THE EFFECT OF VARYING LUNG VOLUME ON INTRAORAL AIR PRESSURE AND AIR FLOW RATE: A REPORT OF THREE EXPERIMENTS

A THESIS

Submitted to

Michigan State University

in partial fulfillment of the requirements

for the degree of

MASTER OF ARTS

Department of Audiology and Speech Sciences

SUZANNE M. HAMZIK

1975

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To determine the effect of lung volume on intraoral air pressure, volume velocity, and intraoral air pressure duration, five normal adult females participated in three experiments. The subjects performed required speech tasks on four vital capacity percentages. Results indicated that intraoral air pressure and intraoral air pressure duration did not fluctuate dramatically as a function of lung volume, whereas volume velocity did. The results are discussed with reference to potential feedback strategies for maintaining target pressures in the face of fluctuating lung volume.

Accepted by the faculty of the Department of Audiology and Speech Sciences, College of Communication Arts and Sciences, Michigan State University, in partial fulfillment of the requirements for the Master of Arts Degree.

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Sincere appreciation to my good friends and colleagues who participated in this study and who often gave me support and encouragement.

Finally, my love and gratefulness to my parents for their confidence in my abilities and who always told me, "You can do it."

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CHAPTER I

INTRODUCTION

In its capacity as generator for the driving forces required in speech production, the respiratory system undergoes a rather complex series of musculo-mechanical adjustments for even the simplest of utterances. Generally, these adjustments are accomplished to provide a relatively constant subglottic air pressure for conversational speech at normal loudness levels (Netsell, 1969). The adjustments are accomplished by muscular activity which counteracts the passive recoil forces of the respiratory apparatus. At extremes of the vital capacity (VC), these recoil forces are increased and concomitantly greater muscular effort is required. It must be recognized that subglottic pressures may change as a function of overall intensity levels (Hixon, 1973), transient alterations in stress (Ladefoged, 1967; Netsell, 1969), and speaking effort (Prosek and Montgomery, 1969).

It has been suggested that despite the transient variations in subglottal pressure which characterize conversational speech, there is an average or background pressure upon which these brief "pulsatile" variations are superimposed (Hixon, 1973; Hixon et al., 1973). Inherent within this suggestion is the possibility that speakers establish a priori a target subglottic pressure which will satisfy the requirements for a proposed utterance (e.g., loud, soft, effortful, etc.). Once established, the respiratory system operates to maintain the target pressure in the face of fluctuating lung volumes. Both Ladefoged (1967) and Netsell (1969) have lent credence to this suggestion by reporting relatively constant subglottic pressure levels regardless of the phonetic element produced. Small decrements in subglottic pressure were recorded during the plosive stage of voiceless stop consonants which Netsell interpreted as passive responses to changes in supraglottal resistance.

If the assumption of a target subglottic pressure is accepted, it implies a relatively effective sensory feedback system which operates to maintain the target pressure through continuous adjustments in muscular effort. The nature of such a feedback system is currently unknown, but several physiological mechanisms could contribute sensory data. First, Wyke (1966, 1969) has suggested that laryngeal mucosal mechanoreceptors, in response to air pressure fluctuations within the larynx, may provide some reflex adjustment in the respiratory musculature. Second, supraglottal feedback systems may also influence respiratory adjustment. Hutchinson and Putnam (1974) reported aerodynamic changes during oral sensory deprivation which might be interpreted as the result of subglottal compensations in the face of a reduced supraglottal feedback load. Specifically, there was evidence of an increased respiratory driving force. Finally, Prosek and House (1975) have suggested that the principal sensory feedback parameter may be volume velocity and that vocal tract pressures result from this flow rate. Sears and Newsom-Davis (1967) also emphasized the primacy of air flow rate and suggested that the respiratory muscles, particularly the intercostals, respond reflexively to fluctuating loads on the respiratory apparatus thereby satisfying the demand for a constant air flow rate.

In view of the dependence of subglottic pressure upon respiratory adjustments and the organization of these adjustments on the basis of lung volume and recoil forces of the respiratory apparatus, it is surprising that there are incomplete data relating the effects of different lung volumes on pressure and flow rate events within the vocal tract. It is recognized that speech is generally accomplished with midrange lung volumes simply because at the extremes of VC, the respiratory mechanism is much less compliant and, consequently, more difficult to control (Hixon, 1973). However, since it is possible to generate speech beyond mid-volume ranges, the question arises as to whether or not speakers will achieve pressure targets at respiratory extremes which are comparable to those attained in the midvolume range. If subjects do preserve similar pressure configurations throughout the range of VC, it would support the existence of a relatively well developed adaptive feedback system. However, high variability in pressure values could suggest a relatively trivial role for sensory feedback or a feedback system whose adjustments become progressively more difficult to achieve in the presence of extreme mechanical constraints.

Statement of Problem

The purpose of this study was to assess the effects of variations in lung volume on selected aerodynamic variables in an effort to clarify the role of sensory feedback in the control of respiratory events during speech. For purposes of this study, it is important to recognize that, to a first approximation, subglottic air pressure and supraglottic air pressure are equivalent during production of voiceless consonants (Netsell, 1969; 1973). This fact permits a limited evaluation of subglottic air pressure without the necessity of a tracheal puncture. In addition to measurement of vocal tract pressure, simultaneous measures of oral volume velocity were obtained in the present study to determine the relation of pressure and flow events as a function of varying lung volumes. Finally, in anticipation of certain temporal adjustments resulting from mechanical constraints at respiratory extremes and oxygen requirements at low lung volumes, duration variables were also investigated. The general purpose of this study was completed through three separate experiments, the rationales for which will be explained in the appropriate sections to follow.

CHAPTER II

EXPERIMENTAL PROCEDURES

General Method

Subjects

Five healthy young adult females (mean age 23.2) served as subjects in the present study. All had vital capacities (VC) within normal limits and reported no history of respiratory pathology, allergies or recent upper respiratory infection (within one month prior to the experiment). None reported any history of speech or hearing problems. All spoke general American English, Four of the subjects were from the Midwest and one from the East. A further criterion for inclusion in the study was the subject's ability to complete two speech tasks representative of actual experimental requirements on 10% of their VC's: (1) the first 48 syllables of Lincoln's Gettysburg Address and (2) ten repetitions of the syllable /tʌ/ at a rate of 1/second.

Equipment

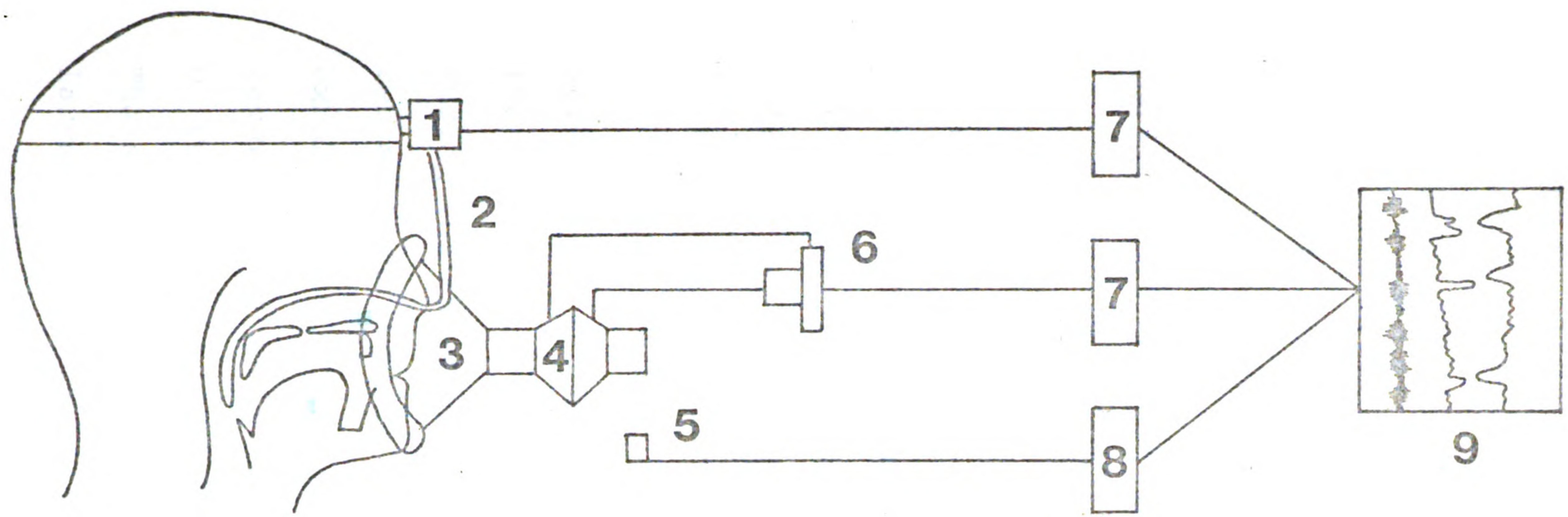
Determination of VC and experimental lung volumes was accomplished using a nine-liter respirometer (Collins, P-900). Evaluation of the response characteristics of the respirometer revealed speed accuracy to be within ±1%. The volume recording was found to average 12 cc/sec. less than actual volume input and this correction factor was taken into consideration for all volume measures.

To sense intraoral air pressure, a catheter (#12 French) was inserted through the nasal cavity until it was visible in the oropharynx with the orofice perpendicular to the egressive flow of air. The catheter was attached to a pressure transducer (Stratham, PM131TC ± 5-350), amplified (Honeywell, Accudata 113 Bridge Amplifier), and recorded on one channel of an optical oscillograph (Honeywell Visicorder 1508B). Air flow rates were obtained using a large, tightly-fitting face mask coupled to a pneumotachograph (Hewlett-Packard, custom made). This pneumotachograph houses a mesh screen which provides a resistance to air flow. The drop in pressure across the screen was assumed to be linearly related to volume velocity. In the present study, the pressure drop was sensed by a differential pressure transducer (Statham, PM15E ± 0.04 PSID), amplified (Honeywell, Accudata 113 Bridge Amplifier), and recorded for a second channel of the oscillograph. During all experimental sessions, the screen was heated with a small electric current to prevent resistance changes from accumulation of moisture. Simultaneous oscillographic and tape recordings of the audio signal were obtained using a high quality microphone placed near the distal end of the pneumotachograph. The instrumental array for this experiment is presented in Figure 1.

Static calibration of the pressure system was accomplished using a U-tube water manometer. Air flow rate callibrations were completed with a flow rotor meter (Fisher-Porter, 10A1027). Known pressure and volume velocity inputs were equated with appropriate galvanometer deflections prior to each experimental session.

The frequency response of the pressure system was determined using the method described by Prosek and House (1975).

