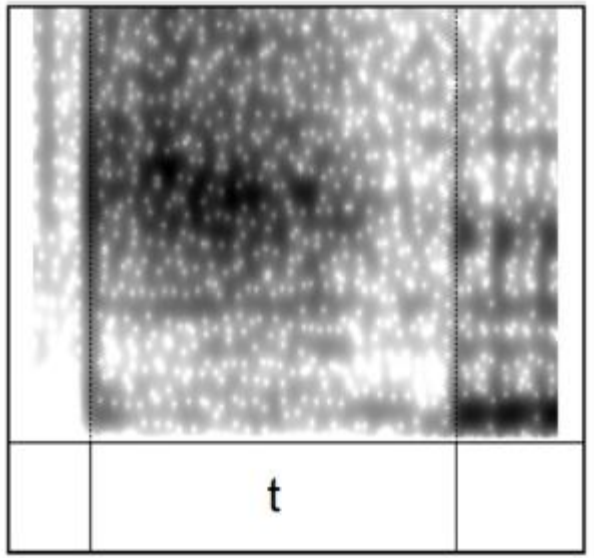


cp. a real spectrogram



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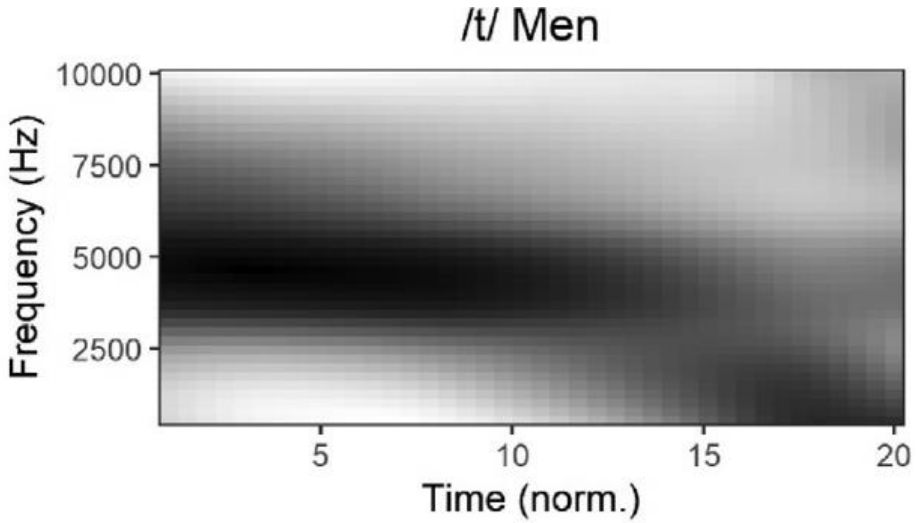

