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The effects of flattening fundamental frequency contours on sentence intelligibility in speakers with dysarthria

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Abstract

This study explored the relationship between F0 variability and intelligibility in persons with motor speech disorders. The literature suggests that monopitch may have detrimental effects on the intelligibility of individuals with dysarthria (and other speech disorders), but few studies have examined the independent effect of a flat F0 contour on intelligibility in speakers with articulatory difficulties. An LPC resynthesis technique was used to reduce the speakers' sentence F0 range by 25%, 50% and 100% (flattened F0). Two dysarthric speaker groups were evaluated, one with prosodic inadequacy and imprecise articulation (hypokinetic) and one with imprecise articulation only (UUMN). Speech intelligibility was assessed using a word transcription task and an interval-scaling task. Results argue strongly for the perceptual importance of sentence-level F0 variations on speech intelligibility even when the F0 range is severely restricted. Results also suggest that the contribution of F0 to intelligibility may vary with type of dysarthria.

Keywords: Dysarthria, prosody, intelligibility.

Introduction

The term 'monopitch' is frequently used to describe certain types of dysarthria (Darley *et al.*, 1969a, b). The lack of F0 variability across an utterance (the presumed physical basis of this term) has been substantiated by several acoustic studies (Yorkston and Buekelman, 1981; LeDorze *et al.*, 1992; Bunton *et al.*, 2000). However, relatively little attention has been focused on how much the perceptual

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system utilizes information supplied by prosodic patterns and its relationship with speech intelligibility. Kent and Rosenbek (1982) reported that flattened F0 contours blur the contrast between adjacent units in the speech signal and have a detrimental effect on intelligibility. However, they also noted that intelligibility and prosodic disturbance are not necessarily equally impaired in all subjects.

Variation of F0 has been reported to contribute to intelligibility of neurologically normal speech. Prosody has been shown to be an important perceptual cue for vowel identity (Traunmuller, 1981), stop consonant voicing (Haggard *et al.*, 1970), syllable stress (Lehiste, 1970), and marking lexical boundaries (Liss *et al.*, 1998). Bradlow *et al.* (1996) studied both global and fine-grained differences among talkers as these differences correlated with inter-speaker differences in intelligibility. They concluded that a highly intelligible speaker was one who produces sentences with a relatively wide range of F0, a relatively expanded vowel space that includes a substantial F1 variation, precise articulation of the point vowels and a high precision of inter-segmental timing. Two studies that examined the independent effects of F0 contour on intelligibility in utterances produced by persons with no history of speech disorders showed significant differences in intelligibility between the original utterances and those with flattened F0 contours (Laures and Weismer, 1999; Laures *et al.*, 1999). This decrease in intelligibility was found for subjects whose articulatory precision was intact. For speakers with neurologic disease, who experience articulatory difficulties, there is little published information about the independent relationship between reduced F0 variation and speech intelligibility (for a review see Ramig, 1992). In developing an acoustic-phonetic model of intelligibility in dysarthria (Kent *et al.*, 1989), it is of interest to know how much sentence-level prosody contributes to speech intelligibility deficits, in the presence of segmental-level articulatory deficits. The present study was designed to determine how a lack of sentence-level F0 fluctuation contributes to speech intelligibility deficits in two groups of speakers with dysarthria. Speakers with hypokinetic dysarthria as the result of Parkinson's Disease typically exhibit decreased F0 ranges along with some segmental-level articulatory deficits. Alternatively, speakers who experienced a cerebrovascular accident resulting in unilateral upper motor neuron dysarthria typically have imprecise consonants but do not exhibit difficulties with prosody.

