The Effects of a Flattened Fundamental Frequency on Intelligibility at the Sentence Level

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The purpose of this preliminary experiment was to evaluate the effect of a flattened fundamental frequency (F_0) contour on sentence intelligibility. The perceptual dimension *monotone pitch* is frequently used to describe the speech of persons with dysarthria, and relatively flat F_0 contours have been noted in several acoustic studies of dysarthria. To determine the independent effect of a flattened F_0 contour on sentence intelligibility a resynthesis technique was used that held timing and spectral characteristics of utterances constant while allowing parametric control over successive pitch periods. Two male speakers produced low-probability utterances selected from the SPIN test, which were then resynthesized with a flattened F_0 contour. Speech intelligibility was assessed using two measures: one involving word transcription and the other interval scaling. These measures were collected from 10 listeners. The results showed that both measures were significantly lower when the F_0 contour was flattened, as compared with naturally varying contours. Several different explanations are proposed for this effect, which can and should be explored in greater detail using the resynthesis technique given the prominence of this characteristic in dysarthria.

KEY WORDS: fundamental frequency, speech intelligibility, prosody, dysarthria

Prosody is considered to be an important factor in spoken communication and has been the target of investigations in various research fields. The contribution of prosody to the comprehension of language has been studied from several perspectives, including its use in the recognition of spoken words and its relationship with syntax and discourse structure (Cutler, Dahan, & Donselaar, 1997). Although it is assumed that prosody plays an important role in the speech intelligibility deficit of dysarthria (and in other speech disorders: see Weismer & Martin, 1992), there is little experimental work in this area. There are, however, several observations in the literature suggesting that careful work is needed to understand the contribution of prosodic phenomena to speech intelligibility deficits.

Prosodic measures have been restricted to either separate acoustic or perceptual analyses or a combination of both to delineate dysarthric and normal speech production, differentiate dysarthria types, and characterize the severity level of dysarthria. Kent and Rosenbek (1982) provided an acoustic description of the prosodic disruptions found in ataxic, right hemisphere, and Parkinsonian dysarthrias. Monopitch was consistently noted as a perceptual descriptor of the utterances described by these authors; the underlying acoustic phenomenon was a flattened F_0 contour. Darley, Aronson, and Brown (1969) included prosodic disruptions in three of the deviant speech clusters utilized to classify types of dysarthria. Five of the seven neurologic disorders studied in their investigation were described as having prosodic insufficiency that included monopitch. With respect to severity, monopitch has been noted as the most frequent prosodic problem for individuals with dysarthria, with mildly dysarthric individuals presenting more monotonic speech than those with severe dysarthria (Schlenck, Bettrich, & Willmes, 1993). Additionally, severity of dysarthria has been found to be highly correlated with judgments of monotony in speakers with Parkinson disease (Kim, 1994).

Yorkston, Beukelman, and Bell (1988) argued that prosody is important in the perception of segmental information. This is a reasonable assumption given that F_0 has been implicated as an important perceptual cue to vowel identity (Traünmuller, 1981), stop consonant voicing (Haggard, Ambler, & Callow, 1970), syllable stress (Lehiste, 1970), and marking lexical boundaries (Liss, Spitzer, Caviness, Adler, & Edwards, 1998). Bunton, Kent, Kent, and Rosenbek (in press) reported that as the range of F_0 variability decreases in individuals with dysarthria, intelligibility also decreases. Similarly, increases in the speech intelligibility of individuals with dysarthria following biofeedback training for improvement of intonation, mean F_0, and speech rate have been reported (LeDorze, Dionne, Ryalls, Julien, & Quellet, 1992). In addition, prosody has been noted as an important factor in the teaching of speech to the hearing impaired. Speech of the hearing impaired is frequently characterized as having limited variation of F_0 (Sussman & Hernandez, 1979; cited in Maasen & Povel, 1984). Maassen and Povel (1984) demonstrated that intelligibility of the speech of the hearing impaired improved with computer-implemented correction of F_0 contours.