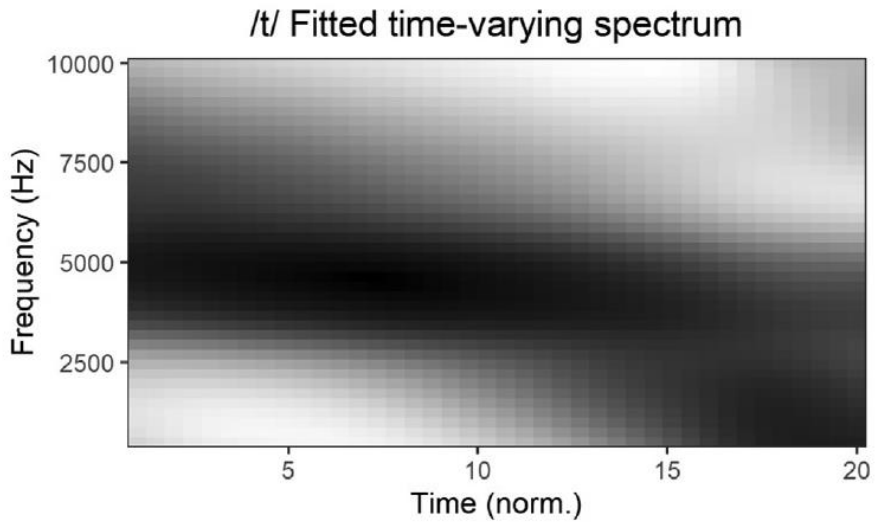

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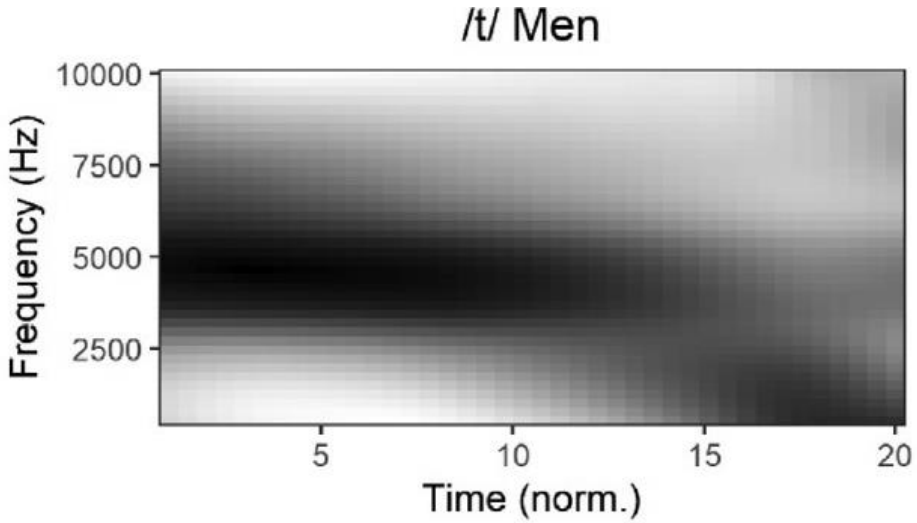

