Research Article

The Impact of Contrastive Stress on Vowel Acoustics and Intelligibility in Dysarthria

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Purpose: To compare vowel acoustics and intelligibility in words produced with and without contrastive stress by speakers with spastic (mixed-spastic) dysarthria secondary to cerebral palsy (DYS_{CP}) and healthy controls (HCs).

Method: Fifteen participants (9 men, 6 women; age $M = 42$ years) with DYS_{CP} and 15 HCs (9 men, 6 women; age $M = 36$ years) produced sentences containing target words with and without contrastive stress. Forty-five healthy listeners (age $M = 25$ years) completed a vowel identification task of DYS_{CP} productions. Vowel acoustics were compared across stress conditions and groups using 1st (F1) and 2nd (F2) formant measures. Perceptual

intelligibility was compared across stress conditions and dysarthria severity.

Results: F1 and F2 significantly increased in stressed words for both groups, although the degree of change differed. Mean Euclidian distance between vowels also increased with stress. The relative probability of vowels falling within the target F1 $\times$ F2 space was greater for HCs but did not differ with stress. Stress production resulted in greater listener vowel identification accuracy for speakers with mild dysarthria.

Conclusions: Contrastive stress affected vowel formants for both groups. Perceptual results suggest that some speakers with dysarthria may benefit from a contrastive stress strategy to improve vowel intelligibility.

This investigation was designed to evaluate how contrastive stress production affects vowel acoustics and listener perception in speakers with and without dysarthria secondary to cerebral palsy (CP). CP refers to a heterogeneous group of early onset, nonprogressive motor disorders secondary to perinatal neurologic insult (Rosenbaum et al., 2007). Recent estimates suggest a world-wide CP prevalence of 2.11 per 1,000 births (Oskoui, Coutinho, Dykeman, Jetté, & Pringsheim, 2013). Communication limitations are often documented in individuals with CP (Bax, Tydeman, & Flodmark, 2006; Hustad, Gorton, & Lee, 2010; Rosenbaum et al., 2007) and include dysarthria (Ansel & Kent, 1992; Platt, Andrews, Young, & Quinn, 1980), a neuromotor disruption to speech production that may affect any or all of the speech subsystems (Duffy, 2005; Yorkston, Beukelman, Strand, & Hakel, 2010). Just as classification of CP is based on gross motor signs (spastic, dyskinetic, ataxic, or mixed; Rosenbaum et al., 2007), dysarthria in CP falls within similar categories (Hustad, 2010), with spastic dysarthria being the most prevalent.

Characteristics of Dysarthria Secondary to CP

The dysarthria presenting with CP (DYS_{CP}) is frequently characterized by distortions or errors of speech segments (consonants and vowels). Documented inaccuracies include voicing, place of articulation, and/or manner of production errors (Ansel & Kent, 1992; Kim, Martin, Hasegawa-Johnson, & Perlman, 2010; Platt, Andrews, & Howie, 1980; Platt, Andrews, Young, & Quinn, 1980). Distorted or inaccurate vowel productions also contribute to the speech intelligibility deficits observed in DYS_{CP}. For instance, a study of speakers with mixed dysarthria secondary to CP found that reduced intelligibility could be partially explained by difficulties with vowel contrasts (e.g., high–low, front–back, tense–lax; Ansel & Kent, 1992). Similarly, the intelligibility deficits of Mandarin speakers with DYS_{CP} were related to high–low and front–back vowel contrasts (Liu, Tseng, & Tsao, 2000). The ability to achieve accurate placement at the extremes of the articulatory space, the corner vowels, is also reduced in speakers with DYS_{CP} (Liu, Tsao, & Kuhl, 2005; Platt, Andrews, Young, & Quinn, 1980) and is related to decreased speech intelligibility (Kim, Hasegawa-Johnson, & Perlman, 2011; Liu et al., 2005).

Prosodic deficits also characterize DYS_{CP}, although their role in speech intelligibility is less understood than segmental contributions. Although investigations of prosody

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production in DYS_{CP} show exaggerated and redundant cue use (Patel, 2003; 2004), prosody production may be a relative strength for enhancing communication. For instance, speakers with DYS_{CP} are able to produce perceptually distinct stress and question-statement contrasts (Patel, 2002; Patel & Campellone, 2009). Prosody serves a number of linguistic functions, including the ability to signal stress, rhythm, intonation, and pause structure (Lehiste, 1976), which contribute to the ability of the listener to decode both typical (Shattuck-Hufnagel & Turk, 1996) and dysarthric (Liss, Spitzer, Caviness, & Adler, 2002; Liss, Spitzer, Caviness, Adler, & Edwards, 2000) speech. Moreover, prosodic prominence can promote segmental clarity (de Jong, 1995; Erickson, Fujimura, & Dang, 1999). Therefore, capitalizing on the relative strength of prosody production in speakers with DYS_{CP} may promote speech intelligibility and the communicative success of speakers with dysarthria.

Prosodic Modulation Strategies

In fact, strategies using prosodic modulation to improve the intelligibility of speech in dysarthria are well documented (see review by Yorkston, Hakel, Beukelman, & Fager, 2007). These modulations may be globally implemented across the speech utterance, such as rate reduction or increased loudness (Tjaden, Lam, & Wilding, 2013; Yorkston et al., 2007). Alternatively, strategies may be localized and target specific syllables or words within an utterance, such as emphatic stress production (Liss & Weismer, 1994).

