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Speech Production Characteristics of the Hearing Impaired

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SPEECH AND LANGUAGE: Advances in Basic Research and Practice, Vol. 8

ISBN 0-12-608608-7

I. INTRODUCTION

One of the most devastating effects of congenital hearing loss is that normal development of speech is often disrupted. As a consequence, most hearing-impaired children must be taught the speech skills that normal-hearing children readily acquire during the first few years of life. Although some hearing-impaired children develop intelligible speech, many do not. For many years it was believed that profoundly hearing-impaired children were incapable of learning to talk. Carrying this belief to the extreme, Froeschels (1932) even suggested that all deaf children exhibited some behavior problems "due to the fact that the profuse motor release connected with speech is impossible in their case" (p. 97).

Within the last decade, advances have been made in studying the speech of the hearing impaired. This is largely due to the development of sophisticated processing and analysis techniques in speech science, electrical engineering, and computer science that have increased our knowledge of normal speech production. In turn, these technological advances have been applied to the analysis of the speech of the hearing impaired as well as to the development of clinical assessment and training procedures.

The oral communication skills of hearing-impaired children have long been of concern to educators of the hearing impaired, speech–language pathologists, and audiologists because the adequacy of such skills can influence the social, educational, and career opportunities available to these individuals. Since the introduction of PL 94-142 and the emphasis on mainstreaming, there is an even greater likelihood that many professionals will need to learn about, or upgrade their knowledge of, the speech of hearing-impaired children. The intent of this article is to provide the clinician, student, and researcher with a comprehensive description of the speech characteristics of this population. It is assumed that the reader has some familiarity with the effects of congenital hearing loss on speech and language development as well as some exposure to acoustic and articulatory phonetics. It should be noted that the majority of information available about the hearing impaired is concerned with children with severe and profound sensorineural hearing losses (losses of 70 dB HTL or greater). In comparison, relatively little is known about the speech of hard-of-hearing children (losses less than 70 dB HTL). It is for this reason that most of this article is devoted to children who are severely and profoundly hearing impaired.

In order to present an in-depth coverage of speech production processes, we have opted to discuss language skills only in those instances where there is no clear-cut separation between language and speech. Likewise, the auditory skills of the hearing impaired will be discussed only to the extent that factors such as hearing level and auditory capabilities affect speech production skills. The emphasis on speech production is not meant to suggest that an aural/oral teaching method is the only appropriate educational plan for hearing-impaired children. The issues involving educational methodologies are not of primary concern here. Rather, it is the belief of the authors that every hearing-impaired child is entitled to speech training services even if a realistic goal of such training may be only the development of functional (survival) speech skills. Before optimal teaching strategies can be selected, however, teachers and clinicians must have a thorough understanding of the nature of the problems that they are trying to remediate.

II. DEVELOPMENTAL ASPECTS OF THE SPEECH OF THE HEARING IMPAIRED

A. Vocalization Patterns

For many years it was believed that the vocalization development of hearing and hearing-impaired infants was the same, at least through the babbling stage. After this period, hearing-impaired infants were reported to stop babbling. This notion was based primarily on Mavilya's (1968) data, which showed a marked decrease in the number of vocalizations produced by three congenitally hearing-impaired infants (12–16 weeks old at the start of the study) over a 3-month period. Recent data obtained by Stark (1982) do not support the findings of Mavilya. Stark observed for a group of hearing-impaired infants 15–24 months old an overall increase in rate of vocal output with age. Mean number of vocalizations were also observed to increase as progressively higher levels of vocal output were attained by the infants. In general, the stages of vocalization behavior of the 15- to 24-month-old hearing-impaired infants were similar to those of a group of normal-hearing infants 9–48 weeks of age. An important point which should be made is that the speech behavior of the infants in both the Stark and Mavilya studies was recorded before the children had been fitted with hearing aids. Stark found that the level of vocal development reached by the children before they were fitted with amplification did not appear to be predictive of their later progress in learning speech. The vocal development of some children progressed rapidly after they were given hearing aids while the vocal development of others did not.