The catheter was sealed in a 1/8 inch microphone adapter (Bruel and Kjaer pistonphone, #4220). The pistonphone emitted a constant sound pressure output of 124 dB. The input voltage to the pistonphone was varied using a variable DC power supply (EICO #1020) which resulted in alterations in the frequency of the output. The frequency range from 15 to 200 Hz was sampled in approximately 10 Hz increments and variations of sound pressure in the coupler were recorded on the optical oscillograph. The frequency response of the pressure system was essentially flat through the



1 Pressure Transducer
2 Catheter
3 Face Mask
4 Pneumotachograph
5 Microphone
6 Pressure Transducer
7 Bridge Amplifier
8 Galvonometer Amplifier
9 Optical Oscillograph

FIGURE 1 : INSTRUMENTAL ARRAY USED FOR RECORDING AERODYNAMIC DATA

frequency range tested except for a resonance at 100 Hz. This was of little concern since the pressure variations of interest in speech are of a magnitude less than 50 Hz (Prosek and House, 1975).

A similar procedure was used for the flow rate system with one lead of the differential transducer sealed in the adapter and the other plugged.

Experimental Procedure

For all three experiments, the required speech tasks were completed at each of four vital capacity percentages (10% VC, 40% VC, 70% VC, and 100% VC). These percentages were selected to represent both extreme and midrange lung volumes. The percentages were calculated from an average of five VC maneuvers completed by each subject prior to the experiment sessions.

When the average VC and selected percentages were determined for each subject, they were marked on the respirometer recording paper to serve as targets during the experimental session. For a given VC percentage, the subject was instructed to inhale maximally, exhale into the respirometer until the pre-set recording pen deflected from the 100% VC mark to the 0% VC mark, and inhale back up to the target percentage. The subject then held her breath by occluding the larynx, placed her nose and mouth tightly into the facemask, and completed the required speech task. The three experiments were conducted in the same order for all subjects, buth the target volumes were randomized for each subject during each experiment to control for sequencing effects.

Three aerodynamic parameters were investigated for all three experiments: (1) peak intraoral air pressure defined as the maximum excursion of the pressure trace from the established baseline for the selected phoneme, (2) peak air flow rate defined as the maximum excursion of the pressure trace from the established baseline for the selected phoneme, and (3) intraoral air pressure duration defined as the duration of the pressure pulse for the selected phoneme as measured along the established baseline. The point of onset was determined as the point of departure of the pressure trace from the baseline, and the offset was established at that point where the pressure trace returned to the baseline or the steady state of the following phoneme. The total pressure duration was further divided into onset duration (duration from point of onset to point of peak pressure) and offset duration (duration from point of peak pressure to point of offset). Since some of the measures involved subjective decisions by the experimenter, measures of inter- and intrajudge reliability were computed by selecting 16 traces at random for analysis by another trained person. In addition, the experimenter re-measured these traces at least one week following the first measurement. Interjudge reliability for peak pressure ($\pm$ 1 mm H_2O) was 93%, for peak air flow rate ($\pm$ 10 cc/sec) was 93%, and for total duration ($\pm$ 20 msec) was 93%. Intrajudge reliabilities were 93%, 95%, and 95%, respectively.

CHAPTER III

INDIVIDUAL EXPERIMENTAL RESULTS

Experiment I

Rationale

The purpose of this study was to observe the relation of intraoral air pressure, intraoral air pressure duration and air flow rate as functions of various lung volumes.

Procedures

Two phonemes, /t/ and /s/, were chosen for analysis. These phonemes were selected primarily because they are voiceless and hence, the intraoral pressures recorded would be very nearly identical to the subglottic pressures generated. Moreover, they are representative examples of two different consonant classes (stop and fricative). These two phenemes were considered a sufficient sample inasmuch as previous research has established that phonemes in the same consonant class have similar aerodynamic properties (Arkebauer et al., 1967; Isshiki and Ringel, 1964; Hutchinson, 1973). The phonemes were spoken in the nonsense word /haCʌC/ which appeared in the neutral carrier phrase "say ______ again." The subjects were requested to say each phrase three times without inhaling, for each of the four lung volumes studied. (See Appendix A for instructions to the subjects.)

Results and Discussion

Figure 2 depicts the intraoral air pressure and air flow rate results of Experiment I. (The raw data are provided in Appendix B.) Inspection of Figure 2a reveals that intraoral air pressure values fluctuated slightly as a function of lung volume for both /t/ and /s/. Specifically, both phonemes were associated with little change between 10% and 40% VC as well as between 70% and 100% VC. However, a slight increase in peak pressure (approximately 1 cm H_2O) occurred between 40% and 70% for both phonemes. Therefore, the intraoral air pressures remained relatively constant at both low and high lung volumes. However, the transition from low to high volumes was marked by an increase in peak pressure.

Air flow rate data are presented in Figure 2b. (The raw data appear in Appendix B.) Air flow rates varied directly as a function of lung volume. This was particularly evident in the case of /t/ where the air flow rate difference between 10% and 100% VC was over 700 cc/sec. The results for /s/ were qualitatively similar to those for /t/ but the magnitude of change

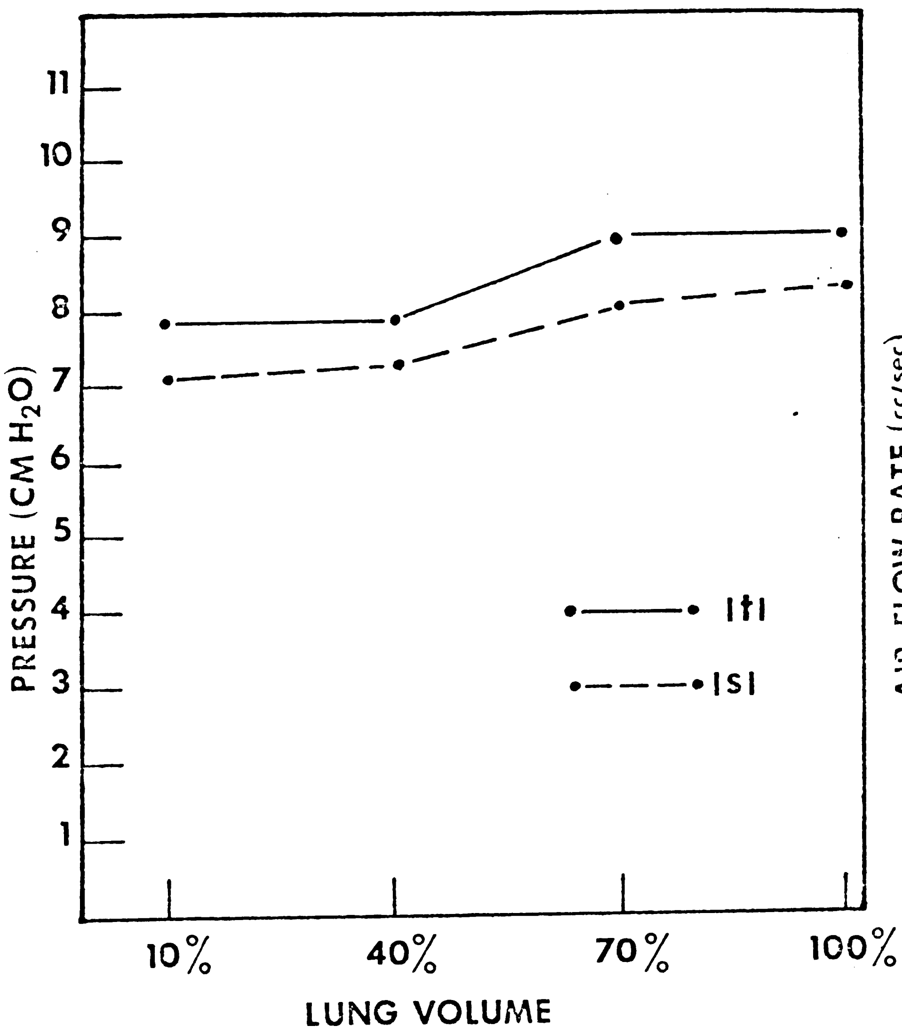


FIGURE 2a: INTRAORAL AIR PRESSURE VALVES AS FUNCTION OF VARYING LUNG VOLUME DURING PRODUCTION OF / t / AND / s /.

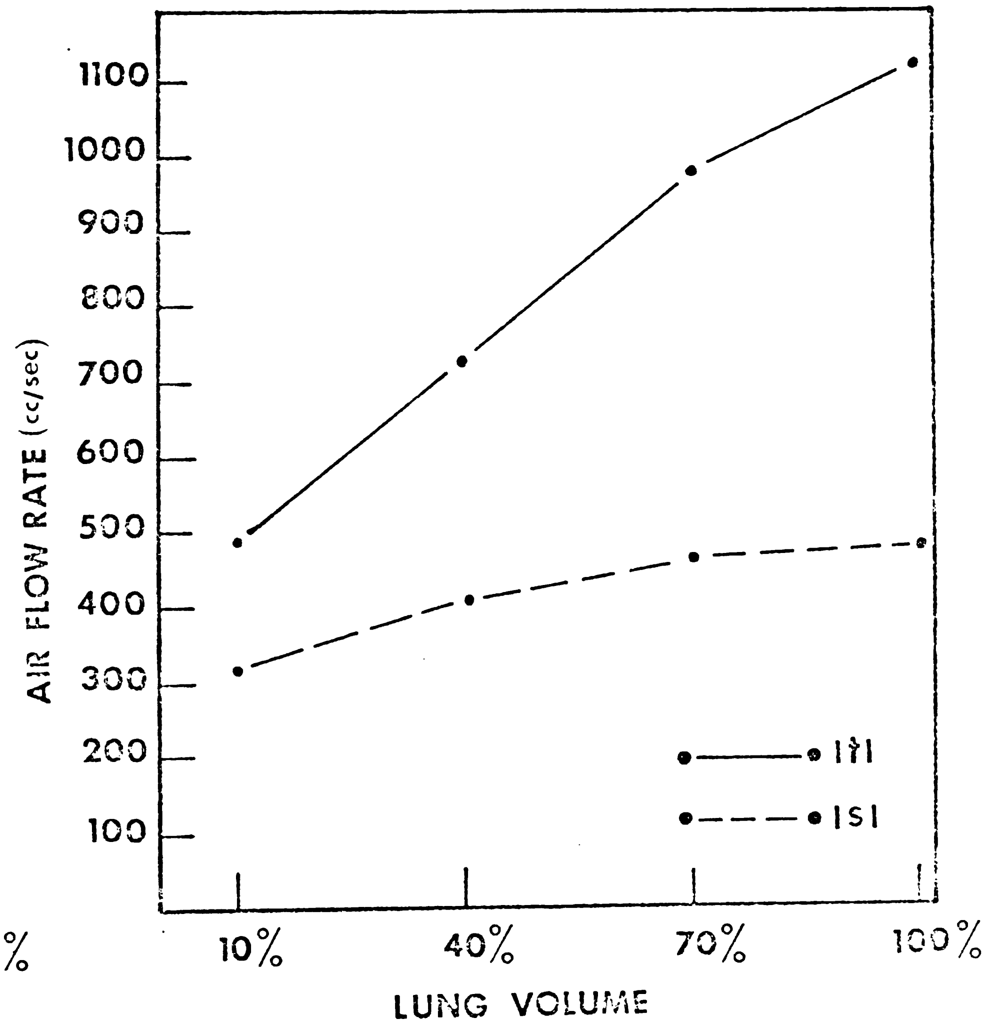


FIGURE 2b: AIR FLOW RATE VALVES AS FUNCTION OF VARYING LUNG VOLUME DURING PRODUCTION OF / t / AND / s /.

from 10% to 100% VC was considerably less pronounced (approximately 170 cc/sec).

