DOWNTREND IN F_0 AND P_{sb}

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In the present paper we examine the simultaneous downtrend in fundamental frequency and subglottal pressure that is often observed for running speech. In particular, we will test the hypothesis that the downtrend in fundamental frequency is caused by a gradual decrease in subglottal pressure during the course of an utterance. In the literature various ways to model the downtrend in fundamental frequency have been proposed. Our conclusion is that whether the hypothesis stated above is true depends on the model of downtrend adopted.

1. Introduction

A simultaneous downtrend in fundamental frequency (F_0) and subglottal pressure (P_{sb}) has often been observed for running speech (Lieberman, 1967; Ohala, 1970; Collier, 1974, 1975; Atkinson, 1978; Gelfer, 1987; Strik & Boves, 1993). As it is known that changes in P_{sb} will affect F_0, everything else being equal (Titze, 1989), it seems plausible to assume that both downtrends are related. However, a considerable deal of controversy surrounds the relation between the two downtrends (see e.g. Ohala, 1978, 1990; Cohen, Collier & ’t Hart, 1982; Ladd, 1984).

Research on the relation between the downtrend in F_0 and P_{sb} is impeded by the fact that there is still no consensus on the correct way to model the downtrend in F_0. In the literature various models have been proposed. Many of these models consist of two components: a short-term or local component and a long-term or global component. In these models the global component is used to model the downtrend in F_0. Only some of these models provide a physiological explanation of both components. Ohman (1968), Collier (1975), and Fujisaki (1991) agree that the local component is controlled by the laryngeal muscles, but they do not agree about the control of the global component. According to Ohman (1968) and Fujisaki (1991) downtrend is also controlled by the laryngeal muscles, while according to Collier (1975) it is controlled by P_{sb}.

In Strik & Boves (1993) the relation between F_0 and some of the physiological mechanisms that are known to be important in the control of F_0 is studied by means of a qualitative analysis. Based on our own data and data from the literature it was concluded that from a physiological viewpoint the following hypothesis is plausible: the downtrend in F_0 is due to the downtrend in P_{sb}. However, this hypothesis is not unchallenged. In this article we will discuss the two main counter-arguments:

1. the lowering in P_{sb} cannot explain all of the decrease in F_0 (section 4.2); and
2. downtrend is part of the linguistic code, and thus it must be controlled by laryngeal muscles and not by P_{sb} (section 4.3).

The fact that this issue is still controversial is expressed in the conclusion of a recent article by Ohala (1990): "It must be concluded that the question of whether F_0 declination is caused by laryngeal or by respiratory activity has still not been answered definitively." The purpose of this article is to clarify the relation between the downtrend in F_0 and P_{sb}.

In the literature different models of intonation are available, which are motivated both by phonetic and phonological considerations. The primary goal of the present article is to study the relation between the downtrend in F_0 and P_{sb}. For this reason we look primarily at intonation from a physiological point of view. As a consequence, we try to avoid theory-laden terms like e.g. ’downdrift’, ’declination’ and ’baseline’ as much as possible. Instead we predominantly use the more neutral term ’downtrend’. In some sections we refer to previous studies in which the term ’declination’ is generally used. In these cases we will also use the term ’declination’. In this article ’downtrend’ and ’declination’ are seen as synonyms, and are used to denote the gradual lowering of a signal during a whole utterance.

The outline of the article is as follows. In section 2 material and method are described. Each experiment consisted of two parts. In part one the subjects were instructed to sustain vowels, and in part two they produced meaningful sentences. The results for ’sustained phonation’ are described in section 3. These results are then used in the argumentation of section 4, in which the results for ’running speech’ are presented. In section 4.1 our physiological model of intonation is described. Subsequently, the two counter-arguments mentioned above are discussed in section 4.2 and 4.3, respectively. Section 5 contains a general discussion. Finally, some conclusions are drawn in section 6..

2. Material and method

Recordings were made of the audio signal, electroglottogram, lung volume (V_l), P_{sb}, and the activity of the sternohyoid (SH) and vocalis (VOC) muscles for two Dutch male subjects. Both subjects had normal phonation and hearing, but had not received special voice training. In addition to these signals, the activity of the cricothyroid (CT) muscle was also measured for subject LB (the second author), and oral pressure for subject HB. The electromyographic (EMG) signals of the laryngeal muscles were high-pass filtered, full-wave-rectified, and integrated over successive periods of 5 ms. All EMG signals were shifted forward over their mean response times, using the procedure described in Atkinson (1978).

The measurements were made while the subjects produced sustained vowels and meaningful Dutch sentences with different intonation patterns. The sentences spoken by subject LB were "Piet slikte zijn pillen met bier" (SU: Short Utterance); and "Piet slikte gisteren zijn vierentwintig gele pillen liever in stilte met bier" (LU: Long Utterance). The sentences produced by subject HB were "Heleen wil die kleren meenemen" (SU: Short Utterance); "Heleen en Emiel willen die kleren liever wel weer meenemen" (LU: Long Utterance); and "Indien Emiel die kleren wil meenemen, willen wij ze eerst wel even zien" (SWC: Sentence With Comma). These sentences contain mainly high vowels, in order to minimize the involvement of the SH in articulatory gestures.

The intonation contours produced were one "pointed hat" (HB-SU1, early stress); two "pointed hats" (HB-SU2, LB-SU2 and LB-LU2, early and late stress, F_0 is lowered in between); a "flat hat" (HB-SU3, LB-SU1 and LB-LU1, early and late stress, F_0 is kept high in between); and question intonation (HB-SU4, HB-LU4, LB-SU3 and LB-LU3). The intonation pattern of HB-SWC is more complex. For an explanation of the notions "pointed hat" and "flat hat" the reader is referred to ’t Hart, Collier & Cohen (1990).

