Information in Spoken Language
A quantitative approach

Rob van Son
Chair of Phonetic Sciences
ACLC
University of Amsterdam

LOT winterschool 2006
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Introduction

Spoken language is mostly sound: Speech

- To understand speech we must understand speaking and hearing
- Hearing limits the information we can distill from sound
- Articulation limits what we can produce within these limits
- What information can be extracted from speech sounds?
- How can we study this?
- How can we study human speech processing?
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The speech chain consists of **articulation, sound, and hearing**

- The speech chain is **not** symbolic
- Articulation is preceded by formulation
- Hearing is followed by recognition
- Both formulation and recognition center around phonemic segments and words
- However, speech does contain neither, just sound
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"Er was eens een oud kasteel"

- Display of pressure versus time
- Words are aligned with sound
- Using computer readable (SAMPA) phoneme symbols
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1.5 ms of an /s/ sound from "was"

- Samples taken at 44.1 kHz (CD audio)
- Quantize at 16 bit (≈ 65000 amplitude levels)
- Maximum audio frequency 22.05 kHz (Nyquist frequency) but generally much less
- Dynamic Range ≈ 96db (≈ 6db/bit)
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Acoustics of speech: Digital sound and band-width

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Acoustics of speech: Amplitude and sound level

Intensity contour of "Kasteel"

- Intensity versus amplitude
- Intensity in db ($10 \cdot \log_{10}(\text{SoundEnergy})$)
- Intensity you hear is not the intensity you measure $\Rightarrow$ correct for human perception ($dBA$)
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Acoustics of speech: Durations

Phoneme segmentation of "Kasteel"

- Determine the boundaries of words, syllables and phonemes
- Use waveform, ear, and spectrum
- Segmentation is ambiguous and laborious
- Start with automatic segmentation (for speed)
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- frequency of a pure tone (top, 125 Hz)
- distance between the components in a mixture of harmonic tones (eg, 125 Hz)
- closest harmonic fit in complex sounds (bells)
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- from the possible repeat frequencies using an autocorrelation function
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**Acoustics of speech: Pitch contours**

*Hummed sound*

\( F_0 \) makes the melody, or intonation, of an utterance

- There is a general decrease of \( F_0 \) over an utterance: The *declination*
- \( F_0 \) movements indicate emphasized words: pitch *accents*
- \( F_0 \) movements and *declination resets* indicate boundaries
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The anatomy of the human ear (l) and cochlea (r)

- Sound enters the ear canal (left)
- The ear drum transfers the sound over the ossicles to the oval window into the cochlea
- The cochlea (right) converts sound into nerve excitations

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Hearing: The human ear

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Hearing: The basilar membrane

- The ear analyses sounds roughly into $\log(\text{Power}(\text{Frequency}))$ vs. $\log(\text{Frequency})$
- Speech is analyzed in the same way
- Use power spectra of sounds

Frequency map of the basilar membrane from [Moore(2003)]
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Hearing: Loudness

Relation between perceived loudness and frequency

- The absolute threshold varies with frequency
- Best hearing between 800Hz and 6000Hz
- Human speech needs 400Hz - 3400Hz (telephone speech)
- Loudness JND is around 1 dB (soft sounds)

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Hearing: Critical bands

- Sounds grouped in *critical bands* (CB)
  - CB is around 30 times JND
  - One signal per critical band
  - 3 CB per Octave
  - Time resolution $\approx 25\text{ms}$

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Hearing: Example of /ɛ/

Note the harmonic structure and the "bumps"
Note the harmonic structure and the low level of high frequencies
Note the noisy structure and the broad bandwidth
How much information can the ear extract at a minimum from speech?

- Frequencies: 400Hz - 3400Hz → 3 octaves ≈ 9 CBs
- Dynamic range ≈ 30dB per CB, → 5 bit / CB
- Time resolution ≈ 25ms
- Information available: \( \frac{9\, CB \times 5\, bit}{0.025\, sec} \approx 1800\, \text{bit/second} \)
- Just an order of magnitude estimation
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How much information is actually needed?

