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SOME EFFECTS OF CONTROLLED CHANGES IN FUNDAMENTAL VOCAL FREQUENCY, INTENSITY, AND NASAL TRACT COUPLING ON ORAL AND NASAL AIR FLOW RATES IN A SINGLE CLEFT PALATE SPEAKER.

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SISTER LOURDES LEAL

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SOME EFFECTS OF CONTROLLED CHANGES IN FUNDAMENTAL VOCAL FREQUENCY, INTENSITY, AND NASAL TRACT COUPLING ON ORAL AND NASAL AIR FLOW RATES IN A SINGLE CLEFT PALATE SPEAKER

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## CHAPTER I

## INTRODUCTION

Investigation of the physiologic events associated with changes in the acoustic signal of speech remains a significant area of inquiry in speech research. While acoustic analyses of the speech signal permit certain physiologic inferences, acoustic data alone provide limited information concerning these physiologic processes. For this reason there has been an increasing interest in additional measures that bear a more direct relationship to the physiologic events within the vocal tract. Cineradiographic measures (11, 50, 56, 35) have provided useful data regarding physiologic changes in the vocal tract configuration during speech production; yet radiographic data afford only a two-dimensional display of the structural relationships. Aerodynamic measures (62, 80, 81, 83), in contrast, provide a three-dimensional correlate of the physiologic modifications within the vocal tract.

In an attempt to understand the dynamic speech processes, investigators have employed air flow measures to study the relationships between oral and/or nasal flow rates and vocal intensity, vocal frequency, duration of phonation, adequacy of consonant articulation, nasality perception, and adequacy of velopharyngeal valving (10, 20, 35, 36, 41, 44, 46, 50, 52, 63, 74, 80, 81, 83). For the most part, these investigators have studied the relationships between air flow measures and vocal pitch and intensity in normal speakers or in groups of subjects with velar incompetency. No studies, to the present, have dealt with the interrelationships among these air flow and acoustic variables under specified oral-nasal coupling conditions.

There is evidence that coupling the oral to the nasal tract results in an attenuation of the speech signal by adding an additional source of damping (34). It has also been speculated that, since vocal pitch and intensity are closely related, nasal tract coupling results in adjustment of vocal frequency (6). The degree of power loss imposed by the addition of a nasal side branch appears to vary for individual vowels (34, 56).

Results of air flow studies point to interrelationships among pneumatic and acoustic phenomena. There is evidence, for example, that vocal pitch and intensity increments are associated with increments in oral air flow rate (81). Presumably, greater expiratory effort would be required to overcome the power loss imposed by increases in coupling area. Because of differences in the impedance characteristics of vowels, there is reason to suspect that high and low vowels differ with respect to oral flow rate (10). Such impedance differences could also be expected to result in differences in nasal flow rates for high and low vowels (81).

In view of the interrelationships among oral and nasal air flow measures, velopharyngeal valving, vocal intensity, vocal frequency, and vowel production, there is a need to investigate the interactive effects of controlled changes in these variables. It is the purpose of the present study to examine the effects of changes in vocal pitch, vocal intensity, and oral-nasal coupling on oral and nasal air flow rates for selected vowel productions in a single cleft palate speaker. The following chapters present a review of relevant literature, the design of the experiment, the results, and the conclusions.

CHAPTER II

# REVIEW OF LITERATURE

In an attempt to identify physiologic correlates of the speech signal, research investigations have been concerned with aerodynamic studies of phonation volume (90, 79), intraoral pressure (19, 1, 20, 21), and oral and nasal air flow measures (36, 10, 63, 74, 81, 80, 83). Although the relationships among vocal frequency, vocal intensity, and oral and nasal air flow have been investigated (36, 81), the effects of systematic changes in oral-nasal coupling, fundamental vocal frequency, and vocal intensity on oral and nasal air flow have not been previously reported. It is the purpose of the present chapter to review research studies pertaining to: (a) fundamental vocal frequency and intensity characteristics of vowels and their relationship to nasal tract coupling; and (b) oral and nasal air flow rates as they relate to variations in vocal pitch and intensity.

## Frequency, Intensity, and Coupling Characteristics of Vowels

The characteristic fundamental vocal frequency and intensity of vowels produced by normal subjects have been topics of extensive investigation. In the following sections, the literature describing these secondary acoustic characteristics of vowels will be summarized. This summary will be followed by a review of studies dealing with the effect of oral-nasal coupling on vowel frequency and intensity.

## Vowel Fundamental Frequency and Intensity

Available research findings suggest that fundamental vocal frequency differences exist among vowels. Taylor (75) studied mean fundamental vocal frequency of each of eight vowels produced in a "s_t" environment. For his male subjects, the mean fundamental vocal frequency for each of the eight vowels [i], [I], [ɛ], [æ], [ɔ], [U], and [u] were 149, 148, 138, 133, 132, 136, 150, and 152 Hz, respectively. The mean fundamental vocal frequency of these same eight vowels produced in a "h_d" environment were studied by Peterson and Barney (60). These investigators reported the mean fundamental vocal frequency of the vowels [i], [I], [ɛ], [æ], [ɑ], [ɔ], [U], and [u], produced by male subjects, to be 136, 135, 130, 127, 124, 129, 137, and 141 Hz, respectively. Studies by Black (2) and by House and Fairbanks (33) of the fundamental vocal frequency of vowels produced by male speakers reveal essentially similar relationships.

Comparison of the results of these studies reveals the following trends: (a) high vowels tend to have higher fundamentals than low vowels (b) tense vowels tend to have higher fundamentals than lax vowels, and (c) closed vowels tend to have higher fundamentals than open vowels. This relationship of fundamental vocal frequency and tongue position is explained in part by Taylor's speculation (75) that there is a "dynamogenetic radiation" of tension from tongue musculature to the laryngeal muscles. Thus, the increase in tongue height of a "high" vowel as compared to a "low" vowel is accompanied by a greater increase in tension of the tongue musculature. Variation in lingual tension may be transmitted to the laryngeal musculature creating corresponding variations in vocal fold tensions and in vocal pitch level.

It is well established that vowels differ in terms of their relative power. Sacia (67) investigated the relative power of eleven vowels produced by eight male and eight female normal speakers. Each vowel was phonated in a consonant-vowel-consonant (CVC) context using [t] as the initial consonant. The data for individual vowels are reported in terms of "mean power" which is defined by the investigator as the power read from a wattmeter that is proportional to the ordinary voltmeter or ammeter deflection. The relative mean power, reported in microwatts, of vowels produced by male subjects is [æ] 44, [ɔ] 37, [U] 33, [o] 33, [i] 33, [ʌ] 29, [u] 27, [ɛ] 26, [I] 25, and [e] 22.

Sacia and Beck (68) later presented the relative mean power of the same eleven vowels in a study of the conversational speech of the same sixteen subjects. The trends for the relative vowel power are similar to those reported for the same vowels produced in CVC contests. A range of 3.2 dB is reported between the vowels with greatest and least power.

Black (2) investigated the natural frequency, duration, and intensity of eleven vowels produced by 42 males and read in eleven monosyllabic words, each containing one of eleven vowels in a "t_p" environment. Vowel intensities were derived by taking the peak vertical displacement of a graphic level recorder stylus as an indication of vowel peak intensity in words. These measures, read in decibels directly from the level recorder, presumably represent r.m.s. voltage. The results of this study are reported in relative intensity in decibels, using the least intense vowel [i] as a reference (0.0 dB). The relative intensities for the vowels [o], [ɑ], [æ], [ɔ], [ɛ], [I], [u], [U], [ʌ], [e], and [i], in decreasing order, were 3.71, 3.69, 3.44, 3.22 3.12, 2.86, 2.56, 2.52, 2.21, 1.77, and 0.00 dB, respectively. The range of the intensities for the vowels reported was 3.7 dB; the means for the [i], [e], and [ɑ] vowels are significantly different. If the mean intensities for the [i] and [e] vowels are omitted, the range for the vowels is reduced to 1.5 dB.

Vowel intensities were also investigated by Fairbanks, House and Stevens (34) who had ten male subjects phonate 110 monosyllabic words, ten each for the eleven common American vowels. The monosyllabic words consisted of each vowel combined with one of eight voiceless consonants in a CVC arrangement. Mean intensities are reported for the ten subjects and derived over the ten productions of each vowel. The relative intensities of the vowels [æ], [ɔ], [ɑ], [o], [e], [ɛ], [U], [ʌ], [i], [u], and [I] are 18.3, 17.6, 17.5, 16.8, 16.7, 16.0, 15.7, 14.9, 14.8, 14.1, and 13.8 dB, respectively. Significant variations in intensity among productions of the same vowel were assumed to be the result of consonantal environment.

Lehiste and Peterson (47) utilized a single male speaker who produced each of nine isolated vowels and six dipthongs twenty different times at a controlled pitch level of 145 Hz. Mean intensities, reported in sound pressure levels relative to .0002 dyne/cm$^2$ for the vowels [ɑ], [ə], [ɔ], [U], [æ], [ɛ], [I], [u], and [i] are 85.5, 85.0, 84.8, 83.1, 82.9, 81.4, 80.2, and 80.2 dB, respectively.

Comparison of the results of the studies of relative vowel intensities reveals that the "low" vowels [ɑ], [ə], [ɔ], and [æ] tend to be produced with greater relative acoustic power than "high" vowels, such as [i] and [u]. It is possible that the differences in findings that exist among the various studies are attributable to differences in the design of the investigations. For example, although Fairbanks, House, and Stevens (13) and Black (2) utilized the same eleven vowels, the studies differed in the number of subjects and types of speech sample employed. Further, the findings of House and Stevens (34) indicate that consonant environment may have a substantial effect on relative vowel power. The use of different consonant contexts employed in the studies here reviewed may be a source of inconsistency in the reported data.

It is also generally acknowledged that a close relationship exists between vocal intensity and fundamental vocal frequency. Zemlin (93, p. 160), for example, stated, "It is interesting to note that as intensity is increased there is a tendency for the pitch of phonation to also increase." Black and Moore (3, p. 51) also noted this relationship of pitch and intensity:

> . . . pitch tends to rise with increases in loudness. This is not surprising, for certainly the vocal folds become more taut with an increase in muscular tonicity. Indeed physical effort with the hands tends to raise the frequency of the vocal-fold action.

The allusion to the relationship of general muscular tonicity and vocal pitch level, made by these authors, is similar to the speculations of Taylor (75) previously described. Lehiste and Peterson (47, p. 189) stated that "phonetic variations in pitch level are due, to a considerable degree, to the intrinsic relative amplitude of the vowel to which the pitch is applied." These investigators suggest that it is probable that the variations in pitch associated with vowels in CVC contexts are influenced by the intrinsic intensity of the syllable nuclei; that is, higher pitch may be a compensation for a lower intrinsic amplitude of the nuclei.

Apparent trends across the studies reviewed include the following: (a) high-tense, closed vowels display higher fundamental frequency than low-lax, open vowels, (b) vowels differ in their acoustic power, (c) vocal intensity of vowels varies as a function of the consonantal environment, (d) vowels produced with greater acoustic power tend to be associated with lower fundamental vocal frequency than vowels produced with less intrinsic power.

## Intensity and Oral-Nasal Coupling

It is generally accepted that an abnormal coupling of the oral and nasal cavities has an effect on the overall output of the vocal tract. As the velum is raised or lowered to alter coupling during speech, the size and shape of this tract is modified; consequently, the resonance characteristics of the system are altered. Coupling efficiency of the vocal tract is directly determined by the proportion of laryngeally-generated sound energy reaching the outer air. Excessive nasal tract coupling results in a reduction of this coupling efficiency.

That the nasal cavity acts as a damping rather than a resonant chamber was proposed by Russell and Cotton (66) in their early study of the relative intensities of the oral and nasal components of nasalized and non-nasalized vowels. Two enclosed microphones and an oscillograph were utilized to record the relative intensities of the nasal and oral speech signal for vowels sustained at eight different pitch levels. The nasal signal, when averaged across all subjects and pitch levels, was 30 dB less intense than the "oral" signal during the production of the [ɑ], [o], [ɔ], and [ae] vowels. The nasal signal was 17 dB less intense during the non-nasal production of the [i] vowel. However, when the vowels were nasalized, the intensity of the nasal signal, equaled or exceeded the "oral" signal. These results supported the presence of a transmission loss associated with excessive nasal tract coupling in nasalized speech.

House and Stevens (34) employed an electrical analog to study the effect of varying degrees of oral-nasal coupling on the acoustic output of the vocal tract. Their results indicated that the overall level of intensity of the artifical vowels decreased as coupling increased; moreover, the individual vowels responded differently to changes in the degree of nasal tract coupling. The high vowels [i] and [u] were consistently weaker in overall intensity levels in all coupling conditions, while the low vowels [a], [ae], and [ɑ] revealed a relatively greater loss of acoustic power as nasal coupling increased.

In a study of the effects of nasalization of vowels, Fant (14) investigated the influence of four nasal coupling conditions upon the acoustic spectra of four vowels, [i], [e], [ɑ], and [u]. Input impedances equal to velopharyngeal coupling area dimensions of .00 $cm^2$, .16 $cm^2$, .32 $cm^2$, .65 $cm^2$, and 2.6 $cm^2$ were utilized to evaluate the effects of coupling. Gradual increases in coupling size introduced spectral changes in the vowels which included increases in formant band width and reduction of formant intensity. However, the degree of spectral changes varied according to the vowel and the coupling size. As the coupling area was increased, the intensity of the first formant tended to decrease and the intensity level of the nasal output was increased.

In a recent study, Olson (59) investigated the effect of controlled changes in velopharyngeal coupling on nasal and "oral" sound pressure levels of the speech of a single non-nasal speaker. The single subject was fitted with a speech appliance that allowed varying velopharyngeal apertures. The subject was recorded speaking at four intensity levels under each of ten coupling conditions using eight vowels which were retested in each of four consonant environments. Because of the subject's inability to monitor intensity, a single intensity at the subject's "comfort" level was utilized. The amount of oral-nasal coupling was determined by graduated rings inserted into the pharyngeal section of a speech appliance which permitted velopharyngeal orifice sizes ranging from 0/16 to 8/16 of an inch in diameter. His results indicated that as coupling increased oral sound pressure levels decreased. Olson reported that the variation across vowels between 4/16 and 6/16 of an inch indicated the critical range of coupling which had the greatest effect on the speech signal.

The findings of the Olson study (59) are in agreement with that of Fant (14) who reported nasal tract coupling in the range of .16 $cm^2$ to .65 $cm^2$ introduced major changes in simulated vowel spectra. This critical range reported in the Fant study includes an equivalent 6/16 and 8/16 of an inch in diameter.

Comparison of the above studies reveals the following general trends: (a) increased oral-nasal coupling results in a loss of acoustic power of the "oral" signal, (b) this transmission loss varies with different vowels, (c) a critical range of oral-nasal coupling appears to differentially affect the acoustic spectra of the vowels.

## Vowel Frequency and Oral-Nasal Coupling

Although there is little direct evidence that abnormal oral-nasal coupling results in either a fundamental vocal frequency or vocal pitch range differing from normal, there is reason to suspect that this may be true.

Curtis (6) reported that for a hypothetical speaker with a cleft palate, unable to attain reasonable velopharyngeal closure, both the dynamic intensity range and the vocal pitch range are likely to be significantly reduced. Curtis suggested that this hypothetical cleft palate speaker would generate increased effort to compensate for the greater energy absorption accompanying nasal tract coupling. Since vocal effort and subglottic pressure tend to be related to vocal intensity, Curtis concluded (6, p. 56),

> When one increases his effort in order to raise his subglottic pressure and, hence, his intensity level, he involuntarily tends to raise his pitch. Since the speaker with a cleft must generate abnormally high subglottic pressure for all intensity levels, his pitch may be expected to be higher than average for all intensity levels with the result that the lower end of his pitch range may be limited.

In spite of the obvious importance of this hypothesis, there is relatively little data concerning differences in fundamental vocal frequency or in pitch range between normals and speakers with velar incompetency. Cobb and Lierle (4, p. 223), in describing speech difficulties of 56 cleft palate subjects, noted: "There was a decided lack of pitch variation and intensity." However, no data regarding the extent of such pitch limitations was reported. Spriestersbach (71) reported that judgments of a speaker's effective use of pitch variations were negatively correlated with perceived nasality.

In a study of spectrographic differences among nasal and normal speakers, Dickson (7) reported fundamental vocal frequency measures for twenty normal male speakers, ten functionally-nasal and ten cleft palate speakers. He found that the most severely nasal subjects in both the cleft palate and the functionally nasal groups displayed higher fundamental vocal frequencies than the normal-speaking group.

In a later study of the fundamental vocal frequency of sustained vowels, Flint (18) utilized thirteen male and seven female cleft palate speakers, matched with twenty normal speakers in sex and age. Her results indicate that the female cleft palate subjects displayed significantly lower fundamental frequencies than female normal speakers, while the male cleft palate subjects averaged slightly but not significantly lower fundamental frequencies than the male normal speakers.

Rampp (64) investigated the fundamental vocal frequency of four vowels produced at each of four intensity levels by groups of twenty cleft palate subjects, ten male and ten female; and normal speakers matched to the cleft palate sample in age and sex. For the male group, the cleft palate and normal speakers displayed similar mean fundamental frequencies for each of the experimental vowels at each intensity level. For the female group, significantly lower mean fundamental frequencies occurred in production of the vowels [i] and [u] for the cleft palate than for the normal speakers.

A comparison of the above findings suggests that fundamental vocal frequency for female cleft palate speakers appears lower than that of normal-speaking controls. Inconsistent results have been obtained in studies of vowel productions by male and female subjects in cleft palate groups. The differences in the findings for male subjects may possibly be explained by the speech sample and/or subject sample utilized. Consonant context may alter the fundamental frequency of the speech sample obtained as compared to that observed for sustained vowels. Dickson's data is based on the study of vowels in CVC contexts, while the data of Flint and Rampp are based on the study of isolated vowels. It may also be that differences in the subject samples across these studies are important in explaining dissimilar findings. Cleft palate subjects with greater velopharyngeal incompetency may employ higher fundamental frequencies than subjects with minimal velar deficiency. Fundamental frequency differences between male cleft palate and normal speakers deserve further study.

## Frequency, Intensity, Coupling, and Air Flow

In recent years there has been an increasing interest in the role of the breath stream in the regulation of vocal pitch and intensity. This interest has been generated by the expanding body of research data which indicates that a study of aerodynamic phenomena is important to an understanding of the physiologic events that underlie phonation (45, 77, 92, 36). In the following sections, the literature dealing with results of studies of oral and nasal air flow, as they relate to pitch and intensity regulation, are summarized.

## Oral Air Flow

While the interrelationship of oral flow rate, vocal pitch, and vocal intensity have obvious importance to researchers interested in speech, there is no extensive literature in this area. In an early study of vowels, Russell and Cotton (66) investigated the volume of air utilized in the production of the [ɑ] vowel, sustained at various pitch and loudness levels. They measured the volume of breath utilized in phonation of [ɑ] for a specified length of time and calculated breath flow in liters per minute. The pitch levels utilized were within the chest register; the two loudness levels used were a "maximum" loudness and "comfort" speech loudness levels. These authors reported that the maximum possible loudness level required only 30% more air than the normal loudness level. In an attempt to explain the increased intensity with relatively little change in air flow, the authors suggest that the open phase of the glottic cycle is shortened, coinciding with the increased subglottic breath pressure. Thus, the glottal puff possesses more energy because of increased velocity and the abrupt explosion in its release by the vocal cords.

Russell and Cotton (66) also reported that breath flow changes as a function of vocal pitch at each of the two intensity levels. During the production of both the [ɑ] vowel at the "comfort" intensity level and at the "maximum" intensity level, breath flow showed a progressive increase as vocal frequency was increased from 87 to 220 Hz. However, a slight decrease in breath flow occurs as pitch continued to increase from 220 to 300 Hz.

It is generally accepted by laryngeal physiologist that as subglottic air pressure and air flow are increased, with all other parameters including intensity being held constant, a rise in vocal pitch is observed. Some disagreement concerning this relationship, however, is evident in the research. Piquet *et al.*, (61) introduced air through a cannula into the trachea of a human cadaver and noted that increasing air flow caused the resulting sound to be louder, but not higher in pitch. Similar observations were made by Fessard and Vallencien (16), and Dunker and Schlosshauer (9) utilizing anesthetized dogs whose larynges were artificially stimulated. These studies suggest that varying air flow within physiologic limits does not appear to alter pitch. However, in studies employing living dogs, Hast (23) and Isshiki (38) reported a rise in pitch, as judged by the experimenter, with an increase in air flow rate. Rubin (65), using an anesthetized dog, reported that a rise in vocal intensity is observed by increasing air flow at a constant pitch and/or increasing cordal resistance (pitch) at constant air flow.

Ladefoged and McKinney (46) investigated the interrelationship of subglottal pressure, effective sound pressure, and judgments of loudness by 30 listeners. Words were pronounced by the speaker at a number of different intensities with no restrictions on pitch level. No significant relationship between subglottal pressure, air volume velocity, and fundamental vocal frequency was reported. There was, however, a relatively high air volume velocity when a high pitch was produced with a comparatively small subglottal pressure. Draper, Ladefoged, and Whitteridge (8) have noted that the mean pressure below the vocal folds remains stable during phonation which the speaker judged to be produced at a constant "loudness" level.

Luchsinger (51) investigated expiratory air flow volume velocity and sound pressure for two groups of singers sustaining tones in the "chest," "middle," and "head" registers at different levels of intensity. At increased intensity levels, higher volume velocities and greater air expenditures were observed. Volume velocity decreased as pitch increased; however, weak low tones were sung with small volume velocity, while weak high tones were produced with a greater volume velocity.

Van Hattum (80) investigated the amount of air used by eleven cleft palate subjects and eleven normals during sustained vowel phonation at two intensity levels and two pitch levels. Following maximum inhalation, each subject phonated for ten seconds and his remaining air was exhaled into a spirometer. The cleft palate subjects used a greater quantity of air than did the normal speakers, in spite of the fact that the cleft palate subjects had smaller vital capacities than the normals. At an intensity level of 75 dB, the cleft palate subjects used less air than at 90 dB, which was the reverse of the pattern observed for the normal subjects. The cleft palate subjects also used less air at 300 Hz than at the lower pitch level of 200 Hz; similar results were not observed for the normal subjects.

Recent studies support the existence of an interaction between frequency, intensity, and oral air flow rates. Isshiki (36) investigated simultaneous recordings of air flow rate, air volume, subglottic pressure, and sound pressure level during phonation by a single male subject. The vowel [ɑ] was sustained at varying levels of intensity from 65 to 95 dB and at different pitch levels ranging from $E_2$ to $C_5$. At low pitch levels, no specific relationship was observed between changes in flow rate and changes in vocal intensity. At medium pitch levels, air flow rate increased slightly as vocal intensity increased; at high pitch levels, air flow rates increased proportionately as intensity increased.

Vaughn (81) investigated oral flow rates during sustained phonation of four vowels at four pitch levels and two intensity levels. The 20 male subjects, all of whom had received voice training and whose "habitual" fundamental vocal frequency approximated 145 Hz, were instructed to sing a musical scale at a predetermined uniform "comfort" intensity level and at a level six dB more intense. The four pitch levels studied approximated 145, 175, 220, and 260 Hz. The greatest mean oral air flow rates, averaged over the four pitch levels and the two intensity levels, occurred for the vowels [u], [ɑ], [i], and [æ], in decreasing order. A progressive increase in oral air flow was observed from the lowest to the highest pitch levels. At both the "comfort" and "intense" levels, oral air flow means averaged over all vowels and pitch levels were significantly larger for the "intense" level of production. This intensity effect varied across vowels. At the higher level of vocal intensity, the oral flow means were significantly greater for the vowels [i], [u], and [ɑ], than the means for all vowel productions at the "comfort" level and greater than the mean for [æ] at the "intense" level.

Yanagihara and Koike (91) made simultaneous measurements of air flow rate, total air volume, fundamental frequency, and vocal intensity in 22 normal adults during comfortably sustained phonation of the vowel [ɑ] at three different pitch levels. A significant correlation was reported between the total air volume available and the maximum duration of sustained phonation. Mean air flow rate increased with a rise in pitch from "medium" to "high" pitch, but this increase was not observed from "low" to "medium" pitch. Increases in vocal intensity were generally associated with increases in mean flow rates at high pitch levels; however, no predictable relationship existed between vocal intensity and oral flow rate at "low" or "medium" pitch levels.

Summarizing the above research studies of oral flow rate, the following conclusions appear warranted: (a) oral air flow rate and maximum phonation time appear to be a function of vital capacity, (b) oral air flow rate appears to be related to vocal frequency and intensity changes; such that, at higher pitch levels, air flow rate tends to systematically increase with vocal intensity; (c) oral air flow rates for individual vowels vary with the amount of oral constriction and are differentially affected by systematic changes in vocal frequency and intensity.

## Nasal Air Flow

The interaction of oral and nasal tract resistances appears to have an influence upon both oral and nasal air flow rates. Nasal air flow rate, for instance, appears to be dependent not only upon the actual nasal pathway resistance but also on the amount of oral impedance (50).

Vaughn (81), in the study previously cited, reports nasal air flow rates during sustained phonation of four vowels at four pitch levels and two intensity levels. The two intensity levels employed included a predetermined, uniform "comfort" intensity level and a level six dB more intense. The four pitch levels employed approximated 145, 175, 220, and 260 Hz. The results, reported by Vaughn, indicate no significant relationship between either vocal pitch or vocal intensity and nasal air flow. However, there was a significant pitch-by-intensity interaction.

That is, there was a significant decrease in nasal air flow for the two highest pitch levels, at the greater intensity level.

Vaughn also reports a significant vowel main effect. There was significantly greater nasal air flow across all pitch and intensity levels for the open vowels [ɑ] and [æ] than for the closed vowels [i] and [u]. He further reports that the vowels [i] and [u] exhibited a progressive decrease in nasal air flow as pitch was increased, over both intensity levels; however, the vowels [ɑ] and [æ] revealed divergent patterns. These findings suggest that increased vocal pitch and intensity and oral impedance variation in vowel production have an effect on the tightness of the velar seal utilized in the normal production of vowels (81).

Emanuel (10) investigated nasal and oral air flow for plosive consonants, combined with two vowels [i] and [ɑ] in CV, VCV, and VC contexts, produced by 50 male and female normal speakers. These syllables were produced at a conversational level of intensity and in a monotone. Emanuel found a significant vowel main effect over all consonants for the male speakers, but not for the females. That is, there was greater nasal air flow for plosive consonants combined with [ɑ] than the same plosives combined with [i]. Assuming that the vowel influence on the nasal air flow for the plosives is based on the degree of closure required for the vowel, these results could be interpreted to mean that the vowel [ɑ] is produced with a less complete velar seal than the vowel [i].

Previous research employing cleft palate subjects has suggested that nasal air flow is generally related to the size of the nasal aperture. Quigley (63) investigated nasal air flow rate for 35 cleft palate subjects and 13 normal speakers during sustained phonation of vowels. Mean nasal air flow rates for the cleft palate subjects were lower for the vowel [ɑ] than for the [i] or [u]; this trend, however, was the reverse of that observed for the normal subjects. Mean nasal air flow for the vowel [u] was highest for the cleft palate subjects but lowest for the normal speakers.

In a recent study, Hyde (35) investigated nasal air flow rates for 15 cleft palate adults and 15 normal speakers during phonation of sustained vowels and CV syllables. Her results indicated that there were no remarkable differences between the mean nasal air flow rates for the sustained vowels; however, her cleft palate subjects produced the vowel [ɑ] with lower nasal air flow rates than that for [i] and [u]. Since the low vowel [ɑ] is produced with less oral impedance than [i] and [u], it is possible that the lower nasal flows for [ɑ] are related to the decrease in oral impedance for this vowel. This line of reasoning is compatible with the findings of Machida (52) and Warren and Devereaux (86) which suggest that, in cases of velopharyngeal inadequacy, variations in oral impedance can differentially affect nasal air flow rates.