Global Strategies

Of the prosodic modulation strategies, the implementation of increased loudness to improve speech production enjoys the most comprehensive evidence base. The Lee Silverman Voice Treatment (LVST/LVST-LOUD; e.g., Fox, Morrison, Ramig, & Sapir, 2002; Ramig et al., 2001) program has been systematically studied in speakers with hypokinetic dysarthria secondary to Parkinson's disease (PD). This intervention requires patients to increase loudness across the speech signal, which results in increased vocal sound pressure level (Ramig et al., 2001), slow rate, and increased fundamental frequency variation (Ramig, Countryman, Thompson, & Horii, 1995). In addition, two studies investigating the implementation of LSVT-LOUD with children with spastic dysarthria secondary to CP found parents reported more precise articulation (Fox & Boliek, 2012) and increased word intelligibility immediately after treatment (Boliek & Fox, 2014).

Rate alteration, another global strategy, entails either increasing (Turner, Tjaden, & Weismer, 1995; Weismer, Laures, Jeng, Kent, & Kent, 2000) or reducing (Tjaden, Sussman, & Wilding, 2014; Tjaden & Wilding, 2004; Turner et al., 1995) speaking rate. Although the motivation for increasing speech rate may be to mitigate perceived slow speech that potentially affects naturalness and intelligibility, rate reduction affords a larger temporal window for achieving articulatory precision (Dromey & Ramig, 1998).

Slower rate likely facilitates speech intelligibility through the enhanced demarcation of word boundaries and increased processing time afforded the listener (Tjaden et al., 2014). Results of studies evaluating the relationship between rate reduction and speech intelligibility for speakers with dysarthria have been mixed, with some finding improved speech intelligibility (Yorkston, Hammen, Beukelman, & Traynor, 1990), including for speakers with severe spastic dysarthria secondary to CP (Hustad & Sassano, 2002). Other studies have not found a positive relationship (Van Nuffelen, De Bodt, Vanderwegen, Van de Heyning, & Wuyts, 2010; Weismer et al., 2000). Inconsistent findings are likely related to methodological differences across studies, such as approaches to eliciting rate reduction (e.g., Hammen, Yorkston, & Minifie, 1994) and participant characteristics, including dysarthria severity.

A third type of global prosodic modulation strategy is clear speech, the exaggerated speech resulting when a speaker attempts to compensate for a listener's perceptual restrictions (Smiljanić & Bradlow, 2009), such as hearing impairment (Ferguson & Kewley-Port, 2002; Ferguson, 2004) or nonnative language status (Ferguson & Kewley-Port, 2007). Clear speech is characterized by hyperarticulation, increased loudness, reduced rate (Tjaden et al., 2013), and increased fundamental frequency range variability (see Smiljanić & Bradlow, 2009 for review). This strategy has been shown to effectively improve speech intelligibility across a wide range of speakers, listeners, and noise conditions (Ferguson & Kewley-Port, 2002; Smiljanić & Bradlow, 2009).

A few investigations have evaluated the benefits of clear speech in speakers with dysarthria (Goberman & Elmer, 2005; Hanson, Beukelman, Fager, & Ullman, 2004; Tjaden et al., 2014). Goberman and Elmer (2005) found that speakers with dysarthria secondary to PD reduced articulation rate and increased both fundamental frequency and its variation when producing clear speech. Furthermore, more than one half of the participants with PD increased vowel clarity, as demonstrated by an increase in vowel space area. Tjaden et al. (2014) observed that producing both clear and loud speech resulted in increased speech intelligibility relative to slow and habitual speech for speakers with multiple sclerosis or PD. Increased speech intelligibility has also been observed posttreatment following an intensive therapy using clear speech in speakers with nonprogressive dysarthria (Park, Theodoros, Finch, & Cardell, 2016).

A Local Strategy

Emphatic stress could arguably be described as clear speech that is targeted or localized to one syllable or word as it is characterized by localized hyperarticulation (de Jong, 1995), and increased loudness, duration, and fundamental frequency (Crystal & House, 1988; Lehiste, 1976). The effect of emphatic stress on speech intelligibility in dysarthria is less well understood than other types of prosodic modulation, but supports top-down processes by highlighting salient words and demarcating word boundaries (Liss, 2007; Yorkston, Beukelman, Strand, & Bell, 1999).

and shows promise for improving segmental intelligibility in speakers with motor speech disorders (Connaghan & Patel, 2013; Liss, 2007; Liss & Weismer, 1994).

Prosodic Modulation and Vowels

A common approach to measuring the effect of prosodic modulation strategies on dysarthric speech is to evaluate changes to vowel formants. Various measures of the first (F1) and second (F2) vowel formants can serve as proxies for articulator position and the degree of articulation and size of the working space (Kent, Weismer, Kent, Vorperian, & Duffy, 1999; Stevens & House, 1955). Vowel production in dysarthria has been characterized by formant centralization (Sapir, Ramig, Spielman, & Fox, 2010), abnormal formant frequencies for high and front vowels (Kent et al., 1999), and reduced vowel space area (e.g., Liu et al., 2005; Tjaden & Wilding, 2004).

