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An evaluation of articulatory working space area in vowel production of adults with Down syndrome

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Introduction

Reduced speech intelligibility is a widespread problem for individuals with Down syndrome and has been documented in clinical case studies, surveys, and reports (Buckley, 2000; Chapman & Hesketh, 2000; Chapman et al., 1998; Heselwood et al., 1995; Kumin, 1994, 2001, 2002a, b; Miller & Leddy, 1998; Rosin & Swift, 1999; Swift & Rosin, 1990; Stoel-Gammon, 2001). Factors believed to underlie the reduced intelligibility include significant differences in both anatomy (e.g., midface hypoplasia combined with an average sized tongue) and physiology (low muscle tone in the lips and tongue) related to the syndrome. It follows that one of these factors, or a combination of both, may prevent a speaker from making precise articulatory movements resulting in reduced intelligibility (e.g., Miller and Leddy, 1998). Although differences in anatomy and physiology have been described clinically (Van Borsel, 1996), little information can be found in the research literature describing speech articulation and the resultant acoustic characteristics of speech in individuals with Down syndrome. The purpose of this project was to measure acoustic vowel space area and articulatory working space for two adult speakers with Down syndrome. These measures are believed to represent the integrity of vowel articulation and have been shown to correlate with speech intelligibility scores (Weismer et al., 2000; Turner, Tjaden, & Weismer, 1995). Measures of acoustic vowel space area are based on values for the formant frequencies of the four English corner vowels, and presumably, reduced formant space coincides with small movements of individual articulators (i.e., articulatory working space). These measures have not been used previously to study the speech production deficit in individuals with Down syndrome.

Individuals with Down syndrome have fairly well documented variations in their skeletal, muscular, and nervous systems compared to typically developing individuals. While not all of these differences have a direct effect on speech production, they offer a starting point for discussing speech production abilities in individuals with Down syndrome. For example, absent and/or reduced bone growth in the bones of the head and face has implications for attachment locations and support of muscles used during speech production (Frostad, Chleall, & Melosky, 1971; Kisling, 1966; Roche, Roche, & Lewis, 1972; Sanger, 1975). Poorly differentiated midface muscles and/or additional facial muscles may contribute to difficulties with articulation (Bersu, 1976, 1980). Variations in the size of the oral and

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pharyngeal cavities (Ardran, Harker, & Kemp, 1972) influences how sound travels through those spaces and directly affects the acoustic characteristics of the output. Reduced size of the oral cavity and a high palatal arch (Redman, Shapiro, & Gorlin, 1965; Borghi, 1990) may influence tongue placement for articulation of speech sounds (Swift, Rosin, Kidhr, & Bless, 1992; Rosin, Swift, Bless, & Vetter, 1998). Similarly, the large tongue relative to the size of the oral cavity may interfere with articulatory placement (Miller & Leddy, 1998). Difficulty sequencing and timing speech movements has also been proposed as a component of this speech production deficit. Kemper (1988) reviewed the neurology literature and concluded that people with Down syndrome have fewer cortical neurons and a decreased neuronal density compared to typically developing individuals. In addition, delayed neural myelination, atypical dendrite structure and altered cellular membranes have also been identified (Florez, 1992; Scott, Becker & Petit, 1983). Combined, these anatomic and physiologic differences may affect speech production by disrupting the accuracy, speed, consistency, and economy of speech movements, thus altering the sequencing and timing of speech production.

In addition to, or perhaps resulting from these anatomic and physiologic differences, it has been noted clinically that some individuals with Down syndrome demonstrate difficulties with oral motor skills and/or oral motor planning. Oral motor skills refer to the strength and movement of the oral facial muscles, especially movements related to speech while oral motor planning skills refer to the ability to combine and sequence sounds into words, phrases and sentences. There is little doubt that these difficulties, if present, affect speech intelligibility. Numerous studies examining the nature of the difficulty with oral motor skills and oral motor planning in typically developing children have been completed (e.g. Caruso & Strand, 1999; Davis, Jakielski, & Marquart, 1998; Forrest, 2003; Shriberg, Aram, & Kwiatkowski, 1997a, 1997b; Strand & McCauley, 1999; Strand & Skinner, 1999). Although the presence of these impairments has also been observed clinically in children with Down syndrome, few studies in the research literature describe the problems with oral motor skills/ planning in this population.

