

# CONTROLLED VARIABLES IN SENTENCE INTONATION\*

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## INTRODUCTION

In describing the acoustic characteristics of sentence intonation, the terms *downdrift* and *declination* have been applied to the behavior of both the rapid variations in fundamental frequency ( $F_0$ ) corresponding to syllable prominences whose peaks comprise the envelope of an  $F_0$  contour (see, for example, Cooper & Sorenson, 1981), and the slower variation in  $F_0$  that defines a reference level upon which these local prominences are superimposed (see, for example, Cohen, Collier, & 't Hart, 1982). Recently, there has been considerable interest in the mental representation of various aspects of declination (Breckenridge, 1977; Cooper & Sorenson, 1981; Liberman & Pierrehumbert, 1982; Pierrehumbert, 1979) and, by extension, the control or regulation of the physiological variables involved in its realization (Atkinson, 1973; Collier, 1975; Gelfer, Harris, Collier, & Baer, 1985; Maeda, 1976). Unfortunately, cognitive processes are not readily observable. However, to the extent that they are expected to have some *physical* reality, examining the patterns of control of the physiological processes that ultimately bear on the acoustic aspects of sentence intonation should provide some insight into the *psychological* reality of declination.

In the first part of this paper, we will examine the behavior of subglottal pressure ( $P_s$ ) during speech in order to determine whether the time course of the drop in subglottal pressure associated with declination is a controlled variable in sentence intonation, or, alternatively, the passive consequence of lung deflation. Obviously, the rate at which air is used in producing speech depends on the phonetic characteristics of utterances (Klatt, Stevens, & Mead, 1968). For example, because of the reduced airflow resistance at the glottis and the configuration of the vocal tract for a voiceless fricative, substantially higher airflow rates occur for utterances containing the syllable /fa/ than for those containing syllables composed of voiced continuants, such as /ma/. If the lungs were allowed to deflate passively, we would expect subglottal pressure to decline at different rates over the course of these syllables. However, there is evidence indicating that lung deflation during speech is not a purely passive phenomenon. For example, Draper, Ladefoged, and Whitteridge (1960) and Mead, Bouhuys, and Proctor (1968) found subglottal pressure to be stable throughout sustained voice production, thus suggesting that the muscles of the respiratory system are marshalled in such a way as to maintain  $P_s$ . However, these studies have examined only sustained phonations of constant amplitudes that also require constant pressures. On the

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other hand, subglottal pressures during speech are known to vary dynamically. What we do not know, then, is whether the variation in pressure over time is the natural by-product of unchecked expiratory forces, or whether it reflects ongoing control of the respiratory musculature in order to produce dynamically stable pressures. By using reiterant speech (Kelso, V-Bateson, Saltzman, & Kay, 1985; Larkey, 1983) in which a sentence is mimicked with a high flow syllable, “fa,” or a low flow syllable, “ma,” we can discover whether the time course of pressure variation is the by-product of unchecked expiratory forces, or whether it is dynamically stable. Moreover, to the extent that  $F_0$  mirrors  $P_s$ , we can perhaps gain insight into the factors responsible for declination itself.

In the second part of this paper, we will address the phenomenon known as  $F_0$  resetting. It has been suggested that the declination function is sensitive to the syntactic structure of an utterance. Thus, in a two-clause utterance, the  $F_0$  contour may be discontinuous at the major syntactic boundary so that a single falling contour no longer characterizes the declination function (Cooper & Sorenson, 1981; Fujisaki & Hirose, 1982; Maeda, 1976). However, there is some question as to which aspect of the  $F_0$  trajectory actually defines resetting in these instances. For example, Fujisaki and his colleagues (Fujisaki & Hirose, 1982; Fujisaki, Hirose, & Ohta, 1979) have developed a model of intonation that allows for two basic inputs, the phrase level and accent level commands, which are realized as the ‘voicing’ (baseline) and ‘accent’ (syllabic) components, respectively. According to this model, it is the voicing component that may be reset at clause boundaries, while the accent components vary independently of the baseline, and, therefore, independently of syntactic structure.