These findings are significant, given a positive relationship between vowel space area and perceptual intelligibility in typical speakers (Bradlow, Torretta, & Pisoni, 1996). In fact, changes to vowel formants that reflect expansion to working space have been observed simultaneously with increases to intelligibility for some speakers with dysarthria when using slowed, though not faster (Weismer et al., 2000) rates (Tjaden & Wilding, 2004); increased loudness (Spielman, Ramig, Mahler, Halpern, & Gavin, 2007; Tjaden & Wilding, 2004); and clear speech (Tjaden et al., 2013). Similar findings have been noted for typical speakers producing emphatic stress (Erickson, 2002; Hay, Sato, Coren, Moran, & Diehl, 2006), though the effect of contrastive stress on the speech produced by individuals with dysarthria is unclear.

In addition, dysarthria may distort vowels and affect vowel contrasts (e.g., high vs. low; back vs. front) differentially (Lansford & Liss, 2014b). In fact, Lansford and Liss (2014b) found that a measure of dispersion of the front vowels to be the most reliable indicator of dysarthria relative to healthy speech.

Purpose

Building upon previous work that examined the effect of global prosodic modulation on vowel production, the goal of the current investigation was to evaluate the effect of a local strategy (contrastive stress) on vowel formant measures and perceptual intelligibility in speakers with and without DYS_{CP}. Investigating the role of contrastive stress in speech intelligibility in this population will not only further our understanding of speech impairment in dysarthria but also potentially provide support for targeting prosody in speech intervention. The following experimental questions were addressed:

1. Does contrastive stress change vowel formant measures in speakers with dysarthria secondary to CP and healthy controls (HCs)?
2. Does contrastive stress increase perceptual vowel intelligibility in speakers with dysarthria secondary to CP across severity?

Methods

Participants

All participants were monolingual speakers of American English, with hearing thresholds at or below 25 dB HL for 0.25, 0.5, 1.0, 2.0, 4.0, and 8.0 kHz in at least one ear. Participants demonstrated adequate vision, language, and cognitive skills to complete the experimental task.

Speakers

Speech samples from individuals with DYS_{CP} and HCs were previously collected in the Communication Analysis and Design Laboratory at Northeastern University. Descriptions of 12 DYS_{CP} (nine men, three women) and 12 sex- and age-matched (± 5 years) HC (nine men, three women) participants are reported elsewhere (Patel & Campellone, 2009). Samples from an additional three DYS_{CP} (three women) participants and three sex-, but not age-, matched HC speakers were also included to obtain a final data set of 15 DYS_{CP} (nine men, six women; age $M = 42$ years) and 15 HCs (nine men, six women; age $M = 36$ years). The speakers with DYS_{CP} were diagnosed with spastic or mixed-spastic dysarthria, as determined by a certified speech-language pathologist (SLP), using standard formal and informal assessments, and confirmed by a second SLP. Speech severity was determined using the modified version of the Assessment of Intelligibility of Dysarthric Speech (AIDS; Yorkston & Beukelman, 1981). Categorizations of dysarthria severity were adapted from ranges proposed in previous studies (Patel & Campellone, 2009; Whitehill & Ciocca, 2000). On the basis of the AIDS scores, dysarthria severity was classified as mild (scores between 75% and 100%), moderate (scores between 45% and 74%), or severe (scores between 0% and 44%), resulting in five speakers per severity group. This rating was confirmed by a certified SLP. Description of the participants has been provided (see Table 1).

Listeners

Forty-five monolingual speakers of American English (three men, 42 women; age range = 19–35 years, age $M = 25$ years) with no history of speech, language, or hearing impairments served as listeners. Participants were either graduate students in speech-language pathology or members of a speech-science laboratory group.

Tasks and Stimuli

Speaking

Audio samples were collected in either a sound-treated, audiometric booth or in a quiet room at a location convenient to the participant (e.g., within residential or clinical facility). Speech recordings were made using a Mini-Disc recorder (MDP-500; HHB, London, England) and a head-mounted microphone (SM10A; Shure, Niles, IL). Each speaker produced a series of five utterances comprising monosyllabic words. Each utterance was populated with either high (/i/, /ɪ/) or low (/æ/) vowels to control for vowel

Table 1. Description of participants with dysarthria secondary to cerebral palsy (DYS_{CP}) and healthy controls (HCs).

DYS _{CP} participant	Sex	Age	AIDS score ^a	Severity rating	HC participant	Sex	Age
DYS1	F	21	83	Mild	HC1	F	22
DYS2	M	21	87	Mild	HC2	M	23
DYS3	M	21	40	Severe	HC3	M	24
DYS4	M	29	67	Moderate	HC4	M	28
DYS5	F	31	71	Moderate	HC5	F	30
DYS6	M	34	84	Mild	HC6	M	29
DYS7	M	38	85	Mild	HC7	M	35
DYS8	M	44	63	Moderate	HC8	M	42
DYS9	F	48	82	Mild	HC9	F	23
DYS10	M	50	43	Severe	HC10	M	48
DYS11	M	54	47	Moderate	HC11	M	53
DYS12	F	58	36	Severe	HC12	F	36
DYS13	M	61	60	Moderate	HC13	M	58
DYS14	F	62	31	Severe	HC14	F	37
DYS15	F	64	36	Severe	HC15	F	59

^aScore from modified version of *Assessment of intelligibility of dysarthric speech* (Yorkston & Beukelman, 1981).

height. Multiple repetitions of each phrase with neutral or varying stress placement were produced. Neutral sentences were produced in imitation, and contrastive stress was elicited through contextual scenarios, which required the speaker to answer clarifying questions. Although the full data set contained a minimum of five repetitions of each utterance per participant (see Patel & Campellone, 2009), only the first three repetitions that included stress on the targeted word and their neutral cognates were subject to analysis in the current investigation. Target words were excised from the utterances using Praat (version 5.3.84; Boersma & Weenink, 2014) and included 36 tokens per participant and 1,080 tokens overall. The utterances, elicitation questions, and target vowels are found in Table 2.