While no consensus on the basis for the reported reduction in speech intelligibility exhibited by individuals with Down syndrome has been achieved, clinical descriptions of aberrant speech acoustics and a perceptually recognizable disorder leads researchers to speculate that changes in articulatory movements are the key to understanding the reduced speech intelligibility reported in this population. Consistent patterns of phonetic errors have been reported for adolescent and adult Dutch speakers (Van Borsel, 1996) and adult English speakers with Down syndrome (Bunton, Leddy, & Miller, 2009). In both studies, vowel errors ranked within the top six errors reported. Vowel errors included, front-back (e.g., /i/ vs. /u/) and high-low (e.g., /ɛ/ vs. / æ /) based on articulatory descriptions of vowel production as well as long-short vowels (e.g., /i/ vs. /ɪ/) based on duration. Explanations for the high rate of vowel errors differed between the two studies. Van Borsel (1996) suggested that these findings support a delay in phonological development whereas Bunton and colleagues (2009) speculated that the high error rates reflect reduced motor control for production. Data from several studies of speech acoustics were used to support the speculation of Bunton and colleagues. For example, Borghi's (1990) data demonstrated voicing errors consistent with motor speech impairment, Swift, Rosin, Khdir & Bless (1992) showed that people with Down syndrome have difficulty maintaining adequate intraoral pressure for speech, and Kimmelman, Swift, Rosin & Bless (1985) reported highly variable formant transition patterns. These aerodynamic and acoustic findings were never related to speech intelligibility.

Similar to other speech disorders, the high rate of vowel errors observed for individuals with Down syndrome can be related to the speaker's production of unusual or reduced formant

transitions and slopes as well as reduced vowel space area (calculated based on the first (F1) and second (F2)) and may be correlated with reductions in speech intelligibility. In healthy speakers, Bradlow et al. (1996) reported that vowel space dispersion and F1 range were significantly correlated with overall sentence intelligibility. A similar finding was reported by Smith (1975) for a group of deaf children. Monson (1976a) suggested that this restricted vowel space contributed significantly to the reduced intelligibility for a group of 36 deaf children. He further reported correlations of .74 and .45 between sentence intelligibility and the spectral ranges of F2 and F1, respectively. In a companion study, Monson (1976b) reported F2 transitions for deaf children that were characterized by reduced frequency extents and speculated that this attribute may contribute to reduced intelligibility. Similarly, speakers with a broad group of speech disorders, known collectively as dysarthria, have been shown to have reductions of vowel space areas (Turner, Tjaden & Weismer, 1995; Weismer, Jeng, Laures, & Kent, 2001; McRae, Tjaden & Schoonings, 2002; Tjaden & Wilding, 2004). Findings from these studies have varied widely in the predictive value of vowel space area for speech intelligibility. For example, Tjaden & Wilding (2004) report that vowel space area accounted for only 6–8% of the variance in intelligibility ratings for females with Parkinson disease and multiple sclerosis. In contrast, both Turner et al. (1995) and Weismer et al. (2001) reported that vowel space area accounted for about 45% of the variance in intelligibility scores for speakers with dysarthria related to amyotrophic lateral sclerosis. Higgens and Hodge (2002) reported that vowel space area predicted 64% of the variance in sentence intelligibility for children with dysarthria. Neel (2008) speculated that discrepancies in the published studies examining disordered populations, may be related to the nature of the speech disorders exhibited by the different populations. For example, speakers with some types of dysarthria may have articulatory movements that are impaired such that they cannot produce distinctions in formant frequencies for vowels. Speaker populations, on the other hand, who produce relatively few vowel errors as part of their presentation would likely not show differences in formant productions. Even though the relation of vowel space area and overall speech intelligibility has not been clearly defined, for speakers with Down syndrome who produce a high number of vowels errors, it is reasonable to hypothesize that vowel space area will be correlated with reduced overall speech intelligibility