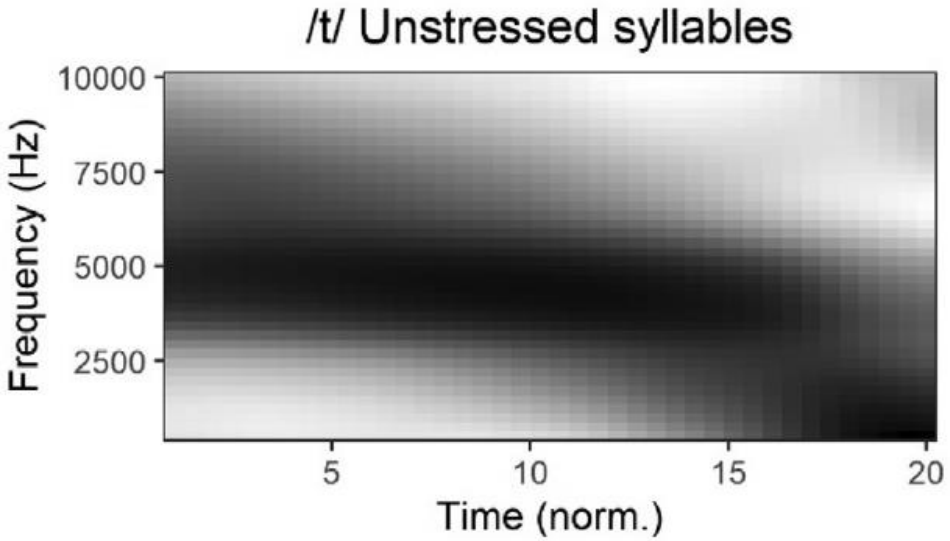

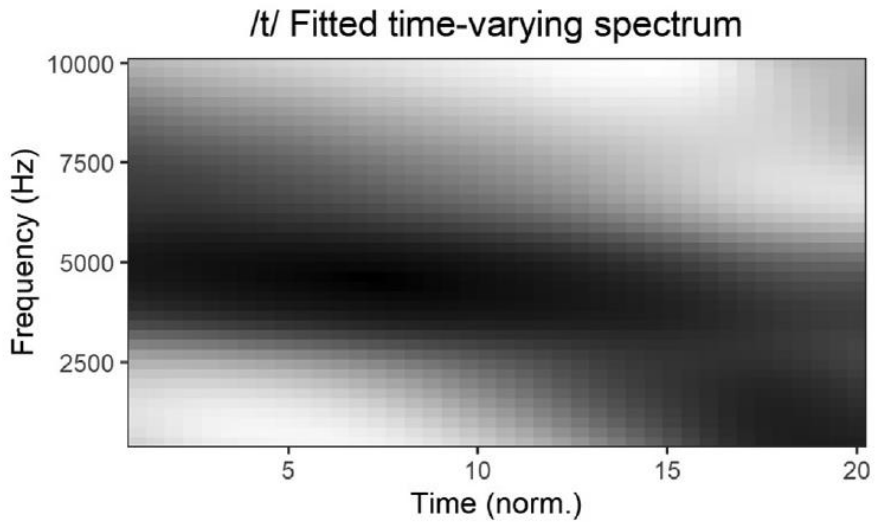

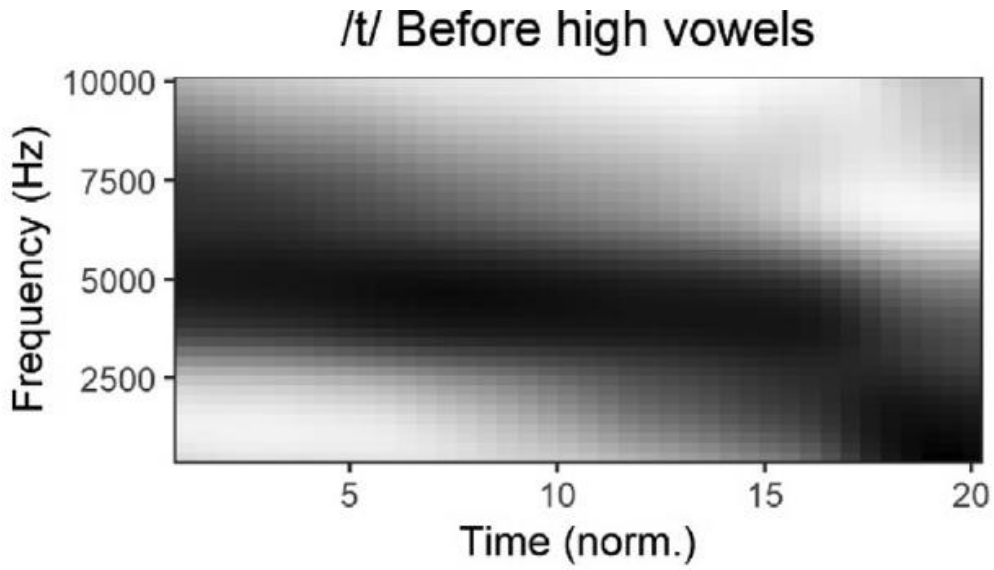

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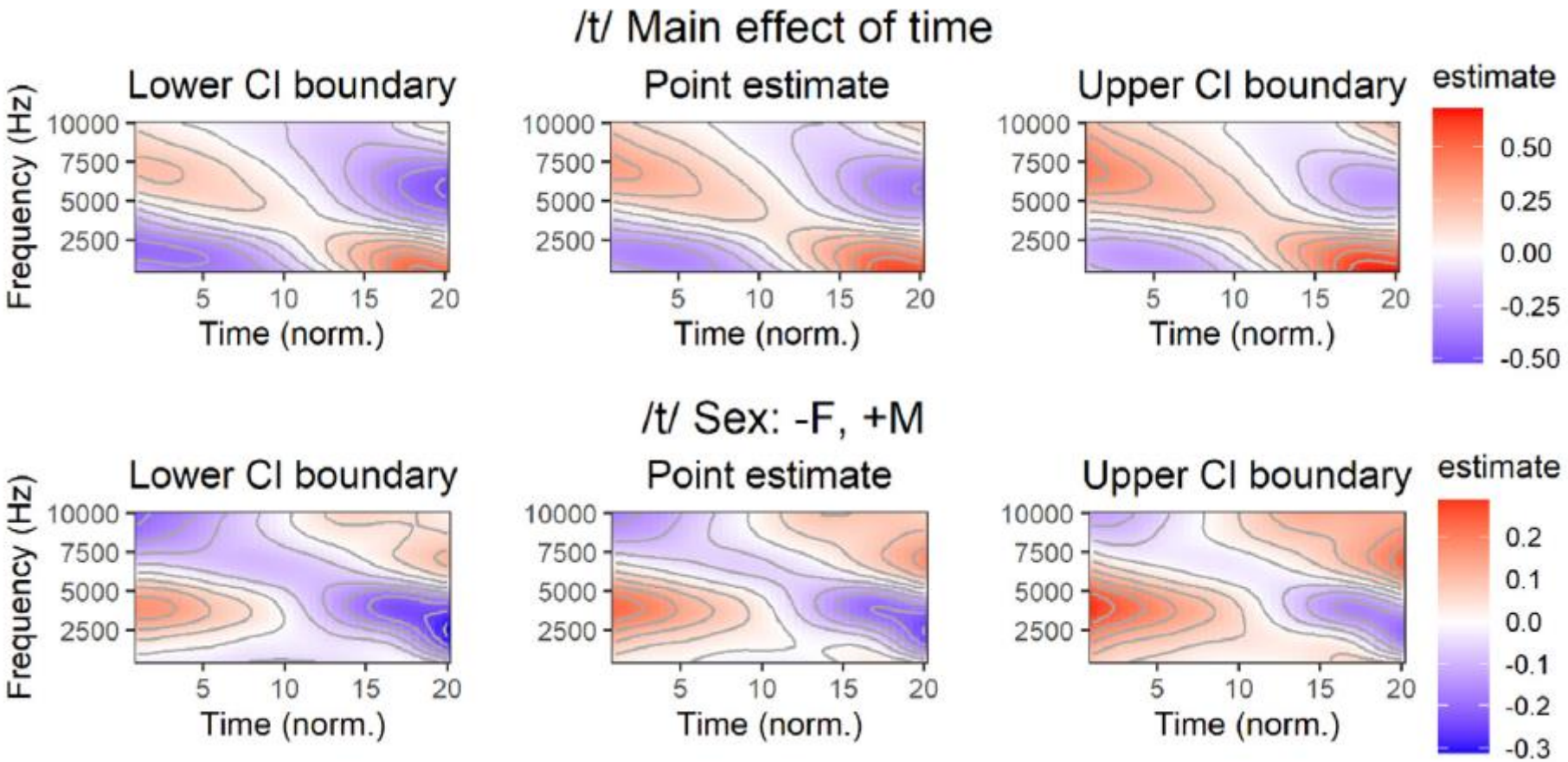