Although the literature suggests that a monotonic pitch may have detrimental effects on the intelligibility of speech among individuals with dysarthria (and other speech disorders), studies investigating the independent impact of a flat F_0 contour on speech intelligibility are sparse (for a review refer to Ramig, 1992). In particular, in developing an acoustic-phonetic model of speech intelligibility in dysarthria (Kent, Weismer, Kent, & Rosenbek, 1989), it would be of interest to know how much sentence-level F_0 fluctuation contributes to speech intelligibility deficits, independent of segment-level articulatory deficits. As a first step, there is need for an existence-proof of an independent effect of F_0 contour on speech intelligibility. Wingfield, Lombardi, and Sokol (1984), using a vocoder technique, demonstrated for a single speaker that utterances deprived of F_0 variation were less intelligible than utterances with normal prosody. In the present experiment, controlled utterances and LPC-based resynthesis of F_0 were used in an attempt to replicate and extend the findings of Wingfield et al. (1984). It is the purpose of this preliminary study to see if the speech intelligibility of selected speakers with no history of speech disorder is affected by flattening of an F_0 contour and, by implication, the associated perceptual phenomenon of monotonic pitch.

Method

Speakers

The speech samples were provided by two male participants with no known history of neurological disease affecting the speech mechanism. One older man, Speaker 1 (age: 80 years), and one younger man, Speaker 2 (age: 21 years), participated. Both were native speakers of English.

Listeners

Five women (mean age: 25.8 years) and 5 men (mean age: 23.8 years) participated in the listening portion of the main study. Listeners were native speakers of English with no self-report of hearing loss or professional training in speech sciences or experimental psychology.

Materials and Procedure

Each speaker read nine sentences selected from the Speech Perception in Noise (SPIN) Test (Kalikow, Stevens, & Elliot, 1977). The SPIN Test was designed to assess everyday speech reception in a competing noise environment. Sentences are classified as high or low predictability according to the predictability of the key word (the final word in the sentence) given contextual cues from the remainder of the sentence. Each sentence was produced once with habitual prosody and once with a somewhat exaggerated prosody. This was to ensure the existence of a clear difference between the range of fundamental frequencies covered in the original and flattened utterances ($\bar{X}$ = 143 Hz across somewhat exaggerated prosodic sentences; $\bar{X}$ = 68 Hz across habitual prosodic sentences; the typical F_0 ranges for the kind of simple declarative utterances produced for this experiment are approximately 70–150 Hz [Silverman, 1987; Kim, 1994]). The somewhat exaggerated prosodic sentences were used for resynthesis and throughout the listening portion of this experiment because of the larger range of fundamental frequencies characterizing their production. Each sentence within the present study was randomly chosen from those designated within the SPIN Test as having low predictability. The classification of low predictability was important to minimize the effect of context influencing responses of listeners during the transcription portion of the listening task. The stimulus material is listed in the Appendix. Each sentence was recorded direct-to-disc using a Realistic microphone and CSpeech, a computer program for recording, editing, and analyzing speech (Milenkovic, 1994). The resynthesis of the speech samples required a direct-to-disc technique to avoid the phase distortion associated with tape recording.

Synthesis of Speech Samples

The synthesis of the speech samples was produced using the Dx Program (Milenkovic, 1997). This program enables sentence level F_0 modifications that do not affect formant frequencies or speech timing. Each sentence was first resynthesized using the LPC synthesis technique before changing the F_0 contour. The mean F_0 across all voiced segments of each sentence was then computed. Following this, the F_0 contour of each voiced segment was flattened completely by changing all periods to match the mean F_0 of the sentence. The assumption is that a flat F_0 contour will result in a monotone perception. Spectrograms of selected original, resynthesized without flattening, and resynthesized flattened contour utterances are presented in Figure 1. A comparison of the formant frequencies and segment durations of each spectrogram reveals almost identical patterns. The process of synthesis and flattening leaves the filter function and timing of the original utterances essentially intact.