Reduced formant transitions and consequent reduced vowel space area, are thought to be due to smaller underlying articulatory movements. Consistent with this assumption are data from two kinematic studies examining movement of the articulators by tracking the time-varying positions of up to eleven flesh point markers (X-ray microbeam data; XRMB). These studies reported differences in extent and speed of movement (i.e., total movement space and amplitude) for speakers with Parkinson disease (PD) and Amyotrophic Lateral Sclerosis (ALS) compared to age-matched healthy controls (Yunusova, Weismer, Westbury, & Lindstrom, 2008; Bunton, Westbury, & Weismer, 2000). Significant group differences (i.e., PD vs. ALS) were found for several of the measures as well. Overall, speakers with dyarthria were found to have less distinctive articulatory movements that occupied more central regions of the vocal tract compared to speakers without dysarthria. These XRMB findings are consistent with earlier studies that utilized cineoradiographic data from speakers with dysarthria (Kent & Netsell, 1978; Kent, Netsell, & Bauer, 1975). Similar studies in other speaker populations have not been completed. For speakers with Down syndrome who have consistent vowel errors and reduced speech intelligibility, it can be hypothesized that they may experience similar reductions in movement space (or amplitude) for speech production.

The aim of the present study was to measure acoustic vowel space area based on the four American English corner vowels for two adults with Down syndrome and two age-matched control speakers and relate them to measures of articulatory working spaces and movement

speed for the same vowel samples based on flesh-point tracking data (XRMB). This study represents a first attempt to link acoustic measures believed to correlate with speech intelligibility to measures of articulation in this population.

Method

Procedures for this study were approved by the Institutional Review Board at the University of Wisconsin-Madison. Speakers received monetary compensation for their participation.

Speakers

Speakers in the present study included two adult males with Down syndrome (DS01 & DS03) and two age- and sex- matched control speakers (JW55& JW59). The two male control speakers were selected from the XRMB speaker database (Westbury, 1994). Speakers with Down syndrome lived in group-home settings within the community and held part-time jobs. Speaker characteristics, including age in years, adaptive function age, and speech intelligibility are shown in Table 1. The Adaptive Function Age Equivalency Scores from the Vineland Scales (Sparrow, Balla, & Cicchetti, 1985) for the speakers with Down syndrome were completed as part of separate study by the second author (Leddy, 1996). Intelligibility scores were based on the single-word intelligibility test reported by Bunton, Leddy, and Miller (2009).

Screening Session

For the two speakers with Down syndrome, an initial session was scheduled and the investigators traveled to each speaker's home to complete an initial screening. Speakers were screened to ensure that they could read at a single word level as reading was required for participation in the XRMB data recording protocol. No further cognitive testing was completed. Speakers passed a hearing screening at 25 dB HL for frequencies of 0.5, 1, 2, and 4.0 KHz bilaterally (American Speech-Language-Hearing Association, 1997). Speakers were also screened for metal dental work to determine if they were eligible to participate in the XRMB protocol as metal dental work interferes with tracking of the pellets and limits data acquisition. There was no screening session for the control speakers, questions regarding dental work were asked over the telephone. Hearing screening was completed during the experimental session.

Speech Sample and Pellet Array

Prior to placement of the pellets needed to track articulator movement, all speakers completed the entire speech task protocol under conditions identical to the main experiment. This was done to establish the recording routine and to familiarize speakers with the speech material. The speech sample consisted of 53 monosyllabic words and 6 sentences spoken at a habitual speaking rate. The monosyllabic words were selected from the Kent, et al. (1989) single word intelligibility test. Results of the intelligibility testing have been reported previously (Bunton, Leddy, & Miller, 2009). The two control speakers (JW55 & JW59) participated in a longer speech task protocol of which the words and sentences produced by the speakers with Down syndrome were a subset (Westbury, 1994).

The standard pellet array and procedures for the collection of kinematic data in the XRMB facility was used (Westbury, 1994). The pellet array included eleven flesh point gold pellets, four of which were on the tongue, two on the mandible, two on the lips, and three fiducial markers (two on the bridge of the nose and one on the buccal surface of the maxillary incisors). The sampling rates during tracking varied by pellet; however, raw sagittal plane marker trajectories were smoothed and resampled at a uniform rate of 145 samples/second prior to analysis. Other post-processing steps included head movement correction and re-

expression of the marker coordinates relative to a subject-specific, anatomic head-based coordinate system.