The use of nasal flow rate as an index of the size of the nasal aperture has been questioned by Warren (85). This investigator reports that nasal flow rate appears to be linearly related to the size of the nasal aperture in the range of velar competence, .00 $cm^2$ to .20 $cm^2$. For openings greater than this, however, only a weak relationship between these measures is evident. The relatively weak relationship between nasal air flow and velopharyngeal opening may be explained on the basis of data obtained by Warren and Devereaux (86), Warren and Ryon (88) and

Machida (52). These studies suggest that nasal air flow varies as a function of both oral constriction and nasal tract resistance. They point out that when oral constriction is decreased, there is an immediate decrease in oral pressure which must be compensated by an increase in expiratory effort. When nasal tract resistance is high, oral pressure can be sustained by relatively small increases in effort. If nasal tract resistance is low, greater effort is required to sustain the same oral pressure and greater nasal flow results.

Summarizing the results of nasal air flow studies, the following trends seem apparent: (a) nasal air flow rate appears to decrease at higher pitch and intensity levels, (b) nasal air flow rate for vowels varies with the degree of oral impedance and tightness of velar valving, (c) nasal air flow rate tends to be increased with an increase in velar aperture size within a range of velar competency of .00 $cm^2$ to .20 $cm^2$, and (d) nasal air flow has not been shown to be significantly related to velar aperture size in the range of velar incompetency at coupling greater than .20 $cm^2$.

# CHAPTER III

## DESIGN OF THE INVESTIGATION

The purpose of the present study was to investigate the volume velocity of oral and nasal air flow produced by a single cleft palate adult speaker when the amount of nasal tract coupling was controlled and while he phonated three isolated vowels at specified pitch and intensity levels. The amount of nasal tract coupling was controlled by the use of a specially designed speech prosthesis which was constructed with removable concentric rings fitted into the pharyngeal section of the bulb.

Measures of oral and nasal air flow were obtained by means of a warm-wire anemometer with independent recordings of the nasal and oral channels. These measures were obtained for an adult cleft palate speaker producing each of three vowels, [i], [ɑ], and [u], at each of four selected pitch levels (105, 140, 175, and 210 Hz), at each of three intensity levels (65, 70, and 75 dB SPL), under each of six conditions of oral-nasal coupling.

### Research Questions

Specific research questions to be answered include the following:

1) What changes occur in oral and nasal air flow with variations in the degree of nasal tract coupling?

2) How do the vowels [i], [ɑ], and [u] differ with respect to oral and nasal air flow?

3) What is the effect of varying intensity, with pitch held constant, on oral and nasal air flow for the three vowels under different degrees of nasal tract coupling?

4) What is the effect of varying pitch, with intensity held constant, on oral and nasal air flow for the three vowels under different degrees of nasal tract coupling?

## Speech Sample

The speech sample utilized in the present study consisted of three vowels [i], [ɑ], and [u] each sustained for four seconds. These vowels were selected because they represent the extremes of the traditional vowel triangle and permit a study of the effect of differences in tongue height and placement within the oral cavity. Moreover, these vowels vary with respect to the acoustic power with which they are produced. Similarly, these vowels vary with respect to the amount of velar valving required in production (56).

## Research Appliance

The obturator utilized in the present investigation was specially constructed by a prosthodontist for the subject in this investigation. The prosthetic appliance included a palatal section designed with dental clasps to allow secure placement and retention. The pharyngeal section of the appliance was constructed with an aperture in the central portion of the bulb which enabled placement of five concentric aluminum rings. These rings could be removed one at a time to provide six conditions of nasal tract coupling. The orifice dimensions associated with each of the six coupling conditions are as follows:

1) .000 $cm^2$ of opening,

2) .031 $cm^2$ of opening,

3) .126 $cm^2$ of opening,

4) .283 $cm^2$ of opening,

5) .504 $cm^2$ of opening,

6) .785 $cm^2$ of opening.

## Subject Sample

A 30-year-old male with a repaired congenital bilateral cleft of the lip and palate served as the subject in the present study. This subject had successfully worn a prosthetic appliance for the past seven years. His intelligence and articulation competency were judged to be within normal limits. Frontal and lateral headplate X-rays were obtained which revealed the absence of any significant obstruction of the nasal passageway. Since air flow rate has been related to measures of vital capacity (90), the subject's vital capacity was measured by means of a Collins 13.5 Liter Respirometer. His vital capacity, 3566 cc, was somewhat less than the predicted vital capacity of 4252 cc for his age (30 years), weight (183 pounds), and height (five feet nine inches).

The subject had cooperated in previous experimental research investigations and had experience in monitoring intensity levels in isolated vowel production. The subject's skill as a professional piano tuner provided experience in adequately matching pitch levels.

In a pilot study, it was determined that the subject was capable of producing the three vowels over a one-octave range at each of the intensity levels from 65 to 75 dB SPL, at the mask-to-microphone distance used in this study. At intensity levels greater than 75 dB, the subject's ability to produce these vowels over this pitch range decreased sharply. On the basis of these preliminary trials, it was decided to limit the intensity levels in this study to 65, 70, and 75 dB SPL. Four pitch levels, incorporating points within an octave range were selected: 105, 140, 175, and 210 Hz. It was found that the subject could produce vowels at each of these pitch levels at each of the three intensities with a reasonable number of practice trials.

## Instrumentation

The principle components of the instrumentation utilized in the present investigation included:

1) oral and nasal air flow measurement systems including an anemometer assembly and an oscillographic redorder,

2) an intensity-monitoring and recording system by which amplitude displacement of the speech signal was displayed, and

3) a pitch-monitoring system with a digital readout that displayed the frequency of the speech signal.

A block diagram of the instrumentation utilized appears in Figure 1.

### Description

Oral and nasal air flow measurement. The warm-wire dual channel anemometer assembly consisted of the following:

1) a dual-channel anemometer (Flow Corporation, 701 L),

2) a hard-rubber face mask and sensing wires,

3) two Direct Current (DC) amplifiers (Honeywell, Accudata 104),

4) a multi-channel oscillographic recorder (Honeywell, Visicorder 1508),

5) a pure-tone oscillator (Heath, Model EUW 27).

The anemometer measured volume velocity by recording voltage changes associated with the cooling of a sensitive electrically-heated

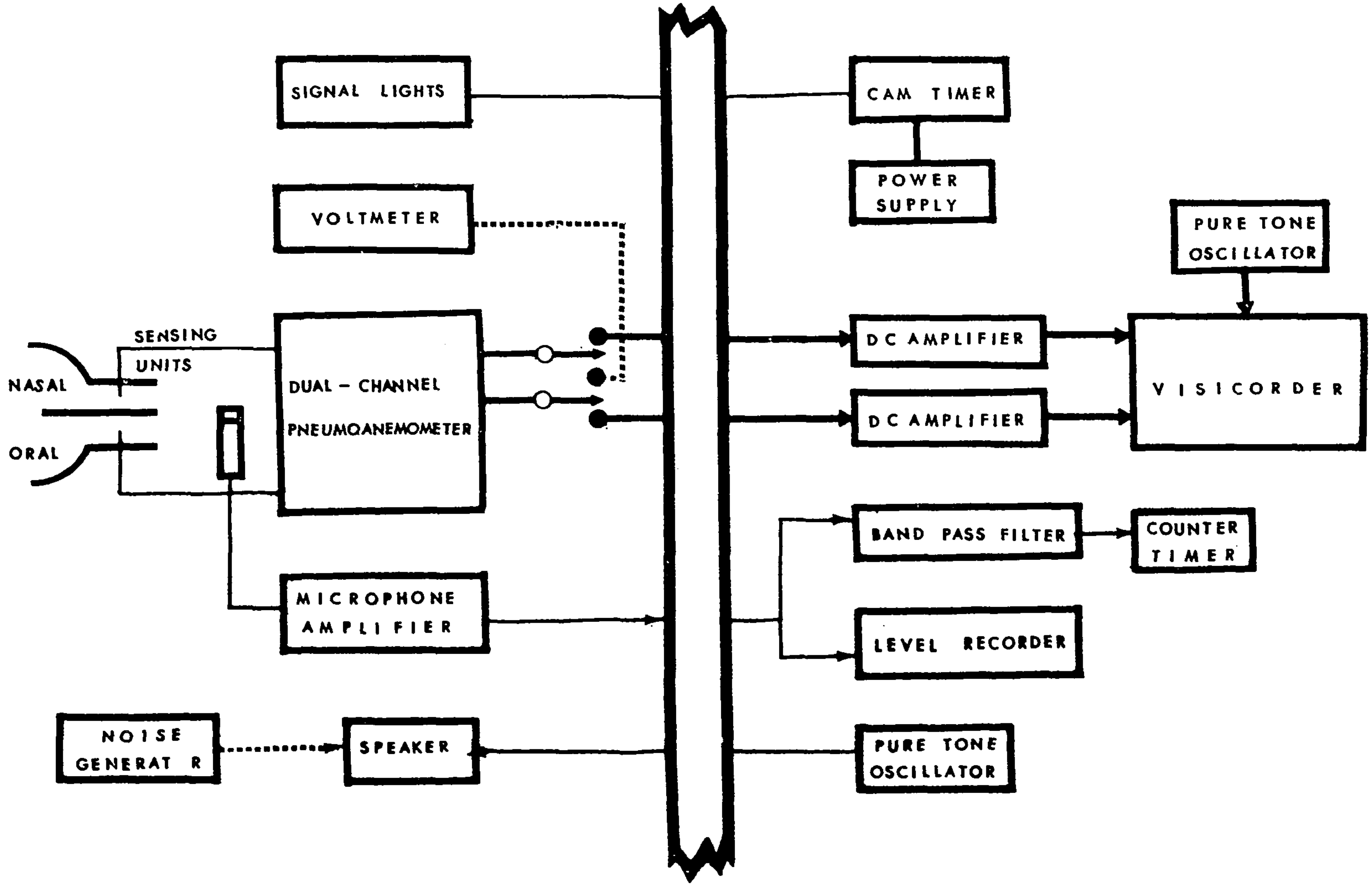


Figure 1.--Simplified block diagram of the research apparatus.

sensing wire, a feedback amplifier increased the current to restore its original temperature. Voltage variations, which occurred as a result of current changes, were recorded at the output terminals.

In order to separate the oral and nasal channels, a plastic partition was inserted throughout the length of the mask and metal tube. A silicone rubber ridge was built out from the partition to fit above the upper lip of the subject. The delicate platinum sensing wires (approximately .18 inches in length and .0005 inches in diameter) were inserted into the upper and lower channels of the four-inch metal tube attached to the mask.

Two DC amplifiers were utilized from the output of the dual-channel anemometer to the input of the oscillographic recorder. An amplifier attenuator setting of X10 was used in this study.

The multi-channel oscillographic recorder, which was utilized to record the voltage variations for the oral and nasal channels, included galvanometers that reflected voltage changes by deflection of a light beam. This deflection was recorded on photo-sensitive paper, which was rapidly exposed to display the wave trace. To obtain a base line measure, a trace was recorded with the DC amplifiers in the shorted mode for a zero voltage reading on the oscillographic recorder, a 100 Hz reference frequency was recorded to provide an external time base.

Intensity monitoring and recording system. The intensity-monitoring system was designed to permit simultaneous monitoring of the intensity of the speech signal and recording of the amplitude displacement of that signal. The major components of the intensity-monitoring and recording system included the following:

1) a half-inch condenser microphone cartridge (Bruel and Kjaer, Type 4143),

2) a cathode-follower preamplifier (Bruel and Kjaer, Type 2615),

3) a wind screen (Bruel and Kjaer, Type UA 0052),

4) a microphone amplifier with a sound level meter dial (Bruel and Kjaer, Type 2603),

5) a graphic level recorder (General Radio, Model 1521 B).

The frequency response of the condenser microphone, which was designed for sound measurement in a sound field, was calibrated by the manufacturer to be flat within $\pm$ 2 dB from 20 to 20,000 Hz. The frequency response for the condenser microphone was obtained and found to agree with the manufacturer's specification.

The wind screen was attached to the microphone cartridge and utilized to decrease the noise level of the air flow. Since the microphone was placed 10 centimeters from the edge of the face mask tube, it was thought that the noise effect of the directed air stream might contaminate the intensity measurement. The nose-cone shape of the wind screen permitted the least possible resistance to the air stream. According to the manufacturer's specifications, the wind screen covering the microphone cartridge had little effect on the frequency response below 10,000 Hz, within $\pm$ 4 dB up to 5,000 Hz. A frequency response with the wind screen in place was obtained and found to agree with the manufacturer's specifications.

The cathode follower, designed for the Bruel and Kjaer condenser microphone, transformed the high source impedance required of the microphone to the relatively low output impedance required for the succeeding microphone amplifier.

The microphone amplifier, with a potential gain of 100 dB, had a linear frequency response from 2 to 40,000 Hz. The amplifier served as a sound level meter by indicating sound pressure of the signal in decibels re .0002 dyne/cm$^2$. In this study, the subject used the meter of the microphone amplifier as a guide in maintaining the experimental intensity levels.

To monitor further the amplitude displacement of the signal, the intensity of the acoustic signal was recorded by means of a graphic level recorder. The level recorder was equipped with an 80 dB input potentiometer which was accurate within ± 1% of full scale decibel value. A level recorder writing speed of 20 inches per second and a paper speed of 15 inches per minute was utilized. The level recorder paper was lined in two decibel steps.

Pitch-monitoring system. The pitch-monitoring system included all instrumentation described for the intensity-monitoring system, except for the level recorder, in addition to the following equipment:

1) a pure-tone oscillator (Hewlett Packard, Type 200 ABR),

2) a band-pass filter (Spencer Kennedy Laboratories, Model 302),

3) a digital counter-timer (Transistor Specialties Incorporated, Model 361).

The four specified pitch levels were presented to the subject prior to each phonation by means of a pure-tone oscillator and speaker. To monitor the pitch produced by the subject, the acoustic signal from the microphone was presented through a 60 Hz band-pass filter to a counter-timer. The band-pass filter settings for the two lower experimental pitch levels required of the subject included a high-pass setting of 90 Hz and a low-pass setting of 150 Hz; whereas, for the two higher pitch levels, a high-pass setting of 160 Hz with a low-pass setting of 220 Hz were utilized. The counter-timer produced a digital readout of the cycles observed in the filtered speech signal over a one-second duration sampling. To monitor further the subject's vocal pitch, the actual number of cycles produced in a one-second interval was determined from the oral air flow trace.

## Calibration

Oral and nasal air flow measurement. In order to convert a known voltage readout to air flow rates, calibration of the anemometer and face mask was completed prior to and following each session of the data collection. The calibration was accomplished in the following manner. A compressed-air source (tank capacity of five cubic feet at thirty pounds per square inch) was connected to an air volume meter (American Meter Company, Model 807 10-M 425) which in turn was attached to the metal output tube of the anemometer face mask by means of a rubber and plastic coupling hose. The sensing wires were inserted in the face-mask tube and were connected to the anemometer. The output terminal of the anemometer was connected to a digital voltmeter (Hewlett Packard, Model 3440A) and digital recorder with a paper printout (Hewlett Packard, Model J 74 562A).

The nasal and oral channel inputs of the face mask were alternately sealed off with earmold solution, while the opposite non-sealed channel was calibrated. Prior to calibration, the anemometer unit was adjusted for zero voltage reading at zero air flow for each channel. The air control valve at the compressed-air source was then opened until there was a steady flow of air, measured by the air volume meter, and air passed into the mask at a sufficient rate to produce a voltage reading. By measuring the volume rates of air flow corresponding to ten voltage points within the output voltage range of the anemometer, it was possible to construct a least squares line relating output voltage to volume rate of air flow. The conversion of mean voltage variations to volume velocity of air flow was accomplished by means of a mathematical formula of the least squares line fitted on the basis of the initial calibration data for each channel of the anemometer. On the basis of repeated calibrations prior to and following each data-collection session, it was determined that the anemometer unit remained in calibration throughout the experiment.

In recording the voltage measures during the data collection, the amplifying and recording systems were calibrated in the following manner. The anemometer outputs were connected to the two DC amplifiers which were attached to the oscillographic recorder. With the DC amplifiers in the "short" position, the light beams for each channel on the oscillographic recorder were positioned and stabilized by means of a screw adjustment of the galvonometers. Amplitude settings for the paper readout of the oscillographic recorder were calibrated by reproducing a reference voltage and noting the amount of light beam deflection. A constant one-volt input was recorded which resulted in a five-line excursion on the oscillographic recorder paper. The paper was lined in two-millimeter steps. Thus, each half-line excursion or the width of one-millimeter represented .1 volt.

An external time base was provided by means of a 100 Hz reference frequency recorded on the third channel of the oscillographic recorder. A one-second interval was determined by counting off 100 cycles from the peak of the first to the peak of the last cycle.

Intensity recording system. To verify the accuracy of the vocal intensity recording, the graphic level recorder was calibrated with a known reference. Utilizing a white noise generator (Grason-Stadler, Model 901 B) as a sound source, signals were presented through the microphone and microphone amplifier at 75, 70, and 65 dB. These signals were reproduced as 5 dB decrements on the chart paper of the graphic level recorder.

## Procedures

### Recording Procedures

The experimental data were collected in a sound-treated testing suite in the Department of Communication Disorders, University of Oklahoma Medical Center. This environment was selected because it was free of large air currents and could be maintained at a constant uniform temperature. The sequence of procedures consisted of the following:

1) warm up and calibration of the instrumentation,
2) adjustment of the face mask,
3) presentation of the desired frequency stimuli,
4) practice session, and
5) recording of the signal.

All instruments were turned on and warmed up for thirty minutes prior to the immediate calibration. The metal outlet tube of the face mask was temporarily covered to obtain steady zero reading. The anemometer was adjusted to zero voltage reading on the digital voltmeter and then switched to the DC amplifiers and oscillographic recorder.

The subject was seated in an examining chair with its head-rest adjusted to maintain his head in a comfortable position. The face mask was supported by means of a clamp attached to a horizontal copper bar; the bar was suspended between two microphone stands. The microphone stands were adjusted to the required height. A mask-to-microphone distance of ten centimeters was verified each time the mask was removed from the subject's face.

The subject was instructed to sustain each of the three vowels [i], [ɑ], and [u] for four seconds duration while monitoring intensity on the sound level meter. One of the experimenter's assistants stationed in the testing suite verified the accuracy of the subject's monitoring of intensity. The level recorder was utilized as the final measure of intensity and was monitored by the experimenter. Intensity was judged acceptable within ± 1 dB of the specified levels. In almost all instances, vowels judged acceptable by the experimenter's assistant and the subject on the basis of sound level meter readings were also acceptable on the basis of inspection of the level recorder trace.

The stimulus tone for the selected pitch level was presented and the subject practiced matching this tone. To assist in the pitch-monitoring, another of the experimenter's assistants closely observed the digital readout of the counter-timer. Vocal pitch was judged acceptable within ± 5 Hz of the specified levels. However, measures of fundamental frequency made from the oral air flow trace were employed as the ultimate measure of pitch-monitoring to guarantee that the pitch level produced fell within ± 5 Hz of the specified levels. In almost all instances, vowels judged acceptable from the counter-timer readout were also acceptable on the basis of measures of the oral air flow trace.

Signal lights were placed within easy view of the subject. An initial amber light warned the subject to prepare for phonation by taking a breath, while a red light indicated the required duration of phonation.

During the two runs of the experiment, a prosthodontist was in attendance and had the task of building out the pharyngeal section of the obturator to assure a complete seal between the oral and nasal cavities in the no-coupling condition with all the rings in place. In the first run of data collection, the pharyngeal section was expanded to the extent that the subject reported some discomfort. During the second run, the bulb impinged less strongly on the lateral walls, in spite of the fact that no nasal air flow was registered. This procedure may have allowed the subject greater latitude in adjusting the side walls of the pharynx against the pharyngeal bulb during the second than in the first run of the experiment.

When the pharyngeal section of the obturator had been adequately built out along the lateral walls, the subject replaced his appliance and the face mask was secured by means of rubber straps drawn behind the headrest of the examining chair. To test the appliance seal, the subject was asked to phonate the vowels used in this study. The appliance was judged to be tightly fit when no nasal flow was recorded during phonation of the vowels.

The face mask was then removed and the appropriate number of rings withdrawn from the appliance to achieve the desired coupling area. With the appliance and the face mask replaced, the subject was ready for data collection.

The experimenter required the subject to perform 36 tasks in each of the six coupling conditions. Each task involved the production of a specific vowel at a specific intensity level and at a specific pitch level. Each task was repeated as often as necessary to meet the intensity and pitch criteria.

The order of presentation of vowels, vocal pitch, and vocal intensity levels was randomized for each of the six coupling conditions used in this study. To avoid the continual removal and adjustment of the speech appliance once it had been placed, this randomization of vowels, vocal pitch, and intensity levels was effected within each coupling condition rather than across all coupling conditions. The order of the coupling conditions, however, was randomly selected. The experiment was replicated in separate sessions and different randomization schedules were employed in each of the two runs.

Due to the unavailability of the subject, the collection of the data extended over several sessions and the period over which the data was collected varied for the two runs. In the first run, the data was recorded in six sessions over a three-month period. The data for the second run was collected in three sessions over a four-day period. The 36 tasks or speech samples for each coupling condition took approximately four hours for each condition in the first run and approximately two hours for each condition in the second run.

## Measurement Procedures

Measurements of the oral and nasal air flow traces were obtained for each of the three vowels, [i], [ɑ], and [u], at each of four pitch levels, at each of three intensity levels, in each of the six coupling conditions. The measurements were made in terms of millimeters of trace excursion at the beginning, middle, and end of the middle one-second segment of each four-second vowel record. This segment of the vowel was selected as being the least affected by onset and terminating influences. These measurements were converted from millimeters of trace excursion to anemometer voltage equivalents and then to mean volume rates of air flow in accordance with the previously described mathematical formula of the least squares line. The decision to measure at the beginning, middle, and end of the segment was made following a comparison of three possible methods. The mean volume rates of oral and nasal air flow for each of 36 randomly selected vowel productions were computed by taking the average of twenty measures made at .05-second intervals over the one-second segment. Then, the average of ten measures taken at .1-second intervals over the one-second segment was computed. The air flow values thus obtained were compared to those obtained when the mean volume rate of flow was calculated on the basis of measurements made at the beginning, middle, and end of the one-second segment. The differences in mean rate of air flow yielded by the three methods, as determined by an analysis of variance, were not statistically significant. Therefore, the mean air flow rates for the remaining sustained vowels were computed by using three points because of the greater simplicity of this method.

The reliability with which the millimeter measurements could be made was estimated by a standard measure-remeasure reliability procedure. The experimenter measured 36 randomly selected vowel productions at the beginning, middle, and end of the one-second segment. These measurements were repeated after a one-week period. The agreement between the two measurements was high, with a maximum discrepancy of .5 millimeters at any point. Hence, the final measurements were made to the closest one-half millimeter.

# CHAPTER IV

## RESULTS AND DISCUSSION

The present study was designed to investigate the changes in oral and nasal air flow rates associated with the sustained production of selected vowels at each of four vocal pitch and three vocal intensity levels under each of six conditions of oral-nasal coupling. A 30-year-old adult male with a repaired bilateral complete cleft of the lip and palate served as the subject. Variations in the degree of oral-nasal coupling were obtained by means of removable concentric rings that were placed in the pharyngeal section of a speech appliance worn by the subject. The rings were removed one at a time to produce six coupling conditions ranging from no-coupling to an opening of .785 $cm^2$.

Three vowels, [i], [ɑ], and [u] were each sustained for a period of four seconds at each vocal pitch and intensity level under each of the six coupling conditions. The vocal pitch levels employed corresponded (± 5 Hz) to the following reference fundamental frequencies: 105, 140, 175, and 210 Hz. The vocal intensity levels corresponded (± 1 dB) to 65, 70, and 75 dB SPL at a mask-to-microphone distance of ten centimeters.

A dual-channel, warm-wire anemometer was utilized to measure the volume rates of oral and nasal air flow. The data were recorded on a multi-channel chart recorder which provided a graphic representation of the volume rate of oral air flow and simultaneously occurring volume rate of nasal air flow for each vowel in each experimental condition. The mean oral and nasal air flows occurring during the four-second duration of vowel production constituted the quantitative data of this study.

To facilitate the discussion of the results, the three intensity levels, 65, 70, and 75 dB SPL, utilized in the present study, are designated Intensity Levels (ILs) I, II, and III, respectively. The four pitch levels corresponding to 105, 140, 175, and 210 Hz are designated Pitch Levels (PLs) I, II, III, and IV in that order. The six coupling conditions, .000 $cm^2$, .031 $cm^2$, .126 $cm^2$, .283 $cm^2$, .504 $cm^2$, and .785 $cm^2$ are designated, in order of increasing coupling, Coupling Conditions (CCs) I, II, III, IV, V, and VI. The two replications of the experiment are referred to as Run I and Run II. The terms "oral air flow" and "nasal air flow" are substituted for the more complete terms "mean volume rate of oral air flow" and "mean volume rate of nasal air flow," measured simultaneously. Measures of oral and nasal air flow are reported in "liters per minute" abbreviated "lpm."

For purposes of organization and discussion, the results of the present study will be reported in four sections: (1) vocal intensity, (2) vocal pitch, (3) vowels, and (4) oral-nasal coupling. Within each section the oral air flow data will be followed by that for the nasal air flow data. Because of apparent differences between the data in the two runs, an inferential statistical analysis was not attempted. The results of the two runs are presented separately in each section.

## Vocal Intensity

The mean oral air flows and standard deviations obtained at the three intensity levels used in this study, taken over the three vowels, four pitch levels, and six coupling conditions, are presented in Table 1. Means and deviations are presented separately for Run I, Run II, and for the Runs combined. Comparison of the means in Table 1 reveals that, in both runs, five dB increments in vocal intensity from 65 to 75 dB tend to be associated with consistent increments in oral air flow rate. In both runs, the greatest mean flow rate occurs at IL III, followed in order of decreasing flow by those at ILs II and I. Similar mean flow rates are employed at ILs I and II in each run of the experiment. The differences among the means in each run are small in comparison to the variability evident within each run.

TABLE 1

ORAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF THREE INTENSITY LEVELS DERIVED OVER ALL PITCH LEVELS, VOWELS, AND COUPLING CONDITIONS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Intensity Levels | | I | II | III |
|---|---|---|---|---|
| Run I | Means | 9.82 | 10.05 | 11.37 |
| | SDs | 3.50 | 4.21 | 3.77 |
| Run II | Means | 9.14 | 10.27 | 13.14 |
| | SDs | 3.69 | 5.08 | 4.62 |
| Runs combined | Means | 9.50 | 10.16 | 12.25 |
| | SDs | 3.61 | 4.67 | 4.31 |

In view of the subject's variability within and between runs, the present data provide no clear evidence of an increased oral flow rate with changes in the experimental intensity levels. The consistency of the differences among the means for the three intensity levels in the two runs, however, suggests that such a relationship may exist.

Nasal air flow means and standard deviations obtained at the three intensity levels, taken over all vowels, pitch levels, and coupling conditions, are presented in Table 2. Comparison of the nasal air flow means for the three intensities reveals that the relationship between vocal intensity and nasal air flow is different in the two runs.

TABLE 2

NASAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF THREE INTENSITY LEVELS DERIVED OVER ALL PITCH LEVELS, VOWELS, AND COUPLING CONDITIONS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Intensity Levels | | I | II | III |
|---|---|---|---|---|
| Run I | Means | 3.56 | 3.84 | 3.86 |
| | SDs | 3.24 | 3.36 | 4.41 |
| Run II | Means | 5.32 | 4.85 | 4.68 |
| | SDs | 2.53 | 2.76 | 2.79 |
| Runs combined | Means | 4.45 | 4.34 | 4.27 |
| | SDs | 3.04 | 3.11 | 3.71 |

In Run I, the lowest nasal air flow mean is observed at IL I, followed in order of increasing flow by those at ILs II and III. However, for Run II, the rank order is reversed with the lowest mean flow at IL III, 4.68 lpm, followed in order of increasing flow by those at ILs II and I. Nasal air flow means are consistently higher in Run II than in Run I. Inspection of the standard deviations reveals somewhat greater variability in Run I than in Run II. The size of the deviations in both runs is large with respect to the size of the differences among the means.