Some sentences were also produced in reiterant form, using either the syllable /fi/ or /vi/. The subjects repeated each sentence 5 to 8 times. The raw signals of these repetitions were used to calculate median signals for each intonation contour. The method of non-linear time-alignment and averaging was used to average all signals, including F_0 (Strik & Boves, 1991). The procedures used for recording and processing the data are described in more detail in Strik & Boves (1992).

3. Sustained vowels

Before the actual measurements of the physiological signals were made, our subjects were trained to produce prolonged vowels for different combinations of F_0 and intensity level (IL). When the subjects were asked to sustain a given vowel, a gradual lowering of F_0 and IL was generally observed. Subsequently, when they were explicitly instructed to keep F_0 and IL constant, the downtrend in F_0 and IL diminished, but it was usually still present. Finally, the subjects were given on-line visual feedback of F_0 and IL. In this condition they often managed to keep both F_0 and IL fairly constant during the production of a vowel.

After the training sessions actual measurements of the physiological signals were obtained. The subjects were given on-line visual feedback and were again instructed to keep F_0 and IL constant for a sustained vowel. This task was repeated for different combinations of F_0 and IL. The measurements show that the subjects usually managed to keep F_0 and IL at the target values. At the beginning of the utterances some variation in P_{sb} and the activity of the laryngeal muscles was observed, probably to reach the target levels for F_0 and IL. Apart from the initial variation the physiological signals usually remained constant for the rest of the utterance. Different combinations of F_0 and IL were achieved by different levels of P_{sb}, SH, CT, and VOC. The results of this part of the experiment are described in more detail in Strik & Boves (1987).

This experiment shows that subjects who had no special voice training can keep F_0, IL, and P_{sb} constant during a simple utterance (a sustained vowel), but only if they are supported by visual feedback. Subjects report that keeping F_0 and IL constant requires more effort than allowing a gradual decline, and feels less natural. Without visual feedback F_0 and IL (and probably also P_{sb}) tend to fall gradually during the course of an utterance, even if subjects are instructed to keep F_0 and IL constant. The results obtained for sustained phonation will be used as support for the argumentation in the next section on running speech.

4. Running speech

4.1. A physiological model of intonation

In Strik & Boves (1993) we proposed a qualitative model of F_0 control in running speech. Our model describes consistent behaviour of P_{sb}, CT, VOC, and SH that was observed in the data of subjects LB and HB, and in other data presented in the literature. Figures with the average signals for the recorded utterances of subjects LB and HB can be found in Strik & Boves (1993). Here we will only display the average signals of a typical utterance (see Fig. 1), in order to illustrate our model.

The four physiological signals mentioned above were chosen because it is known that they are important in the control of F_0. In our model intonation and its physiological control take place at two levels, viz. a global and a local level. This is in accordance with other physiological models of intonation proposed in the literature (like Ohman, 1968; Collier, 1975; and Fujisaki, 1991).

Short-term variations in F_0, P_{sb}, SH, VOC, and CT have often been observed (see e.g. Fig. 1), i.e. all five signals clearly have a local component. But it is not immediately clear whether all of these five physiological signals also have a global component.

** Insert Figure 1 about here. **

Global level

A gradual lowering of P_{sb} and F_0 during the course of a major syntactic constituent is often observed (see e.g. Lieberman, 1967; Ohala, 1970; Collier, 1974, 1975; Atkinson, 1978; Gelfer, 1987; Strik & Boves, 1993). The domain in which the downtrends in F_0 and P_{sb} occur has previously been given many different names, among other things "breath group" (Lieberman, 1967), "intonation group" (Breckenridge, 1977), "utterance" (Pierrehumbert & Beckman, 1988), "clause or clause complexes" (Clark & Yallop, 1990), or "major phrase" (Honda & Fujimura, 1991). In this article we will use the term utterance. Within the recorded sentences there were no inspirations (resets of V_l), nor any resets of F_0 or P_{sb}.

Our definition of a global component is a gradual change spanning the total duration of an utterance. Therefore, in our model P_{sb} and F_0 have a global component. The global component of F_0 and P_{sb} in our model will be called $F_{0,g}$ and $P_{sb,g}$, respectively. In this article the terms $F_{0,g}$ and $P_{sb,g}$ will be used for the global components of our model alone. Global components of other models will be denoted otherwise.

The model presented in Strik & Boves (1993) is a qualitative model. To illustrate our model a possible quantitative decomposition of F_0 and P_{sb} in a global and a local component is shown in Fig. 1. $P_{sb,g}$ was obtained by manually fitting an exponential function through most of the valleys of P_{sb} (Fig. 1). Because it is assumed that F_0 varies linearly with P_{sb} (Titze, 1989), $F_{0,g}$ was defined in the following way: $F_{0,g} = B_0 + B_1 * P_{sb,g}$. The values of B_0 and B_1 that gave a satisfactory result for this utterance were 70 Hz and 5 Hz/cm H_2O (Fig. 1), respectively. We would like to note that the manually fitted trend lines are only presented here to illustrate our qualitative model, and to give an example of a procedure that can be used to obtain the global and local components of P_{sb} and F_0. These manually fitted trend lines are not used for further analysis in the present article. Instead we will use a more objective statistical method in the following section.

A gradual change in the activity of SH, VOC, or CT during a whole utterance was not observed in any of our recordings nor in published data of other researchers (as far as we know). Sometimes the activity of these three laryngeal muscles varied slowly during part of the utterances, but no instance of a slow increase or decrease during the whole utterance (just like P_{sb} and F_0) was found. It must therefore be concluded, both from our own data and the data presented in various other papers, that in general SH, VOC, and CT do not seem to have a global component.

