EXPLORING ACOUSTIC MEASURES OF VOWELS (VSA, FCR3, VAI4, VFR) IN CHILDREN WITH HEARING IMPAIRMENT

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ABSTRACT

The aim of this study was to evaluate the significance of four derived acoustic measures of speech in Hindi speaking children with hearing impairment (Group I, n=16). Typically developing children (Group II, n=30) were included as control group. The derived measures considered were vowel space area (VSA), formant centralization ratio (FCR3), four vowel articulation index (VAI4) and the vocalic anatomical functional ratio (VFR). These were derived from formant frequencies (F1 & F2) of vowels /ɑ/, /i/, /u/, and /æ/. Parametric statistical analysis was performed to compare these measures across the groups. Results indicate a statistically significant difference in VSA, FCR3, VAI4, and VFR between the groups. VSA was found to be the most significant measure. Hence, these derived acoustic measures can aid in developing automatic speech assessment tools and in evaluating the efficacy of speech therapy techniques for children with hearing impairment.

Keywords: vowel space area, formant frequencies, hearing impairment.

1. INTRODUCTION

Speech is a primary mode of communication, and listeners to speech of children with hearing impairment (HI) experience reduced speech intelligibility. This is primarily because of the presence of articulation errors associated with speech production in children with HI. Extent of articulation errors depend on type (sensorineural or conductive), degree (moderate, severe, or profound), and onset of hearing loss.

Children with HI exhibit errors in place of articulation (substitution) and voicing (voiced become voiceless sounds & vice versa). Articulatory errors are often observed in posteriorly articulated sounds because the articulatory gestures are less visible. Besides, errors in consonant clusters were also identified. Children either omit consonant or insert schwa /ə/ vowel during the production of clusters [1].

The vowel substitutions are frequently observed in children with HI. They attempt to produce the back vowels more appropriately compared to the front vowels. The vowels with closer degree of stricture are difficult to articulate than open vowels [2, 3, 4]. However, Stein [5] reported that back vowels are produced anteriorly by children with HI. In addition to these errors, neutralization of vowels (sounds like schwa /ə/ vowel), diphthongization of monophthongs [6, 3], vowel nasalization [7] are also reported.

Speech of children with HI exhibit variations in the formants of the vowel production compared to typically developing children (TDC). Acoustic analysis provides a quantitative assessment that has the potential to precisely evaluate the formant characteristics and severity of speech disorders. This will further assist in monitoring the prognosis of speech therapy [8]. Objective assessment through acoustic analysis also aids in the development of tools for automated assessment of severity of speech disorders.

First formant (F1) and second formant (F2) determine the vowel space area, which is a measure of acoustic space of vowels. The acoustic space is an indicative of the vowel distinctiveness during the production. The acoustic studies in children with HI have revealed an overlap between vowel formants indicating limited formant space. A significant degree of overlap between the vowels in the vowel space would result in vowels to be less differentiated, and more centralized [9, 10, 3, 11]. The reduced vowel space can result in reduced intelligibility of speech of these children with HI compared to TDC [4].

Many researchers have investigated the interactions of acoustic measures of speech in spectral and temporal domain [4, 6, 10]. Vorperian and Kent[12] evaluated the acoustic characteristics of vowel quadrilaterals by measuring vowel space area (VSA), formant centralization ratio (FCR3), four vowel articulation index (VAI4) and the vocalic anatomical functional ratio (VFR) in speakers with Down syndrome. VSA is a measure of acoustic space, FCR3 is a measure of vowel centralization, VAI4 is a measure of vowel contrast, and VFR is a measure of contrast of high vowel /i/ and /u/. The results of the study [12] show reduced VSA, VAI4, and VFR values and increased FCR3 in speakers with Down syndrome compared to their peers.

However, there were no considerable investigations made to measure FCR3, VAI4, and VFR of the speech in Hindi speaking children with HI. Evaluating these measures improves the understanding of the vowel space for speech production in children with HI. These measures can aid in developing tools for automated assessment of severity of disordered speech. Thus, the purpose of this investigation was to evaluate VSA, FCR3, VAI4, and VFR in children with HI (group I) and TDC (group II), compare and find the significance.