Cooper and Sorenson (1981) suggest, too, that declination is reset at clause boundaries in a way that is relevant to the syntactic structure of an utterance. However, in contrast to Fujisaki, they measure declination, and thus gauge resetting, on the basis of the relationship of syllable peaks; specifically, the height of the first peak in a second clause to that of a sentence-initial peak. Furthermore, they suggest that the resetting of peak  $F_0$  directly mirrors a speaker’s intention to signal the syntactic structure of the sentence, and that resetting is planned in some detail at the outset of an utterance. While we recognize that there is an interaction between syntax and the realization of sentence intonation, we hypothesize that the *extent* to which  $F_0$  is reset is *not* planned prior to the execution of an utterance even if the presence or absence of resetting may be planned. Fujisaki has suggested that resetting is triggered when a significant pause occurs at the clause boundary. Taking this notion a step further, we would suggest instead that it is not only the pause but also the new inspiration that may accompany it that in turn influences  $F_0$  indirectly through the resetting of such variables as subglottal pressure and/or laryngeal muscle activity. Thus, we hypothesize that  $F_0$  resetting will depend on the presence or absence of a pause and inspiration at clause boundaries.

## METHODS

Two speakers served as subjects for the first part of this study, and one of the two served as a subject for the second. Both are native speakers of Dutch, fluent in English, and both were aware of at least some of the purposes of this work. They were chosen as subjects primarily because of their willingness, and ability, to tolerate the invasive procedures required.

Lung volume was inferred from the calibrated sum of thoracic and abdominal signals from a Resptrace inductive plethysmograph, and airflow rate (cc/sec) was derived from calculations of

volume over time. Subglottal pressure was recorded directly, but differently, for the two subjects, RC and LB. For RC, a pressure transducer (Setra Systems 236L) was coupled to the subglottal space by means of a cannula inserted percutaneously through the cricothyroid membrane. For LB, a miniature pressure transducer (Millar SPC-350) was introduced pernasally through the posterior glottis into the trachea. While the percutaneous approach is certainly the more invasive procedure, it provides a signal that is easier to calibrate, because the miniature transducer cannot be calibrated outside the body, and it is highly sensitive to changes in temperature that occur within the trachea upon inspiration (Cranen & Boves, 1985). Unfortunately, we did not recognize these difficulties at the time of recording, so that the pressure signal could not be calibrated properly. However, while absolute values for the pressure data for the subject using this device are uninterpretable, the relative pressure levels should be valid, since temperature changes affect the zero offset but not the sensitivity of the transducer. For both subjects, EMG techniques previously described (Harris, 1981) were used to record from the cricothyroid muscle. Fundamental frequency was derived from the output of an accelerometer (Stevens, Kalikow, & Willemain, 1975) attached to the pretracheal skin surface. For LB, a cepstral technique was used to extract  $F_0$  from the signal. For RC, the accelerometer output was sampled using a Visipitch period-by-period  $F_0$  extractor. This latter procedure is equal in accuracy to the former  $F_0$  extraction technique, but has the advantage of on-line sampling at one-half real time. However, it became available to us only after the data for the first subject had been analyzed.

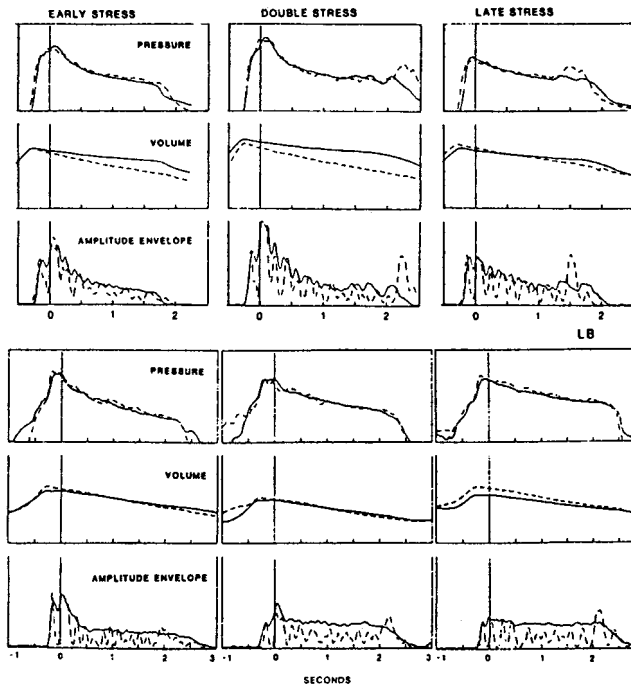
### Stimuli

In the first experiment, the two subjects produced reiterant forms of Dutch utterances, using the syllables /ma/ and /fa/ (Appendix A). These utterances were also produced in three lengths, with three different emphatic stress configurations (early, double, and late). Thus, there were nine utterance types per reiterant condition (i.e., /ma/ or /fa/). However, the stress and length conditions will not be discussed separately here, except to be noted in the examples shown, because the differences among them have been discussed previously (Gelfer et al., 1985).