## Vocal Pitch

Oral air flow means and standard deviations obtained at the four pitch levels used in this study, taken over the three intensity levels, three vowels, and six coupling conditions, are displayed in Table 3. Table 3 shows that the greatest mean flow rates in Run I occur at PL II followed in order of decreasing flow by those at PLs IV, III, and I. In Run II, the greatest mean flow rate was found at PL IV followed in decreasing order by those at PLs I, III, and II.

TABLE 3

ORAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF FOUR PITCH LEVELS DERIVED OVER ALL INTENSITY LEVELS, VOWELS, AND COUPLING CONDITIONS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Pitch Levels | | I | II | III | IV |
|---|---|---|---|---|---|
| Run I | Means | 9.38 | 11.05 | 10.50 | 10.71 |
| | SDs | 2.77 | 3.99 | 4.04 | 4.40 |
| Run II | Means | 11.99 | 8.82 | 9.91 | 12.74 |
| | SDs | 3.09 | 3.90 | 3.75 | 6.59 |
| Runs combined | Means | 10.69 | 9.93 | 10.21 | 11.73 |
| | SDs | 3.21 | 4.10 | 3.91 | 5.70 |

Inspection of Table 3 discloses a greater difference among the means for the four pitch levels in Run II than in Run I. The range of differences for the means in the two runs suggests that greater differences in oral flow rate are associated with changes in pitch level in the second than in the first run of the experiment. Inspection of the standard deviations reveals a slightly but consistently greater variability at the highest pitch level (PL IV) in both runs.

The preceding data do not support the presence of a consistent relationship between pitch level and oral flow rate in the two runs. This is best seen by inspecting differences in the order of the means in Run I and II. For instance, the mean at PL II is the highest in Run I and the lowest in Run II; the mean at PL I is the lowest in Run I and among the highest in Run II.

Nasal air flow means and standard deviations obtained at the four pitch levels taken over all vowels, intensity levels, and coupling conditions are presented in Table 4. Inspection of the means in Table 4 reveals that slightly greater means are obtained for Run II than for Run I. Comparisons across the four pitch levels in both runs indicate that PLs III and IV are associated with greater nasal air flow rates than PLs I and II in both runs. However, the pattern of increased nasal air flow with changes in pitch level varies within each run. A slight increase in nasal air flow is observed with each increase in pitch level from PL I to III in Run I; however, in Run II this increase is observed from PL I to IV. PL IV in Run I is produced with slightly less nasal air flow than PL III in the same run.

Comparison of the standard deviations, presented in Table 4, indicates somewhat larger values in Run I than in Run II. The size of the deviations appear large in comparison to the size of the differences between means. For example, in PLs I and III in Run I, the size of the deviations exceeds the mean which suggests a markedly skewed distribution of the values at these levels. In view of the variability within the data, there is no clear evidence of an increase in nasal flow rate with an increase in vocal pitch level. Trends within the data in the two runs, however, suggest that the nasal air flow may be somewhat greater at PLs IV and III than at PLs II and I.

TABLE 4

NASAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF FOUR PITCH LEVELS DERIVED OVER ALL INTENSITY LEVELS, VOWELS, AND COUPLING CONDITIONS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Pitch Levels | | I | II | III | IV |
|---|---|---|---|---|---|
| Run I | Means | 3.08 | 3.68 | 4.48 | 3.78 |
| | SDs | 3.36 | 2.90 | 5.01 | 3.04 |
| Run II | Means | 3.94 | 4.93 | 5.23 | 5.70 |
| | SDs | 1.97 | 2.72 | 2.31 | 3.32 |
| Runs combined | Means | 3.51 | 4.30 | 4.85 | 4.75 |
| | SDs | 2.78 | 2.88 | 3.92 | 3.33 |

## Pitch-by-Intensity Interaction

To determine the extent to which increments in vocal intensity are accompanied by increments in oral flow rate at each of the four pitch levels, the data are arranged to show this relationship. Figure 2 presents a plot of oral air flow means at each of three intensity levels for each of the four pitch levels. The means are averaged over the three vowels and all coupling conditions. Figure 2 illustrates that, although the size of the increment varies in the two runs, there are fairly consistent increases in oral flow between ILs II and III at each of the four pitch levels. The exception to this trend occurs at PL III, Run I, where

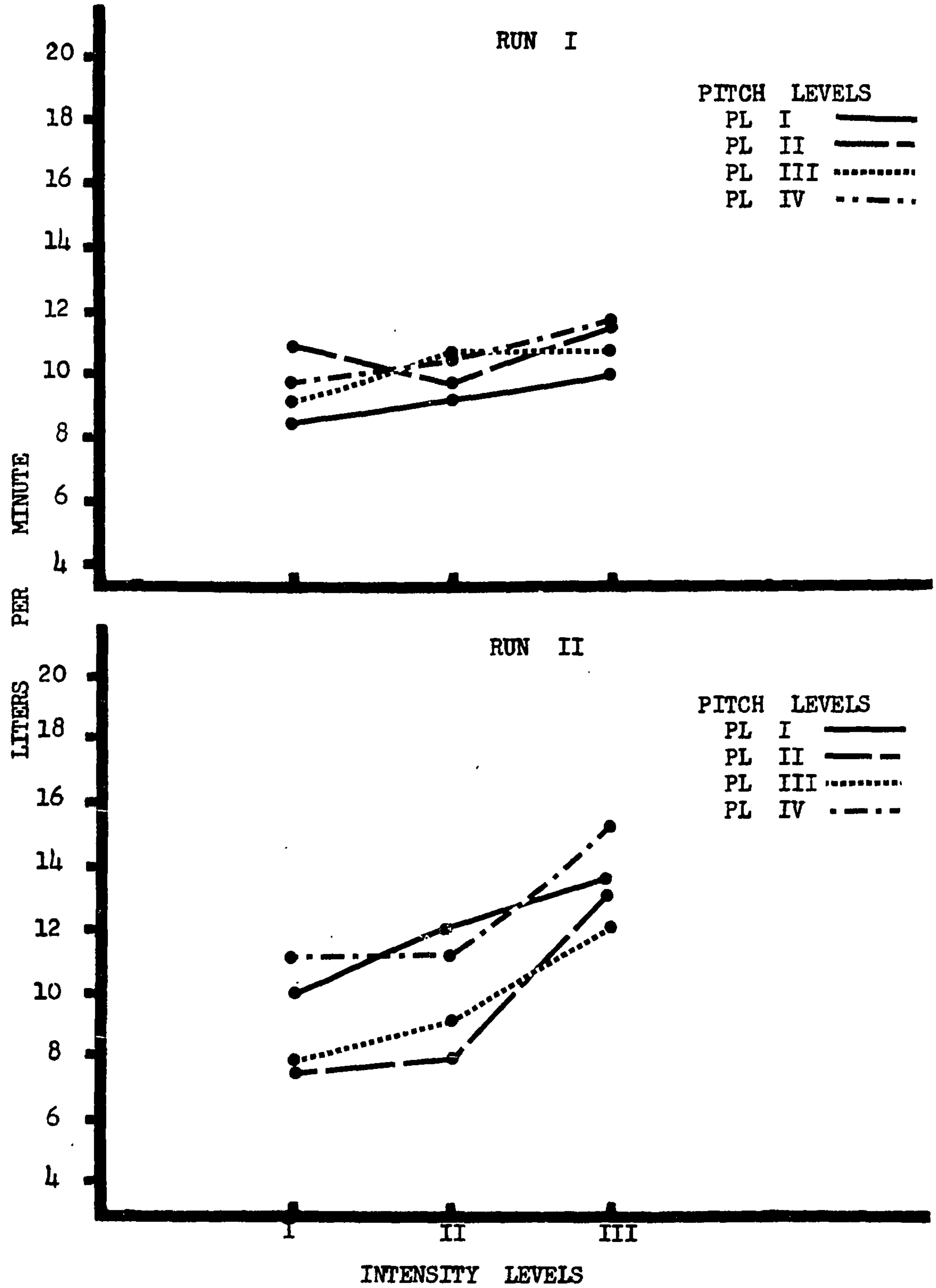


Figure 2.--Oral air flow means for each of four pitch levels at each of three intensity levels for the two runs when the means are derived over all vowels and coupling conditions.

little change in flow between the two intensity levels is evident. Between ILs I and II, the pattern of flow change is more variable. While again there is a trend toward an increased flow rate between these intensity levels at PLs I and III, this increase is not apparent at PLs II and IV. Little change in flow rate occurs between ILs I and II at PL IV in either run; a decline in flow rate between ILs I and II occurs at PL II in Run I.

The above findings are consonant with those previously discussed in relation to vocal intensity; that is, there is a trend toward small increments in oral flow with increments in vocal intensity from 70 to 75 dB SPL (ILs II to III) at each of the four pitch levels. There is a suggestion of a pitch-by-intensity interaction at the lower intensity levels. The data suggest that a change in intensity from 65 to 70 dB SPL (ILs I to II) results in an increase in oral flow to a greater extent at PLs I and III than at PLs II and IV.

The data in Figure 2 suggest that increments in vocal intensity result in greater increments in oral flow in Run II than in Run I of the present experiment. This finding suggests that the subject was able to attain the experimental intensities, while maintaining the required pitch, with lesser increases in oral flow in the first than in the second run.

The effects of changes in vocal pitch level at each of the three intensity levels are similar to those reported in relation to the overall pitch effect; that is, there is no consistent relationship between changes in pitch level and oral flow rate at any of the three intensities in the two runs. One exception to this statement may be the tendency for vowels produced at the highest pitch level (PL IV) to be associated with the greatest oral flow. Examination of the means for the four pitch levels at each of the three intensities reveals considerable variability.

To explore the effect of changes in vocal intensity on nasal air flow at each of the four pitch levels, the data are arranged to show this relationship. Nasal air flow means for each of three intensity levels at each of the four pitch levels are presented in Figure 3. Means are derived over all vowels and coupling conditions. Inspection of Figure 3 shows, as indicated in the overall intensity effect, a variable relationship between vocal intensity and nasal air flow in the two runs. The overall pitch effect, discussed previously, indicates that nasal air flow tends to be greater at higher pitch than at lower pitch levels. The present analysis suggests that this relationship is consistently evident in the two runs only at IL II. The above data suggest that nasal flow is not consistently related to changes in vocal intensity and that the relationship between vocal pitch level and nasal flow varies as a function of vocal intensity.

## Vowels

The mean oral air flows and standard deviations associated with the production of the three vowels, taken over the three intensity levels, four pitch levels, and six coupling conditions, are presented in Table 5. Examination of Table 5 reveals that the largest mean flow in Run I occurs for the vowel [u], followed in order by those for [ɑ] and [i]. In Run II, the largest mean flow is seen for [i], followed by those for [ɑ] and [u]. It can be seen that the differences among the vowel means in both

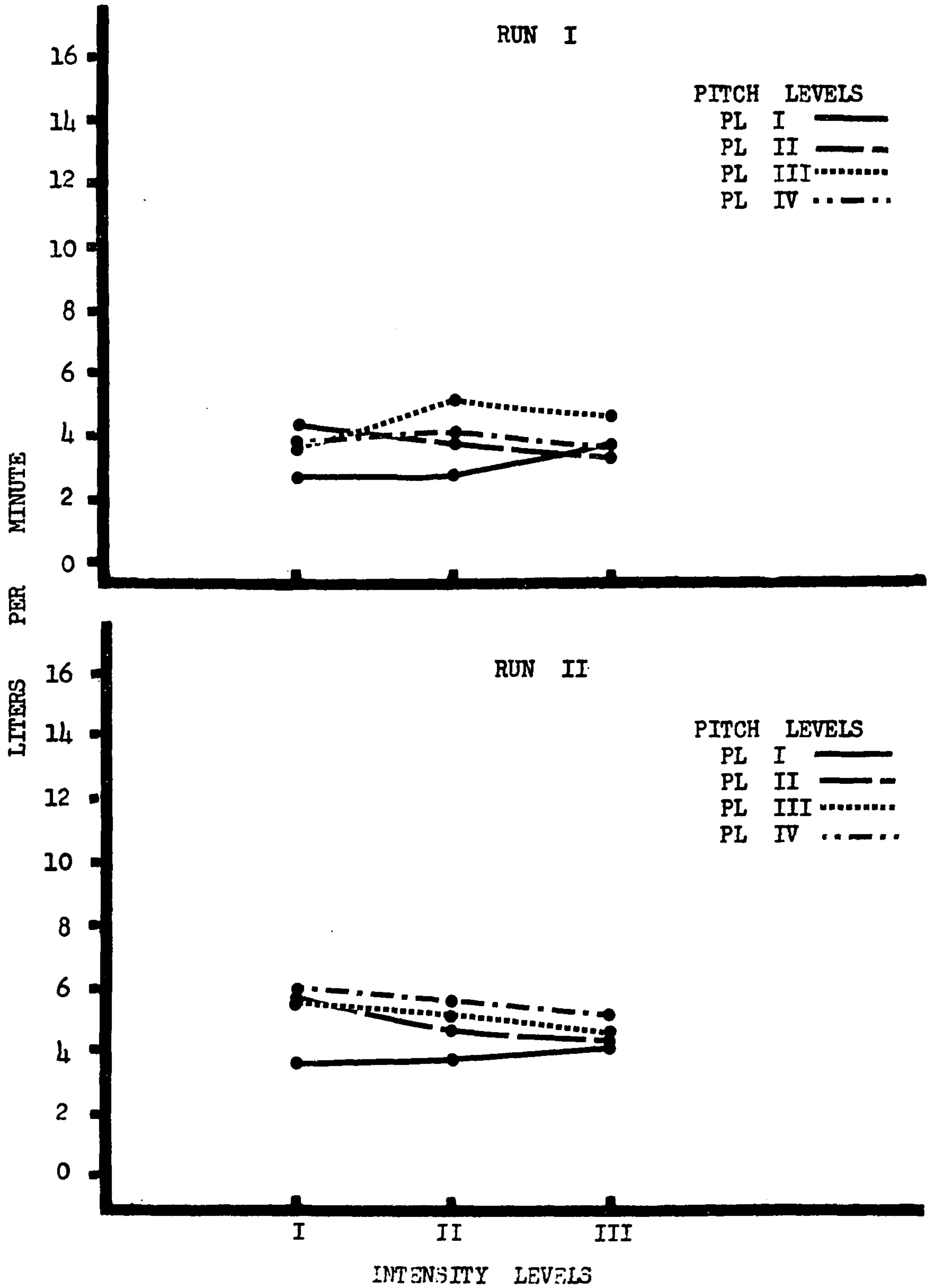


Figure 3.--Nasal air flow means for each of four pitch levels at each of three intensity levels for the two runs when the means are derived over all vowels and coupling conditions.

runs are small, amounting at most to 1.36 lpm between [i] and [u] in Run I. It may also be seen that the rank order of the vowel means differs for the two runs. The variability within runs is relatively large; standard deviations range from 3.49 lpm for [ɑ] in Run II to 5.85 lpm for [i] in Run II. Differences in the subject's performance in the two runs and the variability evident within runs do not support the presence of a difference in mean oral flow rate among the vowels studied.

TABLE 5

ORAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF THREE VOWELS DERIVED OVER ALL PITCH LEVELS, INTENSITY LEVELS, AND COUPLING CONDITIONS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Vowels | | [i] | [ɑ] | [u] |
|---|---|---|---|---|
| Run I | Means | 9.68 | 10.52 | 11.04 |
| | SDs | 3.89 | 3.75 | 4.20 |
| Run II | Means | 11.28 | 11.21 | 10.11 |
| | SDs | 5.85 | 3.49 | 4.67 |
| Runs combined | Means | 10.48 | 10.87 | 10.56 |
| | SDs | 5.03 | 3.64 | 4.47 |

The mean nasal air flows and standard deviations associated with the production of each of three vowels, taken over all intensity levels, pitch levels, and coupling conditions are presented in Table 6. Inspection of Table 6 reveals that the rank order of the nasal air flow means in both runs is [i], [u], and [ɑ], in order of decreasing flow. The means in Run II are slightly, but consistently, higher than those of Run I.

TABLE 6

NASAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF THREE VOWELS DERIVED OVER ALL PITCH LEVELS, INTENSITY LEVELS, AND COUPLING CONDITIONS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Vowels | | [i] | [ɑ] | [u] |
|---|---|---|---|---|
| Run I | Means | 4.35 | 2.97 | 3.94 |
| | SDs | 4.[illegible]9 | 3.08 | 3.64 |
| Run II | Means | 5.49 | 4.20 | 5.17 |
| | SDs | 2.83 | 2.23 | 2.85 |
| Runs combined | Means | 4.92 | 3.58 | 4.56 |
| | SDs | 3.62 | 2.76 | 3.32 |

Inspection of the standard deviations indicates a consistently greater variability in Run I than in Run II. Again, the differences among the vowel means in each run are small in relation to the size of the standard deviations. The present data indicate that slightly greater nasal flow rates occurred in the production of the [i] and [u] than for the vowel [ɑ] in each of the two runs.

Vowel-by-Intensity Interaction

Figure 4 presents a plot of the oral air flow means for each of the three vowels at each of the three intensity levels. These means are averaged over all pitch levels and coupling conditions. Examination of the vowel means in Figure 4, at each of the intensity levels, fails to reveal a consistent order among the means for the three vowels at any intensity. These findings are consistent with those previously discussed in relation to the overall vowel effect.

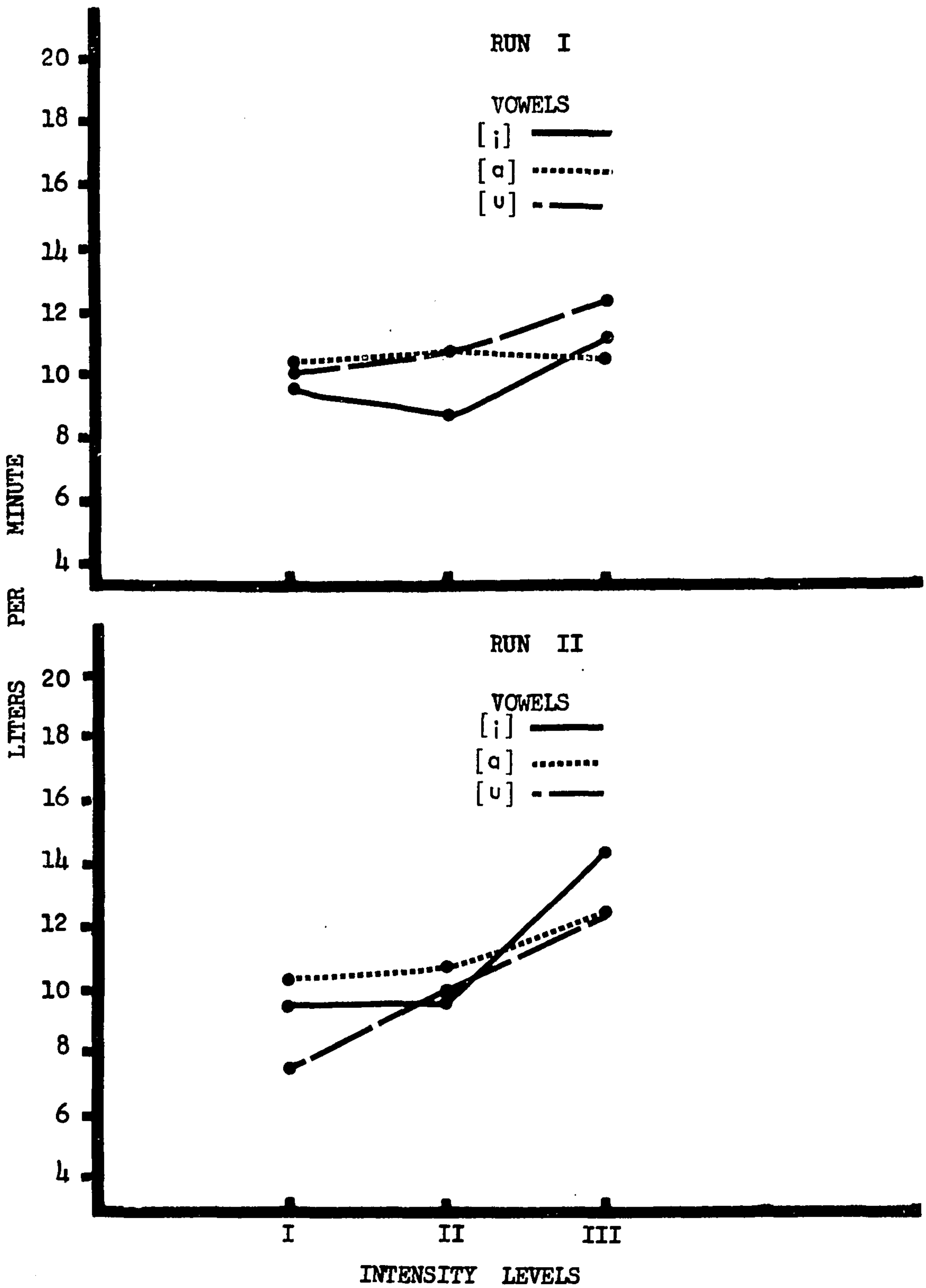


Figure 4.--Oral air flow means for each of three vowels at each of three intensity levels for the two runs when the means are derived over all pitch levels and coupling conditions.

The data in Figure 4 indicates that, as shown in the vocal intensity effect, there is a trend toward increased oral flow from ILs II to III for the vowels [i] and [u] in both runs. While a similar increase is observed for the vowel [ɑ] in Run II, there is little difference in flow between these intensities for [ɑ] in Run I. For the most part, changes in intensity level for ILs I to II are marked by variable changes in flow rate depending on the vowel considered. There is little difference between the mean flows at these intensities for [ɑ] in both runs and for [i] in Run II. A small decline in flow is seen for [i] in Run I. The means for the vowel [u] show a consistent increase from ILs I to II in both runs. These findings suggest that, at lower intensity levels, changes in oral flow with changes in vocal intensity vary as a function of the vowel produced.

Inspection of the nasal air flow means in Figure 5 reveals findings similar to that observed in the overall vowel effect. The means for the vowels [i] and [u] exceed that for [ɑ] at all intensity levels in Run I and at ILs II and III in Run II. An exception to this trend exists at IL I in Run II where there is little difference among the means. The inconsistency between runs again fails to support the existence of a clear relationship between vocal intensity and nasal air flow.

## Vowel-by-Pitch Interaction

Oral air flow means for each vowel, taken over all intensity levels and coupling conditions, at each of the pitch levels, are plotted in Figure 6. Comparison of the vowel means at each of the four pitch levels fails to reveal a consistent pattern among the means for the three vowels at the various pitch levels in the two runs. Examination of the

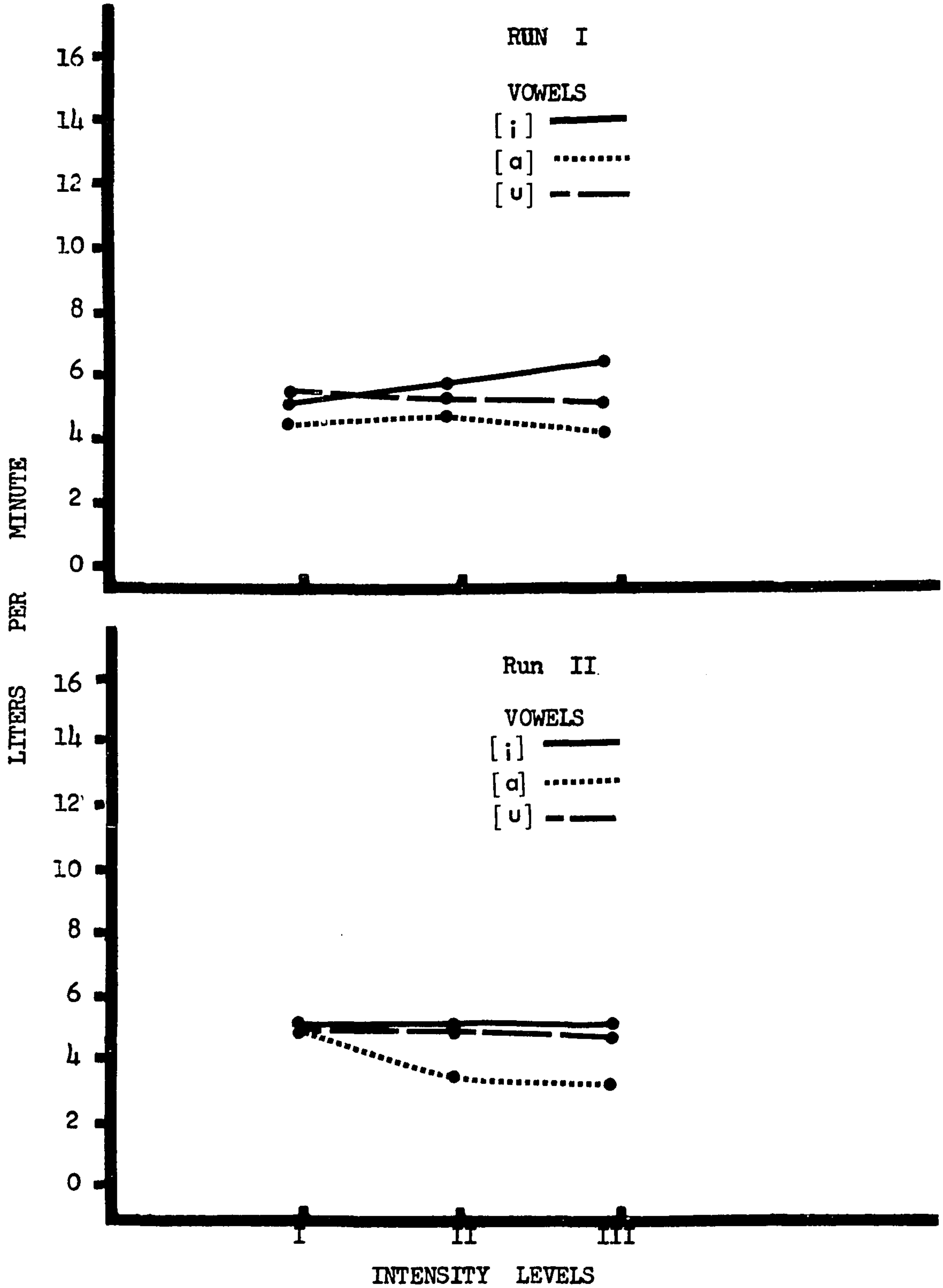


Figure 5.--Nasal air flow means for each of three vowels at each of three intensity levels for the two runs when the means are derived over all pitch levels and coupling conditions.

