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Physiological Aspects of Speech Produced by Deaf Persons

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INTRODUCTION

THIS paper presents an overview of recent research findings regarding the physiology of deaf speech. Consideration will be given to speech breathing and aerodynamics, laryngeal functioning, and articulatory dynamics. Each topic is introduced with a brief discussion regarding normal physiological speech processes and research techniques. Each topic's introduction is followed by a detailed discussion of recent research findings regarding the physiologic speech processes of deaf persons. Attempts will be made to illustrate how aberrant processes contribute to the speech errors of the deaf.

Deafness often gives rise to oral communication problems that are very complex in nature. The speech produced by many deaf persons is frequently unintelligible to even the most experienced listener. Moreover, it is frequently difficult to determine the exact nature of the speech errors that reduce intelligibility. Seemingly simple errors of articulation may be related to abnormal respiratory and laryngeal activities. Complexities of this nature pose major problems when one is attempting to help deaf persons improve their speech intelligibility. Moreover, many of the assumptions regarding the physiological nature of the speech of deaf persons are based on acoustic analysis. Caution must be taken when one attempts to make inferences regarding physiological processes from acoustic output. The acoustic signal is the end result of many integrated physiological processes. It is frequently difficult, therefore, to make accurate physiological assessments from the acoustic signal. In this respect, the study of speech physiology may provide important insights regarding the physiological nature of the deaf person's unintelligible speech.

Speech physiology is a rapidly growing discipline concerned with the neuromuscular, biomechanical, and aerodynamic events associated with speech production. These physiological processes are considered to be the most fundamental properties of speech production. The application of physiological research techniques has provided much information regarding normal and abnormal speech processes. One advantage of studying speech physiology is the close relationship between physiological processes and acoustical output. Through careful analysis, one can determine how certain physiological events affect the speech signal. As such, intelligible speech can be viewed as the determined product of temporally coordinated neuromuscular, biomechanical and aerodynamic events. Conversely, unintelligible speech can be viewed as the mismanagement of these events. A clear understanding of the nature of this mismanagement could lead to a better appreciation of how deafness affects the control of speech production. Furthermore, such an understanding could lead to the development of more effective remedial procedures. These remedial procedures would be designed to alter aberrant behaviors that directly underlie the deaf person's unintelligible speech.

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Abbs and Watkin (1976) pointed out that the study of speech physiology has only recently become sufficiently sophisticated to take a permanent position in traditional speech science investigation. Additionally, the techniques used to study speech physiology have not been widely utilized to study the speech of the deaf. Thus, on the speech of deaf persons, data is limited. The precise relationships between aberrant physiological activity and resultant oral communication problems are not fully understood. Such data could, however, provide insights regarding why some deaf persons produce intelligible speech while others produce unintelligible speech. The research discussed in this article illustrates that important inroads are being made toward an understanding of the physiological nature of deaf speech. The first topics to be considered are speech breathing and aerodynamics.

SPEECH BREATHING AND AERODYNAMICS

We breathe to maintain life. Respiratory processes additionally provide the primary driving energy for speech production. Our understanding of normal speech breathing processes has been greatly enhanced by the recent research of Hixon *et al.* (1973, 1976). These researchers have described the biomechanical events associated with air volume displacements during speech breathing. Moreover, their theoretical formulations and measurement procedures form the cornerstone for much of the research regarding speech breathing patterns of the deaf. As such, brief consideration will be given to the theoretical basis for their measurement technique.

The term "chest wall" refers to all extrapulmonary parts of the body that share changes in the volume of the lungs. The chest wall is functionally divided into two parts — the rib cage and the abdomen. The two parts of the chest wall are separated by the diaphragm. A volume of air can be expelled from the lungs by an independent displacement of the rib cage or abdomen or any combination of relative displacements of the two parts.

A volume of air displaced by the lungs is reflected by an equal volume displacement of the chest wall surfaces. Thus, relative volume displacements can be determined by measuring the magnitude of chest wall movements. Hixon *et al.* (1973, 1976) used electromagnetic transducers to detect anteroposterior diameter changes of the rib cage and abdomen. These transducers are commonly called magnetometers. The principle for determining relative volume displacements of the chest wall using magnetometers is as follows. Small coils encased in plastic are taped to the anterior surface of the rib cage and abdomen. These coils generate a magnetic field. Coils are also taped to the posterior surface of the rib cage and abdomen parallel to their anterior coil mates. The posterior coils sense the strength of the magnetic field generated by the anterior coil mates. As air is inhaled and exhaled, the anteroposterior diameters of the rib cage and abdomen increase and decrease. As a result, the strength of the magnetic field between the anterior and posterior coils increases and decreases. Voltages induced in the sensor coil are inversely proportional to the distance between the anterior and posterior coil mates. With appropriate spirometric calibrations one can determine the independent volume displacements of the rib cage and abdomen. One can also determine the relative lung volumes used during speech. To appreciate how deaf persons may mismanage normal speech breathing processes, it is necessary to consider normal speech breathing. The discussion regarding normal speech breathing is limited to parameters that have been investigated in the deaf. It is not intended to be a complete treatment of normal speech breathing processes.

Hixon *et al.* (1973, 1976) have observed that normal speech breathing patterns are highly individualistic and task dependent. There are, however, certain respiratory adjustments that are fairly consistent across normal speakers during discourse type utterances. For example, speech is typically restricted to the midrange of lung volume. Speech is generally initiated from levels slightly above the end inspiratory level. The end inspiratory level is the level achieved at the termination of a quiet inspiration. Normal speakers rarely continue an utterance beyond the functional reserve capacity. The functional reserve capacity is the volume of air remaining in the lungs at the end of a quiet expiration. Hixon and his associates suggest that speaking within the midvolume range is mechanically efficient. The midvolume range is the least demanding portion of the vital capacity range with respect to the muscular costs against the elastic recoil of the system. It is not efficient to speak outside the midvolume range because the respiratory system is less compliant at very high or low volumes.