Intraoral air pressure duration data are summarized in Figure 3. For both phonemes, the onset duration was larger than the offset duration. No remarkable fluctuations in onset and offset values resulted as a function of changes in lung volume except in the case of offset duration for /t/. In this instance, there was a slight increase in duration with increases in lung volume. This may have resulted from the increased intraoral air pressure associated with larger lung volumes. Perhaps the greater pressures simply requred longer venting times after release of the constriction. The total pressure durations also increased slightly as a function of lung volume, but the magnitude of change was relatively small (less than 20 msec).

By way of summary, the results of Experiment I have demonstrated very slight increases in peak intraoral air pressure and air pressure durations with increases in lung volume. A much more obvious change occurred with the variable of air flow rate where the increments in lung volume resulted in higher volume velocities, particularly for the phoneme /t/.

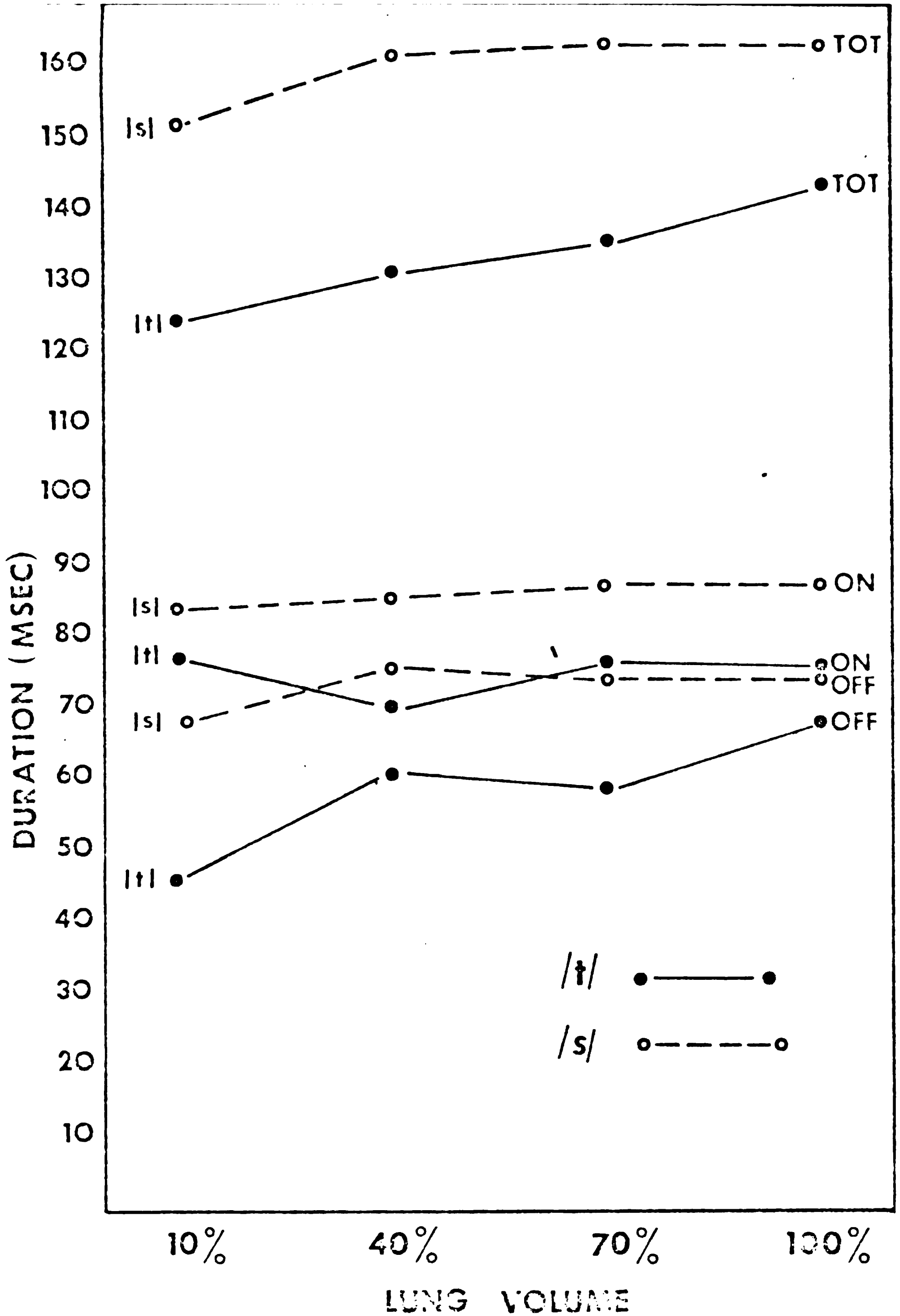


FIGURE 3: INTRAORAL AIR PRESSURE DURATION DATA OF I t I AND I s I.

Experiment II

Rationale

Brown and McGlone (1969) reported that peak intraoral air pressure fluctuates little with repetition of the same phoneme or when that phoneme is placed in sentence context. The results of Brown and McGlone's study would support the concept of a target vocal tract pressure which the subject assumes in the production of a given phoneme. Whereas the study by Brown and McGlone was well controlled in terms of vocal intensity and fundamental frequency, no consideration was given to the influence of varying lung volumes. Therefore, the purpose of Experiment II was to replicate a portion of the study by Brown and McGlone controlling the variable of lung volume and extending their observations to the additional parameters of intraoral air pressure duration and air flow rate.

Procedures

As in the study by Brown and McGlone, the speech stimulus used in Experiment II was the syllable /tʌ/. All subjects were required to produce this syllable in synchrony with light-flashing metronome at the rate of 1/sec. The subjects completed this task for each of the four lung volumes studied. The subjects were not permitted to inhale between productions of /tʌ/.

(See Appendix A for instructions to the subject.) For purposes of convenience in analyzing the data, the ten productions of /tʌ/ at each lung volume were grouped into five pairs of two productions each. The data were then averaged over the two sets of values in each pair.

Results and Discussion

The results for the peak intraoral air pressure parameter are presented in Figure 4. (See Appendix C for the raw data.) Visual examination of this figure reveals considerably higher peak pressures for the first paired productions regardless of lung volume. However, there was very little change in pressure for any lung volume from the second through the fifth pairs. Moreover, with the possible exception of 10% VC, the pressures obtained during production of the last five pairs of /tʌ/ were very similar for all lung volumes. The values for 10% VC were approximately 1 cm H_2O below those recorded for the other lung volumes.

The results of the air flow rate measures are provided in Figure 5. (See Appendix C for raw data.) Two general observations emerged from inspection of this figure. First, there was a general decrease in volume velocity with continued production of /tʌ/. Second, there appeared a direct relationship between lung volume and air flow rate which was generally preserved across paired productions of /tʌ/. That is, higher lung volumes

