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FLOYD WESLEY EMANUEL

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AN EXPERIMENTAL STUDY OF ORAL AND NASAL AIR FLOW DURING PLOSIVE CONSONANT PRODUCTION

APPROVED BY

Donald J. Counts

[illegible]

John W. Keys

Howard B. Kuhn

Bruce R. Pierce

DISSERTATION COMMITTEE

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AN EXPERIMENTAL STUDY OF ORAL AND NASAL AIR FLOW DURING PLOSIVE CONSONANT PRODUCTION

CHAPTER I

INTRODUCTION

Since valid judgments of speech defectiveness cannot be made without a clear understanding of normal speech, it is important that speech pathologists have reference to measurement data concerning as many parameters of normal speech as possible. Because of the complexity of speech, however, it is not possible to investigate the total process in a single study; rather, it is necessary to consider one aspect of the process at one time. Viewed as a physical phenomenon, speech may be arbitrarily dichotomized into: (1) the acoustic signal, and (2) the underlying physiological events which produce this signal.

It may be noted that objective study of the acoustic signal has been accelerated by the advent of recording instrumentation and the subsequent development of devices for analyzing the signal. Although useful information may be obtained by analysis of the acoustic speech signal, this analysis cannot be depended upon to reveal the nature of the underlying physiological processes which produce it. Peterson (30) has pointed out that:

> While the acoustical wave of speech is a uni-dimensional pressure function of time, the analysis of this wave into its essential acoustical parameters is a complex and difficult process. These acoustical parameters do not in general have a simple and direct correspondence to the physiological parameters. In addition, disturbing noise is normally added, so that the acoustical signal is a somewhat incomplete and degraded representation of the physiological activity. With special instrumentation, in fact, it may be easier to observe certain aspects of the physiological activity directly rather than through analysis of the acoustical wave.

It appears, therefore, that to understand the physiological processes underlying speech sound production, it may be best to study these processes more directly.

In recent years, study of the specific physiological events underlying speech has also received impetus from improvements in the design and application of research instrumentation. For example, notable progress has been made in the utilization of x-ray and high speed photographic techniques in evaluating the function of the velum and the vocal folds, respectively. In spite of the fact, however, that all speech sounds are the result of modifications of the expiratory breath stream, relatively few analyses of the air stream itself have been made.

Study of the air flows utilized in speech is of interest in that it may provide fundamental information concerning the physiology of sound production. Such information is useful, not only because it is basic to an understanding of normal speech, but also because deficiencies in or poor control of the expired air flow can result in speech disorders. Since errors in consonant production are among the most pervasive of speech problems, quantitative information concerning the air flows utilized in production of these sounds by normal speakers could be expected to be useful in understanding the misarticulations present in the speech pathologies. Further, because modifications in the air stream in speech are related to the valving action of the articulating oral and pharyngeal structures, quantification of these variations may be useful in investigations of the valving action of the articulators. Measurement of the relationship between oral and nasal air flow in the production of various speech samples, for example, could be expected to aid in the understanding of velar function during speech. In this respect, simultaneous measures of the oral and nasal breath streams during the normal production of pressure consonants would be of particular value in that such data might be subsequently applied in studies of consonant misarticulations associated with velar pathology.

The present study was concerned with measurement of oral and nasal air flow in normal speech. It was undertaken because of the paucity of research relating to this subject, and because of the importance of objective data concerning oral and nasal air flow to speech pathologists and phoneticians. Specifically, the study was an investigation of oral and nasal air flow in the production of plosive consonants in various syllable and vowel contexts. A review of related literature, the plan of the study, the findings, and the conclusions of the study may be found in the following chapters.

CHAPTER II

REVIEW OF LITERATURE

Long before speech was first studied experimentally, observers were aware of a dependent relationship between variations in breathing and speech quality. Awareness of this relationship led to the formation of many imaginative theories about the "proper" type of breathing for speech (21). Experimental studies (13, 19, 28, 32) conducted to test these theories failed to support the concept that there is a preferred type of breathing for speech. Indirectly, they indicated a need for systematic collection of detailed objective data concerning air flow in speech.

A review of current literature reveals a deficiency of measurement data regarding air flow in speech sound production. Those studies which have purported to measure air flow in speech have, for the most part, involved measurement of the integral curve of air flow (total air volume). Fleisch (11), however, has pointed out that the integral curve does not permit analysis of the air flow in speech in sufficient detail. He has suggested that it would be advantageous to measure instead the differential curve, i.e., the curve showing the speed of air flow at each instant. To date, there have been few such studies. Studies in which oral and nasal air flow have been considered simultaneously but separately have also been few.

Reports of experimental investigations of air flow in speech are found primarily in the literature of speech pathology and phonetics. In this presentation, the relevant literature is presented under two major headings: (1) speech and the respiratory process, and (2) respiratory air measurement.

Speech and The Respiratory Process

There is general agreement among authorities (1, 14, 20, 21) that the primary purpose of respiration is to provide for metabolic gas exchange, and that speech is a function which has been superimposed on the respiratory mechanism in the course of evolutionary development. A corollary of this concept of a respiratory functional hierarchy is the belief, expressed by Gray and Wise (14), that the vocal mechanism has not been and will never be modified through evolution to perform the secondary speech function more efficiently. Regardless of the validity of these concepts of an evolutiionary relationship between speech and respiration for life, even casual observation reveals that the act of speaking requires modification of the vegetative respiratory pattern. In this section, relevant findings and observations regarding speech and respiration are reported.

Respiratory Rate

Respiratory rate may be considered to be the rate at which complete breathing cycles (inspiration plus expiration) occur. In rest breathing, the rate is basically determined by metabolic requirements. Heffner (17, pp. 12-13) has stated that:

> The rate of respiration when the body is at rest is determined by the requirements of the blood stream. Whenever the content of carbon dioxide in the blood reaches the critical point, the nerves which cause the diaphragm to contract are automatically stimulated and new air is breathed in. On the whole, the normal rate of breathing (for adults) may be said to range from 10 to 20 inhalations per minute.

The rest breathing rate varies within and among individuals (20), however, according to body position, body type, the emotional state of the individual, sex, age, and other factors affecting metabolic requirements.

During breathing at rest, the ratio of inspiratory to expiratory time is approximately unity (17, 20, 21, 29). There is usually a pause between inspiratory and expiratory phases, although the pause may disappear altogether when the respiratory rate is increased or when the relative speed of expiration is reduced (21). While the respiratory rate is relatively constant during rest breathing, it is determined primarily by the nature of the utterance during speech. Heffner (17) has indicated that speech is characterized by more or less closely integrated sound sequences between each two of which the speaker takes in a new breath. Hence, the rate of speech breathing varies considerably. Generally, the expiratory phase of respiration is lengthened in speech while the inspiratory phase is shortened, although, as Peterson (29) has reported, the ratio of exhalatory to inhalatory time may extend from unity to extremes of forty to fifty. Typical ratios reported for normal conversational speech lie between five and ten.

The rate of respiration during speech is, therefore, determined, primarily, by metabolic requirements and, secondarily, by the nature of the utterance. The most obvious change in the respiratory pattern in speech is a general tendency to lengthen the expiratory phase and to shorten the inspiratory phase.

Respiratory Volume

Respiratory volumes are conventionally measured by means of spirometry. Kaplan (21), summarizing the results of numerous spirometric studies, has reported that, for adults, there is a maintained reservoir of about 3,000 cc of air in the lungs at all times which is known as stationary air. During rest breathing, about 500 cc of tidal air enter and leave the pulmonary passages. By forcing, about 1,500 cc of complemental air can be inspired in excess of the tide. In forced expiration about 1,500 cc of air in excess of the tide can be exhaled. This is called supplemental air and is that portion of the stationary air which can be exhaled by forcing. There is, however, an additional 1,500 cc of stationary air, called residual air, which cannot be forced out by any expiration. The total lung capacity is about 5000 cc, the sum of the tidal, complemental, and stationary air.

Another measure, vital capacity, is often considered because of the ease with which it can be assessed and its usefulness in evaluating respiratory function. Vital capacity is the amount of air that can be expelled by an individual after as deep an inspiration as possible, and is equal to the sum of the tidal, complemental, and supplemental air. Vital capacity measurements are usually reduced to standards based on an individual's surface area. Kaplan (21) has reported that the standard is approximately 2,600 cc of air per square meter for adult males, and 2,000 cc per square meter for adult females.

Wiksell (45) studied the maximum amount of air that could be inhaled or exhaled when abdominal, medial, and thoracic types of breath control were employed and when no attempt was made to control the type of respiration. His measurements were made by means of a spirometer and pneumographs connected to specially designed linear tambours. He found that "uncontrolled" respiration is conducive to a greater volume of breath movement than any of the special types of breathing studied. Gray (14), on the basis of a number of studies done under his direction, concluded that the amount of air actually used in breathing is small, and that the average quantity of air which passes into and out of the lungs during a single respiratory cycle is usually no more than about thirty cubic inches, or about thirteen percent of the vital capacity. He noted, however, that this figure varies considerably, ranging from approximately five to thirty-five per cent of the vital capacity.

Gray also noted that the amount of air used in uttering a single phrase (the amount of air that is actually taken into the lungs at one time in reading and speaking) is generally little more than that used in rest breathing. He concluded, on the basis of his research, that there is no evidence that persons who use a large amount of tidal air, either in actual volume or in proportion to vital capacity, have better voices or are better speakers than those who use less tidal air, actually or proportionately. Furthermore, Idol (19), one of Gray's students, reported that more than one-half of a group of 140 subjects breathed more deeply for "life purposes" than for speech. She also found that an individual who used a large percentage of his vital capacity in casual breathing was also likely to use a large percentage of his vital capacity in speaking.

The research cited suggests that there is considerable variation among individuals with respect to the amount of air utilized at rest and during speech. However, the volume of air needed for speech apparently does not usually exceed that needed to satisfy metabolic requirements, and, as Gray and Wise (14) have indicated, there is no evidence that quality of tone, strength of tone, or ability to control the strength of tone is in any way dependent upon the amount of air one can draw into the lungs.

Types of Breathing During Speech

Prior to the accumulation of research data, it was popularly thought that certain types of breathing were preferable in speech. Kaplan (21, p. 104) has noted that:

> The upper and lower chest muscles may be activated almost independently in breathing, and historically arguments arose over which type was preferable for speech. Many French workers of the early nineteenth century emphasized upper-chest breathing. In 1885 Mandle, a French physician, attacked this view, and his counterproposal for abdominal breathing was carried to an extreme by English investigators. There are also advocates of a medial breathing between the chest and abdominal types.

Research, however, failed to support the contention that any special type of breathing is superior for speech. Gray (13) compared voice quality ratings of subjects with the extent of their abdominal and thoracic movements during speech. His data showed no essential relation between abdominal and thoracic predominance and quality of voice. Sallee (32), studying the relationship between depth and type of respiration and audibility of speech, reported no significant relationship between depth of respiration or respiratory type and speaker audibility.

By means of a linear tambour, Partridge (28) studied thoracic, medial, and abdominal excursions during respiration. He analyzed the breathing movements of 100 subjects grouped according to body type. Fifty ectomorphs and fifty endomorphs were studied during five different respiratory conditions: "vegetative breathing in the supine position; vegetative breathing in the standing position; breathing in the reading situation; breathing in the speaking situation; and forced respiration." Partridge found a predominance of medial breathing among both ectomorphs and endomorphs for all conditions except the supine position, where abdominal movements predominated. The relative extent of abdominal excursion and the frequency with which abdominal movements predominated were found to be greater among ectomorphs than among endomorphs. It was concluded that the habitual respiratory pattern is related to general body type.

In a review of studies of respiratory movement, Peterson (29, p. 143) concluded that:

> The studies indicate that respiratory movements are highly complex in character and are probably related in some degree to body type. They also indicate very little relationship between speech characteristics or qualities and types of respiratory movement or control as measured by pneumographic displacements.

It is apparent from the above that a dogmatic insistence on special types of breathing for speech is not justified by the research which has been carried out to this time.

Expenditure of Air in Speech

Exhalation of air from the lungs results from a decrease in the anteroposterior, vertical, and lateral dimensions of the rib cage, effected primarily by the contraction of the abdominal muscles. The space available for the lungs in the thoracic cavity is decreased, and this causes a pressure to be exerted against them. The increase in pressure forces a part of the air out of the lungs producing the exhalatory air stream. Since the lungs are not muscular, they do not actively assist in respiration.

In point of fact, the intrathoracic pressure during exhalation is not positive with respect to atmospheric pressure. Rather, it is merely less negative during exhalation than it is during inspiration. Kaplan (21, p. 106) has indicated:

> The intrathoracic pressure is always negative. This is because the thorax, which is a closed chamber, expands at birth and permanently reduces its internal pressure. Moreover, the lungs stretch, and being elastic, tend to produce a continuous pull away from the chest wall. These factors explain a permanent negative pressure, which is about 5 mm at the end of expiration. With each inspiration the thorax expands more than the lungs do, and the intrathoracic negativity increases to about 10 mm below atmospheric pressure. This changing negativity prevents collapse of the lungs, and it is also responsible for the rhythmic expansion and compression of the lungs. For the most part, the lungs are controlled by the thoracic movements.

With respect to atmospheric pressure, the air pressure within the lungs is slightly negative during inspiration, and slightly positive during exhalation.

The pressure of air within the lungs and respiratory passages is known as the pulmonary or intrapulmonic pressure. According to Kaplan (21), this pressure is atmospheric at rest since the respiratory passages communicate freely with the air. A negative pressure of two to three millimeters (below 760 mm mercury) is developed during inspiration, and a positive pressure of two to three millimeters is developed during expiration. The variations in speech are greater since the pressures are built up against the closed or partially closed glottis. Even so, Kaplan has indicated that "the blast pressures employed in speech are not very great." Peterson (29, p. 141) has noted the paucity of research regarding intrapulmonic pressures during speech. He stated that:

> One would expect that when speech is produced, the sublaryngeal pressures must somewhat exceed those for casual breathing. Such driving pressures would likely be required both for phonation and for articulation. However, there appear to be few quantitative measurements of intrapulmonic pressures during speech.

Stetson and Hudgins (40) studied breathing with respect to syllable production. Their study indicated that, in rest breathing, air is expelled through pressure caused by the weight and elasticity of the structures displaced by inspiratory muscles. Forced expiration is effected chiefly by the contraction of the abdominal wall musculature. In breathing for speech where more than 2.5 to 4 syllables per second are uttered, the abdominal muscles are held rigid and fixate the inferior border of the rib cage. In this way they afford resistance for the muscular pulses accomplished by the internal intercostal muscles. These investigators used the term "chest pulse" to indicate the breathing movements generated by the costal muscles in building up the pressure needed to activate the vocal folds. According to Stetson and Hudgins, the chest pulse occurs with each syllable.

The air flow from the lungs during speech is governed by the articulating laryngeal and oral structures. The first of these structures encountered by the moving air stream during production of voiced sounds is the vocal folds. On the basis of their research, Russell and Cotton (31, p. 56) reported that:

> Stroboscopic examination of the vocal cords has shown definitely that the vocal cords are completely closed for a certain short length of time during each period of (their) vibration. The duration of this contact phase varies from a fraction of the time during which the glottis is open, to over twice the duration of the open phase, depending on the pitch, quality, and loudness of the voiced sound, etc.

As Van den Berg (41) has indicated, the exact way in which the vocal folds are activated during speech remains a subject of debate. The neuro-chronaxic theory, originally set forth by Husson, suggests that each opening of the glottis is started by a contraction of the musculus vocalis. The myoelastic-aerodynamic theory, on the other hand, postulates that the vocal folds are actuated by the stream of air delivered by the lungs and trachea. Bogert and Peterson (6, p. 145) appear to be in agreement with the myoelastic-aerodynamic theory in that they have indicated that oscillations of the vocal folds are determined by the driving bursts of air which escape periodically through the glottis. They have stated that: "The burst rate determines the fundamental frequency of the sound, and it is well known that the oscillations within the resonators above need have no integral relationship to the vocal cord rates."

Regardless of the manner in which the vocal folds are opened, during each open phase a minute puff of air is emitted. Russell and Cotton (31, p. 56) measured the volume of each puff of air by means of a sensitive six-liter spirometer designed and constructed by Cotton. These researchers reported that there was "a very nearly uniform 'puff volume' in a range of more than one octave in pitch variation."

Roudet, who is cited by Scripture (33), investigated the expenditure of air per second when the vowel [a] was produced at a pitch of about C_2. He found that "feeble intensity" utilized 11 cc; "medium intensity", 17 cc; and "strong intensity", 24 cc. On the basis of these findings, Judson and Weaver (20) concluded that, in the production of individual speech sounds, the volume of air expended bears a definite relation to the intensity of sound produced and that an increase in intensity results from a greater escape of air due to the greater excursion of the vocal folds.

Russell and Cotton (31) also reported an increase in expenditure associated with an increase in vocal intensity of the vowel [a], although the increase was proportionately small in comparison to the increase in intensity. They found that only thirty per cent more air was required for the maximum possible vocal intensity than for the normal vocal intensity level, a vocal intensity range of approximately 20 decibels. Kaplan (21) has reported that the most efficient sounds, in the sense that they require the least breath expenditure, are vowels. The voiceless fricatives, such as [f] and [s], use the most breath output.

Arnold (1, p. 37) has reported a study by Luschsinger in which a pneumotachograph was utilized to study the volume of air exhaled during production of tones by singers. According to Arnold:

> They [the singers] produced various tones of the chest, middle, and head registers, and tried to maintain equal loudness of each tone. Many empirical conceptions could be confirmed or elaborated: (1) the air volume decreases with rising pitch; (2) the head voice thus requires a very small air volume; (3) an increase of air volume with rising pitch is pathologic (tremolo, dysodia, etc.); (4) the air volume grows with the covering of tones; (5) the air volume grows with increasing loudness: weak low tones require a small volume, loud low tones require a large volume; (6) however, there are some peculiar exceptions: weak low tones were sung with small volumes, while weak high tones required a higher volume.

There would appear to be agreement among the studies cited that an increase in vocal intensity is normally accompanied by an increase in oral air flow, although there is an indication that this flow may be proportionately smaller than the increase in intensity. The relationship between pitch change and oral air flow is less well defined. There appears to have been no study of nasal air flow in relation to either intensity or pitch change.

More recently, Black (5) studied intraoral air pressure required for the production of certain isolated consonants and consonant-vowel combinations. In order to do this, he found it necessary to adapt various aircraft instruments to his purposes. His procedure involved placing a small rubber tube in the anterior area of the subject's mouth. The tube was connected to an air pressure measuring apparatus so that air pressure measurements could be obtained as subjects spoke specified sounds and syllables. Black reported that voiced consonant sounds were associated with significantly lower intraoral pressures than voiceless consonant sounds. His data also suggested that intraoral breath pressure is significantly higher for continuant than for plosive sounds except when these two types of speech elements occur in the middle of a spoken word. Although the data from this study have been extensively cited, Black (5) pointed out certain limitations of his approach. He stated that:

> The mechanical technique that was employed in this study is subject to review in subsequent approaches that may utilize less cumbersome equipment. There was doubtless some distortion of normal speech due to the readers having a pressure tube in the mouth. Furthermore, reading the dial of the indicator involved approximations.

In another study of oral air pressures, Goddard (12) reported that over ninety per cent of her sample of five-year old boys and girls with normal articulation could achieve eight ounces or more of intraoral breath pressure as measured by an oral manometer. However, some of her speakers impounded only five ounces per square inch of breath pressure in production of pressure consonants.

As indicated by the studies cited above, the audible speech signal is the result of modifications in the exhaled air stream. The production of pressure consonants involves the generation of air pressures below the level of the glottis for all voiced sounds and behind the articulating oral structures for all voiceless and many voiced sounds. The research presented suggests that the relationship between the dynamic process of air pressure build-up, release, and flow is, as yet, ill-defined and little understood. Many areas of relationship between expiration and speech sound production are virtually unexplored. Since defective consonant production is one of the most pervasive of all speech problems, there is a particular need to obtain quantitative information regarding oral and nasal expiratory air flow during normal consonant production to which similar data from persons with speech disorders may be compared. Apparently, of those cited, only the study by Black (5) offers data regarding this important subject.

Speech Disorders Due to Faulty Breath Control

The study of air flow is important, not only because it is basic to normal speech sound production, but also because deficient flow or faulty control of the flow can result in speech disorders. At the present time, it is known that faulty breath support and/or control is a factor in many speech disorders, and is suspected of being a factor in others.

Carrell (9) claimed to observe a difference between normal and speech defective children in vital capacity. He concluded that speech defective children as a group were physically inferior and that they made poorer use of their structural possibilities. Stetson (40) has indicated that any failure in timing between the chest pulses and muscular activities at the glottis may produce phonatory disorders. Hardy (16) has recently reported data suggesting that an inability to build up adequate intraoral air pressure due to defective velopharyngeal valving may contribute to the speech difficulties of some cerebral palsied children. Speech problems in the cerebral palsied population have been traced to inadequate breath support for speech, asynchronous breathing, and to poorly timed or inadequate valving of the breath stream (16). Counihan, Bzoch, Starr (10, 7, 37), and others have suggested that an inability to control the expiratory breath stream due to defective velopharyngeal valving underlies many articulation errors in the speech of persons with the cleft palate. Spriestersbach and Powers (35) have commented:

> Researchers in the area of cleft palate . . . have found that individuals with cleft palates misarticulate with greatest frequency those sounds for which oral breath pressure is highest for normal speakers. These findings suggest that cleft palate speakers typically have difficulty building up enough air pressure in the oral cavity for the adequate production of speech.

Van Hattum (42), in a spirometric study of air used in production of sustained vowels, reported that his cleft palate subjects used a greater percentage of their available air supply during phonation and had lower vital capacities than his normal subjects. Mysak (26) has recently advanced the theory that one of the chief causes of the syndrome labeled "cleft palate speech" is the development of speech skills on an "abnormal pneumatic matrix." Hess and McDonald (18) investigated the nasal air pressure associated with consonant production in cleft palate speakers, utilizing a U-tube water manometer as an air pressure measuring device. These investigators obtained nasal manometric readings from twenty cleft palate speakers articulating consonant-vowel monosyllables and trisyllables. Their study included twenty-four consonants each combined with the vowel [a]. They found that, in their cleft palate subjects, "consonants normally requiring greater intraoral pressure involve greater nasal pressure when articulated by cleft palate speakers."

This brief survey of speech pathology literature illustrates the need for a comprehensive understanding of air flow phenomena, not only in normal speech, but in speech disorders as well. The literature cited indicates that little quantitative data are available relative to air flow phenomena and that data which are available have been obtained with relatively insensitive instrumentation.

Respiratory Air Measurement

Recent improvements have been made in instrumentation designed to measure the air utilized in speech. These improvements include the development of instruments capable of measuring the air stream directly and continuously, with minimal impedence to the flow. In the following pages, representative types of instruments which have been employed in the measurement of air flow in speech will be described.

Spirometers

The wet spirometer, as described by Steer and Hanley (38), is a type of gasometer which is used widely to measure breathed air volume. This device consists of a metal tank for air, an exhaust valve for resetting, and a scale. The instrument was invented in 1849 by Hutchinson and was described (38, p. 183) as follows:

> The Spirometer is merely a vessel or receiver, inverted in another vessel, which contains water, like an inverted wine glass in a tumbler of water; by means of a flexible tube, communication is made with the inverted receiver, and air is blown into it. The receiver then rises, assisted by counterbalance weights; the degree of ascent being according to the volume of air introduced. Such instruments have been known as Pulmometers.

Examples of the use of the wet spirometer in speech research may be found in the work of Van Hattum (42), Spreistersbach, Moll, and Morris (34), and Hardy (16), to name only a few.

A dry spirometer has also been designed recently. The principle of operation of the instrument is basically that of a turbine in that exhaled air strikes small vanes causing the vanes to rotate. The rotation is registered by a needle on a calibrated dial. Steer and Hanley (38) indicate that this instrument is much less cumbersome and space consuming than the wet spirometer, but that it appears to be less reliable and more dependent upon the force with which the breath is exhaled.

Tambours

Tambours frequently have been employed in measurement of oral and/or nasal air pressure in speech, and have also been used in the measurement of bodily movement during respiration. Basically, a tambour is a drum-shaped appliance consisting of a closed cylinder with one end covered by an elastic membrane. The air to be measured is passed into the tambour by means of a tube, and the increase in pressure behind the elastic membrane displaces it outward. Generally, a stylus is attached to the membrane by a mechanical linkage, and the movements of the diaphragm are thus recorded on a kymograph or similar recording instrument. Scripture (33) suggested the use of tambours in the evaluation of velopharyngeal valving as early as 1902, and indicated that the action of the velum may be studied by comparing the breath curve from the nose with that from the mouth. He suggested that this could be done by connecting a nasal olive of convenient size and a mouth trumpet with small tambours, the two tambour points being synchronously registered.

Pneumotachographs

The pneumotachograph, invented by Fleisch (11), is an instrument for measuring the velocity of respiratory air. The instrument is based on the principle that, in an inflexible tube with a nonturbulent air current, the current volume is proportional to the difference in pressure between two points in the tube. Accurate recording of this difference in pressure yields a velocity curve, the ordinate values of which correspond to the volume rate of flow per unit time.

Fleisch (11, p. 53) has pointed out that it is frequently advantageous to record the differential curve of air flow. The curve shows the speed of the air flow at each instant, rather than the integral curve of total volume and manifests details which are not apparent in the integral curve. Fleisch has indicated:

> The only method which indicates how the breathed air circulates and the magnitude of the force exerted by the respiratory muscles during the different phases of respiration is the recording of the speed of air flow; this method will also tell us whether there is a pause at the end of the inspiration or expiration.

Hot-Wire Anemometers

The hot-wire probe or anemometer is a device which may be utilized to measure air flow in speech and was, in fact, the type of device which was utilized in collection of data for the present research. The principles of operation of the hot-wire anemometer and problems associated with its use have been discussed at length by Lion (22). This instrument functions on the principle that a stream of air (or other gas) will cool a heated wire with a known coeffecient of resistivity at a rate proportional to the gas velocity. The wire used must be very fine and have a large coefficient of resistivity. Nickel and platinum are suitable materials. The wire, heated by an electric current, is cooled by the stream of air flowing over it. The consequent heat loss causes a decrease of the wire temperature and thus of the wire resistance. Lion (22, pp. 129-132) has indicated that:

> The system can be used in two ways, either the heater voltage or the heater current is kept constant, and the resistance variations of the wire are used as a measure for the flow velocity of the gas in the vicinity of the probe. The transfer function, resistance variation versus gas flow velocity, increases first steeply and, at higher velocities, with gradually decreasing slope. The method is suitable for measurement of small velocities. Alternatively, the resistance of the wire, i.e. its temperature, is kept constant by varying the heater current of the voltage, and the current or voltage variations are used as a measure of the gas flow velocity.

The finer the wire, the faster will it follow a fast variation in flow velocity. The diameter of wires used for this purpose varies from 0.1 millimeter to the micron range. Lion has indicated that platinum-wollaston wires of a thickness of the order of one mu respond, in general, to gas-velocity fluctuations in the frequency range of 1,000 to 10,000 cps. He has stated that: "The hot-wire method is the only method which permits the local measurement of velocity and velocity fluctuations in unsteady flow. It can be used in flow fields with high gradients and fast variations of velocity." He has also indicated that the method is applicable for flow velocities ranging from 0.5 cm/sec to velocities in the supersonic range.

The hot-wire anemometer is particularly suitable for measuring the differential air flow curve in speech, since the flow is rapidly changing and requires an instrument of extreme response sensitivity. The anemometer's property of responding to a wide range of flow rates is a distinct advantage in measuring these variations. A second advantage is that the sensing wire of the anemometer is of extremely small diameter; therefore, the air flow in speech can be measured with negligible impedence to the flow.

With regard to limitations of the system, Lion (22, p. 131) has indicated that:

> The transducer is apparently not (or very little) influenced by humidity and, at least at steady flow and low velocities, by the pressure of the medium. But the temperature of the conduit wall can be a disturbing influence if the hot wire is in close proximity to the wall (order of 2mm). This influence is reduced at high gas velocities. Errors are also caused by the deposit of dirt or dust upon the wire, by mechanical stress in the wire, and by vibration of the suspension wires under the influence of the gas-stress impact. Further errors can be caused by a variation of the composition of the gas mixture.

A survey of relevant literature suggests that instruments which have been employed previously in the measurement of oral and nasal air flow in speech sound production, with the exception of the pneumotachograph and the hot-wire anemometer have one or more of the following deficiencies: (1) do not measure air flow from the nose and mouth simultaneously, separately, and continuously; (2) lack the sensitivity necessary to detect subtle changes in the volume rate of air flow in speech sound production; (3) involve the introduction of foreign objects into the oral and nasal cavities, thereby altering normal conditions so that the data may be suspected of being contaminated by the method of data collection; (4) involve subjective examiner judgments in determining measurements; and (5) do not produce an automatically obtained, permanent record of the data.

Summary

The literature reviewed in this chapter indicates that certain general relationships between respiration and speech have been defined. It is clear that, in the act of speaking, the expiratory breath stream is modified in systematic ways which result in speech sound production. It is also evident that there are certain minimal respiratory requirements for normal speech, since speech disorders may result from inadequate breath support or control. However, no particular type of breathing has been identified as being preferable for speech. Electronic instruments suitable for making fine analyses of the breath stream in speech, notably the hot-wire anemometer and the pneumotachograph, have only recently been developed, and most previous studies of expiration and speech sound production have utilized relatively insensitive instrumentation of earlier design. This may, in part, explain the paucity of literature defining specific relationships between expiration and speech sound production. The lack of literature in this area, however, indicates a need for detailed analysis of breath stream phenomena in speech utilizing modern, electronic instrumentation.

Defective consonant production is one of the most pervasive of all speech problems; therefore, from the point of view of the speech pathologist, there is a need to obtain quantitative information regarding oral and nasal expiratory air flow during normal consonant production to which similar data from persons with speech disorders may be compared. Data regarding the differences occurring in consonant oral and nasal air flow when consonants are produced in various vowel and syllable contexts would be of particular interest. The literature reviewed suggests that such data is virtually nonexistent at the present time. The present study, therefore, sought to investigate oral and nasal expiratory air flow associated with normal consonant production. The specific consonants studied and the procedures employed in this study are discussed in detail in the following chapter.