Methods

Speakers

Ten sentences randomly selected from the *Fisher-Logemann Test of Articulation Competence* (1971), each 5–7 words in length, collected from four speakers diagnosed with Parkinson's Disease (PD: 2M, 2F), four with left cerebrovascular accident (LCVA: 2M, 2F), and two with right CVA (1M, 1F) were analysed and used as perceptual stimuli in the present study. The set of ten sentences was different for each speaker, and was collected as part of a larger database on speech intelligibility. Speaker characteristics can be found in table 1. The range of intelligibility scores, calculated from the Kent *et al.* (1989) intelligibility test, ranged from 85% to 96%. This range of intelligibility was selected based on previous work demonstrating that the habitual amount of F0 variability decreases as overall intelligibility scores decrease (Bunton *et al.*, 2000). The type of dysarthria was identified by an experienced speech pathologist (ibid.). These two types of dysarthria (hypokinetic and

Table 1. *Speaker characteristics. The type of dysarthria is based on judgements of the final author who is a certified speech pathologist. The duration column includes time between diagnosis and recording as well as length of time their speech has been affected if different from medical diagnosis*

Subject	Gender	Age	Diagnosis	Duration	Dysarthria	Intelligibility mean (SD)
CS	M	69	R CVA	27 days	UUMN	86.7 (5.23)
TD	F	23	R CVA	11 days	UUMN	93.4 (2.7)
FL	F	78	L CVA	12 days	UUMN	87.5 (1.6)
BL	M	71	L CVA	9 days	UUMN	92.9
MB	F	66	L CVA	18 days	UUMN	85.46 (2.6)
BT	M	56	L CVA	8 days	UUMN	86.52
EB	F	75	PD	4 y speech/8 y Dx	hypokinetic	92.52
LW	F	61	PD	10 y speech/15 y Dx	hypokinetic	95.25
LA	M	70	PD	16 y	hypokinetic	92.63
LB	M	68	PD	1 y	hypokinetic	88.95

unilateral upper motor neuron) were selected based on the perceptual prominence of suprasegmental characteristics associated with one but not the other, while both dysarthrias are characterized by articulatory imprecision. Ten healthy, age-matched speakers (five male, five female) were included as controls.

Acoustic analysis

To quantify the habitual use of frequency variation for each speaker, the F0 minimum and maximum were recorded for each utterance using Cspeech (Milenkovic, 1997). In addition, peak frequencies associated with each vocalic segment in the utterance were measured, to ensure that the syllable structure of the utterance was unchanged during resynthesis of the utterances (see below).

Resynthesis

A linear predictive coding (LPC) based algorithm that allowed for sentence-level F0 modifications and did not affect the temporal or formant frequency characteristics of the utterances was used for resynthesis in the present study (Milenkovic, 1999). Each utterance was resynthesized prior to modifying the F0 contour. These unmodified, resynthesized utterances were used as control items in the listening experiments to ensure that the technique itself did not have any effect on the intelligibility of the sentences. The F0 contour of the utterance was then modified in three ways: (1) each voiced segment was flattened by setting all pitch periods equal to the mean value calculated over the entire utterance (hereafter referred to as flat F0); (2) the range of F0 variability was reduced by 25% while maintaining the syllable structure of the utterance; and (3) the range was reduced by 50%. For conditions 2 and 3, peak F0 for each vocalic segment was subtracted from the mean. This value was multiplied by the percentage decrease (25% or 50%) and the resultant value was added to original peak value, thus bringing the peak 25% (or 50%) closer to the mean value. For example, if the F0 mean for an utterance was 150 Hz and the individual peak was 200 Hz and a reduction of the F0 range by 25% was desired, the following equation applies $[(150-200)\times 0.25+200=187.5\,\text{Hz}]$. This procedure was used for

each individual peak within the utterance thereby preserving the F0 contour of the speaker's original production. An example of a spectrogram and F0 contour for an original utterance (panel a) an unmodified, resynthesized utterance (panel b), one with an F0 range reduced by 25% (panel c), and one with a flat F0 (panel d) are shown in figure 1 to illustrate that the resynthesis technique did not modify the spectral and temporal properties of the utterance. The utterance shown is 'They all know what I said' produced by a NG female speaker. The 800 utterances (ten utterances per speaker × four resynthesis conditions × 20 speakers) were placed into a single list to be used during the perceptual portion of the experiment.