Local level

At the beginning of utterances CT, VOC, and P_{sb} may have extra high values, and the result will be a so-called ’initial rise’ of F_0 (Fig. 1). At the end of utterances SH activity often increases while P_{sb} drops sharply. If these effects occur during voiced sounds at the end of the utterance, final lowering of F_0 is observed (Fig. 1). Alternatively, increased SH activity and P_{sb} release may be delayed until after the last voiced sound, in which cases final lowering is absent (e.g. in most interrogative utterances). The initial rise and final lowering of F_0 will add to the F_0 fall that results from the downtrend in $F_{0,g}$ alone (Fig. 1).

The local component of P_{sb} ($P_{sb,l} = P_{sb} - P_{sb,g}$) is generally positive. SH, VOC, and CT only have a local component, which is always positive because these signals can never become negative (see section 2). Finally, the local component of F_0 ($F_{0,l} = F_0 - F_{0,g}$) is positive when the effect of the F_0-raising mechanisms (VOC, CT, and $P_{sb,l}$) is larger than the effect of the F_0-lowering mechanisms (SH), and $F_{0,l}$ becomes negative when the net effect of F_0-raising and F_0-lowering mechanisms is negative.

Hypothesis

To conclude this section, in our physiological model of intonation SH, VOC, and CT do not have a global component, while F_0 and P_{sb} do have a global component. A two-component model was chosen, because from a physiological point of view this seems to be the model that best describes the data. Because a downtrend in $F_{0,g}$ and $P_{sb,g}$ is often observed, the following hypothesis seems likely: The downtrend in $F_{0,g}$ is due to the downtrend in $P_{sb,g}$. This hypothesis has been challenged for different reasons. Two frequently adduced counter-arguments are discussed in the next two sections.

4.2. The F_0-P_{sb} ratio

4.2.1 Counter-argument 1

An argument used against the above-mentioned hypothesis is that the variation in $P_{sb,g}$ cannot explain the total variation in $F_{0,g}$, because the F_0-P_{sb} ratio (FPR) observed in running speech is often larger than 7 Hz/cm H_2O (e.g. Maeda, 1976; Ohala, 1978). Studies of the rate of F_0 change resulting from a change in P_{sb} alone (generally by externally induced pressure variations) have revealed that the FPR should be in the range 2-7 Hz/cm H_2O (e.g. Ladefoged, 1967; Baer, 1979). In the present article this range will be called the FPR-range. Because the FPR obtained for utterances often seems to exceed the FPR-range, the hypothesis is either rejected totally (Ohala, 1978), or an additional mechanism is invoked to explain (part of) the decrease in F_0 (the tracheal pull mechanism of Maeda, 1976).

Indeed, there seem to be no reasons to assume that the FPR obtained in experiments with externally induced pressure variations differs from the FPR in running speech. But the problem is that the FPR obtained for running speech depends on the way in which the downtrend in F_0 and P_{sb} is defined and modelled.

4.2.2 Modelling the relation between F_0 and P_{sb}

In the literature several methods have been proposed to model the downtrend in F_0, such as the difference between F_0 at the beginning and at the end of an utterance (see method 1 below), the baseline of Maeda (1976), and the bottomline and topline of Cooper & Sorensen (1981). Baseline, bottomline, and topline are trend lines which are generally fitted manually, just like $P_{sb,g}$ and $F_{0,g}$ in Fig. 1. Most probably, the fitting is done manually because it is difficult to define a mathematical error function that could be used to derive the trend lines with an optimization algorithm.

We have done a number of experiments to determine the parameters of the downtrend components. The results of two experiments, in which different definitions of downtrend were used, are presented below. For this aim six utterances of subject LB and six utterances of subject HB were used. For each subject, there are four declarative and two interrogative utterances (see Table I). All signals, including the F_0 signals, are average signals (section 2). Figures with the average signals for these twelve utterances can be found in Strik & Boves (1993). The average signals for one utterance of subject LB are shown in Fig. 1.

Method 1

In this method the F_0 and P_{sb} values are taken at two instances, one near the beginning (T_1) and one near the end (T_2). The following values are then calculated: $dF_0 = F_0(T_1) - F_0(T_2)$, $dP_{sb} = P_{sb}(T_1) - P_{sb}(T_2)$, $FPR_1 = dF_0/dP_{sb}$. The total fall in F_0 and P_{sb} from T_1 up to T_2 (dF_0 and dP_{sb}, respectively) is used to model the downtrend in F_0 and P_{sb}, respectively. Basing dF_0 on two F_0 values is error prone. In some studies the F_0 values are obtained from a trend line (e.g. the baseline in Maeda, 1976), while in other studies the F_0 values are taken from a single, representative F_0 contour (e.g. Collier, 1975; Gelfer, Harris, Collier & Baer, 1983; Collier, 1987). Our data processing procedure allowed us to average the F_0 curves of all repetitions of a given sentence, therewith making the estimation procedure more reliable. In previous studies various choices of T_1 and T_2 have been made, based on different motives (see e.g. Gelfer et al., 1983). In this study T_1 is the first voiced frame, and T_2 the last voiced frame of each utterance. These instants of T_1 and T_2 were mainly chosen because the values of F_0 and P_{sb} at these time-points can be determined very easily for each utterance. Given this choice of T_1 and T_2, all relevant values were calculated for the twelve utterances of subjects LB and HB (see Table I).

