SUB-GLOTTAL ACTIVITY DURING SPEECH

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During the last five years studies of sub-glottal activity during speech have taken place in many laboratories. I have been associated with those in the Phonetics and Physiology Departments of the University of Edinburgh (in collaboration with M. H. Draper and D. Whitteridge), the Communication Sciences Laboratory in the University of Michigan (in collaboration with N. McKinney), and the Speech Transmission Laboratory, Royal Institute of Technology, Stockholm. The present paper is a brief consolidated account of all these investigations; it is largely based on a number of previous papers (Draper, Ladefoged and Whitteridge, 1957; Ladefoged, Draper and Whitteridge, 1958; Draper, Ladefoged and Whitteridge, 1959; Draper, Ladefoged and Whitteridge, 1960; Ladefoged, 1960; Ladefoged and McKinney, forthcoming). Details of the techniques, subjects and results are reported more fully in these papers.

The impetus for all these investigations originally came from studying the work of R. H. Stetson (particularly Stetson, 1951). It will be obvious that in the research to be described, we are much indebted to Stetson, who had an intuitive appreciation of many points which, with the means at his disposal, he was unable to substantiate. Furthermore, his shrewd insight often suggested possibilities which we might have overlooked. Stetson's main conclusions were: (1) *Every* syllable is accompanied by a "ballistic chest pulse" produced by the action of the internal intercostal muscles. (2) In "open syllables" (e.g. *tea, spa*) the collapse of the lung is checked by an active inspiratory effort by the external intercostal muscles. (3) In a stressed syllable the action of the internal intercostal muscles is reinforced by the abdominal muscles, led by rectus abdominis.

Since we disagree with all of these conclusions, it is necessary to give a brief review of Stetson's experimental technique. Stetson obtained most of his data from three sources: (1) Kymograph recordings of movements of the body wall. In our view recordings of such movements can hardly be regarded as valid indications of the use of specific muscles. Movements of the chest wall can be brought about in different ways; and the muscles nearest to the moving points are not necessarily in active contraction at all. (2) Recordings of the air pressure in the trachea of tracheotomized subjects. These likewise do not provide direct evidence concerning the muscles which are used to regulate the variations in air pressure. (3) Recordings of the pressure of the air in the lungs as shown by variations in the pressure of an air-filled balloon in the stomach. As we will show, recordings of this kind do not give a satisfactory indication of the pressure of the air in the lungs, and they definitely cannot be used as a complete proof that certain kinds of muscular activity are involved in speech.

The most satisfactory method of obtaining direct evidence concerning the muscles involved in an action is by means of the technique known as electromyography. (See Ladefoged, Draper and Whitteridge, 1958, for a brief account of some of the features of this technique.) Stetson made some recordings of this kind; but in the publications we have examined (which include nearly all the articles by Stetson and his co-workers listed in the bibliography in the second edition of *Motor Phonetics*) there are only two illustrations of these, one showing the syllables *pup, pup, pup* spoken at a slow rate, and the other showing the same syllable *pup* spoken at an increasing rate. These recordings are technically inadequate, and it seems very doubtful whether they do in fact show the activity of the muscles indicated in the legends; and in any case, despite the accompanying text, they do not substantiate the conclusions stated above.

As Twaddell (1953) has pointed out, Stetson's writings are full of unsignaled transitions and other hazards. In addition, for those who are unaccustomed to assessing instrumental techniques, there is the difficulty of deciding whether Stetson is making a statement based on reliable evidence, or whether he is propounding a hypothesis. The major part of Stetson's work should be considered as a hypothesis attempting to explain how the respiratory muscles might be involved in speech, rather than an account of the observed action of these muscles.

THE ACTION OF THE RESPIRATORY MUSCLES

Our first finding in our investigations of the activity of the respiratory muscles during speech was that the amount and kind of activity depended on both the sub-glottal pressure and the amount of air in the lungs. Accordingly, as well as making electromyographic recordings of the various respiratory muscles (generally using concentric needle electrodes), we also had to make simultaneous recordings of the sub-glottal pressure (using a technique to be described below) and of the volume of air in the lungs (using a body plethysmograph connected to a Krogh spirometer).

A typical recording showing the relation between the volume of air in the lungs and the sub-glottal pressure is reproduced in the upper parts of Figure 1. This shows first, a normal breath of a little more than half a litre; second, a deeper inspiration as the subject prepares to speak; and third, a decrease in volume during the utterance (counting from one to 32 at conversational loudness). During the utterance there is an increase in the mean level of the sub-glottal pressure; after the utterance the sub-glottal pressure returns to the previous mean level and respiration continues. Small fluctuations, approximately one for each stressed syllable, can be seen on the pressure record during the utterance.

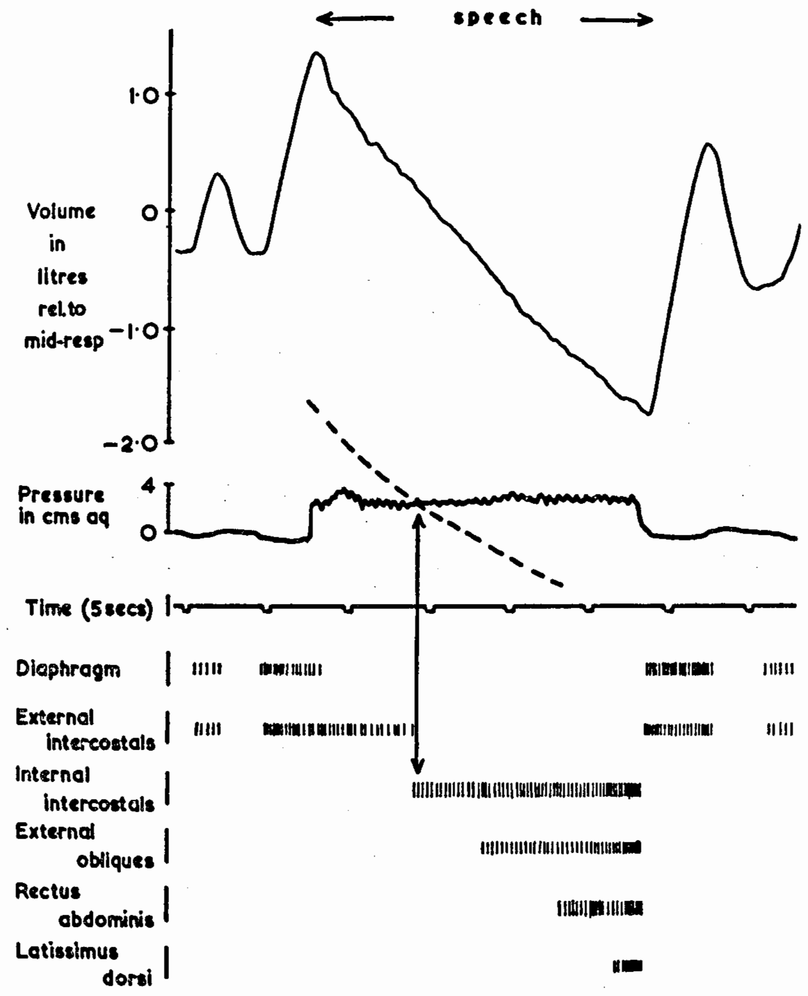

Fig. 1. Upper part of figure, a reproduction of a record of the variations in the volume of air in the lung and the sub-glottal pressure during respiration and speech (counting from one to 32 at a conversational loudness). Lower part of figure, a diagrammatic representation of the muscular activity which was observed to accompany such pressure and volume changes. The dashed line which has been superimposed on the pressure record indicates the relaxation pressure associated with the corresponding volume of air in the lungs. It is equal to zero when the amount of air in the lungs is the same as that at the end of a normal breath. The arrows indicate the moment when the relaxation pressure is no longer greater than the mean pressure below the vocal cords. At this moment the external intercostal activity ceases, and that of the internal intercostals commences.