Listening Task

Each sentence was presented via a loudspeaker placed one meter away from the listener, who was seated in a sound-treated booth. A constant level of white noise was mixed with the speech signals to generate a noisy listening environment, thus avoiding ceiling effects in the response patterns. A S/N ratio was established by measuring the frequent peaks of speech at approximately 70 dB using a sound level meter at a distance of one meter from the loudspeaker. The noise level was set 4–5 dB below the frequent peaks of speech. The first listening section consisted of four sections, each comprising 18 sentences; the first 9 sentences were produced by Speaker 1 and the second 9 sentences were produced by Speaker 2. Each listener was provided with written and oral instructions for the tasks. Within the first portion of the listening task the listener heard the flattened F_0 sentences and transcribed them orthographically. Listeners were instructed to transcribe the words in the sentences as accurately as possible. During the second portion each listener was directed to assign a value of intelligibility to each flattened F_0 sentence on a 7-point, equal-appearing interval scale. For the purpose of the scaling part of the experiment, intelligibility was defined for the listeners as the ease with which the spoken words were understood, with 1, 4, and 7, defined as 0%, 50%, and 100% intelligible, respectively. The third and fourth portions followed the same procedure; however, in this part of the experiment listeners transcribed and scaled the original utterances. The utterances produced by Speaker 2 were randomized differently between the flattened and original utterances and differed from the utterance sequence of Speaker 1.

Additional Listening Conditions

Two additional listening conditions tested the potential confounding effects of the quality of synthesis and stimulus order upon intelligibility scores. To measure the impact of the synthesis quality on the transcription scores and intelligibility scale values, two listeners (one male, one female) not included in the main listening group listened to the resynthesized version of the sentences produced by the older male speaker before the modification of the F_0 contours. As in the main experiment, sentences were presented in competing white noise at a signal-to-noise ratio of 4–5 dB. To examine possible learning effects that were due to the fixed order of presentation of flattened utterances followed by original utterances, 10 additional listeners (5 female, 5 male), who met the same inclusion criteria as the listeners in the main experiment, transcribed and scaled just the original utterances under signal-to-noise conditions and presentation orders replicating those previously described.

Data Analysis

Analysis of the data was completed by calculating and averaging the number of correctly transcribed words. A word was scored as correct when it was transcribed orthographically exactly as it was intended by the speaker (i.e., when it matched the orthographic rendition read by the speaker). Scaled values for each utterance were also averaged across listeners. The nonparametric Friedman test was used to separately analyze the word transcription and scaling data.

Results

Acoustic Characteristics of the Speakers

A comparison of the spectrograms of the two speakers suggested a difference in total utterance duration, indicating that one speaker had a slightly faster speaking rate. This appears to be confirmed by the data in

Figure 1. Spectrograms and waveforms for *She has known about the drug* produced by the older male participant. Top: Original. Middle: Resynthesized without flattening. Bottom: Resynthesized with flattening. The frequency calibration lines are at 1000 Hz intervals; the time interval between hash marks on the x axis = 100 ms.