** Insert Table I about here. **

In all utterances dP_{sb} is positive (Table I). For subject LB dP_{sb} is always larger than for subject HB. For both subjects dP_{sb} for the interrogative utterances is smaller than dP_{sb} for the declarative utterances. At the end of each question there is a marked increase in F_0, and consequently dF_0 is negative for the questions. But for all declarative utterances dF_0 is positive. For the declarative utterances, dF_0 of subject LB is always larger than dF_0 of subject HB. Partly this is because dP_{sb} is larger for subject LB, as noted above. In addition, for subject LB the CT and VOC often show increased activity at the beginning of an utterance, which causes an initial rise in F_0, and the SH is increased at the end of the utterance during the final lowering of F_0. Both effects will cause dF_0 to be larger than the fall in F_0 resulting from dP_{sb} alone, i.e. both P_{sb} and the laryngeal muscles participate in dF_0.

The values of FPR_1 can be seen in Table I. Only three of the twelve FPR_1 values are within the accepted FPR-range. FPR_1 for the four questions is negative because dF_0 is negative, four of the eight values of FPR_1 for the statements are larger than 7 cm H_2O and one is smaller than 2 cm H_2O. Based on these FPR_1 values one could conclude that the downtrend in P_{sb} cannot explain all the downtrend in F_0, and thus other factors should contribute to the downtrend in F_0. If downtrend is defined in this way, then this conclusion is correct. After all, dF_0 does depend on both dP_{sb} and the activity of the laryngeal muscles (especially for subject LB, as explained above).

The FPR-range is obtained from experiments with externally induced pressure variations (e.g. Ladefoged, 1967; Baer, 1979). The goal of these experiments was to determine the FPR for F_0 changes that result from P_{sb} changes alone, i.e. one tried to keep other processes that influence F_0 (like the laryngeal muscles) constant (see e.g. Baer, 1979). In these studies the points in a scatterplot for F_0 as a function of P_{sb} could usually be fitted reasonably by a straight line. In Fig. 2 an F_0-P_{sb} scatterplot is given for a short utterance of subject LB. Clearly, in this scatterplot the points are not grouped around a straight line. The reason is that during this utterance the other factors which influence F_0 are not constant. Drawn in Fig. 2 is the straight line that connects the first and the last voiced frame. FPR_1 is the slope of this line. In Fig. 2 one can see that the FPR obtained in this way depends heavily on the exact choice of T_1 and T_2. To sum up, method 1 has two important drawbacks:

1. other factors that can affect F_0 are not constant over the course of an utterance; and
2. because the other factors are not constant it is hazardous to make estimates of the FPR which are based on the values of F_0 and P_{sb} at two instants only.

** Insert Figure 2 about here. **

Method 2

In method 2 a multiple regression analysis is used, in which F_0 is the criterion and P_{sb}, VOC, and SH are the predictors (Footnote 1). The outcome of the regression analysis are the coefficients A_i of the regression equation: $F_0 = A_0 + A_1{*}P_{sb} + A_2{*}VOC + A_3{*}SH$. The FPR is the regression coefficient between F_0 and P_{sb}: $FPR_2 = A_1$. This method does not have the drawbacks of method 1 because a correction is made for some important other factors which influence F_0, and the regression coefficient is based on the data of all voiced frames.

The multiple regression analysis decomposes F_0 into four components: A_0, $A_1{*}P_{sb}$, $A_2{*}VOC$, and $A_3{*}SH$. The first component is the constant A_0. VOC and SH do not have a global component either (section 4.1), and thus in this statistical model the downtrend in F_0 is due to the downtrend in P_{sb} alone. This is in line with the physiological model presented in section 4.1, except for one essential difference. In method 2 P_{sb} is not decomposed into a global and a local component. However, because there are no reasons to assume that the FPR is different on a global and a local level, this does not seem to be a problem. Consequently, the P_{sb} component in the regression analysis ($A_1{*}P_{sb}$) contains both the slow downtrend in F_0, and the part of the local variations in F_0 which is due to the local variations in P_{sb}. The other part of the local variations in F_0 is in the VOC and SH component ($A_2{*}VOC$ and $A_3{*}SH$), respectively.

Instead of using the multiple regression analysis we could have based our estimates of the FPR on the global trend lines $P_{sb,g}$ and $F_{0,g}$. To that end, $P_{sb,g}$ and $F_{0,g}$ should have been determined in the way described in section 4.1, i.e. by making manual fits for all utterances. This is certainly possible, but we prefer to use objective, statistical methods (like the multiple regression analysis described in the current section) instead of more subjective methods in which trend lines are fitted manually.

For all voiced frames of the twelve utterances a multiple regression analysis was performed in which F_0 was the criterion and P_{sb}, VOC and SH were the predictors. The resulting FPR_2 values (i.e. the A_1 values) can be seen in Table I. The resulting values of A_0, A_2 and A_3 were not used for further analysis. Of the 12 FPR_2 values, 11 are in the FPR-range, and one is slightly larger than the maximum of the FPR-range. If the CT had been used as a predictor instead of the VOC for subject LB, then FPR_2 would have been 6.44 Hz/cm H_2O for this utterance, and thus it would have been within the FPR-range (Footnote 1). Also for the interrogative utterances FPR_2 is always within the FPR-range, while this was never the case for FPR_1. The rise of F_0 at the end of questions is usually due to an increase of CT, VOC, and P_{sb}. In method 2 a correction is made for the increase in VOC, and the result is that the FPR_2 is within the FPR-range. The rapid increase in P_{sb} at the end of the questions is part of P_{sb}, and will also explain part of the end rise in F_0.

