

A Longitudinal Study of Infant Speech Production Parameters: A Case Study

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01 Introduction

Motivation

- Infant children's speech processing plays important role in detection of language delay and early communication disorders, automated reading tutoring, or emotional state assessment.
- In order to design and improve performance of such applications, good understanding of children's speech structure and its development over time is necessary.

Objective

- Study of infant speech production within the interval of 11 to 35 months of age, sampled with a step of 4 months.
- Analyzed parameters: fundamental frequency, formants, vocal tract length, average spectrum, spectral slope, duration of voiced segments, number of voiced segments in conversational turn, and recently proposed pitch micro-contour patterns.
- Design of a simple automatic age classifier.

02 Corpus

Overview of LENA Corpus

- Children speech database acquired by the LENA Foundation.
- More than 65,000 hours of recorded data.
- Subjects are recorded starting from 2 months through 36 months of age.
- Each recording is conducted during an "ordinary" day in the child's natural environment.

Data Subset Utilized in Present Study

- Longitudinal data from a healthy female infant acquired within the interval of 11 to 35 months of age, with a sampling step of 4 months. Analyzed data set comprises 7 recordings acquired at the age of 11, 15, 19, ..., 35 months.
- For each age sample, segments containing child's utterances were selected, yielding 5 minutes of speech per age.
- Recordings are stored in 16 kHz/16 bit format.

03 Speech Production Analysis - F₀

Fundamental Frequency - Literature Overview*

- Age 0-5 months: F₀ increases in both cry and non-cry utterances.
- Age 0-12 months: F₀ increases in hunger cries.
- Age 3, 6, 9 months: F₀ slightly increases at 6 months, followed by slight decrease at 9 months.
- Age 8-26 months: not significant changes of F₀ in monosyllables and bisyllables.
- Age 8 months-3.5 years: difficult to track any significant longitudinal trends in F₀.
- Age 5-17 years: males - significant F₀ drop starting from 11 to 15 years, no significant change later; females - significant drop at 7-12 years, no significant change later.
- Age 8.5-11.5 years: F₀ in females decreases.

*Multiple sources → observations may be at times contradictory

04 Speech Production Analysis - F₀

Fundamental Frequency (F₀)

- F₀ extracted using cross-correlation RAPT algorithm.
- Average F₀ displays an increasing trend in the interval of 11-35 months (slope $\mu = 1.64$ Hz/month, correlation coefficient $R^2 = 0.96$).
- Vertical bars represent 95% confidence intervals.

05 Formants

Formants - Literature Overview

- Age 0-5 months: F₁ increases in both cry and non-cry utterances.
- Age 4-60 months: F₁ decreases in females; F₁ decreases in males till approx. 30 months; F₁ decreases in both females and males in 4-18 months for some vowels, increase in other vowels.
- Age 8-18 months: F₁ decreases between 10-19 months in Canadian French speakers, no clear trend in Canadian English; F₂ decreases in Canadian English in 10-18 months, rather steady in Canadian French.
- Age 15-36 months: F₁, F₂ relatively unchanged till 24 months; significant decrease in 24-36 months.
- Age 5-16 years: F₁, F₂ decrease in most of the analyzed vowels.
- Age 8.5-11.5 years: F₁ mostly decreases between 10 and 11.5 years, F₂ mostly decreases between 8.5-10 years, F₃ consistently decreases in 8.5-11.5 years.

06 Formants

Second Formant Frequency (F₂)

- Formants extracted using algorithm that combines linear prediction of spectral envelope and dynamic programming (in WaveSurfer).
- Average F₂ displays descending trend with age. Similar was observed also for F₁ and F₃ (F₁ slope $\mu_1 = -2.21$ Hz/month, correlation coefficient $R^2 = 0.22$; F₂ slope $\mu_2 = -8.56$ Hz/month, $R^2 = 0.71$; F₃ slope $\mu_3 = -5.50$ Hz/month, $R^2 = 0.48$).
- Correlation coefficients of the F₁ and F₂ trends are considerably higher than in F₃.

07 Vocal Tract Length (VTL)

VTL - Literature Overview

- Studies of VTL typically employ resonance imaging (MRI).
- New-born babies: typical values of vocal tract length (VTL) ranging ~7 cm.
- Birth to 18 months - accelerated VTL growth.
- Female/male adults: 13-18 cm in female and male adults.
- Location of higher formant frequencies is believed to be more correlated with VTL compared to lower formant frequencies, which are strongly dependent on the rate of the jaw opening and vertical position of the tongue.
- In the original version of the vocal tract length normalization (a popular technique used for normalizing inter-speaker vocal tract differences to improve automatic speech recognition), the warping parameter proportional to VTL differences is estimated from the inverse of higher formant frequencies.
- In our study, inverse of F₂ used for estimation of VTL changes.
- VTL varies with the production of distinct → averaging F₂ over longer speech segments (utterances) to estimate average, phone independent VTL.