Although Stark found no difference in rate of vocal output between the normal-hearing and hearing-impaired infants, differences in the phonemic repertoire were present between normal infants and hearing-impaired infants who were judged to be at the same level of vocal development. Syllable shape (e.g., CV, VC, CVC) was similar among the children but the inventory of vowel- or consonant-like sounds was more limited in the samples produced by the hearing infants. On the whole, the spontaneous vocalizations of the hearing-impaired infants tended to be more stereotyped than those of hearing infants of the same age. Mavilya also observed that the phonemic aspects of the vocalizations of the hearing-impaired infants in her study were different from those reported for infants with normal hearing. Specifically, she observed a severe delay in the development of consonant sounds in the vocalizations of the hearing-impaired infants, with vowels produced more often than consonants.

In an earlier study, Stark (1967) analyzed the phonemic aspects of the vocalizations of six congenitally hearing-impaired children between the ages of 16 and 19 months before they were fitted with hearing aids. Analysis of the infants' vocalizations revealed that the following sounds were used by all six babies: (1) a low front vowel, such as /æ/; (2) a neutral mid-vowel or schwa; (3) an aspirant /h/, which could precede or follow vowel sounds; (4) a syllablic nasal consonant usually identified as /m/; and (5) a glottal stop. An interesting observation made during this study was that the emotive vocalizations of the hearing-impaired infants, such as whimpering, sighing, crying, and laughing, did not sound deviant, and therefore this aspect of vocal behavior did not provide diagnostic information about the hearing status of infants.

In summary, the results of Stark's (1982) research do not support the belief that hearing-impaired infants simply stop vocalizing upon completing the babbling stage. Differences between the vocalizations of normal-hearing and hearing-impaired infants do emerge at an early age, but the differences are seen in phonemic production rather than rate of vocal output. A comprehensive overview of speech sound inventories in the speech of the hearing impaired appears in the following section.

B. Speech Sound Inventories

Phonetic inventories have been obtained from the spontaneous samples of hearing-impaired children ranging from 11 months to 7 years of age (Carr, 1953; Lach, Ling, Ling, & Ship, 1970; Stark, 1982; Sykes, 1940; West & Weber, 1973). Although these studies report differences in the frequency of specific vowel sounds in the samples of hearing-impaired children studied, the pattern of vowel production is remarkably similar. The vowels most commonly used by young hearing-impaired children include the central vowels /ʌ, ə/ and the low front vowels /æ, ɛ/. The extreme high vowels /i, u/ occurred relatively infrequently in the children's samples. The exception to this pattern was reported by Carr (1953) whose 5-year-old hearing-impaired subjects used a wider range of vowels than noted above. There is some evidence that this pattern of vowel usage changes over time. For example, Lach *et al.* (1970) found that over a 1-year period young hearing-impaired children, 11–32 months of age, who were enrolled in a preschool program tended to shift from the frequent use of the schwa vowel to other vowels, with the greatest increase in usage observed for /I/. Carr (1953) also compared the relative frequency of each vowel type in the speech of 5-year-old hearing-impaired children to that of hearing children and noted that the hearing-impaired children used vowels in a manner and degree similar to hearing infants of 11 to 12 months of age. The hearing-impaired children were also found to use vowel sounds more often than consonant sounds. In another study, Sykes (1940) found that 4- to 7-year-old hearing-impaired children produced almost half of their vowel sounds in isolation and not in combination with a consonant.

Analyses of consonant production have shown that young hearing-impaired children produce front consonants /b, p, m, w/ more often than they produce back consonants (Carr, 1953; Lach *et al.*, 1970; Sykes, 1940), and they have been found to use front consonants with greater frequency than do hearing children (Carr, 1953). In a longitudinal study, Lach *et al.* (1970) analyzed consonant usage by manner of production. Before the children began a preschool program, 66% of all consonants produced were glottal sounds and approximately 25% of the sounds were nasal consonants. After 1 year in the program, the glottal sounds were used only 44% of the time. There was also a large increase in the usage of plosives and semivowels due primarily to an increased use of /b/ and /w/. Fricatives and affricates were used only rarely even after 1 year of training. With only one exception, all children produced a significantly greater number of consonants and vowels after 1 year of training, with a concomitant increase in the consonant-to-vowel ratio.