Data Collection

The sound pressure wave was recorded with a directional microphone (SHURE SM81 Condenser) placed at mouth level. The microphone signal was fed into a 15-bit resolution A/D converter programmed to sample at 21,739 times per second and to store the resulting digital stream synchronously with pellet position histories on SMD computer disks. Prior to digital conversion, an anti-aliasing filter (−3 dB at 7500) was applied to the microphone signal. Further details regarding recording procedures can be found in Westbury (1994).

Acoustic Measures

The vowel formant frequencies were measured using LPC formant analysis to generate *F*1-*F*2 trajectories for each of the corner English vowels /i, æ, u, ɑ /. Formant frequencies for the corner vowels were measured from a common set of twelve single syllable words produced by all speakers [*feed, sheet, geese, fast, had, cash, food, shoot, school, chop, knot, box*]. The automatic formant tracking option in CSpeech (Milenkovic, 2002) yielded formant trajectories that were superimposed on the digital spectrogram. Formant tracks were individually inspected and manually corrected for tracking errors. *F1-F2* frequency was measured by centering a 30-ms time window at the three points within the vowel nucleus, 20, 50, and 80% of the vowel duration. Only the values from the temporal midpoint (50%) were used to calculate vowel space area. Measures of formant values at 20% and 80% of the vowel duration and total vowel duration measures were included for descriptive purposes.

The vowel space area was calculated by bisecting the 4-vowel quadrilateral (in *F1-F2* space) into two triangles. The area for each triangle was calculated using Heron's formula and the areas for the two triangles were summed. To facilitate this analysis, formant values for the three productions of each vowel were averaged prior to calculation of vowel space area.

Articulatory Movement Measures

Sagittal-plane position for the four tongue pellets (blade, dorsum, and two intermediate locations; hereafter T1, T2, T3, and T4) were recorded at the temporal midpoint of each vowel. This corresponded to the time point used to calculate acoustic vowel space area. Based on these measures, articulatory phonetic working space was defined by pellet as the areas enclosed by tongue fleshpoint locations for the four vowels in each word group as listed above. An example is shown in Figure 1 for speaker JW59 (control speaker). Orientation of the figure is with the most anterior tongue pellet (T1) on the right side of the figure and more posterior pellets (T2, T3, T4, respectively) leftward. The two bold lines outline the speaker's hard palate and posterior pharyngeal wall. Reference lines (grey) represent the occlusal plane (MaxOp) and central mandibular incisor reference pellet (placed just below the lower central incisors). The four points shown for each pellet represent the position of that pellet measured at the midpoint of each English corner vowel; lines connecting the points represent the area used to calculate articulatory working space.

Speed

The speed history for each pellet (i.e., the magnitude of the rate of change of position with respect to time) was calculated based on the following formula

$$V(t)=\sqrt{\left(\frac{dx}{dt}\right)^2+\left(\frac{dy}{dt}\right)^2}$$

where the velocity vector (*dx/dt, dy/dt*) at each position sample was estimated using a three-point central difference formula (Tasko & Westbury, 2002; Yunusova et al., 2008). During the vowel the pellets traveled from the position at vowel onset (V_0) to a position that corresponded to a local minimum (V_m) in the speed history and then to a position at vowel offset (V_1). A figure showing the two part vowel-related movement trajectory in the jaw based coordinate system is shown in Figure 2. To accurately represent movement speed across the entire vowel, speed was calculated separately for two parts of the vowel-related movement trajectory (s1 and s2, respectively).

Results

Formant Frequencies & Vowel Space Area

Formant frequencies (F1-F2) measured at 20%, 50%, and 80% of the vowel duration. No systematic differences between group were found as a function of measurement point (U=55.5, p=.34), therefore, only the F1/F2 measures at the 50% point are reported (plotted as vowel space area in Figure 3). Overall, formant values were more centralized for speakers with Down syndrome compared to those produced by the control speakers. Centralization was noted along the F1 axis for the vowels /ɑ/ and / æ / where the F1 values are lower for speakers with Down syndrome than control speakers, and along the F2 axis for the vowels / i/ and /u/ where F2 values for /i/ were lower than the controls and F2 values for /u/ were higher than controls.