In the second experiment, one of the subjects, RC, produced three similar English sentences. For two of the sentences, the syntactic boundary was moved in order to alter slightly the length of each clause. The third sentence conjoined two clauses similar to those comprising the first two sentences (Appendix B). The subject's task was to produce each sentence under two conditions: no pause and no inspiration at the clause boundary, and both a pause and an inspiration at the clause boundary.

## RESULTS: EXPERIMENT 1

Averaged subglottal pressure, lung volume, and the amplitude envelope for utterances of Length 2 with various emphatic stress configurations are shown for both subjects in Figure 1. It is apparent from this figure that, for the subglottal pressure, there is little difference between the /ma/ and /fa/ utterances apart from the presence of local perturbations in the curve of the /fa/ utterances. The acoustic amplitude envelopes of the two reiterant utterance types show no substantial difference in overall acoustic amplitude, and, as would be expected, resemble the subglottal pressure contours in overall shape. However, despite the uniformity of the pressure curves, the lung volume curves for the two utterances show the change in volume over time to be



**Figure 1.** Averaged subglottal pressure (panel 1), Respirtrace (panel 2), and amplitude envelope (panel 3) curves for comparable /ma/ and /fa/ utterances for subjects RC (top) and LB (bottom). The vertical line in each panel denotes the line-up point used for averaging the tokens of each utterance type, which in these utterances is the onset of the vowel for the first syllable receiving lexical stress. The solid curves represent the reiterant /ma/ utterances, and the dashed curves the reiterant /fa/ utterances. The maximum and minimum values for pressure on the y axis are 13 cm H<sub>2</sub>O and 0 cm H<sub>2</sub>O for RC, 9 cm H<sub>2</sub>O and -6 cm H<sub>2</sub>O for LB. For respiratory valence, values range from 5 liters to 2 liters for RC, and from 5 liters for 1 liter for LB. The audio amplitude is in arbitrary units.

greater for the /fa/ utterances, as is evidenced by the steeper slopes. Thus, for both subjects, we observe no apparent relationship between airflow rate and the  $P_s$  contours.

In order to quantify these data, we plotted the distributions of subglottal pressures and airflow rates for the two utterance types. For subglottal pressure, we measured average levels over a fixed time interval, rather than differences over time, in order to neutralize any segmental effects. Since our earlier work demonstrated that effects of such variables as sentence length are reflected in initial peak pressure values (Gelfer et al., 1985), we were careful to eliminate these portions of the curves from the measured interval. By calculating the averages over an interval of 600 ms, from 400 to 1000 ms, after the occurrence of the first lexically stressed syllable, we were able to avoid averaging values under these peaks, at the same time being able to include data from some of the shortest utterances.

The same interval was used to calculate the change in lung volume over time. However, because the Respirtrace curves are rather smooth and not prone to perturbation due to segmental effects, we calculated the difference in volume between the two points in order to derive the rate of decline (i.e., airflow rate).

The distributions of  $P_s$  measures for all tokens of the /ma/ and /fa/ utterances are shown in Figure 2. The difference between the means of these distributions is statistically nonsignificant:  $p > .2$  for RC;  $p > .5$  for LB. By contrast, the difference in airflow rate for the /ma/ and /fa/ utterances (Figure 3) is statistically significant for both subjects,  $p < .001$ . Thus,  $P_s$  appears to remain stable despite the significant differences in airflow secondary to the phonetic structure of these utterances.

## RESULTS: EXPERIMENT 2

In this experiment, Subject (RC) produced three two-clause utterances under conditions where pausing and inspiration were directly manipulated. In the first condition, he produced each repetition of each utterance with neither a pause nor inspiration at the clause boundary. In the second condition, all tokens were produced with both a pause and inspiration at the clause boundary.

