EMERGENCE OF THE VOWEL SPACE IN VERY YOUNG CHILDREN WITH DOWN SYNDROME: AN EXPLORATORY CASE STUDY

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ABSTRACT

The current study presents the preliminary results of an investigation into the development of the vowel space in one female child with Down syndrome (DS). Vowel productions at five points in time, ranging from 1;0 to 3;8 years of age, have been analysed to produce age-specific F1-F2 vowel plots and to calculate metrics quantifying changes in their size and dimensions.

The results show that changes in DS vowel space area and shape are non-systematic, lacking the definite developmental trajectories present in the productions of typically developing children. An explanation of outcomes using the DIVA model of speech acquisition is proposed.

Keywords: Acoustic vowel space, language acquisition, Down syndrome, babbling.

1. INTRODUCTION

The development of speech production in individuals with Down Syndrome (DS) is often reported to be delayed and protracted but sequentially typical, particularly in its earliest stages [5, 9]. Nevertheless, speech production difficulties, resulting in low intelligibility, are common in children with DS and often persist into adult life [2, 9]. In particular, the transition from babbling to first words is difficult and prolonged, in contrast to both mentally-age matched and TD children who move more smoothly through this process [9]. Whilst it is recognised that DS speech patterns may differ from those of TD children from as early as the first year of life [5], little is known about the early stages of speech production development in DS [2].

Speech production impairments in DS do not appear to have their origin in cognitive deficiencies but are likely to occur due to anatomical differences and impairments of motor control [5]. A normal-sized tongue in a small oral cavity and low muscle tone (hypotonia) result in a constrained range and weak articulatory motions of the lips, tongue, and jaw [2, 3]. In addition, a high flat palate may reduce the acoustic tolerance requiring higher articulatory precision [5]. A further adverse factor to successful acquisition of speech production is the prevalence of hearing impairment in DS [5, 9].

When investigating the development of early speech production abilities, the emergence of the vowel space (VS) is pertinent. The acoustic vowel space appears early and is reported to be largely established by age 36 months in TD children [11]. Furthermore, vowels are highly correlated with intelligibility [11] and thus relevant to successful communicative functioning.

For children, adolescents and adults with DS, acoustic studies have yielded mixed results as to the distinctiveness of vowel production of speakers with DS [5]. Studies, that have identified significant differences, describe a collapse of the front-back distinction at the close and open borders of the VS [3, 6, 12]. Similarly, the open-close plane is also contracted for both front and back VS margins [3, 6]. This produces a centralised acoustic vowel space, corresponding to a limited articulatory working space [3], and a smaller vowel space area (VSA) [6, 12] which likely contributes to low intelligibility [3, 5]. Increased variability in vowel production has also been reported [5, 12]. The data can be explained by limited control of tongue placement and timing [5].

No studies of vowels in children with DS in the prelinguistic period were found. In TD children, raw VSA (reported in Hz^2), formant frequencies and formant variability all decrease as the vocal tract lengthens with increasing age [11]. The open-close axis (F1) of the VS stretches in the first and the front-back (F2) axis in the second year of life [8], producing a proportionally bigger acoustic vowel space in spite of an overall reduction in VSA. Variability of F1 frequencies stabilises before F2 variability [11].

2. AIM

The aim of this paper is to describe changes in the size and dimension of the vowel space area of a child with DS over a period of 32 months (from age 1;0 to 3;8). The data are part of an exploratory longitudinal study of the development of speech production from babbling to early words in one male and one female child with DS.

3. METHODOLOGY

3.1. Participants and materials

The female participant E.C. is an only child with Down syndrome (Trisomy 21). Her general health has been good with hearing not considered a concern and generally good motor control.

Spontaneous babbled vocalisations have been recorded at six points in time at ca. six monthly intervals (1=1;0, 2=1;4, 3=2;0, 4=2;6, 5=3;0, 6=3;8). Recordings were obtained by the child's parents in the home, using a portable digital recorder. Note that recordings at point 5 were not available.