A plot showing the mean vowel space area for each speaker is shown in Figure 3. In the plot, mean values of F1 and F2 across the three words containing that vowel are shown for individual speakers. Evidence of a reduced vowel space area for speakers with Down syndrome (solid line) can be seen in both the F1 and F2 dimensions compared to control speakers (dashed line). The calculated vowel space area for the speakers with Down syndrome and the controls are listed in Table 2. Group differences in vowel space area were not compared statistically because of the limited number of speakers in each group (n=2).

Vowel Duration

Vowel durations were longer, in general, for tokens produced by speakers with Down syndrome compared to the control speakers. Mean duration values for the speakers with Down syndrome were as follows: /i/=125 msec, / æ /=212 msec, /u/=129 msec, /ɑ/=206 msec. For the control group, means were /i/=119 msec, / æ /=189 msec, /u/=121 msec, /ɑ/ =198 msec

Articulatory Working Space Area

Articulatory working space areas were calculated based on tongue pellet position quadrilaterals for each speaker by pellet by word group condition (see Fig. 1). Means each pellet and speaker are listed in Table 3. The most anterior pellet is identified as T1 and the most posterior pellet is T4. Pellets T2 and T3 are located mid-palate. Differences between the speaker groups were found for the T2, T3, and T4 pellets whose area was roughly 30% smaller for speakers with Down syndrome compared to the control speakers. Group differences for the T1 pellet (most anterior) were minimal (<10%). Statistical comparisons were not completed due to the limited number of speakers in the present study.

Speed

Summary statistics in Table 4 show that vowel related movements of the T2, T3, and T4 pellets were slower in speakers with Down syndrome compared to the control speakers for both s1 and s2 (on average 6.3 mm/s slower). No group differences were found for the T1 pellet (<1.1 mm/sec difference).

Discussion

The goal of the present report was to describe vowel production characteristics for the four English corner vowels produced in monosyllabic words by two adult speakers with Down syndrome. These data were compared to those of two neurologically normal age- and sex-matched adults. Findings show a reduced acoustic vowel space area, reduced articulatory working space, and reduced speed of articulatory movement for speakers with Down syndrome compared to the control speakers.

The relatively compressed acoustic vowel space, shown for the speakers with Down syndrome, suggests a reduced acoustic contrast among vowels and a loss in perceptual distinctiveness. Liu, Tsao, and Kuhl (2005) demonstrated that vowels produced within a small acoustic space can be mapped onto reduced intervowel perceptual distance compared to vowels from typical talkers, thus increasing the difficulty normal listeners have in mapping the degraded acoustic signals onto existing phonetic categories. It is of interest that the absolute vowel space area values found for speakers with Down syndrome were comparable to those reported for speakers with intelligibility deficits related to dysarthria (Weismer, Jeng, Laures, & Kent, 2001; McRae, Tjaden & Schoonings, 2002; Tjaden & Wilding, 2004; Turner, Tjaden & Weismer, 1995) and deaf adolescents (Monson, 1976a). Previous work in dysarthria has shown that vowel contrasts make important contributions to speech intelligibility (Weismer, Kent, Hodge, Martin, 1988; Ziegler, Hartmann, & von Cramon, 1988; Bunton & Weismer, 2001; Liu, Tsao, & Kuhl, 2005). An acoustic-perceptual analysis of the relations between vowel working space area and speech intelligibility is not straightforward, however, as it is likely that a number of distorted acoustic features for vowels, such as extremely long duration, atypical formant slope, breathy voice, inconsistent vowel intensity, and unstable speaking rate in addition to absolute formant location contribute to reduced intelligibility (Kent et al., 1978).