Before the patterns of muscular activity that accompany these pressure and volume variations can be discussed, we must consider the four factors which may affect the pressure of the air below the vocal cords. (1) The pressure will be decreased by an inspiratory muscular effort, such as lifting the rib cage by means of the external intercostals or contracting the diaphragm. These are both actions which enlarge the thoracic cavity. (2) The pressure will be increased during an expiratory muscular effort which could involve such muscles as the internal intercostals, the external obliques or rectus abdominis, all of which can function so as to decrease the size of the thoracic cavity. (3) The pressure will be affected by the resistance to the air stream at the glottis or elsewhere in the vocal tract. But any variation in the amount of this resistance will affect not only the pressure below the vocal cords but also the rate of flow of air out of the lungs. In the utterance illustrated in Figure 1 the mean rate of flow during a number of consecutive words shows little variation. Consequently the mean resistance cannot have varied during the course of the utterance. (The rate of flow of air during a single word is, of course, far from constant; and the concomitant variations in the amount of resistence may have an effect on the pressure of the air below the vocal cords. But this will not affect the mean or background pressure measured over a period of several seconds.) (4) The final factor affecting the tracheal pressure is the relaxation pressure (Rahn, et al., 1946) that is, the sum of the forces from the abdomen and the forces exerted by stretched lung tissues and the elastic structures of the rib cage. The lungs consist of a number of air chambers contained within elastic membranes which may be likened to toy balloons: when they are inflated they have a tendency to collapse; and the larger the volume of air inside them, the larger the pressure of that air. After a maximal inspiration, when the rib cage has been fully raised and the lungs expanded so that the elastic membranes are considerably stretched, the relaxation pressure may be very large, more than 30 cm of water; but after a normal inspiration, such as occurs in quiet breathing, the relaxation pressure will be only about 5 cm of water.

The four factors affecting the pressure of the air below the vocal cords may be considered by an analogy with a pair of bellows which has (1) a mechanism to pull the handles apart, corresponding to the inspiratory activity of the diaphragm and the external intercostals; (2) an opposing mechanism which will pull the handles together, corresponding to the expiratory activity of the internal intercostals and other muscles; (3) a variable orifice, corresponding to variations in the constrictions at the glottis and in the vocal tract; and (4) a spring between the handles, corresponding to the relaxation pressure, which will exert a considerable force on the handles when they have been pulled wide apart, but which will exert less and less force as the handles come together, and will tend to keep the handles apart, with continually increasing force, as soon as the bellows have been closed beyond their normal unsqueezed position (which corresponds to the position of the lungs at the end of a normal expiration).

The muscles regulating the air pressure during utterances such as that in Figure 1 have to be operated in such a way as to maintain a constant mean background pressure in the lungs, despite a steady decrease in the relaxation pressure or, in terms of the analogy, the effect of the spring. This may be done in various ways. If, after a deep inspiration, the relaxation pressure is much greater than the pressure required below the vocal cords, then inspiratory muscles are used to decrease the pressure in the lungs. As the volume of air in the lung decreases, and thus the relaxation pressure becomes less, the inspiratory muscles usually cease acting and the pressure necessary for speech is maintained by bringing expiratory muscles into action. Towards the end of a long utterance, when the volume of air in the lungs is very small, a large number of expiratory muscles may be needed to keep the mean pressure constant.

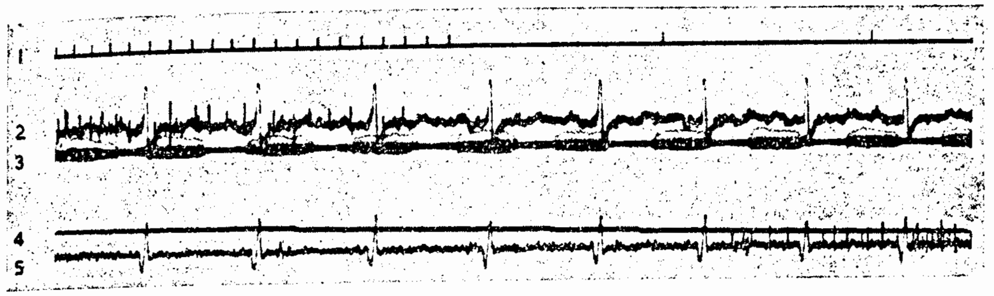

Fig. 2. Part of the display on two twin-beam CRO's during the repetition of the syllable [m ɑ]: (1) time marker, tenth seconds; (2) decreasing activity of the external intercostals (retouched); (3) microphone; (4) volume of air in the lungs; (5) increasing activity of the internal intercostals (retouched).

This pattern of activity was nearly always observed in the subject who produced the utterance shown in Figure 1. The lower part of this figure is a diagrammatic representation of the muscular activity which was typical of his manner of using the respiratory muscles to maintain a steady mean pressure. During the first part of an utterance beginning after a deep inspiration, the external intercostals remain in action, regulating the pressure of the air below the vocal cords by checking the descent of the rib cage. As the volume of air in the lungs decreases, the action of the external intercostals diminishes and eventually ceases altogether when the volume of air in the lungs is slightly less than the volume after a normal inspiration. From this moment on, expiratory activity is needed in order to maintain the pressure below the vocal cords and accordingly the internal intercostals come into action with gradually increasing intensity. When the volume of air in the lungs is a little below that at the end of a normal expiration, the action of the internal intercostals is supplemented by various other muscles, such as the external obliques, rectus abdominis and latissimus dorsi.

The dashed line in the pressure curve in Figure 1 indicates the relaxation pressure which would be produced by the forces acting on the air in the lungs in the absence of any muscular action. At the beginning of the utterance it is about 16 cm of water, and it comes down to zero when the volume of air in the lungs is the same as that at the end of an expiration in normal quiet breathing. It may be seen that the external intercostals provide a checking inspiratory action as long as the relaxation pressure is higher than the required tracheal pressure.