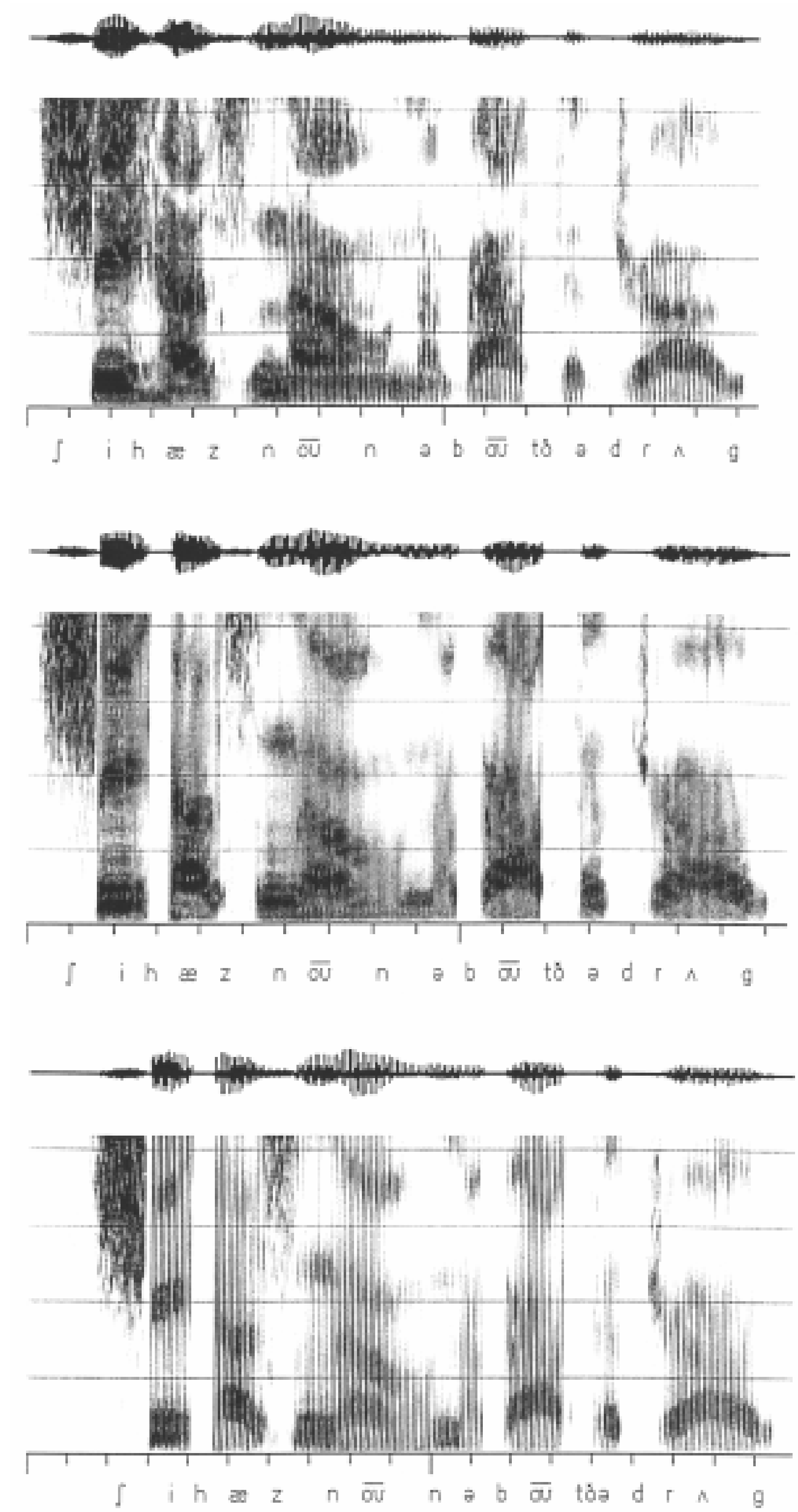

Table 1, which shows that Speaker 2 tended to produce longer vocalic segments than Speaker 1. The habitual F_0 of Speaker 2 also tended to be higher than the F_0 of Speaker 1, as illustrated in Figure 2. Thus the flattened utterances of Speaker 1 and Speaker 2 had different F_0 characteristics, although within a speaker the F_0 was the same for all flattened utterances.

Transcription and Scaling Data

Figure 3 plots the average number of correctly transcribed words as well as average scale values for the original and flattened utterances, with speaker as the parameter. The total words produced by each speaker was 53 per condition. The average number of correctly

Table 1. Selected vocalic durations (in ms) from two of the utterances used in the current investigation. Vocalic segments are indicated by italics in the orthographic rendering of the sentences.

Vocalic segment	Older speaker	Younger speaker
The *ol*d man discussed the d*i*ve.		
/ol/	125	226
/æ/	212	177
/aɪ/	162	241
She has kn*ow*n ab*ou*t the d*ru*g.		
/o/	110	183
/aʊ/	110	135
/rʌ/	145	153

Figure 2. Waveforms and F_0 contours produced by the younger (top) and older (bottom) speaker for the same utterance shown in Figure 1. The F_0 contours are shown with the uncorrected errors (the large increments, typically seen at consonant-vowel interfaces), but the smooth parts of the contours show the F_0 difference between the younger and older speaker.