Accurate production of vowels requires precise tongue posture, control and timing and inappropriate tongue positioning has been shown to result in a compression of the acoustic vowel space (reflecting centralized vocal articulations) in speakers with dysarthria (Weismer & Martin, 1992; Weismer 1997). Evidence of limited tongue movement during vowel production for the speakers with Down syndrome is reflected in the small articulatory space areas and reduced speed measured for the three tongue body pellets (T2, T3, and T4). Lack of difference in vowel space area for the tongue-tip pellet (T1) is not surprising since control of the tongue tip may be more important for the precision needed to produce consonant constrictions than for vowels. Speakers with Down syndrome produced relatively fewer consonant errors (except voicing) compared to vowel, liquid, and glide errors (Bunton, Leddy, & Miller, 2009).

It is curious that no differences in vowel duration (based on the acoustic record) were found between the groups given the differences in speed for these three tongue pellets. A measure of the movement extent (e.g., Euclidean distance) for each of the tongue pellets during the vowel nucleus could be used to address this discrepancy directly. It may be the case that for speakers with Down syndrome, the reduced pellet speed corresponds to a shorter distance traveled during the vowel nucleus, possibly due to a biomechanical constraint. It also

possible that the vowel duration is a strong phonological constraint and thus could overrides the goal of achieving an acoustic target through movement.

The limited working space area and differences in speed found for vowels in the present study could be related to the assertion in the literature that speakers with Down syndrome have large tongues relative to the size of their oral cavity (Ardran, Harker, & Kemp, 1972) or poor muscle tone (Henderson, 1985). Attributing the small size of the articulatory working space to differences in anatomy and physiology alone, however, may be inadequate. Studies of speech intelligibility in children following partial tongue resections have shown no improvements in speech intelligibility (Katz & Kravitz, 1989; Parsons, Iacono, & Rozner, 1987). Further, a study of jaw stiffness in children with Down syndrome reported no differences compared to controls (Connaghan, 2004). Findings from these studies suggest that differences in anatomy and physiology may not be sufficient to degrade speech production abilities to the extent suggested by the poor speech intelligibility scores reported. An alternative hypothesis (Miller & Leddy, 1998; Kumin 2001), suggests that it is primarily the neurological system that influences speech production in people with Down syndrome. In other words, impairments in the motor constraints influence the precision of speech production and an individual's ability to adapt to their unique speech structures (i.e., skeletal or muscular differences). This assertion requires further investigation, including more extensive studies of articulation by speakers with Down syndrome, but the preliminary findings from the present study support the idea that differences in movement control may contribute significantly to the large intelligibility deficits seen in these speakers.

The small number of participants in the present study did not allow for statistical correlations of measures of acoustic vowel space area, articulatory working space area, speed, and speech intelligibility scores. Qualitatively, however, the data suggest that the reduced vowel production characteristics may relate to the relatively low speech intelligibility scores reported for these speakers (Table 1; Bunton, Leddy, & Miller, 2009). A large scale study of articulation skills in adults with Down syndrome is needed to test this hypothesis directly. Much of what is currently known about the speech production deficit associated with Down syndrome is based on perceptual studies; therefore, the current study is a first step in detailing the articulation skills in this population.

Summary

The present study provides a unique look at vowel articulation for speakers with Down syndrome. Both speakers in the present study had significantly reduced speech intelligibility scores at the single-word level and this is believed to be related to the reduced vowel space areas and limited articulatory working spaces and speeds measured. These findings support the hypothesis that differences in movement control may contribute significantly to the intelligibility deficits reported clinically for adolescents and adults with Down syndrome.

