ANALYSIS OF CHILDREN’S SPEECH: DURATION, PITCH AND FORMANTS

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ABSTRACT
Magnitude and variability of duration, pitch and formant frequencies are computed for speech collected from five to eighteen year-old children. The study confirmed that reduction in magnitude and variability are the primary indicators of speech development. Specifically, parameters below adult range exhibit wider dynamic range of vowel duration, longer suprasegmental duration, and larger temporal and spectral variations. These trends diminish around age twelve. Children’s speech acoustic characteristics fully develop to adult level in both magnitude and variability around age fifteen. Change of formant frequencies in male speakers parallels the growth of the vocal tract, while for female speakers the presence of such a linear trend is not clear. We conclude that the primary factors governing the acoustic patterns during speech development are anatomical maturation of the speech apparatus and speech motor control in terms of agility and precision.

1. INTRODUCTION
An important issue in the study of speech development in children is to investigate the age at which magnitude and variability of acoustic parameters reach adult range and how these acoustic parameters vary as a function of age, gender, and speech sounds. In-depth knowledge on age-dependent acoustic patterns and their variability should be valuable for speech applications such as automatic recognition of children’s speech [1], evaluation and training of deaf children, and text-to-speech synthesis. Such knowledge is also important for associating acoustic development in children with the underlying anatomical development of the vocal organs, which is essential for the creation of a better developmental model of the vocal tract for speech production research [2].

In this paper, speech duration, pitch and formant frequencies are measured together with temporal and spectral variability using a recently collected children’s speech database [4]. The database enables a cross-sectional study from age five through age eighteen with an approximate one-year age resolution of one-year, filling the age gap that existed in previous studies (eg.,[3]) and providing a more detailed view of speech development. This paper is organized as follows: The database used in this study is briefly described in Section 2. In Section 3, the procedure used to estimate the acoustic parameters is described and evaluated. The results of this experimental study are presented in Section 4 followed by a discussion of speech development in children.

2. SPEECH DATABASE
The database used in this study was collected from 436 children of age five through age eighteen, with resolution of one-year of age, as well as 56 adults, of both genders. The speech material consisted of ten monophthongs and five diphthongs of American English vowels and five phonetically-balanced sentences repeated twice by all subjects. Target words for vowels were produced in the carrier sentence “I say uh – again,” except for children of ages five and six. The target words for the monophthongal vowels are beam (IY), bit (IH), bet (EH), bat (AE), pot (AA), ball (AO), bat (AH), put (UH), boot (UW), and bird (ER). Recordings were made in a sound-treated booth located inside a glass/panel enclosure, using a high-fidelity microphone (Brüel & Kjaer model #4179) connected to a real-time waveform digitizer with 20 kHz sampling rate and 16-bit resolution. An detailed description of subjects, data collection procedures, and the recording environment can be found in [4].

3. MEASUREMENTS
In this section, the automatic procedure used to measure the duration, pitch and formant frequencies is presented and evaluated by comparing its results to corresponding hand-measured data points for a small subset of the data. The automatic segmentation procedure used to obtain the phonemic, word and sentence boundaries is also outlined.

3.1. Duration
In order to process the large number of waveforms (over 23,000 files) within a reasonable amount of time, the phonetic level segmentation of each waveform was automatically computed by aligning the speech frames to the states of the corresponding phonemic units (hidden Markov models) trained from the children speech database [5]. Duration was measured directly from the start and end points of the target segment under consideration with a 10 msec resolution.

The accuracy of the automatic segmentation was evaluated from hand–measured durations of 160 randomly selected vowel segments. Mean difference between the automatically computed and the hand–measured values was 17.3 msec and the standard deviation was 36.7 msec. In general, vowel durations were systematically underestimated by the automatic procedure and thus vowel durations obtained in this study may be somewhat shorter than their actual values. However, the automatic segmentation of /s/ and the end-point detections of the five sentences were quite accurate.