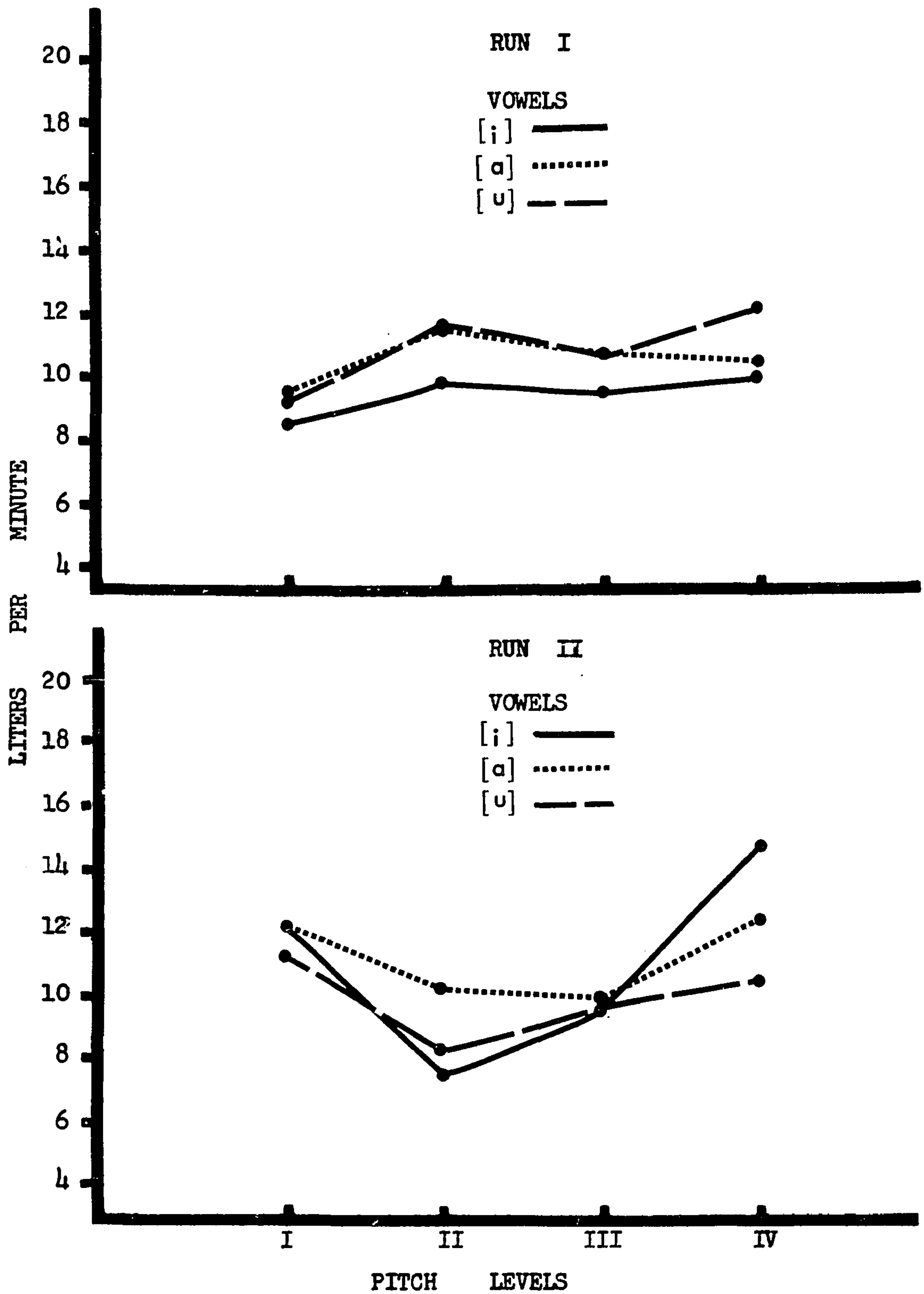


Figure 6.--Oral air flow means for each of three vowels at each of four pitch levels for the two runs when the means are derived over all intensity levels and coupling conditions.

patterns of change in oral air flow with changes in pitch level in the two runs points up this variability. In Run I, all vowels display a slight increase in mean flow from PLs I to II; thereafter, little change in flow occurs as pitch level is increased. In Run II, there is a decline in mean flow from PLs I to II, and an irregular pattern of increased flow as pitch level was increased. This variability in the subject's adjustments to vowel production at these pitch levels seems to constitute an important source of the run differences observed in this study.

Nasal air flow means for the three vowels at each of the four pitch levels are presented in Figure 7. The means are averaged over all intensity levels and all coupling conditions. Inspection of the means in Figure 7 reveals that the rise in nasal air flow with each increase in vocal pitch, found in the overall pitch effect, seems primarily attributable to the progressive increase in nasal flow for the vowel [i] in both runs. Increments in nasal flow with increases in pitch are seen for [ɑ] and [u] from the first to the second pitch level, but as pitch is increased thereafter there is little change or, at times, a decrease in nasal flow rate. These findings suggest that changes in nasal flow with changes in vocal pitch vary as a function of the vowel produced.

The trends in the nasal air flow data in Figure 7 are consistent with those discussed previously in relation to the overall vowel effect; that is, there is a tendency for the vowel [ɑ] to be characterized by lower nasal flow than for the vowels [i] and [u]. This trend is consistently observed at PLs III and IV. While [ɑ] also tends to be associated with lower mean flows at the two lowest pitch levels, there is some inconsistency from run to run.

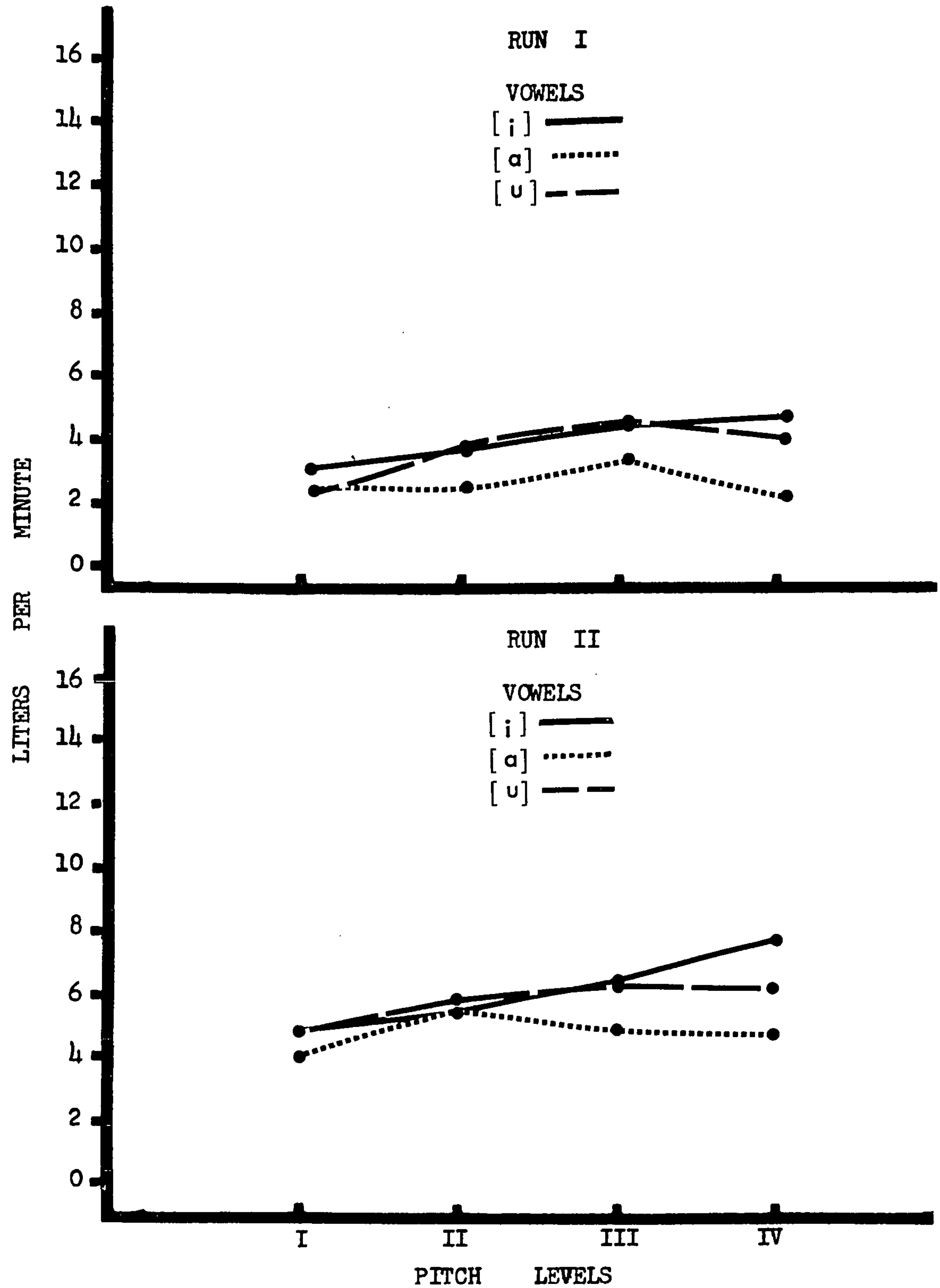


Figure 7.--Nasal air flow means for each of three vowels at each of four pitch levels for the two runs when the means are derived over all intensity levels and coupling conditions.

## Oral-Nasal Coupling

The overall effect of nasal tract coupling on oral air flow is displayed in Table 7. In Table 7, the mean oral air flow and standard deviations found for each of the six coupling conditions are presented for Run I, Run II, and for the Runs combined. The means and deviations are taken over the three vowels and all pitch and intensity levels. Examination of the means in Table 7 reveals some differences in the subject's performance in the two runs. In Run I there is evidence of an irregular decrease in oral flow rate to CC IV, a sharp increase in flow at CC V, and a decline in flow at CC VI. In Run II, a pattern of decreasing oral flow is seen to CC III, with an irregular increase in flow from CC IV through VI. Interestingly, the mean flow in CC VI is the highest flow recorded in Run II, while the mean flow in the same coupling condition is among the lowest flows recorded in Run I. Further, the mean flow in CC V is the highest flow in Run I, while the flow for CC V is among the lowest recorded in Run II. The difference in the pattern of the data for CCs V and VI between the two runs appears to be a major source of the difference between the runs.

Examination of the standard deviations in Table 7 suggests that the variability of the subject's performance within each run is relatively large. This variability seems to be greater during Run II than Run I. The size of the deviations does not appear to follow a particular pattern; that is, larger deviations do not occur consistently in the smaller or the larger coupling conditions. The degree of variability within and between runs precludes a definitive statement concerning the effect of nasal tract coupling on oral air flow.

In spite of this variability, there are certain trends within the data that are of interest and which seem compatible with present information concerning coupling effects. Examination of the means in Table 7 suggests that a decreased oral air flow is usually associated with an increase in the area of nasal tract opening. In both runs, four of the five means in CCs II through VI are lower than that found in CC I (no-coupling). Only in CC V in Run I and CC VI in Run II do the means exceed that in the no-coupling condition and, in these instances, the difference among the means is small.

TABLE 7

ORAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF SIX COUPLING CONDITIONS DERIVED OVER ALL PITCH AND INTENSITY LEVELS AND VOWELS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Coupling Conditions | | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|---|
| Run I | Means | 11.86 | 10.04 | 9.94 | 8.41 | 13.19 | 9.02 |
| | SDs | 4.03 | 2.98 | 3.26 | 3.70 | 4.38 | 3.28 |
| Run II | Means | 12.35 | 11.20 | 7.15 | 11.09 | 10.34 | 13.07 |
| | SDs | 4.12 | 5.70 | 2.87 | 3.17 | 4.82 | 5.09 |
| Runs combined | Means | 12.11 | 10.62 | 8.54 | 9.75 | 11.76 | 11.04 |
| | SDs | 4.08 | 4.58 | 3.37 | 3.70 | 4.82 | 4.73 |

Table 7 also shows that, in both runs, there is a consistent decrease in oral flow from CC I to the intermediate coupling conditions (CC IV in Run I and CC III in Run II). At these areas of opening, .283 $cm^2$ and .126 $cm^2$, respectively, the lowest oral flow rates are recorded. After this low point is reached in each run, there is a trend toward an increase in oral flow to a level that approaches or slightly exceeds that found in the no-coupling condition. This pattern is not entirely consistent. At CC VI, Run I, for instance, the mean flow is only slightly greater than that found in CC IV which is the lowest mean flow recorded in that run.

The differences in the mean flows found at CCs V and VI between the two runs may have special interest. If it is assumed that increases in the area of nasal opening are associated with decrements in oral flow rate, it might be expected that the subject would attempt to compensate for such loss by an increase in expiratory effort. It will be recalled that the experimental task required the subject to maintain uniform intensity levels in the production of vowels in each of the six coupling conditions. If it is assumed that each increase in the area of nasal opening resulted in some increase in the transmission loss of the acoustic signal (6, 34), it can be speculated that the subject was placed in the position of increasing source intensity, by increasing expiratory flow rate and/or glottal resistance, and/or by decreasing vocal tract impedance. The differences that exist among the means in the two runs may be due to the subject's employment of different mechanisms of intensity increase, particularly at the more open coupling conditions.

To study the effect of oral-nasal coupling on nasal air flow, the means and standard deviations for each of the six coupling conditions are presented in Table 8. These means and deviations are derived over all vowels, intensity and pitch levels. Inspection of these nasal air flow means in Table 8 reveals slightly different patterns of flow across coupling conditions in the two runs. In Run I, there is a gradual increase in nasal air flow from CCs I to IV followed by a sharp increase of mean flow in CC V and a sharp decrease in CC VI. However, the mean flow in CC VI, Run I, remains greater than the mean flow for CC IV. In Run II, there is an irregular pattern of increase in nasal flow from CCs I to VI. Comparison of the standard deviations reveals that the greatest variability occurred in CC V, Run I, and CC VI, Run II, which may be related to the higher nasal flow rates in these two conditions.

TABLE 8

NASAL AIR FLOW MEANS AND STANDARD DEVIATIONS FOR EACH OF SIX COUPLING CONDITIONS DERIVED OVER ALL PITCH AND INTENSITY LEVELS AND VOWELS FOR EACH OF TWO RUNS AND RUNS COMBINED

| Coupling Conditions | | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|---|
| Run I | Means | 1.34 | 1.84 | 2.66 | 3.06 | 9.28 | 4.38 |
| | SDs | 1.30 | 2.00 | 1.31 | 1.95 | 4.65 | 2.75 |
| Run II | Means | 3.47 | 4.43 | 3.70 | 4.93 | 5.11 | 8.07 |
| | SDs | 2.29 | 1.79 | 1.64 | 2.25 | 1.86 | 3.25 |
| Runs combined | Means | 2.40 | 3.13 | 3.18 | 3.99 | 7.19 | 6.22 |
| | SDs | 2.14 | 2.30 | 1.58 | 2.31 | 4.11 | 3.54 |

Intensity-by-Coupling Interaction

Oral air flow means for each of the three intensity levels in each of the six coupling conditions are presented in Figure 8. In each run, the means are averaged over all vowels and pitch levels. Examination of the means in Figure 8 also suggests that the effects of changes in vocal intensity on oral air flow rates are not the same in all coupling conditions and in the two runs. In Run II, for example, there is a

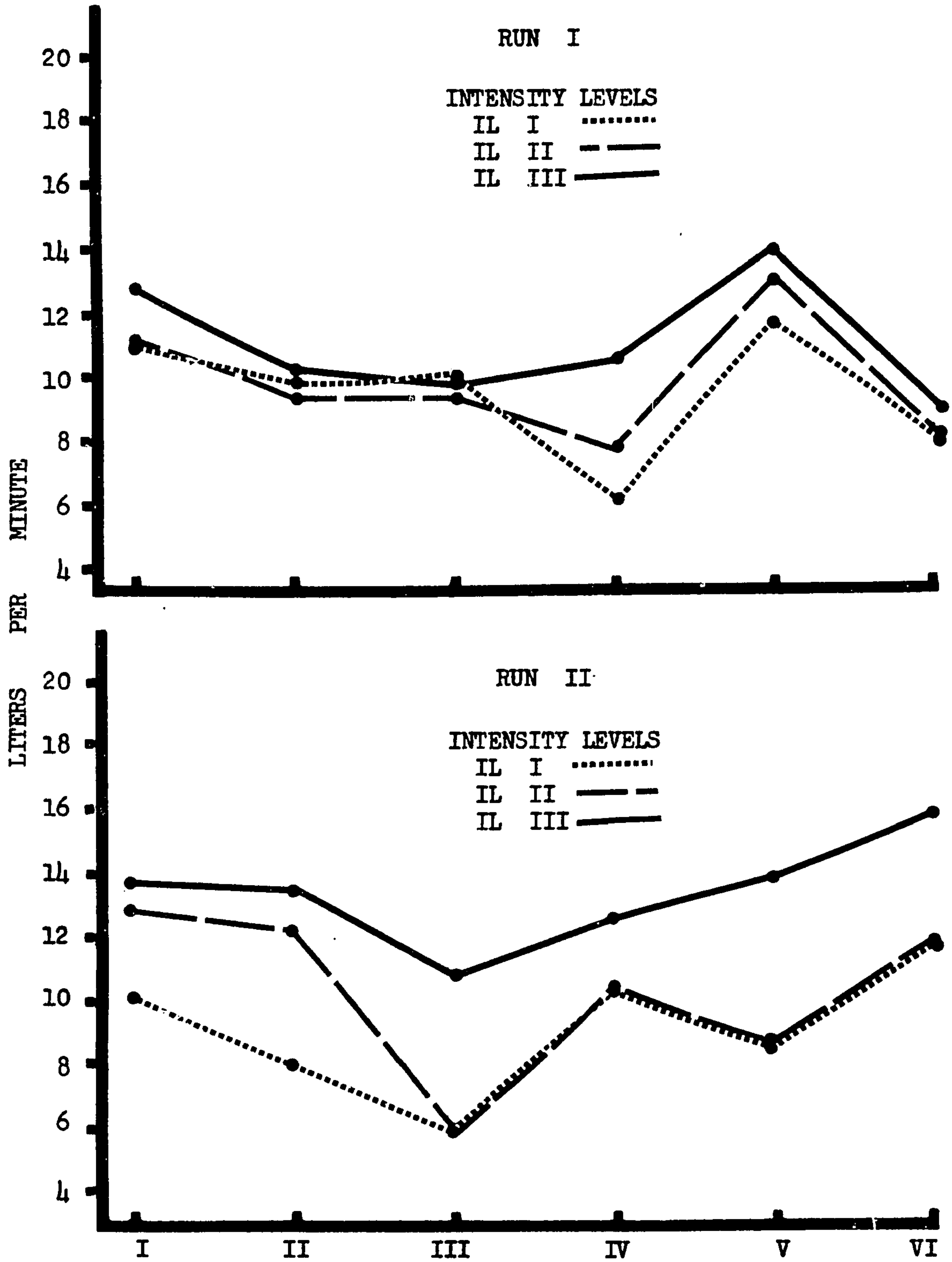


Figure 8.--Oral air flow means for each of three intensity levels at each of six coupling conditions for the two runs when the means are derived over all vowels and pitch levels.

consistently greater mean oral flow rate at IL III than at ILs II and I in all coupling conditions. In CCs I and II, the means at IL II exceed those at IL I, but the flow rates at these intensities are almost identical in succeeding coupling conditions. During Run I, the mean flow rate at IL III exceeds those at ILs II and I in only four of the six coupling conditions, and in these instances, the differences among the means are small. The mean flow rates at ILs I and II are similar in all coupling conditions.

The above findings are consistent with the trends previously reported in relation to the overall intensity effect; that is, there tends to be greater oral air flow at IL III than at ILs I and II. This trend is observable in most coupling conditions in the two runs. The data also suggest that there is little difference in the oral flow rates at ILs I and II. The slightly greater mean flow rates at ILs II than I seen in Table 7 for the runs combined are most likely due to the differences in mean flow between those intensity levels in CCs I and II in Run II. In most other instances, the flow rates at these intensities are quite similar. Thus, while the present data shows that greater oral flow rates tend to be associated with the highest intensity level, the relationship between oral flow and vocal intensity can be seen to be variable between runs and among coupling conditions.

It is quite possible that the subject varied in the extent to which he employed an increased expiratory flow rate versus increased glottal resistance in achieving the experimental intensities in each coupling condition. Such changes in the mechanism of increasing oral intensity could well account for the differences observed in the two runs.

It is also possible that, assuming little variation in the mechanism of intensity increase in the two runs, the subject altered the impedance of the oral tract by adjusting tongue height, particularly for the high vowels, or by varying the degree of mouth opening. The present experiment does not permit a cogent explanation as to which of these variables account for the variation in the data.

To examine the effect of increased nasal tract coupling on nasal air flow at each intensity level, the nasal air flow means for the three intensities at each of the six coupling conditions are presented in Figure 9. These means are taken over all vowels and pitch levels. Inspection of the means in Figure 9 reveals findings similar to those reported in the overall intensity effect. That is, no consistent relationship between increased intensity and nasal air flow at any of the coupling conditions is observed. The rank order of the nasal flow means for the three intensity levels in each coupling condition is quite variable between runs.

The present data are compatible with those reported in the discussion of the overall coupling effect. That is, in both runs there is an irregular pattern of increased nasal air flow with increased area of coupling. A major exception to this trend is seen in the nasal flow mean at IL I in Run II where there is little increase in nasal air flow from CCs I through V. It would seem that the high nasal flow mean at IL I in CC I, as opposed to the essentially flat pattern of the means at IL I, Run I, is a major source of the high nasal air flow value observed in the no-coupling condition in the overall coupling effect in Table 8.

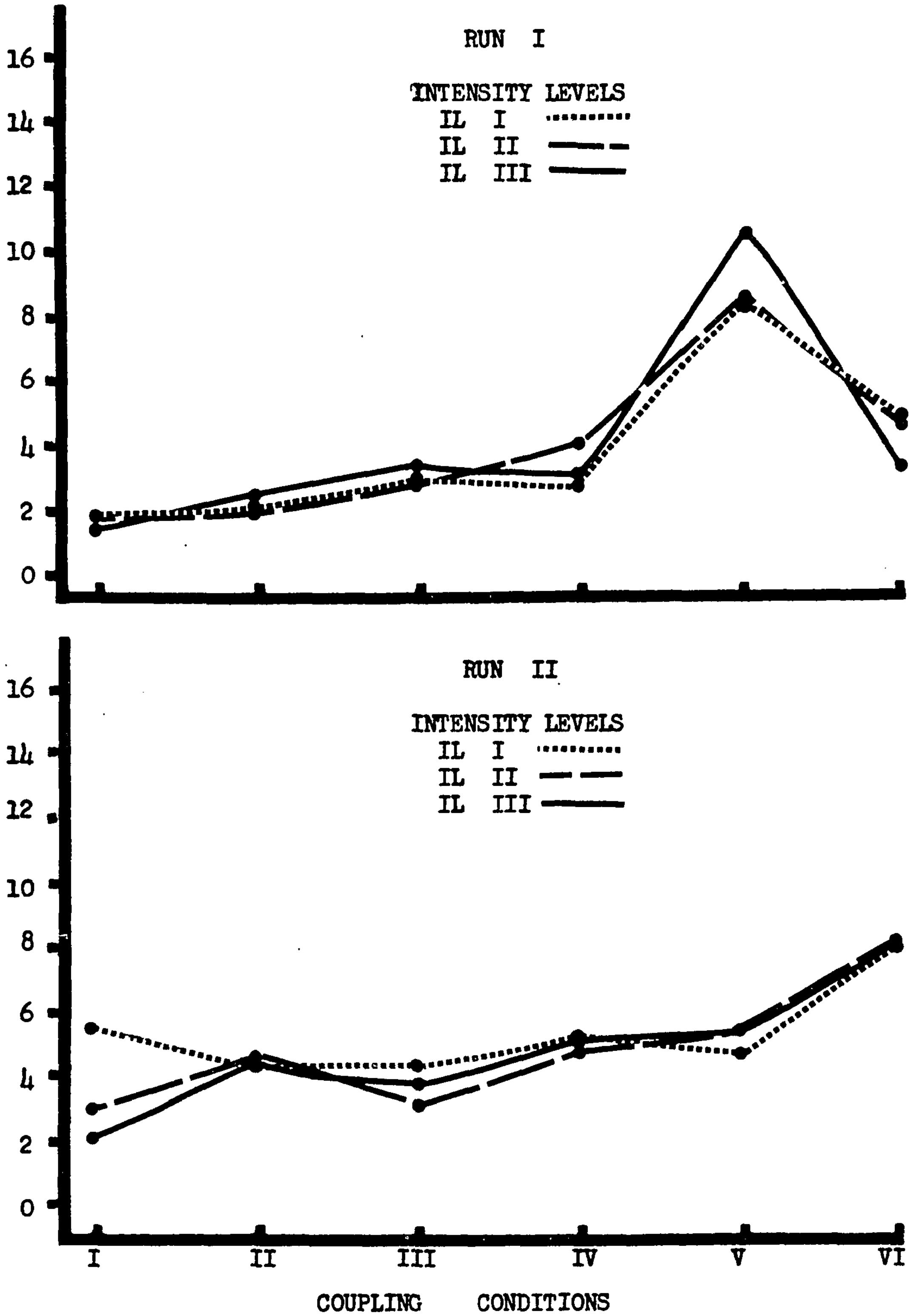


Figure 9.--Nasal air flow means for each of three intensity levels at each of six coupling conditions for the two runs when the means are derived over all vowels and pitch levels.

## Vowel-by-Coupling Interaction

To determine whether the coupling effect is similar for each of the three vowels, oral air flow means for each vowel in each of the six coupling conditions were plotted. These means, averaged over all pitch and intensity levels, are displayed in Figure 10. In general, the coupling effect in each run for each vowel is similar to that reported in previous analyses of the coupling effect. One exception, however, is the pattern of the means for the vowel [i] in Run I. Figure 10 shows that the means for [u] and [ɑ] display an irregular pattern of decreased flow to a low point in CC IV. The means for [i] indicate a decline to CC II, but there is little change in flow as coupling is increased to CC IV. This stands in contrast to the data for Run II in which all vowels, including [i], show an irregular pattern of decreasing flow to a low point in CC III.

In the analysis of the overall coupling effect in Table 7, a major point of difference between the two runs was a sharply elevated mean flow rate for CC V in Run I that is not seen in the same coupling condition in Run II. The data in Figure 10 suggest that the sharply increased flow rate for the vowel [u] in this coupling condition during Run I is a primary source of the run differences. The wider differences among the vowel means in CC V in Run I than in Run II suggest that the influence of the vowel on oral flow varied substantially from run to run.

Figure 10 also shows a dissimilarity in the rank order of the vowel means in each coupling condition between the two runs. This suggests that oral air flow differences among vowels, if present, are obscured by the variability of the subject's performance from run to run.

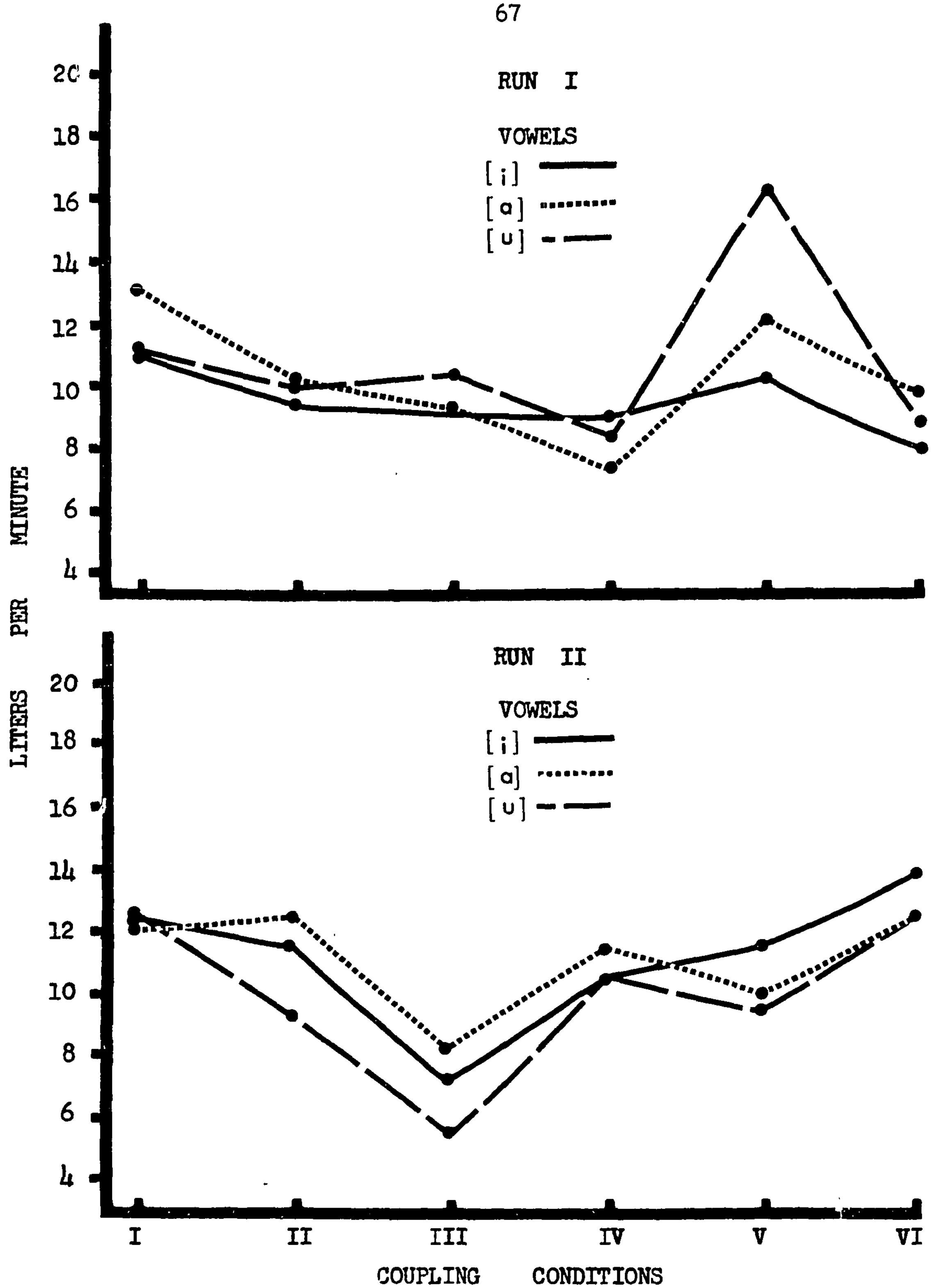


**Figure 10.--Oral air flow means for each of three vowels at each of six coupling conditions for the two runs when the means are derived over all intensity and pitch levels.**

In some respects, the absence of consistent differences among the vowel means is surprising. It might be expected that the low vowel [ɑ], with lesser oral impedance, might be associated with larger oral flow rates than such vowels as [i] and [u] which are characterized by greater oral impedance.