C. Phonemic and Phonologic Skills

A limitation of the simple sound-type inventories, which were discussed above, is that no information is provided on the phonological usage of the speech segments. A tally of consonants and vowels does not reveal whether or not the phonemes were used appropriately. To overcome this limitation, investigators have begun to perform phonemic, phonological, and linguistic analyses on hearing-impaired children's speech (Oller, Jensen, & Lafayette, 1978; Oller & Kelly, 1974; Stoel-Gammon, 1982; West & Weber, 1973).

A comprehensive study was performed by Stoel-Gammon (1982) in which cross-sectional and longitudinal data were obtained on phonological acquisition by hearing children 1:5 to 3:10 years of age, and hearing-impaired children 2:4 to 7:3 years of age. The cross-sectional data showed that, in large part, the patterns of development were similar for the two groups of children, although the rate of development was considerably slower for the hearing-impaired children than for the hearing children. Similar patterns of correct production and error types were present for both groups of children. The set of substitution patterns common to both groups included voicing of initial stops, devoicing of final stops, fricatives, and affricates, and substitution of homorganic stops for fricatives. When errors were common to both groups, they were more frequent in the speech of the hearing impaired than in the speech of the normal-hearing children.

Some differences in the pattern of development between the normal-hearing and hearing-impaired children were also observed in the above study. Errors found to be present only in the hearing-impaired children's speech were: substitution of a glottal stop for the target phoneme, substitution of the palatal fricative /ʃ/ for the affricates /tʃ and ʤ/, and substitution of back consonants /h, k, g/ for other nonlabial consonants. The only substitution which Stoel-Gammon found to occur in the normal children's productions that did not occur in those of the hearing-impaired was depalatization of /ʃ, tʃ, ʤ/, resulting in a substitution of /s/ for /ʃ/ or /ts/ for /tʃ, ʤ/. The data also showed that the substitutions of the hearing-impaired children deviated further from the target phoneme with respect to manner and place of production than did the substitutions of the normal children. In addition, the errors of the hearing-impaired subjects also tended to show a larger range of substitution types (e.g., /k, g/ for /tʃ/) than those made by the hearing children.

The longitudinal data obtained by Stoel-Gammon revealed that the hearing-impaired children progressed toward correct production of target phonemes at a much slower rate than the normal-hearing children and that there was a much greater range and variation of response types both within and across subjects. The preliminary data suggested that the hearing-impaired children passed through three developmental stages. In the first stage, the child produced a wide variety of substitutions for the target phoneme. In the second stage, there was a narrowing of the range of substitutions followed by substitutions with a single sound. In the third stage, the phoneme was produced correctly. Of course, not all hearing-impaired children progress through the third stage, as evidenced by numerous segmental errors which remain in the speech of many hearing-impaired persons even throughout their adult life.

Additional research is needed in order to delineate the stages of speech acquisition in hearing-impaired children. This information is essential to help us better understand why some children develop intelligible speech and others do not. Although there are data which suggest that hearing-impaired children are simply delayed in phonemic acquisition (Oller *et al.*, 1978; Oller & Kelly, 1974; Stoel-Gammon, 1982), we also know that there are differences in the phonology used by hearing children and hearing-impaired children. In fact, there are noticeable differences between the production patterns of the two groups of children at a very early age, and the speech of some hearing-impaired children never progresses beyond the very early stages of development. As we shall see in the following section, the speech production patterns of older hearing-impaired children show many similarities to the patterns of the younger hearing-impaired children. It will also become evident that although, in many cases, hearing-impaired children fail to follow rules typical of normal speech, the deviations in their speech show systematic patterns, indicating that they are using a set of phonological rules even though these rules may differ from those used by normal speakers.