Listeners

Ten graduate students (5M, 5F) served as listeners. All students had taken a graduate-level dysarthria course and had no self-reported hearing loss. Listeners with limited exposure to dysarthric speech were selected to avoid ceiling effects related to either the novelty of the speech or highly tuned listening skills. Listeners were seated in a sound booth and stimuli were presented over a loudspeaker at a comfortable listening level. The order of the utterances from the 800-utterance pool was generated randomly by the computer for each listener to control for order effects. Speakers heard all 800 utterances for each of the listening tasks as well as 40 repeat utterances (ten from each resynthesis condition) to obtain a measure of intra-judge reliability. The listening task was divided into four sections of 420 utterances each and listeners were given a 20-minute break between sections. The first time the listeners heard the utterances (sets 1 and 2), they were asked to write down what they heard as accurately as possible. The second time the listeners heard the utterances (sets 3 and 4) they were asked to assign a scale value of intelligibility using a 7-point equal-interval scale. The scale was defined for listeners as 'A scaling of 1 is equal to 0% intelligible; a scaling of 7 is equal to 100% intelligible. For this study, intelligibility is defined as the ease with which you understand the words spoken'.

Intelligibility measures

The purpose in intelligibility testing in the present study was twofold. The first measure of intelligibility, transcription, was selected to get a measure of the degree to which the listener recovers the discriminations intended by the speaker, that is, to determine the accuracy with which the speaker's intended message was recovered by the listener. The second measure, scaling, provided a quick, overall index of a speaker's intelligibility based on the listeners' perceived effort in recovering the message. Segmental level errors produced by the speakers were not modified during resynthesis of the F0 contours, therefore, an explanatory approach to intelligibility testing designed to identify the phonetic loci of the intelligibility deficit such as presented by Kent *et al.* (1989, 1990, 1992) was not appropriate for the present study.

Data analysis

Data analysis for sets 1 and 2 were achieved by calculating the number of words correctly transcribed for each utterance and speaker, and averaging across listeners. Scaled values (sets 3 and 4) were also averaged across listeners. Non-parametric statistics were used to separately analyse the results of the transcription and scaling tasks.