Nasal air flow means for the three vowels in each of the six coupling conditions are presented in Figure 11. Means are averaged over all pitch and intensity levels. Examination of the means in Figure 11 suggests that the coupling effect in each run for each vowel is similar to that observed in the overall coupling effect; that is, there is an irregular pattern of increased flow as the area of nasal tract opening is increased. As observed in the overall vowel effect, the vowel [ɑ] is associated with less nasal flow than the vowels [i] and [u] in most coupling conditions. It is reasonable to assume that the lesser oral impedance involved in production of this low vowel lessens the amount of air that is channeled through the nasal aperture. The high vowels, [i] and [u], on the other hand, with greater oral impedance tend to be characterized by greater nasal flow with the same degree of nasal patency.

## Pitch-by-Coupling Interaction

The mean oral air flow at each of the four pitch levels in each of the six coupling conditions is plotted in Figure 12. In Figure 12, the means are averaged over the three intensity levels and the three vowels. It may be observed that the effects of coupling in Run II are quite similar to those presented in Table 7; that is, there is an irregular pattern of decreasing flow at each pitch level as coupling is increased to CC III and a trend toward increased oral flow as coupling is increased

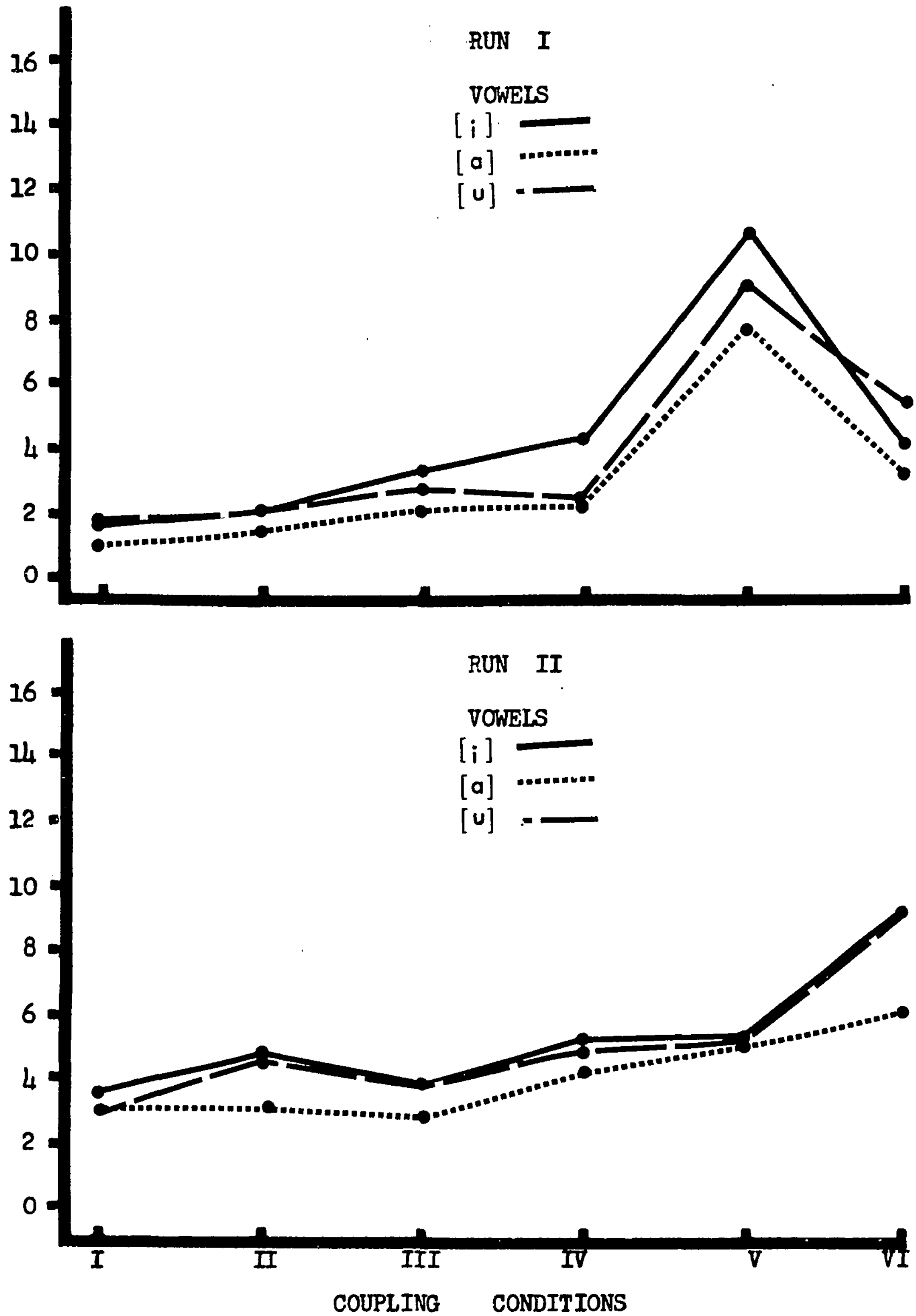


Figure 11.--Nasal air flow means for each of three vowels at each of six coupling conditions for the two runs when the means are derived over all intensity and pitch levels.

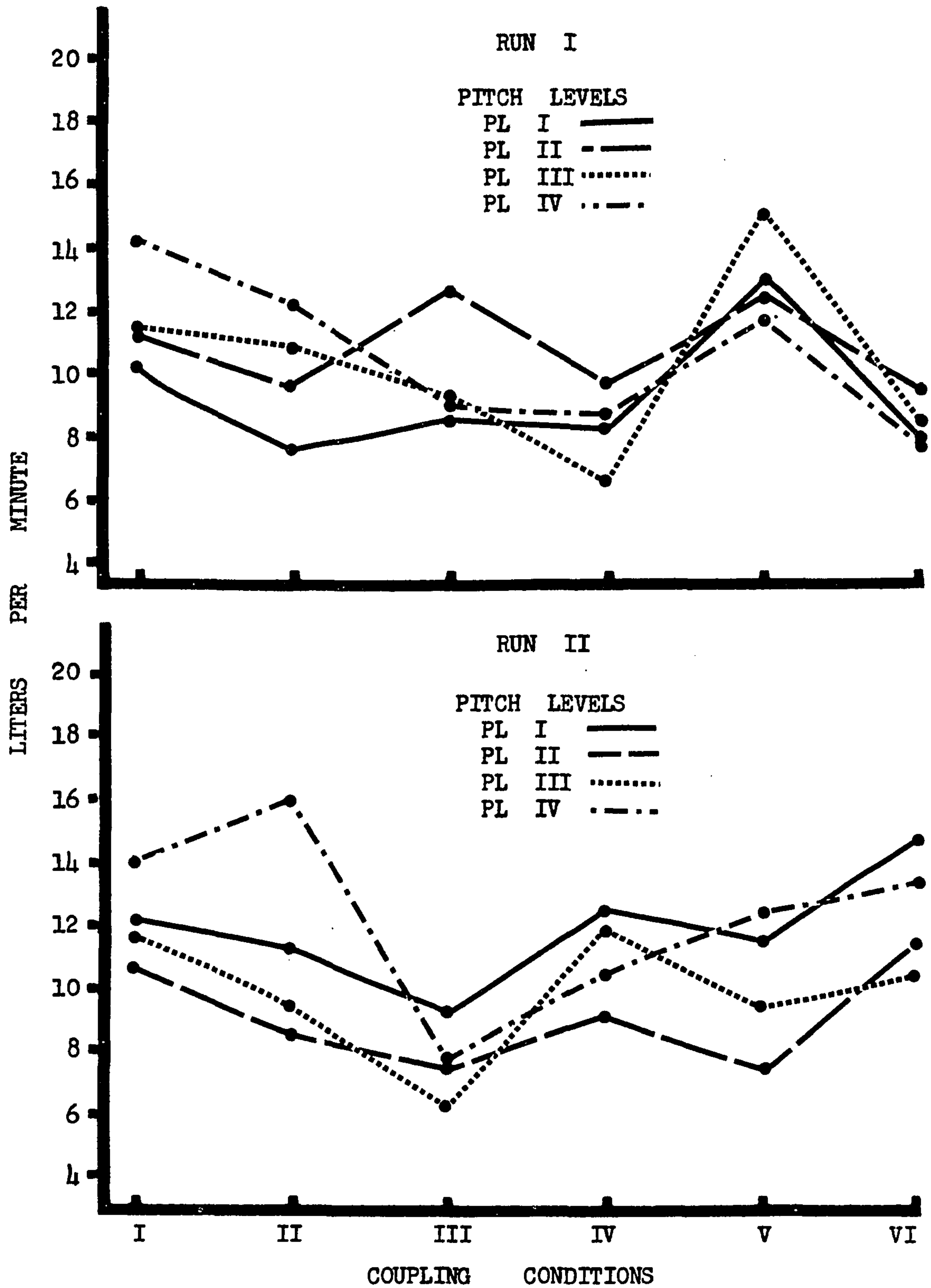


Figure 12.--Oral air flow means for each of four pitch levels at each of six coupling conditions for the two runs when the means are derived over all vowels and intensity levels.

beyond this point. One prominent exception to this trend is seen in CC V at PL II where the mean value is similar to that seen in CC III. The situation in Run I, however, differs somewhat from the trends seen in the overall coupling effect. The pattern of means at PL III and IV follows that seen in the overall coupling effect in Run I. At PLs I and II in Run I, however, the trend is different. In these instances, the low point of oral flow is seen in CC II with a variable pattern of increased and decreased flow in the larger coupling conditions.

Examination of the relationship between pitch level and oral flow in each coupling condition in the two runs fails to reveal a consistent rank order among the means for the four pitch levels. An exception to this generalization is the consistently greater mean oral flow rate at PL IV than at PLs I, II, and III in CCs I and II.

The sharp elevation of oral flow seen in the overall coupling effect in CC V in Run I (Table 7) is, in part, related to high flow rates at PL III in CC V. This rise in flow at PL III, along with the sharply elevated flow for the vowel [u] reported previously, appears to be a primary source of the run differences observed in this experiment. Why this phenomena occurred in the first and not in the second run of the experiment is unknown.

To illustrate the relationship between changes in coupling area and nasal flow rate at each of the four pitch levels, the mean nasal air flows at each of the pitch levels in each of the six coupling conditions are plotted in Figure 13. The means are averaged over the three intensity levels and the three vowels. Examination of the means in each coupling condition shows that, although some variability exists, the overall

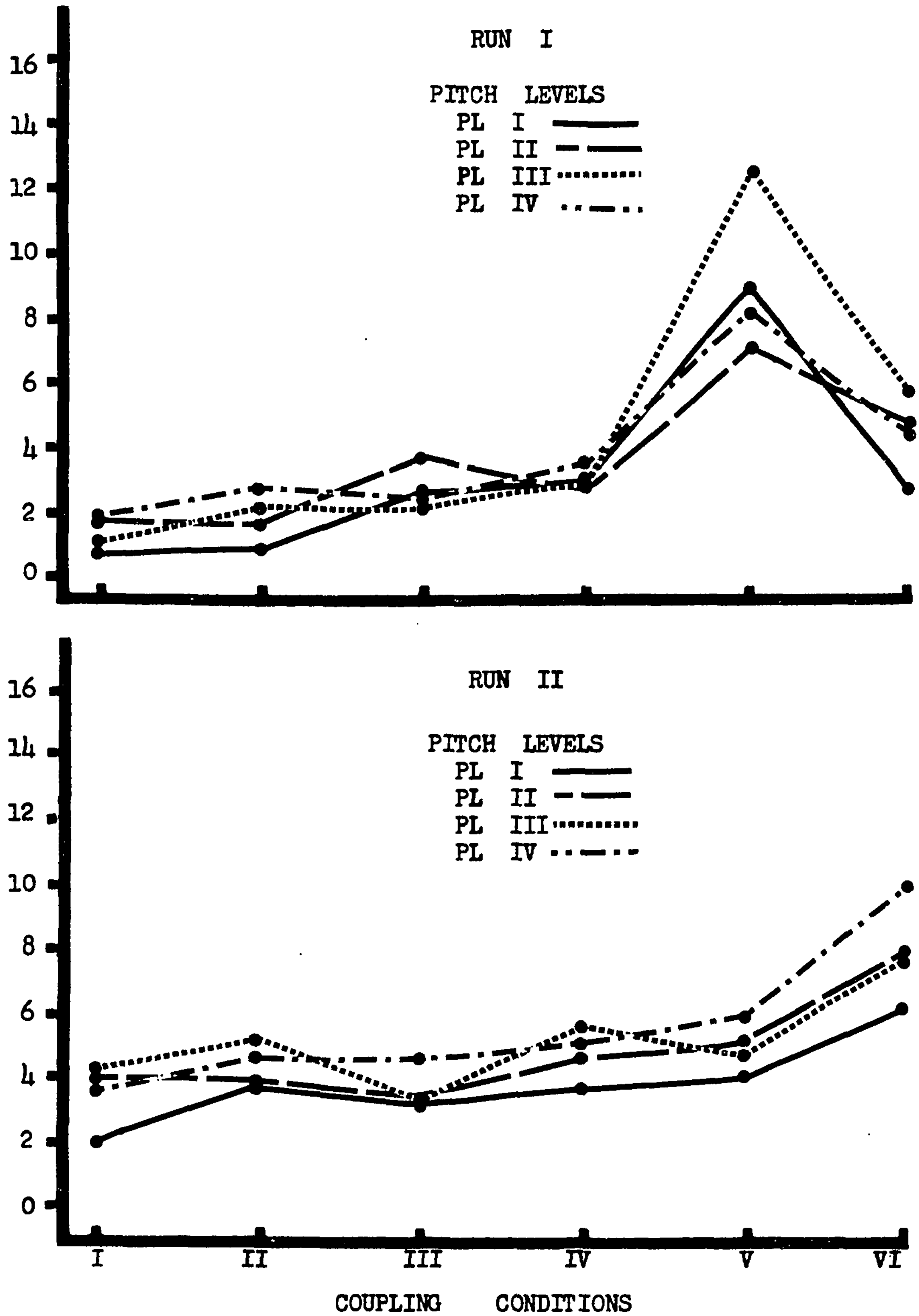


Figure 13.--Nasal air flow means for each of four pitch levels at each of six coupling conditions for the two runs when the means are derived over all vowels and intensity levels.

coupling effect seems to prevail at each pitch level in the two runs. In the pitch main effect it was noted that an increase in nasal air flow was associated with an increase in vocal pitch level. While the means at ILs III and IV tend to be among the highest means, and the mean at IL I tends to be the lowest mean in most coupling conditions in the two runs, there is considerable variation in the data. If a relationship exists between vocal pitch levels and nasal air flow, it is obscured by the variability of the subject's performance from run to run.

### Vowel-by-Coupling-by-Intensity Interaction

In Figures 14 through 16, oral air flow means at each intensity level in each of the six coupling conditions are presented for each of the three vowels for each of the two runs. Means are averaged over all pitch levels. While some variation exists, the means in Figure 14 through 16 show that the effect of coupling on the mean oral air flow for each vowel at each intensity level in Run II is generally similar to that seen in the overall coupling effect; that is, an irregular decline in flow rate to CC III with a trend toward increased flow as coupling area is increased beyond that point. The data in Run I, however, are considerably more variable. Figures 14 through 16 illustrate departures from the trend seen in overall coupling effect which showed an irregular decline in flow to CC IV, a sharp increase in CC V, and a decreased flow in CC VI. This pattern is closely followed by the vowel [ɑ] at all intensities, by [u] at ILs I and III, and by [i] at IL III. The patterns among means at IL I for [i] and IL II for [u], deviate markedly from trends seen in the overall coupling effect.

Figures 14 through 16 generally support the findings of the

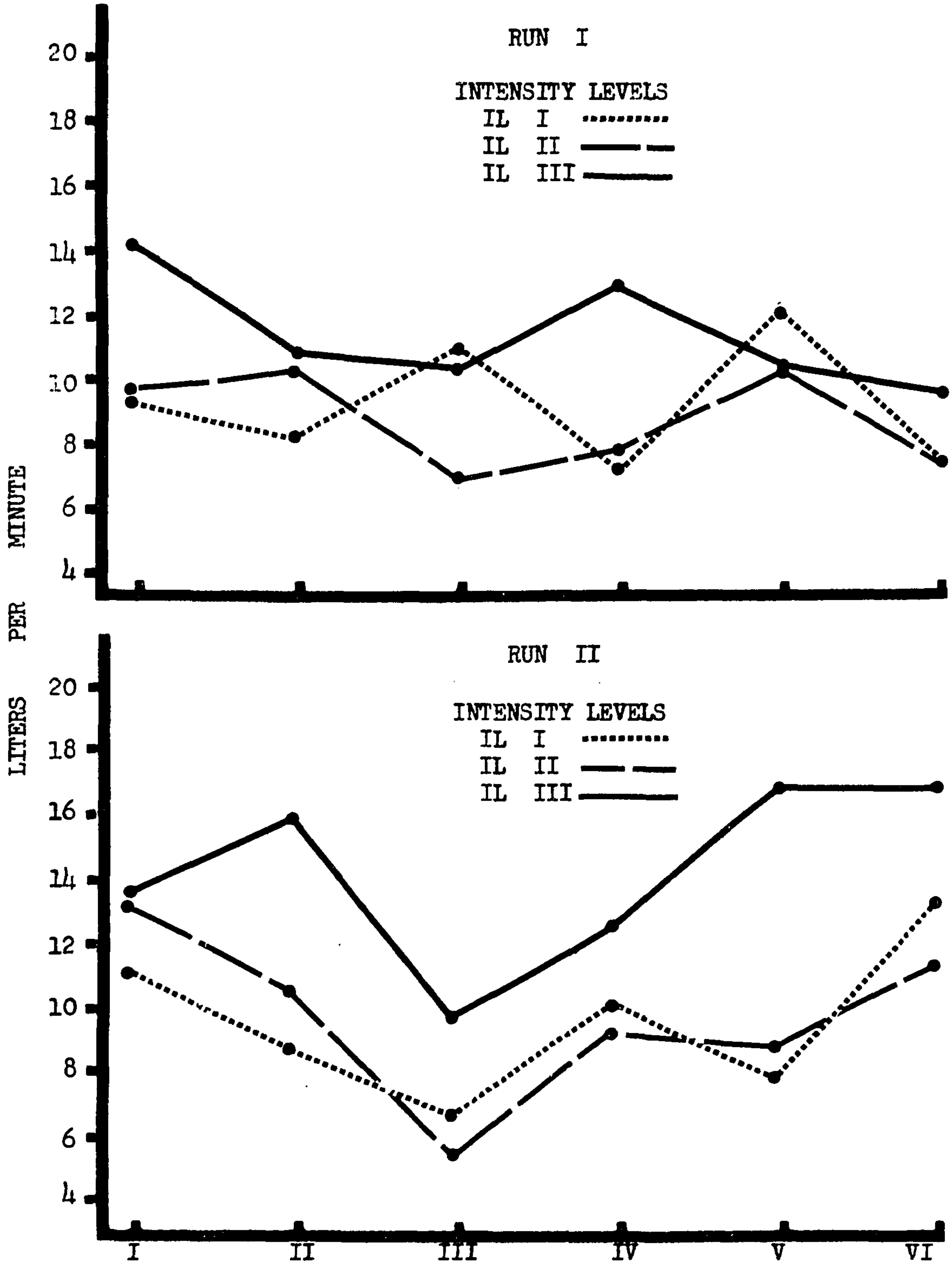


Figure 14.--Oral air flow means for the vowel [i] at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all pitch levels.

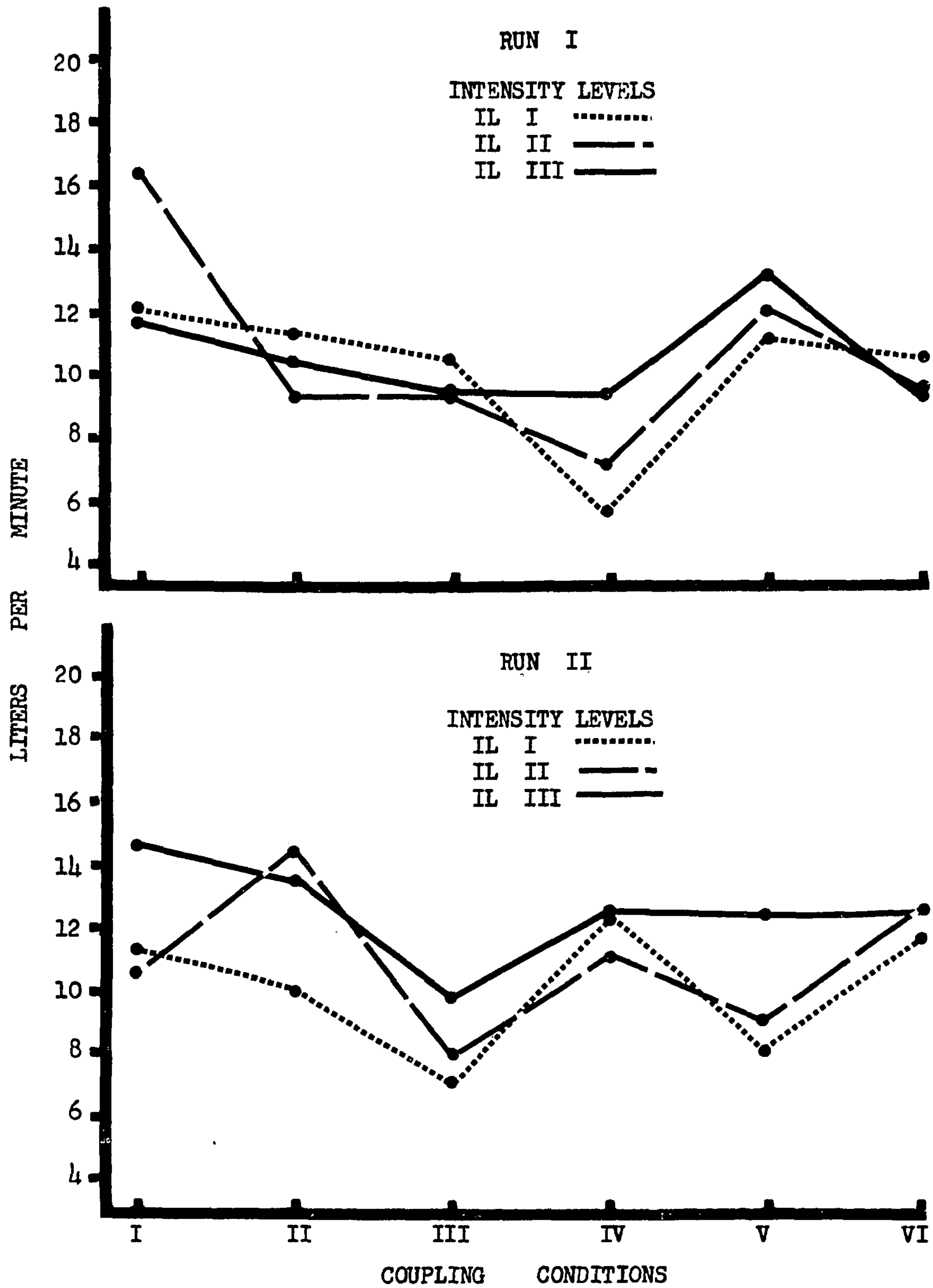


Figure 15.-- Oral air flow means for the vowel [ɑ] at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all pitch levels.

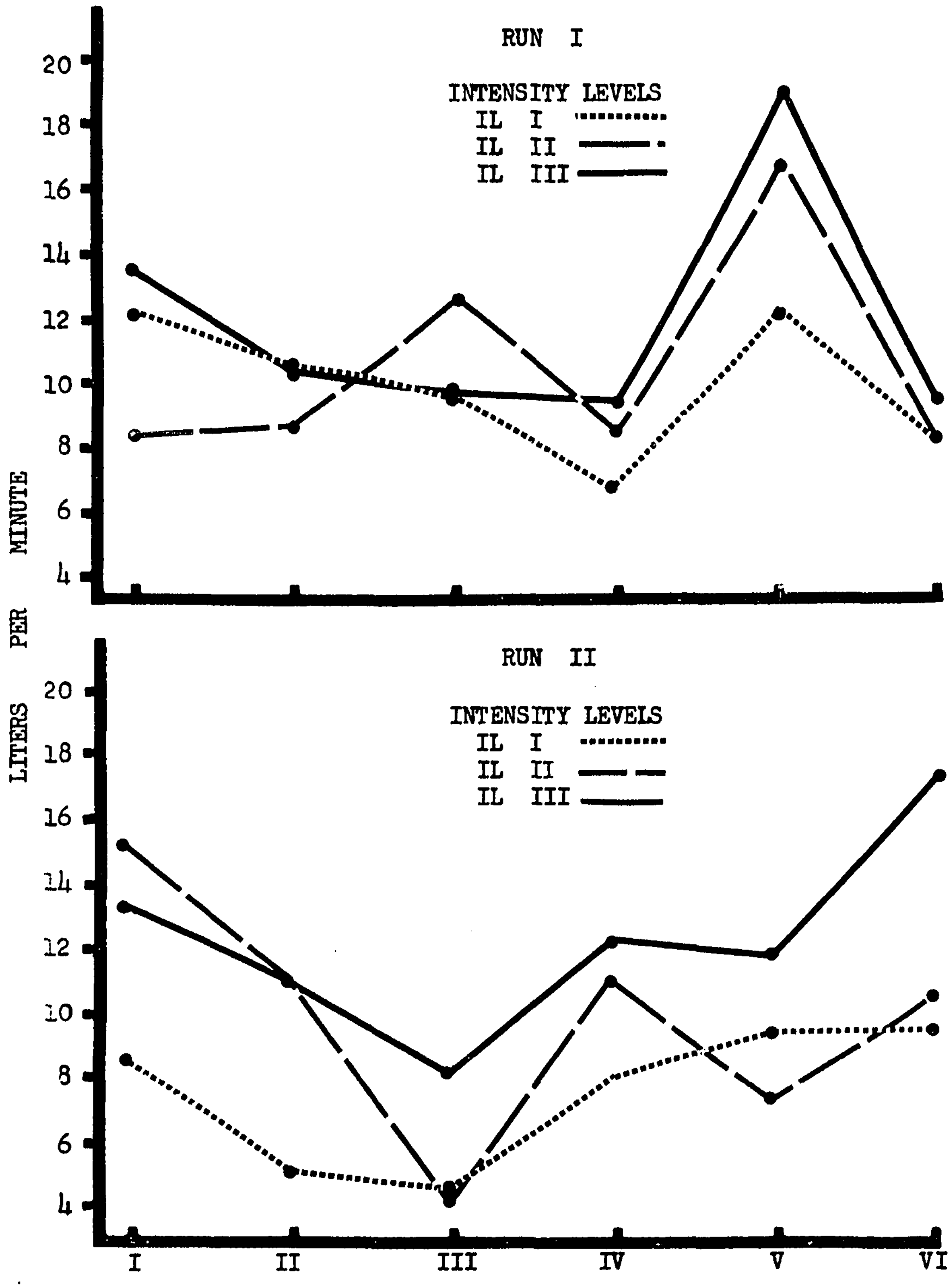


Figure 16.--Oral air flow means for the vowel [ʊ] at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all pitch levels.

overall coupling effect to the extent that there appears to be a decline in oral flow rate to the intermediate coupling conditions (CCs III and IV) followed by a trend toward an irregular pattern of increased flow in the larger coupling conditions. This trend is considerably more evident in the second than in the first run of the experiment. The data also suggest that vowel differences played a more important role in the second run and/or that the subject altered the manner in which he produced vowels to attain the intensity levels used in this experiment.