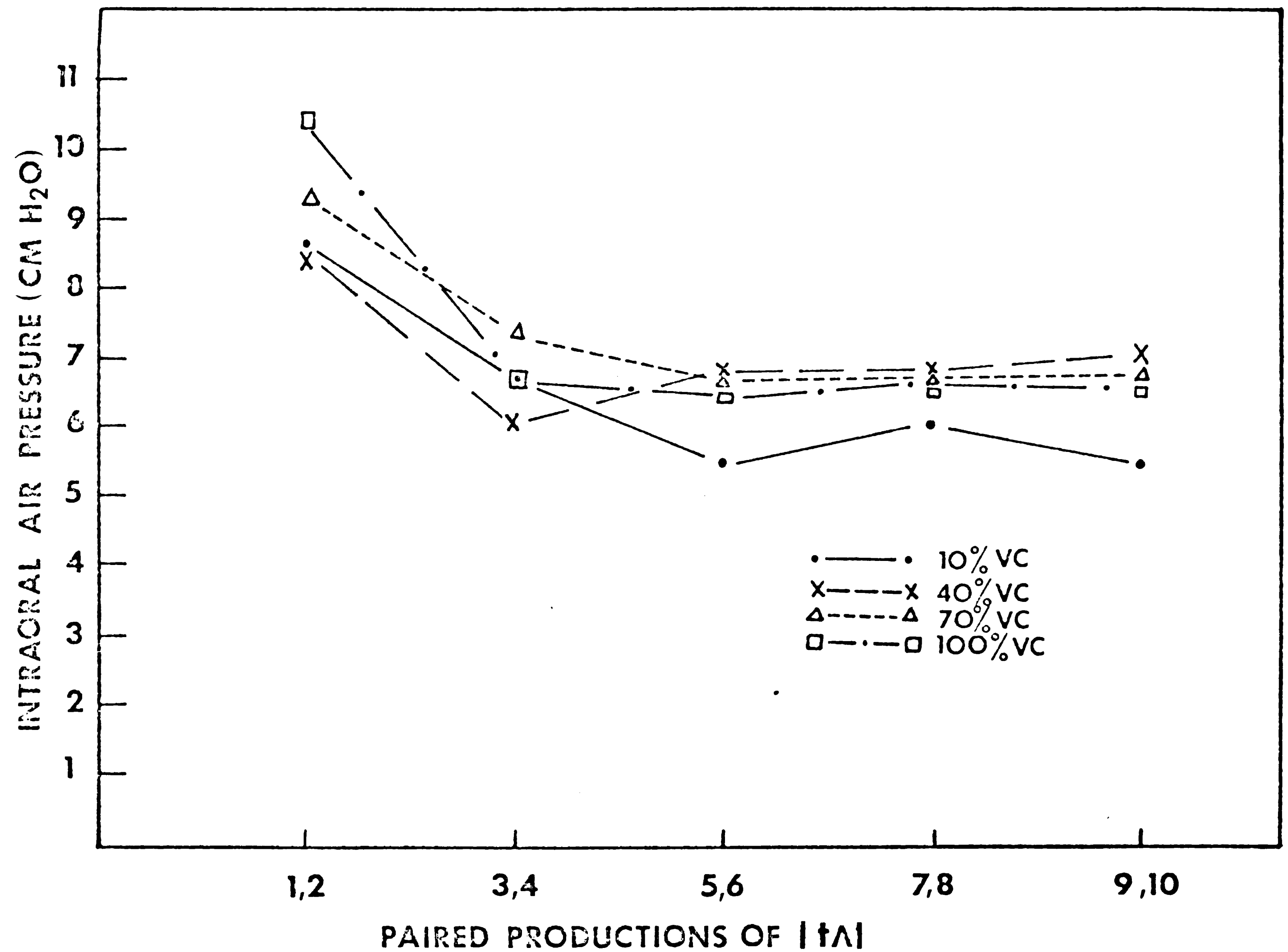


FIGURE 4: INTRAORAL AIR PRESSURE VALVES FOR THE PRODUCTIONS OF | t ʌ |

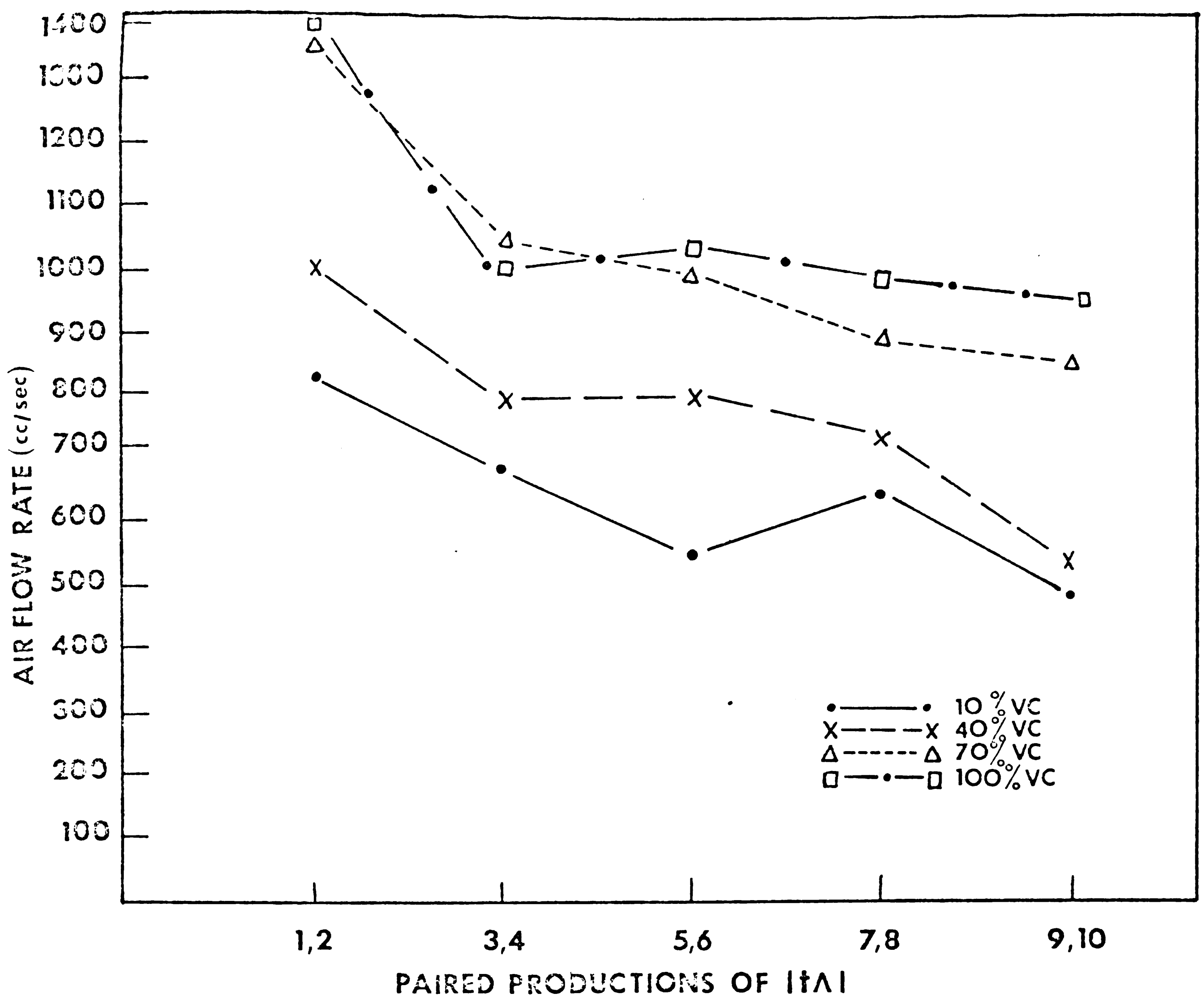


FIGURE 5: AIR FLOW RATE VALVES DURING PRODUCTIONS OF / t ʌ /.

were associated with higher air flow rates regardless of the paired production under consideration. An exception to this latter observation was noted during the second paired production where the mean volume velocity for 100% VC fell slightly below that for 70% VC. The greatest magnitude of change for all lung volumes was noted between the first and second paired productions. For the middle three paired productions, the air flow rates remained relatively constant with a general decrement in amplitude appearing between the fourth and fifth pairs. This final decrement was pronounced for the two lower lung volumes.

A similar profile of values was noted in the case of intraoral air pressure duration. The onset and offset data are presented in Figure 6. (See Appendix C for raw data.) As was the case in Experiment I, onset durations exceeded offset durations. High onset and offset values were recorded for the first pair of productions. However, the durations for all lung volumes appeared to stabilize within a relatively narrow range by the third and fourth paired productions with some variability reappearing for onset measures in the final pair. The same pattern noted for onset duration may be seen for total durations in Figure 7.

The larger magnitudes of all variables noted for the first pair of productions at each lung volume

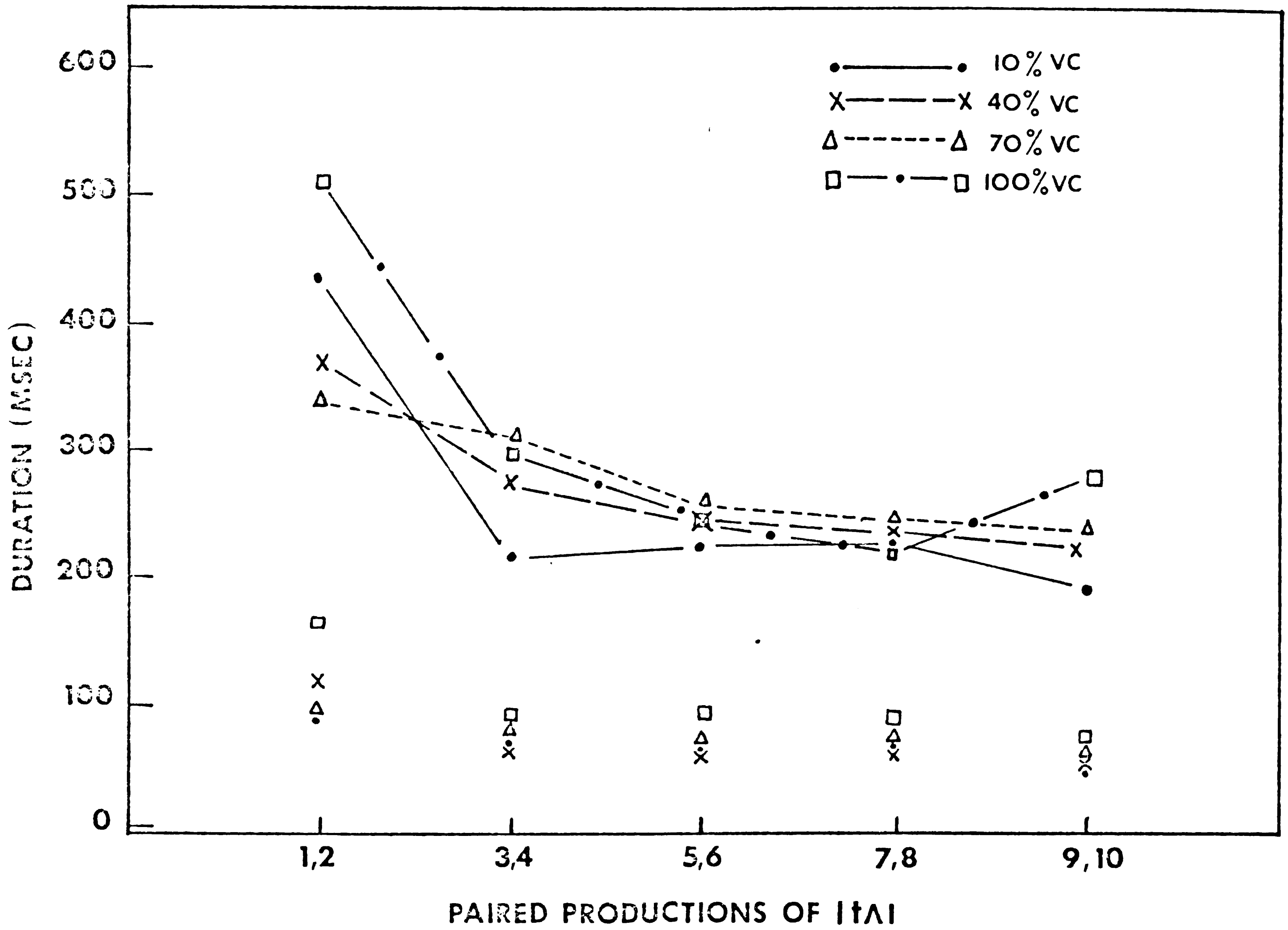


FIGURE 6: ONSET AND OFFSET VALVES FOR THE PRODUCTION OF /tʌ/.