The recordings at each age were subdivided into utterances. An utterance was defined as the stretch of vocalisations between two in-breaths. Utterances which were obscured or part-obscured by external noise or overlaid by parental speech were excluded. Each utterance was transcribed (but note Oller's [7] comments on the transcription of babbling) and text grids were produced using PRAAT [1].

Table 1: Definition of corner vowels [i'], [a'] and [u'] for triangular vowel space plots.

	F1	F2
[i']	min F1	max F2
[a']	max F1	F2 at max F1
[u']	min F1	min F2

Table 2: Definition of corner vowels [i'], [a'], [ɑ] and [u'] for quadrilateral vowel space plots.

	Diffuse/Compact		Acute/Grave
[i']	F1 and F2 at max D/C value	[a']	F1 and F2 at max A/G value
[ɑ']	F1 and F2 at min D/C value	[u']	F1 and F2 at min A/G value

Table 3: Overview of vowel space metrics. Note operators for multiplication '·' and division '÷'.

1	***Quadrilateral Vowel Space Area*** [11]
	qVSA = 0.5 · [(F2i' · F1a' + F2a' · 1ɑ' + F2ɑ' · F1u' + F2u' · F1i') − (F1i' · F2a' + F1a' · F2ɑ' + F1ɑ' · F2u' + F1u' · F2i')]
2	***Back-front ratios (open & close)*** [6]
	F2 [i']-[u'] BFRC = F2i' ÷ F2u' F2 [a']-[ɑ'] BFRO = F2a'÷ F2ɑ'
3	***Open-close ratios (front & back)*** [6]
	F1 [a']-[i'] OCRF = F1a' ÷ F1i' F1 [ɑ']-[u'] OCRB = F1ɑ' ÷ F1u'

3.2. Vowel selection and formant measurements

Vowels were included in the study if they were fully voiced and part of a canonical syllable as defined by Oller [7]. Vowels which exhibited nasalisation were excluded.

For each vowel, average F1 and F2 frequencies (for total vowel duration) were measured on FFT spectrograms with LPC formant tracks (using PRAAT [1]). All formant tracks were inspected visually and measurements were adjusted manually as required to ensure maximum accuracy.

3.3. Vowel normalisation

Vowel normalisation was carried out to make age-specific data comparable by reducing the effect of vocal tract differences [4] which in this study are likely to be due to vocal tract growth.

Vowel frequencies were normalised using the original Fabricius-Watt procedure [4]. This method was chosen because it produced a better overlap of both the vowel areas and vowel space centroids at each age. First age-specific vowel plots were produced with the corner vowels [i'], [a'] and [u']. As the babbled vocalisations do not contain target vowel phonemes, the corners of the vowel triangle were defined as in Table 1.

For each vowel triangle, the centroid $S(F_i)$ was calculated using equation (1) below. Finally, the normalised formant frequencies were calculated using equation (2), which includes a modification to the original formula (multiplication by 1000) to remove the fraction.

(1) $S(F_i) = (F_i[i'] + F_i[a'] + F_i[u']) \div 3$

(2) $F_i^N = F_i \div S(F_i) \cdot 1000$

3.4. Vowel plots and metrics

F1-F2 vowel space plots for each age were produced from the raw formant data and from normalised formant data. Quadrilateral vowel spaces were produced as these provided a more accurate fit for the individual data points. For both raw and normalised data, the corner vowels [i'], [a'], [ɑ'] and [u'] at each age were determined using the diffuse-compact (F2−F1) and acute-grave (0.5·(F1+F2)) dimensions as outlined in Table 2. Finally, the metrics outlined in Table 3 were computed to quantify the development of the child's vowel space.

4. RESULTS AND DISCUSSION

4.1. T-Tests

Student's T-tests have been used to assess the significance of the changes in formant frequency values from one age to the next. F1 frequency values from age (a) to age (a+1) are all significantly different ($p<0.05$) with the exception of age 2;6-3;8 (raw data) as well as age 1;4-2;0 and age 2;6- 3;8 (normalised data). F2 frequency values are also all significantly different with the exception of age 1;4-2;0 (raw data) and age 2;0-2;6 (normalised data).