CHAPTER III

DESIGN OF THE INVESTIGATION

The purpose of the present research was to investigate, systematically and objectively, the volume rate of oral and nasal air flow expended by normal speaking subjects during the production of six plosive consonants, and to determine the effects of certain vowel and syllable contexts on these rates of flow. Specifically, four major research questions were formulated for study:

1. How do the plosive consonants [p], [b], [t], [d], [k], and [g] differ with respect to maximum volume rates of oral air flow and simultaneously measured volume rates of nasal air flow?

2. How do the vowels [i] and [a] combined syllabically with the six plosive consonants affect the maximum volume rates of oral air flow and simultaneously measured volume rates of nasal air flow for the consonants?

3. How do consonant-vowel and vowel-consonant-vowel syllable contexts affect the maximum volume rates of oral air flow and simultaneously measured volume rates of nasal air flow for the consonants?

4. What is the combined effect of the type of vowel and the type of syllable context on the maximum volume rates of oral air flow and simultaneously measured volume rates of nasal air flow for the consonants?

In the present experiment the research questions posed above were considered separately for male and female subjects. This was done to determine whether oral and nasal air flow differences among the consonants in the various syllable and vowel contexts tended to be different for the two sexes.

Special instruments, calibrated to measure air volume flow per unit time, were used to measure simultaneously the air flow from the nose and mouth of each subject during the production of the experimental syllables. The rapidly varying air flow rates occurring during production of the syllables were recorded by means of a twin-channel chart recorder. The records thus obtained were graphic representations in time of the changing volume rates of oral and nasal air flow occurring during the production of the test syllables. The quantitative data utilized in this study were obtained by measuring the volume rates of oral and nasal air flow at selected points in the recorded patterns of the consonant elements of each syllable. The selection of subjects, the experimental apparatus, the procedures employed in data collection, and the resulting data are described and discussed in the following sections.

Subjects

Fifty young adult subjects were utilized in this study. Twenty-five male and twenty-five female subjects were selected from volunteers available at or near the University of Oklahoma Medical Center. Subjects selected for study were required to be between the ages of twenty and thirty-six years, to have no abnormality of speech or voice quality, to present no history of prolonged or severe respiratory problems, to have essentially normal hearing for speech in at least one ear, and to be capable of performing the experimental task.

The experimental sample was limited to young adults because the instrumentation employed in the study was suitable for use only with adults, and because of the need for research data relating to air flow phenomena in adult speech. The upper age limit was set at thirty-six years to provide a sample of adult subjects below the age at which vital capacity can be expected to undergo change (47). With respect to age, the subjects were distributed as follows: seven male and nine female subjects were between twenty and twenty-six years of age, ten male and eleven female subjects were between twenty-six and thirty-one years of age, and eight male and five female subjects were between thirty-one and thirty-six years of age. The mean age was 28.5 years for male subjects and 28.2 years for female subjects.

In order to eliminate the possibility of deviant speech patterns resulting in aberrant air flow readings, only subjects with normal speech and voice quality, as judged by an experienced speech pathologist, were included in the experimental group. For the same reason, collection of data on subjects reporting current or recent upper respiratory infections was deferred until the symptoms had passed. It was also decided that persons presenting a history of chronic respiratory problems would not be included in the study since such problems might possibly impair the efficiency of the respiratory system. The sample, selected without regard to race, included forty-six Caucasians and four Negroes.

Each subject's hearing was evaluated by means of an audiometric screening test at 15 db intensity (re audiometric zero) through the speech range of frequencies (500-2000 cps). No subject was found to have a loss of hearing greater than 15 db in the better ear, and none reported a history of recent hearing difficulty.

Apparatus

Instrumentation utilized in data collection included: (a) two pneumoanemometers (Flow Corporation, Model 53A1) with a custom-built face mask housing the sensing elements of the pneumoanemometers; and (b) a dual-channel strip-chart recorder (Sanborn, Model 60-1300B). A simplified block diagram of the instrumentation is presented in Figure 1.

Description

Pneumoanemometer assembly. The pneumoanemometer is a completely transistorized electrical device powered by two rechargeable, sealed, nickel-cadmium batteries. Utilization of two pneumoanemometer units with a specially designed face mask and a suitable chart recorder permits rapid, continuous, separately determined, but simultaneously recorded measurements

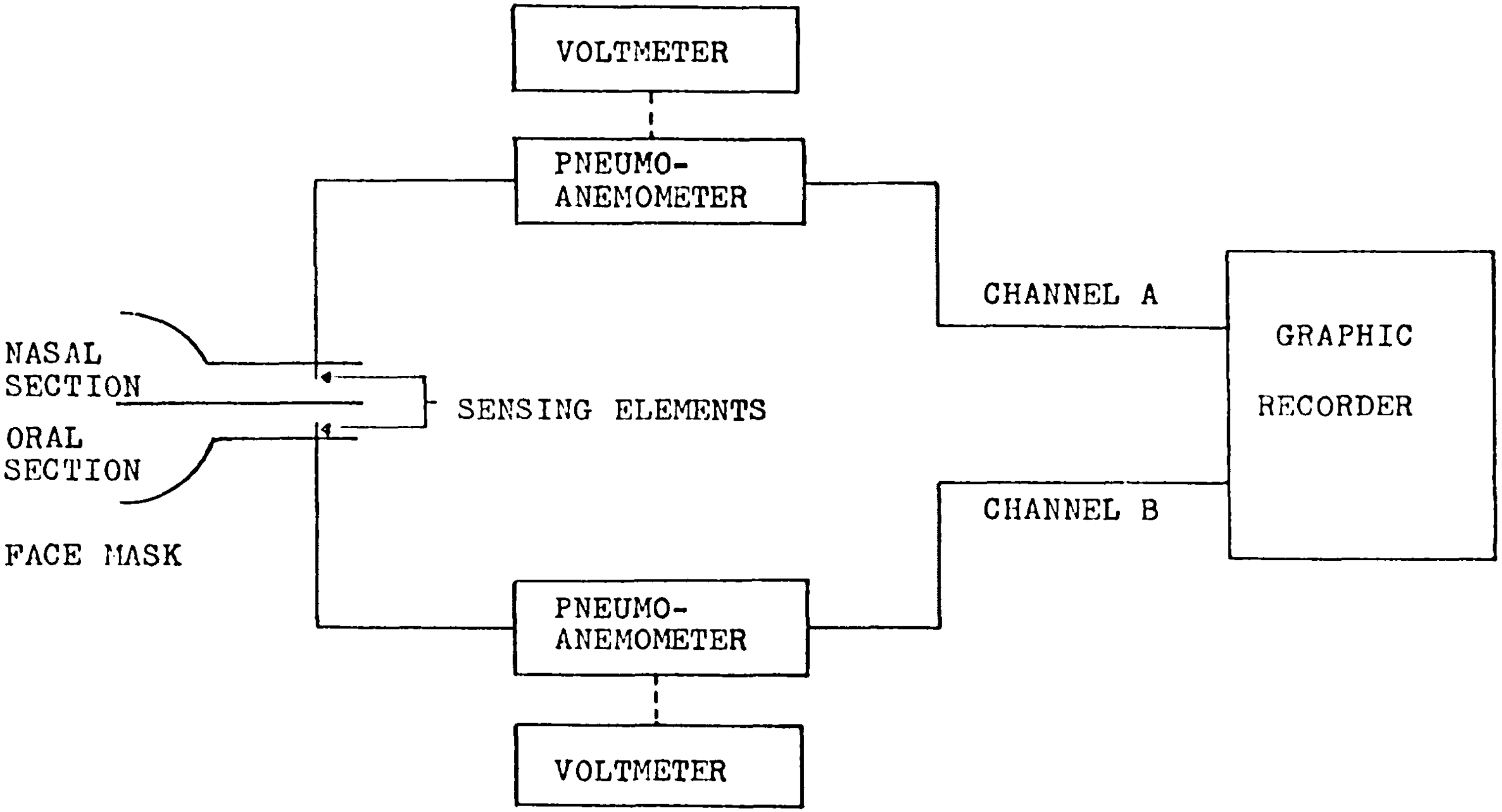

Figure 1.--Simplified block diagram of the research apparatus.

of the volume rate of air flow from the nose and mouth during speech. The small size of the sensing element, a wire approximately 0.188 inches long and .00005 inches in diameter, results in negligible flow interference. Properly calibrated, this instrumentation measures the volume rate of air flow in speech by means of the sensing element which is cooled by a stream of air passing over it. When the sensing element is cooled by the air stream its resistance value changes. This resistance change is reflected in fluctuations in the circuit voltage within the pneumoanemometer units which are proportional to the velocity of the air stream passing the sensing wire at any given instant. Since the sensing element is housed in a tube of unchanging dimensions, the voltage fluctuations are also proportional to the volume of air passing the sensing element per unit time.

The sensing elements of the pneumoanemometers are contained in a short metal tube, four inches in length and seven-eighths inch in inside diameter, which is attached to the face mask. The body of the mask is constructed of plastic, and the surface which fits against the face has an inflatable rubber rim. The metal tube and face mask are divided throughout their length in the midline by a thin, horizontal partition. One sensing wire is located above the partition of the tube; the other is located similarly on the other side of the partition. The partition serves to separate the flow of air from the nose and mouth, causing oral and nasal air flows to pass over different sensing wires. Thus, the volume rate of air flow from the nose and mouth may be measured separately and simultaneously.

In this research, the face mask was attached firmly to the face by means of two rubber straps so that the pneumatic rim of the mask formed an essentially airtight seal against the face. The edge of the partition between the oral and nasal sections of the mask was fitted with a rubber extension which contacted the face above the upper lip and formed a tight seal between the nose and mouth.

Chart recorder. A twin-channel chart recorder was employed to record the output voltages of the pneumoanemometers. The manufacturer's published description indicates that the error of the recorder is less than ± .025 millimeters over the central four centimeters of the chart and less than ± 0.5 millimeters over the outer five millimeters of the chart. For this experiment, the recorder was fitted with twin DC amplifiers (Sanborn, Model 64-300B) to amplify the direct-current output of the pneumoanemometers. The amplifiers were balanced and calibrated to a basic sensitivity of 50 millivolts per centimeter of stylus deflection. An amplifier attenuation setting of X5 permitted recording the entire voltage range of the pneumoanemometers on four centimeters of the five-centimeter chart width. As determined empirically, prior to and following the collection of research data, at this setting each millimeter of stylus deflection above the baseline was equivalent to .025 volt of pneumoanemometer output. Recorder paper speed was set at 100 millimeters per second to permit easy visualization of the variations in air flow occurring within the experimental syllables.

Calibration

The pneumoanemometer, as designed, is a special application of the hot-wire anemometer principle to the measurement of air flow in speech or breathing. The manufacturer's suggested procedure for calibration involved placing the sensing element of the pneumoanemometer in the stream of air generated in a wind tunnel and adjusting the voltmeter of the unit for specified readings at specified air stream velocities. The sensing element was then placed in the tube of the face mask. This calibration procedure appeared to be of questionable validity, since it seemed to ignore certain characteristics of air flow in a tube. The velocity of air in a tube is not the same at all points across the tube diameter, being highest at the center of the tube, and diminishing as the wall of the tube is approached. The average air velocity in the tube varies as a non-linear function of the center tube velocity.

In this research, there was no way of assuring exactly where the sensing wire was placed in the metal tube housing it. Further, the air flows measured were highly variable. It would have been a practical impossibility, therefore, to determine the average velocity or volume of air passing through the tube from a velocity measurement at an undefined point in the stream. It would have been equally impossible to match the oral and nasal sensing elements in sensitivity and position in the tube so that meaningful relative measurements could be obtained. It was necessary, therefore, to devise a method of calibration which would give an accurate measure of the air passing through the face-mask tube and which did not require that the sensing elements be matched in sensitivity or that they be placed in identical positions within the tube. An empirical volumetric calibration procedure, described below, was devised which would satisfy these requirements.

An air compressor with a tank capacity of five cubic feet at thirty psi was utilized as an air source. Pressure in the line from the tank was regulated by an air pressure reducing-valve capable of modifying the line pressure between two and thirty psi. A line pressure of fifteen psi was found to produce a sufficient flow of air to permit calibration of the pneumoanemometers at the upper limits of their capacity to measure, and this line pressure was maintained throughout calibration. Air flow was controlled by a standard laboratory air outlet-valve. From the valve, the air stream was led to a positive displacement air volume meter (American Meter Company, Model AS-8-11) by means of a rubber coupling hose. From this meter, the stream was led by a second rubber coupling hose to a plastic tube of one inch inside diameter. The metal tube of the face mask was inserted into this plastic hose. Since the external diameter of the tube containing the sensing wires was the same as the internal diameter of the plastic hose, a very tight coupling was achieved.

The pneumoanemometer units were then connected to the sensing wires and the pneumoanemometer voltmeters were adjusted to a zero reading. During this procedure, the tube containing the sensing wires was protected from air movement in the room by covering the open end of the face mask. The units were numbered for identification, and the same unit was used with the same sensing wire throughout the research. Since only one sensing wire was calibrated at a time, it was necessary to plug the side of the sensing tube not under test to insure that the entire air stream used in calibration was flowing past the sensing wire to be calibrated. The air outlet-valve was then opened until there was a flow of air sufficient to produce a pneumoanemometer voltmeter reading of .02 volt. The volume of air flowing in one minute, as timed by a stop watch, was measured with the air volume meter. This process was repeated at intervals of .02 volt throughout the output voltage range of the pneumoanemometer (.00 to 1.00 volt), and this same procedure was then repeated for the other unit. Both units were calibrated twice, each on two consecutive days, just prior to the collection of experimental data. The raw data resulting from the calibration trials are shown in Tables 17 and 18 of Appendix A. The calibration curves derived from the two sets of oral air flow data and the two sets of nasal air flow data are shown in Figures 2 and 3, respectively.

Inspection of the calibration data reveals slight differences between the two sets of data taken on two consecutive days; however, the values were generally in close agreement. These data suggest that the pneumoanemometer voltage readings were consistent on repeated measures of a given volume rate of air flow to within approximately .02 volt. There was, however, reason to believe that the slight differences in the two sets of calibration data may have been due to factors other than the variability of the pneumoanemometer units themselves. The pneumoanemometer units were new, and, to all appearances, were functioning as designed. Evidence of the stability and proper performance of the instruments is seen in the fact that when a calibration curve was plotted for the mean of the sets of oral and nasal calibration data, the curve determined by the volumetric method was very similar to the curve determined by the wind tunnel method (see Figures 4 and 5). A new positive displacement air volume meter was used to measure the volume of air flow per minute in this calibration procedure. The manufacturer advised that this meter was originally calibrated against a gas prover meter and that readings at given flow rates should be repeatable with no

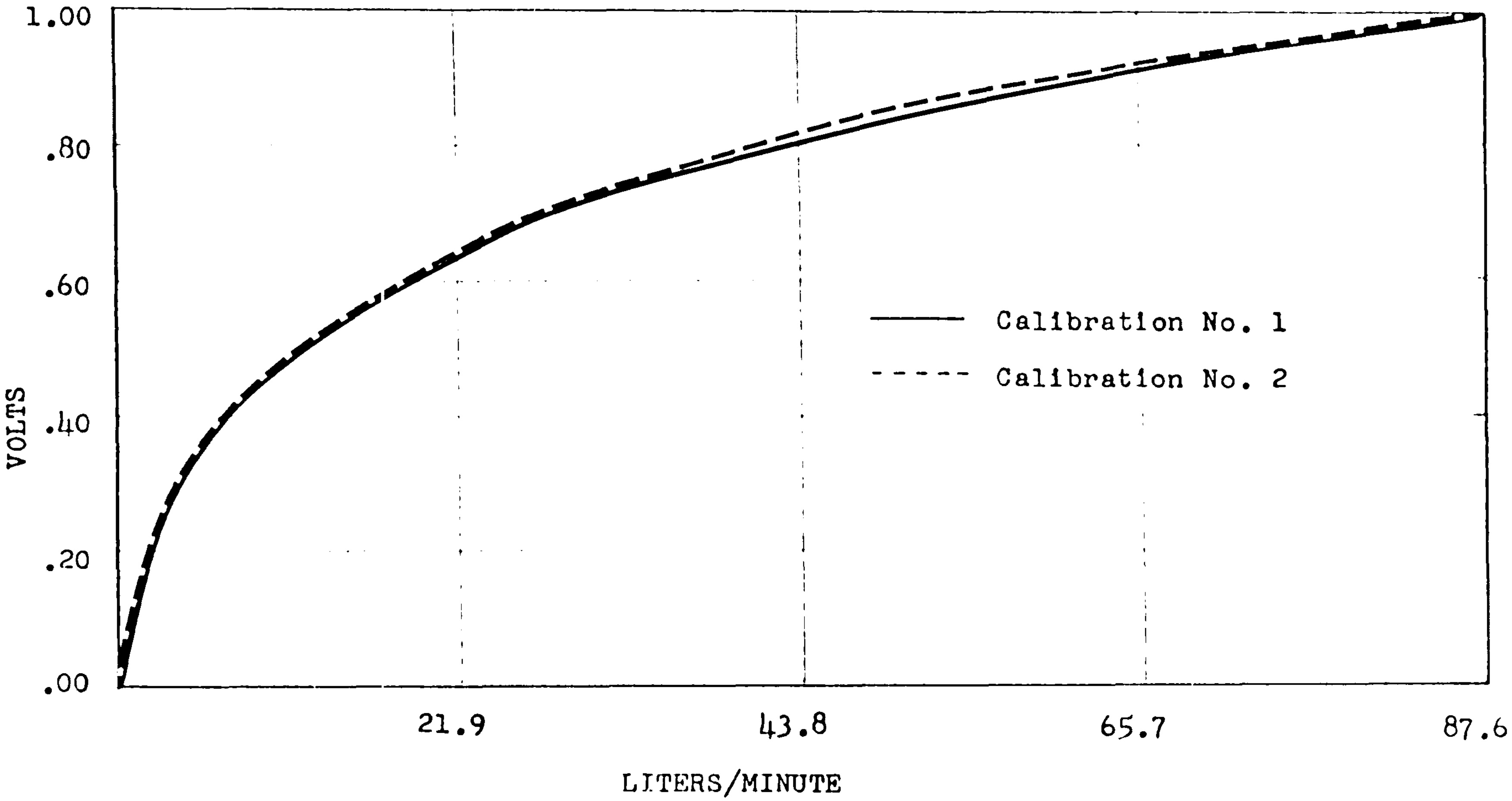

Figure 2.--Calibration curves for each of two sets of oral air flow data taken on consecutive days.

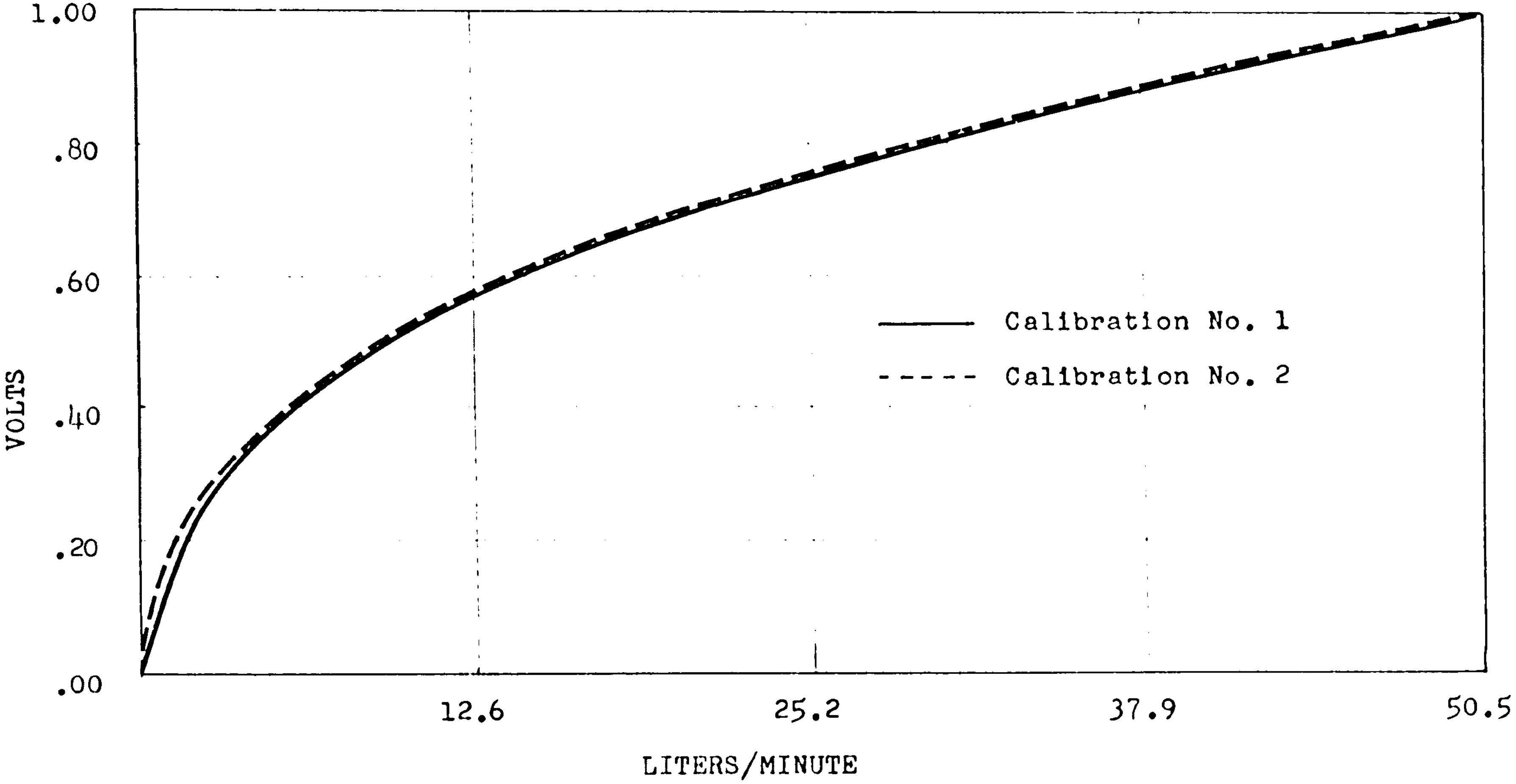

Figure 3.--Calibration curves for each of two sets of nasal air flow data taken on consecutive days.

more than one-tenth of one per cent error.

Thus, while there was reason to have confidence in the instrumentation, slight errors in reading the instruments were possible. It may be recalled that in the calibration procedure the investigator adjusted the air flow until a given voltage reading was obtained on the pneumoanemometer unit voltmeter. A judgment, therefore, had to be made as to when the voltmeter pointer was on a given reading. Though a concerted effort was made to insure that the pointer was always centered on a given reading, small errors in judgment were almost certainly made.

A problem was also encountered in reading the air volume meter with the accuracy desired. At low rates of flow, the indicator on the clock-type face of the air volume meter moved such a very short distance in a minute's time that any error in beginning the reading exactly at the instant the indicator was on zero would have resulted in an absolutely small but relatively large error in air volume measurement. Also, if the researcher was not careful to maintain his eyes at the same position from the beginning to the end of a minute's reading, an error in meter reading was possible. On the basis of experience in pre-experiment trials, it was estimated that errors due to careless head shifting could be as large as .05 liter/minute. Therefore, an attempt was made to eliminate, insofar as possible, such errors in the calibration data by beginning each reading when the indicator was on zero and by maintaining an unchanged position in front of the meter until the reading was made at the end of one minute. In this way, errors in reading the meter, while not eliminated, were reduced.

Another meter reading problem was encountered which could, in part, account for the small differences between the two sets of calibration data obtained in this study. At high rates of flow, the indicator of the air volume meter was moving so rapidly that errors in reading could have been made because the position of the indicator at the end of one minute had to be determined with the indicator in motion. It was estimated that errors in reading the meter of the magnitude of .1 or .2 liters/minute were possible, therefore, at high flow rates. In view of the possibilities for errors, the two sets of raw calibration data were regarded as being in close agreement. It was, of course, also possible that the differences in readings in the two trials represented the variability of measures made with this instrument.

To complete the calibration, a single air flow value at each voltage point was computed by averaging the two air flow values obtained at that point during the two calibration trials. A curve was then fitted to the data collected for each unit, using a least squares fit to a quadratic equation. To provide a close fit of the curve to the data, the calibration data for each unit were divided into three ranges: from .02 to .20 volt, from .22 to .60 volt, and from .62 to 1.00 volt. A curve was then fitted separately to each part. The curves were so fitted that the computed and empirically determined mean air flow values, corresponding to each of the measured voltage points within a given section of the curve, did not differ from each other by more than 1.5 percent of the largest computed air flow value in that section of the curve. The curves thus determined for the oral and nasal air flows are shown in Figures 4 and 5, respectively. The computed volume rates of air flow corresponding to each of fifty voltage points measured for each of the two pneumoanemometer units are shown in Tables 19 and 20 of Appendix A.

The calibration of the units was checked approximately once each week throughout the course of the experiment to insure that the instruments remained in calibration. The volume of air required to produce pneumoanemometer voltmeter readings at intervals of .10 volt throughout the output voltage range of both the oral and nasal units was determined and compared with the original calibration figures. It was determined, by means of these trials, that, within the limitations imposed by the calibration technique, the instruments did not change in calibration throughout the collection of data. It was necessary, however, to establish a new calibration curve for the nasal sensing wire in the instance described below.

When about three-fourths of the experimental data

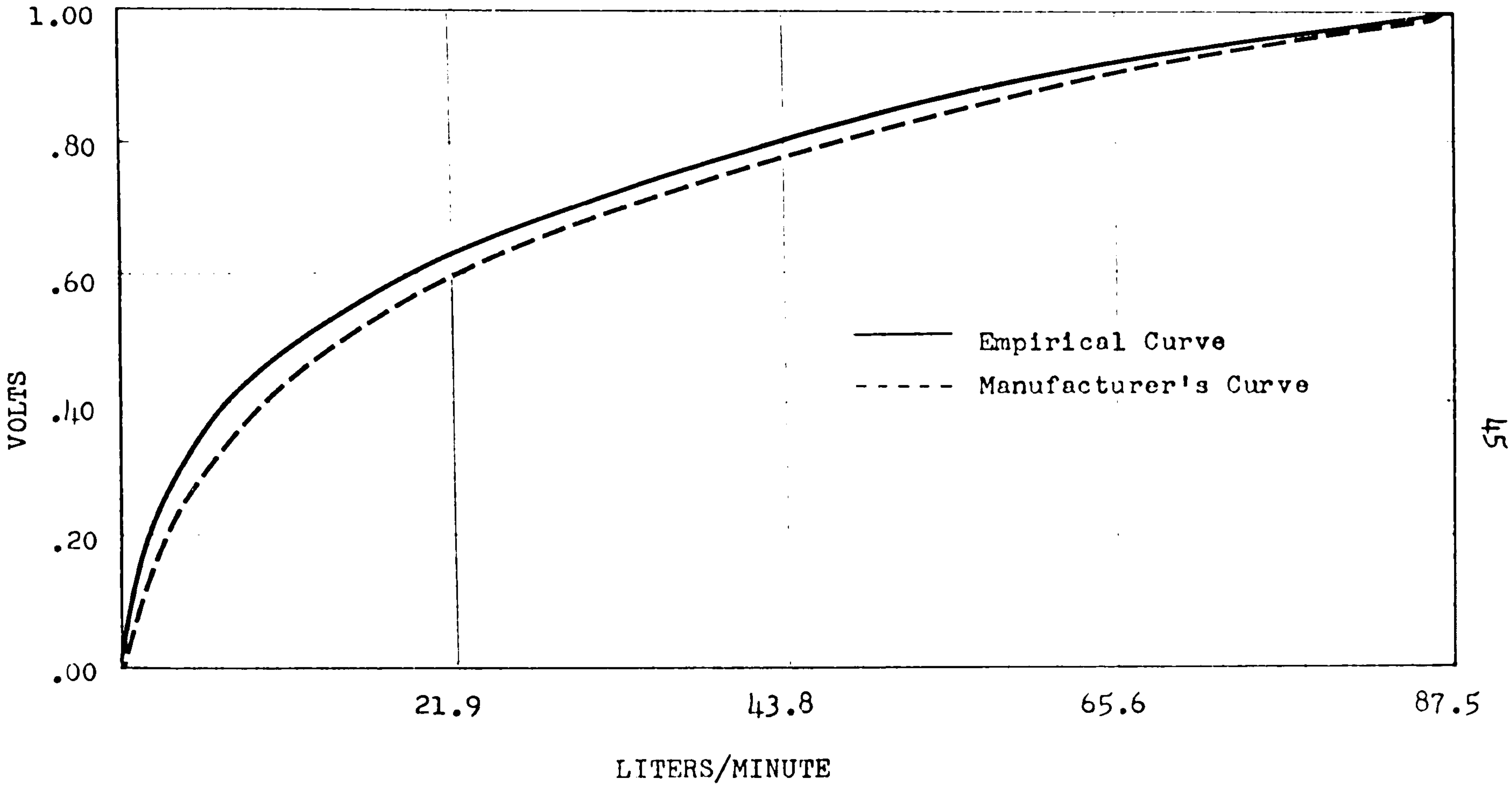

Figure 4.--Empirically determined volumetric curve of calibration for oral air flow and manufacturer's curve determined by the wind tunnel method.