1.1. Objectives of the study

- To measure and compare the formant frequencies (F1 and F2) for four vowels /ɑ/, /i/, /u/, and /æ/ in children with HI (group I) and TDC (group II).
- To estimate the derived acoustic measures such as VSA, FCR3, VAI4, and VFR in children with HI (group I) and TDC (group II) and compare them.
- To establish the most significant derived measure which will aid in the differentiation of the groups.

2. METHOD

2.1 Subjects

The study was conducted using a standard group comparison of 46 participants, and utilized a convenience sampling method. Group I includes 16 Hindi speaking children aged 3-9 years [9 girls (Mean age of 5.39, SD-1.04) and 7 boys (mean age of 6.21, SD- 1.28)] with HI. These children exhibit bilateral sensorineural or mixed hearing loss ranging from severe to profound degree (hearing loss > 71dBHL). All the participants were recommended and fitted with bilateral digital hearing aids. Group II comprised of 30 TDC [13 girls (mean age of 6.31, SD-1.27) and 17 boys (mean age of 6.87, SD-0.98)] in the age range of 3-9 years. They were screened informally by a speech-language pathologist to rule out any speech, hearing, sensory or neurological deficits and other abnormalities. Children with any syndromes or associated abnormalities were excluded from the study. Written consent was obtained from guardians of the participants prior to the study.

2.2 Materials

Stimuli

The vowels (/ɑ/, /i/, /u/, /æ/) embedded in the initial position of meaningful Hindi words were selected as stimuli. For each vowel one meaningful word was selected. Thus, four words (/a:ɡ/, /iːʃʊər/, /u:pər/, and /e:k/) were included as stimuli.

Instrumentation

The stimuli were recorded through a precision *Sound Level Meter Type B & K 2250* with sound recording software BZ 7226. *PRAAT 5.1* software [13] was used to measure the formant frequencies (F1 & F2).

2.3 Procedure

Each participant was seated comfortably in a sound proof room in an upright position. All stimuli were spoken by an adult native Hindi speaker. The samples were recorded by a microphone kept at a distance of 15 centimeters from the participant. Recorded samples were digitized at the sampling frequency of 22.1 kHz represented by 16 bits per sample and stored in a PC. The stimuli were presented with an inter-stimulus interval of 7 seconds, and the participants were instructed to sit relaxed and repeat the Hindi words.

Five repetitions of each word were recorded. The vowels were analyzed for the F1 and F2 formant frequencies by selecting a 50 ms steady-state portion of the midsection of the vowel in the initial position of the word. F1 and F2 were automatically computed by the *PRAAT* Software and the acoustic measures were then derived.

2.4. Analysis

The stimuli recorded from TDC were included in analysis and mean values of F1 and F2 of each vowel were computed. Out of the five repetitions of each word spoken by children with HI, the best recorded word selected by an experienced Speech Language Pathologist was used for analysis. The derived acoustic measures were computed based on the formulas [12] given below.

$$VSA = 0.5 \times [(F2i \times F1ae + F2ae \times F1a + F2a \times F1u + F2u \times F1i) - (F1i \times F2ae + F1ae \times F2a + F1a \times F2u + F1u \times F2i)]$$

$$FCR3 = \frac{(F2u + F2a + F1i + F1u)}{(F2i + F1a)}$$

$$VAI4 = \frac{(F2i + F2ae + F1ae + F1a)}{(F1i + F1u + F2u + F2a)}$$

$$VFR = \frac{F2i}{F2u}$$

Parametric statistical analysis was performed using IBM SPSS tool. Shapiro Wilks Test for normality and Levene test for homogeneity of variance was satisfied ($p > 0.05$). A one way ANOVA was conducted between the groups to compare the effect of hearing loss on formant frequencies and their derived measures for vowels in group I and group II. To evaluate the most significant measure among derived, *G-Power* statistical software was used. The effect size and power of these measures were calculated using this software.