To conclude this section, comparison of FPR_1 and FPR_2 values for sentences has shown that the actual values obtained are crucially dependent on the way in which the F_0-P_{sb} ratio is defined. In our opinion FPR_1, which has been used to refute the above-mentioned hypothesis, is not a fair measure because it isolates P_{sb}, but at the same time ignores all other factors affecting F_0. If some important additional influences are factored out of F_0 by means of a multiple regression analysis, as is done with FPR_2, a completely different picture emerges, which is compatible with the hypothesis that the downtrend in P_{sb} explains the downtrend in F_0. Even though the way in which the influence of the laryngeal muscles on F_0 is modelled is extremely crude (the true relation between the activity of the laryngeal muscles and F_0 is very likely to be non-linear) FPR_2 is a much fairer measure than FPR_1. According to this measure the variation in P_{sb} can explain all the variation in F_0, and no additional mechanisms are necessary. Therefore, too large a total F_0 drop does not seem a reason to reject the hypothesis. Also, and perhaps even more important, arguments about the relation between F_0 and P_{sb} depend fully on the way in which the two downtrends are modelled. As long as the model of F_0 downtrend does not partition out effects not related to P_{sb}, it may remain a valid definition of its own, but it should no longer be used in arguments involving P_{sb}.

4.3 Control of F_0 and P_{sb}

4.3.1 Counter-argument 2

At the basis of the second counter-argument is the idea that the laryngeal muscles can be controlled linguistically, while this is not possible for the respiratory muscles and thus the downtrend in P_{sb} is a passive process. Subsequently, this idea is used as an argument against the above-stated hypothesis: because the downtrend in F_0 is (at least partially) linguistically controlled it cannot result from an automatic process like the downtrend in P_{sb}. The fact that some authors use this argument in the discussion about the physiological causes of declination was also noted by Cohen, Collier & ’t Hart (1982).

The second argument against the hypothesis is expressed most clearly by Breckenridge (1977). She states that declination is part of the linguistic system, and therefore it must be controlled by the laryngeal muscles just as other linguistically significant aspects of F_0 are. A similar line of reasoning is used by Ohala (1978, 1990). In Ohala (1978, 1990) three possible causes for declination are mentioned: (1) tracheal pull (Maeda, 1976); (2) downtrend in P_{sb} (Collier, 1974, 1975); and (3) graded activity in the laryngeal muscles. According to Ohala the first two causes are automatic, non-purposive physiological causes. Because declination is not automatic but controlled, he argues that a model in which linguistic aspects of F_0 are completely determined by actions of the laryngeal muscles is much more likely than a two-component model in which respiratory and laryngeal factors interact.

Clear opinions about the control of the downtrend in P_{sb} can also be found in Gelfer et al. (1983), Ladd (1984) and ’t Hart, Collier & Cohen (1990). Gelfer et al. (1983) studied whether declination is actively controlled. They noted a similar downtrend in F_0 and P_{sb}. They argue that if the declination in F_0 is due to the declination in P_{sb}, then this would suggest that declination is a passive phenomenon. In Ladd (1984) three physiological causes of declination are discussed: (1) the downtrend in P_{sb} (Collier, 1975); (2) the tracheal pull (Maeda, 1976); and (3) F_0 rises are harder to produce than F_0 falls (Ohala & Ewan, 1973). According to Ladd, the downtrend in P_{sb} and the tracheal pull are automatic mechanisms. Finally, according to ’t Hart, Collier & Cohen (1990) the muscular activity involved in the regulation of V_l and P_{sb} is subject to an automatic control system. In their view declination should be seen mainly as an automatic by-product of respiration.

The examples given above clearly illustrate that there seems to be a widespread notion that the downtrend in P_{sb} is an automatic process. If the downtrend in P_{sb} is a completely passive process, then this could indeed be used as a counter-argument against the above-mentioned hypothesis, because there are many indications that declination is under linguistic control, at least to some extent. However, it is not sure that the downtrend in P_{sb} is a passive mechanism. On the contrary, there are many reasons to believe that P_{sb} is controlled. This will be discussed in the next section.

4.3.2 Respiratory system

There are three factors which may affect P_{sb} (see e.g. Ladefoged, 1967):

1. passive forces, like elastic recoil and gravitational forces;
2. active forces, resulting from contractions of respiratory muscles; and
3. the resistance to the air-stream, both at the glottis and in the vocal tract (Z_g).

The pressure that results from passive forces alone is generally called the relaxation pressure (P_{rel}), while the pressure change brought about by active muscle contractions is called the muscular pressure. For a speaker who remains in the same position (usually upright) the gravitational forces are roughly constant and thus P_{rel} would depend on V_l alone. If expiration during speech production were a truly passive process, then the muscular pressure should be zero and P_{sb} should be a function of V_l and Z_g alone. Several observations reveal that this is not the case:

- » Our data show that for repetitions of the same sentence the amount of inspiration before the utterance was not always the same. Consequently, the V_l traces run essentially parallel (see e.g. Fig. 3), while Z_g can be assumed to be reasonably constant. Although the differences in V_l are large, the P_{sb} contours are very much alike (Fig. 3).

** Insert Figure 3 about here. **

- Some of the sentences were also produced in reiterant form, using either the syllable /fi/ or /vi/. The slopes of the V_l traces of these two types of utterances are different, but also in this case the P_{sb} contours showed much resemblance (see e.g. Fig. 4). This was also found by Gelfer (1987).