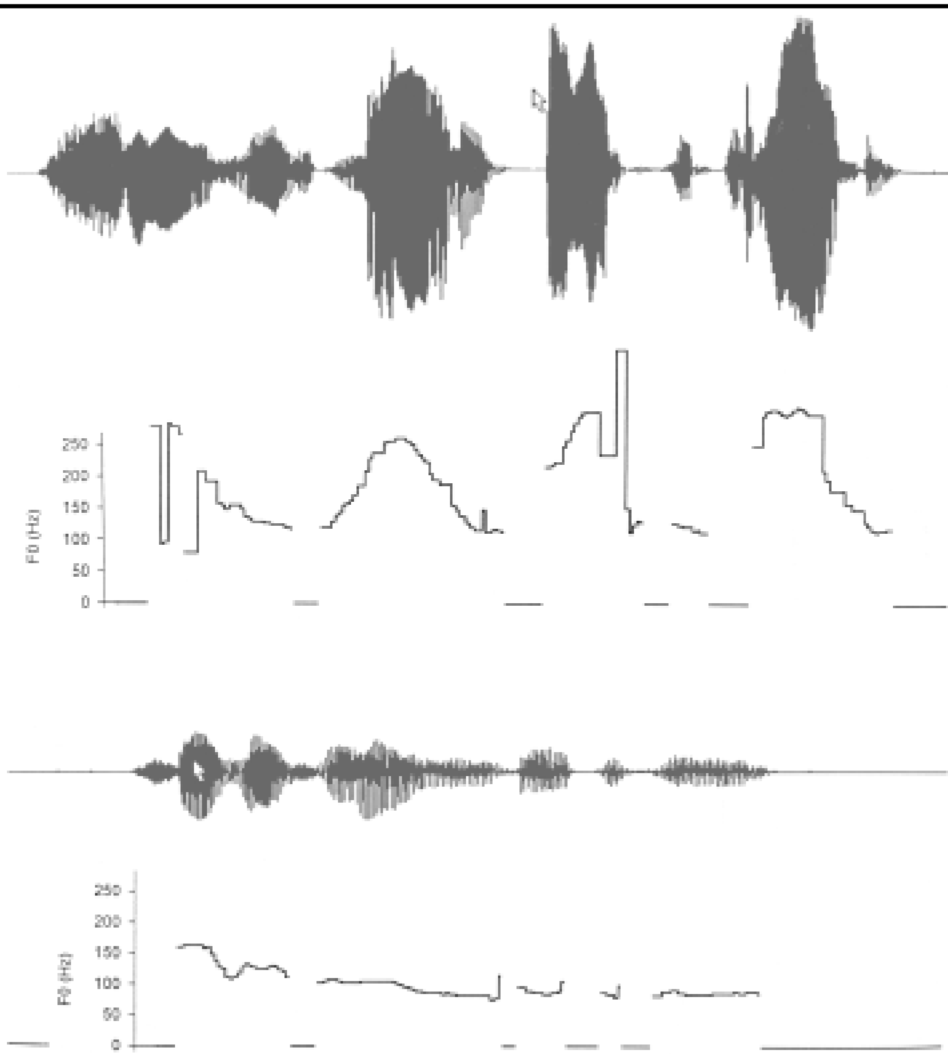

Figure 3. Average number of correctly transcribed words (top) and average scale values (bottom) for both utterance types (original and flattened), with speaker (filled circles = younger speaker, open circles = older speaker) as the parameter.