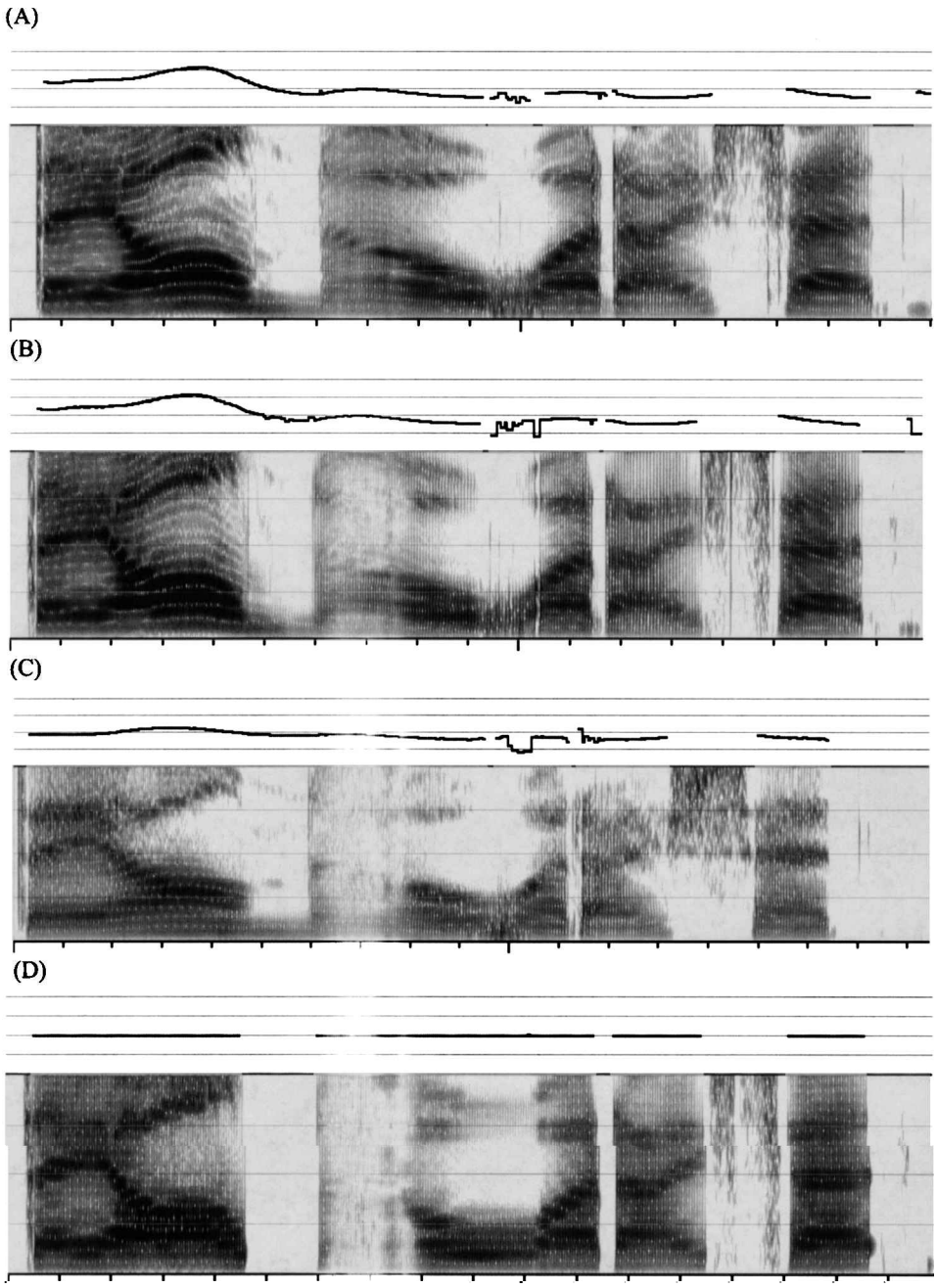

Figure 1. *Examples of spectrograms and F0 contours the token 'They all know what I said'. Panel a is the original utterance, followed by a resynthesized, unmodified condition (panel b), 25% reduced F0 range (c), and flat F0 (d) produced by a NG female.*

Reliability

Forty utterances were repeated from the set of 800 original tokens for each listener to obtain measures of intra-judge reliability. The overall correlation coefficients

between the first and second presentation of each utterance ranged between 0.83 and 0.97 for the ten listeners on the transcription task. For measures of inter-judge reliability, the correlation coefficients were between 0.77 and 0.98 for each speaker across listeners. For the scaling task, reliability was considerably lower for both inter- and intra-judge measures. The inter-judge coefficients ranged from 0.62 to 0.88 and the intra-judge values ranged from 0.54 to 0.78. No systematic shifts (i.e., improvements) in performance were noted for individual listeners across tokens.

Results

Acoustic characteristics of speakers

Table 2 shows the means and standard deviations for the mean F0, mean high and low F0 and the range of F0 variability averaged across the ten utterances for each speaker. To calculate the range of F0 variation, the high and low frequency peaks for each utterance were measured and values were then averaged across the utterances. This method was used rather than subtracting the mean high and low F0 values to account for the variability in performance for individual speakers. The range of F0 across utterances for all disordered speakers was smaller than for the control speakers (see also Bunton *et al.*, 2000). The reduction in range varied from 22% to 68%. A comparison of range of F0 variability with intelligibility scores failed to show a relationship between F0 variability within an utterance and the overall intelligibility score. In fact, the two PD speakers with the highest intelligibility scores have the most restricted frequency ranges. This data can be seen in figure 2. In this figure the NG speakers are represented by diamonds, the PD speakers by squares, R CVA by triangles and L CVA by circles.