The change-over from the use of one set of muscles, the external intercostals, to the use of another set, the internal intercostals, may be seen in Figure 2. In this case the whole utterance consisted of about 20 repetitions of the single stressed syllable

[ma]; but only that part of the recording has been reproduced which shows diminishing activity of the external intercostals (top trace) followed by increasing activity of the internal intercostals (bottom trace). On both these traces the large waves, recurring at regular intervals of almost two per second, are due to the electrical activity of the heart and are, of course, irrelevant to the present observations. The action potentials are the somewhat smaller vertical spikes. The amplification of the activity recorded from the external intercostals was, on this occasion, slightly greater than that recorded from the internal intercostals.

The external intercostals are the muscles principally used to check the descent of the rib cage. The diaphragm, since it is an inspiratory muscle, might be expected, on the basis of the maintenance of constant mean pressure, also to operate in speech as a checking muscle when the relaxation pressure is more than is needed for a particular utterance. But this does not usually happen. The diaphragmatic activity of 11 subjects has been recorded. In the case of nine of these subjects, the inspiratory activity of the diaphragm diminished rapidly, ceasing completely during the first two or three seconds of an utterance after a maximal inspiration. The action of the external intercostals was not recorded at the same time, but other observations indicate that in such utterances the external intercostals are in operation for considerably longer. Thus it appears that the diaphragm did not play a significant part in the speech of these nine subjects. The other two subjects maintained their diaphragms in action not only during the first part of utterances, when the relaxation pressure was high, but also when there was a smaller volume of air in the lungs. They used increased activity of expiratory muscles to offset the apparently unnecessary or excessive diaphragmatic action.

The results we have been considering so far have been concerned with the general level of activity of the muscles over a period of two or three words. We also found that the activity of the internal intercostals, and occasionally that of some of the other muscles, did not increase uniformly as the volume of air in the lungs became less. Instead, bursts of activity were frequently separated by moments of comparative quiescence, somewhat in the way suggested by Stetson (1951).

In order to study this phenomenon, we made many recordings of the muscular activity which occurred when lists of words were read. We found that Stetson oversimplifies the situation by considering the activity of the intercostal muscles in terms of a series of "ballistic movements", each of which either happens or does not happen. There are actually many other possibilities. Not only can the tension of the intercostal muscles be varied over a large range, but also there can be variations in the rate of change of tension. Sometimes a single increase in tension spans a group of articulations including two vowels separated by a consonant closure (our records show that words such as *pity* and *around* may be spoken in this way); and sometimes there are two separate bursts of activity in what is normally regarded as a single syllable (e.g. in *sport*, *stay*, and other words beginning with a fricative followed by a plosive). It is quite clear that there is no simple correlation between intercostal

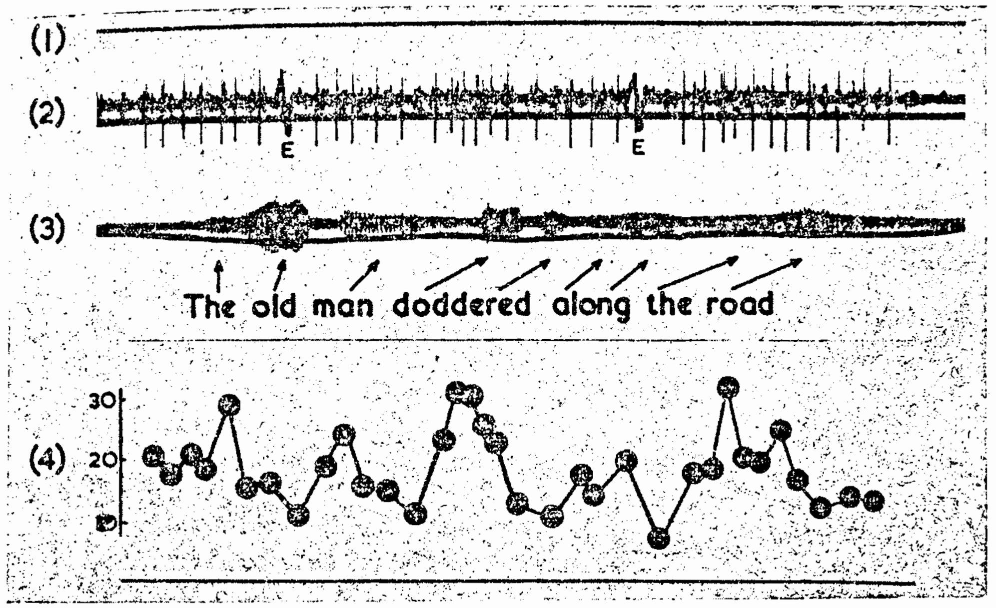

Fig. 3. Internal intercostal activity during speech. (1) Time marker 1/10 and 1/100 seconds. (2) Internal intercostal action potentials (electrical activity associated with the action of the heart indicated by E). (3) Microphone record. (4) Instantaneous frequencies of the single motor unit recorded in (2) in impulses per second.

activity and syllables; and it should be remembered that (as we noted earlier) there is no *evidence* in Stetson to the contrary.

There are, however, two separate phenomena which can be correlated with the bursts of intercostal activity. One is the increase in the rate of flow of air out of the lungs which occurs in some voiceless sounds. We have already mentioned the case of *sport* and *stay*; our records also show major bursts before nearly all [h] sounds (see Figure 2 in Ladefoged, Draper and Whitteridge, 1958). The other phenomenon which may be correlated with the degree of muscular activity is the variation in degree of stress. The activity of the internal intercostal muscles during the phrase "The old man doddered along the road" is shown in Figure 3. Here the variations in muscular activity may be expressed quantitatively, since on this occasion the activity of a single motor unit was recorded. Listeners who heard a tape recording of the utterance agreed that the greatest stress was on the first part of the word *doddered*, and the words *old man* and *road* were also stressed. It can be seen from the graph in the lower part of Figure 3 that the frequency of stimulation of the particular group of muscle fibres being recorded on that occasion is greatest just before *doddered*, and that it is also fairly high immediately before the words *old*, *man*, and *road*.

The internal intercostals were not the only muscles from which we recorded burts of electromyographic activity. Some of our records of subjects reading lists of words show bursts of activity of the external intercostals at the end of isolated, stressed words spoken after a deep inspiration. Typical of these records is Figure 4, which is a