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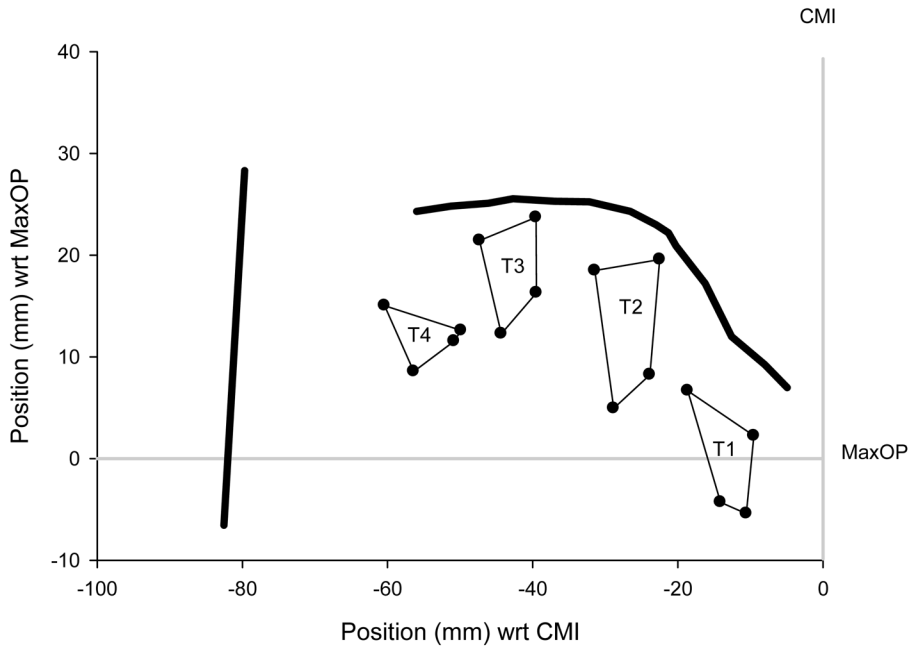

Figure 1.

Sagittal plan positions (with respect to cranial axis) for the four tongue markers measured at the temporal midpoint of each of the English corner vowels. T1 is the most anterior pellet (tongue-tip) and T4 is the most posterior (tongue dorsum). Reference lines (grey) include CMI=central maxillary incisors and MaxOP=occlusal plane.

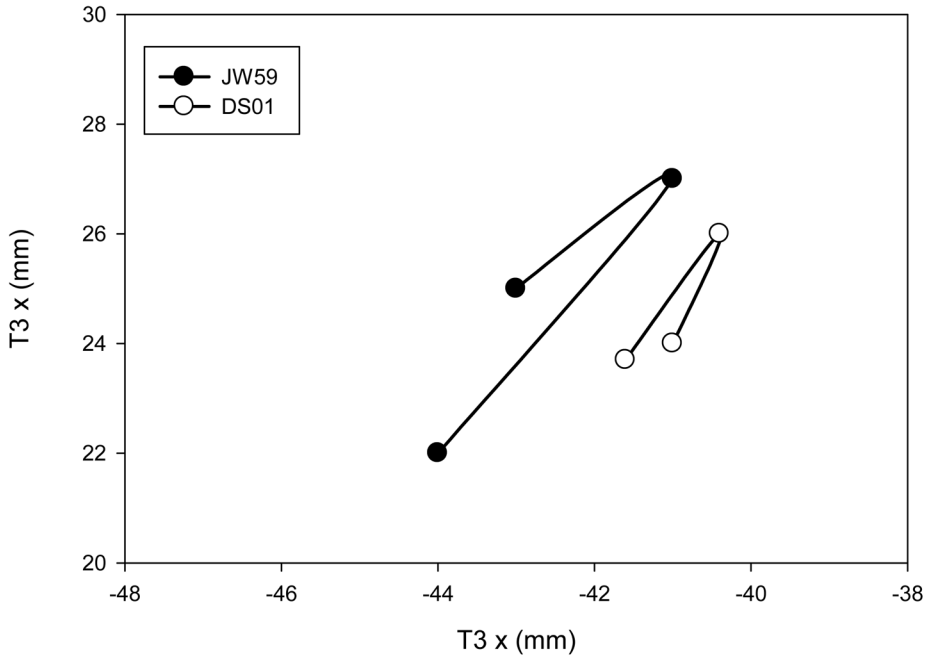

Figure 2.
T3 trajectory expressed relative to the jaw-based coordinate system during the word seed.