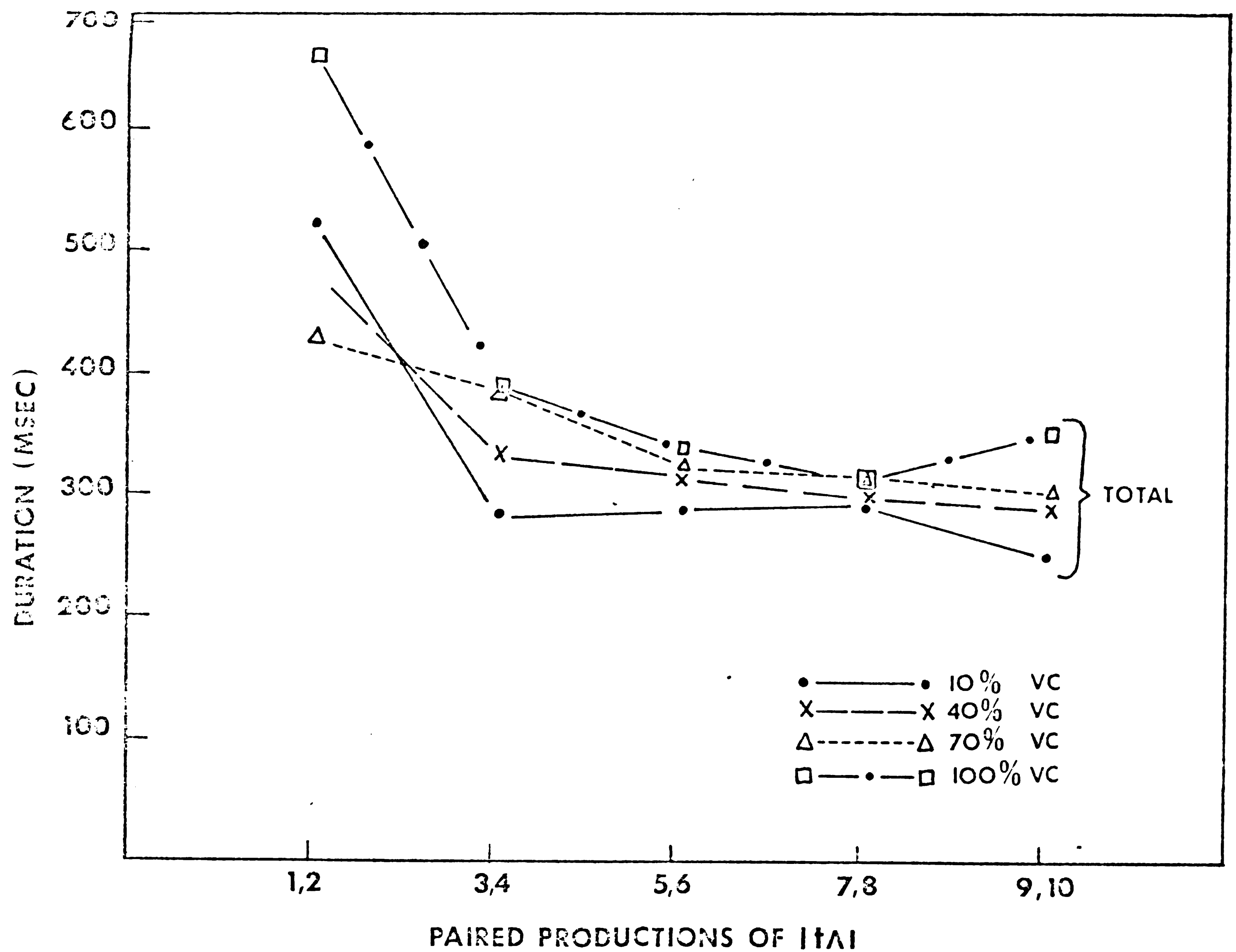


FIGURE 7: TOTAL DURATION VALVES FOR PRODUCTION OF /tʌ/.

was of some concern to the experimenter since such an observation is inconsistent with the findings of Brown and McGlone. One possible explanation for this concerns the subjects' efforts to synchronize initial productions with the metronome flash. In an attempt to coordinate the first syllabic nucleus with the light flash, the subjects may have prolonged the peak pressure allowing it to elevate with the result of higher volume velocities upon release. In addition, Brown and McGlone reported data from only the tenth through fourteenth productions (out of twenty repetitions) to insure "stability" in the utterance pattern.

It may also be observed that the intraoral air pressure durations for /t/ reported in Experiment II are generally higher than those for /t/ in Experiment I. This may be attributed to the efforts by subjects to synchronize the syllable /tʌ/ with the light flash in the latter experiment. In so doing, the subjects apparently began elevating pressure in anticipation of the light flash. Similar results were obtained by Navarre (1975).

In general, intraoral air pressure, intraoral air pressure duration, and air flow rate values showed a decrease for the initial paired stimuli with configurations which are relatively flat for the remaining stimulus pairs.

Experiment III

Rationale

The purpose of this experiment was to extend the observations of Experiments I and II to contextual speech. It was reasoned that more realistic speech stimuli constitute a better indication of typical aerodynamic functioning and hence provide more insight regarding the nature of potential feedback systems in the vocal tract. Accordingly, the subjects were required to read a short prose passage at each of the four experimental lung volumes.

Procedure

A 36-syllable passage (see Appendix E) containing 12 instances of the phoneme /t/ was constructed. The context of /t/ was constrained such that it was always preceded and followed by a linguistic pause, vowel, semivowel, or nasal. This context was chosen to facilitate measurement since all surrounding phonemes are associated with low pressure. Also, such a context minimizes pressure values higher in amplitude or longer in duration which result from abutting high pressure consonants. Finally, the passage was constructed such that when the 36 syllables were divided into four quartiles containing nine syllables each, there were three /t/ phonemes in all quartiles. This arrangement permitted the experimenter to examine changes in the selected aerodynamic variables across time by calculating mean values for each quartile of the passage. At each of the four lung volumes, the subjects were required to read the passage completely without inhaling. (See Appendix A for instructions to the subject.)

Results and Discussion

The results for peak intraoral air pressure are summarized in Figure 8. (See Appendix D for raw data.) Visual inspection of this figure indicates slightly higher pressures for all lung volumes during the first quartile. However, this difference disappeared during the second quartile and the pressure values assumed a plateau throughout the remainder of the passage. In addition, the pressure values for all lung volumes were remarkably similar during the final three quartiles.

As seen in Figure 9, the air flow rates generally decreased from the first to the fourth quartiles. However, a slight increment in flow rate occurred during the third quartile. The reason for this is obscure but may be suggestive of some semantic or syntactic variable which precipitated a slight increase in respiratory effort. Another possibility may have been a subtle increase in effort as the subject encroached more and more on the expiratory reserve volume and the oxygen

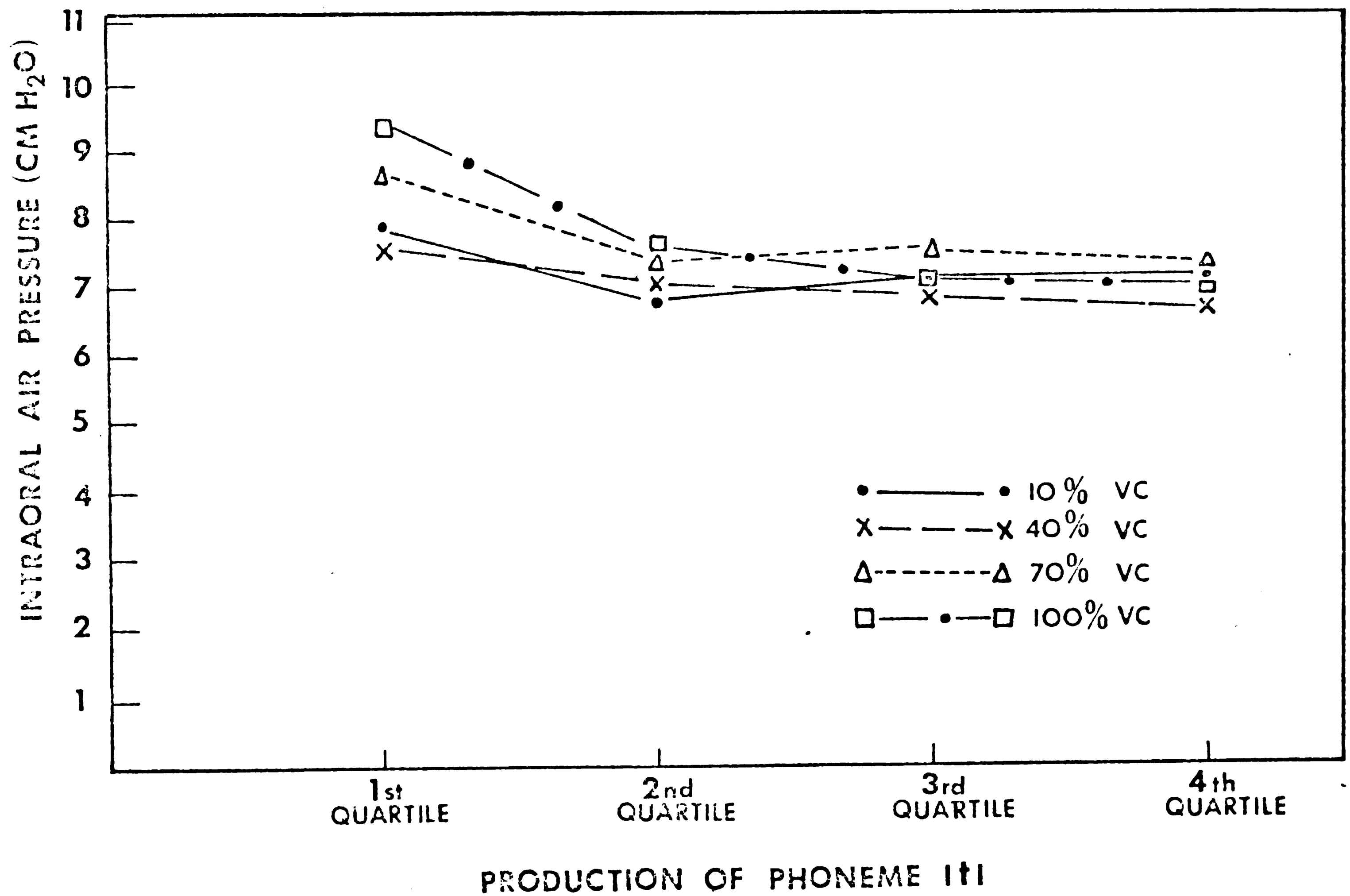


FIGURE 8: INTRAORAL AIR PRESSURE VALVES DURING THE PRODUCTION OF /t/ IN THE EXPERIMENTAL PASSAGE.