Linguistic factors also play a role in speech breathing. Normal speakers appear to have highly developed regulatory patterns that dictate when an inhalation will occur during speech. Hixon (1973) suggested that the respiratory system's task in sustained utterances is to provide a relatively continuous expiration. This continuous expiration is halted occasionally for inspiratory refills or breath holdings. These refills or breath holdings generally occur at sentence or phrase boundaries or other appropriate linguistic points.

The final point regarding normal speech breathing is the relative volume displacements of the rib cage and abdomen during speaking. According to Hixon and his associates (1973, 1976) individuals perform differently with respect to the relative volume displacements of the rib cage and abdomen. These differences probably relate to how the individuals learned to use their muscular system against the passive mechanical properties of the respiratory system. In general, however, the rib cage and abdomen work synchronously.

In summary, the previous section regarded three general aspects of normal speech breathing. The first topic considered was the relative lung volumes used during speaking. The second topic considered linguistic influences on speech breathing. And, the third topic considered the relative volume displacements of the rib cage and abdomen during speech breathing. The research discussed in the next section suggests that deaf persons may distinguish themselves in all three aspects of speech breathing.

Forner and Hixon investigated the speech breathing patterns of ten deaf persons using magnetometers and reported their findings in 1977. In similar fashion to normal hearing speakers, their deaf subjects generally spoke within the mid-volume range of vital capacity. Also, the majority of their subjects initiated speech at lung volumes well above the functional reserve capacity. Three subjects, however, consistently initiated speech at or below the functional reserve capacity. Whitehead (in press) reported similar findings.

Whitehead investigated the speech breathing patterns of fifteen adults using magnetometers. Five of the subjects were normal hearing speakers. The remaining ten subjects were deaf. Five of the deaf subjects exhibited intelligible speech and five exhibited semi-intelligible speech. Whitehead's results indicate that the normal hearing and the intelligible deaf adults typically initiated speech around eight hundred cubic centimeters above functional reserve capacity. This level is slightly above the end inspiratory level. The semi-intelligible deaf adults, however, tended to initiate speech at substantially lower lung volumes. The average lung volume at speech initiation for the semi-intelligible subjects was one hundred twenty five cubic centimeters above functional reserve capacity. Also, the semi-intelligible subjects demonstrated a consistent tendency to continue speaking at lung volumes below functional reserve capacity. Speaking at lung volumes below the functional reserve capacity is rarely observed in normal hearing speakers.

Deaf persons also tend to waste air during sustained utterances. Forner and Hixon (1977) observed that the average air expenditure per syllable of their deaf subjects was 100 cc/sec. This is severalfold greater than the average air expenditure per syllable exhibited by normal hearing speakers. Such air wastage probably accounts for Forner and Hixon's deaf subjects producing only four syllables per breath during sustained utterances. In contrast, normal hearing speakers produce around fourteen syllables per breath. For example, Whitehead observed that his normal hearing and intelligible deaf subjects produced fourteen and ten syllables per breath, respectively. His semi-intelligible deaf subjects averaged only three syllables per breath.

The deaf speaker's tendency to waste air is further complicated by frequent interruptions of the egressive air flow supporting speech. Forner and Hixon (1977) reported that deaf speakers exhibit frequent interruptions for inhalations and breath holdings at linguistically inappropriate points. These abnormal interruptions occur between syllables and thus disturb normal speech prosody.

Despite clinical claims to the contrary, deaf speakers appear to exhibit normal relative volume displacements of the rib cage and abdomen. Forner and Hixon (1977) reported that only one of their ten deaf subjects demonstrated rib cage-abdomen synchronization problems. Similar findings were reported by Whitehead (in press). Thus, rib cage-abdomen synchronization problems are probably not characteristic of deaf speakers in general.

It is also interesting to note that deaf speakers exhibit normal volume adjustments prior to speech initiation. Baken and Cavallo (in press) observed that normal hearing subjects displace air from the abdomen to the rib cage just prior to speech initiation. This reconfiguration of the two chest wall components is thought to optimize support for phonation. Cavallo *et al.* (1981) studied prephonatory volume displacements in deaf subjects. All subjects were congenitally deaf and exhibited unintelligible speech. The procedures used to monitor prephonatory chest wall activity were identical to those used by Baken and Cavallo. Subjects were instructed to phonate a neutral vowel on experimenter command. The results indicate deaf subjects also show abdomen to rib cage volume displacements just prior to speech initiation. These results suggest that deaf persons appropriately tune the respiratory system prior to speech. Observed respiratory abnormalities during speech may be related, therefore, to more general vocal tract discoordinations.

