Variability in vowel formant frequencies of children with cerebral palsy

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Abstract
Cerebral palsy (CP) is a developmental motor disorder and the study of the speech characteristics and developmental speech patterns may provide valuable information on early speech development. Vowels appear early in speech development and they are central to the understanding of the acoustic properties of speech. Therefore, the current study aimed to examine the differences of vowel formant frequencies among five children with cerebral palsy in different severity ranging from ages 3 to 7. First and second vowel formants (F1 and F2) were measured to investigate: 1) the changes of the F1 and F2 values, 2) vowel space, and 3) the vowel space area in CP children of different ages and severity. The major findings are: 1) There was no obvious decline in F2 values from 3 to 7 years old, which indicated delayed speech development; 2) The overlapping ellipses of all vowel spaces illustrated unstable motor control in all the five children; and 3) The five CP children had centralized corner vowels and there was no expansion of vowel spaces at different ages. This indicated their limited motor control.

Keywords: vowel formant frequencies, vowel space, cerebral palsy, Mandarin-speaking
1. Introduction

Cerebral palsy is regarded as the most common cause of severe motor disability in children who are attributed to non-progressive disturbances that occurred in the developing infant brain [1]. Estimation from several different developed countries reported that 1.2-3.0 per 1000 children were diagnosed with cerebral palsy [2][3]. Vowels are central to the understanding of the acoustic properties for speech, and vowels appear early in speech development. Children achieve high degree of accuracy in producing vowels by the age of 36 months [4]. Therefore, the current study focused on vowel acoustical characteristics in five CP children of different ages.

2. Methodology

2.1. The participants

Five children with cerebral palsy participated in current study for investigating the differences of vowel formant in their speech production. General background information is described as follows.

Table 1. CP participants

| Gender | Age (in year; month, day) | Severity of Impairment | CFCS |
|--------|---------------------------|------------------------|------|
| CP1    | Male 2;5,13               | Moderate               | Level II which distributed that the child is effective message sender/receiver with both unfamiliar and familiar communication partners but in a slow path |
| CP2    | Male 2;9,16               | Most Severe            | Level IV which indicated that the child seldom effective message sender/receiver even with familiar partners |
| CP3    | Male 3;11,6               | Moderate               | Between level IV (Self-Mobility with Limitations; May Use Powered Mobility) in between 4th and 6th birthday. |
| CP4    | Male 4;11,16              | Severe                 | Between level III and IV |
| CP5    | Male 6;5,14               | Severe                 | Between level IV (Self-Mobility with Limitations; May Use Powered Mobility) in between 4th and 6th birthday. |

Five participants were observed individually by the Communication Function Classification System (CFCS) [5] as shown in Table 1. CP2 child, in 33 months, was diagnosed with hydrocephalus which caused severe brain damage and speech disorder.

2.2 Data collection and analysis

A 50-minute recording from each child was analyzed, except for CP2. Due to very limited speech data from CP2, two recordings were used. The recordings were made in a quiet classroom with no noise disturbance (CP1) and the participant’s home (CP2, CP3, CP4, and CP5) with quiet environment and fewer disturbances. TASCAM DR-100 recorders with a SHURE wireless microphone system were used for data collection. The acoustic analysis was based on the 50-minute recordings which includes picture-naming task, and
spontaneous conversation between the observer, the child and the mother.

Every word in picture-naming task was transcribed. The first and the second formant frequencies (F1 and F2) of vowels were measured with time-frequency analysis, TF32 (Milenkovic, 2002) with reference to Linear Prediction Coefficient (LPC) and Fast Fourier Transformation (FFT). Vowel space was drawn to suggest the stability of vowels uttered by children with CP of different levels of severity. Furthermore, the corner vowel space areas were calculated with the vowels (/i, a, u/).

3. Results and discussion

3.1. Vowel formant frequencies

The value of F1 and F2 in vowels /i/, /e/, /u/, /a/, /o/ and /o/ were analyzed for each child. The descriptive data for F1 and F2 values of all the 5 children is shown in Table 2. The values of F1 and F2 did not appear obvious differences in children with different ages. However, CP2 had very limited data on the vowel /a/ due to the severe brain damage. He could not successfully produce single word but limited sounds.