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3.2. Fundamental and formant frequencies

The fundamental frequency (F0) and the first three formants (F1, F2, F3) of the ten vowel segments were computed using the automatic pitch and formant-tracking program of the commercial software package ESPYS by Entropic Research Laboratory Inc. The median value of each pitch and formant track was computed as the representative value of the track. The performance of the automatic program was evaluated using a subset of hand-measured data. Mean differences (standard deviation) between hand and automatically measured values in Hz were −7.6 (23.8) for F0, −43.0 (87.2) for F1, −92.4 (183.8) for F2, and −193.1 (400.7) for F3. In general, pitch and formants were underestimated by the automatic program.

Formant values that were clearly erroneous were discarded using the following procedure: the initial formant data were grouped by vowel, age and gender, and outliers in each group were removed using a two-sigma ellipse. Next, each data file was visually examined and whenever one of the F1-F3 values was judged to be too low or too high, the corresponding formant set was discarded. Despite our efforts to remove erroneous formant values some might have escaped the visual inspection process. It is quite possible that the refined formant data set included some underestimated F2 and F3 values, especially for children aged eight and lower. For pitch estimates, the large standard deviation of F0 estimation error was due to a few occurrences of “pitch halving” by the automatic program. These erroneous pitch values were removed by a procedure similar to the one used for the refinement of the formant data. These refined pitch and formant data are presented in this study.

3.3. Spectral envelope

The smooth spectral envelope or equivalently the cepstrum coefficients derived from the spectral envelope are the most common set of features used in automatic speech recognition. Thus, it is important to measure the spectral variability of speech sounds as a function of speaker’s age. In the current study, spectral variability between two repetitions of a target vowel was measured, and between the first and second half segments of each vowel segment were measured. For this purpose, a given vowel segment was analyzed using a mel-frequency filterbank (spanning 100 to 6000 Hz) and the first 12 cepstral coefficients were computed (not energy). The Euclidean distance between the two sets of coefficients was used as a measure of spectral variability.

3.4. Variability measurements

Variability of the temporal and spectral parameters associated within each age group was measured both within and between speakers. Inter-subject variability was computed as the standard deviation of the average value of a given parameter across all subjects in an age group. Intra-subject variability was computed as the difference of the magnitude of a given parameter between two repetitions. Group intra-subject variability was defined as the average intra-subject variability of that group. Finally, the coefficient of variation (COV) was computed as the ratio of inter- or intra-subject variability to the corresponding mean value.

4. RESULTS AND DISCUSSION

In this section, the estimated duration, pitch and formant frequencies are presented, together with temporal and spectral variability measurements. Implications for the illustration of the speech production process for children speakers are discussed.

4.1. Duration

Mean durations of 10 monophongs are shown in Fig. 1(a) for various age groups. ANOVA analysis shows no statistically significant gender difference in vowel duration. As can be seen in Fig. 1(a), five-year-old children display longer vowel durations than older age groups. There is no statistically significant change in vowel duration after age seven. It is interesting to observe that although children of ages five to seven exhibit adult-like pattern of vowel-dependent duration, their relative timing control among vowels in a given context is not well yet established. They show a tendency to overshoot, or sometimes possibly undershoot, vowel duration. This may suggest that the dynamic range of vowel duration is larger for young children than for adults.

The intra-subject COV is shown in Fig. 1(b). Vowel duration variability reaches adult levels around age eleven or twelve, several years later than vowel duration magnitude. A recent study on vowel duration also reported a similar trend [6]. The latency of variability stabilization may be explained as the time required to adjust the wider dynamic range of vowel duration.

In contrast, the analysis of /s/ and sentence duration (not shown in the plots) indicates that both magnitude and variability reach adult levels at approximately the same time, around age eleven or twelve. Fluent productions of sentences and /s/ (in “I say”) might require better coarticulation skills than vowel production in a given context. These results imply that both duration and variability in suprasegmental levels may be governed by a single but collective or emergent factor, the degree of coarticulatory skill. It is interesting to note, that on average, teenagers around age fifteen show shorter duration than adults for both /s/ and for sentence productions.