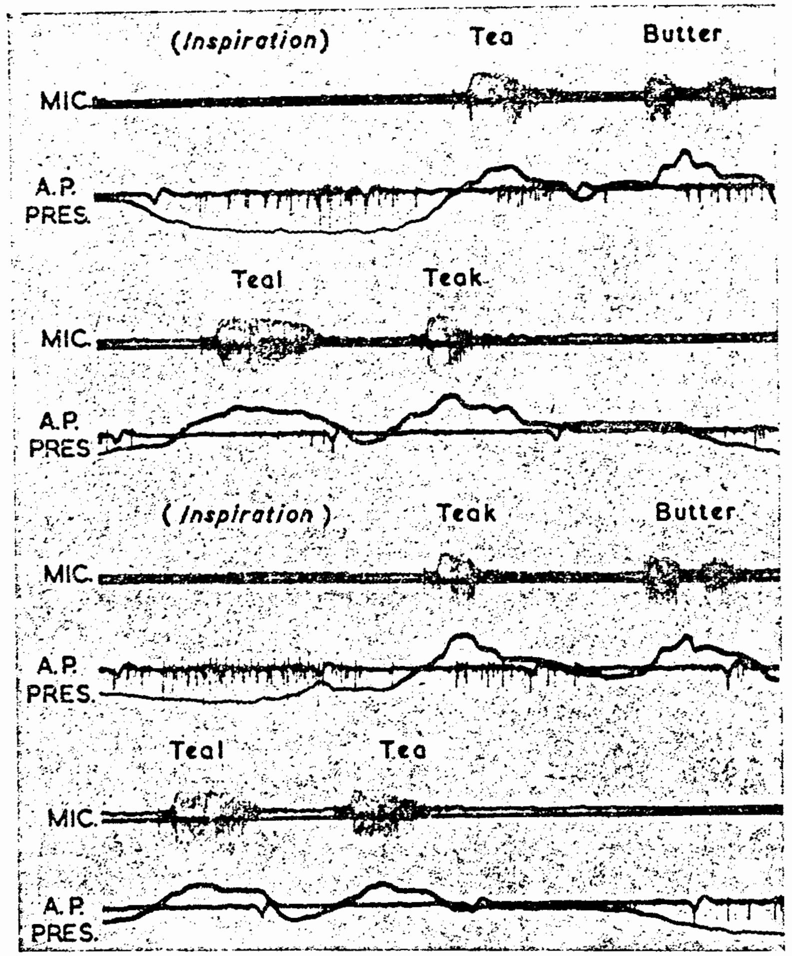

Fig. 4. External intercostal activity when reading lists of words after a deep inspiration. The record, which is continuous, shows the waveforms of the words (MIC); the external intercostal action potentials (A.P.); and the pressure below the voal cords (PRES).

simultaneous recording of the sound waves, the sub-glottal pressure, and the activity registered by a concentric needle electrode in the external intercostals. This muscle is clearly active during the inspiratory phase of respiration when the pressure of the air in the lungs is less than that of the outside air; and there are further bursts of activity towards the end of each of the first two or three words after each inspiration. These bursts occur irrespective of whether the word ends in a consonant closure or not. After the first inspiration the word *tea* is checked by inspiratory activity; but after the second inspiration, when the same word occurs later in the utterance, it is not followed by a burst of external intercostal activity. In the second breath group the word *teak* is arrested by inspiratory activity.

It should be emphasized that in the majority of conversational utterances which we have recorded there is no action at all of the external intercostals. Activity is commonly observed only when talking quietly after a deep inspiration. We could not find any evidence for Stetson's statement that English syllables with a certain kind of phonetic structure are always checked by the action of the external intercostals.

We did not find bursts of activity of rectus abdominis in most of the speech which we recorded. Stetson believed that rectus abdominis reinforced the action of the internal intercostals in stressed syllables. We could find no evidence for this, except perhaps in cases of very emphatic stressing, when the pressure in the lungs may be unusually high. Our observations are that in normal conversational English the abdominal muscles are in action only at the end of a very long utterance. In most utterances the air pressure is regulated solely by the intercostals. Of course on the parade ground, or in other ceremonial languages (Pike, 1957), the abdominal muscles may play a more important part.

STUDIES OF SUB-GLOTTAL PRESSURE

In the course of the research which led to these conclusions, we had to develop a system for measuring sub-glottal (tracheal) pressure. We have found that variations in tracheal pressure can be simply correlated with suitable records of oesophageal pressures.

We are at present obtaining oesophageal pressure records from a small latex balloon 1.5 cm diameter 2.0 cm long, sealed to the end of a polythene catheter of 4 mm bore. The balloon is passed through the nose into the oesophagus until it is just above the bifurcation of the trachea. This is usually about 34 cm from the external nares for a subject 1.8 m tall. When the balloon is filled with 2 ml of air, an approximate sphere of air is held between the thin posterior membrane of the trachea and the vertebral column. Thus any pressure changes in the trachea are transmitted to the air in the balloon. The pressure in the balloon can be recorded in two different ways; the catheter can be connected either to a tambour system enabling records to be made on a kymograph; or, if a more rapid frequency response is required, an electronic transducer system may be used.

Three different sets of investigators have independently shown that appropriate oesophageal pressure records may be used as a good indication of tracheal pressure. Van den Berg (1956) compared oesophageal pressure records with pressures recorded through a catheter passed between the vocal cords on one subject; we (Draper, Ladefoged and Whitteridge, 1958) reported a comparison between oesophageal pressure and tracheal pressure recorded from a needle passed between the third and fourth tracheal rings in the midline on one subject; and Strenger (1959) has reported a similar experiment on five subjects.

We have, however, sometimes noted a slight difference in the recorded value of the two pressures. There are some non-linearities in the oesophageal system, arising

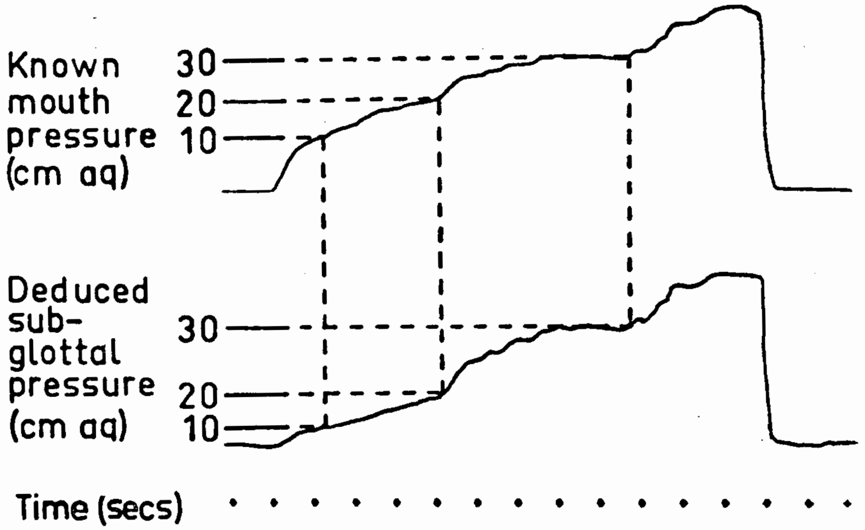

Fig. 5. A record of the variation in pressure in the mouth and in the oesophagus while blowing against a resistance. In these circumstances the mouth pressure is the same as that in the trachea.

from the effect of exerting pressure on the rubber balloon on the end of the catheter. Fortunately there is a simple way of overcoming this difficulty and, in effect, of "calibrating" the oesophageal pressure recording system in terms of the tracheal pressure. We can do this without making a tracheal puncture, since in some circumstances, such as blowing against a resistance while maintaining a very low rate of flow of air, the pressure in the trachea is exactly the same as that in the mouth. Accordingly, at the beginning of each experiment we now make simultaneous recordings while exhaling against a resistance of the mouth and oesophageal pressures; and we calibrate the latter in terms of the former as shown in Figure 5.