The findings of Forner and Hixon (1977) Whitehead (in press) and Cavallo *et al.* (1981) indicated that deaf speakers may have difficulty regulating the respiratory apparatus for speech production. At the very least, deaf speakers do not appear to use the respiratory apparatus in a coordinated efficient manner. Additionally, these respiratory control problems appear to be further complicated by inefficient valving of the air stream. High syllable air volume expenditures strongly suggest inappropriate laryngeal and upper air way modulation of the air stream. Abnormal mechanical adjustments of the respiratory system coupled with atypical upper airway valving could disturb requisite air pressure and flow events associated with normal speech production. Such disturbances could adversely affect many aspects of normal speech production. For example, contrastive syllabic stress is a suprasegmental parameter of spoken English. Deaf persons frequently exhibit abnormal stress patterns. To be accurately perceived as stressed, a syllable should be more intense and higher in frequency than its adjacent syllables. Briefly consider the physiological requirements for making a syllable more intense. The physiological requirements for making a syllable more intense are increased subglottic pressure and glottal resistance. Increasing subglottic pressure appropriately could be difficult if speech were being produced at low lung volumes. Additionally, mistimed or inappropriate laryngeal gestures could virtually prohibit the development of increased subglottic pressure. As a result, the intended stressed syllable would not be more intense than adjacent syllables. Thus, an important perceptual cue associated with stress would be absent. A listener would likely regard such a production as a stress error. Important clinical insights could be gained through a better understanding of the exact physiological processes associated with errors of this nature. Directly studying the air flow and pressure events associated with deaf speech is one way of accomplishing such an understanding.

Aerodynamics is a branch of physics that deals with the forces exerted on air by other gases. In speech research the term aerodynamics refers to the air flow and pressure events associated with speech production. Air pressures and flow vary systematically as a function of laryngeal and upper airway activities. Aerodynamic measures, therefore, reflect certain laryngeal and upper airway processes. Information regarding glottal status, manners of consonantal production, and many other production parameters can be assessed aerodynamically. Generally, speech aerodynamics are measured with a pneumotachograph. A pneumotachograph is a facemask connected to a pressure transducer and amplifier. Variations of air pressure associated with speech are sensed in the facemask. From these pressure variations, accurate estimates of air flow can be derived. Warren (1976) provided an excellent discussion of these measurement procedures. The interested student is encouraged to read his work.

Air flow and pressure events associated with the speech of the deaf are frequently abnormal. In two studies, Whitehead *et al.* (1978) and Whitehead and Barefoot (1980) investigated the aerodynamics patterns of 60 adult subjects during plosive and fricative consonant productions. Twenty of the subjects had normal hearing and normal speech. Twenty of the subjects were deaf, but exhibited intelligible speech. The remaining 20 subjects were deaf and exhibited unintelligible speech.

During production of plosive consonants, the normal hearing and intelligible deaf subjects performed comparably. Both groups exhibited greater average air flow rates during voiceless plosive productions than voiced plosive productions. And, the relative amount of air flow during plosive productions was equivalent for these two groups. The unintelligible deaf subjects, however, did not exhibit greater air flow rates during voiceless plosive productions. Their voiceless and voiced plosive productions were not differentiated in terms of air flow. The unintelligible deaf subject's air flow rates during voiceless plosive productions averaged 500 cc/sec below the rates of the other two groups.

Similar between group differences were observed during fricative consonant productions with one notable exception. When the fricative consonant appeared initially in words, the unintelligible deaf subjects exhibited excessively high average air flow rates. The air flow rates associated with their word initial fricative productions averaged 350 cc/sec above the rates of the other two groups. One can reasonably interpret these findings by considering the underlying physiology.

First, nondifferential laryngeal gestures could result in equivalent air flow rates during voiced and voiceless consonant productions. The unintelligible deaf subjects probably were not employing normal glottal abductory gestures during voiceless consonant productions. The absence of a glottal abductory gesture would also reduce the average amount of air flow during voiceless consonant production. Indeed, the average air flow rates associated with the unintelligible deaf subject's voiceless productions compared favorably to the voiced productions of the other two groups.

Articulatory aspects need to be considered to explain the unintelligible deaf subject's excessively high air flow rates on word initial fricatives. Fricative consonants are normally produced with a high degree of oral constriction. This constriction normally offers resistance to air flow. It is reasonable to suggest that the unintelligible deaf subjects did not achieve normal articulatory configurations during their fricative productions. As such, resistance was reduced and the rates of air flow were high.

The findings of Whitehead *et al.* (1978) suggest a correlational relationship between aberrant air flow patterns and reduced speech intelligibility. Continued aerodynamic research may assist in determining exactly how aberrant aerodynamic patterns relate to reduced speech intelligibility. Aberrant air flow, however, is a reflection of abnormal neuromuscular and biomechanical events. Research procedures designed to assess these events more directly could provide additional and important insights. This is especially true of assessing laryngeal functioning of deaf persons.

LARYNGEAL FUNCTIONING OF DEAF PERSONS

The human larynx is an efficient machine that has important biological functions. Most notably, the larynx protects the lungs from foreign elements. The larynx also serves as the primary source of acoustic energy for speech. Additionally, the laryngeal mechanism plays an integral role in the systematic variation of stress, intonation, and voicing status of certain consonants. The systematic variation of stress and intonation is considered to be a phonatory parameter of laryngeal functioning. The systematic variation of the voicing status of consonants is considered to be an articulatory parameter of laryngeal functioning. The following discussion reflects the functional dichotomy between laryngeal phonatory and articulatory parameters. Phonatory parameters will be considered first.