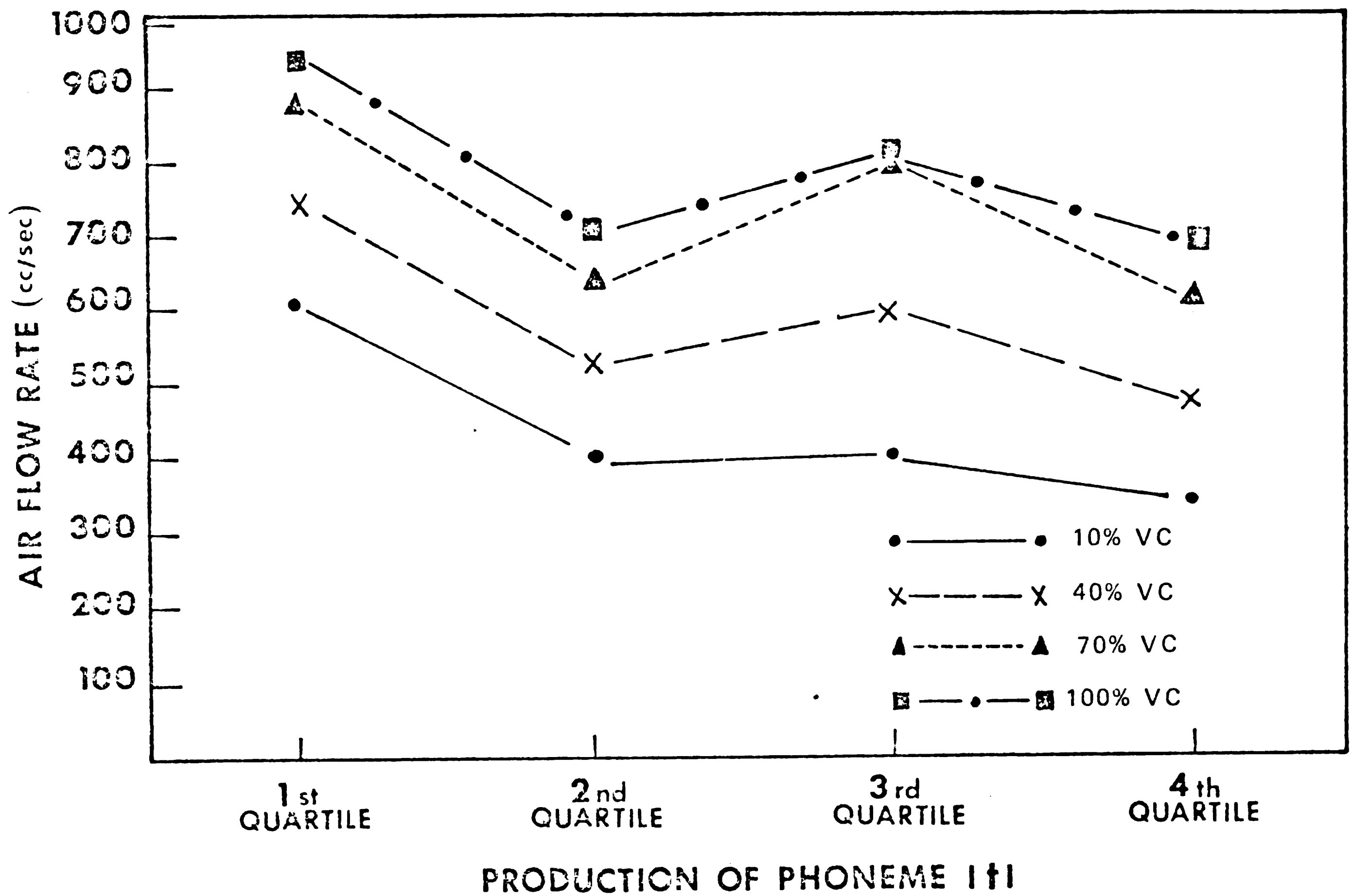


FIGURE 9: AIR FLOW RATE VALVES FOR THE PRODUCTION OF I t I IN THE EXPERIMENTAL PASSAGE.

demands increased. It should also be noted that, as in Experiment II, higher lung volumes were generally associated with higher air flow rates throughout the passage. An exception to this occurred in the third quartile where the volume velocity values for 70% VC and 100% VC coincided.

The duration results in Experiment III were somewhat ambiguous. The intraoral air pressures onset values are depicted in Figure 10. (Raw data may be found in Appendix D.) There was a general decrease from the first to the second quartiles, a levelling off from the second to the third, and a decrease from the third to the fourth in all cases except 10% VC. The intraoral air pressure offset values presented in Figure 11 (see Appendix D for raw data) showed no meaningful or consistent fluctuations across quartiles. Moreover, the fluctuations that occurred were generally of low magnitude (less than 25 msec), and it would appear hazardous to attach special significance to them. Total duration results for Experiment III are shown in Figure 12. The values for 70% VC and 100% VC are very similar across all quartiles. The durations for 10% and 40% VC averaged 25-50 msec lower during the second and third quartiles than those recorded at higher lung volumes. By the fourth quartile, there was very little difference in pressure duration as a function of lung volume.

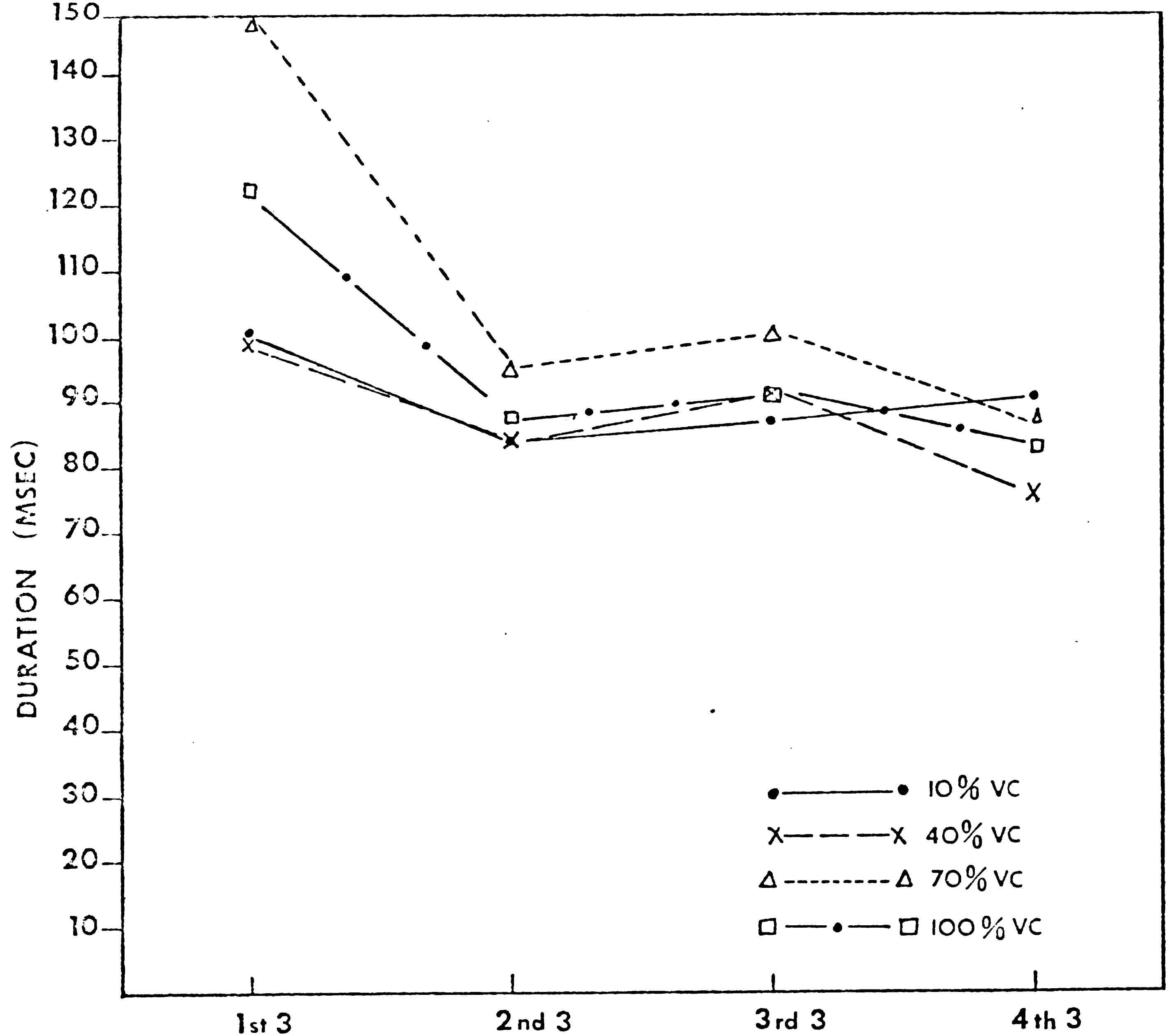


FIGURE 10: INTRAORAL AIR PRESSURE ONSET VALVES.

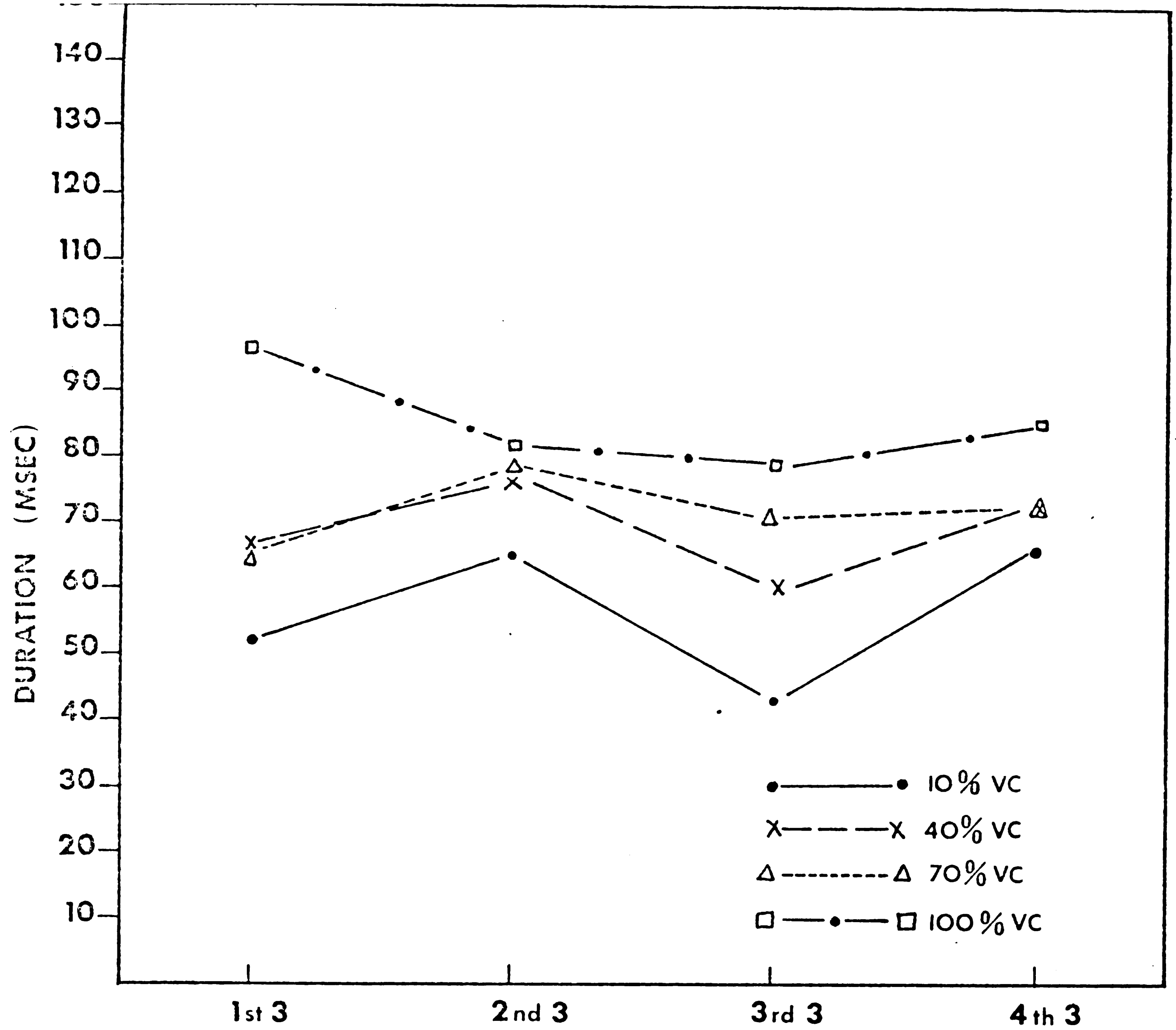


FIGURE 11: INTRAORAL AIR PRESSURE OFFSET VALVES.