Listening

Listeners sat in front of a computer in a soundproof, audio booth or quiet room wearing headphones (K240, AKG Acoustics, Vienna, Austria). After a brief training, the listener was guided through the task using custom software. On each screen, the listener was prompted to play an audio file and then engage in a 12-option, forced-choice task to choose the vowel (monophthong or diphthong) heard. Listeners were instructed to play the word as often as necessary until they made their choice and then progress to the next production. Each listener heard 40 word

productions (36 experimental tokens plus four random repeats to evaluate intrajudge reliability) from three speakers, for 120 total tokens each. Stimuli lists were chosen to include three speakers with similar AIDS intelligibility scores. The lists were randomized, and the order of speakers was counterbalanced across listeners. Productions from each speaker were judged by nine listeners. The listening task ranged in length from approximately 30 to 50 min.

Acoustic Analysis

Recordings were analyzed in Praat (Boersma & Weenink, 2014). Measurements included the F1 and F2 formant value midvowel. A custom routine in Praat extracted the mean F1 and F2 from a 30-ms window centered on the vowel nucleus (Hustad et al., 2010; Tjaden & Wilding, 2004). Sixty-two productions revealed tracking errors and were hand-corrected to acquire vowel formants. The formants from 120 (11%) randomly chosen tokens were reanalyzed by the same investigator to measure intrajudge reliability ($r = .99$, signed-difference $M = 1$ Hz). A second judge who was trained on the acoustic analysis methods reanalyzed the same tokens to measure interjudge reliability ($r = .97$, signed-difference $M = 16.7$ Hz).

Vowel dispersion was measured by modifying established metrics (e.g., front dispersion; Lansford & Liss, 2014b)

Table 2. Elicitation of contrastive stress productions. Questions to elicit contrastive stress target are seen in the left column. Target utterances, words (in italics), and vowels are listed in middle and right columns, respectively. Unstressed targets were repeated from model.

Elicitation question for stressed targets	Target sentence and word	Target vowel
"Who lives near me?"	<i>He</i> lives near me.	/i/
"Who hid his key?"	<i>She</i> hid his key.	/i/
"What did she do with his key?"	She <i>hid</i> his key.	/ɪ/
"What did she do to you?"	She <i>hit</i> me here.	/ɪ/
"Which man ran fast?"	<i>That</i> man ran fast.	/æ/
"Does Sam have fat cats now?"	Sam <i>had</i> fat cats.	/æ/

to compare the distance between front vowels across stress conditions. Specifically, the $F1 \times F2$ centroid of each vowel was calculated for each speaker in the stressed and unstressed conditions. The average Euclidian distance (ED) across the centroids of each vowel pair (e.g., /æ/-/i/, /æ/-/ɪ/, /i/-/ɪ/) was then compared across conditions and groups using repeated-measure analysis of variance (ANOVA).

Model-based clustering (Fraley & Raftery, 2002) was used to measure vowel dispersion and overlap by determining the probability that each vowel production fell within the target acoustic space for the specific speaker. First, the probability that a token fell within each of the three vowel's acoustic space was calculated using a probability density function (PDF). Next, the relative probability that the token fell within the target vowel area was calculated by dividing the target vowel probability by the sum of the probabilities from all three vowels. The product of the relative probabilities for each target vowel was then subjected to statistical analysis. Vowel dispersion (ED) and distinctiveness (PDF) measures are presented for one participant with DYS_{CP} (Figure 1, top two panels) and his HC match (Figure 1, lower two panels), with stressed productions on

the left and unstressed productions on the right. The $F1 \times F2$ coordinates for each vowel repetition are shown, along with the vowel centroids and the ED between each vowel pair (see Figure 1). The relative probability for each vowel is shown near the centroid.

Perceptual Analysis

Perceptual vowel intelligibility was analyzed according to whether or not the listener-identified vowel matched the target (e.g., correct vs. incorrect). A correct score percentage was calculated for each vowel and each speaker. These values were then transformed into rationalized arcsine units (RAUs; Studebaker, 1985) before conducting statistical analysis. Vowel confusions were also recorded, although not subjected to statistical analysis.

For each listener, 12 random words (four per speaker, approximately 10% of the sample) were repeated to evaluate within-listener reliability. Intralistener reliability ranged from 67% to 100% agreement, with a Cohen's κ of .82 across all listeners. Interjudge reliability of listener judgments of target vowels across each group of nine listeners was evaluated using Cronbach's α (.96).

Figure 1. The first by second formant ($F1 \times F2$) plots of /æ/ (grey diamond), /i/ (black triangle), and /ɪ/ (white square) productions in unstressed (left panels) and stressed (right panels) words produced by one participant with dysarthria (DYS_{CP}; top panels) and the healthy control (HC) match (lower panels). The relative probability density function (PDF) is provided for each vowel. The solid lines reflect the Euclidian distance between vowel centroids.

Statistical Analyses

Acoustic dependent measures (F1, F2, ED, PDF) were analyzed both descriptively (e.g., *M*, standard deviation) and using parametric statistics. Separate mixed-model ANOVA with two within-subject measures (stress condition, vowel) and one between-subjects measure (speaker group) were conducted for each dependent variable, with the exception of the ED measure, for which the vowel was not a factor.