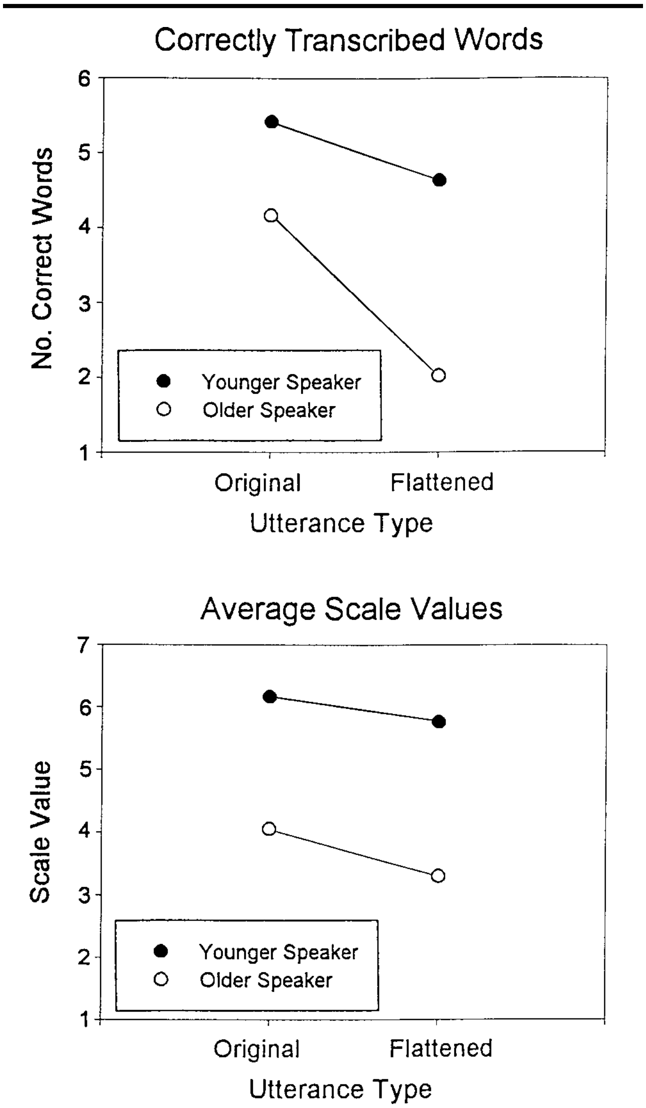

Table 2. The average number of correctly transcribed words as well as average scale values for the original and flattened utterances. Values in parentheses represent standard deviations.

Utterance type	Words	Scaling
	Speaker 1	
Flattened	2.02 (1.79)	3.30 (1.71)
Original	4.17 (1.65)	4.04 (1.72)
	Speaker 2	
Flattened	4.64 (1.11)	5.78 (.83)
Original	5.41 (.82)	6.17 (.77)

transcribed words per sentence (average maximum = 5.88 words) independent of listeners' gender (the effect of gender of listeners on correctly transcribed words [$t(358) = -1.18$, $p > .05$] and scale values [$t(358) = .71$, $p > .05$] was not significant) is displayed in Table 2. These results show that the original utterances and Speaker 2 produced more correct words and higher scale values than the flattened utterances and Speaker 1, but within each speaker the flattening effect was the same. The Friedman test showed significant effects for speaker [transcription: $\chi^2(1, 179) = 89.29$, $p < .05$; scaling: $\chi^2(1, 179) = 143.40$, $p < .05$] and utterance type [transcription: $\chi^2(1, 179) = 83.90$, $p < .05$; scaling: $\chi^2(1, 179) = 27.00$, $p < .05$].

Interjudge Reliability

Interjudge reliability of scaled values revealed a mean standard error of $\bar{X} = .453$, Speaker 1, original; $\bar{X} = .497$, Speaker 1, flattened; $\bar{X} = .245$, Speaker 2, original; $\bar{X} = .206$, Speaker 2, flattened. The interjudge mean standard errors were computed by obtaining the standard errors for each sentence across the 10 listeners and then averaging these across sentences. Additionally, a Spearman's correlation matrix for pairwise combinations of the 10 listeners produced significant correlations ranging from .439 to .874, with a median correlation of .661. Interjudge reliability of correctly transcribed words revealed mean standard errors of $\bar{X} = .393$, Speaker 1, original; $\bar{X} = .453$, Speaker 1, flattened; $\bar{X} = .161$, Speaker 2, original; $\bar{X} = .249$, Speaker 2, flattened. The Spearman correlation matrix for pairwise combinations across the 10 listeners showed a range of .330 to .870, with a median correlation of .711.

The combination of averaged standard errors that are generally less than the reported significant effects, plus the significant pairwise correlations with modestly high median correlations, suggests a fair degree of agreement among the listeners.