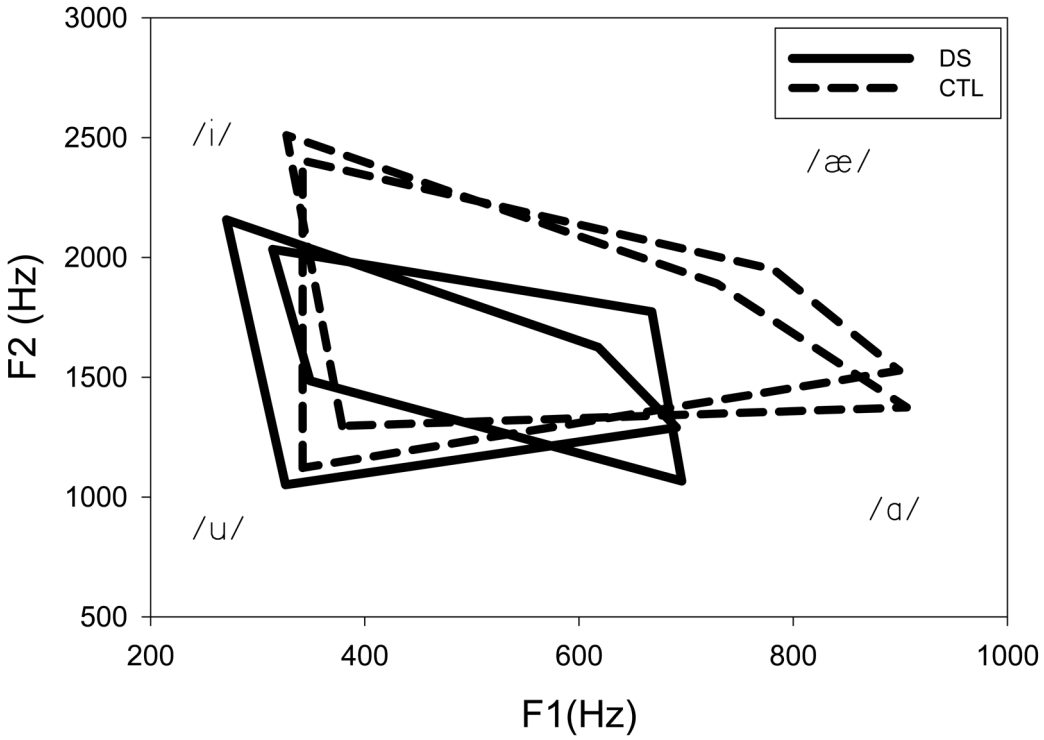

Figure 3.
Mean acoustic vowel space area in Hertz^2 for individual speakers. The vowel notation was included for ease of identifying which corner vowels were centralized by speakers with Down syndrome compared to the control speakers.

Table 1

Speaker characteristics (note: speaker numbers are based on previously published intelligibility data for these speakers (Bunton, Leddy, & Mil0ler, 2009).

Speaker	Age in Years	Adaptive Function Age (Vineland Scales)	Percent Intelligibility (standard deviation)
DS01	29	9;06	57.73 (8.56)
DS03	26	17;06	54.8 (6.92)
JW55	26	Not applicable	99.7 (0.11)
JW59	29	Not applicable	100.0 (0.00)

Table 2

Mean acoustic vowel space area (Hertz^2) calculated for individual speakers.

Speaker	Vowel Space Area (Hz^2)
DS01	283733
DS03	274662
JW55	343130
JW59	361931

Table 3

Articulatory working space area in millimeters^2 for individual speakers.

Speaker	Pellet	Working Space Area (mm^2)
DS01	T1	47.48
DS03		45.24
JW55		49.80
JW59		53.14
DS01	T2	95.02
DS03		88.68
JW55		119.73
JW59		124.16
DS01	T3	58.21
DS03		54.38
JW55		82.99
JW59		86.25
DS01	T4	38.02
DS03		35.11
JW55		44.81
JW59		48.27

Table 4

Average speed (s1 and s1) for individual tongue pellets across vowels tokens.

Speaker	Pellet	s1 (mm/s)	s2 (mm/s)
DS01	T1	26.2	36.7
DS03		27.1	34.0
JW55		29.6	38.9
JW59		30.2	41.1
DS01	T2	26.4	30.8
DS03		24.6	31.7
JW55		27.5	39.2
JW59		31.4	41.8
DS01	T3	24.2	31.9
DS03		26.1	33.6
JW55		35.2	41.5
JW59		33.2	42.1
DS01	T4	28.2	32.4
DS03		27.1	35.1
JW55		32.9	41.8
JW59		34.2	41.6