Table 2. Mean and standard deviation (in parentheses) of F1 and F2 values

| Vowels | /i/      | /e/      | /a/      | /o/      | /u/      | /o/      |
|--------|----------|----------|----------|----------|----------|----------|
| CP     | F1       | F2       | F1       | F2       | F1       | F2       |
| CP1    | 559.5    | 3484.5   | 666.5    | 2713     | 594      | 1160     |
| 2:5,13 | (78.9)   | (375)    | (216)    | (704)    | (118)    | (281)    |
| CP2    | 668      | 2627     | 779      | 2048     | 650      | 1297     |
| 2:9,16 | (69)     | (127)    | (126)    | (711)    | (0)      | (0)      |
| CP3    | 610      | 3265     | 754      | 2709     | 676      | 1259     |
| 3:11,6 | (103)    | (309)    | (101)    | (451)    | (108)    | (533)    |
| CP4    | 479      | 3580     | 731      | 2888     | 555      | 1161     |
| 4:11,6 | (67)     | (183)    | (166)    | (494)    | (103)    | (251)    |
| CP5    | 602      | 3065     | 770      | 2355     | 648      | 1252     |
| 6:5,14 | (100)    | (475)    | (180)    | (769)    | (189)    | (537)    |

Table 2 shows the mean and standard deviation of F1 and F2 of the main vowels produced by each child. Although there was no obvious difference among the severity groups as comparing the F1 and F2 values, CP4 (severe) tended to have lower F1 value in vowels /i/ and /o/, and CP2 (most severe) showed lower F2 value in vowels /i/, /e/ and /a/.

Table 3. Mean and standard deviation (in parentheses) of F1 and F2 (sorted by severity)

| Vowels | /i/      | /e/      | /a/      | /o/      | /u/      | /o/      |
|--------|----------|----------|----------|----------|----------|----------|
| CP     | F1       | F2       | F1       | F2       | F1       | F2       |
| Moderate | 559.5    | 3484.5   | 666.5    | 2713     | 594      | 1160     |
| CP1    | (78.9)   | (375)    | (216)    | (704)    | (118)    | (281)    |
| CP3    | 610      | 3265     | 754      | 2709     | 676      | 1259     |
| 3:11,6 | (103)    | (309)    | (101)    | (451)    | (108)    | (533)    |
| Mean   | 584      | 3374     | 710      | 2711     | 635      | 1209     |
| Severe | 668      | 2627     | 779      | 2048     | 650      | 1297     |
| CP2    | (69)     | (127)    | (126)    | (711)    | (301)    | (527)    |
| CP4    | 479      | 3580     | 731      | 2888     | 555      | 1161     |
| CP5    | 602      | 3065     | 770      | 2355     | 648      | 1252     |
| Mean   | 583      | 3090     | 760      | 2430     | 617      | 1236     |

The frequency of occurrence of each vowel is described in Table 3 which indicated that vowel /i/ and /a/ appeared more frequently than other vowels since the age of 2. Data from
CP2 (severe) showed the opposite outcome in which vowels /i/ and /a/ appeared only 14% (6%+8%) and vowels /o/ and /ə/ appeared 77% (39%+38%). This may due to the limited spontaneous speech production that the child produced.

Table 4. The frequency of occurrence of each vowel

|          | /i/ | /ɛ/ | /o/ | /a/ | /o/ | /ə/ |
|----------|-----|-----|-----|-----|-----|-----|
| CP1 (2;5,13) | 25% | 7%  | 16% | 24% | 14% | 14% |
| CP2 (2;9,16)  | 6%  | 8%  | 1%  | 8%  | 39% | 38% |
| CP3 (3;11,6)  | 23% | 8%  | 12% | 26% | 15% | 16% |
| CP4 (4;11,16) | 24% | 9%  | 7%  | 26% | 21% | 13% |
| CP5 (6;5,14)  | 22% | 15% | 16% | 11% | 25% | 12% |

3.2. Overall vowel space

The vowel space for all vowels is illustrated in the following figures. Figure 1 shows that the child at 29 months had not yet developed mature vowel production. The ellipses of vowel space were overlapping and centralized. CP2 had very unstable vowel production in which the ellipses are large. That is, the range of individual vowel was big. The vowel space for CP3 showed overlapping ellipses, which also indicated unstable vowel production. Even in the oldest child (6 years and 5 months of age) in this study, the production of vowels still appeared to be immature.
The vowel space above indicated the unstable vowel production by CP children in different ages. Table 5 displays the range of F1 and F2 values, and the data showed that CP1 had a very unstable F2 value in vowel /i/. CP2 had the smallest range of F2 in vowel /o/ even though CP2 was the most severe child with brain injury. The descriptive data also indicated that CP5 (77 months) had very unstable motor ability in which the range of F2 values of vowel /i/ was very large (from 940Hz to 3446Hz).