** Insert Figure 4 about here. **

- Speakers can keep their P_{sb} constant during the production of a long sequence of /ma/ syllables (Collier, 1987), and during sustained phonation (section 3). In both cases the activity of the measured laryngeal muscles also remained constant, so Z_g was probably constant. The fact that speakers can keep P_{sb} constant while V_l is decreasing also proves that P_{sb} is not simply a function of V_l and Z_g alone.
- During phonation P_{sb} should not become smaller than a threshold value below which phonation is not possible (the so-called phonation threshold pressure, see Titze, 1992). Furthermore, the loudness of the speech is determined to a large extent by P_{sb}, and thus P_{sb} should be kept within a certain range to produce speech with the desired loudness. After inspiration at the beginning of an utterance P_{rel} is often larger than the desired P_{sb}, while at the end of an utterance P_{rel} is often lower than the desired P_{sb} (see e.g. Ladefoged, 1967). If the respiratory muscles were not used, then P_{sb} and the loudness would decrease rapidly; soon P_{sb} would be smaller than the phonation threshold pressure and phonation would stop. To prevent this, the inspiratory muscles are used at the beginning of an utterance to keep P_{sb} lower than P_{rel}, while expiratory muscles are used when P_{rel} is lower than the desired P_{sb} (Ladefoged, 1967).

The arguments given above force one to assume that the respiratory muscles are used to control P_{sb} during speech production. The following question then arises: How are the respiratory muscles used to control P_{sb}? According to Ladefoged (1967) and Ohala (1990) the amount of control is limited, i.e. they claim that these muscles are only used to keep P_{sb} reasonably constant above some minimal level. However, many measurements show that in general P_{sb} is not constant but has a tendency to decline, both in sustained phonation (section 3) and in running speech (Lieberman, 1967; Ohala, 1970; Collier, 1974, 1975; Atkinson, 1978; Gelfer, 1987; Strik & Boves, 1993). Furthermore, P_{sb} contours for repetitions of a sentence appear to be very similar in shape as well as in amplitude (see e.g. Fig. 3), too similar to assume that P_{sb} has just a convenient (more or less random) value above its minimum.

If the respiratory muscles are under voluntary control, then they can be used to control P_{sb} during speech production. Active control of the respiratory muscles and P_{sb} in speech production seems likely, given the following arguments:

- » The way the respiratory muscles are used during speech production differs from the way they are used in normal breathing. In normal breathing the duration of inhalations and exhalations is about equal, while in speech production the inspiratory phase is much shorter. Furthermore, it has been observed that the posturing of the respiratory system for speech production (the prephonatory posturing of the chest wall) is different from the posturing for normal breathing (Hixon, Goldman & Mead, 1973; Baken, Cavallo & Weismann, 1979; Baken & Cavallo, 1981).
- » Breathing pauses occur mainly at major constituent breaks (Winkworth et al., 1994). Breathing pauses can also occur at minor constituent boundaries, but as speaking rate increases they are eliminated from these minor breaks (Grosjean & Collins, 1978). Grosjean & Collins (1978) conclude that "it would appear that breathing in speech depends to a large extent on the speaker’s preplanned pause patterns", and thus breathing would be linguistically controlled.

- » The amount of air inspired and the V_l at the beginning of sentences was found to be significantly larger for longer utterances compared to shorter ones, and for major syntactic breaks compared to more minor ones (Winkworth et al., 1994). According to Winkworth et al. (1994) these findings indicate that speakers pre-plan their V_l and the volume inspired. It should be noted that this study concerned reading, and therefore their results suggest that the respiratory muscles are under linguistic control during reading.
- » Indications of extra respiratory activity (i.e. increased lung volume decrement) for stressed syllables were found by Ohala (1977), while Ladefoged (1967) and van Katwijk (1974) actually measured increased activity of respiratory muscles for stressed syllables. Although not all stressed syllables are probably accompanied by extra activity of the respiratory muscles, these results indicate that linguistic control of the respiratory muscles is possible, at least at a local level. If active control of the respiratory muscles is possible at a local level, then it is likely that it is also possible at a global level.

» Loudness is a prosodic, i.e. a linguistic variable. If speakers are asked to increase loudness, they tend to initiate speech at higher lung volumes (Hixon, Goldman & Mead, 1973). Winkworth et al. (1994) also found that louder utterances within the "comfortable loudness" range are generally associated with higher lung volumes. According to Weismer (1985) it is more efficient to start at higher lung volumes for loud speech, because larger values of P_{sb} are needed to generate loud speech. So, not only is this an example of linguistic control of the respiratory muscles, it is also an indirect indication of linguistic control of P_{sb}. But there are also more direct indications of voluntary control of P_{sb}.

» In addition to P_{sb}, a speaker can use many different physiological mechanisms to control F_0, and thus a given F_0 contour could be produced in various ways. Still, the amount of variation between physiological signals (including P_{sb}) of repetitions of the same utterance is relatively small (Strik & Boves, 1991; Strik & Boves, 1993). The finding that the inter-repetition variation in P_{sb} and the other physiological signals is small suggests that speakers have a notion of the manner in which they want to produce an utterance, and that they have a good control over P_{sb} and the other mechanisms.

** Insert Figure 5 about here. **

» Another indication that P_{sb} is actively controlled can be seen in Fig. 5. In the middle of a spontaneous utterance subject HB made a swallowing gesture, probably because the pressure catheter was bothering him. During this interruption P_{sb} suddenly drops to about 5 cm H_2O. For subject HB phonation with such a level of P_{sb} is possible, because comparable and even lower values of P_{sb} were found at the beginning of many voiced intervals of the repetitions of the same utterance. If the subject’s only intention was to provide a P_{sb} above some minimal level at which phonation is possible, he could have kept P_{sb} at approximately 5 cm H_2O. However, before he resumed phonation P_{sb} was raised to approximately the value it had before the interruption, and from that point it started declining again.