- Concatenated phoneme transitions (diphones) are perfectly intelligible
  - There are $\approx 1600$ diphones ($40 \cdot 40$ allophones)
  - $1600$ diphones fit easily in $11$ bit
  - Articulation rate $\leq 15$ phones/second
  - Information needed for recognition: $11 \cdot 15 = 165$ bits/second
  - Compare to $1800$ bits available, ample redundancy
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Speaking: Articulators

- The lungs pump air through the glottal folds
- The glottal folds can vibrate (or not)
- The oral cavity can be constricted at many points
- Alternatively, air can flow through the nasal cavity

Vocal tract and primary articulators

Lungs

- Alveoles (Teeth Ridge)
- Labium (Lip)
- Dentes (Teeth)
- Palate
- Velum
- Tongue
- Pharynx
- Vocal Cords (Glottis)
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Vocal tract and primary articulators
Speaking: Source Filter model of speech

Sound enters the oral cavity (vocal tract) from below and is filtered by the resonances of the cavity.
Oral cavity filter function of /ɛ/ (LPC model). Peaks are formants $F_1$ and $F_2$. The resonances of the vocal tract are called Formants, and numbered from below, i.e., $F_1$, $F_2$, $F_3$, $\cdots$. Normally, the first three are sufficient to describe (voiced) speech.
Vowel formant space of Dutch.

Only two formant values, $F_1$ and $F_2$, suffice to identify a vowel (in the ideal case). However, in normal speech, there is so much overlap and variation that it remains almost impossible.
Speaking: Reduction

Articulation takes effort and humans are “lazy”

- Unimportant, unstressed, items are articulated “less well”
- Leads to less distinctive sound segments
- Visible as a smaller vowel triangle (see above)
- Also found in consonants
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A spectrogram shows the development of the spectrum in time (darker is more power)

- A spectrogram shows the harmonics
- Vowels, fricatives, and plosives are visible
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Spectrograms: Narrow versus Wide band

Two views on spectrograms

- Narrow-band (top): High frequency resolution, low time resolution
- Wide-band (bottom): Low frequency resolution, high time resolution
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- Narrow-band (top): High frequency resolution, low time resolution
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Spectrograms: Formant and Pitch tracking

Formants (red dots) and Pitch (blue line) can be automatically determined and plotted into a spectrogram.
Fricatives are visible as gray noise patches. Plosives as a silent part followed by a noisy burst.
It is actually possible, after a few weeks training, to read spectrograms. All the information needed to "understand" the speech is in the spectrogram [Lander and Carmell(1997)].
Before anything can be done with speech, it has to be written down and transcribed

- Write out orthographically what was said (and check it)
- Align chunks of text roughly with the stretches of speech
- Transcribe the text automatically into phonemes using a lexicon
- Split the orthographic/phonemic text into words
- Align the words/phonemes automatically with the speech
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### Corpora: Transliteration

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Corpora: Transcription

Human annotator transcriptions: Difficult and expensive

- Accents, stress, and boundaries (always ambiguous)
- Handcorrected word-boundaries
- Handcorrected phoneme-boundaries (always ambiguous)
- Check Part-of-Speech tags
- Check Syntax
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Corpora: Identifying and annotating phonemes

Phonemes are not pearls on a string

- Phonemes always overlap and are extremely variable
- A phoneme you hear can appear absent in the waveform
- It is often unclear what phonemes were uttered
- Sometimes, even the order is unclear
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Identifying and annotating phonemes

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Corpora:
ToBI like systems for intonation transcription

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**ToDI symbols (IP: Intonational Phrase)**


<table>
<thead>
<tr>
<th>High</th>
<th>Low</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H*</td>
<td>L*</td>
<td>high/low accent</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>upward/downward movement after L*/H*</td>
</tr>
<tr>
<td>H%</td>
<td>L%</td>
<td>rising/low ending of IP</td>
</tr>
<tr>
<td>%H</td>
<td>%L</td>
<td>high/low beginning of IP</td>
</tr>
<tr>
<td>%HL</td>
<td></td>
<td>Initial falling pitch not marking accent</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td>half-completed fall/rise at end of IP</td>
</tr>
<tr>
<td>!H*</td>
<td></td>
<td>downstepped H*</td>
</tr>
</tbody>
</table>
There is no data like more data

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- Large amounts of data are necessary to model them
- “The best application/research is the one with the largest corpus”
- 10-1000 hours of speech recordings needed
- $10^8 - 10^9$ word text corpus needed
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There is no data like more data

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Corpora: for Speech and Language research

A language corpus is a documented collection of coherent text, speech, video, and transcriptions and annotations of these

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- Meta data (fixed): Information on the items
- Normalization (fixed): All items must adhere to certain guidelines
- Data (fixed): Immutable text or speech records
- Transcriptions and annotations (cumulative): Added value of interpretations and analysis
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Contents \( \left( \frac{2}{3} \text{ Dutch, } \frac{1}{3} \text{ Flemish} \right) \)
- 500 hours (5,650,000 words) recorded in The Netherlands
- 300 hours (3,250,000 words) in Flanders
- 9 million words
- 4250 speakers
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