The myoelastic-aerodynamic theory of vocal fold vibration was formalized by van den Berg (1958). It is generally accepted that vocal fold vibration is the result of an interaction of the myoelastic forces of the vocal folds with the air flow through the glottis. Control over these myoelastic and aerodynamic forces normally permits the speaker to maintain a fairly constant fundamental frequency or pitch. Control over these forces also permits the speaker to systematically vary fundamental frequency to signal changes in stress and intonation. According to Titze (1980), the relative contribution of myoelastic versus aerodynamic forces to the control of fundamental frequency is not fully understood. Electromyographic data reported by Shipp and McGlone (1971) and computer simulations of vocal fold vibration reported by Titze and Talkin (1979), however, indicate that fundamental frequency is controlled by the larynx. The primary determinant of fundamental frequency is the degree of vocal fold tension. Vocal fold tension is a function of vocal fold length and stiffness. Changes in vocal fold length and stiffness are mediated by the intrinsic laryngeal musculature. Additionally, marked changes in intonation appear to be a function of laryngeal muscle activity that affects vocal fold tension. An example of a marked intonation change is the rise in fundamental frequency associated with the termination of an interrogative phrase. Constrastive stress may require alterations in aerodynamic forces operating on the larynx. In addition to increased fundamental frequency, stressed syllables may be of greater intensity than adjacent syllables. Physiologically, the most efficient way to increase intensity is by increasing subglottic pressure. Changes in subglottic pressure are mediated primarily by the respiratory musculature.

Deaf individuals frequently exhibit difficulty controlling these laryngeal phonatory parameters for speech purposes. This lack of control frequently results in abnormal voice qualities and failures to instantiate appropriate intonation and stress patterns. Some of the best data regarding laryngeal control problems in the deaf comes from indirect assessments using reflectionless tube procedures. Briefly, this procedure requires a subject to phonate a neutral vowel into an acoustically reflectionless tube. The tube acts as a pseudo-infinite termination of the vocal tract. Since the tube is reflectionless, vocal tract resonances are damped. Typically, a microphone is placed inside the tube. This microphone records a pressure waveform that is considered to be an approximation of the actual air flow through the glottis. Analysis of the frequency and intensity variations of this pressure waveform provide important insights regarding laryngeal functioning during speech. For example, it is generally agreed that increases in vocal fold tension produce attendant changes in fundamental frequency. Also, increases in subglottic pressure produce attendant changes in vocal intensity. Thus, inferences can be made regarding the physiological mechanisms underlying the frequency and intensity variations of the pressure waveform. Variations in fundamental frequency suggest laryngeal activity. Variations in intensity suggest respiratory activity.

Monsen *et al.* (1979) employed a reflectionless tube procedure to study the laryngeal control problems of twenty deaf adolescents. Data collected from the deaf subjects were compared to data collected from a group of normal hearing subjects. Analysis of the pressure waveforms indicated that the average fundamental frequency of the deaf subjects fell within the range of the normal hearing subjects. The average period to period frequency variability of the deaf subjects, however, was greater than the normal hearing subjects. Similarly, the deaf subject's average period to period intensity variability frequently doubled the values obtained from the normal hearing subjects. These findings suggest that some deaf individuals have difficulty maintaining an appropriate tension balance between the vocal folds. This tension imbalance may be related to the harsh voice qualities frequently exhibited by deaf speakers.

Monsen *et al.* (1979) also investigated how deaf individuals control glottal activity within and between syllables. Each subject phonated a sequence of trisyllabic words that are normally produced with stress on the second syllable. The stressed syllables produced by the normal hearing subjects always had a higher fundamental frequency than the adjacent syllables. Also, the normal hearing subject's stressed syllables were usually of greater intensity than the adjacent syllables. Nine of the twenty deaf subjects produced the stimulus words with frequency and intensity patterns similar to the normal hearing subjects. Eleven of the deaf subjects, however, produced stressed syllables that were characterized by lower fundamental frequencies and intensities than the adjacent syllables.

Monsen and his associates also observed that their deaf subjects frequently could not control fundamental frequency within a syllable. This lack of control was characterized by inappropriate increases and decreases in fundamental frequency of the unstressed syllables. These inappropriate frequency fluctuations resulted in certain portions of the unstressed syllables having a higher fundamental frequency than the stressed syllable.

The findings of Monsen and his colleagues suggest that deaf individuals have difficulty making appropriate adjustments in vocal tension. The inability to control vocal fold tension results in inappropriate fluctuations in fundamental frequency. Their results also suggest that deaf individuals have difficulty coordinating respiratory activity with laryngeal activity. The inability to coordinate respiratory and laryngeal activity results in inappropriate fluctuations in intensity.

High speed laryngeal film data suggest another dimension to the laryngeal control problems exhibited by deaf persons. Metz and Whitehead (1980) filmed laryngeal activity of one normal and four deaf subjects at four thousand frames per second. Each subject was required to produce an /ihi/ syllable on experimeter command. This permitted observation of phonation onset and the laryngeal devoicing gesture associated with the /h/ segment.

Phonation onsets of the normal hearing subject were typically characterized by a coordinated adductory movement of the arytenoid cartilages. This adductory movement of the arytenoid cartilages positioned the vocal folds in the medial plain of the glottis. Generally, the folds did not make physical contact during this prephonatory period. Approximately, one hundred milliseconds after the initial adductory gesture small oscillations of the vocal folds were observed. The oscillations were the vocal folds' response to the egressive air flow from the lungs. The magnitude of these oscillations gradually increased. When a stable vibratory pattern had been achieved, the entire length of the vocal folds participated in the vibration.

Two of the deaf subjects consistently exhibited atypical phonation onsets. In contrast to the normal hearing subject, both deaf subjects positioned the vocal folds in contact with one another. Vocal fold contact prior to phonation onset is not necessarily abnormal. The prephonatory periods of both deaf subjects, however, frequently exceeded 350 ms. When vocal fold vibration began, only the anterior one-third of the vocal folds participated. Apparently, these subjects exerted an abnormally high degree of medial compression on the arytenoid cartilages. This compression prohibited vibration of the posterior two-thirds of the vocal folds. Abnormal vibratory patterns of this nature frequently continued for 200 ms. This abnormal vibratory pattern resulted in very high fundamental frequencies during the first 200 ms. of the initial vowel. It is reasonable to suggest that such abnormal laryngeal postures figure centrally in the deaf's frequent inability to control fundamental frequency and intensity when they initiate speech. More will be said regarding this study later.