Table 2. *Mean and standard deviations shown in parentheses for the mean, high, low, the range of F0 values for each speaker*

Speaker	Gender	Dx	Mean F0	High F0	Low F0	F0 range
CS	M	R CVA	127.6 (4.3)	181.4 (14.8)	101.5 (5.9)	72.3 (13.3)
TD	F	R CVA	179.2 (22.3)	213.5 (15.4)	142.8 (8.9)	79.0 (16.4)
FL	F	L CVA	186.5 (12.4)	242.8 (6.5)	164.7 (9.4)	70.5 (18.4)
BL	M	L CVA	123.1 (16.6)	156.3 (8.4)	114.5 (5.4)	36.0 (17.2)
MB	F	L CVA	158.8 (9.7)	186.9 (4.7)	135.8 (7.4)	55.3 (18.4)
BT	M	L CVA	118.5 (9.8)	164.2 (13.5)	110.0 (10.6)	58.6 (13.2)
EB	F	PD	215.4 (16.8)	240.5 (10.2)	192.5 (6.8)	57.2 (17.1)
LW	F	PD	199.7 (18.4)	215.5 (12.5)	181.4 (8.1)	45.0 (6.9)
LA	M	PD	117.5 (13.1)	146.8 (11.4)	109.8 (10.0)	26.7 (16.1)
LB	M	PD	146.5 (9.8)	168.2 (9.7)	135.3 (4.1)	59.2 (14.6)
NG1	F		231.5 (16.1)	261.5 (13.2)	166.2 (16.8)	110.5 (16.4)
NG2	F		202.8 (11.4)	260.8 (16.7)	154.8 (16.7)	125.7 (17.2)
NG3	F		192.8 (21.5)	245.1 (12.5)	164.2 (21.7)	116.7 (13.7)
NG4	F		215.7 (5.1)	269.4 (5.2)	141.1 (18.4)	132.5 (11.8)
NG5	F		216.7 (7.8)	277.6 (6.5)	175.2 (26.4)	109.5 (16.2)
NG6	M		126.8 (15.2)	188.2 (6.4)	90.5 (16.4)	105.2 (17.4)
NG7	M		158.7 (16.2)	190.9 (13.7)	110.0 (14.3)	89.4 (13.9)
NG8	M		148.9 (9.8)	196.2 (13.4)	92.5 (12.6)	110.5 (17.2)
NG9	M		151.0 (13.4)	199.8 (9.5)	99.9 (13.7)	93.8 (11.7)
NG10	M		133.9 (21.1)	179.5 (13.6)	85.7 (6.9)	98.7 (13.4)

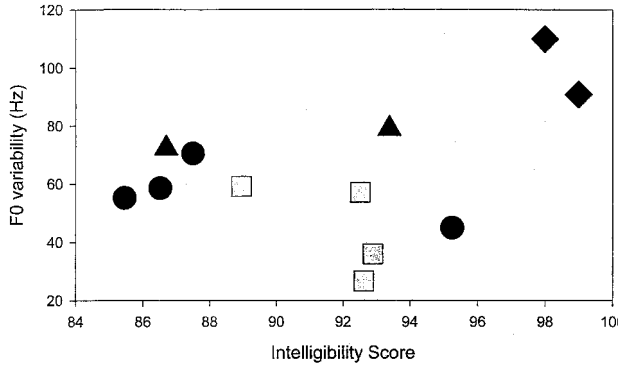

Figure 2. *Speech intelligibility scores plotted against natural F0 range for the three disorder groups and mean values for the NG male and female speakers (diamonds = NG, squares = PD, triangles = RCVA, circles = LCVA).*

Transcription data

Transcription scores were calculated by counting the number of words correctly recorded out of a total of 70. Results of the perceptual transcription task showed an expected decline in transcription score corresponding to the systematic decrease in the F0 range for the NG and CVA speakers (figure 3), although for the NG-M group the reduction in intelligibility was negligible. The PD speakers, on the other hand, showed a decrease in accuracy for the habitual utterances and 25% and 50% reduced F0 range utterances. The utterances with a flattened F0 contour, however, had higher transcription scores than those utterances resynthesized with reduced ranges. The flat F0 transcription scores were comparable to the speakers' habitual utterances. Plots of the frequency range and transcription scores are shown in figure 4 for individual speakers: the three panels of the figure each represent speakers with a different neurological diagnosis. In these panels the female speakers are shown as triangles and the male speakers as circles. The PD speakers (panel a) all showed an increase in transcription scores for flat F0 utterances compared to the tokens