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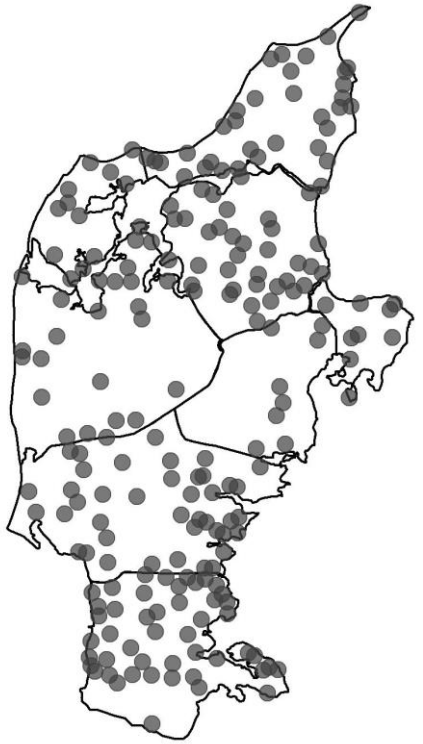
Interim discussion

- MSD /t/ is invariably affricated
- A coronal noise source generally dominates most of the release
  - But **not** the final portion of the release
- The transition from dominant alveolar noise source to dominant glottal noise source is smooth
- The proportion of alveolar <> glottal is modulated by phonetic context

RQ2: Materials

- Legacy corpus of sociolinguistic interviews with elderly speakers recorded between 1971–1976
  (DS 1971–1976; Goldshtein & Puggaard 2019)
- Recordings from 213 different parishes
- 5,103 /t/ tokens
- 5 ms extracted from each release midpoint
  - Multitaper spectrum generated in R



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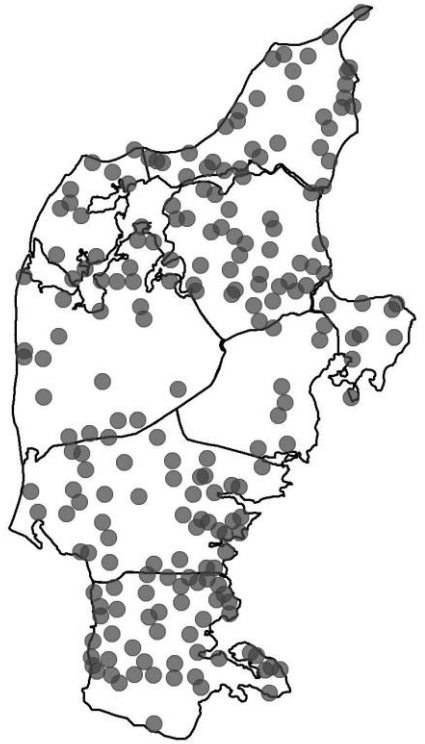
- 5,103 /t/ tokens
- 5 ms extracted from each release midpoint
  - Multitaper spectrum generated in R

- *Hold up, can't we just model the full /t/ release?*
  - Computationally, sure
  - But how to visualize the results?
    Regional variation in how spectral shape varies over time?