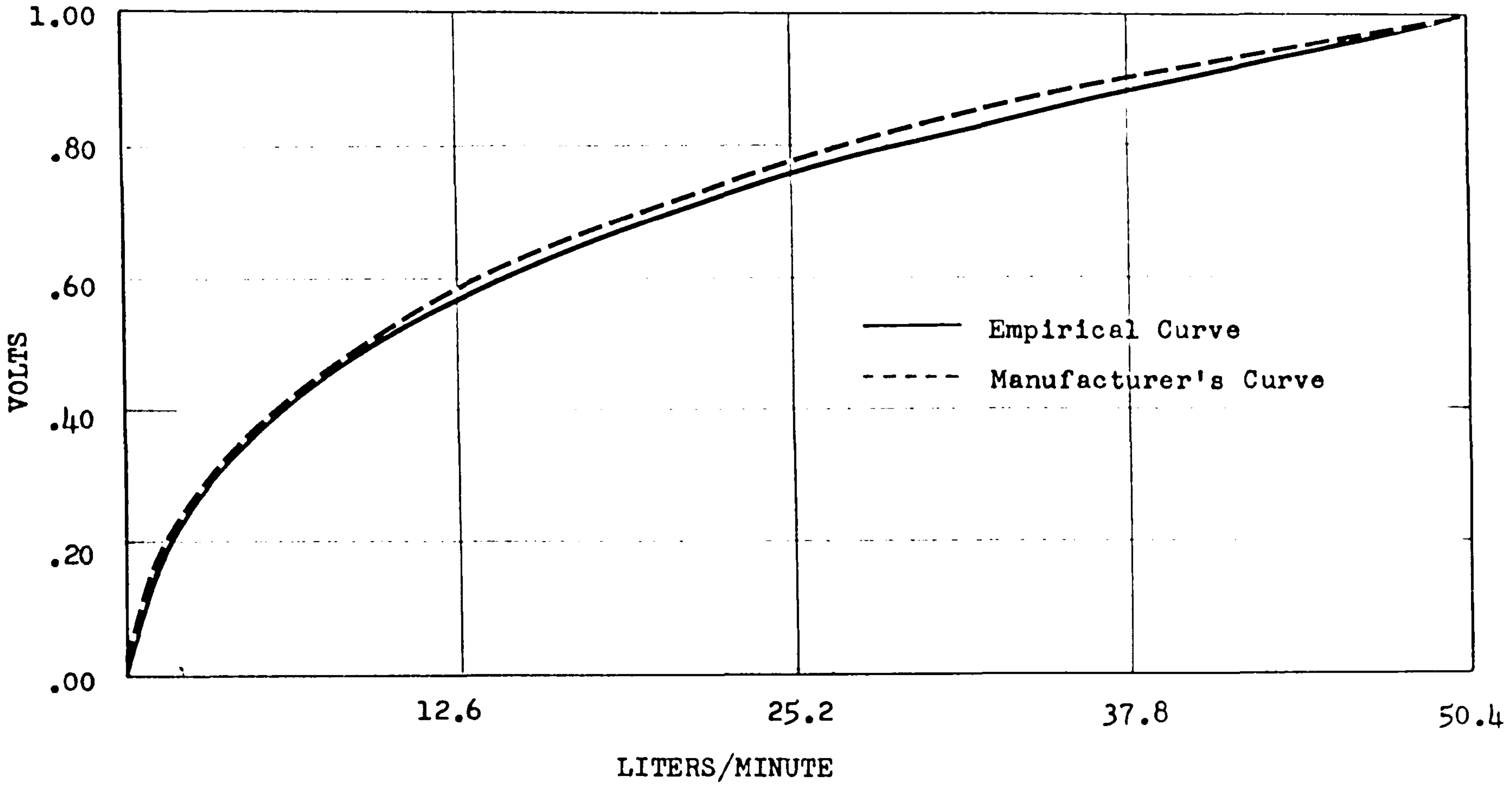

Figure 5.--Empirically determined volumetric curve of calibration for nasal air flow and manufacturer's curve determined by the wind tunnel method.

had been collected, the nasal sensing wire broke. The broken wire was replaced immediately and the pneumoanemometer unit to which it was connected was recalibrated according to the procedure previously described. The raw calibration data and the computed volume rates of air flow corresponding to each of the fifty voltage points measured for the unit are shown in Tables 21 and 22, respectively, of Appendix A. The calibration curve of this replacement wire is shown in Figure 33 of Appendix B. Periodic calibration rechecks indicated that the replacement wire and the unit with which it was connected did not change calibration throughout the remainder of the experiment.

Calibration of the oral and nasal pneumoanemometer units after collection of all data revealed essentially no change in either unit from the original calibration. According to the manufacturer's manual, the pneumoanemometer may be expected to ramin in calibration for approximately one year; data for this study were collected in approximately two months.

The temperature of the air used in calibration was measured at 72°F. The temperature of air expelled from the mouth in breathing is approximately at body temperature (47). Since warmer air has less cooling effect on the pneumoanemometer sensing wires than cooler air, the units tend to underestimate the volume of warmer air. The manufacturer has recommended that data collected on air warmer than the temperature of calibration air should be corrected for the temperature difference by raising the data values by one per cent for each six degrees difference between the temperature of calibration air and air measured in the experiment. The data collected for this research were corrected by raising the value of the collected data by four and one-half per cent, i.e., one per cent for each six degrees difference between 72°F, the temperature of air at calibration, and 99°F, the approximate temperature of the body. It was not possible, because of a lack of appropriate instrumentation, to verify the manufacturer's temperature correction at all air flow rates encountered in the present study. However, by comparing air flow values at selected voltage readings, at air temperatures of 72°F and 99°F, respectively, a difference in readings approximating that reported by the manufacturer was attained. While admittedly gross, this comparison did indicate the presence of the temperature effect. The temperature correction employed is, perhaps, open to question and constitutes a possible source of error in the absolute values for oral and nasal air flow reportedly in this study. It may be noted, however, that even a temperature correction error as much as 6°F would introduce a data error of but one per cent.

Speech Sample

The speech sample used in the present study consisted of thirty-six nonsense syllables. These syllables were composed of six plosive consonants ([p], [b], [t], [d], [k], [g]) combined individually with the vowels [i] and [a]* in three types of syllables: consonant-vowel, vowel-consonant-vowel, and vowel-consonant. Plosive consonants were studied for two reasons. First, pilot study data suggested that the patterns for these sounds were distinctive enough to permit visual separation of the consonant and vowel components of each syllable on the air flow records. This was not true of other consonants such as the voiced fricatives and semi-vowels. Second, they could be subclassified to permit study of the effect of voicing and place of articulation on oral and nasal air flow while holding manner of articulation constant. Three of the plosive consonants studied, [b], [d], and [g], were voiced, and three, [p], [t], and [k], were voiceless. Two of the consonants, [b] and [p], were bilabial; two, [t] and [d], were lingua-alveolar; and two, [g] and [k], were lingua-velar.

The vowels [i] and [a] were selected to permit study of the effect of different vowel contexts on consonant air flow. The vowels [i] and [a] differ in two ways important to this study. X-ray studies of velar valving during vowel production in normal speaking subjects (<u>46</u>) have indicated that the velar valve is predominantly open in the production of [a] and closed during production of [i].

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* In this study the symbol [a] is used to denote the sound of "a" as in "f<u>a</u>ther."

These vowels also differ with respect to lingual position. Phoneticians (17) classify [i] as a high front vowel and [a] as a low back vowel. In the production of [i], therefore, the oral airway is normally more occluded by the tongue than it is in [a].

Since nonsense syllables were used as the speech sample in this study, each subject was practiced until he could produce all syllables correctly. Failure to produce these syllables in accordance with the experimenter's instructions resulted in disqualification of only one subject.

Procedure

Prior to the collection of data, each subject was instructed and practiced in the production of the experimental syllables. Each subject was instructed to produce the three syllables during a single breath at a uniform conversational level of intensity, pitch, and rate. The subjects were also instructed to produce each syllable with uniform stress, to avoid differences which might occur as an artifact of inflectional variations.

It was anticipated, however, that subjects might utilize more breath at the beginning of the three syllable sequence, and less breath toward the end of the sequence. To counterbalance any such order effect, the sequence in which a subject said the syllables was determined by random selection from three arrangements possible in a Latin Square: (1) CV, VCV, and VC; (2) VCV, VC, and CV; and, (3) VC, CV, and VCV.

A four-by-six-inch card indicating the order in which the three syllables were to be produced was prepared for each consonant with each vowel, and each card was color-coded according to the sequence represented. This arrangement facilitated selection of one of the three possible sequences, as chance dictated, and also made it possible to present three syllables to a subject simultaneously in the experimental situation.

All experimental data were collected in a sound-treated test suite at the University of Oklahoma Speech and Hearing Center. This site was chosen for the experiment because there were no strong air currents in the room, and because background temperatures were more stable than in other parts of the building. These conditions were important because of the sensitivity of the pneumoanemometers to air flow and temperature fluctuations within the test room. Since subjects were instructed to speak at a conversational level, a quiet acoustic environment, similar for all subjects, was considered necessary.

Once the subject had been instructed and practiced in the pronunciation of the syllables, a small ball of cotton was affixed with adhesive tape just below the eyes on both sides of the nose. This was done to fill in the angle formed by the sharply rising contours of the nose and face to facilitate a tight fit of the mask. The subject was then seated in an examining chair, and the head-rest was adjusted to maintain the head in a comfortable and stable position.

Since the sensing wires of the face mask can be cooled by air moving either in or out of the tubes in which they are housed, it was important to insure that the mask was stable during the testing. The face mask was mounted by means of a clamp to a metal bar, thirty-six inches long, which was attached at either end to an ajustable stand. This arrangement permitted an easy adjustment of the height and position of the mask to the subject, and held it stable once it was fitted. The stands were then adjusted in height and position until the mask fit tightly against the subject's face. It was then secured in position by means of rubber straps which were attached to both sides of the mask and passed behind the head-rest of the examining chair. A visual inspection was made of the tightness of fit, particularly along the pneumatic rim. If any place where air leakage might occur was visualized, adjustments were made until an apparently tight fit was achieved.

The subject was then asked: (1) to produce and sustain the nasal consonant [m]; and (2) to blow through his mouth. Chart recordings of oral and nasal air flow during both of these trials were made. If the production of the [m] sound resulted in no registration of oral air flow, and if blowing through the mouth resulted in no registration of nasal air flow, the partition of the mask separating the oral and nasal sections was judged to be tightly fit.

The cards containing the experimental syllables were held by an assistant so that they were easily visible to the subject, and data collection was begun on a signal from the examiner. If the subject made an error in pronunciation detectable to the examiner or to himself, or otherwise violated his instructions, the chart recorder was stopped and the error was noted. All test syllables in that three-syllable series were then repeated.

Experimental Data

Examination of the chart records of oral air flow for each of the consonant and vowel combinations indicated that the vowel and consonant elements of each syllable and the implosive and explosive phases of the consonants could be easily distinguished. A sample chart recording of the oral and nasal air flow occurring during production of the bisyllable [ibi] is shown in Figure 6.

In this study, oral air flow was measured in the production of plosive consonants in CV and VCV syllables, but not in VC syllables. In CV and VCV syllables, where the consonant served as the initial or medial syllabic element, the recorded air flow patterns for the consonant and the preceeding and/or following vowel were distinctly different. Examination of the chart recordings of oral air flow for CV syllables, for example, revealed that, for all subjects,

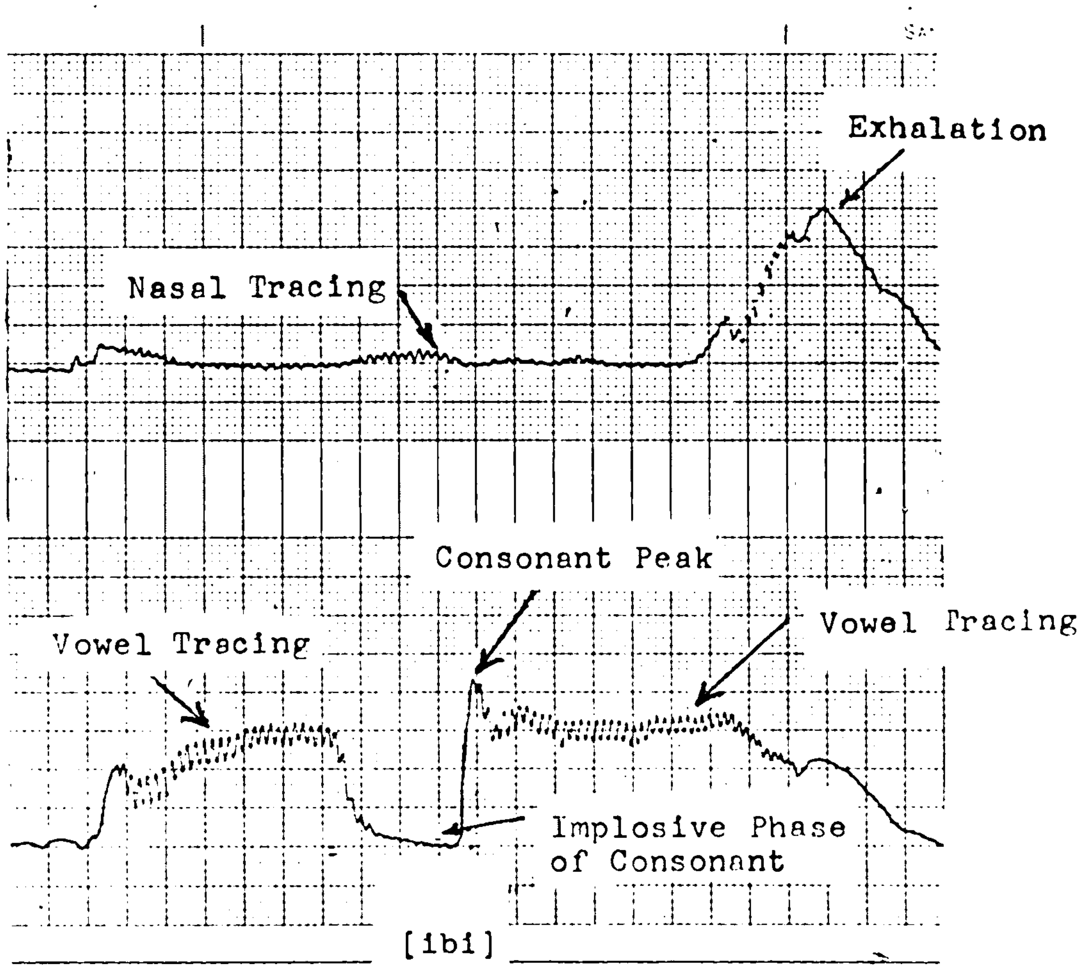

Figure 6.--Chart record of VCV syllable [ibi] produced by male subject.

there was a very little or no oral air flow at the end of the implosive phase of the consonant. Release of the orally impounded air in the explosive phase of the consonant resulted in a sharply rising line on the chart record, indicating a rapid increase in the volume rate of air flow from the oral cavity. In the explosive phase, the maximum flow rate was usually sustained for a period of less than .01 second . This spike was followed by a sustained air flow pattern at a moderate flow rate which was characteristic of vowel production. In general, the pattern for the implosive and explosive phase of the consonants in VCV syllables was similar to that seen for CV syllables. In VC syllables, however, where the consonant served to arrest the syllable, an acceptable acoustic production of the syllable was heard by the examiner whether or not an explosive phase was present. Since subjects were not specifically instructed to release the final consonant, some subjects released it and some did not, so that an explosive phase of the consonant in VC syllables was not always found on the chart record. In addition, the chart record of the explosive phase in VC syllables, when present, was often merged with the record of an immediately-following exhalation. For these reasons, no demonstrably reliable or valid means for determining the maximum oral air flow in VC syllables was found. No attempt was made, therefore, to measure oral air flow in the production of consonants in VC syllables.

The maximum or peak volume rate of oral air flow during consonant production was measured in this study for a number of reasons: First, the point at which peak oral air flow occurred during consonant production was clearly identifiable as being within the consonant phoneme; second, pre-experiment trials indicated that the peak oral air flow in plosive consonant production was one point in the chart tracing which could be reliably determined; third, it was found that this point could serve as a reference to which measurements of nasal air flow could be related; and fourth, it was felt that if changes in the syllable and/or vowel environment affected the consonants at all, it was likely that the maximum volume rate of oral air flow would be among the factors affected. It appeared, therefore, that measurement of maximum volume rates of oral air flow during consonant production was feasible and would yield useful and meaningful information.

Measurements were made to the nearest one-half millimeter of chart excursion. To insure accuracy, measurements were made on all records and repeated a second time. Measurements were made a third time to resolve differences of one-half millimeter or more between the first and second measurements. These data were converted to pneumoanemometer output voltages by means of the formula: voltage = .025 x millimeters of chart excursion. The formula was recommended by the manufacturer of the chart recorder for determining input voltages equivalent to any given chart excursion. As previously indicated, the validity of this formula was verified empirically. The voltage values obtained by means of the formula were converted to equivalent flow rate values in liters per minute in accordance with the calibration curve for each instrument. Each flow rate thus obtained was raised by a correction factor to compensate for the difference in the temperature of air used in calibration and that used in speech. The statistical treatment of these data and the findings for this study are reported in the following chapter.

Summary

Twenty-five young adult males and twenty-five young adult females were utilized as subjects in this study. All subjects were selected from volunteers available locally, and all were required to meet certain standards for selection. Subjects were required to be normal speakers, to be between the ages of twenty and thirty-six years, to have essentially normal hearing in at least one ear, to present no history of recent or chronic respiratory illness, and to be able to perform the experimental task following brief instruction and practice.

Each subject was required to pronounce a series of syllables composed of the plosive consonants [p], [b], [t], [d], [k], and [g] individually combined with the vowels [i] and [a] in CV, VCV, and VC syllables (VC syllables were not analyzed in this experiment). Each subject was required to produce the three syllables involving a given consonant in combination with a given vowel on one exhalation, at a conversational level of intensity, and in a monotone. The requirement for a conversational level of intensity was imposed because it was desired to investigate volume rates of oral and nasal air flow at levels of vocal intensity which were comfortable for the speaker, rather than at artificially imposed intensity levels which might be typical of some speakers, but not of others. Subjects were required to speak in a monotone so that a disproportionate inflection emphasis would not be given any one syllable in the three syllable sequence. To guard further against this possibility, the order of presentation of syllables within a sequence was randomized.

All data were collected in a sound-treated test room which provided a similar speaking environment for all subjects. Subjects were seated during the collection of data. Two pneumoanemometer units, which are specially designed hotwire anemometers, were utilized in data collection. The anemometer sensing elements were contained in oral and nasal sections of an open-ended metal tube which protruded anteriorly from a face mask. A partition in the middle of the tube and face mask separated the oral from the nasal air flow. Because the tube was open at the end, there was negligible impedence to the air flow. Each sensing element was connected to a different pneumoanemometer unit, permitting separate and simultaneous transduction of oral and nasal air flow into continuous voltage analogs. These analogs were recorded on separate channels of a dual-channel chart recorder. The peak volume rate of consonant oral air flow was then located on the chart records of each syllable, and this excursion was measured to the nearest one-half millimeter. The nasal volume rate of flow registered at the instant of maximum oral air flow during consonant production was similarly measured. The measurements thus obtained were converted mathematically to volume rates of oral and nasal air flow expressed in liters per minute.

CHAPTER IV

RESULTS

This study was designed to investigate oral and nasal air flow during plosive consonant production. The plosives [p], [b], [t], [d], [k], and [g] were produced by fifty normal-speaking young adults, twenty-five male and twenty-five female, in consonant-vowel and vowel-consonant-vowel nonsense syllables in combination with the vowel [i] and the vowel [a]. Two pneumoanemometer units and a dual-channel chart recorder were utilized to measure and record the volume rates of oral and nasal air flow occurring during production of the syllables. The chart records of the consonants were then analyzed to determine the maximum volume rate of oral air flow and the simultaneously occurring volume rate of nasal air flow. By means of a mathematical conversion, each datum thus obtained was expressed as a volume rate of air flow in liters per minute.

The data for male and female subjects were analyzed statistically by means of a split-plot-design analysis of variance with a factorial arrangement of treatments and, where appropriate, by the Duncan Multiple Range Test, in order to answer the research questions stated in Chapter III.

Alpha level was set at .05. It may be noted that this study was, in effect, a replication of one experiment on two different groups of subjects classified by sex. Although the data for the two sexes were not compared statistically, trends common to the two sexes or different for the sexes are discussed in the presentation of findings.

In the discussion of findings which follows, there is frequent need to refer to the "mean maximum volume rate of oral air flow" and the "simultaneously measured mean maximum volume rate of nasal air flow" for the consonants studied. However, because of the length of these terms, shorter expressions are usually employed. The reader is advised that whenever the terms "mean oral air flow," "mean nasal air flow," "oral air flow," or "nasal air flow" are used, they are substitutes for the longer and more accurate terms noted above.

Consonant Oral Air Flow

Examination of the summaries of the analyses of variance for the oral air flow data, presented in Tables 1 and 2, indicates that, for both male and female subjects, the consonant, vowel, and syllable main effects, and the vowel-by-consonant, vowel-by-syllable, and consonant-by-syllable interactions are significant. The vowel-by-consonant-by-syllable interaction is not significant for either sex.

Consonant Main Effect

One of the major purposes of this study was to

TABLE 1.--Summary of the analysis of variance for the consonant oral air flow data from twenty-five male subjects

Source	df	ms	F
Vowel (V)	1	1041.20	75.86*
Consonant (C)	5	19267.42	140.37*
VC	5	936.36	6.82*
Error A	264	137.26	
Syllable (S)	1	127393.20	446.01*
VS	1	3042.70	10.65*
CS	5	5118.16	17.92*
VCS	5	291.38	1.02
Error B	288	285.63	

*$P < .05$

TABLE 2.--Summary of the analysis of variance for the consonant oral air flow data from twenty-five female subjects

Source	df	ms	F
Vowel (V)	1	6104.90	48.36*
Consonant (C)	5	17283.54	136.91*
VC	5	1085.40	8.60*
Error A	264	126.24	
Syllable (S)	1	71938.00	36.60*
VS	1	1591.16	8.10*
CS	5	4014.16	20.42*
VCS	5	214.84	1.09
Error B	288	196.56	

*$P < .05$

investigate possible differences in oral air flow among the six plosive consonants tested. Figure 7 presents, for male and female subjects, the mean oral air flow for each consonant averaged over both types of syllable and vowel context. A comparison of these means reveals that males averaged greater oral air flow than females in the production of each of the six consonants. For male subjects, the largest mean air flow was recorded for the [t] sound, followed in order of decreasing flow by the [p], [k], [d], [b], and [g] sounds. The order is similar for female subjects except that the mean for the [g] sound exceeds that for [b]. It is interesting that, for both sexes, greater oral air flow means occurred in the production of the voiceless plosives, [t], [p], and [k], than in the voiced plosives, [d], [b], and [g]. The mean for the [k] sound, which is the smallest of those for the voiceless plosives, substantially exceeds that for any of the voiced sounds.

Summaries of the analyses of variance for the oral air flow data for male and for female subjects are presented in Tables 1 and 2, respectively. Inspection of Tables 1 and 2 indicates that the consonant main effect is significant for both male and female subjects. The presence of this significant main effect indicates that, when oral air flow means are averaged over all syllable and vowel contexts for each of the six consonants, there is a significant difference among the means.

The Duncan Multiple Range Test was used to locate

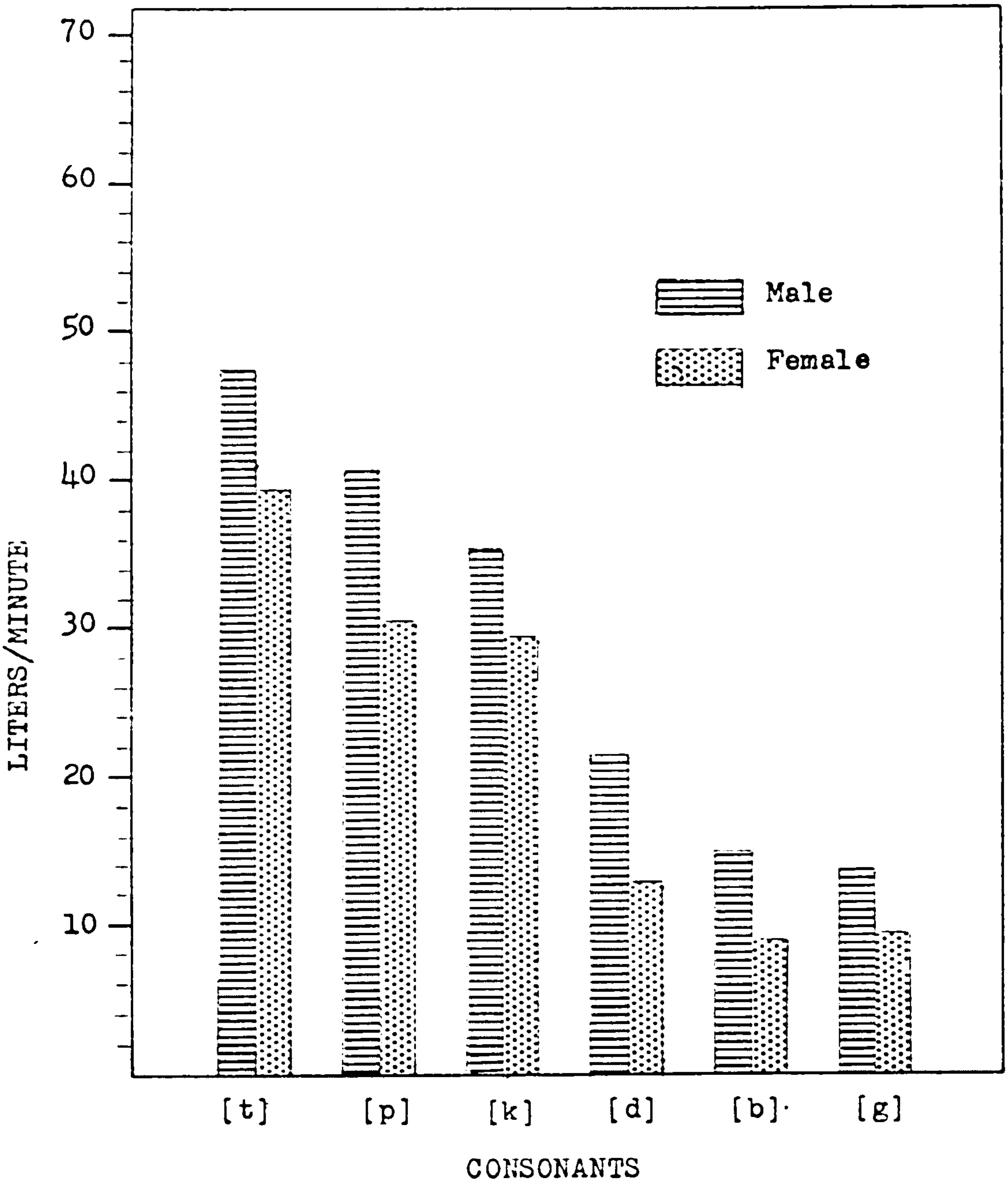

Figure 7.--Oral air flow means for each of the six plosive consonants produced in both CV and VCV syllables in combination with [i] and [a], for twenty-five subjects of each sex.

the significant differences among the consonant means which were detected by the analysis of variance. The results of these tests are presented in Tables 3 and 4. Inspection of Table 3 reveals that, for male subjects, each of the oral air flow means for the [t], [p], and [k] sounds is significantly larger than the means for the [d], [b], and [g] sounds. The means for the [t] and [k] sounds are also significantly different. All other differences among means are not significant. Table 4 shows that, for the female subjects, the means for the [t], [p], and [k] sounds are significantly greater than those for the [d], [b], and [g] sounds. The mean for the [t] sound is significantly larger than the means for [p] and [k], and the mean for the [d] sound is significantly larger than the means for the [b] and [g] sounds. All other differences are not significant.

This analysis indicates that, for both sexes, there is a significantly greater mean oral air flow in the production of the voiceless consonants than in voiced consonants. This finding appears to parallel the finding reported by Black (5) that voiceless consonants are characterized by significantly greater intraoral air pressures than voiced consonants. The only significant pattern with respect to place of articulation revealed by the present findings is that, for female subjects, the lingua-alveolar consonants [t] and [d] involved greater oral air flow means than the other voiceless and voiced consonants, respectively.

TABLE 3.--Duncan Multiple Range Test for differences among oral air flow means for each of the six plosive consonants produced in both CV and VCV syllables in combination with [i] and [a], for twenty-five male subjects

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)
R_p:	10.37	10.93	11.30	11.56	11.78

b) Results

Consonants:	[g]	[b]	[d]	[k]	[p]	[t]
Means:	14.14	15.83	21.29	35.58	40.51	47.28
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	———	———	———			

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

TABLE 4.--Duncan Multiple Range Test for differences among oral air flow means for each of the six plosive consonants produced in both CV and VCV syllables in combination with [i] and [a], for twenty-five female subjects

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)
R_p:	3.15	3.32	3.43	3.51	3.57

b) Results:

Consonants:	[b]	[g]	[d]	[k]	[p]	[t]
Means:	8.86	9.63	13.23	29.69	31.16	39.84
				———	———	———
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Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

Vowel Main Effect

A second major purpose of this study was to investigate the effect of two different vowel contexts on oral air flow occurring in plosive consonant production. The vowels [i] and [a] were chosen to allow comparison of oral air flow means for these consonants when combined with each of two vowels differing in tongue position and in velopharyngeal valving. Figure 8 presents, for male and female subjects, the oral air flow means for plosives combined with [i] and combined with [a]. The means are averaged over the six consonants and both syllable contexts. It may be seen in Figure 8 that both male and female subjects averaged greater oral air flow in production of the consonants combined with [a] than with [i]. Male subjects evidenced greater oral air flow in production of plosive consonants than did females when the consonants were combined with [i] and when they were combined with [a]. However, the differences among the measured values for the two sexes were not tested for statistical significance.

The analyses of variance summarized in Tables 1 and 2 indicate that the vowel main effect is significant. Since the vowel [a] is associated with significantly greater consonant oral air flow than the vowel [i], it may be that the relatively high elevation of the tongue for [i] tends to block partially the oral air flow whereas the relatively low tongue position for [a] does not.