For the perceptual analysis, a mixed-model, repeated-measures ANOVA was conducted. As the perceptual analysis included speakers with DYS_{CP} only, it afforded the opportunity to include severity as a between-subjects factor, whereas vowel and stress condition served as repeated factors. All post hoc testing was subject to Bonferroni correction to control for Type I errors.

Results

Acoustic Findings

Formants

The F1 and F2 group means (with standard deviations in parentheses) and 95% confidence intervals for vowels produced in the stressed and unstressed conditions are provided (see Table 3).

Separate ANOVAs were calculated for F1 and F2 across stress condition and vowels and between groups. For F1, a main effect of condition was found, with a significantly greater F1 in the stressed condition, $F(1, 28) = 82.72$, $p = .00$, $\eta_p^2 = .75$. A main effect of vowel was also found, $F(2, 56) = 255.70$, $p = .00$, $\eta_p^2 = .90$. Post hoc testing revealed that the three vowels differed significantly ($p < .05$), with the F1 of /æ/ being the highest and /i/ being the lowest. No difference was found for F1 between the DYS_{CP} and HC groups, $F(1, 28) = .00$, $p > .05$. However, a significant Condition $\times$ Group interaction, $F(1, 28) = 17.88$, $p = .00$, $\eta_p^2 = .39$, can be explained by the greater increase in F1 with stress production by the group with DYS_{CP}. A significant Condition $\times$ Vowel interaction, $F(2, 56) = 31.04$, $p = .00$, $\eta_p^2 = .53$, was also observed, with /æ/ showing the greatest and /i/ showing the least F1 increase with stress. The Vowel $\times$ Group interaction was also significant, $F(2, 56) = 3.38$, $p = .04$, $\eta_p^2 = .11$. A greater F1 range was observed between the vowels produced by the HCs than by the group with DYS_{CP}. No other interactions were significant.

For F2, a main effect was seen for condition, $F(1, 28) = 45.66$, $p = .00$, $\eta_p^2 = .62$, with F2 significantly higher in the stress condition. A main effect was also observed for vowel, $F(2, 56) = 154.57$, $p = .00$, $\eta_p^2 = .85$. Post hoc testing revealed that /i/ was significantly higher and /æ/ was significantly lower than the other two vowels ($p < .05$). Speaker groups differed, $F(1, 28) = 9.75$, $p = .00$, $\eta_p^2 = .26$, with the group with DYS_{CP} producing significantly lower F2 than did the HCs. The interaction of Condition $\times$ Group was significant, $F(1, 28) = 11.37$, $p = .00$, $\eta_p^2 = .29$, with a greater increase in F2 upon stress production noted for the HC group than for the group with DYS_{CP}. The Vowel $\times$

Group interaction, $F(2, 56) = 11.21$, $p = .00$, $\eta_p^2 = .29$, was explained by greater F2 differences between vowels for the HC group than for the group with DYS_{CP}. No other significant interactions were observed.

The means (with standard deviation bars) of F1 (left) and F2 (right) across stress and vowel condition by dysarthria severity are shown (see Figure 2). Visual inspection suggests that patterns of change are similar across F1 and F2. Differences in variability across groups may be explained by unequal numbers of men and women across the severity groups.

In summary, main effects indicated that both F1 and F2 were significantly higher in stressed vowels compared with unstressed vowels. However, the effect of stress was greater for F1 in DYS_{CP} productions and for F2 in HC productions. The F1 of /æ/ was more affected by stress than was the F1 of the other two vowels. Although no group differences were observed for F1, F2 was higher for HC.

ED

The mean ED between vowel centroids in the F1 $\times$ F2 space was used to evaluate vowel dispersion across conditions and is shown for the stressed and unstressed conditions for both groups (see Table 3). A repeated-measures ANOVA yielded significant main effects for both stress condition, $F(1, 28) = 7.89$, $p = .00$, $\eta_p^2 = .22$, and group, $F(1, 28) = 11.33$, $p = .00$, $\eta_p^2 = .29$, although the Condition $\times$ Group interaction ($p > .05$) was not significant. The mean ED was larger for HCs than it was for the group with DYS_{CP} and was greater in the stressed than in the unstressed condition for both groups.

PDF

The PDF was used to compare the overlap and spread of vowel formants. The relative probability of a vowel falling within the target F1 $\times$ F2 vowel space for each listener was compared across stress conditions and between groups (see Table 3, which includes the means, and standard deviations, of the relative probabilities of each vowel in stressed and unstressed words for each group). Mixed-model ANOVA revealed that relative probabilities significantly differed between the groups, $F(1, 28) = 57.14$, $p = .00$, $\eta_p^2 = .67$, and were greater for the HC group than for the group with DYS_{CP}. Although relative probabilities did not differ between the stressed and unstressed conditions, $F(1, 28) = 2.30$, $p = .14$, there was a main effect of vowel, $F(2, 56) = 8.32$, $p = .00$, $\eta_p^2 = .23$, with /æ/ having the highest and /i/ the lowest probability across condition and groups. A significant Vowel $\times$ Group interaction, $F(2, 56) = 6.72$, $p = .00$, $\eta_p^2 = .19$, can be explained by significant differences in probabilities across vowels for the group with DYS_{CP} but not for the HC group. In summary, although the PDF did not differ across stress conditions, it did differentiate between speaker groups, with HCs demonstrating significantly higher PDFs than did the group with DYS_{CP}.