» Finally, after the two subjects in our study had received instructions they were able to keep P_{sb} fairly constant at different levels (section 3), i.e. their P_{sb} was under voluntary control.

The conclusion of this section is that there are several reasons to believe that the respiratory muscles and P_{sb} are actively controlled. If this is the case, then also the second counter-argument (specified above) cannot be used to refute the hypothesis that the lowering of $F_{0,g}$ is generally due to a decrease in $P_{sb,g}$.

5. Discussion

In this paper we have argued in favour of a major role for P_{sb} in the control of the ubiquitous downtrend in F_0 contours. The role of P_{sb} has been called into question by a number of authors, and for a number of different reasons. The two most important counter-arguments center around the claim that the total F_0 fall in most published data seems to exceed the range that should be expected from the fall in P_{sb}, and the claim that the respiratory system is not suited for so precise a control as needed for the linguistic, communicative purpose served by F_0 downtrend. These counter-arguments have been discussed in sections 4.2 and 4.3, respectively.

Before proceeding to a summary of these discussions we would like to address one additional argument. Ohala (1990) claims that there are examples in the literature that show a gradual downtrend of the activity of CT. It appears that these examples are limited to the contours 11 and 15 in Collier (1974). In these registrations a gradual decline of CT activity can indeed be seen, but only in the second half of the utterances. To the best of our knowledge there are no data showing a gradual variation of CT, VOC or SH over complete utterances. But there are numerous examples of P_{sb} decline that span a complete utterance. Thus, we fully acknowledge the possibility that laryngeal muscles contribute to the total fall of F_0 over the course of an utterance, but the available data more or less force us to accept the conclusion that the contribution of P_{sb} to the control of F_0 downtrend (as the concept is defined in our model) is much more important. For this reason, we think that the physiological validity of the models proposed by Ohman (1968) and Fujisaki (1991), which do not acknowledge a role for P_{sb}, is debatable. Speakers can exploit a large array of physiological means to reach a certain goal, and it would be surprising if some of these means would never be exploited. After all, there is no valid reason to suppose that all subjects should always behave in exactly the same way. But individual examples attesting a possible way of control should not be generalized. For the time being, the data speak in favour of P_{sb}.

Coming back to the arguments related to the F_0-P_{sb} ratio, it must be concluded that fair estimates of that ratio are extremely difficult to obtain from sentence material. In all naturally produced utterances laryngeal muscles affect F_0 in addition to P_{sb}. In order to obtain a fair estimate of FPR these additional contributions must be factored out. That is certainly not done by defining dF_0 and dP_{sb} as the difference between the values observed at the beginning and at the end of an utterance, not even when these values are averaged over a large number of tokens, simply because the F_0 values are affected by laryngeal muscle activity.

A fundamental problem in studying the physiological causes of downtrend is that the literature abounds with definitions of F_0 downtrend. Downtrend, declination or downdrift have been used to denote the tendency of F_0 to decrease during the course of an utterance. This qualitative definition can be interpreted in many different ways, and is hardly suitable for studying the relation between physiology and F_0 downtrend. Therefore, a more precise definition of downtrend is needed. Some of the definitions used in the literature are illustrated in Fig. 6. Fig. 6 shows hand-fitted estimates of a top line, a bottom line, a line connecting the first and last voiced sample in addition to $F_{0,g}$, which was derived in the way described in section 4.1 (this is the same trend line as the one shown in Fig. 1). It can easily be seen that the slopes of these lines differ considerably. There is less literature on the definition of downtrend in P_{sb}. Yet, it is clear that the existence of several essentially different definitions or models of F_0 downtrend makes it impossible to discuss 'the' relation between downtrend in P_{sb} and F_0: the outcome of such a discussion is certain to depend on the exact definition of downtrend that is assumed.

According to our definition of a global component, F_0 and P_{sb} do have a global component while CT, VOC and SH generally do not have a global component. The quantitative statistical analysis has shown that, after correcting for the influence of VOC and SH, the variation in P_{sb} can explain all the variation in F_0 (i.e. the FPR is usually within the correct range). Consequently, in our physiological two-component model the downtrend in F_0 can be explained completely by the downtrend in P_{sb}. However, it is always possible that other (unknown) factors also contribute to the downtrend in F_0. That is a possibility which cannot be ruled out.

This physiological two-component model was chosen because it seems to be the model which best describes the physiological data. If, for some reasons, someone prefers another definition of the global component, like for instance the top- or bottomline in Fig. 6, the conclusion should indeed be that the downtrend in F_0 cannot be determined entirely by the downtrend in P_{sb}, because top- and bottomline are determined to a large extent by the activity of the laryngeal muscles.

To sum up, in our model the downtrend in F_0 could be entirely due to the downtrend in P_{sb}. For other definitions of downtrend this does not have to be the case, i.e. these downtrend could be determined partially by the activity of the laryngeal muscles. However, the downtrend in P_{sb} will always explain part of the downtrend in F_0.

Ideally, trend lines should not be determined by means of hand fitting, but instead by means of formal, mathematical procedures. However, each and every mathematical fit procedure requires the definition of an error (or cost) function, to quantify the discrepancy between the observed data and the model curve. For the time being, such an error function is almost impossible to define, because it is not possible to reach agreement on the weight of details in the deviations. To a considerable extent, these weights depend on one's theoretical opinions about which details in F_0 curves are linguistically relevant and which are not. Another factor complicating the construction of a completely quantitative model of the control of F_0 in running speech is to do with the lack of knowledge about the relation between EMG activity of the laryngeal muscles and elastic properties of laryngeal tissue. In our own models we have assumed a simple linear relationship, but that is not more than a very crude first approximation. Thus, we have to be content with models that contain non-quantitative or non-realistic quantitative components for some time to come.