Another set of experiments which we have undertaken shows that the position of the balloon in the oesophagus is important. Preliminary experiments indicated that there were considerable differences in the pressures recorded in different parts of the oesophagus, particularly towards the end of a long expiration. At this time, in order to push out the small amout of air left in the lungs at the required pressure, many of the muscles of the thorax, abdomen, neck and shoulder girdle are in action. Thus an inappropriately sited balloon may be considerably influenced by factors such as the rising of the relaxed diaphragm as a result of the greatly increased abdominal pressure, or the descent of the larynx due to the action of the muscles of the neck. These effects were investigated by recording the pressure changes during utterances with the balloon both high in the oesophagus where neck muscles exert effects, and low in the oesophagus where abdominal and other influences predominate, and comparing the records with those obtained with the balloon at the level of the bifurcation of the trachea. Figure 6 shows the results that were obtained.

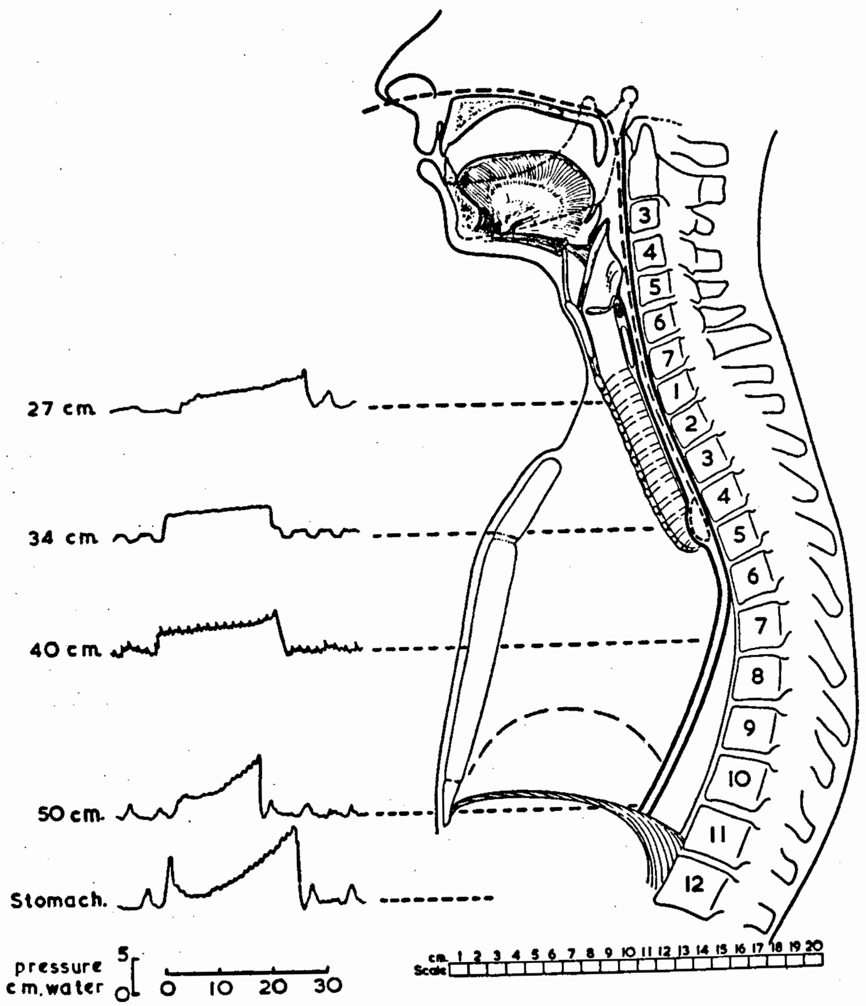

Fig. 6. A diagrammatic scale-drawing to show the position of the balloon in the oesophagus when studying tracheal pressure changes. The bulge of the anterior aspect of the baloon into the thin posterior tracheal membrane has been slightly exaggerated for clarity. The broken line above the diaphragm represents the possible extreme position of the lateral parts of the diaphragm in deep expiration. At the side of the drawing are placed the pressure records obtained during a standard utterance at the levels 27, 34, 40, and 50 cm from the external nares, and from the stomach (60 cm down). The 34-cm level gives the best indication of tracheal pressure changes and, as can be seen, is least influenced by other pressure changes, which become particularly prominent towards the end of a long utterance. (Time scale in seconds.)

At each level the initial pressure changes are much the same, but as expiration proceeds both the records from the upper and from the lower oesophagus show large increases which do not appear to such an extent in the records from the central oesophagus. Increases in the pressure recorded in the upper and lower oesophagus can also be brought about by movements such as bearing down in expiration, or altering the voice quality by pulling the larynx down with the muscles of the neck. However, neither these movements nor those made at the end of a long utterance affect a small inflated balloon at the level of the bifurcation of the trachea. At this level the pressure records are also almost entirely free from artefacts due to heart beats, which can be very inconvenient when the balloon is slightly lower. It must be noted, however, that a balloon anywhere in the oesophagus will be affected by muscular contractions of the oesophagus itself. When these contractions are part of a peristaltic movement they are clearly distinguishable on the records. But sometimes there seem to be slight variations in the oesophageal tone which cause a slow drift in the recorded mean pressure. Provided it is noted, and appropriate changes in the base line are made, this drift is of no importance when examining the comparatively rapid changes in pressure which occur during speech.

We have used this system of recording sub-glottal pressure in a number of experiments. In one such experiment we compared the sub-glottal pressure and the acoustic intensity in twelve examples of each of the words *bee*, *bay*, *bar*, *bore* and *boo*. The results are shown graphically in Figure 7. It may be seen that in the middle part of the vocal range (i.e. for pressures from 10 to 30 cm aq) there is a fairly linear relationship for any one vowel between the intensity in db and the logarithm of the sub-glottal pressure; consequently there is an exponential relationship between the sound pressure level and the sub-glottal pressure. A line with a slope of 1.5 is drawn through the appropriate points for the vowel /ɑ/ and another one through the combined points for /i/ and /u/. The distance between these two lines shows that a given pressure between 10 and 30 cm aq will produce an /ɑ/ which has a little more than 5 db greater intensity than an /i/ or an /u/ produced with the same pressure. The intensities of the vowels /e/ and /ɔ/ for a given sub-glottal pressure are usually between those for /ɑ/ and /i, u/; but the points for /e/ are less well represented by a straight line in these coordinates, and the intensities are often somewhat higher than might have been expected. In an investigation in which the speaker tried to maintain a constant vocal effort while pronouncing a series of vowel sounds, Lehiste and Peterson (1959) found that the difference in intensity between the vowels /i/ and /a/ was between 5 and 6 db; but the intensity of the vowel /e/ was only about 1 db more than that of /i/.