As mentioned earlier, the larynx also serves as an articulator during normal speech. This articulatory function differentiates consonants from one another along the voicing dimension. It is well established that normal hearing speakers use unique laryngeal gestures for production of voiced as compared to voiceless consonants. For example, voiceless consonants are produced with an opening-closing gesture of the vocal folds. Voiced consonants are produced by holding the vocal folds together. The contrastive presence or absence of voicing is chiefly determined by abductory/adductory vocal fold adjustments. These adjustments are timed relative oral gestures associated with consonant productions. Thus, voice onset time distinctions can be regarded as symptoms of the state of the glottis.

Voicing errors are prevalent in the speech of the deaf. Aerodynamic and acoustic measures suggest that deaf persons may use inappropriate laryngeal gestures during certain sound productions. Additionally, these gestures may be inappropriately timed relative to articulatory gestures. Such data suggest that the frequent failure of deaf persons to produce voice onset time distinctions may be related to atypical laryngeal adjustments.

To test this notion, Mahshie (1980) recorded the laryngeal adjustments of four normal and four deaf adults. The subject's productions of voiced and voiceless consonants were filmed with a flexible fiberscopic nasolaryngoscope. This device, commonly called a fiberscope, is a small diameter flexible tube that contains fiberoptic bundles. Small light conducting fiberoptics are arranged in concentric circles around a single large fiberoptic strand. Light from an external source is directed through the small fiberoptic bundles. This light illuminates the area being examined. Images from the illuminated area are transmitted back through the large fiberoptic. These images can then be filmed or videotaped. Mahshie's procedure involved passing the fiberscope through the nasal passage over the velum and into the oropharynx behind the tongue. The fiberscope was then positioned immediately superior to the larynx. The subject could speak freely with a minimum of discomfort.

Mahshie's results indicate that the deaf subject's abductory/adductory vocal fold adjustments during consonantal production differed from the normal hearing subjects. The normal hearing speakers distinguished their voiced and voiceless consonants with adducted and opening-closing gestures respectively. The deaf subjects, however, typically failed to distinguish their voiced and voiceless consonants with unique vocal fold gestures. Listener perceived errors in voicing during the deaf subject's consonant productions were consistently related to these inappropriate gestures. For example, segments produced with adducted vocal folds were usually perceived as voiced, regardless of the intended voicing status. Mahshie's findings also indicate that some deaf speakers may attempt to use unique glottal gestures to distinguish voiced and voiceless consonants. These gestures, however, are frequently insufficient to give rise to the correct perception of the intended sounds.

In summary, these findings suggest that deaf speakers demonstrate varying abilities to alter laryngeal adjustments for consonantal productions. Deaf speakers, however, use inappropriate laryngeal adjustments for a particular voicing class. It appears that deaf speakers productions of voiced and voiceless consonants are accomplished with

Fig. 1. Glottal configuration assumed by a normal hearing female during /h/ production in an /ihi/ syllable. This frame was excised from a film that was exposed at 4000 frames/second.

similar vocal fold gestures. These nondifferential gestures result in acoustically similar speech signals which are regarded as voicing errors by listeners.

Recent high speed film data indicate that some deaf speakers use exaggerated laryngeal gestures during speech, as shown in Figures 1, 2, and 3. Figure 1 shows the glottal configuration assumed by a normal speaker during /h/ production in an /ihi/ syllable. Note that the vocal folds are in a semi-adducted posture. Note also that the vocal folds are in the medial glottal plane. Although the folds continue to oscillate slightly during /h/ production, they do not contact one another. Thus, the air stream is not periodically disturbed.

Figure 2 shows the glottal configuration assumed by a deaf female during /h/ production in an /ihi/ syllable. Note the extremely wide vocal fold separation. The vocal folds are not in the medial glottal plane. Moreover, the vocal folds are not positioned correctly to make a smooth transition to the terminal /i/ segment. This notion is supported by aerodynamic and perceptual data. Whitehead and Metz (1980) demonstrated that this deaf female exhibited excessively high air flow rates during /h/ segment production. Also, Whitehead and Metz noted perceptual discontinuities among the individual segments of the /ihi/ syllable. It was almost as though this deaf person treated each segment of the syllable as a separate entity. Metz and Whitehead suggested that this glottal configuration is an abnormal abductory posture.

The glottal configuration assumed by a deaf male during /h/ production in an /ihi/ syllable is shown in Figure 3. This subject devoiced the /h/ segment with a glottal adductory gesture. This adductory gesture involved the true vocal folds and ventricular folds. Air flow measurements of this