6. Conclusions

In this paper we have investigated the relation between downtrend in F_0 and P_{sb}, an issue that has been undecided despite considerable discussion in the recent literature. The most important conclusion of our own experiments and a detailed analysis of data published in the literature is that the issue is genuinely not decidable, unless there is agreement about the way in which downtrend in F_0 and P_{sb} are defined. In our model of F_0 control presented in this paper we take the view that F_0 and P_{sb} both have a global component, and that these components are related by definition. Other models or definitions of F_0 downtrend, like a line fitted through the F_0 peaks (the topline), include effects of other factors affecting F_0 besides P_{sb}; therefore, these definitions (or models) of F_0 downtrend do not allow a direct link with downtrend in P_{sb}. Also, we have presented data and arguments from our own experiments and from the literature in favour of a tight and precise control of P_{sb} and the underlying respiratory system. Therefore, the phonetic implementation component of any intonation model should include a role for P_{sb}.

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Footnote 1: For subject LB the correlation between CT and F_0 is generally larger than the correlation between VOC and F_0, and thus CT is a better predictor of F_0. But because the behaviour of CT and VOC is almost identical for subject LB, and because the activity of the CT was not measured for subject HB, we have chosen the VOC as a predictor in the regression analysis for both subjects.

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Figure 1. Average physiological signals for the Dutch utterance "Piet slikte gisteren zijn vierentwintig gele pillen liever in stilte met bier" (LU1) spoken by subject LB. Also shown in the first and second panel are the global trend lines $F_{0,g}$ and $P_{sb,g}$, respectively (dashed-dotted lines).

Figure 2. F_0 as a function of P_{sb} for the Dutch utterance "Piet slikte zijn pillen met bier" (SU1) spoken by subject LB. The straight line is the line connecting the first and the last voiced frame. FPR_1 is the slope of this line.

Figure 3. F_0, P_{sb}, and V_l signals for two repetitions of a spontaneous sentence (see Fig. %) spoken by subject HB. The average difference for V_l is 470 cc, and for P_{sb} it is 0.05 cm H_2O.

Figure 4. Average F_0, P_{sb}, and V_l signals for two utterances produced with reiterant speech: /vi/ (dashed) and /fi/ (solid).

Figure 5. F_0, P_{sb}, and V_l signals for a spontaneous utterance spoken by subject HB. The arrow marks the interruption of about 0.5 sec.

Figure 6. Average F_0 signal and trend lines for utterance LU1 spoken by subject LB (The average F_0 signal is the same signal as in the upper panel of Fig. 1). The following trend lines are shown: $F_{0,g}$ (dashed), the line connecting the first and the last voiced frame (dashed-dotted), topline (dotted), and bottom- or baseline (solid).

Table I. Listed from top to bottom are: utterance type, number of voiced samples (N), length of the utterance ($T = T_2 - T_1$) in s, F_0 values of first ($F_0(T_1)$) and last ($F_0(T_2)$) voiced sample in Hz, total fall of F_0 ($dF_0 = F_0(T_1) - F_0(T_2)$) in Hz, average rate of change of F_0 (dF_0/T) in Hz/s, P_{sb} values for first ($P_{sb}(T_1)$) and last ($P_{sb}(T_2)$) voiced sample in cm H_2O, total fall of P_{sb} ($dP_{sb} = P_{sb}(T_1) - P_{sb}(T_2)$) in cm H_2O, average rate of change of P_{sb} (dP_{sb}/T) in cm H_2O/s, $FPR_1 = dF_0/dP_{sb}$ in Hz/cm H_2O, and the regression coefficient between F_0 and P_{sb} (FPR_2) in a multiple regression equation, also in Hz/cm H_2O (for explanations, see also the text).

	subject LB						subject HB					
	declarative utterances				questions		declarative utterances				questions	
utt	SU1	SU2	LU1	LU2	SU3	LU3	SU1	SU2	SU3	SWC	SU4	LU4
N	234	226	558	524	222	490	314	342	288	680	260	435
T	1.42	1.41	3.46	3.40	1.31	3.18	1.66	1.78	1.54	3.62	1.39	2.40
$F_0(T_1)$	150	136	147	136	121	138	119	113	121	132	118	114
$F_0(T_2)$	65	67	66	79	167	169	102	106	102	104	200	188
dF_0	85	69	81	57	-46	-31	17	7	19	28	-82	-74
dF_0/T	60.1	49.1	23.4	16.7	-35.2	-9.7	10.2	3.9	12.3	7.7	-59.0	-30.8
$P_{sb}(T_1)$	9.58	9.92	11.64	11.82	8.44	10.95	6.13	6.47	6.29	5.86	5.83	6.04
$P_{sb}(T_2)$	3.44	3.50	4.82	4.57	4.36	5.10	2.33	1.64	1.42	1.77	4.10	3.96
dP_{sb}	6.14	6.42	6.82	7.25	4.08	5.85	3.80	4.83	4.87	4.09	1.73	2.08
dP_{sb}/T	4.34	4.57	1.98	2.13	3.12	1.84	2.29	2.71	3.16	1.13	1.24	0.87
FPR_1	13.9	10.8	11.9	7.87	-11.3	-5.30	4.47	1.45	3.90	6.84	-47.5	-35.5
FPR_2	3.97	7.63	2.30	4.58	6.48	4.42	3.20	3.02	4.79	3.78	6.25	4.12