These findings may be contrasted with those of Black (5) who studied intraoral air pressures measured during

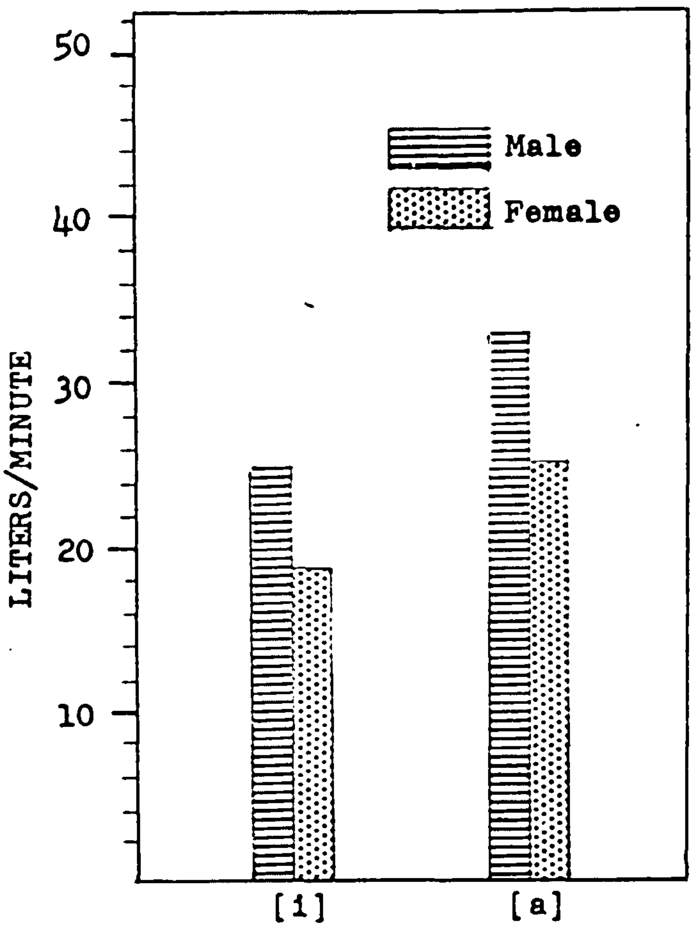

Figure 8.--Oral air flow means for the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five subjects of each sex. The means are over CV and VCV syllables.

production of eight consonants ([p], [b], [d], [t], [v], [f], [z], and [s]) combined with the vowels [a], [i], and [ʌ] in initial, medial, and final syllabic positions. Black found no differential vowel effect on the consonants. He stated that: "The fact that the vowels with varying degrees of openness had no differential effect upon the consonants is interesting. Different consonants are known to affect the vowels that preceed or follow them."

It should be noted that there are certain differences between the present study and Black's study with regard to the number and type of consonants and vowels studied and the experimental prodedure employed. Black considered fricative as well as plosive consonants and included the vowel [ʌ] as well as the vowels [i] and [a] in his experimental syllables. In addition, Black measured intraoral air pressure during the implosive phase of the consonant, while, in this study, the air flow during the explosive phase was considered. Differences between the findings for the two studies may also be related to the manner of data collection. Black reported that, in his study, the order of the vowels was rotated from reader to reader. In this study, the order of vowels was not rotated. It is conceivable, therefore, that the differential vowel effect on consonant oral air flow in this study may have been due, at least in part, to the manner of data collection. It is also possible that the seeming disagreement with Black's findings is due to differences in the sensitivity of the instrumentation employed. Black indicated that "the mechanical technique employed in this study is subject to review in subsequent approaches that may utilize less cumbersome equipment. There was doubtless some distortion of normal speech due to readers having a pressure tube in the mouth." The instrumentation employed in this study was extremely sensitive and may, therefore, have revealed subtle differences not revealed by Black's instrumentation.

Syllable Main Effect

A third purpose of the present study was to determine the differential effect, if any, of the two types of syllable (CV, VCV) on oral air flow occurring in the production of plosive consonants. It was felt that such information would aid in determining whether the position of a plosive in a syllable had an effect on the rate of oral air flow utilized in its production. The oral air flow means averaged over all consonants and both vowels for consonants in CV and VCV syllables are presented in Figure 9. It may be seen in Figure 9 that male subjects utilized greater mean oral air flow in the production of their consonants than did females in each of the two types of syllables. The differences between the values for the two sexes were not tested for statistical significance, however. It may also be noted that, for both male and female subjects, plosives produced in CV syllables involved substantially greater mean oral air flow than consonants produced in VCV syllables.

The analyses of variance summarized in Tables 1 and

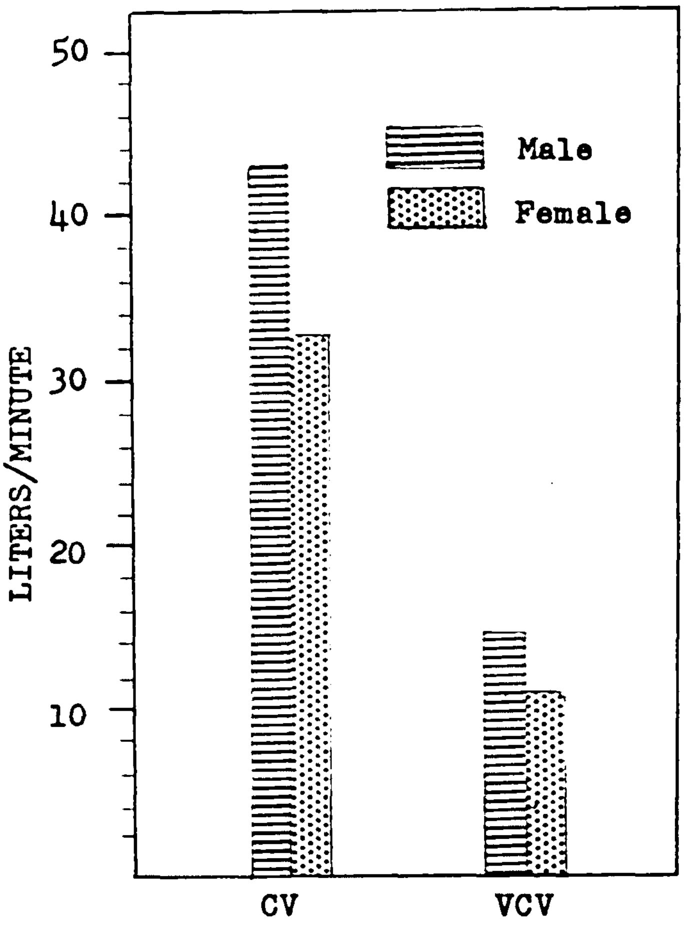

Figure 9.--Oral air flow means for the six plosive consonants produced in CV and in VCV syllables, for twenty-five subjects of each sex. The means are over the vowels [i] and [a].

2 reveal that the syllable main effect was significant for both sexes. These findings suggest that, for both sexes, there is a physiological difference in the way plosive consonants as a group are produced in the initial and medial positions in a syllable. Medial plosive consonants are associated with less oral air flow than initial plosives. These results parallel those of Black (5) who reported significantly greater intraoral air pressures for plosive consonants in the initial than in the medial syllabic position.

Vowel-by-Consonant Interaction

It was reported earlier in the discussion of the consonant main effect that, when the oral air flow means for each of the six consonants were averaged over the two types of vowel and two types of syllables, there were significant differences among certain of the consonant means. In the analysis of the vowel main effect, it was found that when the means were averaged over the six consonants and both syllables the two vowels had a significantly different effect on consonant oral air flow. It was of interest, therefore, to determine if the two vowels affected the oral air flow means for each of the six consonants similarly, or, stated in the converse, if the individual consonants were equally responsive to the vowel influence. Data pertinent to this question is found in the vowel-by-consonant interaction.

Trends in the data making up the vowel-by-consonant interaction may be examined first. The oral air flow means for each of the six consonants in combination with the vowels [i] and [a] for male and female subjects are plotted in Figures 10 through 13. Inspection of these figures reveals that, for both male and female subjects, the rank order of means for the plosives combined with [i] is the same as that reported for the plosive means averaged over both vowels and both types of syllable. For plosives combined with [a], however, the rank order of the means for [p] and [k] is reversed. The mean for [p] exceeds the mean for [k] when the consonants are combined with [i], but the mean for [k] exceeds that for [p] when the consonants are combined with [a]. Inspection of Figures 10 through 13 also reveals that the oral air flow mean for each consonant combined with [a] is, in every instance, greater than that for the same consonant combined with [i].

Figures 10 through 13 also show that, for both sexes, the consonant [t], in each of the vowel contexts, is associated with greater mean oral air flow than the other consonants. These findings also suggest that the consonant [k] is markedly affected by the vowel environment as evidenced by a large difference in the means for this consonant when combined with [i] and with [a]. Other consonants appear to have been affected less markedly.

In Figures 12 and 13, the means for the six consonants are plotted across the two vowel contexts for male and female subjects, respectively. The previously reported

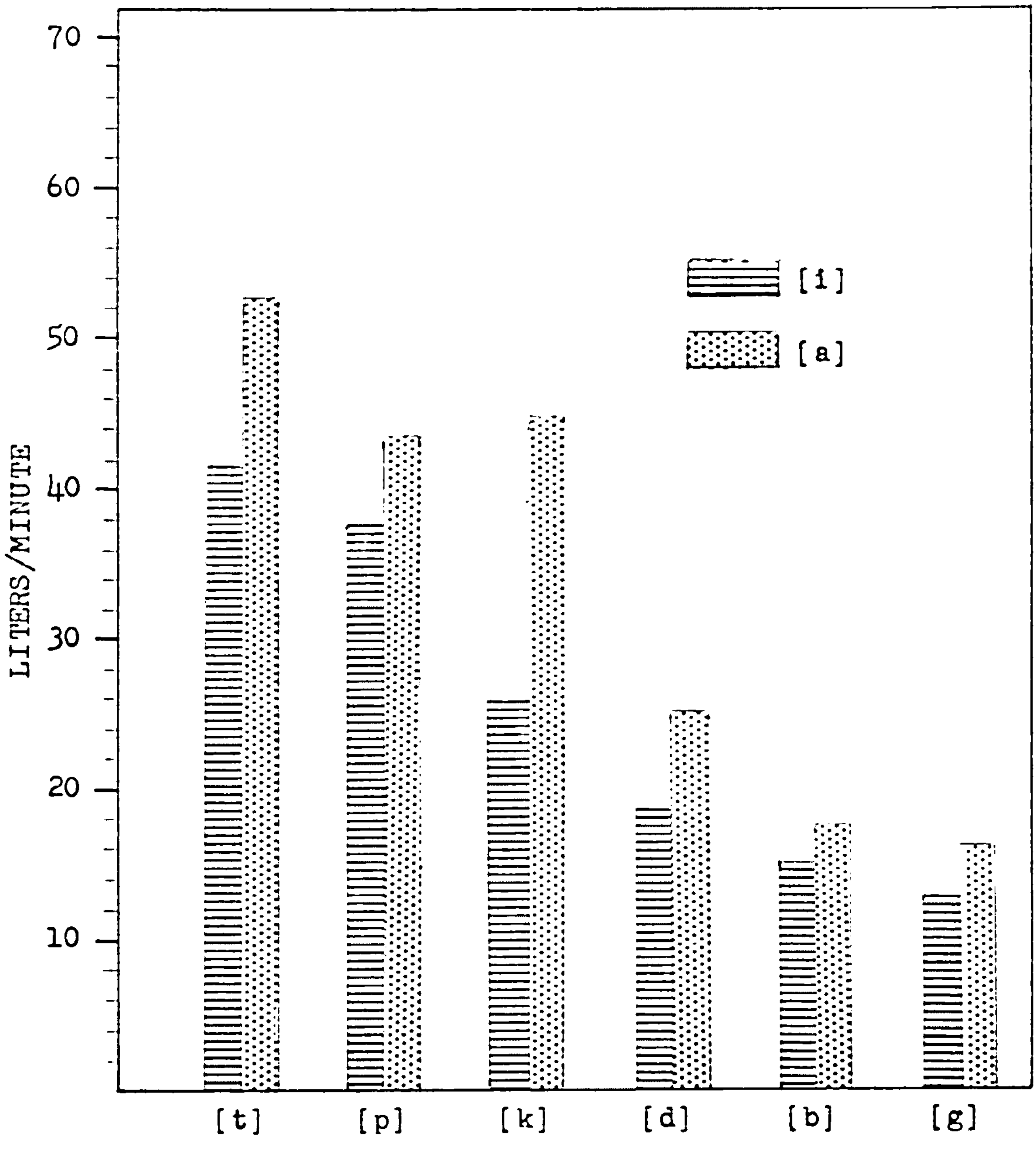

Figure 10.--Oral air flow means for each of the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five male subjects. The means are over CV and VCV syllables.

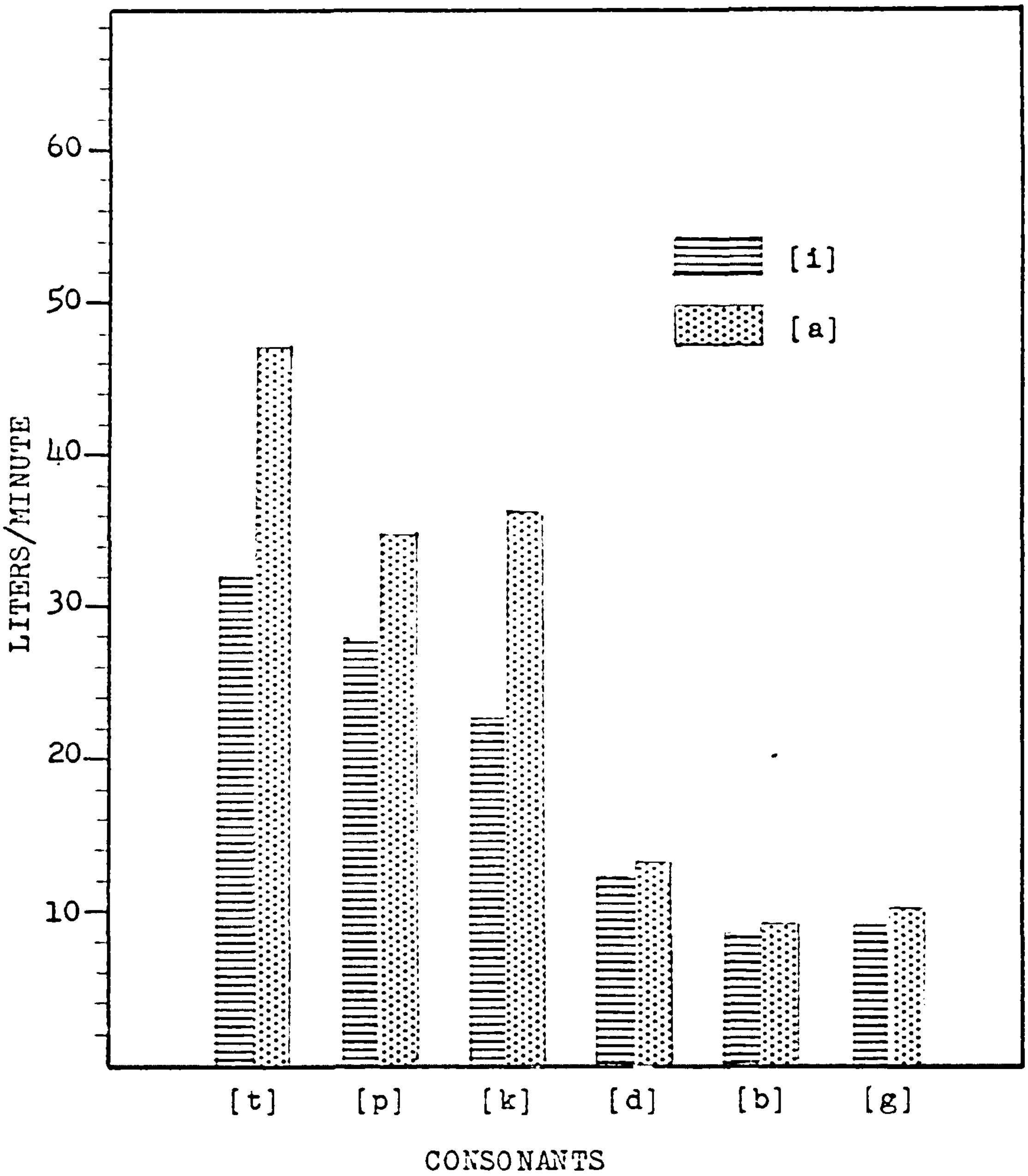

Figure 11.--Oral air flow means for each of the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five female subjects. The means are over CV and VCV syllables.

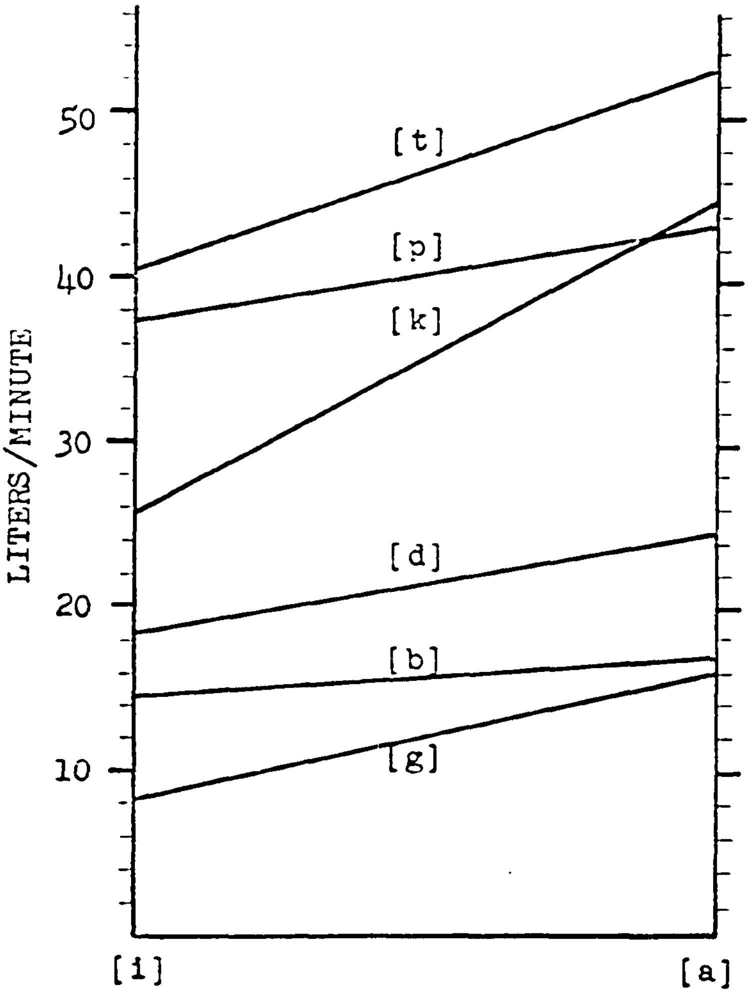

Figure 12.--Oral air flow means for each of the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five male subjects. The means are over CV and VCV syllables.

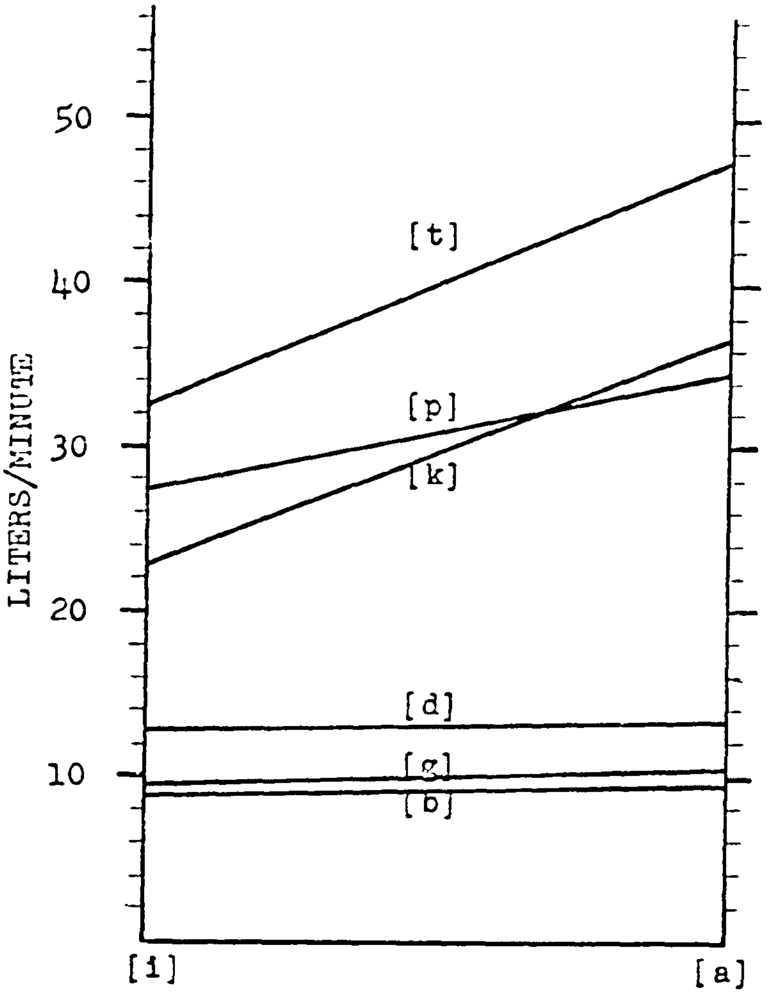

Figure 13.--Oral air flow means for each of the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five female subjects. The means are over CV and VCV syllables.

tendency for voiceless consonants to be associated with greater oral air flow than voiced consonants is seen in the grouping of the voiced sounds at the bottom, for both male and female subjects. It appears, on the basis of these plots, that, for both sexes, the means for the voiceless sounds [t] and [k] are more markedly affected by the difference in vowel environment than are the other plosive consonants.

Analyses of the vowel-by-consonant interaction data, summarized in Tables 1 and 2, indicate that, for both male and female subjects, this interaction is significant. The presence of this significant interaction suggests that differences exist among the differences in the oral air flow means for the six consonants when combined with [i] and combined with [a]. It may be recalled that these means were averaged over both types of syllable. The results indicate that the consonants are not equally sensitive to the vowel effect. The Duncan Multiple Range Test was used to locate the significant differences among the consonant means. Table 5 presents the test results for the male subjects. Interpretation of this table is facilitated if one considers first those consonants in combination with the vowel [a] and then those consonants in combination with the vowel [i]. It is also helpful to consult, in Figure 12, the plots of the means referred to in this discussion. Considering the consonants in Table 5 in combination with [a], it may be seen that the mean oral air flow for the consonant [t] is significantly greater than those for the other consonants. The

TABLE 5.--Duncan Multiple Range Test for differences among oral air flow means for each of the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five male subjects. The means are over CV and VCV syllables

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
R_p:	4.69	4.89	5.05	5.17	5.27	5.34	5.40	5.45	5.50	5.53	5.57

b) Results

Consonants:	[g]	[b]	[g]	[b]	[d]	[d]	[k]	[p]	[t]	[p]	[k]	[t]
Vowel Contexts:	[i]	[i]	[a]	[a]	[i]	[a]	[i]	[i]	[i]	[a]	[a]	[a]
Means:	12.28	14.48	16.00	17.19	18.10	24.48	25.96	37.21	41.59	43.80	45.20	52.96
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Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

voiceless consonants combined with [a] involve significantly greater oral air flow means than the voiced consonants combined with [a]. Among the voiced consonants, the mean for [d] significantly exceeds the means for [b] and [g]. All other differences are not significant.

Considering now the consonants in Table 5 in combination with the vowel [i], it may be seen that the mean oral air flow for the consonants [t] and [p] are significantly greater than the means for the other consonants. The mean for [k] is significantly greater than the mean for the voiced consonants [d], [b], and [g], but is significantly smaller than the means for the other voiceless consonants. The mean for [d] is significantly greater than the mean for [g]. Other differences are not significant. It may be said, therefore, that, for male subjects, the oral air flow means for voiceless consonants in combination with [i] are significantly greater than the means for the voiced consonants with [i]. It may also be seen in Table 5 that, for male subjects, the oral air flow means for consonants combined with the vowel [a] are significantly greater than the means for those same consonants combined with the vowel [i], except for the [b] and [g] sounds. For [b] and [g], no difference is found between the means for oral air flow according to vowel environment.

Table 6 presents the significant differences among means detected by the Duncan Multiple Range Test for female subjects. Interpretation of this table is also facilitated

TABLE 6.--Duncan Multiple Range Test for differences among oral air flow means for each of the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five female subjects. The means are over CV and VCV syllables

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
R_p:	4.45	4.69	4.85	4.96	5.05	5.12	5.18	5.23	5.28	5.31	5.34

b) Results

Consonants:	[b]	[g]	[b]	[g]	[d]	[d]	[k]	[p]	[t]	[p]	[k]	[t]
Vowel Contexts:	[i]	[i]	[a]	[a]	[i]	[a]	[i]	[i]	[i]	[a]	[a]	[a]
Means:	8.44	9.05	9.27	10.20	12.79	13.68	22.97	27.82	32.21	34.51	36.41	47.48
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Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

by examining first the oral air flow means for consonants combined with the vowel [a], and then those for the same consonants combined with [i]. It is also helpful to consult, in Figure 13, the plots of the means referred to in this discussion. Examination of the means for the consonants combined with [a], as shown in Table 6, reveals that the mean for the consonant [t] is significantly greater than the means for the other consonants. The means for [p] and [k] significantly exceed the means for [d], [b], and [g]. Other differences among the consonant means are not significant. Examination of the means for the consonants combined with [i], in Table 6, shows that the means for the consonants [t] and [p] are significantly larger than the means for the other consonants. The mean for the consonant [k] is significantly greater than the means for the [d], [g], and [b] sounds. Other differences among the consonant means are not significant. It may be said, therefore, that, for female subjects, the mean oral air flow for the voiceless plosives combined with [i] and [a] are significantly greater than the means for the voiced plosive consonants with [i] and with [a].

Inspection of Table 6 also indicates that, for female subjects, the means for the consonants [t], [p], [k], and [d] combined with [a] are significantly larger than the means for those same consonants combined with [i]. The means for the consonants [b] and [g] with [a] are not significantly different from the means for those same consonants with [i].

In summary, analysis of the vowel-by-consonant interaction for both male and female subjects indicates that oral air flow means for the majority of the consonants are significantly affected by the vowel environment. Those for the [b] and [g] sounds are apparently not affected. It appears, therefore, that the differences in the means reported for the vowel main effect are attributable primarily to changes in the means for the voiceless consonants and the voiced consonant [d]. It may be concluded, therefore, that, while the means for most of the consonants are greater when combined with [a] than with [i], this is not true for all the consonants. The rank order of means for the consonants combined with [i] is identical with that reported in the analysis of the consonant main effect. The order for the consonants with [a] is also the same as that reported for the consonant main effect, except that the ranks of [p] and [k] are reversed. As indicated in the consonant main effect, however, when the means for [p] with [i] and with [a] and the means for [k] with [i] and with [a] were averaged, the resultant mean for [p] exceeded the mean for [k].

On the basis of inspection of the means involved in the vowel-by-consonant interaction, it appears that the voiceless consonants are more markedly affected by vowel differences than voiced consonants, for both sexes.

Consonant-by-Syllable Interaction

Consonant oral air flow was measured in CV and VCV syllables in order to determine whether these two types of syllable context differentially affected plosive consonant oral air flow. As previously reported, when the oral air flow means were averaged over all consonants and the two vowels, it was found that the consonants in CV syllables had significantly greater oral air flow than in VCV syllables. It was also of interest to determine whether the syllable context affected the oral air flow means for each of the six consonants similarly; or, conversely, if the consonants were equally sensitive to the syllable effect. Analysis of the data making up the consonant-by-syllable interaction provides information relating to this question.

Trends in the data in the consonant-by-syllable interaction may be examined in Figures 14 through 17. It may be seen in these figures that, for both sexes, the rank order of consonant means in both CV and VCV syllables is the same as that reported in the consonant main effect. It may also be noted that each consonant is characterized by a greater oral air flow mean in CV syllables and a lesser mean in VCV syllables than were reported in the consonant main effect. Figures 14 through 17 also show that, in terms of the absolute differences in the means in the two types of syllable, the voiceless consonants appear to be more markedly affected by the difference in the syllable context than the voiced consonants. The greater changes in oral air flow means are evident among the voiceless consonants. In these figures, the tendency for voiceless sounds to be characterized by greater oral air flows than voiced sounds in each of the syllable contexts

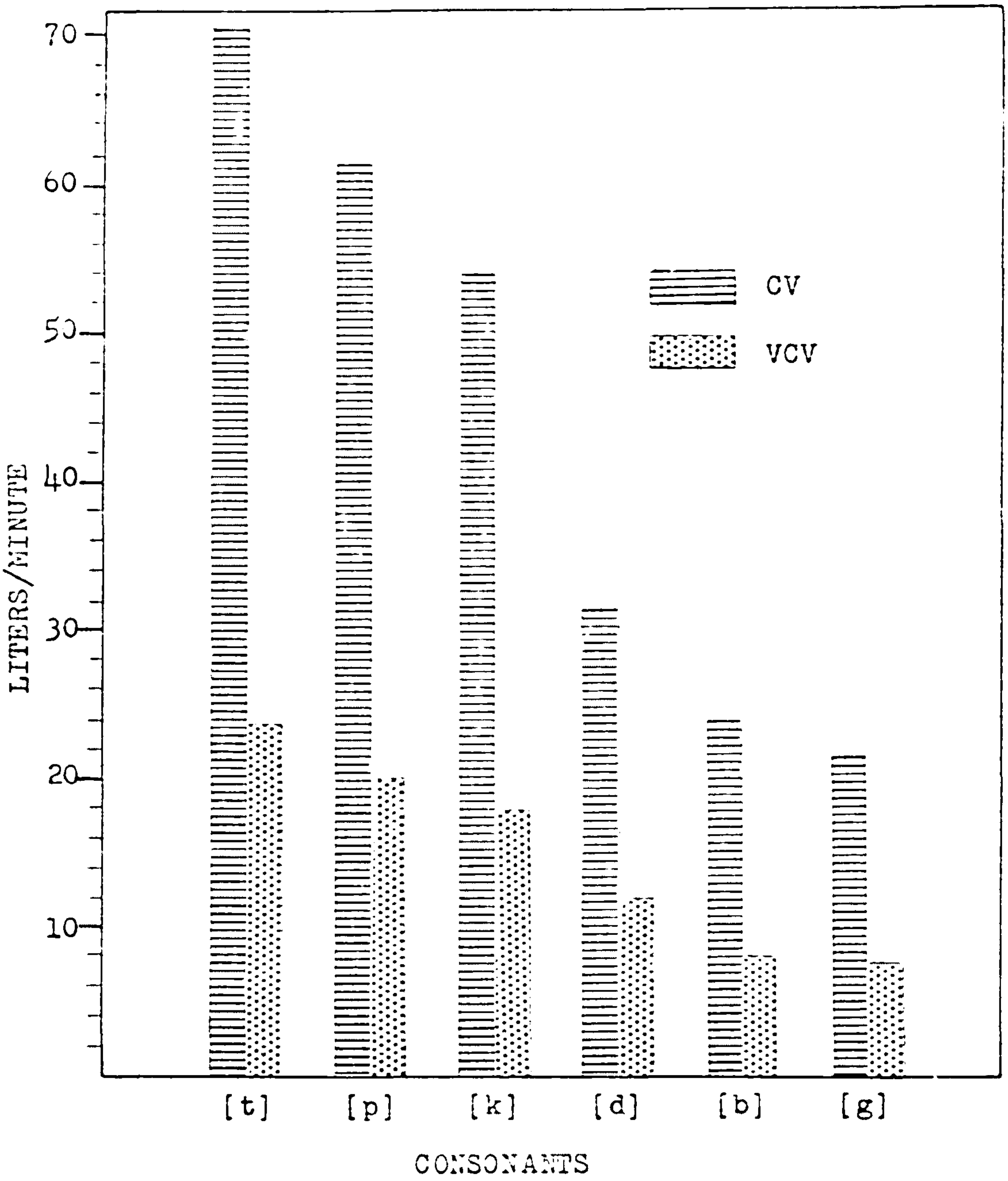

Figure 14.--Oral air flow means for each of the six plosive consonants produced in CV and in VCV syllables for twenty-five male subjects. The means are over the vowels [i] and [a].