Figure 4 shows the averaged Resptrace and  $P_s$  curves for one sentence across the two conditions being considered here (i.e., -pause/-inspiration and +pause/+inspiration). This general picture is identical across sentence types, so we will present graphic displays only for one sentence.

In the absence of both a pause and inspiration at the clause boundary in the first condition (Panel 1), there is a continuous, although choppy, subglottal pressure curve throughout both clauses and across the intervening boundary as well. On the other hand, where both a pause and inspiration occur (Panel 2), there is a concomitant drop in the subglottal pressure during the inspiration, which then increases significantly as expiration resumes.

Despite the differences in pause durations and respiratory activity, the subject produced the same general  $F_0$  contours across conditions (Figure 5). For our analyses,  $F_0$  values were measured for the first peak in the first clause (peak 1A), the last peak in the first clause (peak 1B), and the first peak in the second clause (peak 2A) for the five tokens of each of the three sentences under each condition.

Figure 6 is a schematic representation of the average values, collapsed across sentence type, for each condition. It can be seen that, while the  $F_0$  values for the two peaks (1A and 1B) in the first clause are strikingly similar across conditions, the value of the first peak in the second clause (2A) varies systematically as a function of the pausing/breathing condition at the clause boundary. That is, where there is no pause or inspiration,  $F_0$  falls 8 Hz below those peaks that were preceded by an inspiration (Table 1). This difference is statistically significant as well,  $p < .001$ .

A comparison of  $P_s$  values at peak 2A yields corresponding results. That is, subglottal pressure is significantly higher when a pause and inspiration occur than when they do not,  $p < .001$ . Moreover, when the ratio of frequency change per centimeter of water is calculated for peak 2A between conditions 1 and 2, these ratios fall within the accepted range of 3-7Hz/Cm-H<sub>2</sub>O (Baer, 1979; Hixon, Klatt, & Mead, 1971; Ladefoged, 1963), suggesting that the relationship between the increase in  $P_s$  and that in  $F_0$  could be more than a correlational one. However, before the behavior of  $F_0$  is attributed to the presence or absence of an increase in  $P_s$ , the contribution of laryngeal muscle activity must be determined.

Figure 7 shows the cricothyroid muscle activity for the two conditions for the same sentence. It appears that there is no systematic resetting of CT activity as a function of inspiration at

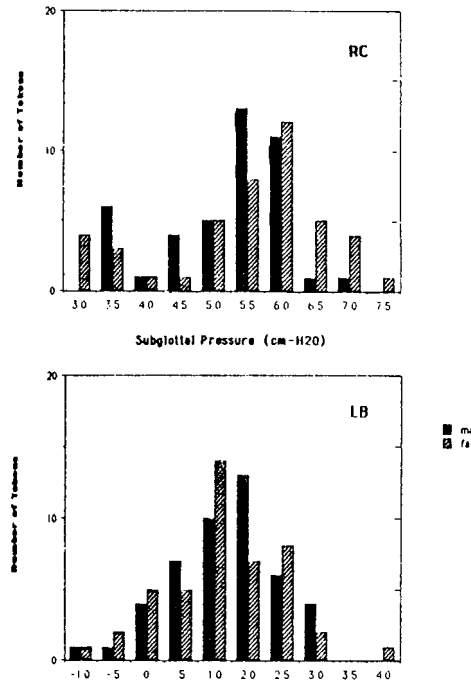


Figure 2. Distribution of  $P_s$  averages for tokens of all /ma/ and /fa/ utterances for both subjects. The solid bars denote the /ma/ tokens, and the dashed bars the /fa/ tokens.