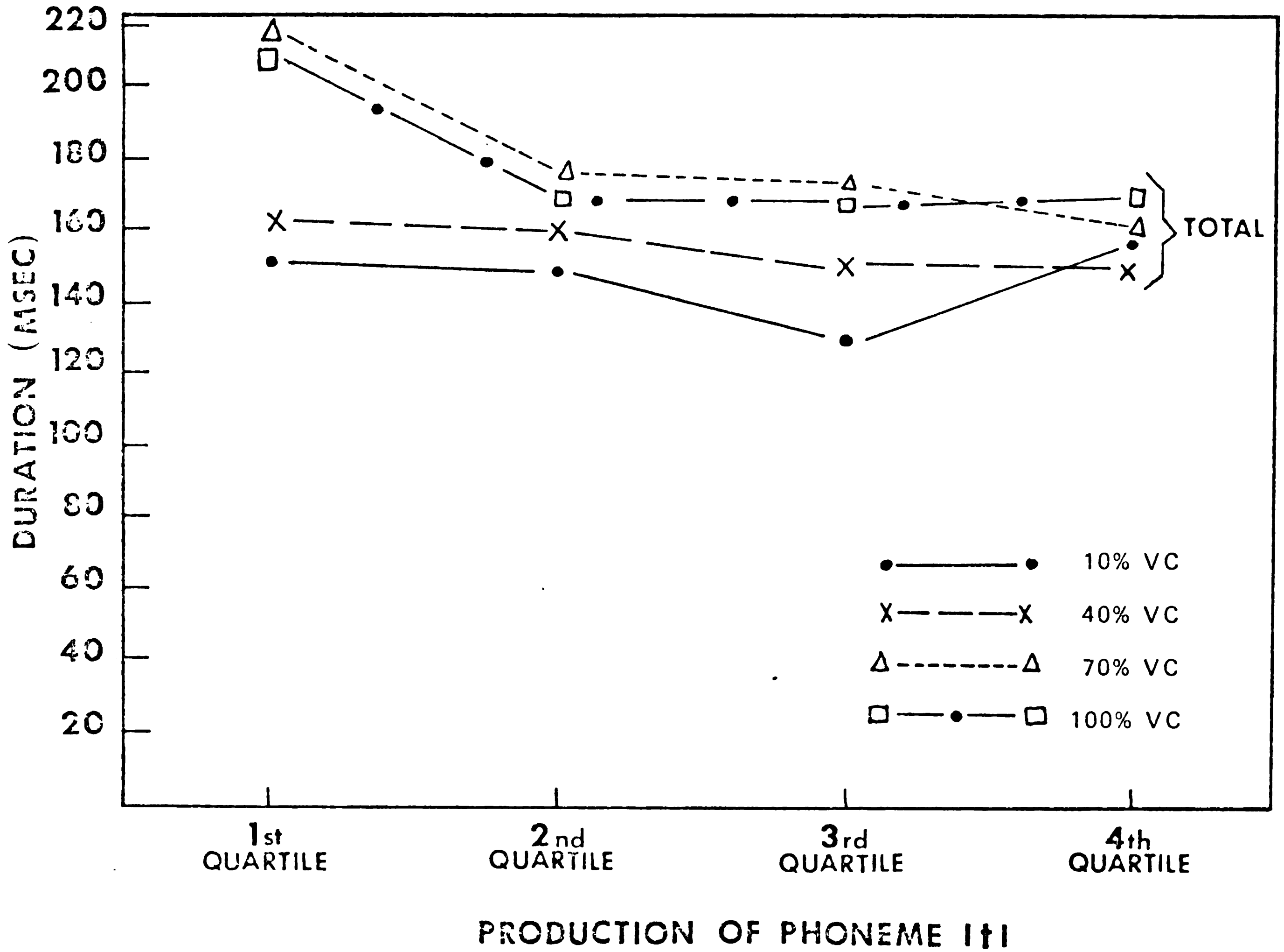


FIGURE 12: OF TOTAL DURATION VALVES FOR THE PRODUCTION OF /t/ IN EXPERIEMNTAL PASSAGE.

To summarize, intraoral air pressure and air flow rate values evidenced relatively similar fluctuations across lung volumes. Intraoral air pressure durations demonstrated variations of low magnitude with the two high lung volumes (70% and 100% VC) having similar duration values and the lower volumes (10% and 40% VC) exhibiting generally lower durations with similar magnitudes.

CHAPTER IV

DISCUSSION AND CONCLUSIONS

By way of summary, the results of the three experiments in this investigation have demonstrated that, with some exceptions, intraoral air pressures are not markedly changed as a function of lung volume. Those variations that did appear generally were of a magnitude less than 1 cm H_2O. The greatest variability in intraoral air pressure appeared not as a function of lung volume but rather in response to the specific speech tasks required. For example, in Experiment II, the greatest pressure values were observed for the first two productions of /t^/ and tended to stabilize in subsequent trials. Only the pressure values for 10% VC appeared to be consistently lower, but this was only evident in trials 5-10, and again the magnitude was less than 1 cm H_2O. In Experiment III, there was no observable relationships between lung volume and intraoral air pressure. The variabilities noted were associated with initial utterance efforts.

The low magnitude variations in intraoral pressure assume increasing significance in view of Malecot's (1966) observation that the human difference limen for intraoral air pressure, in the range of interest for this study, often exceed 1 cm H_2O. He reported the mean difference limen for ten subjects to be 1.04 cm H_2O when the lease pressure was preset at 7.5 cm H_2O, a value similar to those generated in the present experiment (Malecot, 1966, p. 76). Malecot's findings suggest that the variations in the air pressure reported in the present study may well have been below the subjects' difference limen for that feedback stimulus.

In view of these observations, the results of this study support the conclusion that vocal tract air pressure does not generally fluctuate as a function of lung volume. The logical implication of this conclusion is that target vocal tract pressures are set for a given utterance and maintained within the difference limen range despite rather drastic alterations in pulmonary volume. Accordingly, a well developed sensory feedback system must operate to maintain the target pressures through continuous adjustments in muscular effort.

Despite this constancy in intraoral air pressure, peak and flow rate values varied systematically as a function of lung volume. In all three experiments, with sporadic exceptions, a direct relationship between lung volume and air flow rate was observed. These results do not support the suggestion of Prosek and House (1975) that "sensory information from these muscle systems (thoracic and abdominal) might be used to establish the air flow rate appropriate for an utterance" (p. 144). Conversely, the present data indicate that target air flow rates are either highly variable or insignificant for speech production and fluctuate in response to variations in lung volume.

The patterns of variation in intraoral air pressure duration for the three experiments were somewhat less obvious. In general, total pressure durations tended to be somewhat longer for the higher lung volumes, but there were numerous exceptions to this observation. Onset durations generally followed the same pattern as the total durations and offset measures were typically less variable. These variations probably do not reflect changes in lung volume as much as the task requirements and linguistic influences described earlier. It would be hazardous to draw conclusions regarding the slight covariance between lung volume and intraoral air pressure duration in view of the numerous exceptions to this relationship.

Possible Feedback Mechanisms

As mentioned in the Introduction of this paper, several possible mechanisms could operate to provide data to the central nervous system regarding the state of vocal tract air pressure. One possibility concerns the several types of sensory receptors in the human laryngeal mechanism. Wyke (1969) has described a variety of corpuscular nerve endings in the submucosal tissues of the larynx which are designed to fire in response to mechanical displacement. He noted that these mechanoreceptors have very low thresholds and hence respond to small changes in air pressure, of the magnitudes observed in speech. His data have demonstrated that firing of these mechanoreceptors produces reflex adjustments of the laryngeal musculature. If this is accurate, it is possible that some of the vocal tract pressure regulation may be assigned to the laryngeal system. Accordingly, laryngeal adjustments would alter the resistance of the vocal folds to air flow which may indirectly affect pressure. It is also possible that the influence of these laryngeal sensory receptors may be broader than the intrinsic laryngeal muscles. Feedback from the mechanoreceptors may also be shunted to appropriate centers in the central nervous system where executive adjustments in respiratory activity are accomplished.

By no means should the potential feedback system be relegated solely to the laryngeal system. There are well documented sensory receptors in the oral cavity capable of responding to pressure events (Ringel and

Ewanowski, 1965). The findings of Hutchinson and Putnam (1974) lend credence to the potential influence of supraglottal receptors in vocal tract adjustments. Their observation that oral anesthesia resulted in higher intraoral air pressure and elevated air flow rates was interpreted as evidence of a "subglottal compensation for a reduced supraglottal feedback load" (p. 1616). Moreover, the absence of oral sensation may have prevented the subjects from obtaining adequate feedback information regarding the status of target vocal tract pressures. Therefore, the aerodynamic alterations observed by Hutchinson and Putnam may have reflected efforts to increase the sensory sample to ensure attainment of the required target pressures. If this assumption is accepted, it establishes the interactive operation of supraglottal sensory systems and respiratory events. With reference to the present study, oral receptor feedback may play a critical role in regulating respiratory activity to guarantee the maintenance of appropriate vocal tract pressure targets.

Finally, the respiratory muscles themselves must be considered a potential feedback source. Sears and Newsome-Davis (1968) have presented evidence supporting the existence of a reflex mechanism within the respiratory system which operates to adjust thoracic and abdominal musculature in response to differences in "load" upon the inspiratory and expiratory contraction event.

The results of the present study do not allow selection of one or more of these regulation systems as primary. However, the data suggest the existence of a rather elegant sensory feedback system with a considerable degree of dynamic sensitivity for achieving appropriate vocal tract target pressures.

Clinical Implications

As stated in the Introduction, if the assumption of a target subglottic pressure is accepted, it implies a relatively effective sensory feedback system which operates to maintain the target pressure through continuous adjustments in muscular effort. Based on this statement and in view of the relatively stable intraoral air pressure values obtained in this study, several clinical implications emerge.

Obviously, if target pressures are important, persons who have diminished ability to achieve acceptable pressures may have serious problems maintaining a correct manner of speech production. For example, patients with sensory pathologies affecting the vocal tract may have a reduced capability for monitoring pressure information. As a result, the pressures generated may be quantitatively inappropriate and/or widely variable. Similarly, persons with neuromuscular pathologies affecting motor function may not achieve appropriate target pressures despite the integrity of the sensory channels.

Another interesting implication concerns the work of Smith and Hutchinson (1975) with reference to aerodynamic functioning in the hearing impaired. Several subjects failed to achieve appropriate vocal tract pressures for the intended consonants. For example, the aerodynamic results failed to establish a distinct voiced-voiceless contrast. However, a brief training period (10 min) in which the subjects were asked to monitor intraoral air pressure using a visual biofeedback strategy was sufficient to establish a criterion distinction between voiced and voiceless cognates. Such results may suggest that monitoring target pressures is an essential but not necessarily sufficient requirement for developing normal speech. In the absence of auditory feedback, the hearing impaired person has no reference for the accuracy of target pressures. However, when visual feedback is substituted for auditory feedback as a cross-reference, the subjects showed an ability for rapid approximation of appropriate vocal tract pressures.