Table 3. Mean (*M*), standard deviation (*SD*) and 95% confidence interval (95% CI) of first (F1; Hz) and second (F2; Hz) formant groups, probability density function (PDF), and Euclidian distance (ED) in stressed and unstressed productions by participants with dysarthria secondary to cerebral palsy (DYS_{CP}) and healthy control (HC) speakers.

Unstressed										Stressed			
Participants	Statistic	All vowels	/i/	/ɪ/	/æ/	All vowels	/i/	/ɪ/	/æ/				
DYS _{CP}													
F1	<i>M (SD)</i>	473.1 (149.0)	359.4 (59.2)	430.6 (64.6)	629.3 (141.9)	576.5 (196.6)	406.2 (68.4)	545.2 (111.5)	777.9 (169.5)				
	95% CI	434.2, 511.9	330.3, 388.4	399.8, 461.4	559.2, 699.4	529.5, 623.4	375.1, 437.3	498.4, 592.1	697.8, 858.0				
F2	<i>M (SD)</i>	1,893.0 (269.3)	2,050.1 (245.9)	1,963.7 (214.9)	1,665.1 (184.2)	1,930 (267.2)	2,104.5 (268.9)	1,944.6 (235.8)	1,740.9 (158.9)				
	95% CI	1,794.7, 1,991.2	1,921.7, 2,178.4	1,853.7, 2,073.6	1,574.5, 1,755.8	1,829.2, 2,030.8	1,968.9, 2,240.0	1,824.6, 2,064.7	1,657.5, 1,824.3				
PDF	<i>M (SD)</i>	.41 (.44)	.37 (.39)	.21 (.34)	.66 (.48)	.47 (.43)	.47 (.46)	.29 (.35)	.64 (.43)				
	95% CI	.27, .56	.17, .58	.05, .37	.46, .85	.37, .57	.30, .65	.16, .43	.47, .80				
ED	<i>M (SD)</i>	337.7 (152.7)				370.7 (128.3)							
	95% CI	266.6, 408.9				302.5, 438.9							
HC													
F1	<i>M (SD)</i>	507.2 (169.9)	350.8 (50.3)	464.5 (51.0)	706.3 (122.4)	545.0 (208.4)	345.7 (47.2)	491.8 (57.0)	797.5 (130.9)				
	95% CI	468.4, 546.0	321.8, 379.9	433.8, 495.3	636.2, 776.4	498.0, 591.9	314.6, 376.7	444.9, 538.6	717.4, 877.6				
F2	<i>M (SD)</i>	2,068.0 (320.1)	2,377.3 (239.5)	2,059.4 (200.8)	1,767.3 (157.6)	2,178.8 (336.3)	2,508.4 (243.0)	2,166.4 (217.9)	1,861.5 (156.3)				
	95% CI	1,969.7, 2,166.2	2,248.9, 2,505.7	1,949.4, 2,169.3	1,676.6, 1,857.9	2,078.0, 2,279.6	2,372.9, 2,644.0	2,046.4, 2,286.5	1,778.2, 1,944.9				
PDF	<i>M (SD)</i>	.87 (.30)	.77 (.40)	.91 (.24)	.92 (.22)	.99 (.06)	1.0 (.00)	.97 (.10)	.99 (.02)				
	95% CI	.72, 1.0	.56, .98	.75, 1.1	.72, 1.1	.89, 1.1	.83, 1.2	.84, .1.1	.83, 1.1				
ED	<i>M (SD)</i>	476.9 (113.6)				536.1 (129.6)							
	95% CI	405.7, 548.1				467.9, 604.3							

Figure 2. Means (with standard deviation bars) of the first formant (F1; left) and second formant (F2; right) measures for speakers with mild (top panels), moderate (middle panel), and severe (bottom panel) dysarthria classifications, across vowels. The unstressed productions are in grey, and stressed productions are in black.

Perceptual Findings

The accuracy of listener identification of each vowel produced in stressed versus the unstressed conditions by speakers with DYS_{CP}, grouped by dysarthria severity, is shown (see Figure 3). A correct score percentage was obtained for each vowel per listener, transformed to RAUs (Studebaker, 1985), and averaged across listeners. Each panel includes the RAU mean (standard deviation bars) for each vowel, across the dysarthria severity group.

A mixed-model ANOVA comparing listener accuracy across vowels, stress condition, and dysarthria severity indicated that contrastive stress significantly improved the perception of the vowels as correct (e.g., matched target) across the speakers with DYS_{CP}, $F(1, 12) = 10.64$, $p = .01$, $\eta_p^2 = .47$. A main effect for vowel, $F(2, 24) = 4.08$, $p = .03$, $\eta_p^2 = .25$, was observed, with post hoc tests revealing that

/i/ was identified correctly more often than the other two vowels. Differences across dysarthria severity were observed, $F(2, 12) = 10.58$, $p = .00$, $\eta_p^2 = .64$, with post hoc testing indicating that vowels produced by mildly impaired speakers were more often judged correctly than were vowels produced by the moderately and severely impaired speakers ($p < .05$). A significant Stress $\times$ Severity, $F(2, 12) = 11.94$, $p = .00$, $\eta_p^2 = .67$, interaction was also observed, with the group with mild severity demonstrating a substantially greater gain in perceptual accuracy with stress over the other two severity groups.