3. RESULTS

Formants F1 and F2 of the four vowels (/ɑ/, /i/, /u/, & /æ/) across the groups were measured. The results indicated that, relative to the other vowels, F1 values for the vowel /ɑ/ were significantly higher than the other vowels in both the groups. The lowest F1 values were exhibited by vowel /i/ in TDC. Whereas in children with HI /i/ and /u/ exhibited lower F1 values than /ɑ/ and /æ/. In contrast, F2 was noticeably high for vowel /i/ and /æ/ followed by /ɑ/ and /u/ in both the groups as depicted in Table 1 and Figure 1. The standard deviation of F1 and F2 formants were relatively higher in group I than group II except for F2 of vowel /æ/.

Table 1: F1and F2 of vowels across groups in Hertz (Hz)

	Stimuli	HI (Group I) Mean (SD)	TDC (Group II) Mean (SD)
F1 (Hz)	/ɑ/	1067(111)	1121(89)
	/i/	575(113)	402(53)
	/u/	572(142)	518(70)
	/æ/	728(136)	579(56)
F2 (Hz)	/ɑ/	1707(197)	1557 (112)
	/i/	2075(537)	2086(425)
	/u/	1478(343)	1091(303)
	/æ/	1987(368)	2121(397)

Note: TDC=typically developing children, HI=children with hearing Impairment, SD= standard deviation, F1=first formant frequency, F2=second formant frequency

The differences in formant frequencies between girls and boys in both the groups were not statistically significant ($p > 0.05$). Thus, data from girls and boys in each group were combined for further analysis. The results of the combined formant analysis indicated significantly higher F1 in group I for vowel /i/ [F (1, 38) = 42.9, $p < 0.01$] and /æ/ [F (1, 38) = 23.17, $p < 0.01$]. F2 was also high in group I compared to group II for vowels /ɑ/ [F (1, 38) = 9.34, $p < 0.01$] and /u/ [F (1, 38) = 14, $p < 0.01$].

The derived acoustic measures were calculated and compared across the groups. VFR, VAI4, and VSA in group II were higher than those in group I and FCR3 in group I was higher than that in group II. Results indicated a significant between-group difference in derived measures of VFR, VAI4, FCR3, and VSA at $p < 0.01$. The SD across the groups for the parameters were nearly same.

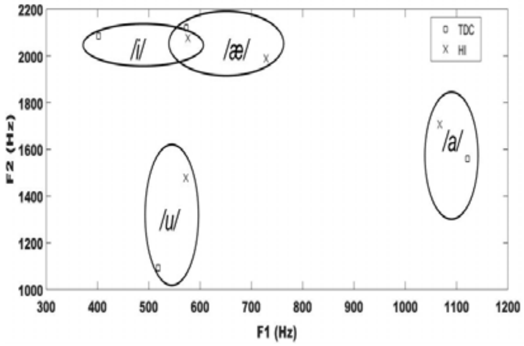

Figure 1: F1and F2 of vowels across groups in Hertz (Hz)

These derived measures VFR [F (1, 38) = 8.74, $p < 0.01$], VAI4 [F (1, 38) = 16.22, $p < 0.01$], FCR3 [F (1, 38) = 17.55, $p < 0.01$] and VSA [F (1, 38) = 47.79, $p < 0.01$] significantly differentiate the groups. VSA was the most significant measure followed by VAI4, FCR3, and VFR based on the power value of the effect size (Table 2).

Table 2: Mean derived acoustic measures with effect size and power.

Participants	VFR	VAI4	FCR3	VSA (kHz)
TDC	2.02	1.67	1.13	-1638
(SD)	(0.59)	(0.26)	(0.18)	(362)
HI	1.47	1.34	1.43	-2430
(SD)	(0.53)	(0.22)	(0.26)	(343)
Effect size	0.96	1.31	11.13	2.24
Power	0.99	0.99	0.99	1.00

Note: TDC=typically developing children, HI=children with hearing Impairment, SD= standard deviation, VFR=vocalic anatomical functional ratio, VAI4=four vowel articulation index, FCR3=formant centralization ratio, VSA=vowel space area.