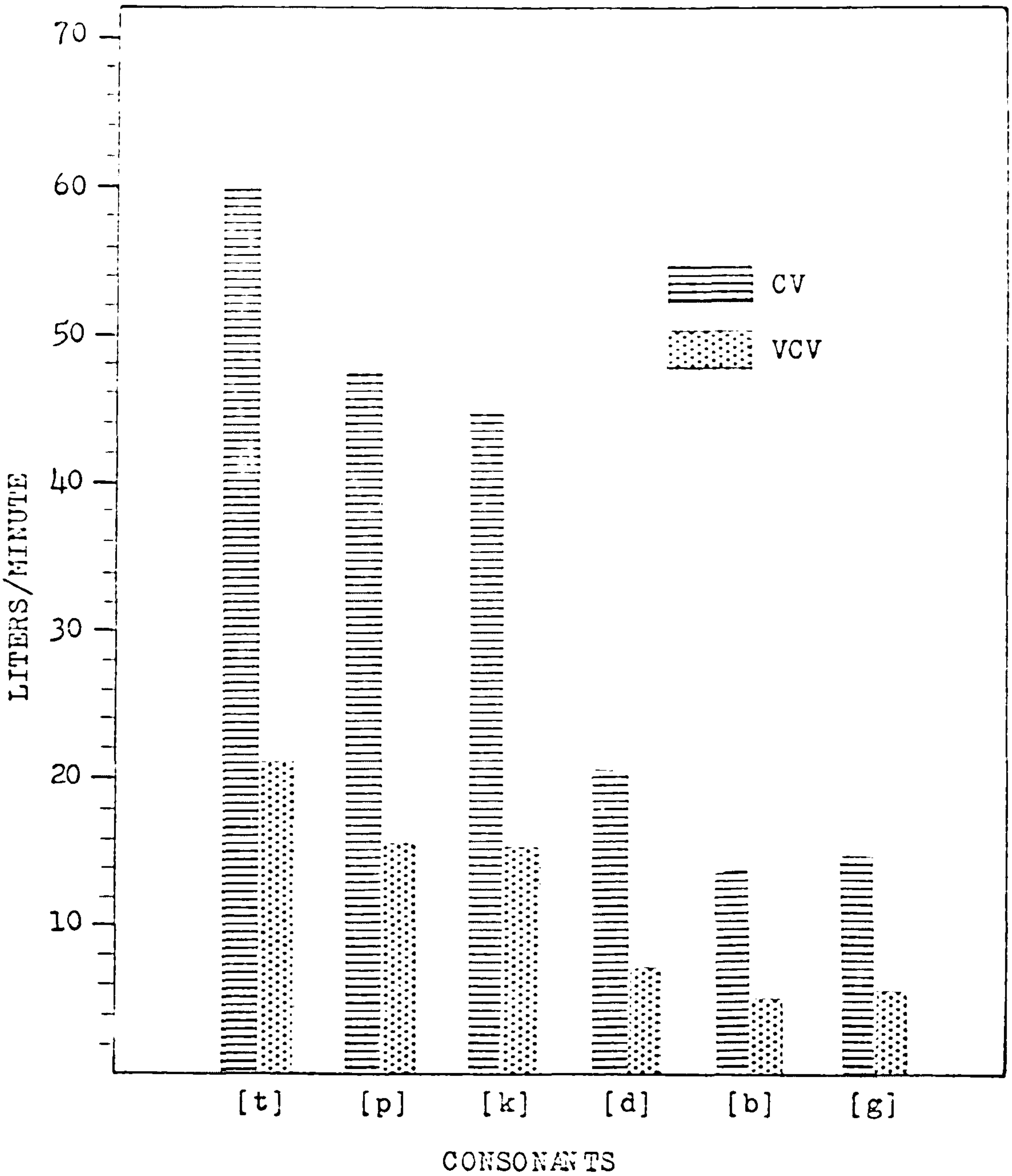

Figure 15.--Oral air flow means for each of the six plosive consonants produced in CV and in VCV syllables, for twenty-five female subjects. The means are over the vowels [i] and [a].

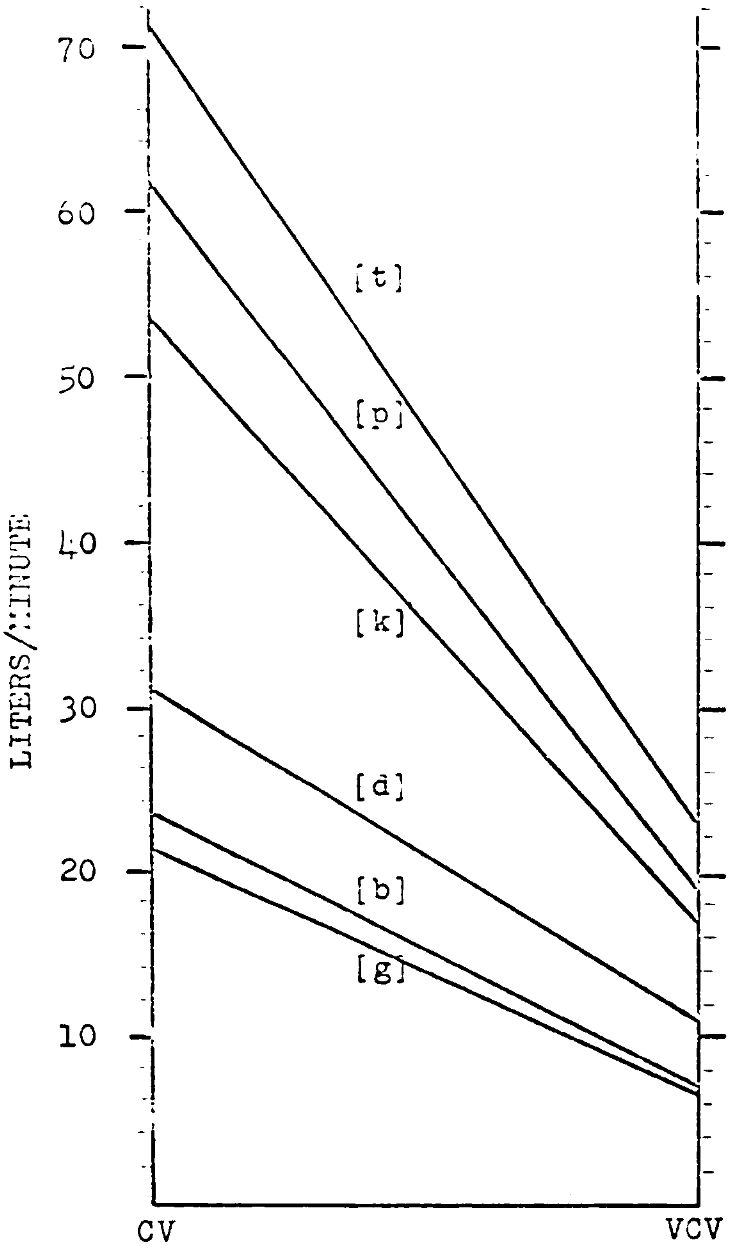

Figure 16.--Oral air flow means for each of the six plosive consonants produced in CV and in VCV syllables, for twenty-five male subjects. The means are over the vowels [i] and [a].

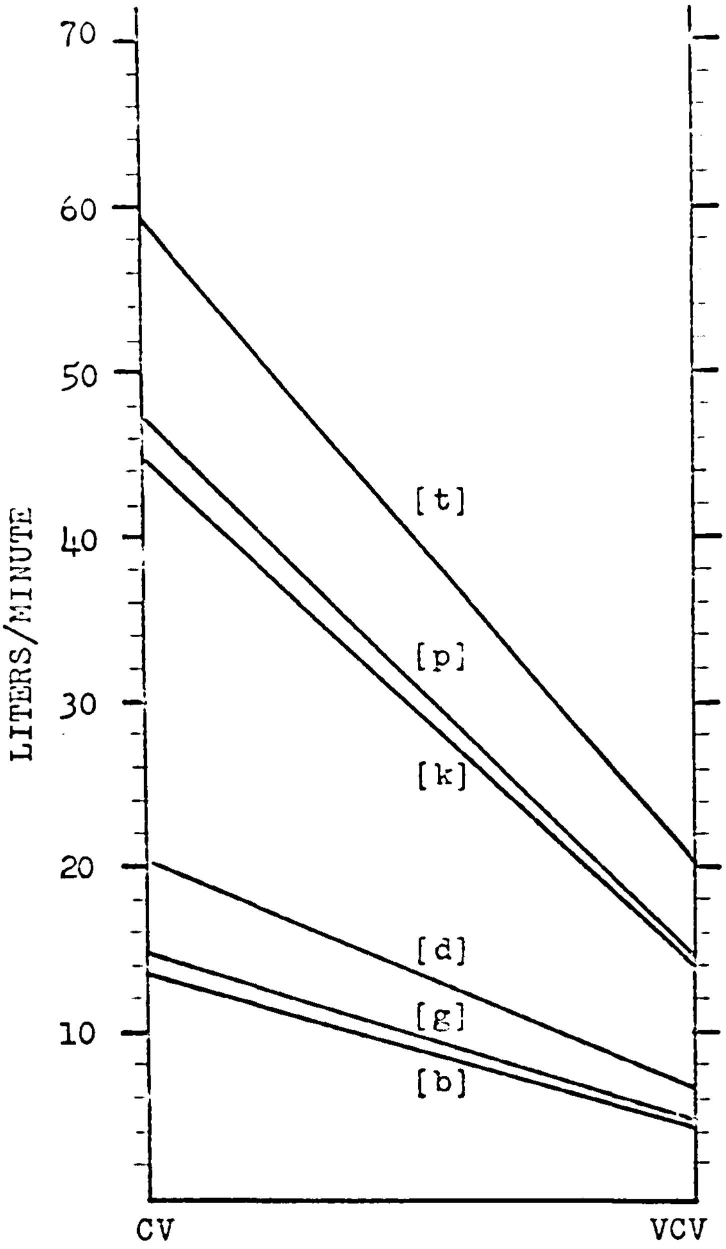

Figure 17.--Oral air flow means for each of the six plosive consonants produced in CV and in VCV syllables, for twenty-five female subjects. The means are over the vowels [i] and [a].

may also be observed.

The analyses of variance summarized in Tables 1 and 2 show that the consonant-by-syllable interaction is significant for both sexes. This indicates that significant differences exist among the differences in the oral air flow means for each of the six consonants in CV as compared to VCV syllables, the means being averaged over both vowels.

The Duncan Multiple Range Test was used to locate the significant differences among the consonant means. The test results for male and female subjects are shown in Tables 7 and 8, respectively. Examination of Table 7 indicates that, for male subjects, the mean oral air flow for each of the six consonants in CV syllables are, without exception, significantly larger than the means for those same consonants in VCV syllables. The means for the consonants [t], [p], [k], and [d] in CV syllables are significantly greater than the means for [b] and [g] in CV contexts and for all consonants in VCV syllables. The voiceless consonant [t] in CV syllables is associated with significantly greater mean oral air flow than any of the other consonants. As previously reported, the [t] sound characteristically involved greater oral air flow than the other plosive consonants when the means for the consonants were averaged over both CV and VCV syllables. However, when the means are taken separately for the two types of syllables and compared, as in Table 7, it may be seen that the means for the consonants [d], [k], and [p] in CV syllables exceed

TABLE 7.--Duncan Multiple Range Test for differences among oral air flow means for each of the six plosive consonants produced in CV and in VCV syllables, for twenty-five male subjects. The means are over the vowels [i] and [a̤]

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
R_p:	6.69	7.05	7.29	7.46	7.60	7.70	7.79	7.86	7.93	7.98	8.03

b) Results

Consonants:	[g]	[b]	[d]	[k]	[p]	[g]	[t]	[b]	[d]	[k]	[p]	[t]
Syllable Contexts:	VCV	VCV	VCV	VCV	VCV	CV	VCV	CV	CV	CV	CV	CV
Means:	7.03	7.81	11.52	17.52	19.84	21.25	23.49	23.86	31.06	53.64	61.18	71.07
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Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

TABLE 8.--Duncan Multiple Range Test for differences among oral air flow means for each of the six plosive consonants produced in CV and in VCV syllables, for twenty-five female subjects. The means are over the vowels [i] and [a]

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
R_p:	5.55	5.85	6.05	6.19	6.30	6.38	6.46	6.52	6.58	6.62	6.66

b) Results

Consonants:	[b]	[g]	[d]	[b]	[g]	[k]	[p]	[d]	[t]	[k]	[p]	[t]
Syllable Contexts:	VCV	VCV	VCV	CV	CV	VCV	VCV	CV	VCV	CV	CV	CV
Means:	4.28	5.01	6.36	13.44	14.24	14.96	15.22	20.10	20.88	44.41	47.11	58.80
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Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

the mean for [t] in VCV syllables. The fact that [d] in CV syllables evidenced greater oral air flow than [t] in VCV syllables demonstrates that a voiced plosive may involve a greater oral air flow in CV syllables than its voiceless cognate in VCV syllables.

The findings for female subjects, as reported in Table 8, are similar to those for the males. The voiceless consonants [k], [p], and [t] in CV syllables have significantly larger oral air flow means than any of the other consonants. The consonant [t] in CV syllables involved a significantly greater mean oral air flow than any of the other consonants regardless of syllable context. The means for the voiced consonants [b], [g], and [d] in VCV syllables are significantly smaller than the means for any of the other consonants regardless of syllable context. The mean for [t] in VCV syllables is not significantly greater than the mean for [d] in CV syllables, again illustrating that a voiceless consonant may involve no more oral air flow than its voiced cognate if the two are measured in different types of syllable.

In summary, analysis of the data in the consonant-by-syllable interaction reveals that, for both sexes, greater oral air flow means are found for the plosive consonants when produced in CV syllables than in VCV syllables. The fact that the interaction is significant indicates that all plosives are not affected to the same degree by the difference in syllables. Inspection of the data indicates that voiceless plosives are affected somewhat more by the difference in syllable context than voiced plosives. It was also found that, for both sexes, one or more means for the voiced consonants in CV syllables were equal to or greater than the mean for the voiceless consonant with the largest mean oral air flow in VCV syllables, [t]. It appears, therefore, that, while voiceless plosives involve greater oral air flow when the sounds are tested in the same type of syllable, this relationship may not hold when the voiced plosive is tested in a CV syllable and the voiceless plosive is tested in a VCV syllable.

Vowel-by-Syllable Interaction

As previously reported, both the vowel context and the type of syllable in which the plosive consonants were tested had an effect on the oral air flow for the plosives as a group, as evidenced by a significant vowel and syllable main effect. As reported in the discussion of the vowel main effect, the overall oral air flow means were larger when the consonants were combined with [a] than with [i]. In the analysis of the syllable main effect, it was found that the consonants were associated with greater oral air flow means in CV syllables than in VCV syllables. The vowel-by-syllable interaction reflects the combined effect of vowel and syllable contexts on the consonant oral air flow means, when the means are averaged over all the consonants. The means involved in the interaction are presented in Figures 18 through 21. In Figures 18 and 19, the consonant

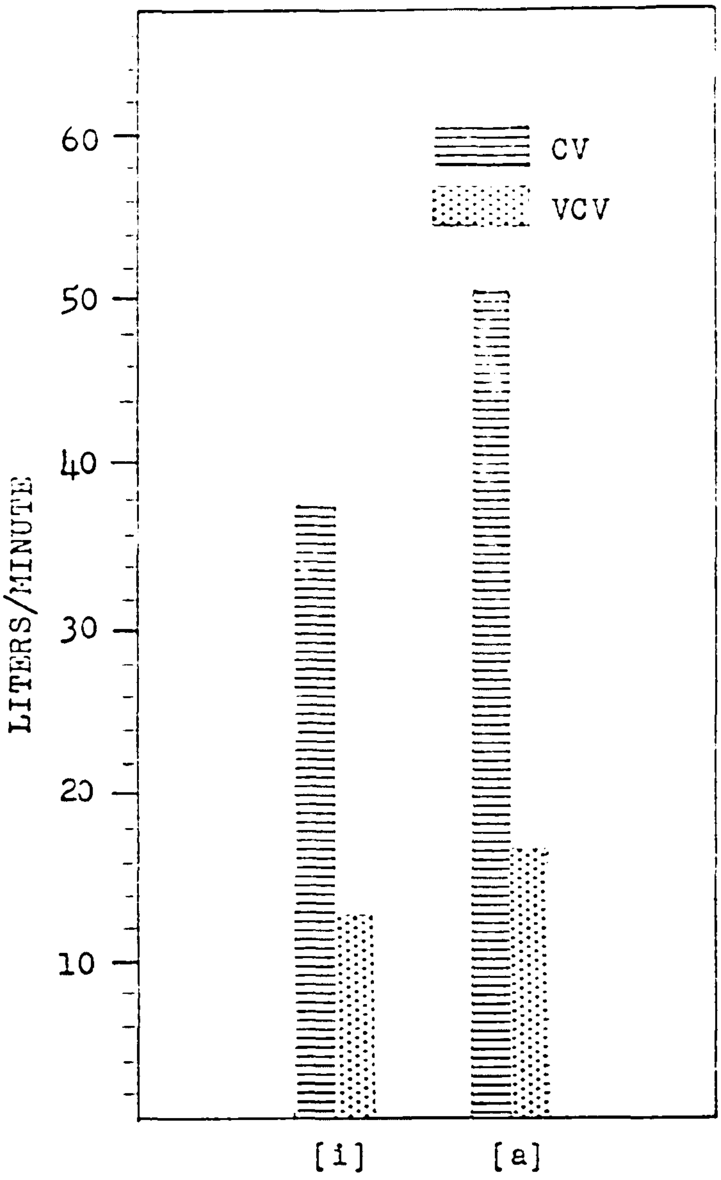

Figure 18.--Oral air flow means for the six plosive consonants produced in CV and in VCV syllables in combination with [i] and in combination with [a], for twenty-five male subjects. The means are over all consonants.

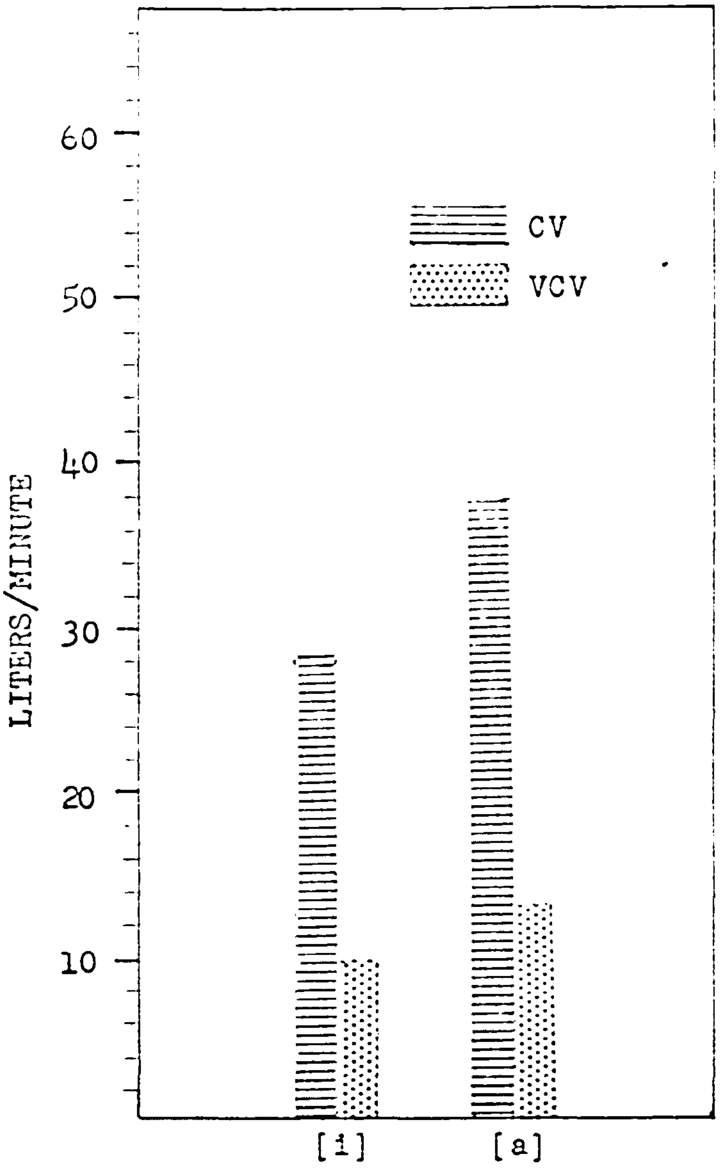

Figure 19.--Oral air flow means for the six plosive consonants produced in CV and in VCV syllables in combination with [i] and in combination with [a], for twenty-five female subjects. The means are over all consonants.

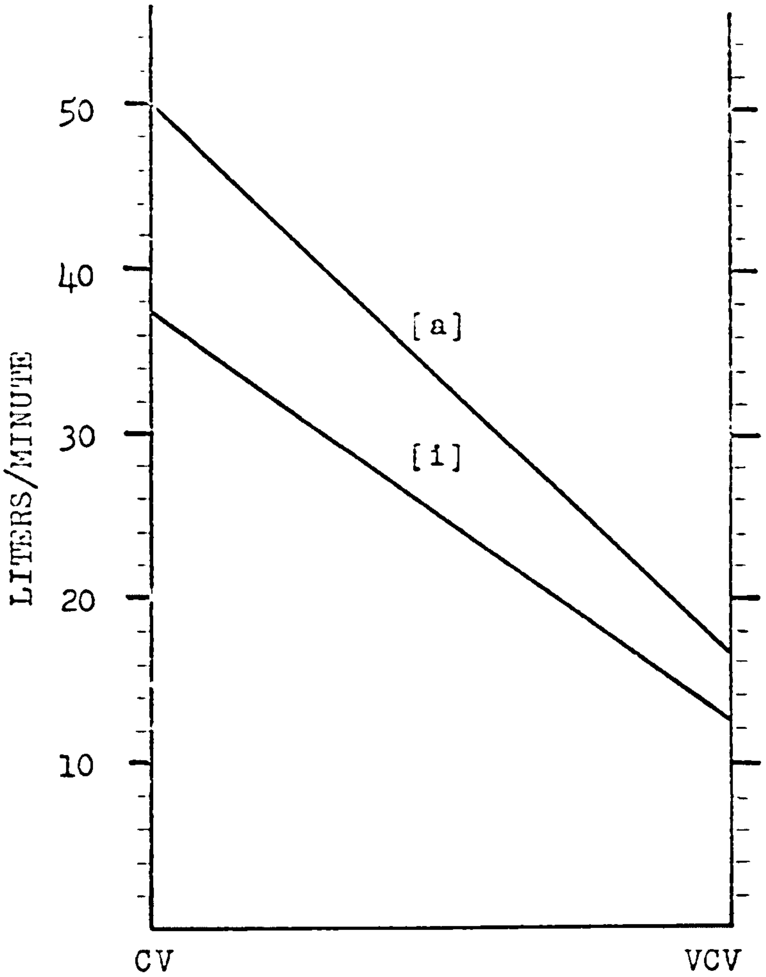

Figure 20.--Oral air flow means for the six plosive consonants produced in CV and in VCV syllables in combination with [i] and in combination with [a], for twenty-five male subjects. The means are over all consonants.

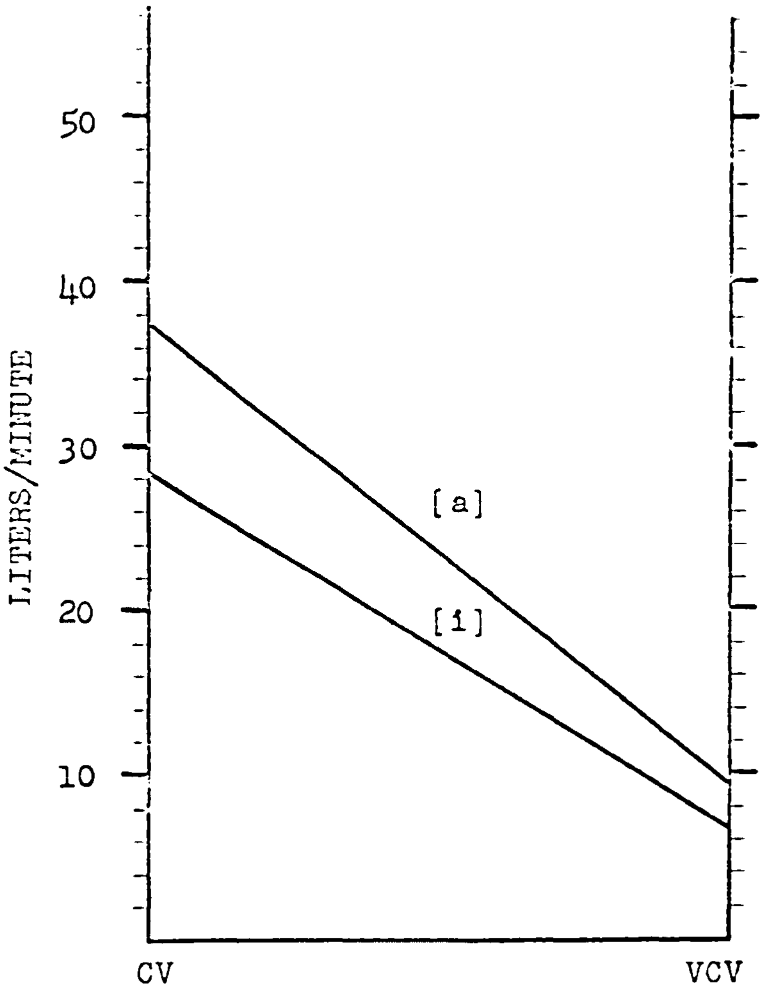

Figure 21.--Oral air flow means for the six plosive consonants produced in CV and in VCV syllables in combination with [i] and in combination with [a], for twenty-five female subjects. The means are over all consonants.

oral air flow means for males and females, respectively, are plotted for syllables by vowels. In Figures 20 and 21, the consonant means are plotted for vowels across syllables for male and female subjects, respectively. In Figures 18 and 19 it may be seen that, for both sexes, there is a greater difference in the effect of the two vowels on consonant oral air flow in CV syllables than in VCV syllables. The larger oral air flow means were recorded for the consonants combined with [a] in both types of syllable, for both male and female subjects.

The analyses of variance summarized in Tables 1 and 2 indicate that the vowel-by-syllable interaction is significant for both sexes. The Duncan Multiple Range Test was used to locate the significant differences among the consonant means. The results of the analysis are shown in Tables 9 and 10. These tables indicate that, for both male and female subjects, the oral air flow means for plosives combined with [a] and with [i] in CV syllables are significantly different. Plosives combined with [a] in CV syllables evidence greater oral air flow means than plosives in all other syllable-vowel contexts. The means for the plosives combined with [a] and with [i] in CV syllables are significantly larger than the means for the plosives combined with either [a] or [i] in VCV syllables. The means for the consonants combined with [i] in VCV syllables are not different from the means for the consonants combined with [a] in VCV syllables. These data also show that, for both sexes, the

TABLE 9.--Duncan Multiple Range Test for differences among oral air flow means for the six plosive consonants produced in CV and in VCV syllables in combination with [i] and in combination with [a], for twenty-five male subjects. The means are over all consonants

a) Shortest Significant Ranges

p:	(2)	(3)	(4)
R_p:	3.86	4.07	4.21

b) Results

Syllable Contexts:	VCV	VCV	CV	CV
Vowel Contexts:	[i]	[a]	[i]	[a]
Means:	12.62	16.45	37.26	$\underline{50.09}$
			———	
	————————	————————		

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

TABLE 10.--Duncan Multiple Range Test for differences among oral air flow means for the six plosive consonants produced in CV and in VCV syllables in combination with [i] and in combination with [a], for twenty-five female subjects. The means are over all consonants.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)
R_p:	3.86	4.07	4.21

b) Results

Syllable Contexts:	VCV	VCV	CV	CV
Vowel Contexts:	[i]	[a]	[i]	[a]
Means:	9.56	12.68	28.20	37.84
				———
			———	
	—————	—————		

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

consonant oral air flow means differed significantly according to the vowel context only in CV syllables. This indicates that the significant vowel main effect previously reported may be attributed primarily to differences in the vowel effect in CV syllables. The data also show that oral air flow means for the plosives are greater in CV syllables than in VCV syllables, regardless of the vowel context.

Consonant Nasal Air Flow

In recent years, the concept that the velopharyngeal valve is tightly closed during the normal production of nonnasal sounds in English has been questioned by theorists and researchers in speech pathology and phonetics. Van Riper and Irwin (42), on the basis of their review of current research regarding velopharyngeal valving, have concluded that a tight velopharyngeal seal is not requisite to nonnasal sound production. They hypothesize, instead, that a "degree" of closure is required for normal resonance and have used the term "functional closure" to mean a closure that is complete enough to avoid the direct auditory consequences of "open nasality."