The finding that increased oral flow rates occur with increments in vocal intensity was reported in the prior analysis of the overall intensity effect in Table 1. This increase in flow is most evident from ILs II to III. Figures 14 through 16 reveal that this intensity effect varies for the three vowels, the six coupling conditions, and the two runs. In Run II, consistently greater oral flow rates are seen at IL III than at ILs II and I only for the vowels [i] and [u]. While IL III is associated with greater oral flow than ILs I and II in several coupling conditions for all vowels, the variability in this relationship among vowels and coupling conditions points to the presence of complex interactions. While these data provide some evidence that greater oral flow is utilized at the highest than at the lower intensities, they also indicate that this relationship is not uniformly seen. It was possible, apparently, for the subject to produce vowels at the 75 dB level, under a variety of coupling conditions, without necessarily employing an elevated oral flow rate above that seen at the lower intensity levels.

Inspection of the rank order of the vowel means in each of the six coupling conditions shows considerable variation from run to run.

This trend is consistent with the finding of the overall vowel effect in Table 5. The data of the present experiment indicate that, if differences in oral air flow rates exist among the vowels studied, the variability between runs, among coupling conditions, and among intensity levels tends to obscure these differences.

In Figures 17 through 19, nasal air flow means at each intensity level in each of the six coupling conditions are presented for each of the three vowels in each of the two runs. Means are averaged over all pitch levels. Inspection of these figures shows that there is a generally progressive, but irregular, increase in nasal flow with increases in coupling area from CC I through CC VI. There are, however, significant exceptions to this trend. Examination of the means at IL I in Run II, for example, reveals a trend toward declining nasal flow from CC I to CC V for [i], little change in flow from CC I to CC IV for [u], and a sharp decline in flow from CC I to CC III for [ɑ]. Similar phenomena may be observed at other intensity levels in both runs. The means at IL II for [i], Run I, and for [ɑ], Run II, evidence little nasal flow change from CC I to CC III and CC IV, respectively. The means at IL III for [i], Run II, show an initial increase from CC I to CC II, but in CC III, Run II, the mean drops to the level seen in CC I. What these patterns reveal is that, while nasal flow tends to increase as the nasal opening increases, this relationship is not inevitable. This apparent lack of a positive relationship between nasal flow rate and aperture size is most clearly seen at the lowest intensity levels and in the first three to five coupling conditions. This finding is not confined solely to these conditions. Possibly the most cogent example of this trend is seen at IL

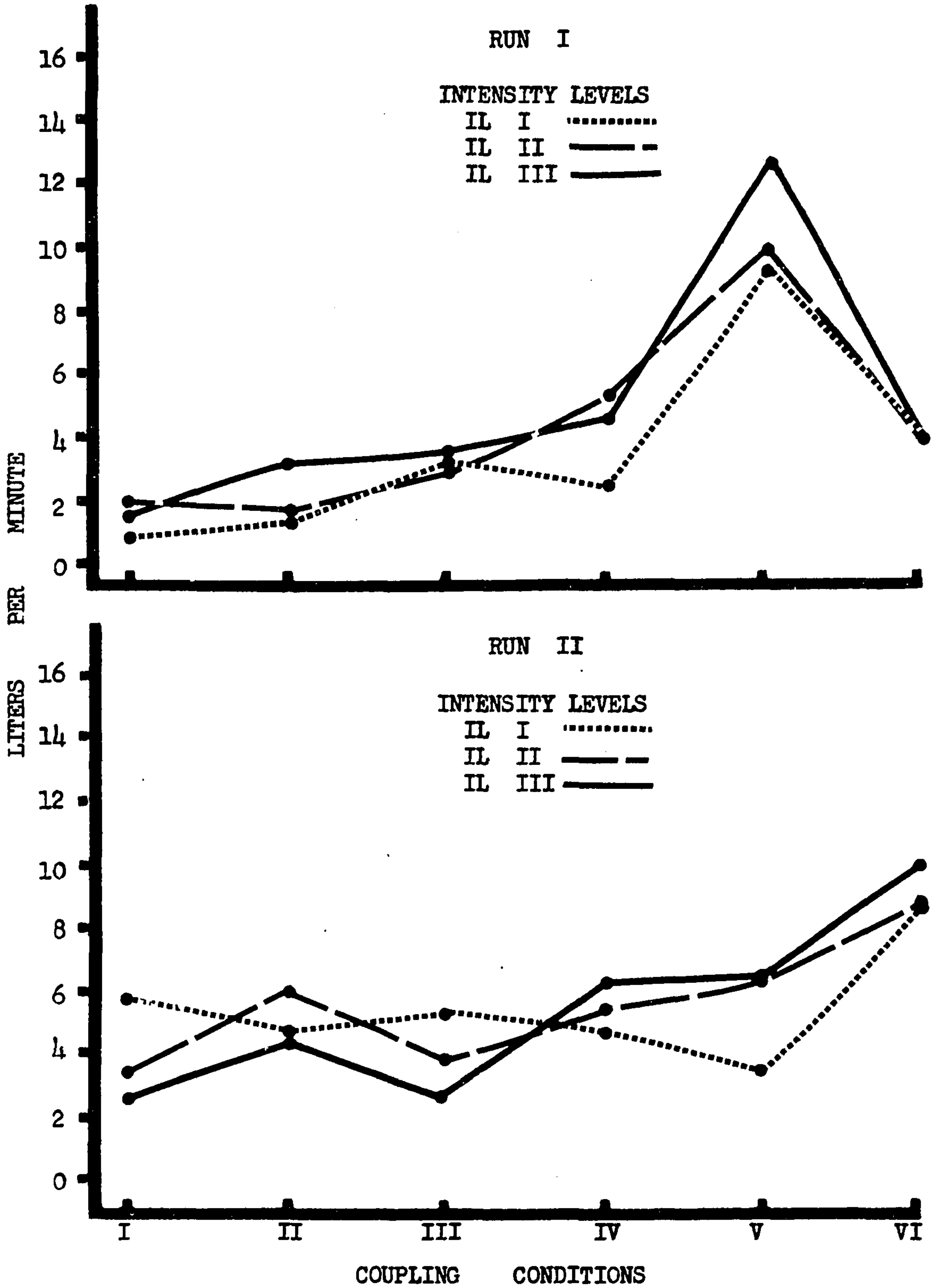


Figure 17.--Nasal air flow means for the vowel [i] at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all pitch levels.

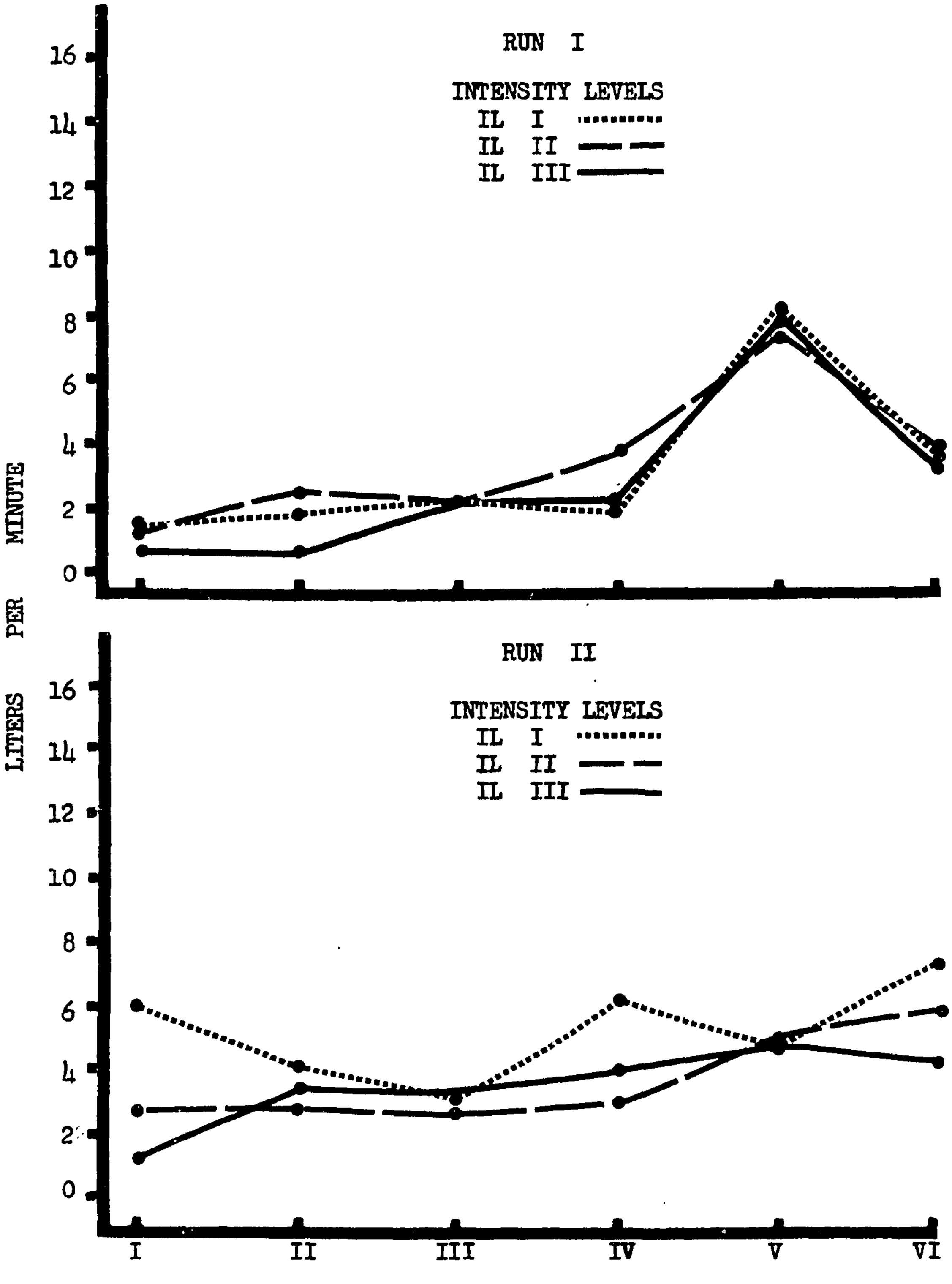


Figure 18.--Nasal air flow means for the vowel [ɑ] at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all pitch levels.

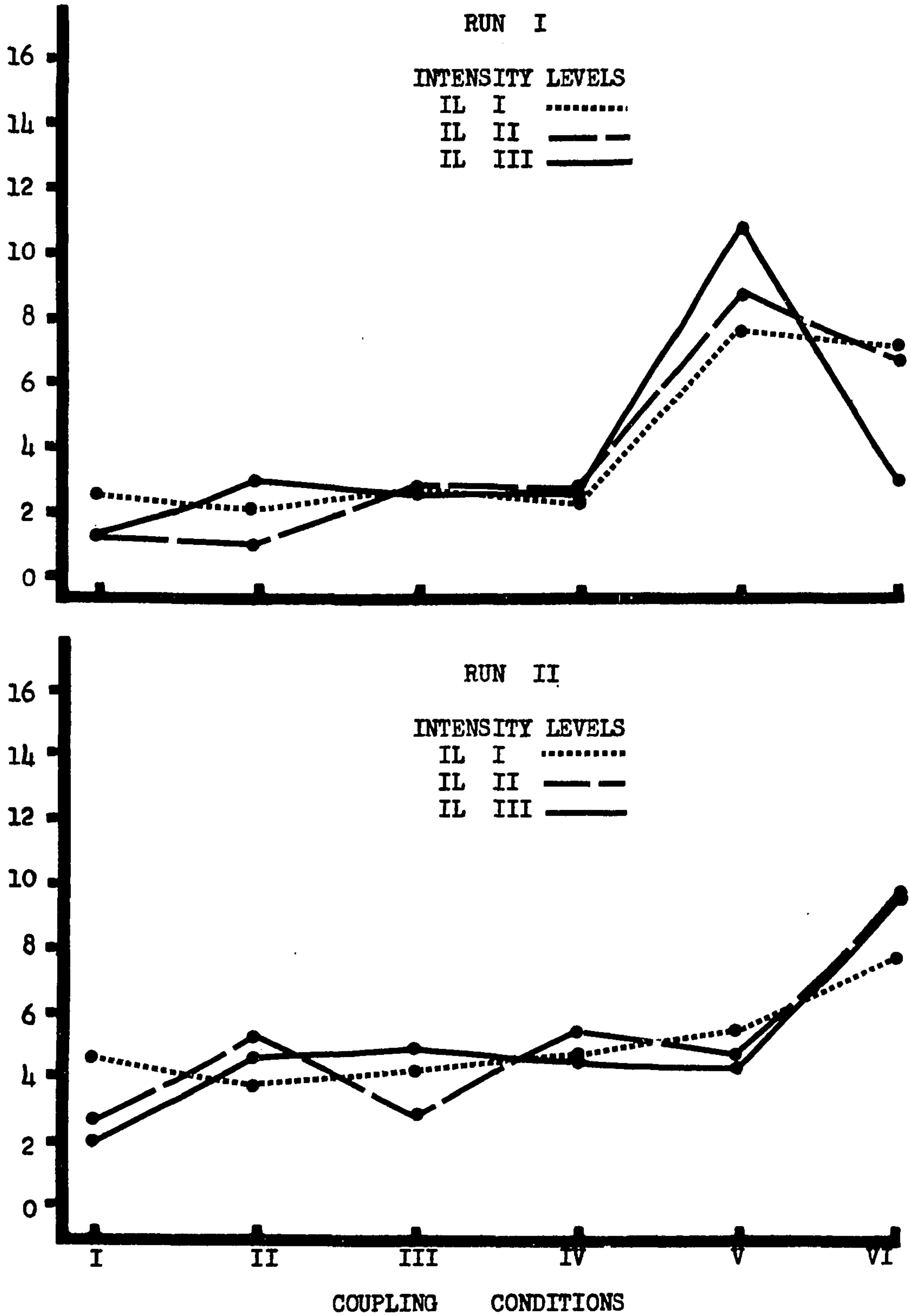


Figure 19.--Nasal air flow means for the vowel [ʊ] at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all pitch levels.

III for CC VI in Run I where the mean nasal flow at the largest coupling condition is similar to that seen at CC II.

The above findings suggest that the effects of coupling on nasal air flow are related to the physiologic mechanisms by means of which intensity changes are effected. The variability in the relationships seen from run to run in the same coupling condition suggests that the same mechanisms were not employed by the subject in repeated runs, nor were they employed consistently within runs across coupling conditions. This interaction raises considerable doubt concerning the use of nasal air flow as an index of nasopharyngeal valving.

The effects of vocal intensity on nasal air flow, as indicated in previous analyses, are not consistent either within or between runs. Examples of this inconsistency are easily available. Increased nasal flow with increased intensity is seen for the vowel [i] in CCs IV, V, VI in Run II and in CC V in Run I. For [u], this relationship is seen in CC V in Run I and CC VI in Run II. An inverse relationship between intensity and nasal flow, however, can be seen for [i] in CC I, Run I; for [u] in CC VI, Run II and for [u] in CC I in both runs; and for [ɑ] in CC I in both runs, and in CC VI in Run II.

While not easily visualized in Figures 17 through 19, the data indicate consistently lower nasal air flow rates in production of [ɑ] than [i] in all except one coupling condition, when comparisons are made at the same intensity level. Mean flow rates for [ɑ] are also usually lower than [u]; in only four instances (CC V, IL I; CCs II and IV, IL II; and CC VI, IL III) is this relationship altered. This finding is consistent with previous analyses which indicated a lower nasal flow during production of the low rather than the high vowels.

Pitch-by-Coupling-by-Intensity Interaction

In Figures 20 through 23 the oral air flow means at each intensity level in each of the six coupling conditions are presented at each of the four pitch levels used in this study. Means are averaged over all vowels. While there is evident variation among the data at each pitch level, Figures 20 through 23 show that the patterns among the means in Run II are generally similar to that shown in this run in the overall coupling effect; that is, an irregular decrease in flow to CC III is observed, with a trend toward increased flow as coupling area is increased beyond this point. Exceptions to this trend occur primarily at PL III, IL II and at PL IV, IL III where an increased flow is seen from CC I to CC II.

The overall coupling effect in Run I revealed an irregular decrease in flow to CC IV, a sharp increase in CC V and a decline in flow in CC VI. It can be seen that at PL I and PL II in Run I, Figures 20 and 21, the pattern of the means across coupling conditions differs from that observed in the coupling main effect. This is particularly true at PL II where the pattern of the means is quite irregular with variable increases and decreases in flow in the various coupling conditions. At PL I, IL I, it can be seen that there is little, if any, change in flow rate across coupling conditions. Only at PL III is the trend of the coupling main effect seen at all of the intensity levels. At PL IV, the overall coupling effect obtains only at IL I and, to an extent, at IL III.

The above data generally support the findings of the coupling main effect to the extent that, at least in one run at each pitch level,

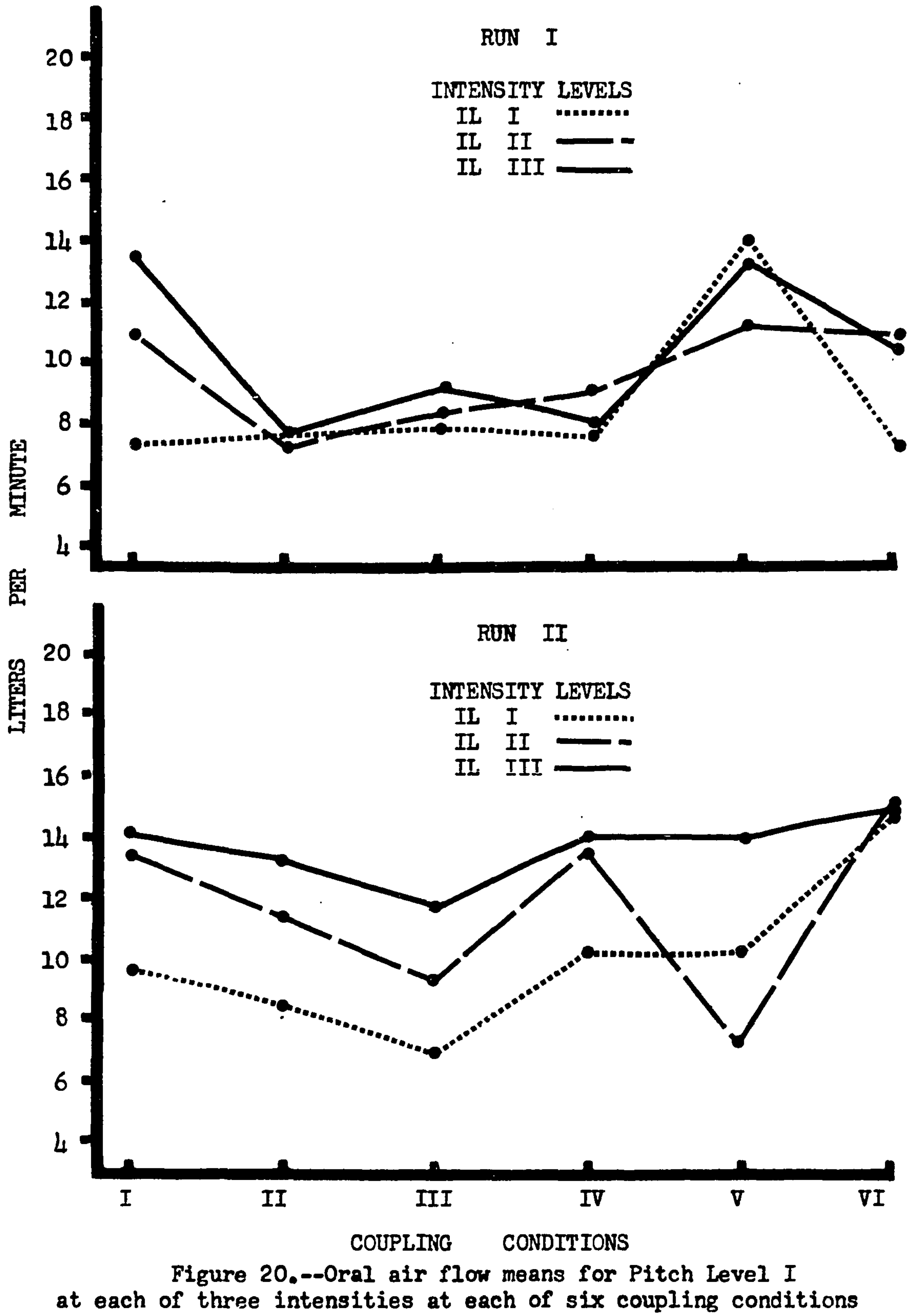


Figure 20.--Oral air flow means for Pitch Level I at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

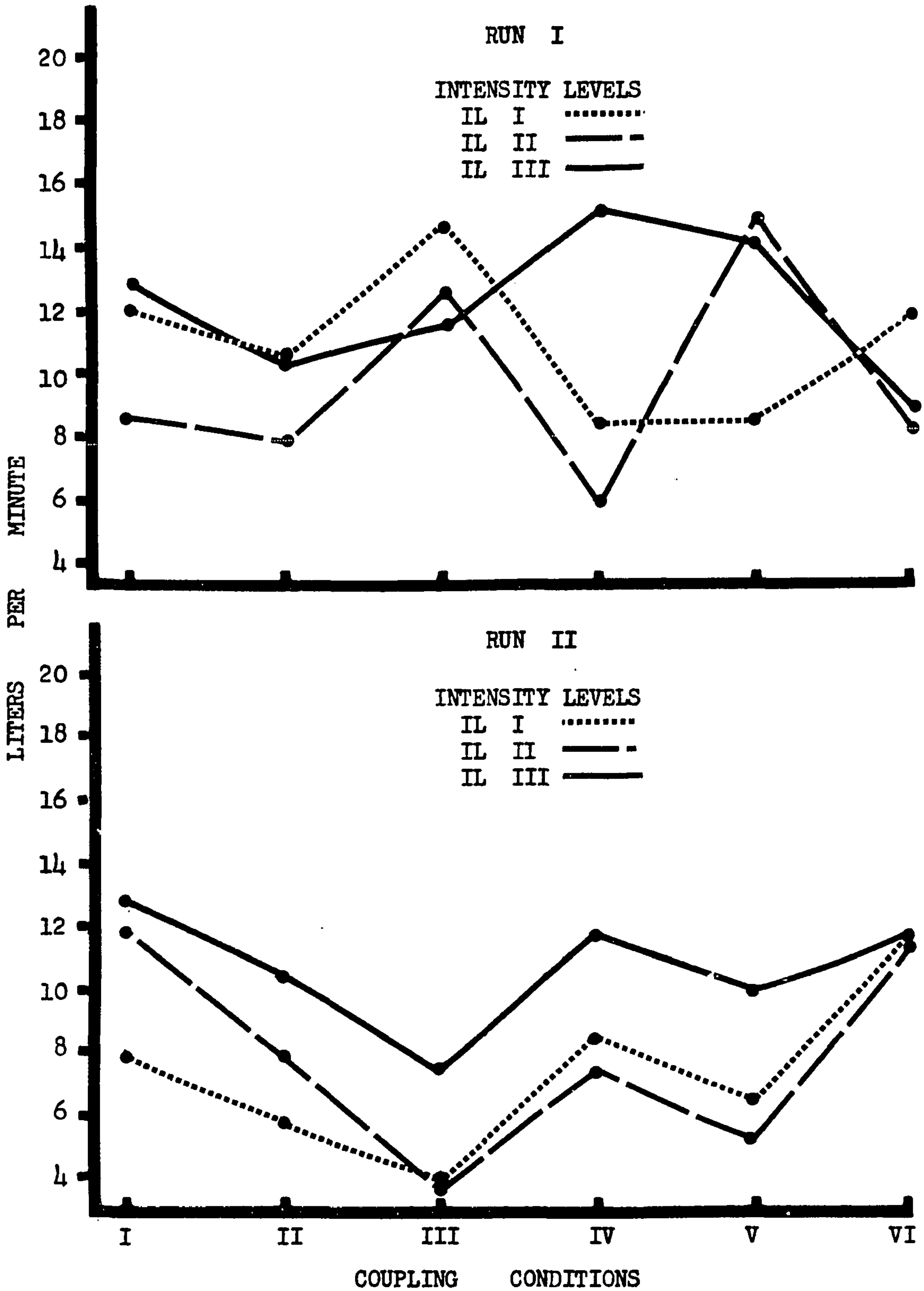


Figure 21.--Oral air flow means for Pitch Level II at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

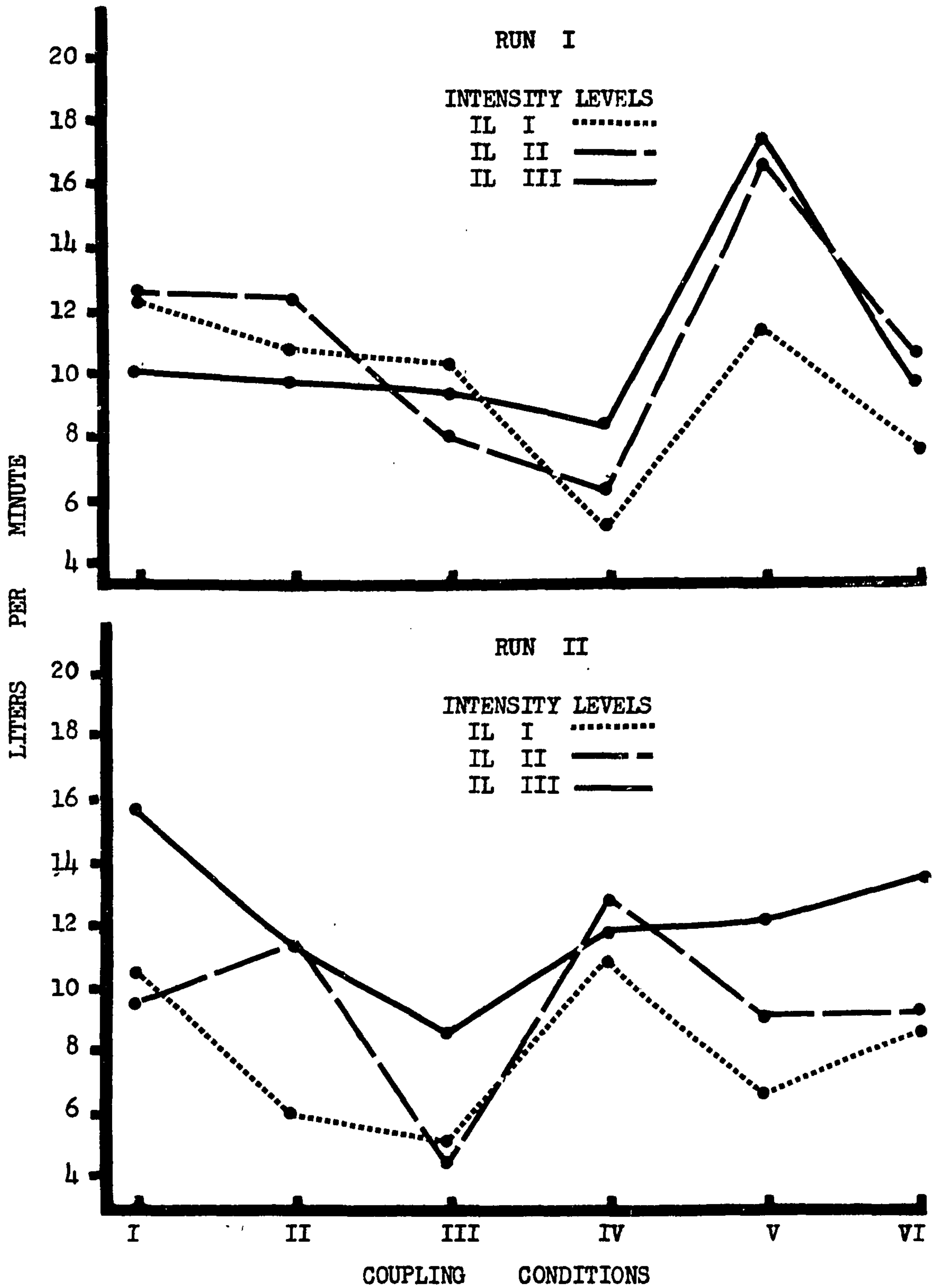


Figure 22.--Oral air flow means for Pitch Level III at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