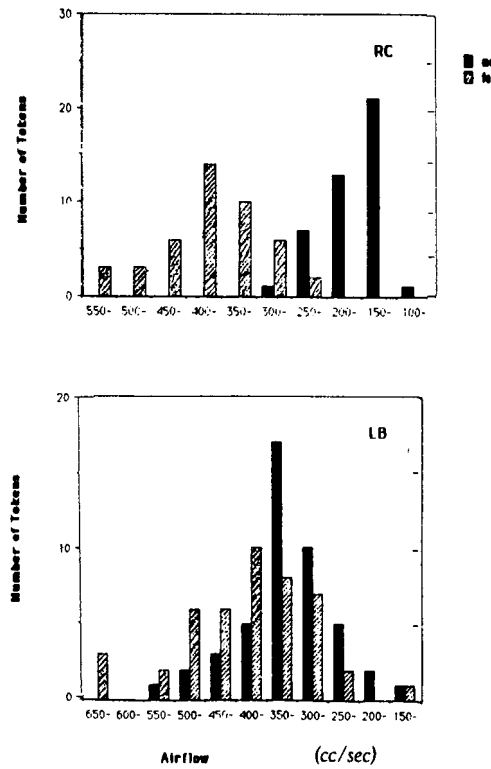
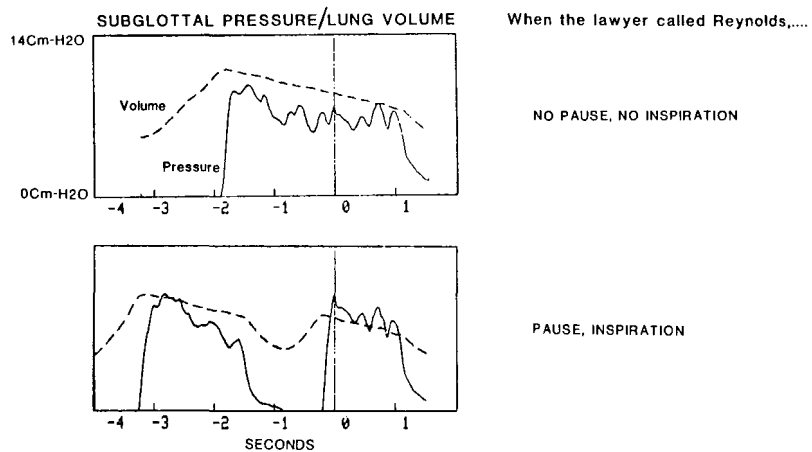
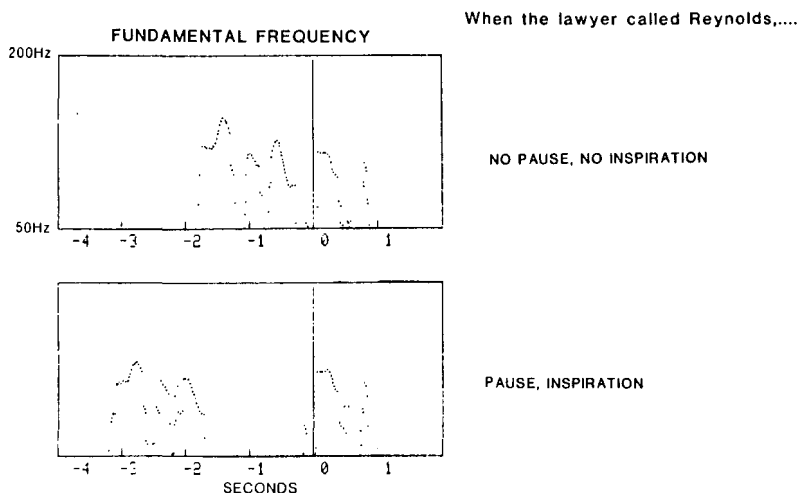


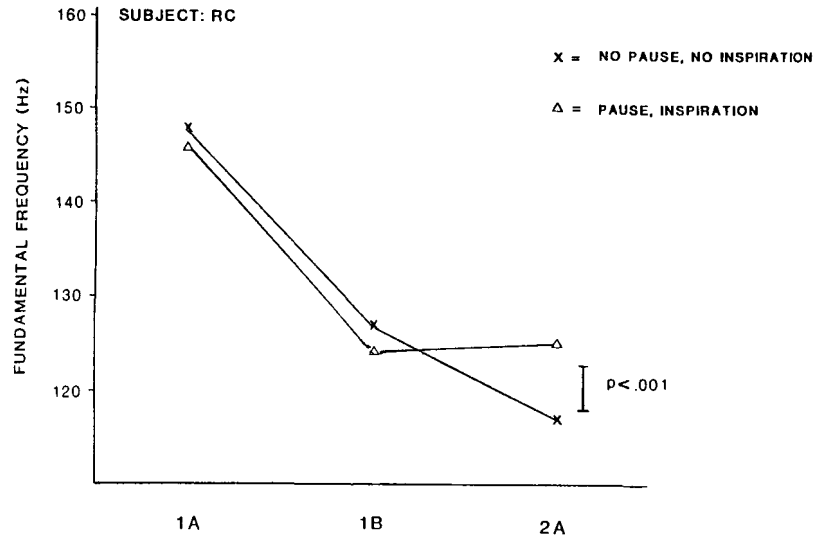
Figure 3. Distribution of airflow rates (cc/sec) for tokens of all /ma/ and /fa/ utterances for both subjects. The solid bars denote the /ma/ tokens, and the dashed bars the /fa/ tokens.