Implications for Further Research

The present study involved observing the relation of intraoral air pressure, intraoral air pressure duration and air flow rate as functions of varying lung volumes. Whereas the results obtained from the five female subjects proved enlightening, further research appears warranted to extend these data to a more representative sample of subjects. First, examination of the age factor would appear valuable. For example, younger children are still developing speech skills and may not exhibit the consistency in achieving target pressures as the adults studied in these experiments. Also, older subjects, whose peripheral sensory mechanisms have deteriorated may evidence poorer skills in achieving target pressures. Secondly, the use of larger subject samples with both males and females is suggested to determine the effect of lung volume on aerodynamic events in relation to physical size. Finally, while this experiment dealt with normative data, it may be valuable to extend these procedures to individuals with vocal tract pathologies.

APPENDICES

APPENDIX A

INSTRUCTIONS TO SUBJECTS

APPENDIX A

INSTRUCTIONS TO SUBJECTS

Instructions for Experiment I

During this experiment, you will be asked to say two nonsense sentences three times each at four different lung volumes. For each lung volume, we will ask you to inhale to the peak of your vital capacity (that is, all the air you can get into your lungs), exhale all of that air into the machine and inhale to one of the colored lines on the paper which we shall specify. When you reach the target value, we will ask you to hold your breath momentarily and place your nose and mouth tightly into the mask. Once in position, we will signal you to say the sentence before you three times without inhaling. Say the sentence in as natural a pitch, intensity and rate as you can. Avoid over-articulating. The sentence you will be asked to say first is:

When you have finished the sentence, lean back and relax. Do you have any questions?

Instructions for Experiment II

During this experiment, you will be asked to say the syllable /tʌ/ ten times at four different lung volumes. For each lung volume, we will ask you to inhale to the peak of your vital capacity (that is, all the air you can get into your lungs), exhale all of that air into the machine and inhale to one of the colored lines on the paper which we shall specify. When you reach the target volume, we will ask you to hold your breath momentarily and place your nose and mouth tightly into the mask. Once in position, a light will flash 1 per second. Time your utterances of /tʌ/ to correspond with successive light flashes with our signal. We will notify you when ten productions have been completed. Say each syllable with as natural a pitch, intensity, and rate as you can. Avoid over-articulating. When you have finished, lean back and relax. Do you have any questions?

Instructions for Experiment III

During this experiment, you will be asked to say a short passage at four different lung volumes. For each lung volume, we will ask you to inhale to the peak of your vital capacity (that is, all the air you can get into your lungs), exhale all of that air into the machine and inhale to one of the colored lines on the paper which we shall specify. When you reach the target volume, we will ask you to hold your breath momentarily and place your nose and mouth tightly into the mask. Once in position, we will signal you to say the passage without inhaling. Say the passage with as natural a pitch, intensity, and rate as you can. Avoid over-articulating. When you have finished, lean back and relax. Do you have any questions?

APPENDIX B

RAW DATA FOR EXPERIMENT I

	10%VC		40%VC		70%VC		100%VC	
	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ
PRESSURE	78.83	17.48	78.56	15.16	89.60	17.62	90.36	15.16
AIR FLOW RATE	494.40	181.51	725.45	192.08	982.76	147.29	1126.43	201.67
ONSET	77.98	9.79	70.33	7.84	77.33	12.36	76.66	7.88
OFFSET	46.66	11.35	61.66	9.60	59.33	11.81	68.66	14.99
TOTAL	125.33	13.59	132.0	13.20	136.66	9.42	144.66	14.07

TABLE 1: EXPERIMENT I – RAW DATA FOR STIMULUS WORD | hat Λ t |.

	10% VC		40% VC		70% VC		100% VC	
	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ
PRESSURE	71.40	12.72	72.7	13.22	80.93	14.0	83.5	16.10
AIR FLOW RATE	327.63	76.66	414.24	71.68	479.32	99.09	493.47	121.73
ONSET	84.66	11.46	86.0	11.43	88.66	12.57	88.66	7.18
OFFSET	68.66	12.57	76.0	17.43	75.33	11.46	75.33	9.56
TOTAL	153.33	17.38	162.0	23.15	164.0	17.43	164.0	14.96

TABLE 2: EXPERIMENT I – RAW DATA FOR STIMULUS WORD I has ʌ s I.

APPENDIX C

RAW DATA FOR EXPERIMENT II

	1st PAIR		2nd PAIR		3rd PAIR		4th PAIR		5th PAIR	
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
PRESSURE	86.75	19.36	67.3	13.64	55.05	13.02	60.90	22.01	55.45	18.33
AIR FLOW RATE	842.96	358.97	693.69	177.07	551.61	169.48	639.14	242.0	486.74	217.4
ONSET	437.0	206.06	218.0	75.86	224.0	72.41	227.0	97.98	194.0	70.17
OFFSET	86.0	51.41	65.0	23.34	64.0	22.89	67.0	26.85	55.0	23.76
TOTAL	523.0	225.43	283.0	75.37	288.0	86.57	294.0	118.16	249.0	84.19

TABLE 3: EXPERIMENT II – RAW DATA FOR STIMULUS WORD
I t Λ I AT 10 % VITAL CAPACITY.

	1st PAIR		2nd PAIR		3rd PAIR		4th PAIR		5th PAIR	
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
PRESSURE	84.44	26.72	60.5	9.33	68.0	7.82	68.5	11.12	71.2	11.57
AIR FLOW RATE	1001.90	237.06	793.24	263.3	776.46	224.69	729.77	140.9	631.11	133.05
ONSET	364.0	262.47	271.0	54.25	248.0	74.65	231.0	95.62	229.0	100.38
OFFSET	116.0	103.94	62.0	20.43	67.0	29.07	66.0	22.21	67.0	34.33
TOTAL	480.0	313.93	333.0	43.47	315.0	78.49	297.0	81.18	296.0	108.54

TABLE 4: EXPERIMENT II – RAW DATA FOR STIMULUS WORD ItΛI AT 40% VITAL CAPACITY.

	1st PAIR		2nd PAIR		3rd PAIR		4th PAIR		5th PAIR	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
PRESSURE	93.15	29.14	72.65	19.91	67.35	17.14	68.05	11.27	67.05	18.28
AIR FLOW RATE	1370.85	40.09	1043.53	317.10	995.53	267.27	892.32	212.58	853.90	169.43
ONSET	337.0	186.25	306.0	68.18	253.0	82.6	245.0	85.53	233.0	81.65
OFFSET	90.0	24.94	80.0	29.81	73.0	23.59	73.0	21.62	69.0	17.91
TOTAL	427.0	196.81	386.0	89.59	326.0	87.71	318.0	97.15	303	79.02

TABLE 5: EXPERIMENT II – RAW DATA FOR STIMULUS WORD /tʌ/ AT 70% VITAL CAPACITY.

	1st PAIR		2nd PAIR		3rd PAIR		4th PAIR		5th PAIR	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
PRESSURE	104.55	30.85	67.45	15.30	64.1	11.47	67.55	13.85	67.5	17.11
AIR FLOW RATE	1387.2	456.29	1016.22	138.48	1029.59	296.43	980.97	324.77	944.81	252.86
ONSET	507.0	226.08	299.0	165.02	245.0	94.54	229.0	109.28	280.0	130.80
OFFSET	161.0	159.40	86.0	34.70	94.0	29.51	87.0	24.51	72.0	12.29
TOTAL	662.70	285.43	385.0	186.97	339.0	108.46	315.0	115.48	352.0	136.60

TABLE 6: EXPERIMENT II – RAW DATA FOR STIMULUS WORD /tʌ/ AT 100% VITAL CAPACITY.

APPENDIX D

RAW DATA FOR EXPERIMENT III

	1st QUARTILE		2nd QUARTILE		3rd QUARTILE		4th QUARTILE	
	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ
PRESSURE	79.07	13.75	68.17	10.05	71.80	14.36	71.1	16.47
AIR FLOW RATE	619.29	160.29	402.97	103.08	402.07	137.11	340.16	92.08
ONSET	101.33	40.68	84.67	15.52	87.34	16.67	91.33	27.48
OFFSET	52.0	18.20	65.33	21.66	43.33	14.47	66.67	22.57
TOTAL	153.34	44.66	150.0	29.14	130.67	29.14	158.0	42.46

TABLE 7: EXPERIMENT III – RAW DATA FOR STIMULUS PASSAGE AT 10% VITAL CAPACITY.

	1st QUARTILE		2nd QUARTILE		3rd QUARTILE		4th QUARTILE	
	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ
PRESSURE	75.86	11.33	70.40	10.20	68.23	10.33	66.97	10.38
AIR FLOW RATE	753.8	188.92	536.35	100.37	595.64	116.11	480.39	83.27
ONSET	96.0	42.72	84.0	25.57	91.33	20.99	76.67	14.96
OFFSET	66.0	25.29	76.67	20.25	60.67	17.91	73.33	24.10
TOTAL	162.0	58.33	160.67	41.65	152.0	26.77	150.0	24.49

TABLE 8: EXPERIMENT III – RAW DATA FOR STIMULUS PASSAGE AT 40% VITAL CAPACITY.

	1st QUARTILE		2nd QUARTILE		3rd QUARTILE		4th QUARTILE	
	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ
PRESSURE	87.63	11.05	74.0	7.43	75.83	9.47	72.06	9.33
AIR FLOW RATE	887.50	207.30	644.72	155.23	816.30	191.17	617.20	119.89
ONSET	149.33	97.20	95.33	46.73	100.0	28.53	86.67	25.26
OFFSET	67.33	28.14	78.67	19.95	70.66	16.67	72.66	22.18
TOTAL	216.67	107.01	174.0	57.79	170.66	37.69	159.33	38.63

TABLE 9: EXPERIMENT III – RAW DATA FOR STIMULUS PASSAGE AT 70% VITAL CAPACITY.

	1st QUARTILE		2nd QUARTILE		3rd QUARTILE		4th QUARTILE	
	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ	$\overline{X}$	σ
PRESSURE	94.10	24.25	76.83	12.28	71.90	10.03	69.27	12.37
AIR FLOW RATE	946.81	217.79	708.64	153.36	810.45	182.63	691.41	162.65
ONSET	122.67	59.21	87.33	20.16	90.0	18.51	83.33	27.68
OFFSET	97.33	63.29	82.67	28.14	79.33	23.13	85.33	25.31
TOTAL	210.0	102.60	170.0	35.45	169.33	33.05	168.67	40.68

TABLE 10: EXPERIMENT III – RAW DATA FOR STIMULUS PASSAGE AT 100% VITAL CAPACITY.

APPENDIX E

STIMULUS PASSAGE FOR

EXPERIMENT III

APPENDIX E

STIMULUS PASSAGE FOR EXPERIMENT III

Tomorrow Tom or Todd will arrive in Trinidad. They will take a trip with the tumbling team. Only ten of the twelve men will make the travelling team.

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