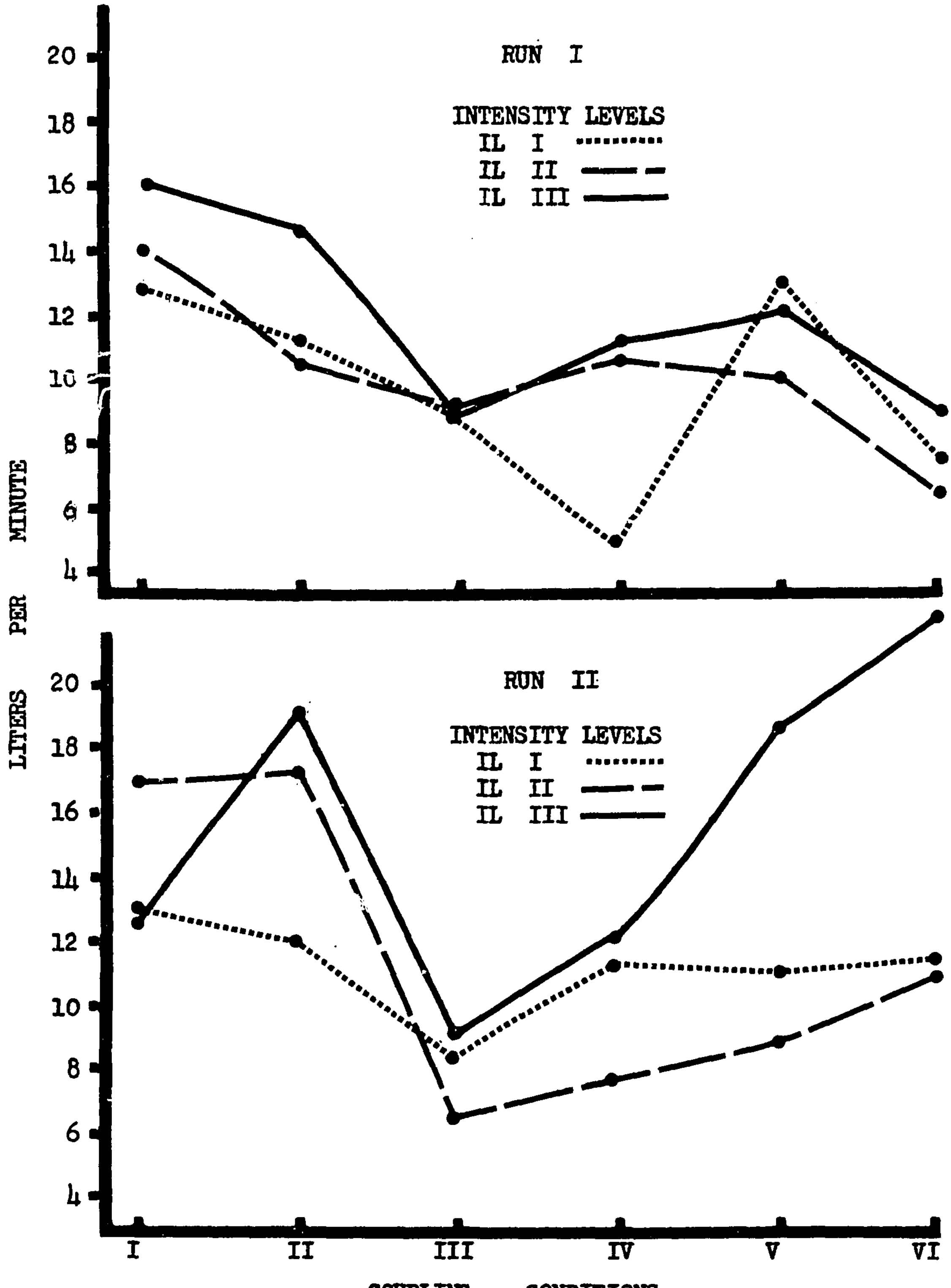


Figure 23.--Oral air flow means for Pitch Level IV at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

there is a trend toward a declining oral flow rate from CC I to the intermediate coupling conditions with a trend toward increased flow as coupling is further increased. The data also show, however, an evident variability between runs, particularly at the lower pitch levels, suggesting that the subject compensated in a different manner for coupling effects in the two runs and that these compensations varied as a function of the pitch and intensity levels involved.

The positive relationship between oral air flow and vocal intensity levels, suggested by the coupling main effect, is not uniformly seen throughout the present data. Inspection of Figures 20 through 23 indicates that, with but few exceptions, the means at IL III exceed those at IL I and IL II at all pitch levels in the six coupling conditions during Run II. The relationship between the means at IL I and IL II is quite variable at the four pitch levels in the six coupling conditions. In Run I, the data do not appear to follow a consistent pattern. The means at IL III do not consistently exceed those at IL I and IL II in the six coupling conditions at the four pitch levels. The relationship among means at IL I and IL II is also variable and reveals no consistent pattern.

The data in Figures 20 through 23 also tend to support the findings of the pitch main effect; that is, there is no consistent relationship between oral air flow and vocal pitch level at each of the four intensity levels in all coupling conditions. While the relationships cannot be seen clearly in the figures, examination of the data suggests that a relationship between vocal pitch and oral air flow may exist in CC I and CC II in both runs of the experiment. Examination of the means in these coupling conditions indicates that the mean oral flow rate at PL IV exceeds that at PL I at each of the three intensity levels in the two runs. The only exception to this trend exists at IL III in CC I during the second run. Since these coupling conditions fall within the range of velar competence, this finding may suggest that a vocal pitch and oral flow relationship exists in subjects with a normal velar valving apparatus.

In Figures 24 through 27, nasal air flow means are presented at each of the three intensity levels for each of the four pitch levels for each of the two runs. Means are averaged over all vowels. Inspection of these figures shows that, while some variation exists, there is an irregular increase in nasal flow rate as the area of coupling is increased from CC I to CC VI. In general, the increases in nasal flow tend to be greater in the larger than in the smaller coupling conditions.

It is also apparent that increasing the size of the nasal opening at a given pitch and intensity level does not necessarily result in an increase in nasal flow. There are numerous examples of instances where the nasal flow mean at a smaller coupling condition exceeds that at a larger coupling condition. Such instances do not deny the relationship between the area of nasal opening and nasal flow but they do suggest that other factors than coupling area influence nasal flow rate. It seems likely, for example, that the elevated nasal flow rates in CC V in Run I are caused by factors other than the size of the nasal port. Examination of the oral flow rates in this coupling condition during Run I indicates that greater oral flow rates were uniformly employed in this condition than in the other conditions in this run. It seems quite pos-

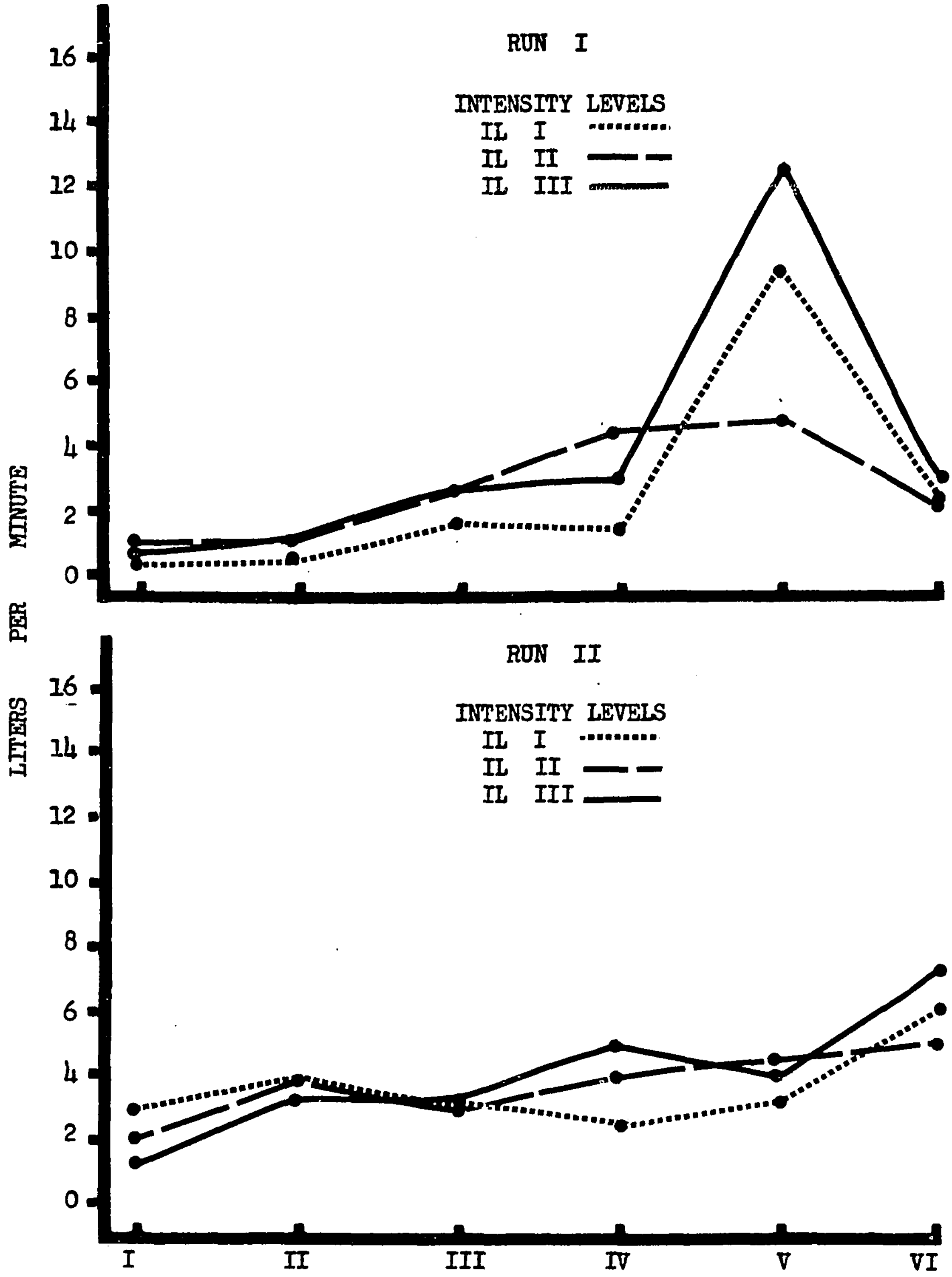


Figure 24.--Nasal air flow means for Pitch Level I at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

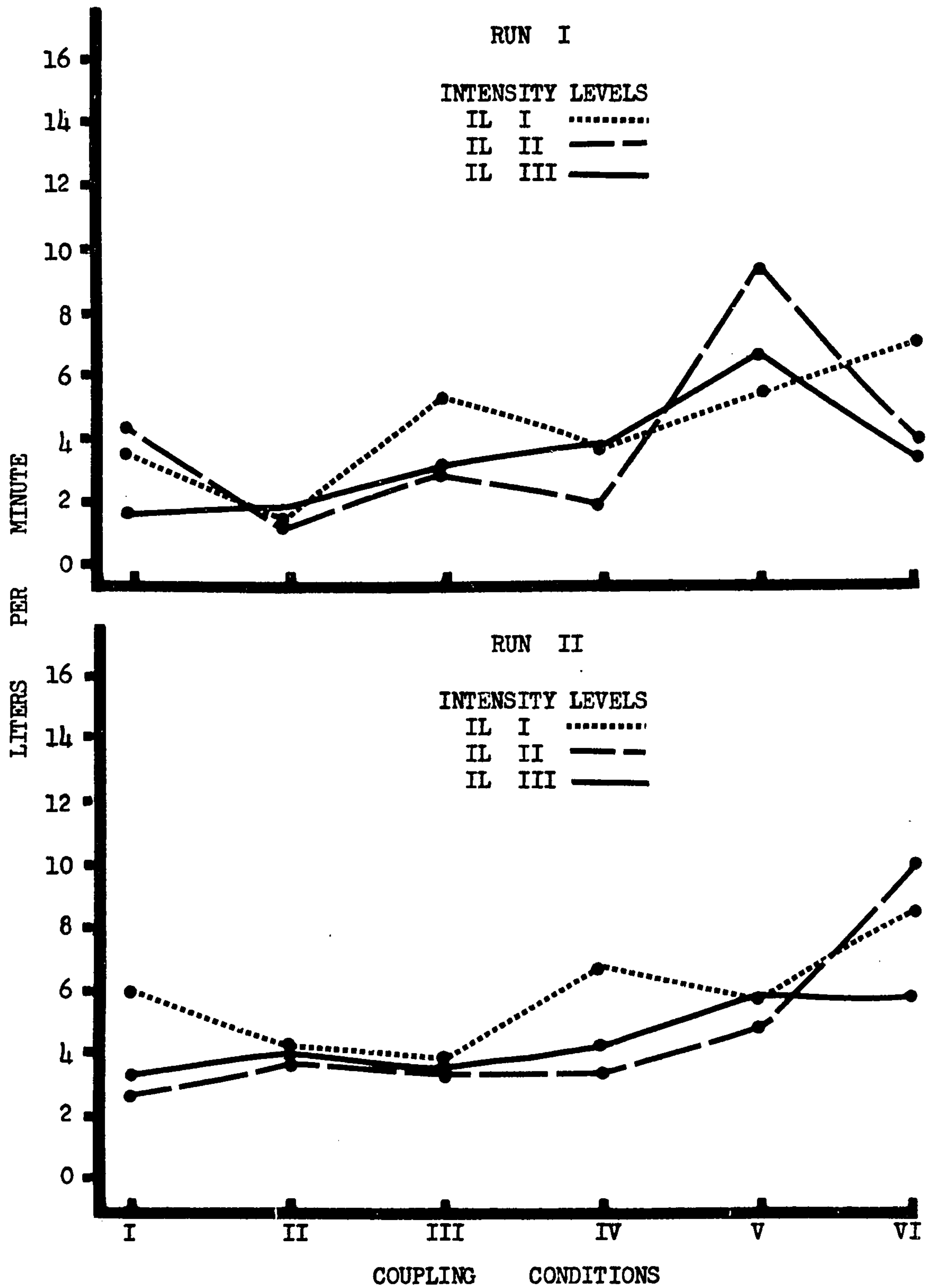


Figure 25.--Nasal air flow means for Pitch Level II at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

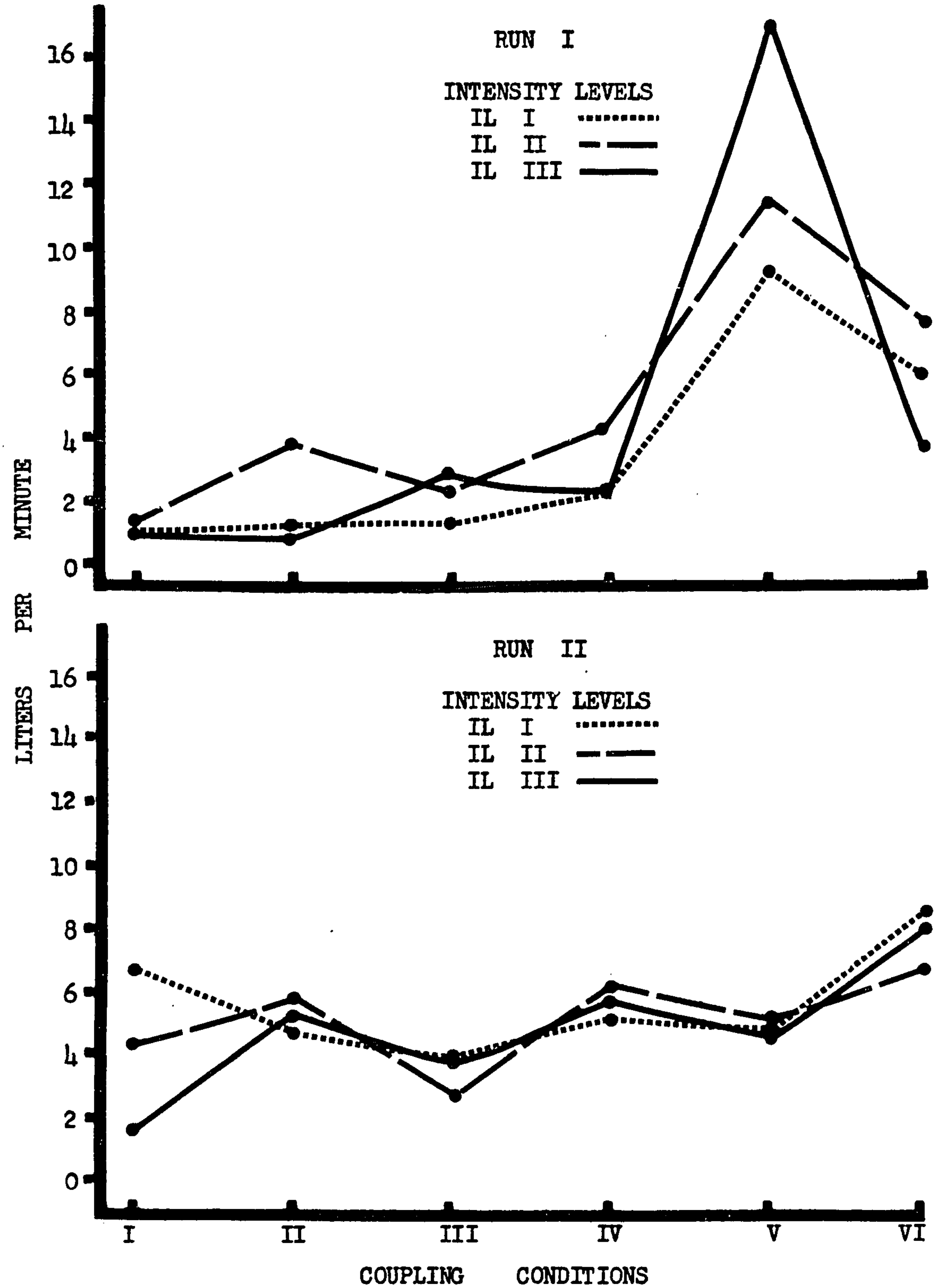


Figure 26.--Nasal air flow means for Pitch Level III at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

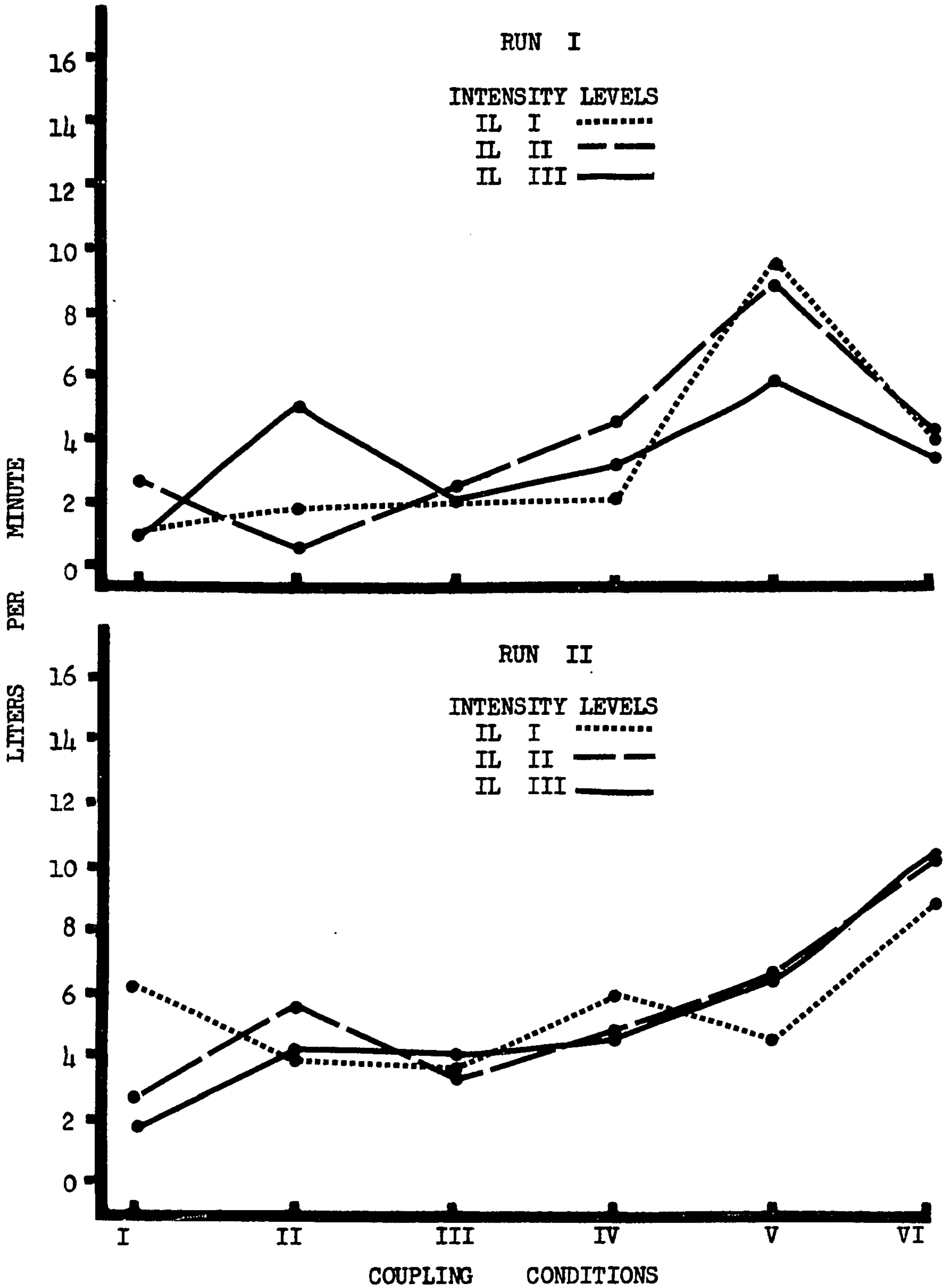


Figure 27.--Nasal air flow means for Pitch Level IV at each of three intensities at each of six coupling conditions for the two runs when the means are derived over all vowels.

sible, therefore, that the elevated nasal flow observed is an artifact of the greater expiratory effort used in this condition in this run. There is also evidence, however, that large nasal flows need not be associated with large oral flows. The largest oral flow seen in any run occurs at IL III, PL IV in Run II. It may be observed that, although this mean is about twice as great as those at IL I and IL II at this pitch level, the nasal air flow mean is only slightly greater. This finding suggests that an increased oral flow rate need not result in proportional increases in nasal flow. These variations in the data may be based on the fact that the amount of air that is channeled through the nose is a function of the oral impedance as well as nasal opening. Given a constant area of nasal opening, variations in oral impedance could result in widely different nasal flow rates. Inconsistencies in the present data could well relate to different oral impedances employed by the subject from run to run and across coupling conditions, pitch levels, and intensity levels within runs.

As noted in discussion of the vowel-by-coupling-by-intensity interaction, the effects of changes in vocal intensity on nasal flow are variable between and within runs. The changes in nasal flow rate with changes in vocal pitch level appear to be equally variable between and within runs. While not easily visualized in Figures 24 through 27, the data indicate no consistent relationship between nasal flow and vocal pitch. Thus, while the pitch main effect suggests a positive relationship between pitch level and nasal flow, this relationship does not consistently obtain when means at the same pitch levels are compared at the same intensity level and in the same coupling condition.

It may also be noted in Figures 24 through 27 that measurable nasal flows occur in CC I, the no-coupling condition. This phenomenon is seen more consistently in Run II than in Run I, but is evident, to some extent, in both runs. The reason for these flows is not clear. There is evidence from other studies (50, 74) that measurable nasal flow occurs even when subjects obtain a complete velar seal as measured in lateral X-ray films. This elevated flow may be explained by the elevation of the velum into the nasal space, producing small nasal flows. It is also possible, however, that a leak existed between the walls of the pharynx and the pharyngeal wall in spite of every effort to obtain a tight seal.

In the present experiment, the pharyngeal section of the speech appliance was built out for each session to a point where no nasal flow was registered in vowels produced at a comfortable intensity. In Run I, the pharyngeal section was expanded to a point where the subject reported some discomfort. During Run II, the bulb impinged less strongly on the lateral walls. It is quite possible that this procedure allowed the subject greater latitude in adjusting the side walls of the pharyngeal bulb during the second than in the first run of the experiment.

## Discussion

The findings of the present experiment indicate a trend toward an increased oral flow rate as intensity is increased from ILs II to III. Increments in vocal intensity between ILs I and II were not accompanied by consistent increments in oral flow rate. In both runs, the relationship between vocal intensity and oral flow rate appears to vary as a function of coupling area, pitch level and the vowel produced. These interactions are seen, to a greater extent, in the first than in the second run of the experiment.

Findings of the present study are compatible generally with the findings of previous studies. Vaughn (81), who studied a sample of normal speakers, reported an increase in mean oral flow rate when intensity was increased from a "comfort" level to a level 6 dB more intense. Van Hattum (79), studying a sample of subjects with velar incompetence, reported that his subjects used a greater percentage of their available air supply during phonation at 90 than at 75 dB SPL. The present data suggest that while trends in these directions exist in all coupling conditions studied, a subject may be capable of varying intensity without accompanying increments in oral flow rate. Within the limitation of this experiment, this appears to be true whether the nasal tract is coupled or uncoupled to the oral cavity.

The present study also shows that there is not a consistent relationship across runs between changes in vocal pitch level and oral flow rate. One exception to this finding was the trend toward greater oral flow rates at the highest pitch level (210 Hz) than at the three lowest pitch levels (105, 140, and 175 Hz) in the smallest coupling conditions (CCs I and II). Since these coupling conditions fall within the range of velar competence, this finding may suggest a relationship between vocal pitch level and oral flow rate in speakers with a normal velar seal. Such an hypothesis is consistent with data reported by Vaughn (81) and by Van Hattum (79) for normal-speaking samples.