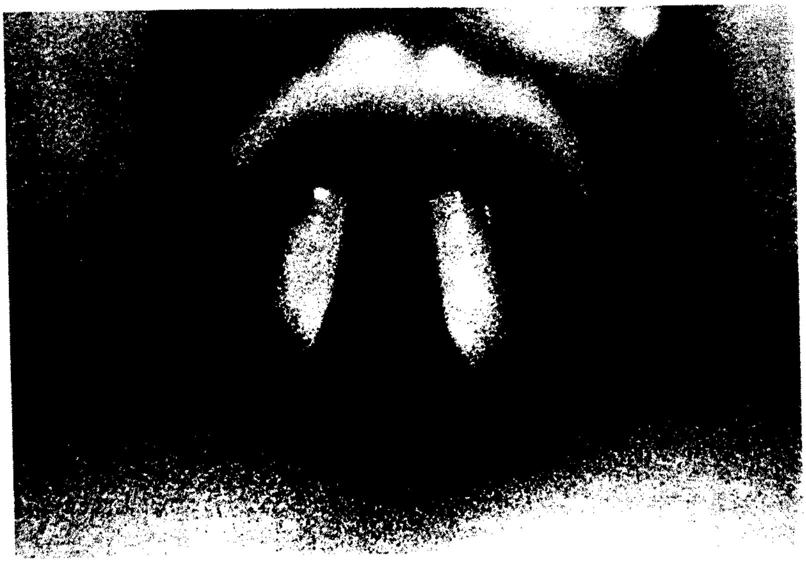

Fig. 2. Glottal configuration assumed by a deaf female during /h/ production in an /ihi/ syllable. This frame was excised from a film that was exposed at 4000 frames/second.

Fig. 3. Glottal configuration assumed by a deaf male during /h/ production in an /ihi/ syllable. This frame was excised from a film that was exposed at 4000 frames/second.

subject's productions of /ihi/ syllables frequently indicated a complete cessation of air flow during /h/ production. Normal reinitiation of voicing for the terminal /i/ vowel was precluded by this abnormal adductory posture. Perceptual discontinuities between the /h/ and terminal /i/ segments were evident.

These data clearly indicate that deaf speakers mismanage laryngeal events during speech production. The nature of this mismanagement appears to be related to abnormal mechanical adjustments of the larynx. Abnormal adjustments seem to interfere with the production of important linguistic parameters. Intonation, stress, and voicing contrasts appear to be deleteriously affected by these abnormal laryngeal adjustments. Such data are interesting in light of some recent acoustic research findings. Reilly (1979) has shown that some deaf individuals use durational contrasts to differentiate stressed and nonstressed syllables. Harris and McGarr (1980) suggested that this reflects a knowledge of the underlying rules governing stress. The absence of frequency and intensity alterations to signal stress may relate to an inability to coordinate respiratory and laryngeal events. The precise nature of these coordination problems is in clear need of further research. Moreover, respiratory-laryngeal discoordinations may be further complicated by laryngeal-supralaryngeal discoordinations. These laryngeal-supralaryngeal discoordinations may give rise to a variety of perceived articulation errors. Some of the research regarding the physiology that may underlie the deaf's articulation problems will be discussed next.

ORAL ARTICULATORY CONSIDERATIONS

Oral articulatory errors of the deaf are well documented. Also, the descriptive research is remarkably consistent with respect to identifying typical segmental error patterns. For example, it is frequently reported that correct production decreases as the place of articulation moves from the front to the back of the mouth. Plosives are more often produced correctly than fricatives. Voiced-voiceless distinctions are often confused. Vowels are frequently substituted for one another, nasalized, or neutralized.

Despite their consistency, these descriptive research findings provide little information regarding the actual nature of the misarticulations made by deaf persons. Recent physiological research, however, provides new insights regarding the underpinnings of these misarticulations. The following arguments will stress that the misarticulations of the deaf are not simply a reflection of inaccurate articulator placements. Rather, these misarticulations reflect a breakdown in interarticulatory timing patterns. This is not a new notion. Hudgins and Numbers (1942) made a similar suggestion 40 years ago. Furthermore, their position was reaffirmed 21 years ago by Calvert (1961). Owing probably to a lack of appropriate instrumentation, little attention has been paid to the nature of these temporal breakdowns.

Recent research regarding the articulation problems of the deaf clearly reflects two important assumptions. First, correct articulations are the result of complex changes in vocal tract configurations as a function of time. Second, appropriate temporal patterning of speech is critical to overall speech intelligibility. Space does not permit a detailed discussion of normal articulatory dynamics. Excellent reviews by Daniloff *et al.* (1980) and by Kent (1976), however, are available to interested readers. Suffice it to say that normal coarticulatory patterns give rise to a highly encoded speech signal. This encoding process provides redundant information regarding the segments that are being produced. Speech intelligibility is greatly reduced when these normal coarticulatory patterns are disturbed.

McGarr and Harris (in press) have demonstrated that deaf speakers exhibit a breakdown in interarticulator timing relationships. This breakdown disturbs normal within word coarticulatory events. Using standard electromyographic and acoustic procedures, they studied lip and tongue activity in one normal hearing and one deaf subject. The lip muscle studied was the obicularis oris. The obicularis oris is the sphincter muscle responsible for closing and puckering the lips. The tongue muscle studied was the genioglossus. The genioglossus muscle is an extrinsic tongue muscle responsible for gross tongue positioning. Each subject produced multiple repetitions of specifically formulated nonsense words. The generalized form of these nonsense words was vowel-consonant-vowel-consonant-vowel-consonant. The consonant was always /p/ and the vowels were either /a/, /i/ or /a/. Thus, the relative timing relationships between lip and tongue gestures could be examined by observing the action potentials of the two muscles. The onsets and offsets of the action potentials were referenced to the acoustic traces of the stimulus words.