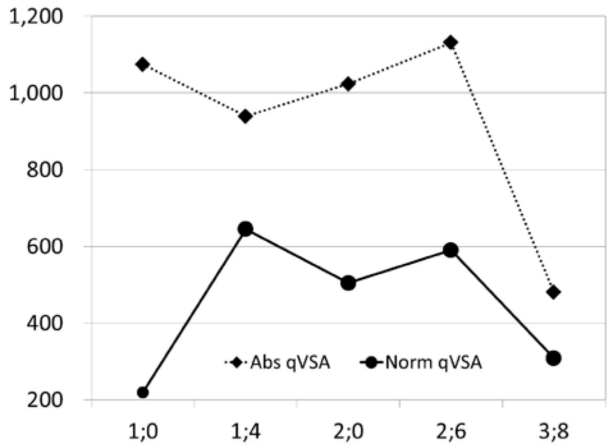
Table 4: Overview of number of vowels analysed at each point in time. Ages given as *years;months.*

	1	2	3	4	5	6
Age	1;0	1;4	2;0	2;6	3;0	3;8
N	75	112	59	70	0	34

4.2. Vowel space area (VSA)

Age-related change in the size of the acoustic vowel space area (VSA) is shown in Figure 1. The raw values indicate that there is an abrupt VSA decrease from age 2;6 to 3;8 which may be due to a growth spurt [11]. Before age 2;6, raw VSA development fluctuates. Normalised values, which discount changes due to vocal tract growth, are similarly non-systematic with some oscillations. Overall, there appears to be no clear trajectory in the development of the acoustic vowel space, in contrast to the systematic decrease over time seen in typical development [8, 11].

Figure 1: Absolute and normalised quadrilateral vowel space area (qVSA) by age in Hz^2. Values on the y-axis given in thousands.



4.3. Vowel space dimensions

Figures 2 and 3 illustrate changes in the dimensions of the acoustic vowel space. The open-close (F1) ratios between the front and back corner vowels decrease over time, amidst some fluctuations of the values. For the back-front (F2) ratios we see an initial increase which is then followed by a drop in the values which is more marked and earlier for the [a'-ɑ'] margin of the VS. The decrease in the ratios is representative of progressively shorter acoustic distances between the corner vowels and an increasingly centralised functional vowel space which will contribute to reduced intelligibility. This trend is opposite to that found in TD children [8].

Figure 2: F1-F2 plots of the raw vowel spaces (top) and normalised vowel spaces (bottom) at each age.

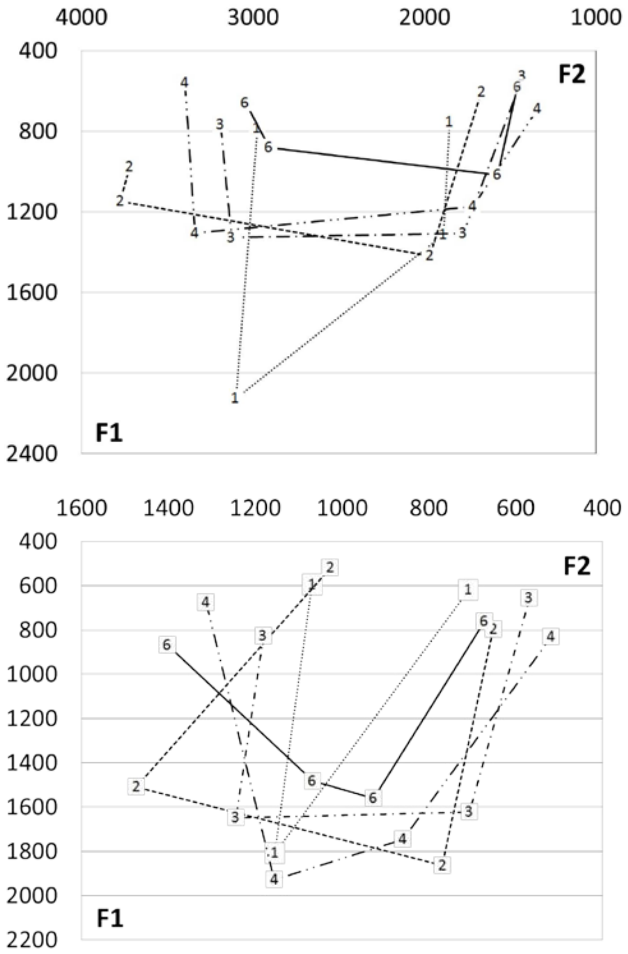
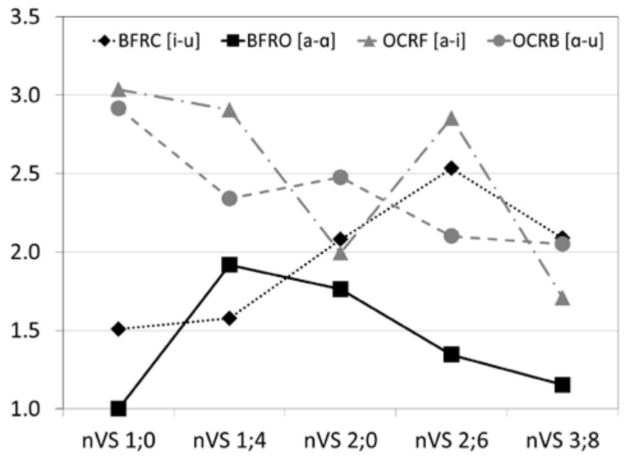


