Aerodynamics of Voiced Stop Production

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Aim

- To characterise aerodynamic parameters of voiced stop consonants including:
  - Slope of the stop release;
  - Voice onset time (VOT);
  - Stop and release duration;
  - Steady state characteristics of phones preceding and following the stop.

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Real Speech

- In real speech the acoustic signature of a stop is not always apparent due to intergestural overlap, which sometimes results in the absence of a clear stop release or burst (Ghosh & Narayanan, 2009).
- New criteria to annotate stop release or burst based on the expected oral flow signal for voiced stops measured with a Rothenberg (1973) mask was defined.

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Method (Data)

- Aerodynamic and electroglottographic (EGG) recordings.
- Four (**4**) healthy adult **speakers** (two females and two males).
- Nine (**9**) isolated **words** with the European Portuguese (EP) voiced stops /b, d, g/ in initial, medial and final word position.
- The same 9 words embedded in **39** different real EP **carrier sentences**.

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Method (Annotation)

- During the closure interval of voiced stops (characterised by regular oscillations in the airflow), the vocal folds remain in their position for voice during the entire closure interval.
- However, the oscillations die out as the back-pressure in the oro-pharyngeal cavity builds, and acts to oppose the lung pressure.

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Method (Annotation)

- Criteria used to annotate the release start and end time (following a closure) was:
  - Release start time – identify an increase of the oral flow signal (in some cases this is visible in the oral flow spectrogram);
  - Release end time – identify a decrease of the oral flow signal and the start of the next phone (Cho et al. 2002).

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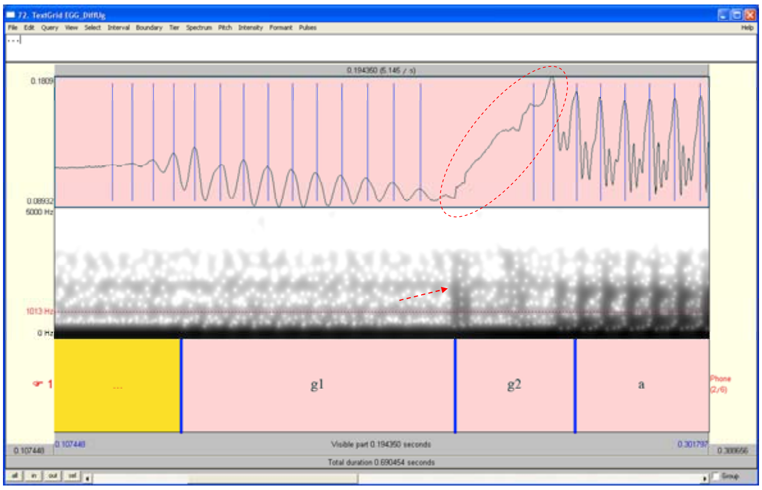
Method (Annotation)



Airflow signal, spectrogram and annotation.

Method (Voicing Classification)

- Analysis of the characteristics of stop production, and those of the phone preceding (Phone 1) and following the stop (Phone 3).
  - Manually labeling the voicing category (voiced, partially devoiced or devoiced) based in Lousada, Jesus and Hall's (2010) criteria.

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Method (Voicing Classification)

- However, this proved to be insufficiently precise for our purposes and we developed an improved method for classification when the voicing is relatively weak such as is found during the closure of a voiced stop.
  - Similar to criteria used previously for voiced fricatives by Pinho et al. (2009) and based only in the oral flow.

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Method (Slope)

- The slope of the stop release was calculated from linear regression, using all flow signal samples from the start to the end of the release.
- Analysis windows (three different production stages):
  - Stop closure
  - Steady state of phones preceding target stop
  - Steady state of phones following target stop

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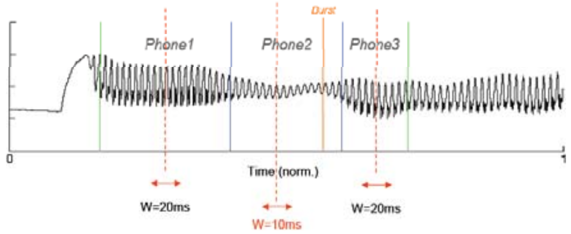
Method (Windows)

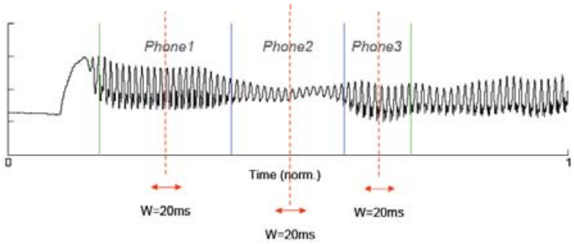
STOPS – with burst

Oral flow



STOPS – without burst

Oral flow



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Method

- Absolute mean oral flow values and amplitude of oscillations were extracted from these windows for all recordings and speakers.