The results indicated that the lip muscle activity of the deaf subject was similar to the normal hearing subject. The deaf subject's tongue muscle activity, however, differed considerably from the normal hearing subject. For example, consider the tongue muscle activity associated with the /pi/ cluster in the nonsense work /apapip/. The normal hearing subject consistently exhibited peak tongue muscle activity for the /i/ vowel coincident with the acoustic /p/ burst release. Thus, the tongue was positioned for the /i/ vowel prior to the lip release of the /p/ segment. This relationship reflects a tight temporal coupling between lip and tongue events. In contrast, the deaf speaker frequently exhibited peak muscle activity for the /i/ vowel after lip release for the /p/. Thus, the tongue was positioned for the /i/ after the /p/ segment had been produced. This breakdown in interarticulator timing reflects a segment-by-segment production strategy. Such a production strategy is void of normal coarticulatory patterns.

Rothman (1977) reported similar breakdowns in speech timing relationships. Rothman used electromyographic and spectrographic procedures to observe tongue movement and voicing onset temporal relationships. Four normal hearing and four deaf subjects were studied. His findings indicated that the deaf subjects frequently initiated or terminated voicing for a given segment without the appropriate tongue gesture. Articulatory gestures either inappropriately preceded or followed voicing onsets and offsets. This finding suggests that deaf individuals may have difficulty coordinating phonatory and articulatory events.

McGarr and Löfquist (1981) also noted that deaf individuals exhibit difficulty coordinating phonatory and articulatory events. These researchers monitored lip and laryngeal activity of one normal hearing and three deaf adults. Lip activity was monitored by a transconductance technique. Electrodes were placed on the upper and lower lip. Lip opening and closing activity was measured by detecting changes in the electrical signal strength between the two electrodes. Laryngeal activity was monitored with a transillumination technique. Specifically, light was introduced into the pharynx via a fiberscope. The amount of light passing through the glottis was sensed with a phototransducer. This transducer was positioned on the body surface just below the cricoid cartilage. A small electrical current is passed through the transducer. The strength of the current varies a function of light hitting the transducer. During production of a voiceless sound light energy readily passes through the glottis. During production of a voiced sound light energy is impeded. Thus, fluctuations in current strength are directly related to the abductory/adductory state of the glottis.

McGarr and Löfquist's subjects produced a series of test words that contained either word initial /p/ or /b/ consonants. All test words were embedded in a carrier phrase. The normal hearing subject's productions of the test words reflected a high degree of coordination between laryngeal and supralaryngeal events. During productions of word initial /p/ test words maximum glottal opening was coincident with lip opening and the acoustic burst. Word initial /b/ test words had no glottal opening gesture. Similar laryngeal and supralaryngeal coordinations were observed in one of the deaf subjects who exhibited intelligible speech. The less intelligible deaf speakers, however, demonstrated timing breakdowns between certain laryngeal and supralaryngeal events. For example, one deaf subject exhibited a glottal opening-closing-opening gesture associated with word initial /p/ test word productions. The glottis was open prior to lip closure for the /p/. As the lips began to close for the /p/ segment, the vocal folds abnormally adducted. Following the lip closure release for the /p/ segment, vocal fold abduction was observed. The maximum glottal opening gesture, however, occurred approximately two hundred milliseconds after lip release. This indicates a breakdown in normal laryngeal and supralaryngeal timing relationships. Such breakdowns probably result in voicing contrast errors frequently reported in the speech of the deaf.

Cinefluographic procedures have recently been employed to study articulatory dynamics in deaf persons. Briefly, cinefluographic procedures involve taking relatively high speed lateral x-ray films of the articulators. Small radiopaque markers are attached to selected articulators and other landmarks within the oral cavity. These markers provide consistent measurement and reference points for the experimenter. Analysis of a cineradiographic films usually involves computer-assisted, frame-by-frame tracking of the markers. Measurements of the marker's trajectories provide a wide variety of spatial and temporal information regarding articulatory activity during speech.

In a recent investigation, Stein (1980) employed cinefluographic procedures to study articulatory dynamics of five deaf subjects. Data from the deaf subjects were compared to the data obtained from two normal hearing subjects. Stein found that many of the articulatory movement patterns of the deaf were similar to the normal hearing subjects. Between group differences, however, were observed regarding certain parameters of consonant productions. Specifically, articulator displacements of the deaf subjects were frequently of greater magnitude than the normal hearing subjects. Also, the deaf subjects frequently exhibited faster articulatory speeds with respect to lip, tongue, and jaw movements. Stein further observed that voice onset times frequently occurred early relative to initial consonant productions. Voice offsets frequently occurred late relative to the production of voiceless terminal consonants. The deaf subjects also exhibited delayed tongue movement onsets toward the second consonant in consonant-vowel-consonant syllables. That is, the tongue lagged behind other articulator movements during vowel to consonant transitions. With respect to vowel productions, the deaf subjects tended to differentiate vowel height with jaw movements. The normal hearing subjects differentiated vowel height with tongue movements. Abnormal tongue dorsum movement patterns were also observed during certain vowel productions. From Stein's detailed analyses, no one articulatory parameter could be isolated as a major contributor to the poor speech intelligibility of the deaf subjects. Furthermore, no group of articulatory parameters could be isolated as a major contributor to reduced speech intelligibility.

Zimmermann and Rettaliata (1981) reported similar cineradiographic articulatory data regarding the speech of a post lingually deafened subject. Data obtained from a deaf subject were compared to data obtained from a normal hearing subject. The deaf subject exhibited faster articulatory speeds for lip, tongue tip, and jaw displacements than the normal hearing subject. The deaf subject exhibited longer transition times and longer vowel durations, also. And, the deaf subject tended to differentiate vowel height with jaw movements. Interestingly, Zimmermann and Rettaliata (1981) reported that all the deaf subject's utterances were judged to be phonetically accurate.