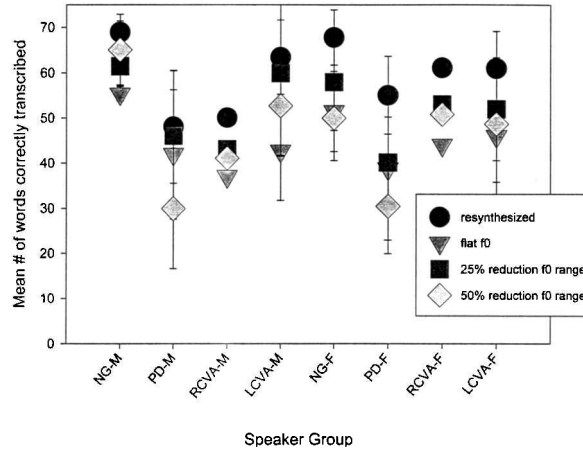

Figure 3. *Means and standard deviations on the transcription task for each speaker group across listeners. The total number of words possible was 70.*

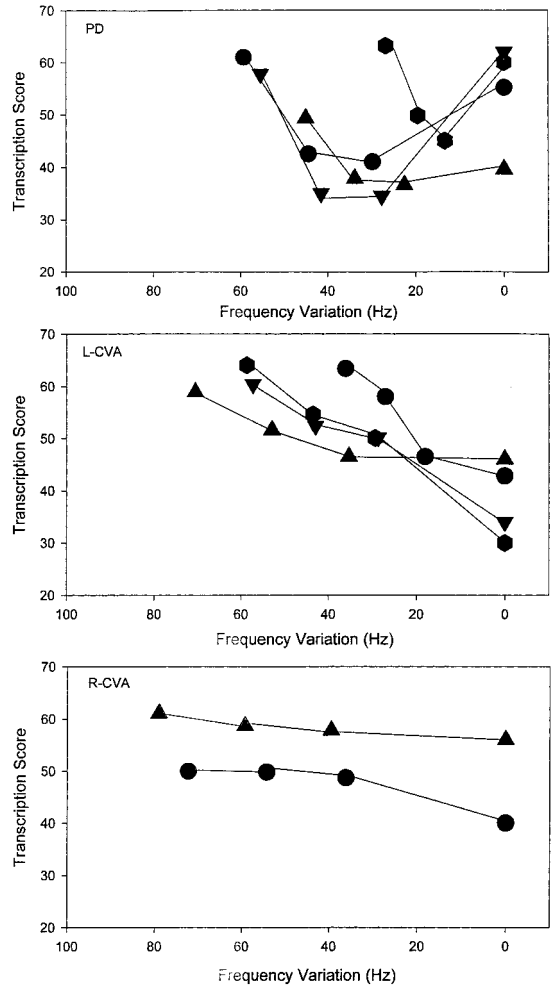

Figure 4. *Transcription scores plotted against F0 variation for individual speakers in the three disorder groups.*

with reduced F0 ranges. Results of non-parametric statistical analysis show significant differences between habitual utterances and range-reduced utterances for the PD speakers and between the habitual utterances and only flat F0 utterances for the other three speaker groups (table 3).

Scaling data

Results of the scaling task were similar to those found for the transcription task (figure 5), the listeners rated utterances with decreased or flat F0 contours as less intelligible or more difficult with scaling scores closer to 1. This is consistent with the decline in transcription scores, with the exception of the PD speakers. For the two female PD speakers there was little change in their scaling scores across the four resynthesis conditions, whereas for the male PD speakers there was a drastic fall in the scaling scores when F0 contours were reduced. This occurred despite

Table 3. *Results of non-parametric statistical analysis comparing the habitual utterances with the modified ones. A letter indicates a significant finding (T = transcription, S = scaling)*

Speaker Group		25% reduction	50% reduction	Flat F0
NG	M			T
	F			T
PD	M	T S	T	
	F	T	T	
RCVA	M			T
	F			T
LCVA	M			T
	F			T