In a second experiment examples of the vowel /ɑ/ were pronounced on a monotone at a variety of pitches and loudnesses. The sub-glottal and mouth pressures were recorded as in the previous experiment. The rate of flow of air out of the mouth was also measured: the subject wore a face mask with a fine wire gauze in the outlet tube; the pressure drop on either side of this gauze was recorded and used as a measure of the rate of flow.

The subject tried to say the vowel at various different loudness levels, making no effort to control the pitch but allowing it to be determined by the sub-glottal pressure (which was, of course, constant for any one loudness level). Figure 8 shows the relationship between the sub-glottal pressure and the rate of flow of air in these circumstances. It will be seen that there is no very precise relationship, probably owing

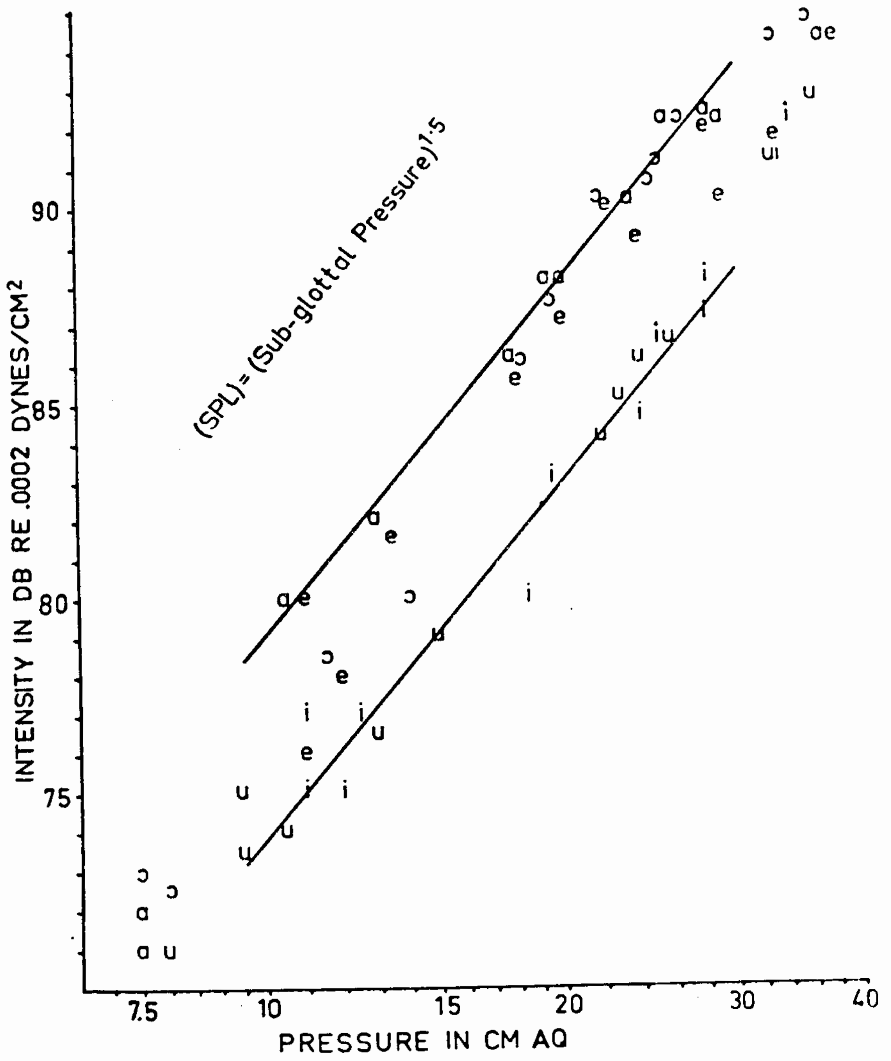

Fig. 7. The relation between sub-glottal pressure and intensity for 12 examples of each of the words *bee, bay, bar, bore, boo.*

to the different modes of vibration of the glottis that occurred; but very approximately, the flow increases linearly with the pressure. Van den Berg (1956) has also suggested that the rate of flow is approximately linearly related to the sub-glottal pressure. The work done in producing a sound is proportional to the product of the sub-glottal pressure and the rate of flow of air through the glottis. Considering this and the relation shown in Figure 8 we may conclude that physiological effort is approximately proportional to the square of the sub-glottal pressure. As a result of the previous experiment we found that :- (Sound Pressure Level) ≅ (Sub-Glottal Pressure)$^{1.5}$. Taking the two experiments together we may say that :- (Physiological Effort ≅ (Sound Pressure Level)$^{1.3}$.

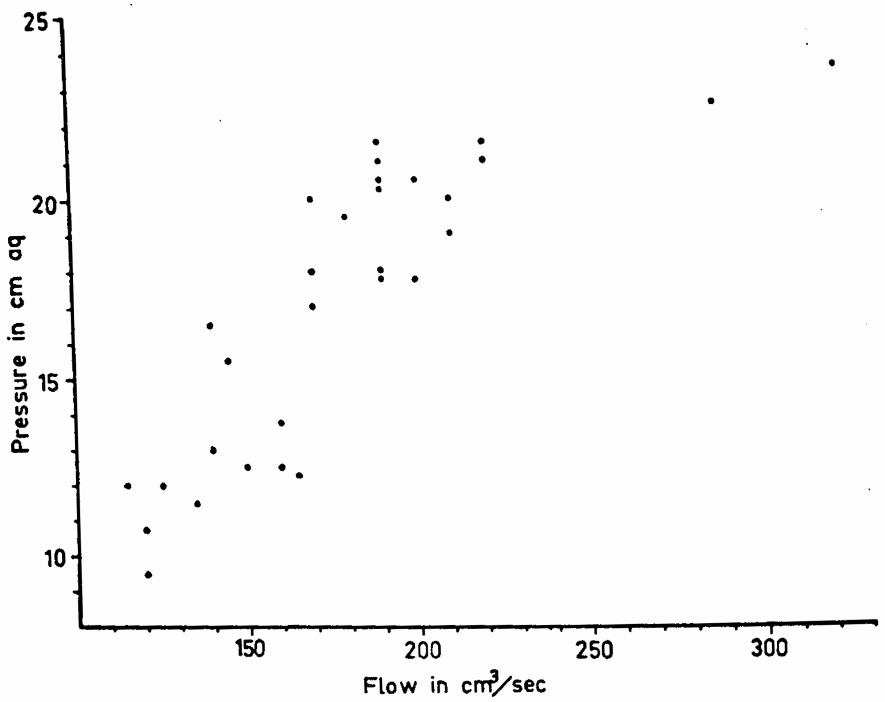

Fig. 8. The relation between sub-glottal pressure and rate of flow of air when saying the vowel [a].