These cineradiographic findings indicate that the mismanagement of certain articulatory parameters may have little impact on speech intelligibility. In deaf speech, however, articulatory aberrations may be coupled with abnormal respiratory and laryngeal activity. In such cases, small articulatory deviations could give rise to large speech distortions. This assertion has support from the research previously discussed regarding the deaf's laryngeal-articulatory coordination problems.

In general, it may be parsimonious to relate the deaf's speech errors to one peripheral system. Such an approach, however, is probably erroneous. Normal as well as abnormal speech output is the end product of respiratory, laryngeal, and articulatory events. Moreover, respiratory, laryngeal, and articulatory events must be timed accurately to produce intelligible speech. The deaf appear to have difficulty executing such temporal coordinations. Probably these difficulties are the result of reduced auditory capacity that directly impacts on the development of the requisite motor skills associated with speech production. More research is needed to determine how these inter- and intra-system timing breakdowns relate to specific speech errors. Additionally, research regarding general aspects of speech motor programming is needed. Such research could shed some light on how the deaf organize speech sequences at the cortical level.

For example, in normal speech syllables are concatenated. It is speculated that this concatenation is the result of a central organization of syllabic sequences. That is, syllable sequences are centrally organized into coordinated units called motor programs. Sequential dependencies and timing constraints are encoded in this motor program prior to its actualization during speech. The information encoded in the motor program is realized as a high concatenated syllabic sequence during speech production.

Sternberg *et al.* (1978) argued that coarticulatory effects result from this central encoding process. These researchers showed lists of words to normal hearing subjects. The lists varied in length from one-to-seven words. The subjects were allowed to silently rehearse each list for approximately four seconds. Upon command, they were instructed to start saying the entire list as fast as possible. These researcher's findings were rather remarkable. The length of time taken to start speaking each list increased as a linear function of the number of words to be produced. There was approximately a ten millisecond per word increase in latency between command and speech initiation. That is, assume it took a subject 400 milliseconds to start speaking a list of three words. That same subject would take 410 milliseconds to start speaking a list of four words. This linear function held up to six words. After six words, the linear function broke down. This latency function presumably reflects the requirements to encode more information into the motor program prior to its execution.

The speech of many deaf persons is void of normal syllable concatenations. It is as though some deaf persons speak using syllable-by-syllable production strategy. This suggests that they may be encoding utterances on a syllable-by-syllable basis. Metz *et al.* (1980) predicted that deaf persons would not demonstrate the linear increase in speech initiation times reported for normals. Specifically, it was predicted that a deaf person's syllable-by-syllable production strategy would be revealed by a flat function. That is, initiating five syllables should not require any more time than initiating one syllable. In each case, only a single syllable would be programmed prior to its execution.

Metz *et al.* (1980) replicated the Sternberg *et al.* (1978) paradigm with four normal hearing and two deaf subjects. The preliminary findings are as follows. The normal hearing subjects performed comparably to Sternberg's normal hearing subjects. There was approximately a 12 millisecond per word increase between command and speech initiation. This function was linear up to five words. Both deaf subjects, however, demonstrated relatively flat functions. This finding indicates that deaf persons may adopt production strategies that differ from normal hearing speakers. The lack of syllabic coarticulatory effects in deaf speech may be related to an abnormal pre-speech motor programming strategy. These results are preliminary and more deaf subjects need to be studied. However, continued research could provide insights regarding the impact of early speech experiences on the deaf's speech production skills.

SUMMARY

Data was presented to illustrate how certain abnormal neuromuscular, biomechanical, and aerodynamic events affect the speech of the deaf. Clearly, our understanding of these events is incomplete. For example, we do not understand how the lack of auditory feedback leads to the development of abnormal speech motor activity among deaf speakers. Some recent insights regarding this issue were presented by Zimmermann and Rettaliata (1981). Early oral communication experiences and/or intervention strategies may be a pivotal dimension in the development of the deaf person's speech motor skills. There is clearly a need for research designed to investigate the development of both normal and abnormal speech motor skills among the deaf. There is a growing body of literature that indicates that the speech errors of the deaf are physiologically complex. Moreover, the complexity of these errors frequently precludes accurate *surface level* description. Such complexity underscores the need for continued physiological investigation. It should be pointed out that much of the research we discussed focused on only *peripheral systems*. While such research is important, studies regarding the interactions among these systems are clearly needed. This point is dramatically illustrated by the cineradiographic findings previously discussed. Major articulatory variations could not account for reduced speech intelligibility completely. The importance of such aberrations may be fully realized only when respiratory and laryngeal events are accounted for. The reasons for such occurrences have been speculated earlier in the paper (p. 39).

The deaf appear to have two major problems regarding the use of the physiological systems supporting speech. One is abnormal physical *posturing* of the speech mechanism. For example, deaf speakers initiate speech from low lung volumes. Furthermore, they continue speaking at lung volumes below the functional reserve capacity. Abnormalities in speech breathing may be exacerbated by abnormal *laryngeal postures* like abnormal abduction during voiceless segment productions. Such postural problems can have a deleterious affect on speech intelligibility. The second major problem, however, probably accounts for most of the speech errors produced by the deaf. Deaf speakers appear unable to appropriately coordinate requisite respiratory and laryngeal events with articulatory events. Without such coordinations, intelligible speech is impossible. A better understanding of both these problems will lead to the development of more effective clinical regimes and early intervention strategies. The clinical regimes should be designed to modify the aberrant behaviors that directly underlie the deaf's speech errors. The research discussed in this article represents the first efforts toward this end.

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