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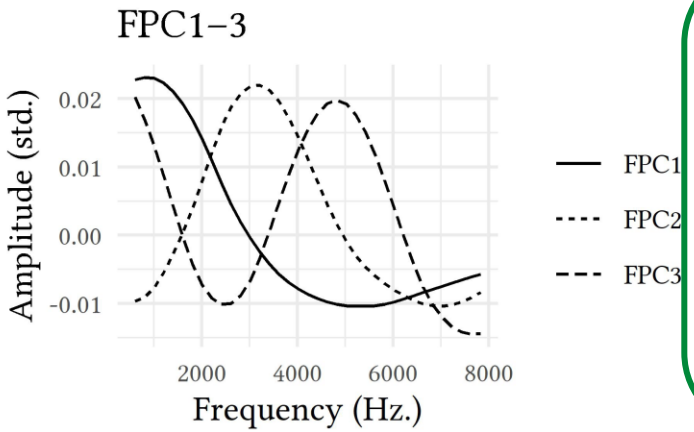
Functional PCA

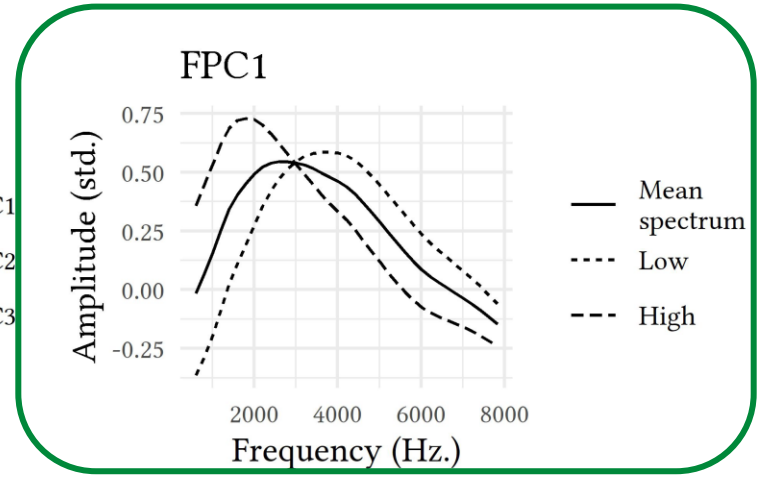
- Spectral variance analyzed with functional PCA
  - Identifies main sources of variance
  - Bottom-up approach is particularly suitable here
    - This is exploratory research, and the existing literature doesn't allow for strong predictions
  - Principal components are independent by definition

- FPCA done in R with `fdapace` (Gajardo et al. 2021)
  - PC scores used as dependent variables in spatial GAMMs
    - Predicting PC scores from geography (longitude × latitude), phonetic context, and speaker sex