Synthesis Quality and Evaluation of a Possible Learning Effect

It is possible that the quality of synthesis may have been a factor in the decreased intelligibility of the flattened utterances. However, comparing the average correct words transcribed ($\bar{X} = 4.22$) and scale value ($\bar{X} = 5.06$) in a subsequent listening task to the averages reported above and displayed in Figure 3 for the original utterances (transcription, $\bar{X} = 4.17$; scaling, $\bar{X} = 4.04$) in the main experiment, it appears that the synthesis had little impact on the transcription data and actually resulted in an increased scale value. This suggests that there was a true effect of the F_0 flattening on the ability of the listeners to recover the words in the sentences and to provide a global scale value for the construct "intelligibility."

Because listeners always heard the original utterances after the flattened utterances, it is conceivable that the reported effects represent an inflation of the transcription and scaling scores for the original utterances merely as a result of hearing and learning the sentence material in the flattened set. Such a learning effect would be demonstrated if scores for the second group of 10 listeners, who heard only the original utterances, were significantly worse than scores for the original utterances from the main experiment. However, the average correct words transcribed and the average scale values (see Table 2) of the main experiment were lower than the averages for this second group of listeners [transcription, $\bar{X}$ = 4.82 (*SD* = 1.27), Speaker 1; $\bar{X}$ = 5.56 (*SD* = .82), Speaker 2; scaling, $\bar{X}$ = 5.37 (*SD* = 1.01), Speaker 1; $\bar{X}$ = 6.63 (*SD* = .55), Speaker 2]. Additionally, the percentage of words correctly transcribed from the original utterances in this experiment and the main experiment ranged from 81 to 88%, which is comparable to the approximately 80% intelligibility for words in sentences at a signal-to-noise ratio of 4–5 dB found by Miller, Heise, and Lichten (1951). This suggests that in the main experiment the scores of the original utterances were not inflated and F_0 flattening had a real effect on speech intelligibility.

Discussion

This experiment was designed to study the effect of flattened F_0 contours and, by implication, monotonic pitch on sentence-level speech intelligibility produced by normal speakers. The results indicated that a flattened F_0 contour decreases intelligibility both in terms of listeners' scaled ratings and transcription accuracy. These results are consistent with the findings of Wingfield et al. (1984), even though there are substantial differences between the two experiments. Wingfield et al. (1984) used a vocoder to flatten F_0 contours, whereas the present technique used an LPC-based resynthesis technique to modify the F_0 contour. In addition, listeners in Wingfield et al. (1984) heard a connected discourse and reported what they heard after substantial stretches of speech material. This suggests a memory component in the response patterns reported by Wingfield et al. (1984) that may be differentially affected by the reduced quality of the flattened utterances (e.g., see Duffy & Pisoni, 1992). Nevertheless, even when relatively simple utterances are used and when alternate measures of intelligibility are obtained, the effect of a flattened F_0 contour seems to remain. The present results, when taken with those of Wingfield et al. (1984), argue strongly for careful consideration of why the integrity of sentence-level F_0 variations might contribute to speech intelligibility. Several potential explanations are offered here.

An explanation for the effect of a flattened F_0 on intelligibility is derived from the work of Cutler and Foss (1977). Their investigation supports the hypothesis that suprasegmentals are crucial to sentence comprehension. The rise and fall of the F_0 contour directs the listener's attention to the content words of an utterance, which are typically stressed. The location of words that are more highly stressed are predicted by the form of the preceding F_0 contour and therefore receive higher processing priority, resulting in better comprehension. This suggests that if the F_0 contour is flattened, the listener would have more difficulty comprehending high-content components of an utterance because an important cue to their location has been deleted. The results of Cutler and Foss (1977) may also be applied to the observation within the present study that there were a large number of errors on the final word of each sentence. The final word in each sentence is a content word, which in the case of the flattened F_0 sentences would not have the benefit of the predictive acoustic cues demonstrated by Cutler and Foss (1977).