To further examine the types of perceptual errors that listeners made, confusion matrices (see Table 4) were created to analyze the percentage of productions identified for each of the vowel/diphthong options in unstressed (Table 4, top section) and stressed (Table 4, lower section) vowels.

Figure 3. The rationalized arcsine unit (RAUs) scores reflecting accurate identification of target vowels (/æ/, /i/, /ɪ/) in unstressed (light grey) and stressed (black) words. Panels depict productions by speakers with mild (top), moderate (middle) and severe (bottom) dysarthria.

Discussion

Numerous studies have documented a positive relationship between vowel clarity and intelligibility of speech produced by healthy speakers (Ferguson & Kewley-Port, 2002; Kewley-Port, Burkle, & Lee, 2007; Neel, 2008) and speakers with dysarthria (Kim et al., 2011; Liu et al., 2005; Liu, Tseng, & Tsao, 2000; Lansford & Liss, 2014a, 2014b; Tjaden et al., 2013). Furthermore, investigations comparing the implementation of global prosodic strategies, such as increased loudness and clear speech, with habitual speech have revealed improved acoustic vowel clarity and increased speech intelligibility (e.g., Sapir et al., 2010; Tjaden et al., 2013; Tjaden & Wilding, 2004). The current investigation was designed to determine whether similar changes are observed when speakers with spastic dysarthria

secondary to CP used a localized, prosodic modulation strategy by placing emphatic stress on a word within an utterance. Contrastive stress affected vowel formants in speakers both with and without DYS_{CP} and improved perceptual vowel intelligibility in speakers with DYS_{CP}, although speakers with mild dysarthria drove the perceptual findings.

Summary of Findings

Measures of Vowel Formants

Increases in both F1 and F2 in stressed contrasts versus unstressed contrasts suggest that both the lowering and advancement of the tongue were used in stress production, given the inverse relationship between F1 and tongue height and the direct relationship between F2 and tongue advancement (Stevens & House, 1955). Although advanced tongue

Table 4. Confusion matrix for vowel judgments of words produced by participants with dysarthria secondary to cerebral palsy (DYS_{CP}). Target vowel is indicated by *Expected* and the percentage of occurrence of that target vowel meeting the judgments indicated in the *Actual* columns. Top panel includes vowels produced in unstressed words, and lower panel includes vowels produced in stressed words.

Unstressed	Actual	i	ɪ	eɪ	ɛ	æ	ə	aɪ	ɑ	ʊ	oɪ	o	u
	Expected												
	i	60	10	11	2	1	1	0	0	2	0	0	12
	ɪ	15	42	9	17	3	3	1	0	4	0	1	6
	æ	0	1	6	25	28	22	8	3	2	0	5	1
Stressed	Actual	i	ɪ	eɪ	ɛ	æ	ə	aɪ	ɑ	ʊ	oɪ	o	u
	Expected												
	i	63	9	14	2	0	2	0	0	2	0	1	5
	ɪ	10	47	14	15	2	2	1	0	3	1	1	4
	æ	0	2	4	13	47	13	13	3	2	1	1	1

Note. Percentages are rounded and may not add to 100. Bolded numbers indicate the percentage that the target vowel was correctly identified.

placement (e.g., higher F2) of front vowels is consistent with an expansion of the vowel working space, the explanation for the observed increase of F1 (e.g., tongue lowering) of the two high vowels (/i/ and /ɪ/) upon stress production is more complex. Whereas the hyperarticulation strategy of stress production (de Jong, 1995) presumes that vowels are strengthened through exaggerated articulatory placement, the sonority expansion strategy of stress production (Edwards & Beckman, 1988) postulates that increased intensity contributes to the realization of prominence. These strategies diverge in the prediction of F1 changes given vowel height; hyperarticulation predicts a reduction in the F1 of high vowels, with a simultaneous increase in the F2 of front vowels, whereas sonority expansion predicts an F1 decrease, regardless of vowel height. Studies of healthy speakers revealed increased F2 upon emphatic stress production (Cho, 2005; Lindblom, Agwuele, Sussman, & Cortes, 2007), with inconsistent findings for the F1 of high vowels (Cho, 2005; Erickson et al., 1999; Mo, Cole, & Hasegawa-Johnson, 2009). The current findings of a main effect of increased F1 with stress placement, regardless of vowel height, across speaking groups provide further support for the sonority-expansion strategy.

Group differences in F2 highlight potential restrictions in lingual protrusion–retraction in speakers with DYS_{CP} (Liu et al., 2005). Although F2 increased with stress for both groups, that increase was greater for HCs. Moreover, F2 was lower for the group with DYS_{CP} than it was for HCs across stress conditions, suggesting less overall tongue advancement and the pervasiveness of tongue advancement–retraction limitations in DYS_{CP} (Kent & Netsell, 1978).

Measures of Vowel Dispersion and Distinctiveness

Various measures of vowels within the F1–F2 space have been related to speech intelligibility. For instance, vowel space area was relatively highly correlated with intelligibility in young-adult Mandarin (Liu et al., 2005) and

English (Kim et al., 2011) speakers with DYS_{CP}. However, other studies have suggested that it is unclear whether vowel space distortions differentially affect vowels (e.g., front vs. back) across the vowel space area (Kim et al., 2011; Lansford & Liss, 2014b). Alternatively, measures of vowel dispersion and listener perception are related in speakers with dysarthria (Lansford & Liss, 2014a), including speakers with DYS_{CP} (Kim et al., 2011). Therefore, the current investigation included two measures that captured vowel dispersion and distinctiveness: the ED and PDF. Our finding that the ED between vowel centroids was significantly reduced in the group with DYS_{CP} is consistent with reduced front vowel dispersion in speakers with dysarthria (Lansford and Liss, 2014b).