- Relative vowel-stop and stop-vowel amplitudes were computed.

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Results (Slopes)

- The slopes of the stops releases show no significantly different values for the three different places of articulation
- There was a difference of approximately 10%, for all stops, between male and female speakers:
  - **Male**: 78.9% ± 8.5%;
  - **Female**: 69.0% ± 11.5%.

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Results (Slopes)

- These results could be related to those presented by Higgins et al. (1998).
  - The idea that glottal area and resistance affect peak oral air flow was supported by findings of higher peak oral air flow for men than women, adults than children, and voiceless than voiced consonants.

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Results (Slopes)

- Greater burst energy for a stop can be expected in two cases (Cho et al. 2002):
  - when there is a relatively smaller amount of linguopalatal contact, resulting in a fast release, as opposed to a larger contact area;
  - when the airflow is greater at the release (which is presumably due to a greater air pressure behind the constriction immediately before the release).

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Results (Slopes)

- Bilabial stops showed higher Voice Onset Time (VOT) values (-58.5ms to -64.6ms) than dental and velar stops (-49.0ms to -57.6ms).

VOT (ms)	/b/	/d/	/g/
Male ♂	-58.5 ± 23.4	-49.0 ± 25.7	-39.1 ± 58.6
Female ♀	-64.6 ± 25.9	-54.0 ± 28.2	-57.6 ± 33.4
All ♂&♀	-61.9 ± 24.7	-51.9 ± 27.0	-49.7 ± 45.9

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Results (Place)

- **Stop duration**
  - /b/: 88.2 ± 27.7 ms
  - /d/: 81.9 ± 28.3 ms
  - /g/: 87.8 ± 28.6 ms
- **Release duration**
  - /b/: 34.3 ± 15.1 ms
  - /d/: 29.5 ± 12.3 ms
  - /g/: 35.5 ± 14.2 ms

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Results (Gender)

- **Voice Onset Time** (VOT)
  - Male ♂ -49.5 ± 36.1 ms
  - Female ♀ -58.0 ± 28.8 ms
- **Stop durations**
  - Male ♂ 79.1 ± 28.6 ms
  - Female ♀ 92.8 ± 26.29 ms
- **Release durations**
  - Male ♂ 28.6 ± 11.4 ms
  - Female ♀ 35.3 ± 14.8 ms

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Results (Absolute Values)

Oral Flow (cm3/s)

Male ♂	Phone1	Phone2	Phone3
/b/	351 ± 151	18 ± 36	320 ± 120
/d/	311 ± 166	28 ± 56	300 ± 124
/g/	341 ± 136	19 ± 39	317 ± 119
Female ♀			
/b/	196 ± 98	36 ± 23	209 ± 96
/d/	211 ± 109	18 ± 18	191 ± 91
/g/	188 ± 93	36 ± 30	184 ± 86
All ♂&♀			
/b/	274 ± 148	24 ± 31	264 ± 122
/d/	262 ± 148	23 ± 42	244 ± 121
/g/	264 ± 139	28 ± 36	247 ± 122

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Results (Relative Values)

Relative Oral Flow (%)

	/b/	/d/	/g/
Male ♂	91.7 ± 15.3	87.0 ± 23.5	91.9 ± 18.0
Female ♀	77.7 ± 18.0	88.5 ± 14.3	76.1 ± 24.3
All ♂&♀	84.7 ± 18.0	87.8 ± 19.3	83.9 ± 22.6

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Conclusions

- A decrease in amplitude of the oral flow waveforms during the stops, relative to the amplitude of the previous and following phone, was observed for all speakers.
- Absolute amplitude values for female speakers were lower than for males.

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Conclusions

- Inspection of typical vowel and stop oral flow values
- Observation of the phoneme boundaries set during the annotation phase

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Weak voicing (Pinho et al. 2009)

– Voicing where the ratio of average airflow in the stop to that in the preceding or following phone is less than **70%**

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Future Work

- The mechanics of vocal fold vibration (e.g., onset and offset of vibration, opening and closing quotients of the vibratory cycle) have an impact on aerodynamic variables measurable from real speech that should be incorporated in realistic speech models.
- Aerodynamic variables can be used to understand the effect of variability in stop production on the performance of stop detectors.

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