4.2. Pitch

The average pitch of male and female speakers averaged across all vowels is shown in Fig. 1(c) as a function of age (inter-subject variation shown with error bars). No statistically significant gender difference exists in pitch up to age twelve. For male speakers, there is a significant F0 drop from age eleven to age thirteen and there is no significant pitch change after age fifteen. This indicates that pubertal pitch change in male children starts between ages twelve and thirteen, and ends around age fifteen. About a one-octave pitch drop is observed during puberty. The relatively large inter-subject variability at ages thirteen and fourteen suggest that the onset-time of puberty is speaker-dependent. For female speakers, the pitch drop from age seven to age twelve is significant, indicating that the laryngeal growth in females ends around age twelve and thus pitch reaches adult levels after that age. On average, teenagers after puberty show lower pitch values than adults. Intra-subject COV indicates that pitch variability progressively decreases with increasing age and reaches adult levels around age twelve or thirteen for both genders. Teenagers show, on average, less variability than adults.

4.3. Formant frequencies and scaling factors

Two-sigma ellipses of several vowels are shown in Fig. 1(d) in the F1/F2 space. The vowel positions produced by 8-year old boys in the current database (Fig. 1(d)) are slightly compressed or centralized, compared to the children’s formant data in [7], most possibly due to the con-
4.4. Spectral variability

In Fig. 1(g), the mean cepstrum distance between two repetitions of the same vowel by the same speaker is shown. Clearly, young children exhibit more spectral variability than adults between two repetitions of the same utterance. A similar trend can be also observed in formant variability. This suggests that young children, especially below age ten, have not fully established their own optimal articulatory vowel targets in a given context.

In Fig. 1(h), the mean cepstrum distance between the first and the second half of each vowel segment is shown as a function of age and gender. It is clear that even within a vowel utterance, children younger than ten display greater spectral variability. This is most likely due to excessive and/or abrupt tongue movement during the transition from the vowel to the final consonant /d/, /t/ or /l/, which signifies that children are less-skilled in co-articulation. Therefore, adult-like co-articulation skills are achieved around age twelve.

As can be observed from Fig. 1(h), teenagers around age fifteen display less within-vowel spectral change than all other age groups. This could be possibly due to the faster speaking rate for teenagers (see Sec. 4.1). Further, female adults display greater within-vowel spectral variation during transitions than male adults.

5. CONCLUSIONS

In this study, we have measured the duration, pitch, and formant frequencies of speech collected from speakers ages five through eighteen with a resolution of one-year of age. Reduction in magnitude and within-subject variability over time are two major indicators of speech development. Specifically, when compared to adult, children below age ten exhibit wider dynamic range of vowel duration, longer segmental and suprasegmental durations, higher pitch and formant values, and larger within-subject variability. This trend diminishes around age twelve and, in both magnitude and variability, children’s speech fully develops to adult levels around age fifteen for male speakers and age fourteen for female speakers. Change of formant patterns in male speakers parallels the vocal tract growth, while for females such a linear trend is not clear. Teenagers around age fifteen differ from both children and adults in that they speak faster, have lower pitch values and exhibit less temporal and spectral variability. We conclude that the primary factors governing the acoustic patterns during speech development are anatomical maturation of the speech organs and speech motor control in terms of agility and precision.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Figure 1: (a) Mean duration of 10 monophthongs. (b) Intra-subject coefficient of variation (age 19 corresponds to adult speakers). (c) Mean pitch of male and female speakers. (d) Two-sigma ellipses for vowels (dotted circles correspond to adult speakers in this database). (e) Plot of mean F1 and F2 of vowels /iy/, /ae/, /aa/, /ao/, and /uw/. (f) Mean formant scaling factors as a function of age and gender. (g) Mean cepstral distance between two repetitions of the same vowel. (h) Mean cepstral distance between the first- and second-half segments of all vowels.