There is an increasing body of research literature to support the concept of functional closure, much of it from x-ray studies of velopharyngeal valving in normal-speaking subjects. For example, Moll's cinefluorographic study (25) indicated that variations in the tightness of the velopharyngeal valve occurred during vowel production, not only as a function of the vowel produced, but also as a function of the phonetic context of the vowel. He indicated that there is a need to study the variations in closure for consonant sounds as well. Moll, however, apparently felt that cinefluoroscopy did not permit a three-dimensional and continuous analysis of velopharyngeal valving. In preparation for this study, it was reasoned that if there is not a tight velopharyngeal seal during the explosive phase of plosive consonant production, then small but detectable nasal air flows might occur during these sounds. It was decided, therefore, to investigate the possibility that nasal air flows are present during the production of plosive consonants. It was felt that the data obtained would provide an accurate representation of the measurements which could be expected for normal speaking subjects under the present experimental conditions, utilizing the present instrumentation. Also, such information could be expected to be useful in future research in which subjects with velar pathology are studied using this instrumentation.

The nasal air flow data were analyzed statistically in the same manner as the oral air flow data. The summary of the analysis of variance for male subjects is presented in Table 11, and for female subjects in Table 12. It may be seen in Table 11 that, for male subjects, the consonant and vowel main effects and the consonant-by-syllable and vowel-by-consonant-by-syllable interactions are significant. For female subjects, only the consonant and syllable main effects

TABLE 11.--Summary of the analysis of variance for the consonant nasal air flow data from twenty-five male subjects

Source	df	ms	F
Vowel (V)	1	9.87	25.97*
Consonant (C)	5	10.85	28.55*
VC	5	.72	1.89
Error A	264	.38	
Syllable (S)	1	.71	2.84
VS	1	.07	.28
CS	5	1.37	5.48*
VCS	5	1.38	5.52*
Error B	288	.25	

*P < .05

TABLE 12.--Summary of the analysis of variance for the consonant nasal air flow data from twenty-five female subjects

Source	df	ms	F
Vowel (V)	1	1.00	.63
Consonant (C)	5	11.02	6.93*
VC	5	.70	.44
Error A	264	1.59	
Syllable (S)	1	9.18	16.10*
VS	1	.08	.14
CS	5	1.18	2.07
VCS	5	.23	.40
Error B	288	.57	

*P < .05

are significant. These findings are reported in detail in the following pages.

Consonant Main Effect

One of the major purposes of this phase of the study was to investigate possible differences in nasal air flow among the six plosive consonants. Figure 22 presents, for both sexes, the nasal air flow for each consonant averaged over both types of syllable and both vowels. A comparison of the means shows that, for male subjects, the greatest mean nasal air flow was measured in the production of [p], with successively smaller means for [b], [g], [d], [t], and [k]; for female subjects, the order from largest to smallest mean was [p], [b], [t], [d], [k], and [g].

The analyses of variance summarized in Tables 11 and 12 reveal that the consonant main effect is significant for both sexes. It may be noted in Figure 22 that, for female subjects, the means for the voiceless consonants [t], [p], and [k] slightly exceeded the means for these consonants as produced by male subjects. The means for the voiced consonants [d], [b], and [g] for male subjects, however, slightly exceeded the means for these consonants as produced by female subjects.

The Duncan Multiple Range Test was used to locate the significant differences which were detected by the analysis of variance. The results for male and female subjects are presented in Tables 13 and 14, respectively. It may be

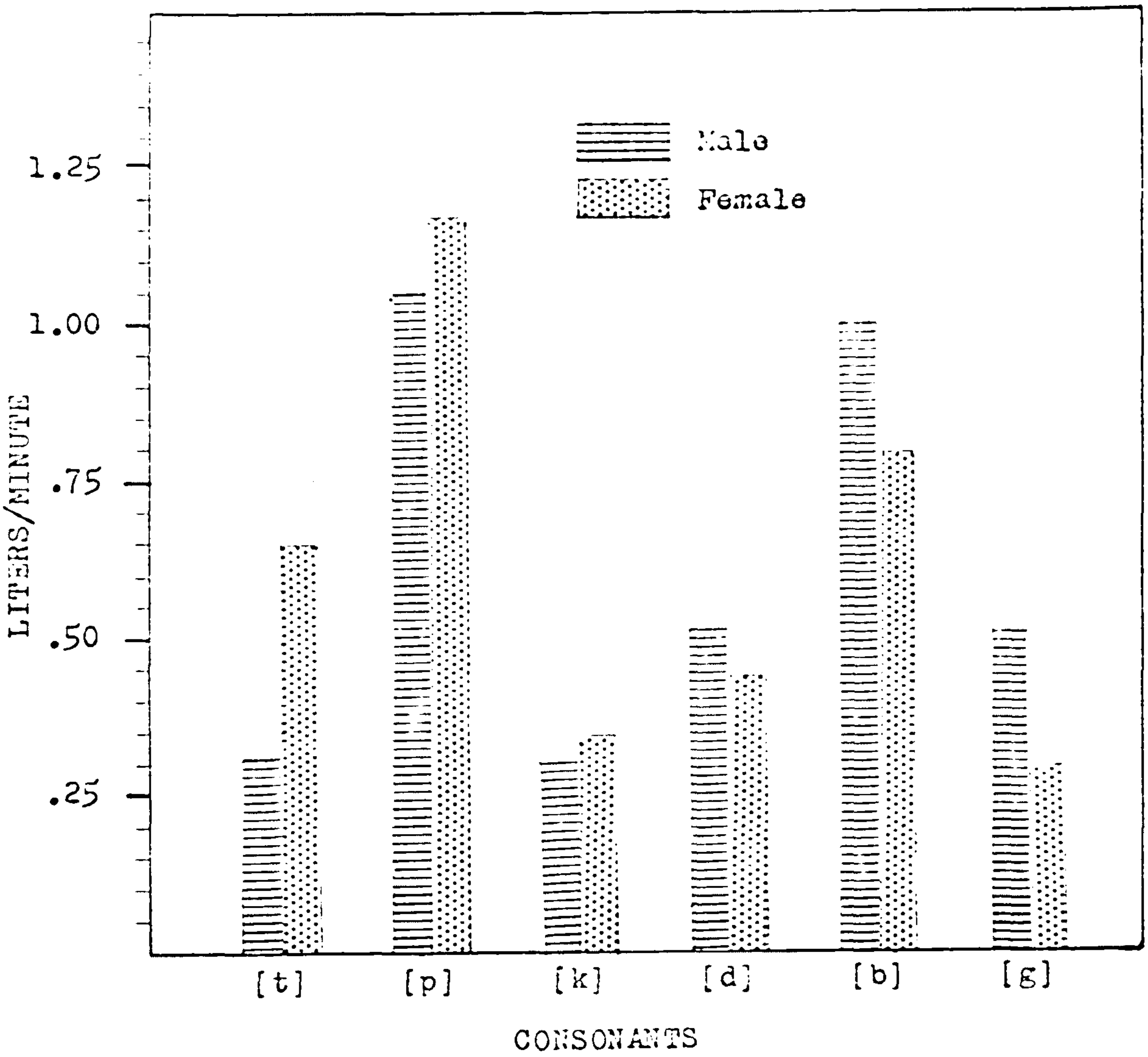

Figure 22.--Nasal air flow means for each of the six plosive consonants produced in both CV and VCV syllables in combination with [i] and [a], for twenty-five subjects of each sex.

TABLE 13.--Duncan Multiple Range Test for differences among nasal air flow means for each of the six plosive consonants produced in both CV and VCV syllables in combination with [i] and [a], for twenty-five male subjects

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)
R_p:	.17	.18	.19	.19	.20

b) Results

Consonants:	[k]	[t]	[d]	[g]	[b]	[p]
	.30	.32	.51	.52	1.00	1.05
	———	———	———	———	———	———

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same lines are not significantly different.

TABLE 14.--Duncan Multiple Range Test for differences among nasal air flow means for each of the six plosive consonants produced in both CV and VCV syllables in combination with [i] and [a], for twenty-five female subjects

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)
R_p:	.35	.37	.38	.39	.40

b) Results

Consonants:	[g]	[k]	[d]	[t]	[b]	[p]
Means:	.29	.34	.43	.65	.79	1.17
			―――	―――	―――	―――
	―――	―――	―――	―――		

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same lines are not significantly different.

seen in Table 13 that, for male subjects, the nasal air flow means for [p] and [b], although not significantly different, are significantly greater than the means for the other consonants. The means for [g] and [d] are significantly greater than the means for [k] and [t], but the differences between [g] and [d] and between [k] and [t] are not significant. For the male subjects, then, the consonants tended to pattern themselves according to place of articulation for the sounds with the largest means, [p] and [b], and according to voicing characteristics thereafter. Table 14 indicates that, for female subjects, production of the plosive [p] involved a significantly greater mean nasal air flow than the other consonants, and that the mean for [b] significantly exceeded those for [g] and [k]. Other differences among the consonant means are not significant.

In summary, the mean nasal air flow for all consonants is quite small, and measured differences among the means for the six consonants frequently fail to reach significance. However, the data indicate that relatively large nasal air flows are associated with production of [p] and [b] for male subjects and with [p] for female subjects. For both sexes, the consonants [k] and [g] are associated with significantly smaller nasal air flow means than either [p] or [b]. For males, the greatest nasal air flow means are found in the production of the bilabial consonants [p] and [b], followed in order of decreasing air flows by the voiced plosives [g] and [d], and the voiceless plosives [t] and [k].

The means for nasal air flow may be compared with the means for oral air flow for the six plosives. It may be noted that, for both sexes, there is a significant difference in oral air flow for voiced and voiceless plosives. However, the consonants do not order themselves in this way for nasal air flow for either sex. For both sexes, the bilabial consonant [p] is associated with a relatively large mean nasal air flow, and the means for the bilabial sounds [p] and [b] significantly exceed the mean for [k]. It may be said, therefore, that [p] is characterized by relatively large oral and nasal air flow means, while [k] is characterized by a relatively large mean oral air flow and a relatively small mean nasal air flow. For males, [b] is characterized by a relatively small oral air flow mean and relatively large nasal air flow mean. On the basis of these data, it appears that it is not possible to predict the relative size of the nasal air flow means for plosive consonants from their oral air flow means, or vice versa.

Vowel Main Effect

A second purpose of this phase of the study was to investigate the effect of the two vowel contexts on nasal air flow in production of plosive consonants. As indicated previously, the vowels [i] and [a] were chosen to allow comparison of mean nasal air flow in consonants combined with two vowels which differed in tongue position and velopharyngeal valving. The nasal air flow means for consonants combined with [i] and with [a] are presented in Figure 23 for both male and female subjects. It is apparent in Figure 23 that males, as a group, show less nasal air flow in the production of plosives combined with [i] than with [a]. Females, however, evidenced greater nasal air flow in the production of plosives combined with [i]. The differences among the means for male and female groups were not tested for statistical significance, however.

Analysis of the vowel main effect shows the effect of the syllabic vowel on consonant nasal air flow means when the means are averaged over all consonants and both types of syllable. These analyses, summarized in Tables 11 and 12, indicate that differences between the consonant means in the two vowel contexts are significant for males, but not for females. For females, then, a difference was not detected in mean nasal air flow for the consonants as a group when the means were averaged over both types of syllable and considered separately for the two vowel contexts. Males, however, had significantly larger nasal air flow means in consonants combined with the vowel [a] than with [i].

For males, therefore, consonants combined with the vowel [a], which is produced with the tongue relatively low in the mouth and, according to x-ray study (<u>46</u>), with a relatively lax velar seal, are characterized by greater nasal air flow. For the females, however, the lack of a significant vowel effect is also of interest. It appears that this sample of female subjects tended to produce the plosives in

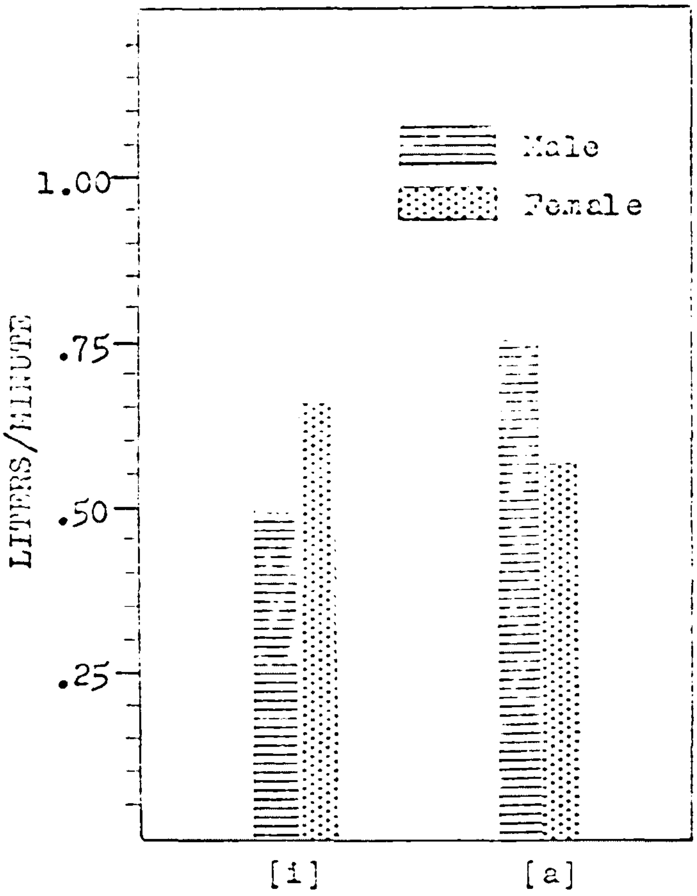

Figure 23.--Nasal air flow means for the six plosive consonants produced in combination with [i] and in combination with [a], for twenty-five subjects of each sex. The means are over CV and VCV syllables.

a way that resulted in similar nasal air flow means when the consonants were combined with [i] and with [a].

It may be noted, also, that, for both sexes, plosives produced with [a] are characterized by greater oral air flows than plosives produced with [i]. For males, then, plosives combined with [a] are associated with greater mean oral and nasal air flow than plosives combined with [i]. For females, however, plosives combined with [a] are associated with greater oral air flow means, but not with greater nasal air flow means, than plosives combined with [i]. This finding suggests a possible sex difference with respect to vowel influence on velopharyngeal valving during plosive consonant production. Examination of the data suggests the possibility that male subjects achieve a tighter velopharyngeal valve during production of consonants combined with [a] than with [i]. Females, on the other hand, seemed to achieve a similar velopharyngeal valve during production of consonants combined with [i] and with [a]. This possibility might be explored in future research.

Syllable Main Effect

A third purpose of this phase of the study was to investigate the effect of the two syllable contexts, consonant-vowel and vowel-consonant-vowel, on the nasal air flow means for the six plosive consonants. The nasal air flow means, averaged over all consonants and both vowels for consonants in CV and VCV syllables, are presented in Figure 24,

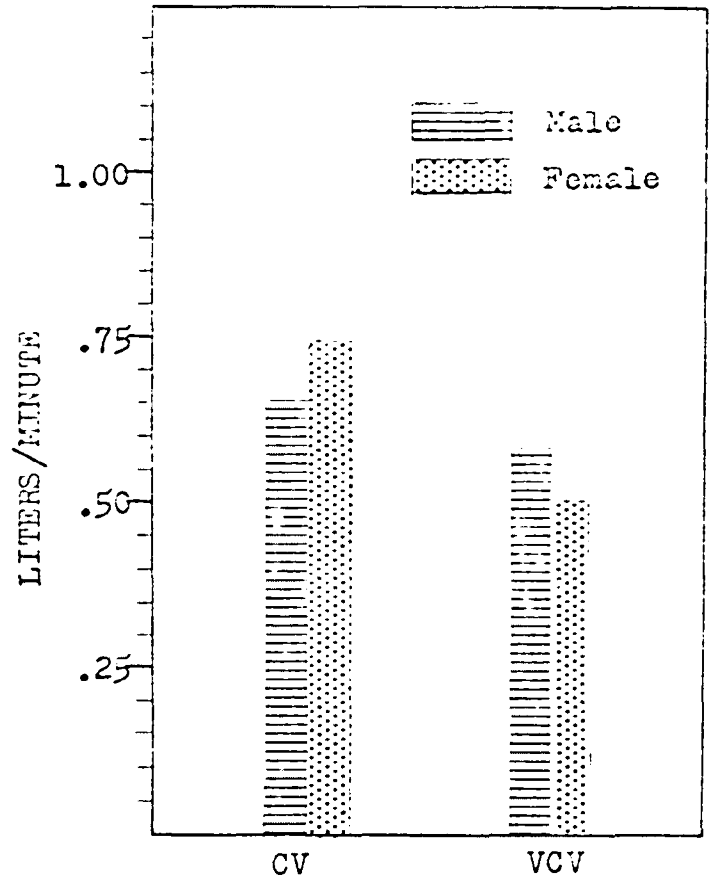

Figure 24.--Nasal air flow means for the six plosive consonants produced in CV and VCV syllables, for twenty-five subjects of each sex. The means are over the vowels [i] and [a].

in which it may be seen that female subjects evidence greater mean nasal air flow in the production of CV syllables than in production of VCV syllables. Males also display a greater mean nasal air flow in CV syllables than in VCV syllables, but the differences between the means is small. The mean for the consonants produced in CV syllables by female subjects slightly exceeds the mean for consonants produced in CV syllables by males. Males, however, evidence a slightly greater mean nasal air flow in production of consonants in VCV syllables than females.

The summaries of the analyses of variance presented in Tables 11 and 12 indicate that the syllable main effect is significant for female subjects, but is not significant for male subjects. It is interesting to note that, while the difference in vowel context differentially affected nasal air flow only for male subjects, differences in syllable context differentially affected nasal air flow only for female subjects. On the basis of these analyses, it appears that, for the female subjects, there may be a physiological difference in the way plosive consonants are produced in CV and VCV syllables.

The nasal air flow means reported in the syllable main effect may be compared with the means reported in the discussion of the syllable main effect for oral air flow. For both sexes, substantially greater oral air flow means were associated with the production of plosives in CV syllables than in VCV syllables. For female subjects, then, production of plosives in CV syllables resulted in larger oral and nasal air flow means than production of plosives in VCV syllables. For males, however, production of plosives in CV syllables resulted in a greater oral air flow mean, but not a significantly greater nasal air flow mean, than production of the consonants in VCV syllables.

Consonant-by-Syllable Interaction

Consonant nasal air flow was measured in CV and VCV syllables in order to investigate further the influence of syllable context on plosive sound production. As previously reported in the discussion of the syllable main effect, when the nasal air flow means were averaged over all consonants and both vowel contexts, it was found that female subjects had significantly larger nasal air flow means in consonants produced in CV than in VCV syllables, while male subjects evidenced no significant difference in nasal air flow in the two syllable contexts. When the summaries of the analyses of variance of nasal air flow data for male and female subjects are examined in Tables 11 and 12, however, it may be noted that the consonant-by-syllable interaction is significant for male subjects, but not for females. This indicates that the differences among the means for the individual consonants averaged over both vowels, but considered separately for the two syllable contexts, are different.

The nasal air flow means for male subjects for each of the six consonants, averaged over both vowel contexts, but considered separately for CV and VCV syllables, are shown in Figures 25 and 26. Inspection of Figure 25 indicates that the means for [p] and [b] are greater in CV syllables than in VCV syllables. The means for the [k], [d], and [g] sounds, however, are slightly greater in VCV syllables than in CV syllables. The means for [t] are the same in both CV and VCV syllables.

The Duncan Multiple Range Test was used to locate significant differences among the means for consonants in the two syllable contexts. The results are presented in Table 15. Table 15 indicates that the means for [p] and [b] in CV syllables are significantly greater than the means for the other consonants, regardless of syllable context, except for [p] and [b] in VCV syllables. The mean for [b] in VCV syllables is significantly greater than the means for [t] and [k] in both CV and VCV syllables. Other differences among the means are not significant. Therefore, the source of the interaction must be determined on the basis of inspection of the means in Figures 25 and 26. Since a significant interaction indicates that the differences between the means for the plosives in CV syllables and VCV syllables are different, Figures 25 and 26 may be inspected for evidences of failure of the differences between consonant means to be the same. Inspection of these figures suggests that the syllable effect on the bilabial consonants [p] and [b] is marked,

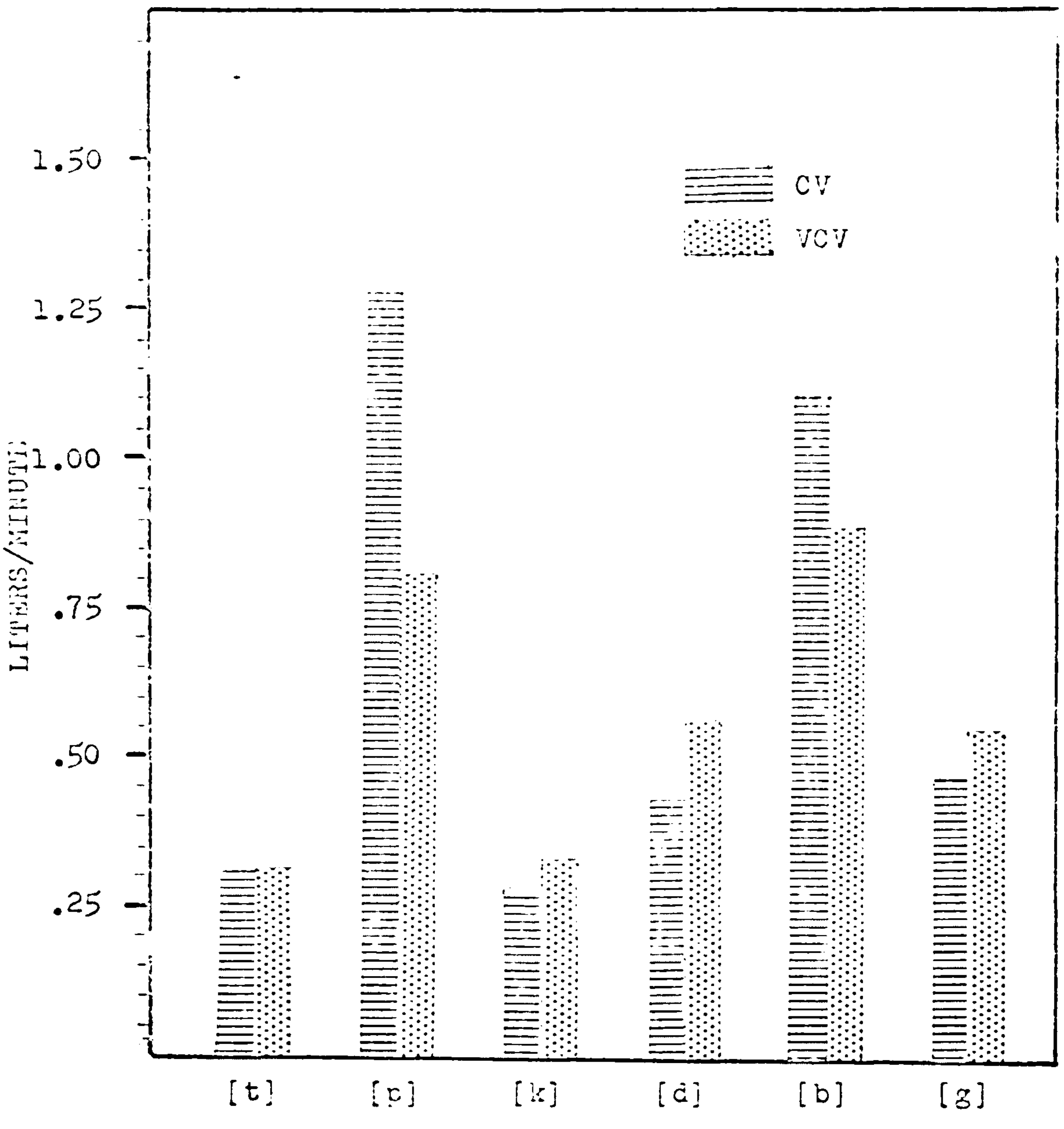

Figure 25.--Nasal air flow means for each of the six plosive consonants produced in CV and VCV syllables, for twenty-five male subjects. The means are over the vowels [i] and [a].

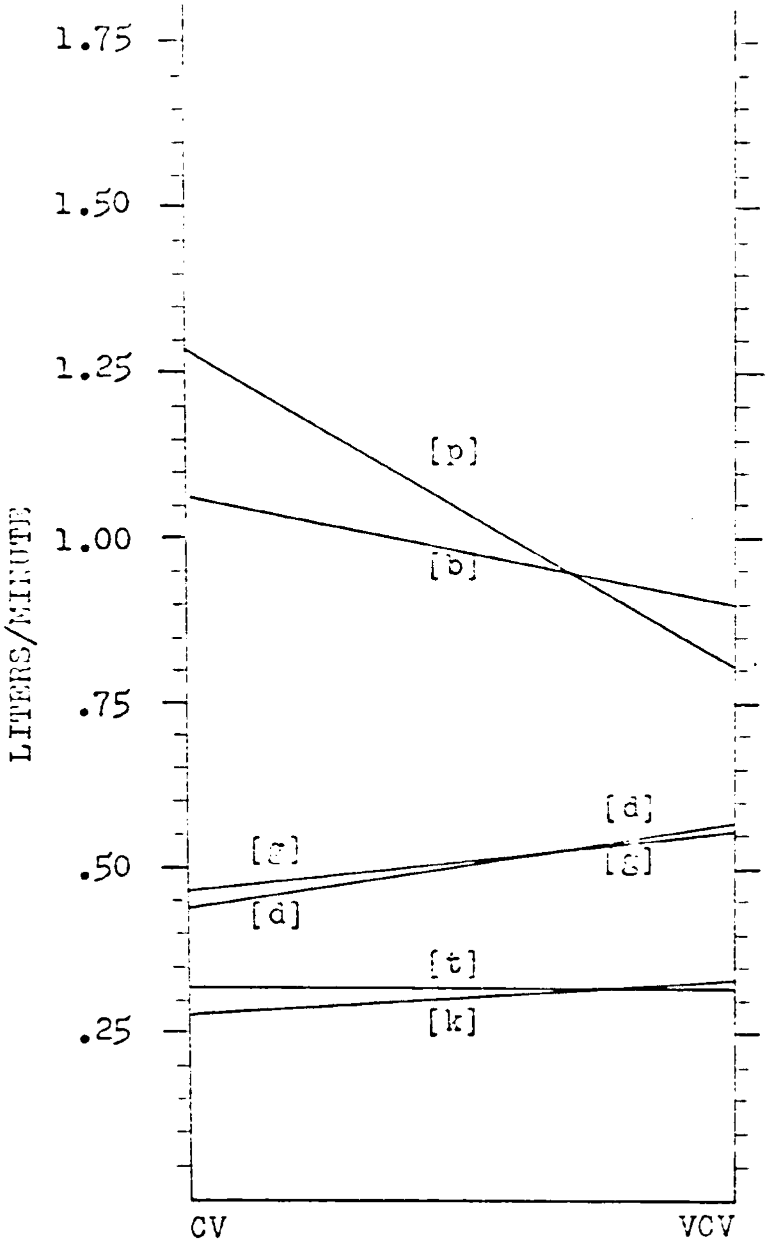

Figure 26.--Nasal air flow means for each of the six plosive consonants produced in CV and in VCV syllables, for twenty-five male subjects. The means are over the vowels [i] and [a].

TABLE 15.--Duncan Multiple Range Test for differences among nasal air flow means for each of the six plosive consonants produced in CV and VCV syllables, for twenty-five male subjects. The means are over the vowels [i] and [a]

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
R_p:	.462	.487	.503	.515	.525	.531	.538	.543	.548	.551	.554

b) Results

Consonants:	[k]	[t]	[t]	[k]	[d]	[g]	[g]	[d]	[p]	[b]	[b]	[p]
Syllable Contexts:	CV	VCV	CV	VCV	CV	CV	VCV	VCV	VCV	VCV	CV	CV
Means:	.28	.32	.32	.33	.44	.47	.56	.57	.81	.90	1.12	1.29
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	———	———	———	———	———	———	———	———	———			

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

whereas for [t], [d], [k], and [g] the syllable effect is slight. It is apparent, therefore, that, for male subjects, nasal air flow means for the plosives are differentially affected by the type of syllable in which they are tested. For the consonant [p], in particular, the syllable effect appears to be relatively strong. In contrast, there appears to be no appreciable syllable effect for the [t] sound.

For male subjects, the syllable effect on the individual consonants is not the same, and/or the consonants are not equally responsive to changes in syllable context. However, the lack of a significant consonant-by-syllable interaction for females indicates that the syllable effect is similar for each of the six consonants, and/or that each of the consonants is similarly sensitive to the syllable influence.

When the consonant-by-syllable interaction on oral air flow data was presented for male subjects, it was noted that the oral air flow means for each of the six plosives were significantly greater in CV syllables than in VCV syllables. It was also noted that the mean for the voiceless consonant [t] in CV syllables exceeded that of the other consonants and that the mean for [b] exceeded the means for all other consonants, excepting [g] in CV and in VCV syllables. In contrast, the consonant [t] is associated with relatively small nasal air flow means in both CV and VCV syllables, and the consonant [b], with a relatively large nasal air flow in both CV and VCV syllables.

Vowel-by-Consonant-by-Syllable Interaction

A fourth major purpose of this phase of the study was to determine the combined effect of vowel and syllable contexts on consonant nasal air flow. The vowel-by-syllable interaction was not significant for either sex, indicating that differences among the means for the consonants as a group combined with [i] and with [a] in CV and VCV syllables were similar. However, inspection of Tables 11 and 12 indicates that the vowel-by-consonant-by-syllable interaction is significant for male subjects, but not for females. This indicates that, for the male subjects, the differences in mean nasal air flow for the six individual consonants in the various syllable-vowel contexts are different. In Figures 27 and 28 the consonant means making up this interaction are shown for CV and VCV syllables, respectively. These same means are plotted in Figure 29 for consonants with the vowel [i] across syllables and in Figure 30 for consonants with the vowel [a] across syllables. A further plot of the means is shown in Figures 31 and 32. In Figure 31, the means are plotted for the consonants in CV syllables across the vowels [i] and [a], and in Figure 32 for the consonants in VCV syllables across the vowels [i] and [a].