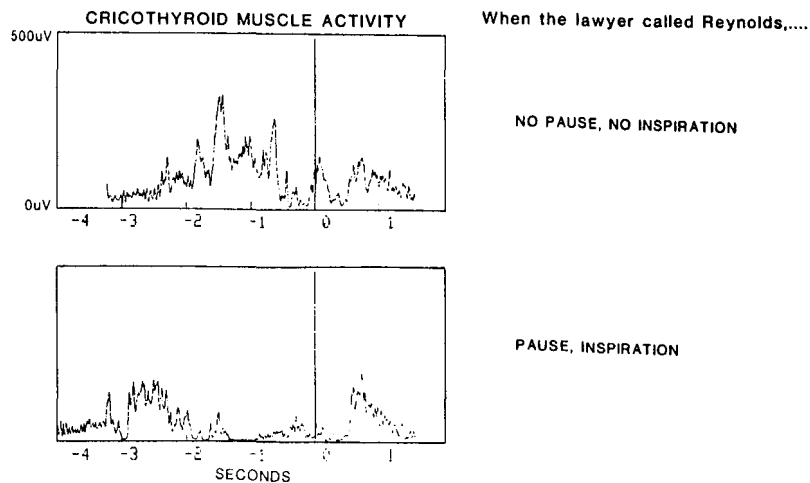
**Figure 4.** Averaged subglottal pressure and Respirance curves for a representative sentence across conditions. The first panel represents the no pause, no inspiration condition, and the second panel represents the pause plus inspiration condition. The line-up point, depicted by the vertical line, represents the onset of voicing for the vowel in the word ‘plan’ in the second clause. The same line-up point was used for all three sentence types.



**Figure 5.** Averaged  $F_0$  contours for a representative sentence across conditions. The first panel represents the no pause, no inspiration condition, and the second panel represents the pause plus inspiration condition. The line-up point, depicted by the vertical line, represents the onset of voicing for the vowel in the word ‘plan’ in the second clause. The same line-up point was used for all three sentence types.



**Figure 6.** Schematic representation of the mean  $F_0$  values (peaks 1A, 1B, 2A), collapsed across sentence types, for both conditions. The X's denote the no pause, no inspiration condition, and the triangles's the pause plus inspiration condition.



**Figure 7.** Averaged cricothyroid muscle activity for a representative sentence across conditions. The first panel represents the no pause, no inspiration condition, and the second panel represents the pause plus inspiration condition. The line-up point, depicted by the vertical line, represents the onset of voicing for the vowel in the word 'plan' in the second clause. The same line-up point was used for all three sentence types.



Table 1

## Values at Peak 2A

|            | Fundamental Frequency |              | Subglottal Pressure |              |
|------------|-----------------------|--------------|---------------------|--------------|
|            | -Pause/-Insp          | +Pause/+Insp | -Pause/-Insp        | +Pause/+Insp |
| Sentence 1 | 116                   | 123          | 7.8                 | 9.9          |
| Sentence 2 | 117                   | 122          | 8.6                 | 10.1         |
| Sentence 3 | 118                   | 130          | 9.1                 | 11.6         |
| Mean       | 117                   | 125          | 8.5                 | 10.5         |

|            | Condition 2 - Condition 1 |                | Ratio                  |
|------------|---------------------------|----------------|------------------------|
|            | F <sub>0</sub>            | P <sub>s</sub> | Hz/Cm-H <sub>2</sub> O |
| Sentence 1 | 7                         | 2.1            | 3.33                   |
| Sentence 2 | 5                         | 1.5            | 3.33                   |
| Sentence 3 | 12                        | 2.5            | 4.80                   |

Averaged F<sub>0</sub> and P<sub>s</sub> values for peak 2A for the three sentences and the ratios of Hz/Cm-H<sub>2</sub>O calculated between the no pause/no inspiration and the pause plus inspiration conditions.

the clause boundary. In fact, there is more CT activity following the clause boundary in the first condition, where no inspiration occurs. It would thus appear that CT contributes little, if any, to F<sub>0</sub> resetting in this case, and that the increase in P<sub>s</sub> following an inspiration could indeed account for the amount of resetting observed. The above results suggest that when both a pause and inspiration occur, there is a significant increase in P<sub>s</sub> and F<sub>0</sub> values relative to those occurring when there is neither a pause nor an inspiration. However, in comparing only these two conditions, we are unable to separate the relative effects of breathing and pausing on resetting.