Table 5. Range of F1 and F2 values

|       | /i/ | /e/ | /o/ | /a/ | /o/ | /s/ |
|-------|-----|-----|-----|-----|-----|-----|
| CP1   |     |     |     |     |     |     |
| 2;5,13| Min | 423 | 2281| 1382| 431 | 867 |
|       | Max | 687 | 3788| 3271| 740 | 1375|
| CP2   |     |     |     |     |     |     |
| 2;9,16| Min | 563 | 2546| 1206| 650 | 1297|
|       | Max | 727 | 2843| 1030| 2835| 1677|
| CP3   |     |     |     |     |     |     |
| 3;11,6| Min | 437 | 2583| 559 | 1130| 740 |
|       | Max | 788 | 3832| 943 | 3711| 1000|
| CP4   |     |     |     |     |     |     |
| 4;11,16| Min | 385 | 3230| 384 | 1288| 338 |
|       | Max | 611 | 4008| 876 | 3272| 723 |
| CP5   |     |     |     |     |     |     |
| 6;5,14| Min | 335 | 940 | 571 | 890 | 555 |
|       | Max | 816 | 3446| 1166| 2847| 1169|

3.3. Vowels area

The scatter plots in Figure 2 illustrate the distribution of the three corner vowels (i.e., /i/, /u/ and /a/) for each child. The blue dots represent the vowel /a/ and its range is scattered apart which indicates the instability in producing vowel /a/ for each child in this study. The lines were drawn to illustrate the changes of vowel space areas in different ages and severity. Previous studies indicated that children tend to have smaller vowel space in early age, and later expand a little when the children are older, then become more centralized. The broader vowel space at early stages corresponds to the increased variability of vowel formants which might be due to immature motor control [6][7]. After acquiring more mature motor control for vowel production, the decreased variability of vowel formants leads to the reduction of F1-F2 space at later stage. However, the current study did not discover obvious change of vowel space in different ages. In this current study, CP1 had larger corner vowel space than CP3 due to age difference. CP2, with severe dysarthria, tended to have very scattered corner vowels distribution due to the difficulty of motor control.
Figure 2. Overall vowel areas
The vowel space with three corner vowels produced by the 5 children with different ages revealed no obvious trend of expansion or concentration of vowel spaces. However, the results indicated that, first, the major difference among participants appeared on F1 formant values, especially for vowel /i/ and /u/. Second, vowel /a/ appeared to be stable with no obvious changes by severity and age differences. Table 6 shows the corner vowel space area for each child. The results indicated that the vowel space tended to be larger in early ages, and then became smaller in older ages.

Table 6. Corner vowel space area (Hz²)

|       | CP1            | CP2          | CP3         | CP4          | CP5          |
|-------|----------------|--------------|-------------|--------------|--------------|
| Severity | Moderate      | Severe       | Moderate    | Severe       | Severe       |
| Age    | 2;5,13        | 2;9,16       | 3;11,6      | 4;11,16      | 6;5,14       |
| Area   | 556655 Hz²    | 278985 Hz²   | 345718 Hz²  | 572422 Hz²   | 439234 Hz²   |

Previous study of children’s developmental changes in vowel production suggested that typically-developing children tended to have high F2 values in vowel /i/ at age 1 and decreased by process of age [8]. The result in current study showed that the F2 value of vowel /i/ in CP1 (29 months) had reached up to 3000 Hz. However, the F2 values of vowel /i/ did not decline with the process of age. CP4 appeared to have more than 3000 Hz of F2 values in vowel /i/ at age of 4. The data in the current study indicated unstable development in vowel production in terms of age difference in respect of F1 and F2 values. The findings are similar to the description in [9] which indicated that the abnormality in vowel development may provide valuable information in the understanding of early speech characteristics and speech development in CP.

Lee (2010) indicated that CP children with dysarthria have smaller vowel space areas than CP without dysarthria and typically-developing children. The five CP children participated in the current study were grouped as CP with dysarthria but in different severity (i.e., moderate and severe). However, the results in current study indicated that CP2 (most severe) had the smallest vowel space areas and CP4 (severe) had the largest vowel space area. In other words, the results did not show clear relation between the

![Figure 3. Vowel space for all participants. CP1 (black); CP2 (red); CP3 (yellow); CP4 (blue) and CP5 (green)](image-url)
severity, F1 and F2 values, vowel space, and vowel space area.

Due to the deficit of speech-motor control, children with cerebral palsy showed no obvious differences in speech production based on the comparison of vowel formant values in CP with different severities and ages. Regarding vowel space, all five CP children had scattered and non-uniform formant values, which reflected that children with CP had limited ability to coordinate and control tongue movement in vowel productions.

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