While studying this relationship between pressure and flow we noticed (as many others have done) that variations of these parameters affect the pitch. As the pressure and flow increase the rate of vibration of the vocal cords also increases, both because the increased flow produces an increased Bernoulli effect (van den Berg et al. 1957) so that the vocal cords are drawn together more quickly, and because the increased pressure also results in their being blown apart after a shorter closed phase. Van den Berg (1957) reported an experiment in which he recorded the change in frequency which occurred when a subject singing a note was pushed in the stomach. We attempted to quantify this effect by a similar experiment. The subject sat with his eyes shut, and tried to maintain a constant note while one of the experimenters pressed against his chest at unpredictable moments. Figure 9 shows part of a record of the variations in sub-glottal pressure, rate of flow and fundamental frequency which occurred. It may be seen that the change in fundamental frequency must be due to the sub-glottal changes rather than to a reflex action affecting the tension of the vocal cords, since in all known human reflexes the response occurs about 100–200 msec after the stimulus. The fact that there is *no* delay between the fundamental frequency changes and the sub-glottal pressure changes indicates that there must be a direct link between the two. The results of a large number of observations are shown graphically in Figure 10. On this subject a change of sub-glottal pressure of about 7.5 cm water produces a change in pitch of about half an octave.

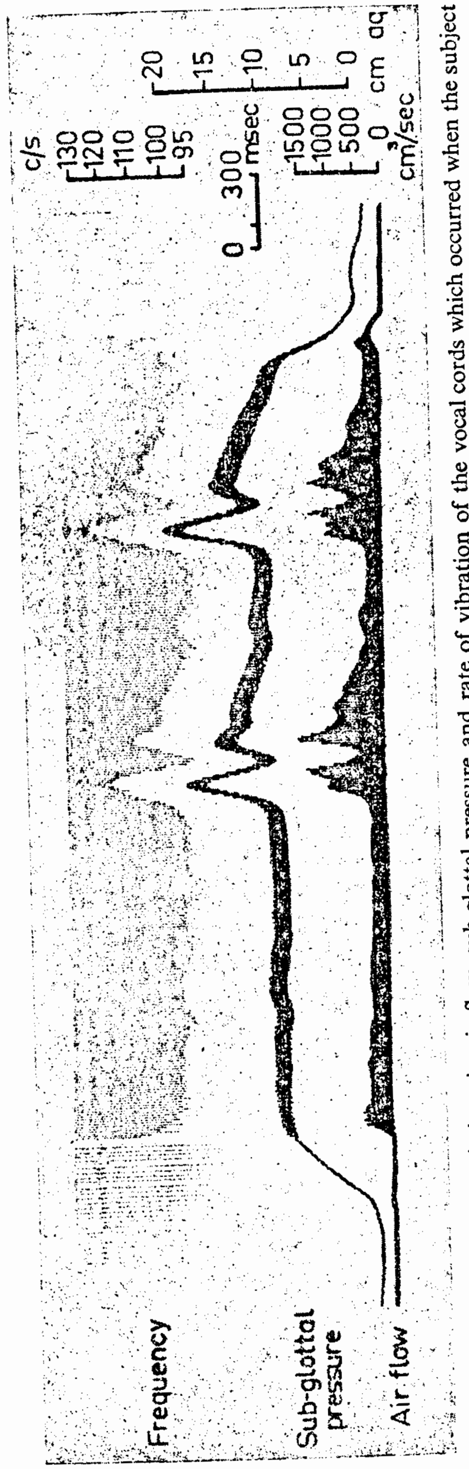

Fig. 9. The simultaneous variations in air flow, sub-glottal pressure and rate of vibration of the vocal cords which occurred when the subject tried to maintain a steady note while one of the experimenters unexpectedly pushed against his chest, twice.

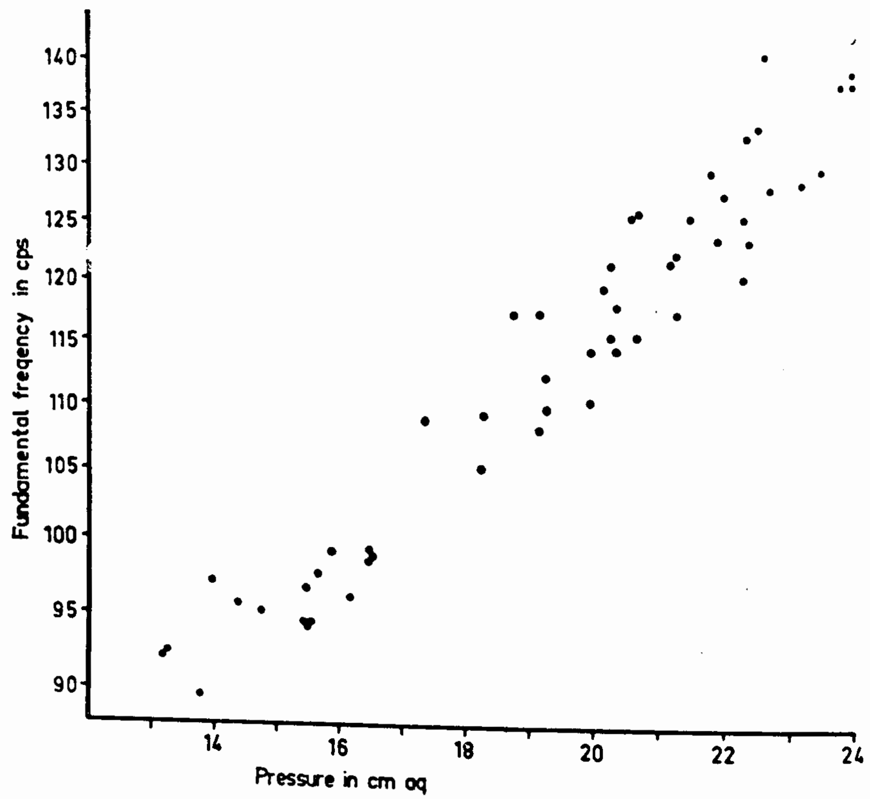

Fig. 10. The relation between sub-glottal pressure and pitch derived from a number of records of the form shown in Figure 9.

In another experiment a test tape was constructed from the twelve examples of each of the five words *bee*, *bay*, *bar*, *bore*, *boo* for which the sub-glottal pressures and intensity were known, plus an additional five words which had been recorded at the same time. We wanted subjects to judge the loudness of all these words in a normal speech context. Accordingly we made 65 copies of a single utterance of the phrase *Compare the words*: *bar and*... About 200 msec after each of these phrases we spliced one of the test words.

Thirty students assessed the relative loudness of these words. Figures 11 and 12 show the results.* When the geometric means of the judgments of the 30 subjects are plotted against the intensities of the words, the points are comparatively clustered for the extreme judgments, but in the middle of the range they are well separated, the points for *bee* and *boo* almost always being judged as being much louder than the examples of *bar* with the same intensity. Conversely, when loudness is plotted against sub-glottal pressure, the points are scattered at the end of the range, but there is a fairly good correlation between judgments of loudness and measurements

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* The data shown here are slightly misdrawn; new figures have been prepared for Ladefoged and McKinney (forthcoming).