With respect to trends in the data, it may be seen in Figures 27 through 32 that, regardless of the syllable-vowel context, the bilabial plosives [p] and [b] are

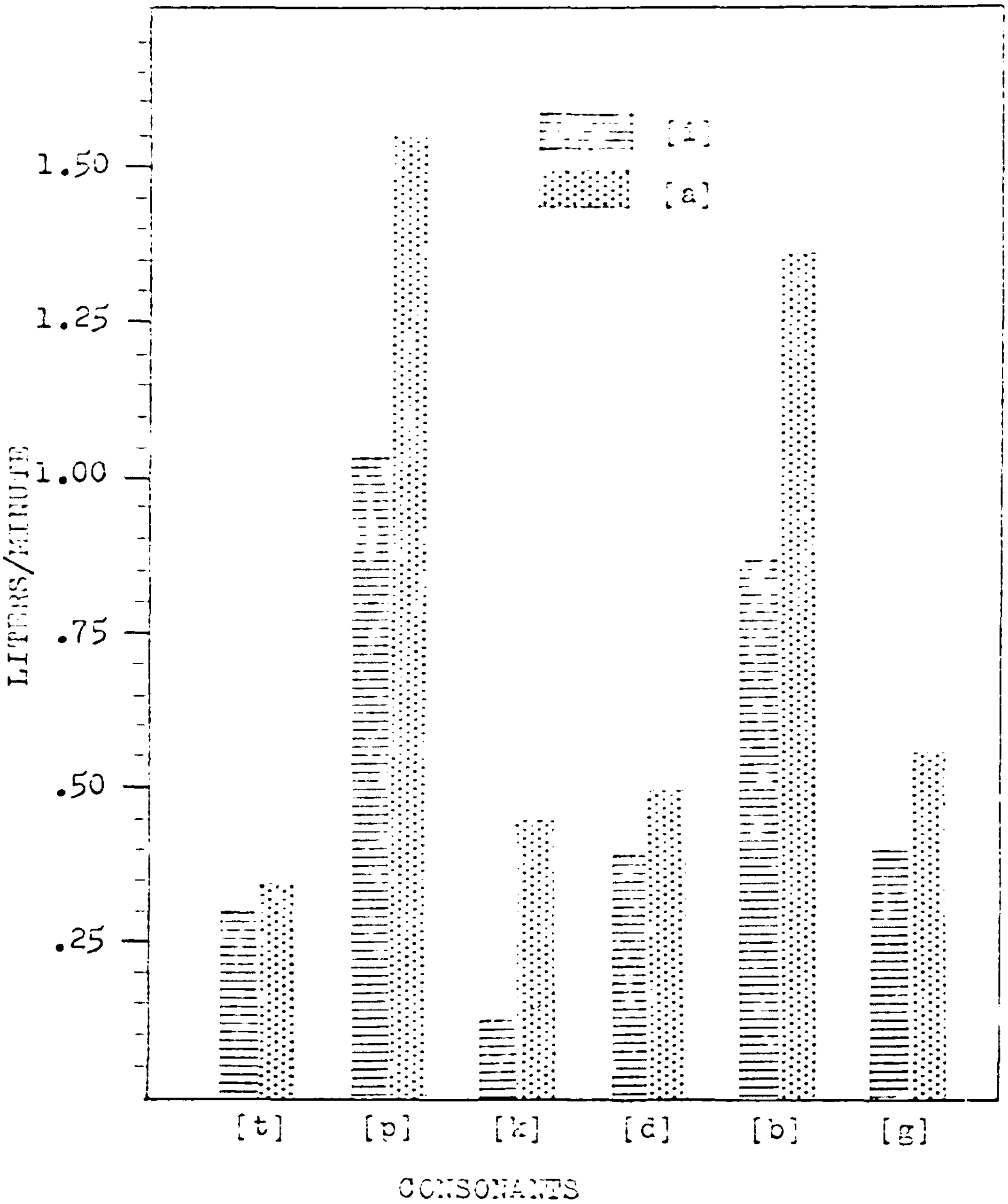

Figure 27.--Nasal air flow means for each of the six plosive consonants produced in CV syllables in combination with [i] and in combination with [a], for twenty-five male subjects.

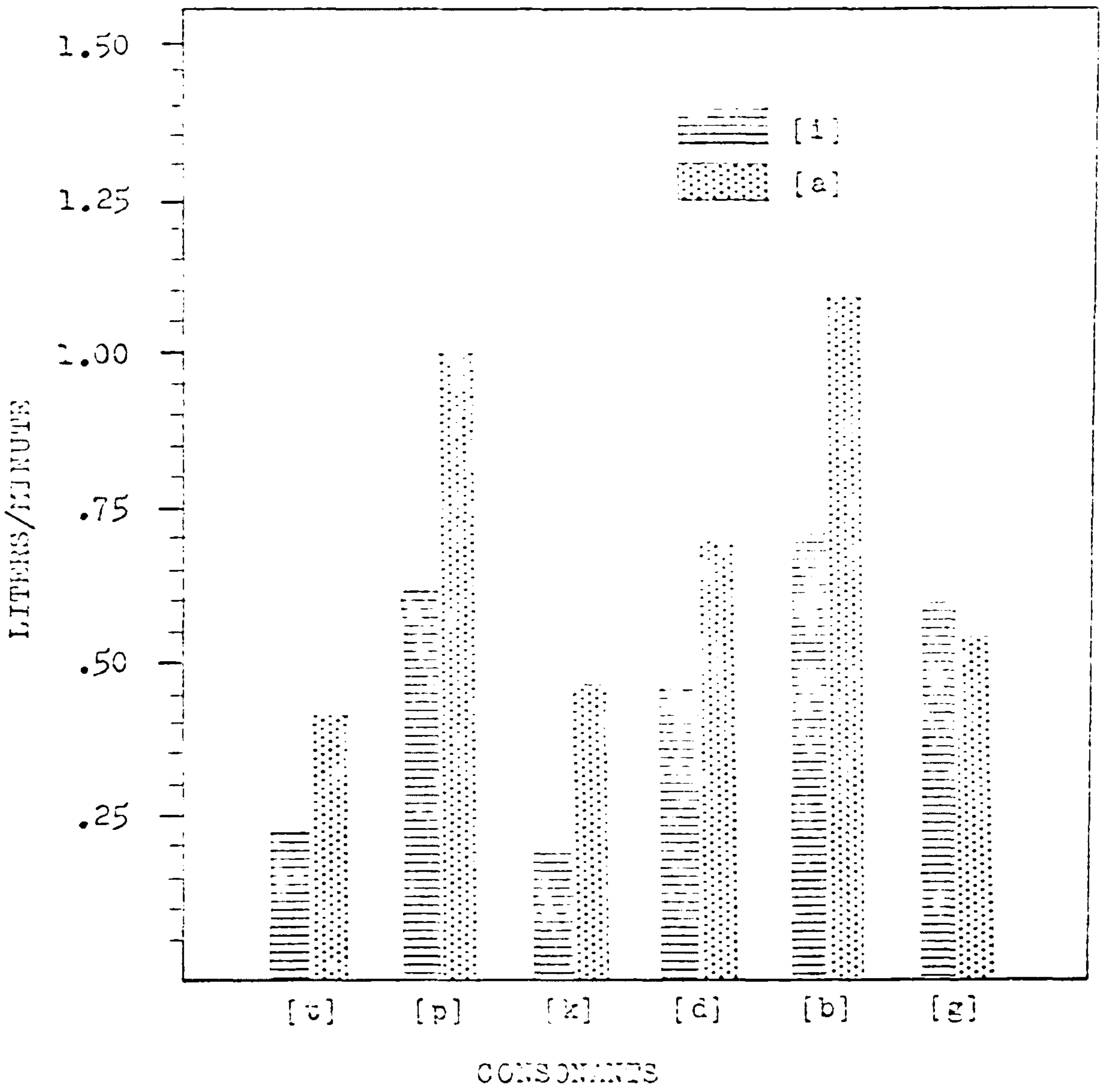

Figure 28.--Nasal air flow means for each of the six plosive consonants produced in VCV syllables in combination with [i] and in combination with [a], for twenty-five male subjects.

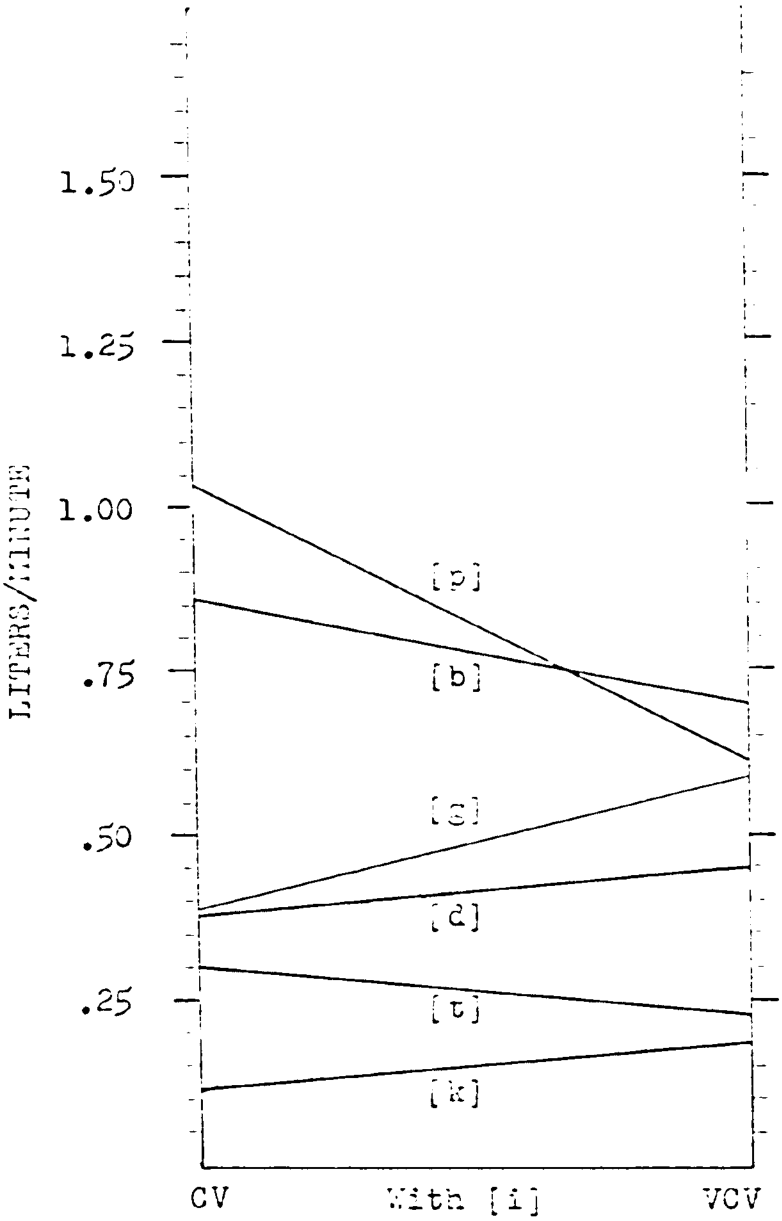

Figure 29.--Nasal air flow means for each of the six plosive consonants produced in CV and VCV syllables in combination with [i], for twenty-five male subjects.

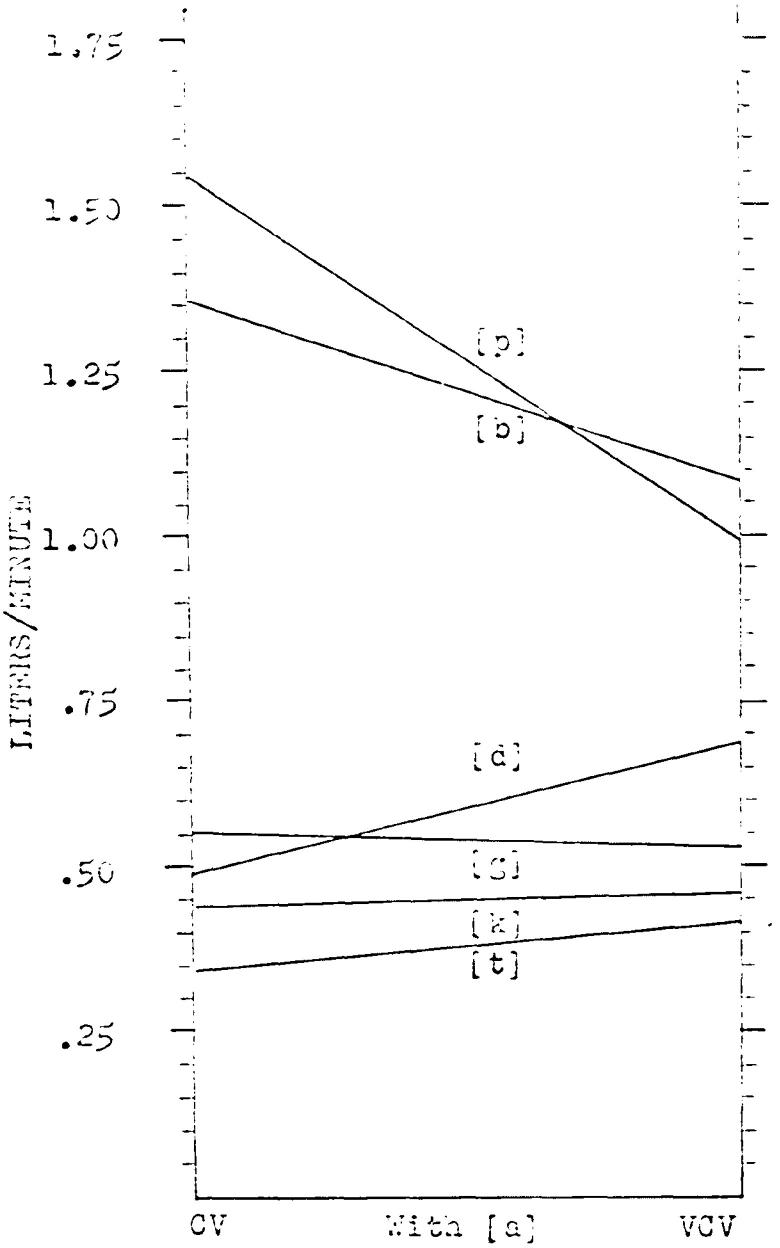

Figure 30.--Nasal air flow means for each of the six plosive consonants produced in CV and in VCV syllables in combination with [a], for twenty-five male subjects.

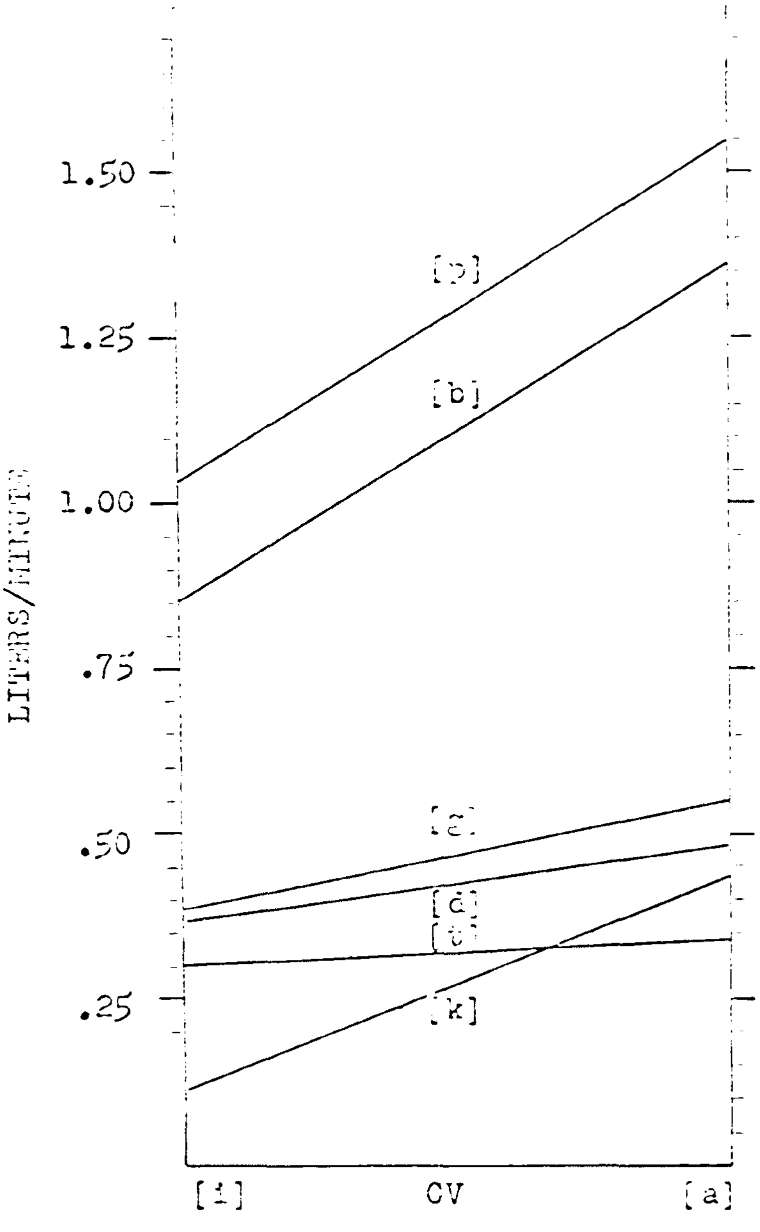

Figure 31.--Nasal air flow means for each of the six plosive consonants produced in CV syllables in combination with [i] and in combination with [a], for twenty-five male subjects.

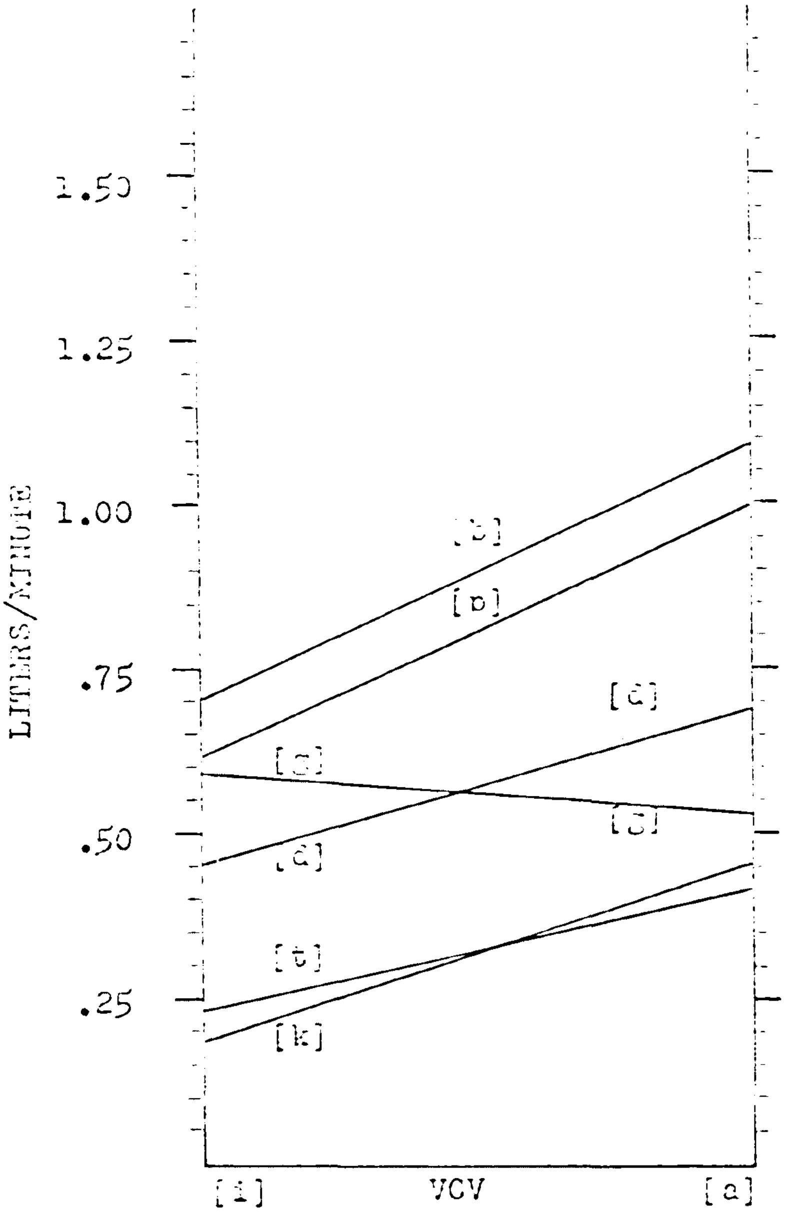

Figure 32.--Nasal air flow means for each of the six plosive consonants produced in VCV syllables in combination with [i] and in combination with [a], for twenty-five male subjects.

associated with the largest nasal air flow means, and that the means for [g] and [d] exceed those for [k] and [t]. There is a clear tendency for greater nasal air flow to occur during production of consonants combined with [a] than with [i] in both syllable contexts. This might be expected since the vowel main effect is significant for male subjects. Figures 29 through 32 also show that the difference between the nasal air flow means for the bilabial consonants and the means for the other plosive consonants is greater in CV syllables than in VCV syllables, regardless of the vowel with which they are combined. It may also be noted in these figures that this difference is greater when the consonants are combined with [a] than with [i], regardless of the syllable context. Further, Figures 29 and 30 show that the mean for the [p] sound exceeds the mean for [b] in CV syllables and that the mean for [b] exceeds that for [p] in VCV syllables. It may also be seen in these figures that the mean nasal air flow for some, but not all, of the plosive consonants is greater in CV syllables than in VCV syllables. The consonant [d], for example, is characterized by a greater mean nasal air flow in VCV syllables than in CV syllables. It is further apparent in these figures that the vowels do not affect all consonants in the same way in the two types of syllable. In CV syllables, for example, the mean nasal air flow for the consonant [g] increased when the syllabic vowel was changed from [a] to [i]. In VCV syllables, however, the mean nasal air flow for the consonant [g] decreased when the syllabic vowel was changed from [a] to [i].

The Duncan Multiple Range Test was used to locate the significant differences among the consonant means in the various syllable-vowel contexts. The results are shown in Table 16. Inspection of Table 16 indicates that many of the differences among the means are too small to be significant. It is helpful to consult Figures 29 through 32 in interpreting Table 16. As previously noted, the means for [p] and [b] exceed the means for [g], [d], [t], and [k] in all syllable-vowel contexts. The Duncan Test indicates that when the plosives are combined with [a] in CV syllables, the means for [p] and [b] are not different, but that each of these means significantly exceed the means for the other consonants. Similarly, when produced in CV syllables with [i], the means for [p] and [b] are not different, but are significantly larger than the means for the other consonants in this syllable-vowel context. The means for [p] and [b] in CV syllables with [a] are significantly larger than the means for these consonants in CV syllables with [i]. The means for [g], [d], [t], and [k] in CV syllables with [i] and with [a] do not differ significantly.

The means for the plosives [b] and [p] do not differ significantly when these sounds are produced in VCV syllables with [a]. However, the means for these two consonants

TABLE 16.--Duncan Multiple Range Test for differences among nasal air flow means for each of the six plosive consonants produced in CV and VCV syllables in combination with [i] and with [a], for twenty-five male subjects

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
R_p:	.282	.297	.307	.314	.320	.324	.328	.331	.334	.336	.338	.340	.342	.343	.344	.346	.347	.348	.349	.349	.349	.350	.350

b) Results

Consonants:	[k]	[k]	[t]	[t]	[t]	[d]	[g]	[t]	[k]	[d]	[k]	[d]	[g]	[g]	[g]	[p]	[d]	[b]	[t]	[p]	[p]	[b]	[b]	[p]
Syllable Contexts:	CV	VCV	VCV	CV	CV	CV	CV	VCV	CV	VCV	VCV	CV	VCV	CV	VCV	VCV	VCV	VCV	CV	VCV	CV	VCV	CV	CV
Vowel Contexts:	[i]	[i]	[i]	[i]	[a]	[i]	[i]	[a]	[a]	[i]	[a]	[a]	[a]	[a]	[i]	[i]	[a]	[i]	[i]	[a]	[i]	[a]	[a]	[a]
Means:	.12	.19	.23	.30	.34	.38	.39	.42	.44	.45	.46	.49	.53	.55	.59	.62	.69	.70	.86	1.00	1.03	1.09	1.36	1.55
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Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

significantly exceed those for [d], [g], [k], and [t] in this syllable-vowel context. The means for [d], [g], [k], and [t] in VCV syllables with [a] are not significantly different. In VCV syllables with [i], the means for [b] and [p] significantly exceed the means for [t] and [k], but are not significantly different from the means for [g] and [d]. The mean for [g] significantly exceeds the means for [t] and [k], but the mean for [d] does not. The means for [d], [t], and [k] are not significantly different in VCV syllables with [i]. The means for [p] and [b] in VCV syllables with [a] are significantly greater than the means for [p] and [b] in VCV syllables with [i]. The means for [g], [d], [t], and [k] in VCV syllables with [a] do not differ significantly from the means for these consonants in VCV syllables with [i], however. Inspection of these data indicates, therefore, that the nasal air flow means for the consonants [p] and [b] are markedly affected by the syllable-vowel context, while the means for the other consonants appear to be affected to a lesser extent. It appears, therefore, that the presence of this significant vowel-by-syllable interaction was due primarily to the relatively marked effect of the different syllable-vowel environments on the [p] and [b] sounds as compared to the other plosives.

CHAPTER V

SUMMARY AND CONCLUSIONS

This study represents an attempt to investigate, in normal adult speakers, the volume rates of oral and nasal air flow expended during the production of six plosive consonants, and to determine the effects of certain vowel and syllable contexts on these rates of flow. A review of relevant literature indicated that there have been few attempts to analyze experimentally the expiratory air stream in speech. This study was undertaken because of the importance of objective data concerning air flow in speech to speech pathologists and phoneticians.

In this study, twenty-five young adult males and twenty-five young adult females were utilized as subjects. All subjects were selected from locally available volunteers, and all were required to meet certain standards for selection. Subjects were required to be normal speakers, to be between the ages of twenty and thirty-six years, to have essentially normal hearing in at least one ear, to present no history of recent or chronic respiratory illness, and to be able to perform the experimental task following brief instruction and practice.

Each subject produced a series of syllables composed of the plosive consonants [p], [b], [t], [d], [k], and [g] individually combined with the vowels [i] and [a] in CV, VCV and VC syllables. Each subject was required to produce the three types of syllables involving a given consonant in combination with a given vowel in one exhalation, at a conversational level of intensity, and in a monotone. A conversational level of intensity was required because it was desired to investigate volume rates of oral and nasal air flow at levels of vocal intensity which were comfortable for the speaker, rather than at artificially imposed intensity levels which might be typical of some speakers, but not of others. Subjects were required to speak in a monotone so that a disproportionate inflectional emphasis would not be given any one syllable in a sequence containing the three types of syllable and to assure a uniform pitch level within the syllable sequence. To guard further against this possibility, the order of presentation of syllables within a sequence was randomized.

In the present study, no attempt was made to measure oral or nasal air flow in the production of consonants in VC syllables. In these syllables, where the consonant served to arrest the syllable, an acceptable acoustic production of the syllable was heard by the examiner whether or not an explosive phase was present. Since subjects were not specifically instructed to release the final consonant, some subjects released it and some did not, so that an explosive phase of the consonant in VC syllables was not always found on the chart record. In addition, the chart record of the explosive phase in VC syllables, when present, was often merged with the record of an immediately-following exhalation. For these reasons, no demonstrably reliable or valid means for determining the maximum oral air flow in VC syllables was found.

All data were collected in a sound-treated test room which provided a similar speaking environment for all subjects. Subjects were seated during the collection of data. Two pneumoanemometer units, which are specially designed hot-wire anemometers, were utilized in data collection. The anemometer sensing elements were contained in oral and nasal sections of an open-ended metal tube which protruded anteriorly from a face mask. A partition in the middle of the tube and face mask separated the oral from the nasal air flow; and, because the tube was open at the end, there was negligible impedance to the air flow. Each sensing element was connected to a different pneumoanemometer unit permitting separate and simultaneous transduction of oral and nasal air flow into continuous voltage analogs. These analogs were recorded on separate channels of a dual-channel chart recorder. The peak oral flow, as indicated by the maximum excursion of the chart recorder stylus, was then located in each syllable, and this excursion was measured in millimeters. The nasal air flow registered at the instant of maximum oral air flow during consonant production was similarly measured. The millimeter measurements thus obtained were converted mathematically to volume rates of oral and nasal air flow expressed in liters per minute.

The data for male and female subjects were analyzed statistically by means of a split-plot-design analysis of variance with a factorial arrangement of treatments and, where appropriate, by Duncan Multiple Range Tests. It may be noted that this study was, in effect, a replication of one experiment on two different groups of subjects classified by sex. Although the data for the two sexes were not compared statistically, trends were discussed.

In the presentation of findings, the terms "mean oral air flow," and "mean nasal air flow" were used. Since the exact meaning of these terms is basic to an understanding of the findings, it may be reiterated that they were used as substitutes, respectively, for the more accurate terms "mean maximum volume rate of oral air flow" and "mean volume rate of nasal air flow measured at the instant of peak oral air flow." The total volume of oral air used during production of a sound, therefore, was not measured; rather, the peak or maximum volume rate of flow was measured. A sound of relatively small peak flow might, conceivably, have involved a greater total volume of air than one of large peak flow, were it sustained longer. Similarly, nasal air flow measurements were made simply at a point in time corresponding to peak oral air flow, and the measurements obtained did not represent the total volume of nasal air during the sound production, and did not necessarily represent either peak or minimal nasal air flow.

Oral and Nasal Air Flow Differences Among the Six Consonants

The first research question posed in the present study was: How do the six plosive consonants differ with respect to volume rates of oral and nasal air flow? The statistical analyses relevant to this question were the consonant main effect and the associated Duncan Multiple Range Tests.