4. DISCUSSION

The current study aimed at evaluating the formant frequencies and derived measures (VSA, FCR3, VAI4, and VFR) in children with HI and TDC. The most relevant acoustic parameters for the perception and production of vowels are the formant frequencies F1 & F2 [14]. Hence, F1 and F2 of the vowels /ɑ/, /i/, /u/ and /æ/ were measured. The results indicated that F1 was high in vowel /a/ and low in vowel /i/ (Table 1) whereas F2 values were in contrast to F1. These variations in formant frequencies can be attributed to the change in the vocal tract resonances as a result of variation in tongue movement. The F1 is inversely proportional to the height of the tongue and F2 is directly proportional to the tongue advancement. The higher F2 of vowel /æ/ can be related to the height and advancement of the tongue. Even though vowel /u/ is also a high back vowel, the F1 and F2 values were relatively lower. This may be because of the protrusion of lips which increases the length of the vocal tract decreasing the resonance frequencies [4, 11]. Relative to group II, an increase in F1 was observed for vowels /i/ and /æ/ in group I. The change in formant frequencies is attributable to the variations in tongue position [14,15]. Increased F1 in children with HI (group I) can be attributed to the reduced tongue height during production.

F2 of vowel /ɑ/ was higher in group I compared to group II. Increase in F2 of /ɑ/ can be due to the effect of vowel neutralization. F2 of back vowels have increased with the advancement in tongue positioning [8, 17]. Children with HI often try to neutralize peripheral vowels [17]. More intense F2 of the back vowels i.e., /ɑ/ was also reported by Nicolaidis and Sfakiannaki [10]. Children with HI exhibit relatively low hearing sensitivity for high frequencies especially above 1 KHz. Hence, more errors are reported for the high and front vowels than low and back vowels [10].

The reduced range of F1 and F2 for both the high to low and anterior to posterior vowel productions were observed in group I (F1 ranged from 572Hz to 1067Hz; F2 ranged from 1478Hz to 2075Hz) compared to group II (F1 ranged from 402Hz to 1121Hz; F2 ranged from 1091Hz to 2121Hz). This indicates less differentiation in the production of the vowels by children with HI compared to TDC. Similar results were reported by Ozbic et al. [4] indicating reduced range of F1 and F2 of vowels in the speech of children with HI compared to the TDC.

Another question addressed by this investigation was whether there was a difference between the group in derived acoustic measures of vowels. Group 1 exhibited reduced VFR, VAI4, and VSA than group II (table 2). Reduced VSA indicate less space for the vowel productions leading to the imprecise articulation of vowels in group I. VFR is a measure of contrast between the high vowel /i/ and /u/. VAI4 is a measure of vowel contrast (/a/,/i/, /u/, /æ/). The reduced VFR and VAI4 values can be attributed to the effect of neutralization due to the imprecise articulation during vowel production.

Increased FCR3 values indicate higher centralization of vowels during production by children with HI compared to TDC [12]. This pattern was also observed in the present study. The consolidation of vowels has often been noticed in the speech of children with HI [17, 18]. Donegan [19] reported that TDC established vowel contrasts as early as three years of age [19].

The third objective of this investigation was to determine the most significant acoustic measure. Results based on power (Table 2) suggest that VSA is the most significant among the measures derived. The formant frequencies F1 and F2 of vowels that are produced by children with HI tend to reduce vowel space during speech production. This led to an attenuated differentiation between the vowels and overlap of formant frequencies of various vowels during the production [17, 18]. Collectively, this investigation suggests that, there is a reduced differentiation in the production of vowels in children with HI. This can be attributed to the limited auditory perception and reduced visibility of articulator gestures during vowel production [20]. Various studies on pre [21, 22] and post [23] lingual children with HI reported reduced VSA in their speech.

The present study is based on pilot-data collected during the initial phase of the project titled "Development of a diagnostic system for articulation disorders". The study will be extended further and will include more number of children with HI in later phase.

5. CONCLUSIONS

The current study revealed that derived measures from the F1 and F2 of the vowels /ɑ/, /i/, /u/, and /æ/ are significantly different in children with HI. Each of these derived measures indicates the presence of a reduced vowel space in children with HI compared to TDC. These acoustic measures are significant to quantify the deviation in disordered speech and hence may aid in providing feedback on the precision of vowel articulation during speech therapy.

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