The PDF is a novel metric that uses model-based clustering (Fraley & Raftery, 2002) to determine the relative probability that each vowel token came from the target vowel F1 × F2 area. This measure takes into account both the spread of vowel tokens within a particular target (e.g., the standard deviation from the centroid), as well as distinction from other vowels in the form of overlap or crowding in the F1 × F2 space. These features are important, given previous work demonstrating the ability of a related measure—the overlap measure—to predict intelligibility in speakers with dysarthria secondary to CP. This approach uses per-speaker analysis of vowel tokens to classify them into their respective categories (Kim et al., 2011). In the current study, although the PDF did not differ between stress conditions, it was significantly higher for HCs than for speakers with DYS_{CP} and may have future utility for the differentiation of speaking groups.

Vowel Perception

Although accurate identification of vowels produced by speakers with DYS_{CP} increased in the stressed condition, this finding was observed primarily for speakers with mild dysarthria. In addition, /æ/ identification accuracy substantially increased with stress relative to /i/ and /ɪ/, with a reduction in vowel centralization errors (misidentification as /ə/) and presumed expansion in acoustic working area (e.g., less misidentification as /e/). This stress benefit is consistent with the significant changes to F1 observed for /æ/, relative to the other vowels.

Prosodic Modulation Strategies

A number of investigations have demonstrated the intelligibility benefits of global prosodic strategies for speakers with dysarthria. Increased loudness (Tjaden et al., 2014) has been shown to improve speech intelligibility in speakers with dysarthria. A demonstrable improvement in intelligibility when implementing clear speech has been demonstrated for healthy speakers (Ferguson & Kewley-Port, 2002), even when the factors of reduced rate and increased loudness were removed (Krause & Braida, 2002). Similar intelligibility gains for speakers with dysarthria are emerging (Goberman & Elmer, 2005; Tjaden et al., 2013). The benefits of slowing speech rate in dysarthric speech

appear to be more nuanced, with some studies showing improved intelligibility (see Yorkston et al., 2007), whereas others do not (Tjaden et al., 2013; Tjaden & Wilding, 2004), likely because of substantial differences in methodological approaches to rate reduction and speaker characteristics.

Global Versus Local Strategies

Despite evidence of intelligibility benefits from some global prosodic modulation strategies, less work has focused on local strategies, such as contrastive stress production. Treatment aimed at modifying contrastive stress, however, has the potential to not only boost the speech signal, such as increased audibility and clarity of speech (Connaghan & Patel, 2013; Patel & Campellone, 2009; Yorkston et al., 2007), but also to facilitate cognitive-perceptual factors, such as listener lexical segmentation and lexical access (Liss, 2007). In addition, local modulations may produce temporal and spectral effects elsewhere in the utterance (Liss & Weismer, 1994).

Although the current study was not designed to compare the benefits of local versus global prosodic modulation strategies, one can reflect on the relative advantages and disadvantages of different approaches for various populations. Individuals with limited breath support or with fatigue may be significantly taxed by effortful prosodic modulation across speech utterances and, therefore, benefit from a local strategy. Moreover, global strategies may reduce natural prosody, such as reduced F0 variation in slowed speech (Patel, Connaghan, & Campellone, 2013), thereby reducing an informative component of the speech signal (Tjaden et al. 2014). An exception to this concern is clear speech, which has been shown to facilitate speech rhythm and results in exaggerated prosody (Smiljanić & Bradlow, 2005).

On the other hand, although emphatic stress highlights the targeted word, the benefit to overall speech intelligibility is unclear. Furthermore, a local strategy may present a greater cognitive load to the speaker (McHenry, 1998) than a strategy applied across speech utterances, thereby being untenable for speakers with impaired cognition or limited resource allocation.

Limitations and Future Directions

These findings suggest that stress production increased vowel intelligibility in words produced by speakers with mild dysarthria secondary to CP. Similar differences were not observed across severity groups for the vowel acoustics, although comparisons were restricted to description and visual inspection because of the small sample size and lack of age and sex matching across groups, key factors in formant analyses. However, understanding the effect of prosodic modulation strategies, including contrastive stress, across the dysarthria-severity range is essential for further understanding of the interaction of prosodic modulation and intelligibility and its clinical implications.

Generalization of the findings is further restricted by the speech stimuli that were used. Although stress contrasts

were elicited with clarification questions to establish ecological validity, neutral (nonstressed) targets were elicited in imitation. It is unclear how these findings translate to naturalistic, spontaneous speech. The current work used a narrow definition of intelligibility that comprised vowel identification accuracy. Future studies will focus on the effect of contrastive stress on word, utterance, and conversational intelligibility. Broadening this focus is even more compelling because contrastive stress placement within an utterance can affect nontarget words (Liss & Weismer, 1994). Although mechanisms of articulatory impairment have been inferred from the acoustic data (e.g., limitations to tongue motion), physiologic examination, such as lingual kinematics, is necessary to confirm the underlying speech motor impairment. The acoustic-perceptual relationship will be further explored by expanding the scope of acoustic measures used. Finally, direct comparisons of global and local prosodic modulation strategies for specific dysarthria subtypes, severities, and individual factors warrant further investigation.

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