Interrelationships among vocal pitch, vocal intensity levels, and oral flow rate found in the present study differ from those reported by Isshiki (36). Isshiki, in a study of a normal subject, reported that increased vocal intensity results in an unchanged or slightly decreased oral flow rate at low pitch levels. He speculates that intensity changes at low pitch levels are effected through increases in glottal resistance. Isshiki (36) also reported that, at high pitch levels, increases in vocal intensity are accompanied by increments in oral flow rates with little concomitant change in glottal resistance. The present data indicate that, when the oral and nasal tracts are uncoupled (CC I), there is a more consistent increase in oral flow rates with increased intensity at the lowest than at the highest pitch level. Since the Isshiki data and that of the present study are based on a single-subject experiment, differences in findings may reflect differences in the way in which intensity is regulated by the individual subjects. If this is the case, generalizations concerning how intensity is regulated in normals must be made cautiously. It is also possible that the differences in findings may be related to differences in the design of the two investigations. The Isshiki study made use of a wider range of vocal intensity and vocal pitch levels than were employed here. Thus, relationships evident in the Isshiki study may have been obscured in the present investigation.

Although there is some variation between runs, the present findings suggest that there is a decline in oral flow rate as coupling area is increased to the intermediate coupling conditions (CCs III and IV), followed by an irregular pattern of increased flow as coupling is further increased. This pattern prevails generally for the three vowels at the pitch and intensity levels used in this study. It would appear that oral flow declines until a critical range of coupling is reached; beyond this range, variable increases and decreases in oral flow occur. This critical range of coupling, in the present study, approximates .126 $cm^2$ to .283 $cm^2$ of opening. Interestingly, Warren and Devereaux (86) found that a .2 $cm^2$ coupling area seemed to be a critical point in separating velar adequacy from inadequacy in CVC productions.

It is possible that the coupling effects observed in the present investigation are related to an interaction between vocal intensity and coupling area. House and Stevens (34) reported that nasal tract coupling results in an increase in the damping characteristics of the vocal tract with a resultant loss in the transmission of sound energy. This finding is supported by the work of Olson (59) who found a progressive decrease in mean oral sound pressure with increases in coupling area from a no-coupling condition to an opening of .196 $cm^2$. As the area of coupling was increased, it might be assumed that the present subject was placed in the position of having to overcome this power loss by either increasing sound energy at the glottal source or by decreasing the impedance to the transmission of glottal source energy through the vocal tract.

It may be speculated that as coupling area was increased to CCs III and IV, the subject was able to compensate for the loss of intensity by increasing glottal resistance. As coupling was increased beyond this range, glottal resistance alone may not have been sufficient to offset the transmission loss, resulting in increased expiratory effort and an increased oral flow rate. The patterns of oral flow seen in the larger coupling areas (CCs V and VI), however, are not always characterized by an increased oral flow rate suggesting that the subject varied in the extent to which he employed glottal resistance versus expiratory effort as a mechanism for increasing intensity. A confounding variable in the present data is that of vocal tract impedance. The subject reported at the conclusion of the experiment that he utilized variations in mouth opening as a way of attaining the experimental intensities. The extent to which adjustments in vocal tract impedance affected oral flow rates in the present study can not be accurately assessed.

The present investigation reveals no consistent differences among the mean oral flow rates for the three vowels [i], [ɑ], and [u]. These data do not lend support to the findings of Vaughn (81) that the vowel [u] is associated with greater oral flow rates than [i]. It should be noted, however, that the differences among the vowel means in the Vaughn study are quite small. Further, Vaughn's data is based on the study of 20 normal males, whereas the present findings are based on the study of a single subject.

Analyses of the nasal air flow data do not reveal a consistent relationship across runs between vocal pitch and intensity levels and nasal air flow. These findings are compatible with findings reported by Vaughn (81) in a study of normal speakers. Present findings related to nasal air flow differences among vowels differ from those reported for Vaughn's normal sample. The present study revealed a fairly consistent trend toward less nasal flow for the vowel [ɑ] than for the vowels [i] and [u]. This trend exists in the small as well as the large coupling conditions. Vaughn (81) reported a significantly greater nasal flow for [ɑ] than for [i] or [u].

The presence of greater nasal flow for the high than for the low vowels in the present study might be expected in that nasal air flow is related to the degree of vocal tract impedance as well as to the area of nasal opening (50). It can be speculated that, given a constant area of nasal opening and a constant oral flow rate, more air will be channeled through the nose in production of vowels with greater than with lesser oral impedance.

As might be expected, there is a trend in both runs toward larger nasal flow rates in the larger than in the smaller coupling conditions. The data also show, however, that increases in the size of the nasal opening do not always result in increments in nasal air flow. In both runs, there are instances of lower nasal flows at the larger than at the smaller coupling conditions. The absence of a consistent positive relationship between nasal flow and coupling area is expected if nasal flow is visualized as a result of the interaction of expiratory effort, glottal resistance, vocal tract impedance, and nasal aperture size. Since the first three of these factors are uncontrolled in the present study, it is likely that the interplay of these variables within and between runs accounts for the relatively weak relationship between nasal flow and nasal aperture size. These findings are consistent with data reported by Warren and Devereaux (86), Warren and Ryon (88), and Machida (52). It seems reasonable to conclude that nasal air flow is not useful as a single index of nasal aperture size.

# CHAPTER V

## SUMMARY AND CONCLUSIONS

The present study was designed to investigate the volume velocity of oral and nasal air flow associated with sustained vowel phonation, at specified pitch and intensity levels, under varying nasal tract coupling conditions, produced by a single adult cleft palate speaker. A prosthetic appliance was specially designed for this subject which contained five concentric rings within the central portion of its pharyngeal section. These graduated rings could be removed one at a time to produce six conditions of oral-nasal coupling, ranging from .000 $cm^2$ to .785 $cm^2$ area of opening. An adult male with a repaired bilateral cleft of the lip and palate served as the subject of this investigation. The subject was required to phonate three vowels [i], [ɑ], and [u] at each of four pitch levels (105, 140, 175, and 210 Hz) at each of three intensity levels (65, 70, 75 dB SPL) under each of the six coupling conditions. Each vowel was sustained for a four-second period. The experiment was replicated twice with different randomization employed in each run.

Oral and nasal air flow measures were obtained by means of a warm-wire anemometer with independent recordings of the nasal and oral channels. The intensity of each vowel production was monitored by the subject who maintained a constant, predetermined needle deflection on the dial of a sound-pressure level meter, and was verified using a graphic level recorder. Fundamental vocal frequency was monitored utilizing instrumentation that provided a digital readout of the signal frequency over the four-second period of phonation, and was verified by a count of the number of cycles per second made in an oscillographic display of the vowel signal.

Oral and nasal air flow means for the three vowels at each of the pitch and intensity levels in each of the six coupling conditions constitute the quantitative data of the present experiment. Because of the evident variation in the data obtained in the two runs an inferential statistical analysis of the data was not attempted.

Within the limitations of this experiment and the apparent differences in the patterns of the data in the two runs, the following conclusions appear to be warranted:

1) There is a trend toward an increased mean oral flow rate as intensity is increased from Intensity Level II (70 dB) to Intensity Level III (75 dB). Consistent differences in mean oral flow rates between Intensity Levels I and II (65 dB and 70 dB) are not found in this experiment.

2) Increments in vocal intensity are not necessarily accompanied by increments in oral flow rate within the range of intensity levels used in this study.

3) Consistent relationships between vocal pitch level and mean oral flow rate are not evident in this study. There is, however, a trend toward greater oral flow at Pitch Level IV (210 Hz) than at Pitch Level I (105 Hz) in Coupling Conditions I and II (.000 $cm^2$ and .031 $cm^2$).

4) There is a trend toward a decline in oral flow rate as coupling is increased from a no-coupling condition to Coupling Conditions III and IV (.126 $cm^2$ and .283 $cm^2$), followed by variable increases and decreases in flow as coupling area is increased beyond these points.

5) Consistent differences in mean oral air flow among the three vowels are not evident.

6) Consistent differences in mean nasal air flow associated with variations in the experimental pitch and intensity levels are not observed.

7) There is a trend toward smaller mean nasal air flow for the low vowel [ɑ] than for the high vowels [i] and [u].

8) Although larger nasal air flows are associated with larger areas of nasal coupling, increments in the size of the nasal aperture are not necessarily associated with increments in the nasal flow rate.

The findings of the present investigation are necessarily limited to the conditions of the present experiment and cannot be extrapolated to either normal-speakers or the cleft-palate population.

For future studies, some changes in the design of the present study may be profitably considered. No attempt was made in the present investigation to control oral orifice dimensions or to gauge the differences in vocal effort in production of the vowel samples. In subsequent studies, it would be valuable to have information that bears on these variables. Simultaneously obtained measures of sub-glottal pressure and intra-oral pressure, and cineradiographic measures of oral orifice dimensions would have aided greatly the interpretation of variation in the data.

Moreover, a second potential source of error was the control of inspiratory intake. In spite of the fact that the subject took a breath prior to each phonation, there was no attempt made to prevent him from varying the amount of air intake. It appeared to the experimenter that the subject inspired a greater amount of air prior to phonation at the highest intensity level and in the greatest nasal tract coupling conditions. On the other hand, for phonations at the lowest pitch and intensity levels, the subject appeared to take in less air. Some control of the amount of available air utilized for each phonation would have been useful.

Control of the oral-nasal coupling must be considered another possible source of experimental error. Variations in the lateral and posterior pharyngeal walls may have introduced additional oral-nasal coupling other than the constant coupling areas afforded by the rings in the speech appliance. In the present experiment, the pharyngeal section of the speech appliance was built out to a point where no nasal flow was registered in vowels produced at a comfortable intensity. In Run I, the pharyngeal section was expanded to a point where the subject reported some discomfort. During Run II, the bulb impinged less strongly on the lateral walls. It is quite possible that this procedure allowed the subject greater latitude in adjusting the side walls of the pharynx against the pharyngeal bulb during the second than in the first run of the experiment.

In general, the subject's variability between runs might have been reduced had the recording sessions been held more consecutively with a shorter time interval between runs. Since the first run was recorded over a considerable period of time, carryover of the practice effects in sustaining vowels at the desired pitch and intensity levels was limited. The second run was recorded within a shorter time period and the subject appeared to experience less difficulty in accomplishing the experimental task.

Finally the use of one male cleft palate adult as the single subject limits the generalizations that can be derived from the present investigation. Additional data from a greater number of subjects of both sexes are needed.

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# APPENDIX A

## Oral Air Flow Measures

TABLE 9

ORAL AIR FLOW MEANS FOR EACH OF THREE VOWELS AT EACH OF FOUR PITCH LEVELS AT EACH OF THREE INTENSITIES FOR EACH OF SIX COUPLING CONDITIONS IN RUN I

| | Coupling Conditions | | | | | |
|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI |
| Vowel [i] | | | | | | |
| 105 Hz 65 dB | 6.68 | 9.64 | 8.24 | 7.12 | 14.80 | 7.44 |
| 70 dB | 9.32 | 6.36 | 7.12 | 6.04 | 7.44 | 9.32 |
| 75 dB | 13.68 | 10.40 | 9.32 | 8.88 | 8.56 | 10.40 |
| 140 Hz 65 dB | 5.28 | 6.36 | 13.44 | 11.04 | 9.96 | 9.32 |
| 70 dB | 6.36 | 7.12 | 9.92 | 4.16 | 13.68 | 6.36 |
| 75 dB | 11.52 | 8.88 | 15.12 | 20.92 | 8.56 | 10.40 |
| 175 Hz 65 dB | 11.52 | 8.88 | 14.64 | 5.28 | 11.52 | 8.56 |
| 70 dB | 9.32 | 13.68 | 4.48 | 9.96 | 15.44 | 7.80 |
| 75 dB | 9.32 | 9.96 | 9.32 | 6.04 | 12.16 | 9.32 |
| 210 Hz 65 dB | 13.68 | 7.44 | 7.44 | 4.92 | 11.52 | 4.16 |
| 70 dB | 13.68 | 13.68 | 4.92 | 10.72 | 4.16 | 5.60 |
| 75 dB | 21.68 | 14.04 | 7.44 | 15.44 | 12.16 | 7.80 |
| Vowel [ɑ] | | | | | | |
| 105 Hz 65 dB | 8.24 | 5.60 | 8.56 | 9.32 | 14.36 | 6.68 |
| 70 dB | 11.52 | 8.88 | 10.40 | 8.88 | 12.92 | 8.24 |
| 75 dB | 11.52 | 7.80 | 9.96 | 6.04 | 16.56 | 10.40 |
| 140 Hz 65 dB | 13.28 | 15.44 | 16.40 | 6.04 | 3.40 | 15.44 |
| 70 dB | 10.40 | 8.24 | 15.44 | 8.56 | 13.28 | 13.68 |
| 75 dB | 13.28 | 12.16 | 8.56 | 12.92 | 11.84 | 8.24 |
| 175 Hz 65 dB | 13.28 | 11.52 | 6.68 | 2.76 | 12.16 | 10.72 |
| 70 dB | 20.60 | 12.16 | 4.92 | 5.60 | 14.36 | 10.72 |
| 75 dB | 10.40 | 10.40 | 10.72 | 8.56 | 18.40 | 9.64 |
| 210 Hz 65 dB | 12.92 | 12.92 | 10.40 | 4.48 | 15.12 | 10.72 |
| 70 dB | 22.44 | 8.24 | 6.36 | 6.36 | 8.56 | 6.36 |
| 75 dB | 11.08 | 11.08 | 8.88 | 10.72 | 6.04 | 9.32 |
| Vowel [u] | | | | | | |
| 105 Hz 65 dB | 7.12 | 7.12 | 6.36 | 6.04 | 14.36 | 7.80 |
| 70 dB | 11.08 | 6.04 | 7.12 | 11.84 | 13.28 | 8.24 |
| 75 dB | 14.04 | 4.48 | 10.40 | 9.32 | 14.80 | 10.40 |
| 140 Hz 65 dB | 17.32 | 10.72 | 14.12 | 8.56 | 12.60 | 12.92 |
| 70 dB | 9.32 | 8.56 | 12.60 | 5.28 | 17.64 | 4.92 |
| 75 dB | 14.36 | 9.96 | 10.72 | 11.52 | 22.04 | 8.56 |
| 175 Hz 65 dB | 11.84 | 11.84 | 9.40 | 7.44 | 10.72 | 3.84 |
| 70 dB | 7.44 | 11.08 | 14.80 | 3.08 | 20.28 | 14.04 |
| 75 dB | 10.40 | 8.88 | 7.80 | 10.72 | 22.04 | 10.40 |
| 210 Hz 65 dB | 12.16 | 13.28 | 8.88 | 5.60 | 13.28 | 8.24 |
| 70 dB | 5.60 | 9.96 | 16.20 | 14.80 | 18.08 | 8.24 |
| 75 dB | 15.44 | 18.72 | 10.72 | 7.80 | 18.72 | 10.40 |

TABLE 10

ORAL AIR FLOW MEANS FOR EACH OF THREE VOWELS AT EACH OF FOUR PITCH LEVELS AT EACH OF THREE INTENSITIES FOR EACH OF SIX COUPLING CONDITIONS IN RUN II

| | | Coupling Conditions | | | | | |
|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | VI |
| Vowel [i] | | | | | | | |
| 105 Hz | 65 dB | 12.36 | 8.88 | 8.16 | 8.88 | 9.92 | 21.64 |
| | 70 dB | 9.40 | 9.40 | 9.92 | 12.36 | 11.16 | 15.16 |
| | 75 dB | 14.12 | 12.36 | 10.64 | 15.88 | 14.64 | 17.64 |
| 140 Hz | 65 dB | 9.40 | 5.36 | 6.40 | 5.88 | 1.88 | 14.64 |
| | 70 dB | 9.92 | 8.88 | 3.60 | 5.36 | 3.60 | 4.68 |
| | 75 dB | 11.16 | 8.88 | 8.88 | 12.36 | 8.88 | 12.36 |
| 175 Hz | 65 dB | 9.40 | 8.88 | 5.88 | 14.12 | 7.64 | 7.64 |
| | 70 dB | 5.36 | 16.40 | 3.60 | 14.64 | 7.64 | 7.64 |
| | 75 dB | 15.16 | 10.64 | 8.88 | 11.16 | 12.16 | 10.64 |
| 210 Hz | 65 dB | 12.88 | 12.36 | 6.40 | 11.68 | 12.16 | 9.92 |
| | 70 dB | 27.44 | 7.12 | 5.36 | 5.36 | 13.44 | 18.68 |
| | 75 dB | 13.44 | 31.64 | 10.72 | 11.68 | 32.16 | 27.44 |
| Vowel [ɑ] | | | | | | | |
| 105 Hz | 65 dB | 8.88 | 8.16 | 8.88 | 11.16 | 8.88 | 11.68 |
| | 70 dB | 16.40 | 14.12 | 11.16 | 14.64 | 9.92 | 14.12 |
| | 75 dB | 14.64 | 14.64 | 12.36 | 12.36 | 15.16 | 13.44 |
| 140 Hz | 65 dB | 11.16 | 8.88 | 2.92 | 16.40 | 8.88 | 12.88 |
| | 70 dB | 7.64 | 8.88 | 4.16 | 8.16 | 5.36 | 16.40 |
| | 75 dB | 15.88 | 12.36 | 26.92 | 13.44 | 9.92 | 10.64 |
| 175 Hz | 65 dB | 11.16 | 3.60 | 7.12 | 9.92 | 5.36 | 10.64 |
| | 70 dB | 6.40 | 11.68 | 5.88 | 8.16 | 12.88 | 8.88 |
| | 75 dB | 15.88 | 14.64 | 8.16 | 12.36 | 12.36 | 14.12 |
| 210 Hz | 65 dB | 13.44 | 19.36 | 8.88 | 12.36 | 9.92 | 12.36 |
| | 70 dB | 11.16 | 22.88 | 10.64 | 11.68 | 8.88 | 12.36 |
| | 75 dB | 11.68 | 12.36 | 9.40 | 11.68 | 12.36 | 12.88 |
| Vowel [u] | | | | | | | |
| 105 Hz | 65 dB | 7.12 | 8.16 | 3.60 | 10.64 | 11.68 | 10.64 |
| | 70 dB | 14.12 | 10.64 | 6.40 | 13.44 | 12.36 | 16.40 |
| | 75 dB | 13.44 | 12.88 | 12.36 | 14.12 | 12.36 | 14.12 |
| 140 Hz | 65 dB | 4.16 | 3.60 | 3.00 | 3.60 | 8.88 | 8.16 |
| | 70 dB | 18.16 | 6.40 | 3.60 | 8.88 | 7.12 | 12.88 |
| | 75 dB | 11.68 | 10.64 | 5.36 | 9.92 | 11.68 | 12.88 |
| 175 Hz | 65 dB | 11.16 | 5.36 | 2.92 | 8.88 | 7.12 | 7.64 |
| | 70 dB | 16.92 | 5.88 | 3.60 | 16.40 | 7.12 | 11.68 |
| | 75 dB | 15.88 | 8.16 | 8.88 | 12.36 | 12.36 | 16.40 |
| 210 Hz | 65 dB | 12.88 | 4.16 | 9.40 | 9.92 | 11.16 | 12.36 |
| | 70 dB | 12.36 | 21.64 | 3.60 | 5.88 | 3.60 | 1.88 |
| | 75 dB | 12.36 | 13.44 | 7.12 | 13.44 | 11.68 | 26.92 |

APPENDIX B

Nasal Air Flow Measures

TABLE 11

NASAL AIR FLOW MEANS FOR EACH OF THREE VOWELS AT EACH OF FOUR PITCH LEVELS AT EACH OF THREE INTENSITIES FOR EACH OF SIX COUPLING CONDITIONS IN RUN I

| | | Coupling Conditions | | | | | |
|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | VI |
| Vowel [i] | | | | | | | |
| 105 Hz | 65 dB | .12 | 1.04 | 2.00 | 2.00 | 11.20 | 3.84 |
| | 70 dB | 1.04 | 2.24 | 2.92 | 6.88 | 3.20 | 2.52 |
| | 75 dB | .12 | 2.92 | 2.92 | 2.92 | 12.12 | 3.20 |
| 140 Hz | 65 dB | 1.04 | .12 | 4.76 | 3.84 | 9.36 | 7.52 |
| | 70 dB | 1.04 | .12 | 2.52 | 2.00 | 10.84 | 3.20 |
| | 75 dB | 2.92 | 3.20 | 4.76 | 7.52 | 3.84 | 3.84 |
| 175 Hz | 65 dB | 1.04 | 2.24 | 1.32 | 2.00 | 7.16 | 2.92 |
| | 70 dB | 2.00 | 3.20 | 2.52 | 5.68 | 14.24 | 3.84 |
| | 75 dB | 1.04 | .12 | 2.92 | 2.00 | 27.44 | 5.96 |
| 210 Hz | 65 dB | 1.04 | 2.00 | 4.76 | 2.24 | 10.28 | 2.52 |
| | 70 dB | 4.12 | 1.32 | 3.84 | 7.52 | 12.40 | 6.24 |
| | 75 dB | 2.00 | 6.60 | 3.84 | 6.60 | 8.44 | 4.40 |
| Vowel [ɑ] | | | | | | | |
| 105 Hz | 65 dB | .12 | .12 | 1.04 | 1.04 | 10.56 | 1.04 |
| | 70 dB | .12 | .68 | 2.00 | 2.92 | 4.40 | 2.00 |
| | 75 dB | .12 | .12 | 2.92 | 2.00 | 16.08 | 4.40 |
| 140 Hz | 65 dB | 3.20 | 1.04 | 4.76 | .12 | 2.92 | 5.32 |
| | 70 dB | .12 | 2.92 | 2.92 | 1.04 | 4.76 | 5.68 |
| | 75 dB | 1.32 | 1.04 | 2.00 | 2.92 | 7.16 | 2.00 |
| 175 Hz | 65 dB | .12 | 2.00 | 1.04 | 3.84 | 10.84 | 3.20 |
| | 70 dB | 1.60 | 4.40 | 2.00 | 6.24 | 10.56 | 5.04 |
| | 75 dB | .12 | .12 | 2.00 | 1.04 | 9.00 | 2.00 |
| 210 Hz | 65 dB | 1.04 | 2.92 | 1.04 | 2.00 | 8.48 | 4.76 |
| | 70 dB | 2.00 | 1.04 | 1.04 | 3.84 | 8.72 | 2.00 |
| | 75 dB | .12 | .40 | 1.04 | 2.00 | .12 | 3.44 |
| Vowel [u] | | | | | | | |
| 105 Hz | 65 dB | .12 | .12 | 2.00 | 1.04 | 6.60 | 2.92 |
| | 70 dB | 2.00 | .12 | 2.92 | 3.84 | 7.16 | 2.52 |
| | 75 dB | 2.00 | .12 | 2.00 | 3.84 | 9.92 | 2.00 |
| 140 Hz | 65 dB | 5.96 | 5.32 | 6.60 | 4.76 | 4.12 | 9.36 |
| | 70 dB | .12 | .12 | 2.92 | 2.52 | 12.68 | 3.20 |
| | 75 dB | .12 | 1.04 | 2.52 | 1.04 | 9.00 | 3.84 |
| 175 Hz | 65 dB | 2.00 | 1.32 | 1.32 | 1.04 | 9.64 | 12.12 |
| | 70 dB | .12 | 3.84 | 2.52 | 1.32 | 9.64 | 14.52 |
| | 75 dB | 2.00 | 2.00 | 3.84 | 3.44 | 15.44 | 2.92 |
| 210 Hz | 65 dB | 2.00 | 1.04 | 1.04 | 2.24 | 10.28 | 5.04 |
| | 70 dB | 2.92 | .12 | 3.44 | 3.20 | 5.68 | 5.32 |
| | 75 dB | 1.32 | 9.00 | 1.60 | 1.60 | 9.64 | 2.92 |

TABLE 12

NASAL AIR FLOW MEANS FOR EACH OF THREE VOWELS AT EACH OF FOUR PITCH LEVELS AT EACH OF THREE INTENSITIES FOR EACH OF SIX COUPLING CONDITIONS IN RUN II

| | | Coupling Conditions | | | | | |
|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | VI |
| Vowel [i] | | | | | | | |
| 105 Hz | 65 dB | 2.00 | 2.92 | 2.24 | 3.84 | 2.92 | 10.56 |
| | 70 dB | 2.92 | 5.68 | 3.20 | 5.04 | 5.04 | 4.40 |
| | 75 dB | 1.32 | 2.92 | 2.00 | 6.60 | 3.20 | 10.28 |
| 140 Hz | 65 dB | 8.48 | 2.92 | 6.60 | 2.92 | 2.92 | 7.80 |
| | 70 dB | 2.24 | 3.84 | 2.92 | 3.84 | 4.76 | 5.96 |
| | 75 dB | 5.96 | 2.24 | 2.00 | 3.84 | 6.60 | 9.00 |
| 175 Hz | 65 dB | 5.04 | 6.88 | 6.88 | 4.12 | 4.12 | 6.88 |
| | 70 dB | 3.84 | 9.92 | 3.44 | 7.52 | 3.84 | 9.64 |
| | 75 dB | 2.00 | 6.60 | 2.92 | 6.88 | 5.68 | 8.72 |
| 210 Hz | 65 dB | 7.52 | 6.24 | 5.68 | 7.80 | 4.40 | 9.36 |
| | 70 dB | 4.76 | 4.76 | 5.32 | 5.32 | 10.84 | 14.92 |
| | 75 dB | 1.04 | 5.68 | 4.40 | 7.52 | 10.84 | 12.12 |
| Vowel [ɑ] | | | | | | | |
| 105 Hz | 65 dB | 2.92 | 4.40 | 2.00 | 2.52 | 4.76 | 4.76 |
| | 70 dB | 2.24 | 2.52 | 2.00 | 4.12 | 4.76 | 4.76 |
| | 75 dB | 1.04 | 2.92 | 3.20 | 3.84 | 4.76 | 3.84 |
| 140 Hz | 65 dB | 6.60 | 5.68 | 2.00 | 13.60 | 5.04 | 6.88 |
| | 70 dB | 3.20 | 2.00 | 3.84 | 2.00 | 5.04 | 11.20 |
| | 75 dB | 1.04 | 3.44 | 2.92 | 3.20 | 5.68 | 4.12 |
| 175 Hz | 65 dB | 6.60 | 2.92 | 3.20 | 4.76 | 3.84 | 9.00 |
| | 70 dB | 2.92 | 2.92 | 2.00 | 2.92 | 6.24 | 2.92 |
| | 75 dB | 2.00 | 2.92 | 5.32 | 5.68 | 3.44 | 6.60 |
| 210 Hz | 65 dB | 7.80 | 2.92 | 5.32 | 4.12 | 5.68 | 9.64 |
| | 70 dB | 2.24 | 3.84 | 2.92 | 2.92 | 4.76 | 5.04 |
| | 75 dB | 1.04 | 4.76 | 2.00 | 2.92 | 5.68 | 3.44 |
| Vowel [u] | | | | | | | |
| 105 Hz | 65 dB | 4.12 | 4.76 | 5.32 | 2.00 | 2.52 | 3.44 |
| | 70 dB | 1.04 | 3.84 | 3.84 | 2.92 | 4.76 | 7.16 |
| | 75 dB | 1.04 | 4.40 | 5.32 | 4.76 | 4.40 | 8.48 |
| 140 Hz | 65 dB | 2.92 | 3.84 | 2.52 | 3.84 | 9.36 | 10.28 |
| | 70 dB | 2.92 | 5.04 | 3.20 | 4.12 | 4.12 | 12.68 |
| | 75 dB | 2.92 | 6.24 | 5.68 | 5.32 | 4.76 | 4.40 |
| 175 Hz | 65 dB | 8.48 | 4.40 | 2.00 | 6.60 | 6.60 | 9.92 |
| | 70 dB | 6.24 | 4.76 | 2.52 | 8.44 | 5.32 | 7.80 |
| | 75 dB | 1.04 | 6.60 | 2.92 | 4.76 | 4.48 | 8.44 |
| 210 Hz | 65 dB | 3.44 | 2.92 | 7.80 | 6.60 | 3.84 | 7.80 |
| | 70 dB | 1.04 | 8.44 | 2.00 | 6.88 | 5.04 | 11.48 |
| | 75 dB | 2.92 | 2.24 | 5.96 | 3.44 | 3.84 | 16.76 |