Our results differ somewhat from those of Collier (1987) who, in certain instances, found a greater amount of resetting. In addition, Collier fails to find the substantial effect of inspiration on P<sub>s</sub> that we do. We believe that these differences may be attributed to differences in the tasks in the two studies. That is, while Collier manipulates the stress configuration (i.e., lo-lo; hi-hi) around the clause boundary, we do not. Thus, the intentional realization of specific intonation contours might result, for example, in greater involvement in CT activity while, at the same time, reducing P<sub>s</sub> activity.

## Discussion

It has been known for some time that the respiratory system acts in such a way as to stabilize subglottal pressure (eg., Draper et al., 1960; Mead et al., 1968). The data presented here not only confirm the results of these earlier studies, but provide evidence that this control is dynamic in nature. Furthermore, this stability is maintained even when the system must respond to perturbations in the form of varying airflow requirements. In other words, if lung deflation were passive in nature, pressure would certainly decline more rapidly for utterances where greater airflow rates are used. However, we have found the rate of pressure decline to be independent of the rate of airflow.

Previous studies in which simultaneous measures of subglottal pressure and fundamental frequency have been recorded during sentence production have noted that, through the most stable portions of these curves, their decline is relatively parallel (see, for example, Atkinson, 1973; Collier, 1975; Lieberman, 1967), although a direct cause and effect relationship has been difficult to establish. However, Gelfer et al. (1985) were able to demonstrate that, in the absence of cricothyroid activity, the fall in pressure accounted for an appropriate fall in frequency. Moreover, the rate of both  $P_s$  and  $F_0$  decline was found to be stable across varying utterance lengths. The data presented here suggest that  $P_s$  is a controlled variable in sentence production, and that  $F_0$  declination is a consequence.

Similarly, the resetting of  $F_0$  at a clause boundary appears to represent the effect of a general resetting of the respiratory system on subglottal pressure following an inspiration. That is, we found  $F_0$  to be significantly higher when an inspiration occurred at the clause boundary than when it did not. At the same time, however, it is difficult to make the claim that the resulting difference of 8 Hz is perceptually salient, for it is also the case that the syntactic structure can be easily recovered when listening to any token of any of these utterances. It is not entirely clear, then, that peak  $F_0$  resetting is a necessary mechanism for encoding syntactic structure on the part of the speaker, or a prerequisite for decoding syntax on the part of the listener. Furthermore, that the extent of  $F_0$  resetting is planned by a speaker, in that it has a place in the mental representation of an utterance, seems untenable. Rather, resetting would appear to be the outcome of an optional speaker strategy—perhaps, for example, whether a speaker chooses to pause or take a new breath, and thus “reset” the whole system, prior to the execution of a second clause—and that this is the level at which it is controlled.

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## APPENDIX A

### *Early Stress:*

Length 1: Je weet dat jan nadenkt.

Length 2: Je weet dat jan erover nadenkt te betalen.

Length 3: Je weet dat jan erover nadenkt ons darvoor met genoeg te betalen.

### *Double Stress:*

Length 1: Je weet dat jan nadenkt.

Length 2: Je weet dat jan erover nadenkt te betalen.

Length 3: Je weet dat jan erover nadenkt ons daarvoor met genoeg te betalen.

### *Late Stress:*

Length 1: Je weet dat jan nadenkt.

Length 2: Je weet dat jan erover nadenkt te betalen.

Length 3: Je weet dat jan erover nadenkt ons daarvoor met genoeg te betalen.

## APPENDIX B

*Sentence 1:* When the lawyer called Reynolds, the plans were discussed.

*Sentence 2:* When the lawyer called, Reynolds' plans were discussed.

*Sentence 3:* The lawyer called Reynolds, and the plans were discussed.