Results

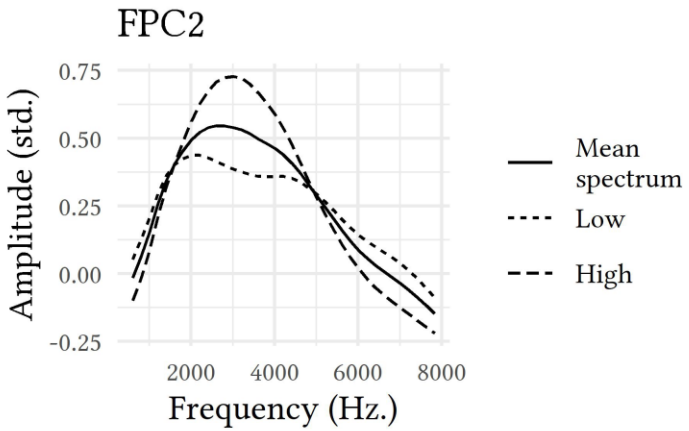
5 PCs account for 95% of variance

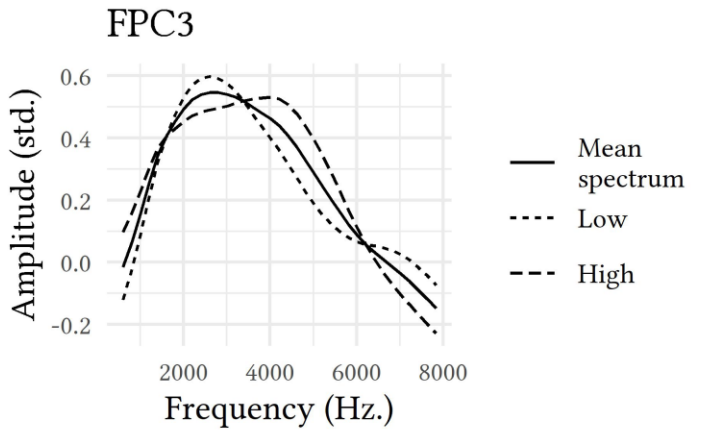




58.4%

18.2%





9.3%

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Results

- Negative s_1 (=spectrum reflecting alveolar noise source)
  - Unlikely before low vowels
  - Unlikely before rounded vowels
  - Unlikely before back vowels
  - More likely from female speakers

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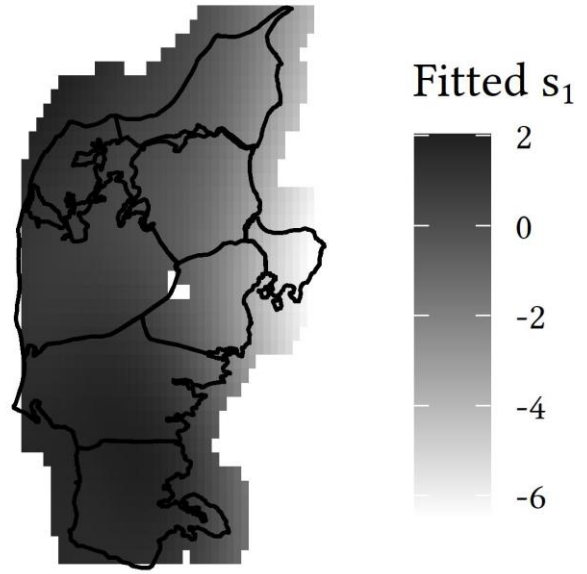
Results

- Negative s_1 (=spectrum reflecting alveolar noise source)
  - Unlikely before low vowels
  - Unlikely before rounded vowels
  - Unlikely before back vowels
  - More likely from female speakers
  - ➢More likely in eastern Jutland (particularly Djursland)
    - Could be a traditional feature of this area
    - Could be because this coincides with the biggest city of the peninsula (Aarhus)



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General discussion

- Time-varying spectral characteristics of MSD /t/ releases suggest the presence of both salient affrication and aspiration
  - Smooth transition from one to the other
  - Relative proportion modulated by speaker and phonetic context
- In most traditional Jutland Danish varieties, the /t/ release midpoint does not reflect a coronal noise source
  - Affrication more likely in certain contexts
  - Affrication more likely in eastern Jutland

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General discussion

- FDA allow us to model spectral shape directly
  - Analyzing main sources of variance with FPCA
  - Using spectral shape as a dependent variable with FOSR
- Largely forgoes the problems of other approaches to analyzing the spectrum
  - Bottom-up approach
  - Fairly easy to interpret
  - Familiar scale

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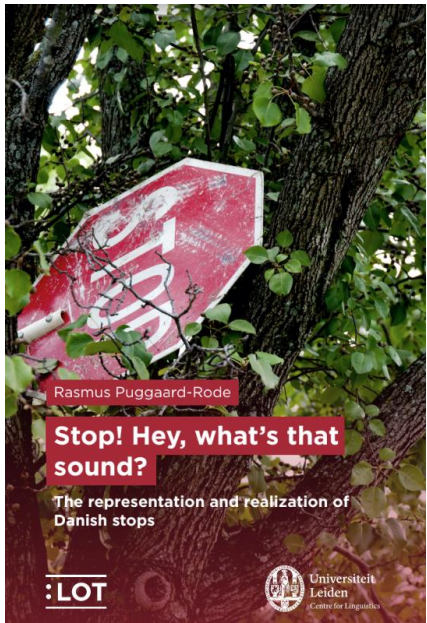

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Tak for opmærksomheden!

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