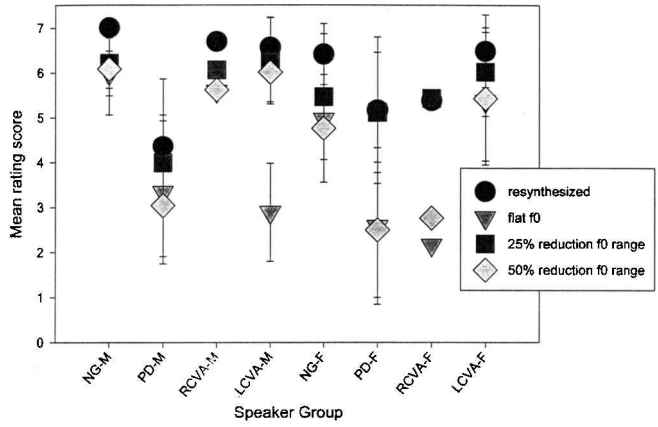

Figure 5. *Mean scaling scores for each speaker group across listeners. A 7.0 Lickert scale was used for this task.*

improvement in transcription scores when the F0 contour was flattened (figure 4). Plots of the F0 range versus scaling scores for individual speakers are shown in figure 6. Similar to the transcription plots, female speakers are represented as triangles and male speakers as circles.

Discussion

This study was designed to explore the relationship between F0 variability and intelligibility in persons with hypokinetic and UUMN dysarthria associated with PD and CVA, respectively. Results argue strongly for the perceptual importance of sentence-level F0 variations on speech intelligibility in the presence of segmental-level errors for both speaker groups. It appears that even though reduced F0 ranges were characteristic of the habitual utterances produced by the dysarthric speakers in the present study (table 2), the frequency information was an important perceptual component of the signal. Further flattening the F0 range using a resynthesis technique resulted in significant decreases in intelligibility for both groups as well as in the control speakers. In the control group decreased intelligibility scores were also seen as the F0 was compressed, however, the effect on overall sentence intelligibility was roughly half that of the disorder groups (figure 3). The mean decrease in transcription

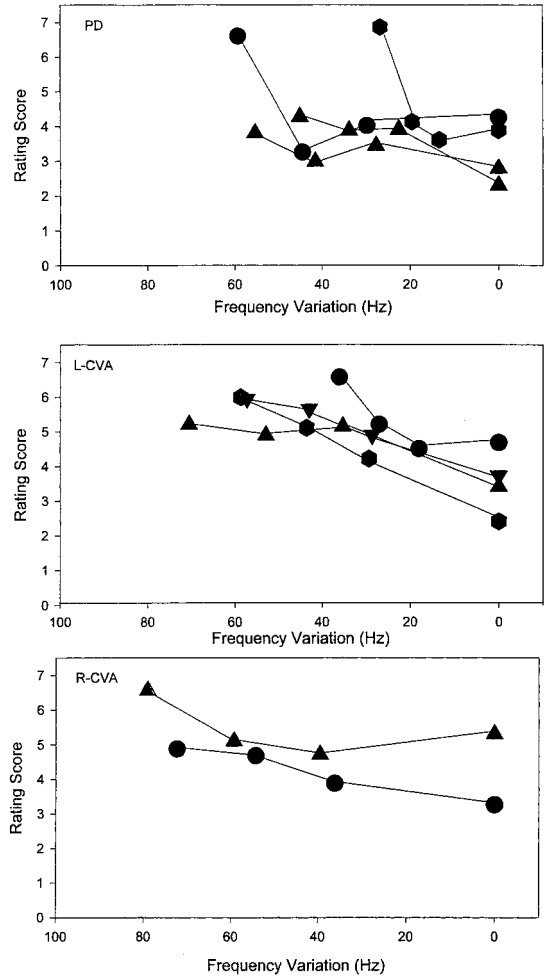

Figure 6. *Scaling scores plotted against F0 variation for the three disorder groups.*

score for the NG-M and NG-F groups were 8.6 and 16.4 words, respectively, whereas the decrease for the CVA groups were between 21.7 and 27.1 words. Comparing the right and left CVA groups, lower transcription scores were found for left versus right although the difference was not statistically significant.