With respect to oral air flow, the presence of a significant consonant main effect indicated that there were differences among the means for the six consonants. Analysis of the consonant main effect, in which the oral air flow means for each consonant were averaged over both types of syllable and both vowels, indicated that, for both sexes, the means for the voiceless consonants [t], [p], and [k] were significantly larger than the means for the voiced consonants [d], [b], and [g]. This finding appeared to be consistent with findings reported by Black (5), who studied intraoral air pressure differences among consonants. While the reasons for these oral air flow differences between voiced and voiceless consonants are not revealed by the present research, they may be due to the action of the glottis in impeding air flow during voiced sound production, and the absence of this action in voiceless sound production. They may also reflect a tendency for speakers to increase the intensity level of voiceless sounds to make them more audible.

Other differences among the consonant means were also found. For the female subjects, the oral air flow means for the lingua-alveolar consonants [t] and [d] were significantly larger than those for the other voiceless and voiced consonants, respectively. The trends for male subjects were similar, but the mean for [d] was not significantly greater than the means for the other voiced consonants and the mean for [t] was significantly greater than only one of the other two voiceless consonants, [k]. It would appear, however, that, because the trends were similar for both male and female subjects, had more subjects of each sex been tested, or had sources of experimental error been further minimized, at least some of the nonsignificant trends might have been significant. Further research is needed to test this hypothesis.

With respect to nasal air flow, the presence of a significant consonant main effect indicated that there were differences among the means for the six consonants. It was noted, however, that the mean nasal air flow values were uniformly small, seldom exceeding one liter per minute. The presence of a nasal air flow reading during production of plosive consonants, which are classified phonetically as nonnasal consonants, raised a question concerning the cause of the flows. Possible causes included: (1) an opening of the velopharyngeal port coincident with the release of air from the mouth during the explosive phase of consonant production; (2) expulsion of air from the nose due to the elevation of the velum in the nasopharyngeal space during closure; and (3) a leakage of oral air flow into the nasal section of the face mask due to movement of the articulating oral structures with resultant displacement of the partition separating the oral and nasal sections of the mask. Further research is needed to explore the specific mechanisms which account for the presence of nasal air flow in production of these sounds. Studies utilizing simultaneous measures of nasal air flow and cinefluoroscopic visualization of velopharyngeal valving may help define the location of the velum in relation to recorded nasal air flow. In any event, these data can be expected to be of value in subsequent studies of nasal air flow in which the present instrumentation is used.

When the consonant main effect for nasal air flow was analyzed, it was found that, for males, the [p] and [b] sounds evidenced significantly greater nasal air flow means than [d] or [g], and that the means for the [d] and [g] sounds were significantly greater than those for [t] and [k]. The differences between the consonants in each pair were not significant, however. Thus, for male subjects, the consonants tended to group themselves according to place of articulation for the consonants with the largest nasal air flow means, [p] and [b], and according to voicing characteristics thereafter. For female subjects, the nasal air flow mean for [p] was significantly larger than the means for the other consonants and the mean for [b] was significantly larger than the means for [g] and [k]. Other differences among the means for each of the six consonants were not significant. It was also noted that, for both sexes, the nasal air flow means for the bilabial consonants [p] and [b] significantly exceeded the means for the lingua-velar consonants [k] and [g].

When the means for both oral and nasal air flow for each consonant were considered, it was observed that it was not possible to predict the relative size of nasal air flow means for plosive consonants from the relative size of their oral air flow means. For example, for both sexes, the consonant [p] was characterized by relatively large oral and nasal air flow means, while [k] was characterized by a relatively large oral air flow mean and a relatively small nasal air flow mean. It appeared, therefore, that plosives which have similar oral air flow means may differ markedly with respect to mean nasal air flow.

On the basis of these findings, it would seem reasonable to generalize that, when the means were averaged over both vowel and syllable contexts used in this research, voiceless plosive consonants evidenced greater oral air flow than voiced consonants, for both sexes. For both males and females, the bilabial consonants [p] and [b] involved significantly greater nasal air flow means than the lingua-velar consonants [k] and [g].

Effect of Vowel Context on Consonant Oral and Nasal Air Flow

The second research question posed in the present study was: How do the vowels [i] and [a] affect volume rates of oral and nasal air flow for the six consonants? The statistical analyses relevant to this question were the vowel main effect, the vowel-by-consonant interaction, and the associated Duncan Multiple Range Tests.

With respect to oral air flow, the presence of a significant vowel main effect indicated that, when the consonants were considered as a group, the vowels did differentially affect their oral air flow. Analysis of the vowel main effect indicated that, when oral air flow measures were averaged over the six consonants and both types of syllable, the consonants evidenced a significantly greater mean oral air flow when combined with [a] than with [i]. These findings appeared to be inconsistent with those of Black (5), who reported no differential vowel effect on intraoral air pressure among the consonants he studied. There were several possible reasons for these differences in findings, including: (1) differences in the number and type of consonants studied; (2) differences in the vowels used in syllabic combination with the consonants; (3) differences in instrumentation employed; and (4) differences in the type of measurements made on the consonants (Black studied intraoral air pressure during the implosive phase of the consonant).

The presence of a vowel-by-consonant interaction significant for both sexes indicated that the vowel influence was not the same for all consonants and/or that the individual consonants were not similarly responsive to the vowel influence.

Analysis of the vowel-by-consonant interaction indicated that, of the six plosives tested, the means for the [p], [t], [k], and [d] sounds differed significantly according to vowel context. It appeared, therefore, that the voiceless consonants and the voiced consonant [d] were more markedly affected by vowel context than were the voiced consonants, [b] and [g]. It was also of interest that the mean oral air flow for the voiceless consonants significantly exceeded the means for the voiced consonants in both of the vowel contexts used in this study. Further, for both sexes, the consonant [t] in combination with the vowel [a] involved a significantly greater mean oral air flow than any other consonant-vowel combination.

With respect to nasal air flow, the vowel main effect was significant for males, but not for females. For females, therefore, the two different vowel contexts apparently did not have a differential effect on the mean nasal air flow when the consonants were considered as a group. For males, however, there was a differential effect. Males employed greater nasal air flow in the production of consonants as a group when they were combined with the vowel [a] than with the vowel [i]. The vowel-by-consonant interaction was not significant for either of the sexes, indicating that the differences which existed among the consonants when combined with [i] and with [a] were similar for all the consonants.

A comparison of oral and nasal air flow means for the consonants considered as a group in the two vowel contexts indicated that, for both sexes, plosives produced with

[a] were characterized by greater oral air flows than plosives produced with [i]. For males, then, plosives combined with [a] were associated with greater mean oral and nasal air flow than plosives combined with [i]. For females, however, plosives combined with [a] were associated with greater nasal air flow means than plosives combined with [i]. Examination of the data suggested the possibility that male subjects achieve a tighter velopharyngeal valve during production of consonants combined with [a] than with [i]. Females, on the other hand, seemed to achieve a similar velopharyngeal valve during production of consonants combined with [i] and with [a]. This finding suggests a possible sex difference with respect to vowel influence on velopharyngeal valving during plosive consonant production.

On the basis of the findings, it seems reasonable to conclude that: (1) for both sexes, plosive consonants, considered as a group, evidenced greater mean oral air flow when combined with [a] than when combined with [i]; (2) for both sexes, voiceless plosive consonants as a group evidenced greater mean oral air flow than voiced plosives when the consonants were combined with [a] than when they were combined with [i]; (3) for both sexes, oral air flow for voiceless plosive consonants as a group was more markedly affected by vowel context than oral air flow for voiced plosive consonants; and, (4) for male subjects, plosive consonants as a group evidenced greater mean nasal air flow when combined with [a] than when combined with [i]. This experiment failed to reveal a significant difference in the effect of the two vowels on nasal air flow for consonants produced by female subjects.

Effect of Syllable Context on Consonant Oral and Nasal Air Flow

Another major area of inquiry in this study concerned the effect of the consonant-vowel (CV) and vowel-consonant-vowel (VCV) syllable contexts on consonant oral and nasal air flow. The third research question posed in this study, therefore, was: How does the type of syllable affect the volume rates of oral and nasal air flow for the six consonants? The statistical analyses relevant to this question were the syllable main effect, the consonant-by-syllable interaction, and the associated Duncan Multiple Range Tests.

With respect to oral air flow, the presence of a significant syllable main effect indicated that, for both sexes, when oral air flow means were averaged over the two vowel contexts and all consonants, the means for consonants in CV syllables were significantly larger than the means for the same consonants in VCV syllables.

The presence of a consonant-by-syllable interaction significant for both sexes indicated that the differences among the oral air flow means for each of the six consonants in the two syllable environments were dissimilar. Analysis of the data for the consonant-by-syllable interaction revealed that, for both sexes, the oral air flow means for each of the six consonants were greater in VCV syllables. Inspection of the data indicated that voiceless sounds were affected somewhat more by the difference in syllable context than voiced consonants. It was also found that, for both sexes, one or more means among the voiced consonants were equal to or greater than the mean for the voiceless consonant [t] which had the largest mean oral air flow in VCV syllables. This suggests that, while voiceless sounds are associated with greater oral air flow than voiced consonants when they are considered in the same type of syllable, a voiced consonant may involve a greater oral air flow when the former is tested in CV syllables and the latter is tested in VCV syllables.

With regard to nasal air flow, the syllable main effect was significant for female subjects, but was not significant for males. For males, therefore, this experiment did not demonstrate that the syllable context differentially affected nasal air flow for the consonants as a group. For females, plosive consonants as a group evidenced significantly greater mean nasal air flow in CV than in VCV syllables.

When nasal air flow means for the six consonants were considered individually, a significant consonant-by-syllable interaction was found for males, but not for females. The syllable main effect was significant for females, indicating that the type of syllable context did differentially affect nasal air flow for the plosive consonants as a group. The lack of a significant consonant-by-syllable interaction for female subjects indicated that the differences between the individual consonant means in CV and VCV syllables were similar. For males, however, the differences between the individual consonant means in CV and VCV syllables were dissimilar, even though the means for the consonants as a group in the two types of syllable were not. Analysis of the consonant-by-syllable interaction for males indicated that the bilabial consonant [p] was markedly affected by the syllable context, whereas the other consonants were affected very little.

For females, greater oral and nasal air flows occurred in production of consonants in CV syllables than in VCV syllables. For males, greater oral air flow occurred in production of consonants in CV syllables than in VCV syllables, but nasal air flow was not differentially affected by syllable context. On the basis of these findings, it seems reasonable to conclude that: (1) for both sexes, plosive consonants considered as a group displayed greater mean oral air flow when produced in CV syllables than in VCV syllables; (2) each of the six plosive consonants tested evidenced greater mean oral air flow in CV syllables than in VCV syllables; (3) oral air flow means for voiceless plosives were more markedly affected by syllable context than those for voiced plosives; (4) voiceless plosive consonants evidenced greater mean oral air flow than voiced plosive consonants in CV and VCV syllables; and (5) for the plosive consonants considered as a group, female subjects evidenced greater mean nasal air flow in CV than in VCV syllables. For males, however, this experiment did not reveal a significant difference in the effect of the two syllables on nasal air flow. It appears, therefore, that there is a difference in the way plosive consonants are produced in CV and VCV syllables which results in a consistent difference in the rate of oral air flow involved in production.

Combined Effect of Vowel and Syllable on Consonant Oral and Nasal Air Flow

The final research question asked in the present study was: What is the combined effect of the type of vowel and type of syllable context on the volume rates of oral and nasal air flow for the plosive consonants? The statistical analyses relevant to this question were the vowel-by-syllable interaction, the consonant-by-vowel-by-syllable interaction, and the associated Duncan Multiple Range Tests.

With respect to the oral air flow data, the vowel-by-syllable interaction was significant for both sexes. This indicated that the effect of vowel context on consonant oral air flow was not the same in the two types of syllable context and/or that the syllable environments were not equally conducive to the operation of a differential vowel effect. Analysis of the data revealed that the oral air flow means averaged over the six consonants differed significantly according to the vowel context in CV syllables, but not in VCV syllables. Plosive consonants in CV syllables in combination with [a] were associated with significantly larger oral air flow means than plosives in other syllable-vowel environments.

The significant nasal air flow finding relevant to this research question was the vowel-by-consonant-by-syllable interaction. This interaction was significant for males, but was not significant for females. The presence of this significant interaction for males indicated that differences among the consonant means in the various syllable-vowel environments were not the same. The findings indicated that the nasal air flow means for the consonants [p] and [b] were markedly affected by the syllable-vowel context, while the means for the other consonants appear to have been affected to a lesser extent, or not at all.

It may be noted, with respect to the oral air flow means for consonants in CV syllables, that the vowel affecting the consonant means followed the consonant in the syllable. The fact that there was a significant difference in the means for plosives combined with [a] and with [i] in CV syllables suggests that the vowel following the consonant did have an effect on the air flow. It may be that these speakers assumed a preparatory set in terms of velar closure for the vowel following the consonant which affected the oral air flow for the consonant. A similar effect was not demonstrated in VCV syllables.

On the basis of these findings, the following conclusions appear to be justified: (1) for both sexes, the mean oral air flow for the plosives considered as a group differed significantly according to vowel context in CV syllables, but not in VCV syllables; (2) for both sexes, plosive consonants in CV syllables in combination with [a] were associated with a larger mean oral air flow than plosives in CV syllables with [i] or in VCV syllables with [i] or [a]; (3) for male subjects, the differences among the nasal air flow means for each of the six consonants were dissimilar in the various syllable-vowel environments studied; and (4) the fact that there was a significant difference in the means for the plosives combined with [a] and with [i] in CV syllables suggests that the vowel following the consonant did have an effect on consonant air flow.

Problems

In the completion of this study, a number of problems were encountered which might profitably be avoided in future research. These problems relate to the calibration of the pneumoanemometer units and to certain aspects of data collection.

Calibration

Some of the basic problems involved in employment of the pneumoanemometer in experimental research in speech are associated with calibration. The manufacturer's recommended procedure for calibration, certain limitations of this procedure, and an alternative calibration procedure evolved for the present study were discussed extensively in Chapter

III. Certain assumptions were made in the calibration procedure followed in this study, however, which should be considered in evaluating the findings of the study.

First, the pneumoanemometer is a temperature sensitive instrument, and, if a discrepancy existed between the temperature of the air used in calibration and that expelled from the nose and mouth in speech, volume rates of air flow recorded during speech would be systematically in error. The error introduced would be directly related to the difference in air temperature under the two conditions. In the present research, it was assumed that air expelled from the nose and mouth in speech was at body temperature and remained at body temperature until it passed the pneumoanemometer sensing wires. Therefore, a temperature correction factor suggested by the manufacturer was used to compensate for the differences in air temperature between the calibration and experimental conditions. However, if the air expended during speech was not at body temperature at the time it passed the sensing wires, the absolute air flow readings obtained would be in error by one per cent for each six degrees of error in the temperature difference. It is possible, therefore, that such a systematic error in the absolute air flow values exists in the data reported for this research.

Second, it is apparent that the calibration procedure used in this research can be no more accurate than the air volume meter utilized in calibration. The air volume meter utilized in this research had certain limitations which may have introduced error in the reported flow readings. It was necessary, for example, to determine air flow readings with the meter indicator in motion. At high rates of flow, an accurate reading was somewhat difficult, and small errors associated with reading the meter were unquestionably present. For future research, it may be advisable to consider meters which can be read with greater accuracy at high rates of flow.

Third, it was not possible to determine the exact pressure at which the volume rates of air flow reported in this study were measured. The line pressure was set at 15 psi in this experiment, and the air volume meter was designed to measure air volumes at line pressure. It was not possible, however, to measure the air pressure at any point in the system except in the line leading from the air compressor to the air volume meter. The volume rates of air flow reported in the present experiment must, therefore, be considered in terms of specific line pressure and the specific metering system utilized in this study. In future research, it would be well to utilize an air volume meter with a pressure meter so that the volume rates of flow could be reported with respect to the pressure at the meter. Further, it would seem desirable to insure that the air pressure at the meter remained stable throughout the calibration procedure. Such an arrangement would provide a standard pressure-volume level which could be readily duplicated in other research.

Data Collection

Another possible source of error in the research data is associated with the collection of dust and other contaminating debris on the sensing wires during calibration or data collection. Experience with the instrument in the present study, however, indicated that direct contact between the sensing wire and any bit of lint or mucus resulted in dramatic changes in the electrical properties of the sensing wire, and, consequently, in the record of air flow. These deviations were so marked as to be readily distinguished from the usual pattern of air flow found in speech. It may also be noted that the calibration of the instruments at the termination of data collection was essentially the same as at the beginning, which would indicate that if the sensing wires had become dirty the effect was not sufficient to alter noticeably the calibration of the instruments.

A question might also be raised concerning the effect of differences in the angle of admission of the air flow to the pneumoanemometer sensing tube on obtained measurements. In the calibration procedure, air entered the oral and nasal sections of the sensing tube of the face mask at a 0° angle of incidence. Under experimental conditions, the air emerging from the nose was projected downward and presumably made an angled turn into the sensing tube of the pneumoanemometer. Air expelled from the mouth, however, presumably entered the tube with approximately a 0° angle of incidence. It would seem possible that, because of the direction of flow from the nostrils, some unusual air currents within the sensing tube might have resulted. The effect such currents might have on the accuracy of measurement of volume rates of nasal air flow, if any, is at present undetermined.

Problems associated with fitting the pneumoanemometer face mask to the facial contours of subjects utilized in the research were also encountered. The size and shape of the mask were not adjustable and alternate masks were not available. No way was found to insure that air was not escaping around the mask rim, and, although in every instance the fit appeared to be airtight, no way of verifying this visual impression was found. It is possible, therefore, that not all of the expired air stream passed the sensing wires of the anemometers.

Another problem was associated with the amount of pressure imposed on the upper lip by the oral-nasal partition of the mask. When the mask was fitted tightly against the subject's face, considerable force was exerted at the juncture of the upper lip and the floor of the nose. This pressure was necessary to insure an airtight seal between the oral and nasal sections of the mask. The extent to which this pressure interfered with normal lip movements during the production of the plosive sounds could not be objectively determined. It was noted, however, that some subjects complained of numbness in their upper lip following the collection of the experimental data. The extent to which a subject's articulation of the consonants and vowels can be considered "normal" under the experimental conditions is, therefore, open to question.

The stability of the face mask during data collection posed an additional problem in this research. Air moving either into or out of the tube containing the sensing wires will result in a registration of air flow. It was necessary to insure, therefore, that the mask was carefully stabilized so that only the air flow exhaled during speech and breathing was registered on the chart record. It was desirable, therefore, to collect data in a room without sources of strong and/or unpredictable air currents. While the arrangement for stability of the mask evolved for this research proved to be satisfactory, if care is not taken to insure the stability of the mask, artifacts due to mask movement can be introduced in the measurements obtained.

In spite of the limitations and problems encountered, it was felt that this study did demonstrate the usefulness of the hot-wire anemometer as a measuring device in analysis of the air stream in speech. It is anticipated that further studies of both normal and pathological speech will be carried out with this instrumentation. For example, the instrumentation may prove useful in studies of the efficiency of air utilization in speech. In this respect, measures of oral and nasal air flow for normal-speaking and speech defective subjects might be compared. It is also anticipated that future research will include studies of speech samples other than those investigated in this study. Air flow patterns occurring in production of words and connected discourse might be profitably investigated, for example. It would also be of interest to determine the effects of variations in vocal intensity and pitch on air flow in speech. It is expected, too, that future research will explore more fully the advantages and disadvantages of various possible methods of analyzing continuous and simultaneously obtained records of oral and nasal air flow in speech. Finally, in modified and improved form, the pneumoanemometer may prove useful clinically in the detection of abnormal air flow patterns in speech.

It appears, therefore, that the study of oral and nasal air flow in speech, utilizing the type of instrumentation employed, should provide many opportunities for potentially important investigations in the future.

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APPENDIX A

Calibration Data

TABLE 17.--Raw calibration data for the oral sensing wire

Unit: 002
Probe: Oral

Data Collected by: Emanuel, Trubey, Vaughn

Pneumoanemometer Settings: Range A Read #1

	Liters/Minute			Liters/Minute	
Volts x 100	T_1*	T_2	Volts x 100	T_1	T_2
2	.12	.12	52	13.10	13.40
4	.19	.29	54	14.45	15.00
6	.29	.36	56	16.30	15.80
8	.42	.43	58	17.80	17.70
10	.63	.68	60	18.90	18.20
12	.86	.90	62	21.05	22.60
14	.88	1.00	64	22.50	24.00
16	1.15	1.06	66	24.60	25.00
18	1.43	1.12	68	27.10	27.40
20	1.48	1.70	70	29.90	30.60
22	1.86	1.75	72	32.40	32.00
24	2.22	2.40	74	33.80	35.00
26	2.85	2.50	76	36.60	36.60
28	3.50	3.30	78	38.20	38.60
30	3.70	3.45	80	41.20	43.40
32	3.90	3.70	82	44.50	45.80
34	4.35	5.00	84	46.10	50.20
36	5.70	5.70	86	50.00	54.40
38	6.10	6.30	88	53.90	56.00
40	7.00	6.90	90	59.10	61.40
42	8.00	7.15	92	65.60	65.00
44	8.30	8.10	94	70.00	70.60
46	9.60	9.20	96	74.00	75.00
48	11.20	10.00	98	80.80	80.00
50	12.35	12.00	100	87.40	87.60

*T=Trial

TABLE 18.--Raw calibration data for the nasal sensing wire

Unit: 001
Probe: Nasal

Data Collected by: Emanuel, Trubey

Pneumoanemometer Settings: Range A Read #1

Volts x 100	Liters/Minute		Volts x 100	Liters/Minute	
	T_1*	T_2		T_1	T_2
02	.12	.14	52	9.70	10.01
04	.28	.28	54	10.80	11.20
06	.38	.31	56	12.40	12.40
08	.49	.50	58	13.40	13.60
10	.58	.60	60	13.60	13.80
12	.70	.72	62	15.30	15.40
14	.88	.92	64	16.90	17.00
16	1.13	1.15	66	17.25	17.70
18	1.31	1.23	68	18.70	19.30
20	1.35	1.52	70	20.50	21.00
22	1.75	1.80	72	22.30	22.60
24	1.90	2.09	74	23.70	23.90
26	2.18	2.34	76	25.20	25.50
28	2.44	2.73	78	27.00	27.90
30	2.80	3.10	80	28.80	29.50
32	3.14	3.60	82	30.40	30.90
34	3.48	3.80	84	31.80	32.80
36	4.15	4.15	86	34.10	34.50
38	5.20	4.75	88	35.70	36.40
40	5.60	5.80	90	38.50	38.80
42	6.00	6.00	92	41.00	41.20
44	6.60	6.90	94	42.60	43.40
46	7.30	7.50	96	45.50	46.10
48	8.30	8.40	98	47.40	47.80
50	9.20	9.20	100	50.30	50.50

*T=Trial

TABLE 19.--Computed volume rate of oral air flow

Volts*	Liters/Minute	Volts	Liters/Minute
2	.10	52	13.13
4	.22	54	14.68
6	.34	56	16.45
8	.48	58	18.13
10	.63	60	19.87
12	.79	62	21.69
14	.96	64	23.59
16	1.14	66	25.56
18	1.33	68	27.61
20	1.54	70	29.73
22	1.82	72	31.92
24	2.22	74	34.19
26	2.67	76	36.54
28	3.15	78	38.96
30	3.68	80	41.45
32	4.24	82	43.68
34	4.84	84	47.78
36	5.49	86	52.02
38	6.17	88	56.41
40	6.90	90	60.95
42	6.84	92	65.63
44	7.99	94	70.45
46	9.22	96	75.42
48	10.51	98	80.53
50	11.89	100	85.79

*Voltage is multiplied by 100

TABLE 20.--Computed volume rate of nasal air flow

Volts*	Liters/Minute	Volts	Liters/Minute
2	.11	52	10.04
4	.22	54	11.06
6	.34	56	12.13
8	.48	58	13.24
10	.62	60	14.40
12	.76	62	15.61
14	.92	64	16.87
16	1.09	66	18.17
18	1.26	68	19.52
20	1.45	70	20.92
22	1.58	72	22.37
24	1.90	74	23.86
26	2.24	76	25.40
28	2.61	78	26.98
30	3.01	80	28.61
32	3.44	82	30.36
34	3.89	84	32.34
36	4.38	86	34.38
38	4.89	88	36.48
40	5.43	90	38.64
42	5.64	92	40.86
44	6.42	94	43.13
46	7.26	96	45.47
48	8.14	98	47.86
50	9.06	100	50.32

*Voltage is multiplied by 100

TABLE 21.--Raw calibration data for the nasal replacement wire

Unit: 001
Probe: Nasal (Replacement)

Data Collected by: Emanuel, Vaughn

Pneumoanemometer Settings: Range A Read #1

Volts x 100	Liters/Minute	Volts x 100	Liters/Minute
02	.18	52	10.35
04	.27	54	10.90
06	.31	56	12.20
08	.51	58	13.80
10	.65	60	14.60
12	.80	62	16.30
14	.83	64	18.20
16	1.15	66	19.10
18	1.20	68	20.70
20	1.50	70	21.50
22	2.00	72	22.50
24	2.22	74	24.50
26	2.38	76	26.30
28	2.70	78	27.80
30	3.18	80	30.00
32	3.50	82	32.30
34	3.92	84	34.30
36	4.72	86	36.40
38	5.30	88	38.00
40	5.62	90	40.80
42	6.00	92	43.10
44	6.50	94	46.10
46	7.55	96	48.50
48	8.45	98	52.50
50	9.20	100	54.20

TABLE 22.--Computed volume rate of nasal air flow for the nasal replacement wire

Volts*	Liters/Minute	Volts	Liters/Minute
2	.11	52	10.34
4	.23	54	11.40
6	.36	56	12.51
8	.49	58	13.67
10	.63	60	14.88
12	.78	62	16.14
14	.93	64	17.45
16	1.10	66	18.80
18	1.27	68	20.21
20	1.44	70	21.66
22	1.78	72	23.17
24	2.10	74	24.72
26	2.45	76	26.32
28	2.83	78	27.97
30	3.23	80	29.67
32	3.66	82	31.78
34	4.11	84	34.00
36	4.60	86	36.30
38	5.11	88	38.66
40	5.64	90	41.09
42	5.77	92	43.59
44	6.59	94	46.16
46	7.45	96	48.80
48	8.37	98	51.51
50	9.33	100	54.28

*Voltage is multiplied by 100

APPENDIX B

Nasal Calibration Curve

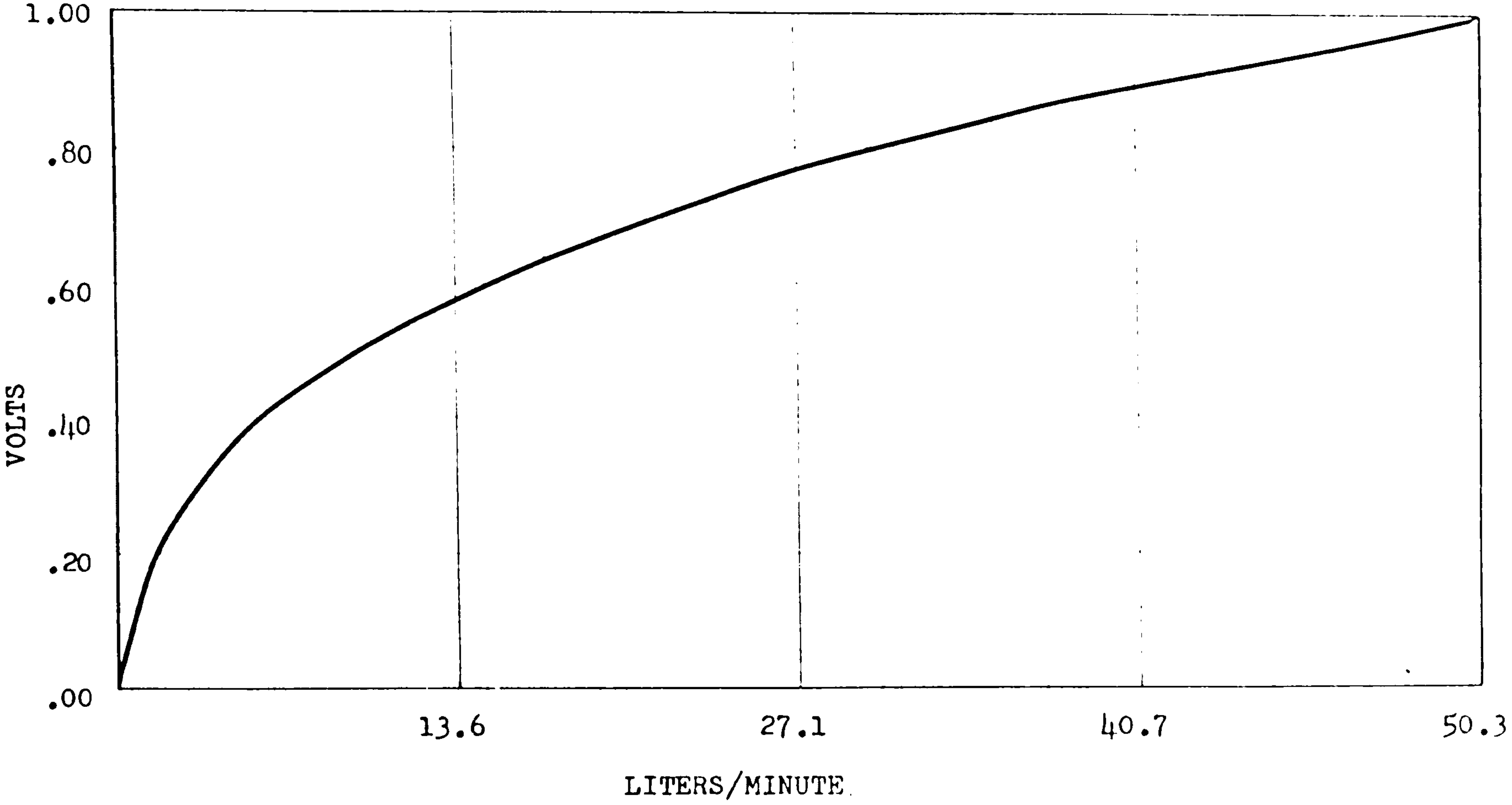

Figure 33.--Calibration curve for the nasal replacement wire.

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