08 Vocal Tract Length (VTL)

Estimation of VTL Changes - Inverse of F₂

- 1/F₂ displays fast increase between 11 and 15 months, while later, till 27 months, remains almost steady.
- Despite the obvious accuracy limitation of this technique compared to MRI, the observed trend seems to correlate well with the accelerated VTL growth reported for the early months after birth.

09 Average Spectrum & Spectral Slope

- Average spectra of the infant subject are compared with the average spectrum extracted from the spontaneous speech of 23 US native adult female subjects from the UTScope database (average age $\mu = 22.2$ years, standard deviation $\sigma = 3.6$ years).
- Average spectrum is extracted from a 25ms window shifted with a skip rate of 10 ms.
- Complementary average spectral slopes are extracted on the frame basis by fitting a straight line into the short term amplitude spectra in log frequency-log amplitude domain by means of linear regression.

10 Average Spectrum & Spectral Slope

Age (Months)	Character	Slope	Range
11	1174	-2.0	1.9
15	1816	-2.4	1.6
19	1983	-2.4	1.6
23	1911	-3.2	1.9
27	1813	-3.0	1.6
31	1824	-2.8	1.6
35	1653	-3.5	1.3

- With increasing age, the number of local minima and maxima in the spectral envelope decreases (envelope smoothing) and the contours slowly approach those of adult speakers.
- Spectral slope - considerably flatter than the one usually seen in adult speakers (typically around -4 to -10 dB/oct), and its tilt increases with age, progressing towards adult values.

11 Voiced Segment Duration

Voiced Segment Durations

- In children (typically 5 years and older), the duration of vowels, consonants, syllables, and sentences tend to reduce with age and approach the one in adults.
- In our study, the duration of voiced speech segments is analyzed. Voiced segments are formed by a non-interrupted sequence of voiced frames.
- Average number of voiced segments per conversational turn is also counted.

	Age (Months)					
	11	15	19	23	27	31
Average	11	15	19	23	27	31
Segment Duration (s)	0.31	0.22	0.32	0.33	0.32	0.43
Segments/Turn	2.3	2.5	2.0	1.8	1.8	2.4

- It can be seen that unlike reported for older children, the durations tend to increase for our subject, while the number of voiced segments per conversational turn either remains steady or reduces.

12 Pitch-Contour Micropattern

Pitch Micro-Contour Patterns

- Recently proposed pattern based approach to pitch contour analysis and modeling is utilized.
- Small set of elementary patterns (9) is defined to fit adjacent pitch sample values in order to describe the pitch contour micro-structure.
- Frequency of occurrence of elementary patterns is analyzed across age sets.
- [x, y] coordinates in the pattern codebook correspond to the [x, y] coordinates in the histograms in the following slides.

- While in the adult histogram the middle - 'flat' - pattern dominates, the pattern distribution in early infant speech is way more uniform. With increasing age, the 'flat' pattern becomes gradually more and more pronounced and the whole distribution approaches the one seen in adults.

13 Pitch-Contour Micropattern

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14 Automatic Age Classification

- The observed production variations can be expected to have a direct impact on coding commonly used in speech systems.
- To evaluate this hypothesis, we train separate acoustic models for each age sample set, yielding 7 models representing 11-months speech, 15-months speech, ..., 35-months speech.
- If the speech coding is age-sensitive, the models will capture age-dependent speech characteristics and can be used for speaker-dependent automatic age classification.
- Gaussian mixture models (GMM) are utilized to model probability density functions (pdf's) of speech parameters.
- Task - pick a pair of most likely adjacent age models out of 6 possible neighbor pairs.
- A GMM maximum a posteriori classifier utilizing modified perceptual linear predictive cepstral coefficients (PLP) provided classification accuracy of 70 %.

15 Conclusions

- This study has presented an initial analysis of speech production development in a healthy female infant subject conducted on the longitudinal data spanning 11-35 months of age.
- Trends in the reduction of formant frequencies and extending vocal tract length with age confirm our intuition and observations presented in the literature.
- On the other hand, the observed gradual increase of F₂ after the 12 months of age, together with the increase of average voiced segment duration and reduction of voiced segments in conversational turns are somewhat surprising.
- Novel approach to children pitch contour analysis and modeling utilizing a codebook of pitch micro-contour patterns has been presented and shown to capture additional aspects of speech production maturing.
- Finally, age dependency of common speech coding strategies has been exploited in the design of a speaker-dependent automatic age classifier.
- Many of the observed differences between the child's and adult speech production can be directly utilized in improving current speech processing techniques.