Any modification of the speech signal that reduces the contrast between adjacent units may have the potential to reduce the salience of acoustic cues to segment identity and, hence, intelligibility. Kent and Rosenbek (1982) found that perception of speech is affected by a disruption of the F_0 contour and temporal dimensions. They reported that natural flattening of the F_0 contour, associated with various motor speech disorders, contributes to a decrease in acoustic contrasts, resulting in a more distorted signal. The dysarthrias studied within their experiment showed only a small and gradual variation of F_0 across syllables in conjunction with limited variation among syllable durations. The natural flattening of the F_0 may have contributed to a decrement in the acoustic contrast between syllables and resulted in decreased intelligibility. Relatedly, Rietvald and Gussenhoven (1987) proposed that frequency contour and speech rate are interdependent. They demonstrated that utterances without tonal boundaries are perceived as possessing a faster rate. This is a consideration with respect to the present study in that the perceived rate of the flattened contour sentences may be increased and thus lead to decreased speech intelligibility. Experiments are needed that address the effects on speech intelligibility of independent manipulations of speaking rate and F_0 contour.

A further explanation for the present findings follows the sufficient contrast hypothesis (Ryalls & Lieberman, 1982). This hypothesis presupposes that vowel intelligibility is reduced at higher F_0s because the formant peaks are undersampled by the relatively wide spacing between source harmonics. Diehl, Lindblom, Hoemeke, and Fahey (1996) found that higher F_0s hinder identification of certain vowel categories because of poorer definition of spectral envelopes. Previous research reviewed by Weismer and Martin (1992) shows that vowels contribute significantly to speech intelligibility. A flat F_0 maintains a constant harmonic spacing within formant peaks, whereas a changing F_0 would increase the density of harmonics within a formant peak. Assuming that the spectral envelope was undersampled for the vowels within the current stimuli because of flattening of the F_0 contour, overall intelligibility could be affected because of decreased vowel identification. One way to address this would be to take known perceptual vowel errors in dysarthric speech (e.g., as demonstrated in Kent et al., 1989) and to see if local (i.e., at the segment level), resynthesized changes in F_0 contour would make a difference in vowel error rates. If the results of Diehl et al. (1996) have application to vowel perception in dysarthric speech, vowels with a natural, relatively flat F_0 characteristic should produce more errors than the same vowels with a resynthesized, time-varying F_0. The current resynthesis technique allows fine, local manipulation of F_0 contour properties and could be used to address this hypothesis.

In conclusion, the results of this investigation indicate that sentence-level speech intelligibility of utterances produced by non-neurologically impaired individuals can be decreased by flattening the F_0 contour. This demonstration is of interest because of the frequent occurrence of relatively flat F_0 contours in dysarthria and the possibility that this contributes to speech intelligibility deficits in this population. In the present study, these effects were shown with a speech signal having good acoustic representations of supraglottal articulation. The older speaker in the present study was less intelligible than the younger speaker, but this finding should not be taken as a demonstration of an age effect because of the absence of multiple speakers within the age groups; the same effect of F_0 flattening in two different speakers should rather be regarded as a replication of the effect. There are various interpretations of these findings that suggest certain avenues for further research. Subsequent investigations should include a larger group of speakers representing both genders. Additionally, the present experiment used white noise to decrease ceiling effects. It may be of interest to use other competing noise, such as multi-talker babble.

The current experiment is primarily of heuristic value in proposing a global effect of F_0 contour on speech intelligibility; these results and those of Wingfield et al. (1984) serve as the existence proof called for in the introduction. Some of these effects were small, though statistically significant, but the replication of the flattening effect with two different estimates of intelligibility points to the importance of the phenomenon. It could be hypothesized that in dysarthric speech, where the acoustic representations of supraglottic articulation are likely to be deficient, the effect of a flattened F_0 contour on speech intelligibility would be even greater. Several potential explanations for the current findings are offered and have relevance to the relationship between speech acoustics and speech intelligibility among dysarthric speakers.

Acknowledgments

This work was supported in part by R01 DC00319 and T32 DC00042. The authors would like to thank Kate Bunton for reading and commenting on an earlier version of the manuscript; in addition, we thank JD and SGW for serving as speakers.

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Received March 9, 1999

Accepted April 12, 1999

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Appendix

Stimulus Sentences:

1. The old man discussed the dive.
2. They're glad we heard about the track.
3. You're glad they heard about the slave.
4. Mr. Smith knew about the bay.
5. I'm talking about the bench.
6. Tom has not considered the glue.
7. Ruth's grandmother discussed the broom.
8. She has known about the drug.
9. He's thinking about the roar.