Figure 3: Normalised vowel space dimension ratios by age. The greater the ratio, the further apart are the corner vowels. A ratio of 1.0 indicates a merger of the concerned corner vowels.



4.4. From babble to first words

Anatomic and motor control issues in DS and their effect on speech development are reflected in the acoustic vowel data presented here. The data may illuminate how DS-specific phonetic characteristics steer the acquisition of phonemic categories such as vowel phonemes.

Principles underlying the DIVA model of speech acquisition [10] may provide an explanation for the difficulties in the transition from babble to early words that are evident in DS but not for mentally age-matched children [9]. The model proposes three phases for speech development: First, a mapping between articulatory movements and auditory outputs is established (systemic) [10]. This is followed by an iterative auditory feedback-matching procedure that generates a mapping between the articulatory movements and language-specific auditory targets (phonemic) [10]. Mature speech production is achieved when no production errors are identified by the auditory feedback system [10]. Effective language acquisition thus relies on the successful matching of somatosensory movement targets, auditory targets and phonetic environment.

Applied to DS, speech motor impairments are predicted to lead to an underspecified mapping between auditory output and articulatory movements (systemic) due to the restricted motor range and control which reduce the range of sounds that can be produced. Atypical anatomical structure and speech motor impairments are predicted to result in divergent sound output which cannot easily be matched to the sounds heard in the infant's language-specific phonetic environment (phonemic). Both taken together are likely to produce fuzzy, unstable representations of somatosensory and auditory targets which remain in a state of constant flux as the system continuously recalibrates to eliminate auditory errors. Thus, early speech production would be marked by oscillations in vocal behaviours, similar to the ones observed in the participant of this study, as the immature speaker attempts and never quite manages to match her acoustically divergent speech output to that of the speakers around her.

In this way the delay in the emergence of first words in DS is generated by atypical motor control and anatomical structure rather than by a higher level break-down. It explains why children with the same mental age who do not present with motor and resonance disturbances will be able to transition more easily from babble to first words. More data is needed to assess whether the observed behaviours in this study are a general feature of DS babble and also whether the proposed explanation holds true.

5. CONCLUSION

This case study shows that acquisition in very young children with DS may be unsystematic with instabilities marked by oscillating values that do not follow a clear developmental trend. The value of the data lies in the fact that they are the first providing a preliminary glimpse of vowel space development in prelinguistic children with DS. Further studies with greater numbers of participants are needed to confirm that the results are representative of DS prelinguistic development and to test out hypotheses explaining the cause of the protracted transition period from babble to early speech.

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