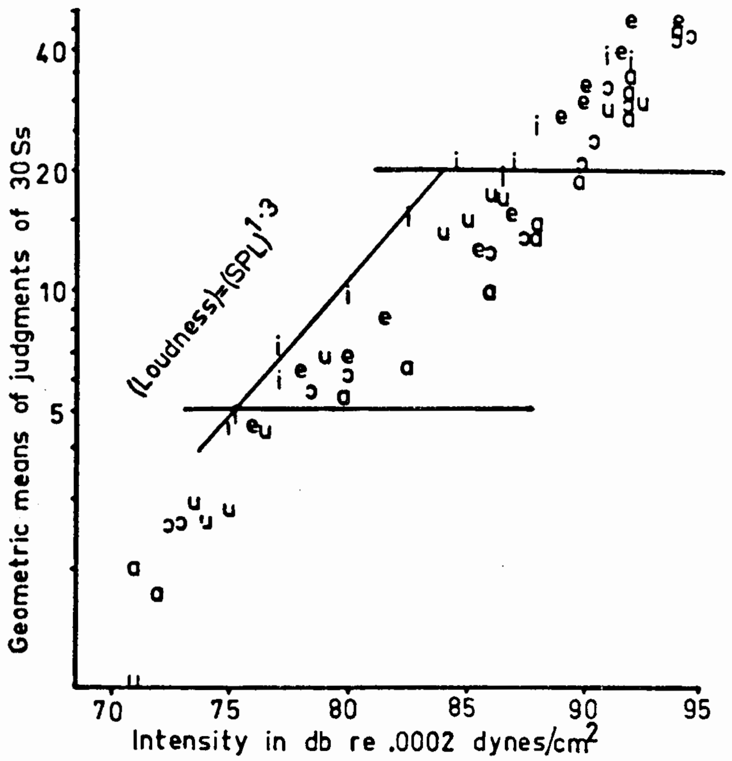

Fig. 11. The relation between loudness and intensity for the words shown in Figure 7.

of sub-glottal pressure for sounds which are considered as being between half as loud and twice as loud as the reference sound. Thus the examples of *bee* which have sub-glottal pressures of 18, 19, 20 and 24 cm aq are judged as being equally loud as the corresponding examples of *bar* which have similar pressures, despite the fact that there is a difference in intensity of at least 5 db between the members of each of these four pairs of words. We may conclude that words which are in the region of those that might occur in ordinary speech tend to be judged in one way; but those which have pressures (or intensities) differing greatly from those possible in a normal speech context are regarded simply as noises and judged in a different way.

We have already seen that physiological effort is proportional to the square of the sub-glottal pressure. The line through the points in Figure 12 indicates the extent to which loudness is also proportional to the square of the pressure. In the middle of the range many of the points come very close to this line. It would appear that the perceived loudness of words which are within the normal speech range is largely dependent on the physiological effort required to produce them.

Our investigation of normal speech is only now leading us to a point where we can begin making an intensive study of the rapid sub-glottal pressure variations which occur during the pronunciation of words and phrases. We now have records of

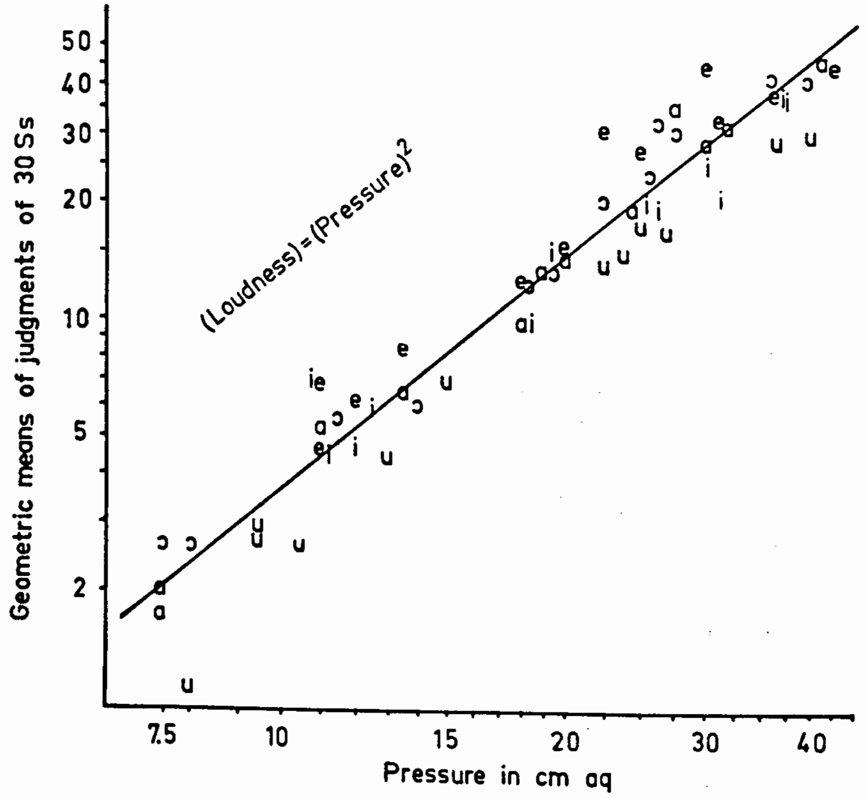

Fig. 12. The relation between loudness and sub-glottal pressure for the words shown in Figure 7.

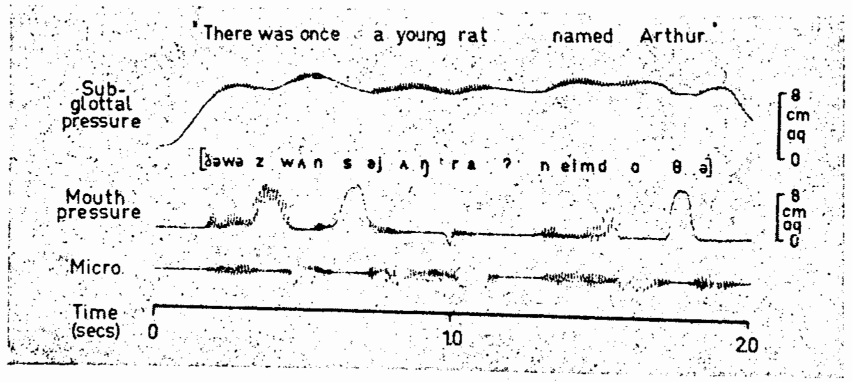

Fig. 13. Mouth and sub-glottal pressures during the pronunciation of a short phrase.

sub-glottal pressure during the pronunciation of many hundreds of words and phrases. As might be expected on the basis of the results of the investigation of muscular activity reported above, we do not find a peak of sub-glottal pressure corresponding to each syllable. Figure 13 shows the pressure variations which occur when reading a short phrase in a normal conversational tone. It may be seen that the syllable *Once*, which carried the major sentence stress, has the major peak of sub-glottal pressure; and the stressed syllables *young*, *rat* and *Ar*(*thur*) are also accompanied by peaks of sub-glottal pressure. But there is only one peak for *There was*, and no separate peak for *a*. So it seems reasonable to conclude that there is sub-glottal activity which may be correlated with phonetic stress; but there is insufficient basis for a chest pluse theory of the syllable.

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