One question guiding this experiment was whether or not there was a critical amount of F0 variability below which speech intelligibility would decrease precipitously. Looking at the findings for the NG speakers in the present study, it does not appear that there is such a value. A continuous and gradual decrease in transcription scores was found as the frequency range was reduced. The same conclusion can be drawn for the CVA speaker groups; a systematic decline in transcription scores, which corresponded to the decreasing F0 range, was found even when the speakers exhibited segmental-level compromise that may have increased the difficulty of the task for the listener. Results for the PD speakers, on the other hand, were peculiar. These speakers showed a similar decrease in transcription scores compared to normal and CVA speakers, but when F0 information was removed entirely from the signal

their transcription scores improved to nearly what they were for their habitual productions (figure 4). One possible explanation for this finding could be that the artificially restricted frequency variability (seen in the 25% and 50% range reduction resynthesis) provided conflicting or ambiguous information within the signal increasing the listeners difficulty in understanding the sentence. This seems consistent with the lower scaling scores found during the second part of the experiment, especially for the two male PD speakers (figure 5). Another possible explanation is that because PD is a degenerative disease these speakers have adopted alternative or compensatory strategies to preserve speech intelligibility in the presence of other system limitations (e.g., ability to modulate F0). In the present case, temporal cues seem to be the most logical candidate and further investigation is warranted. In the utterances which did not contain any frequency information, perhaps listeners were able to successfully alter their perceptual strategies and use these 'exaggerated' duration cues to aid in their understanding of the utterances. For the utterances with artificially limited F0 variability (resynthesized with 25% or 50% range reduction) there may have been a mismatch between F0 and temporal information which resulted in lower transcription scores. Further analysis of a second dysarthria type, also the result of a progressive neurologic disease (e.g. ALS), may shed light on whether and how compensatory strategies are being used by these speakers to maintain speech intelligibility.

Results of the scaling task were consistent with the transcription task: reduction in the range of F0 variability corresponded to lower scaling scores reflective of increased difficulty or effort reported by the listeners. A regression analysis between the transcription scores and the scaling scores, however, showed a fairly strong relationship between the two tasks (figure 7). However, low values of inter- and intra-judge reliability raises questions about the ability of the listeners to perform this task and thus limit conclusions that can be drawn from these results.

It was hypothesized in the present study that in dysarthric speech, where acoustic representations of supraglottic articulation are likely to be deficient, the effect of flattening an F0 contour on speech intelligibility would be greater than for control

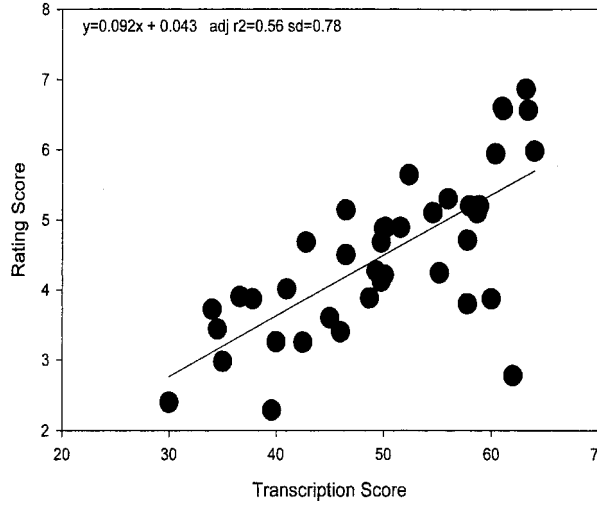

Figure 7. *Regression analysis for the transcription score versus scaling score across speakers.*

speakers who show no articulatory difficulties. Both the neurologically normal speakers and those with neurologic disease showed a decrease in transcription and scaling scores as the F0 range was reduced, however, the effect was larger for the speakers whose articulatory precision was compromised. Further, no critical amount of F0 variability was found, and it appears that syllable contrast resulting from even minor F0 variations is an important perceptual cue, thus contributing greatly to speech intelligibility.

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