III. ARTICULATORY PATTERNS IN THE SPEECH OF SEVERELY AND PROFOUNDLY HEARING-IMPAIRED CHILDREN

A. Production of Consonants

1. Overview

Perhaps of all the speech production errors characteristic of the severely and profoundly hearing impaired, the area that has received the greatest attention is that involving the articulation of consonants, vowels, and diphthongs. Numerous independent investigations (Hudgins & Numbers, 1942; Markides, 1970; Smith, 1975; McGarr, 1980) have been remarkably consistent in identifying typical articulatory errors in the speech of hearing-impaired children who were trained in many different programs. Most of these investigations are of a descriptive nature; that is, either listener judgments or phonetic transcriptions were used to obtain measurements of intelligibility or to describe the articulatory characteristics of the speech. However, some investigators (Calvert, 1961; Monsen, 1974, 1976a–d; Rothman, 1976) have begun to detail some of the acoustic characteristics of the speech of the hearing impaired (e.g., voice onset time, closure duration, formant frequencies). Acoustic analysis of hearing-impaired speech permits a finer grained consideration of some aspects of both correct and incorrect productions than would be possible using methods applied in the descriptive literature.

Of course, production of nonarticulatory aspects or suprasegmentals also contributes to the overall patterns of speech production in the hearing impaired. However, for purposes of organization we will consider the production of suprasegmentals as well as other factors that affect the intelligibility of speech later in this article. This section will present information only on the articulatory or segmental aspects of hearing-impaired children's speech. We will first consider the error patterns detailed in the descriptive literature and then discuss the relevant acoustic data for production of consonants and vowels by hearing-impaired speakers.

2. *Consonant Errors*

Any comprehensive analysis of the articulatory skills of hearing-impaired children must begin with the classic work of Hudgins and Numbers (1942). These authors studied 192 subjects between the ages of 8 and 20 years whose hearing losses ranged from moderate to profound. The students read simple sentences and from recordings their productions were later evaluated by teachers of the deaf for proficiency in articulation as well as rate and rhythm. Error categories were established for consonants, vowels, and diphthongs and an attempt was made to relate these patterns to speech intelligibility.

Briefly, the articulatory errors were divided into substitutions, omissions, and severe distortions of the intended phoneme as well as the addition of adventitious phonemes or syllables. Among the more common error types involving consonants were confusion of the voiced–voiceless distinction, substitution of one consonant for another, added nasality, misarticulation of consonant blends, misarticulation of abutting consonants, and omission of word-initial or word-final consonants. This overall pattern of consonant errors has been replicated in numerous studies (Brannon, 1966; Geffner, 1980; Gold, 1978; Levitt, Smith, & Stromberg, 1976; Markides, 1970; Nober, 1967; Smith, 1975) although the actual percentage of errors in any category may vary somewhat from study to study.

a. Voicing Errors. One of the most frequent consonant errors found by Hudgins and Numbers (1942) was confusion of the voiced–voiceless distinction. In subsequent studies, the direction of this error has sometimes been reported as occurring to the voiced member of the pair (Carr, 1953; Heider, Heider, & Sykes, 1941; Millin, 1971; Smith, 1975) and at other times to the voiceless cognate (Mangan, 1961; Markides, 1970; Nober, 1967).

Smith's (1975) study of 40 severely to profoundly hearing-impaired children enrolled in an oral school for the deaf has been among the most comprehensive since Hudgins and Numbers. The 40 children read sentences containing key words that incorporated the most frequent English phonemes with transition to and from the vowels /i/, /æ/, and /u/ for all places of articulation. Voicing errors were common for these children and most often involved substitutions of the voiced for voiceless pair. Studies by Heider *et al.* (1941) and Carr (1953) have also reported a tendency for hearing-impaired children to use more voiced than voiceless sounds in their spontaneous speech. Indeed, Millin (1971) suggested that one manifestation of the voiced for voiceless problem is inappropriate phonation evidenced at the beginning or end of an utterance.

This error pattern, voiced for voiceless substitution, is opposite to that found by Markides (1970) who studied 110 British hard-of-hearing and deaf children. The children produced words as part of an articulation test. A common error was substitution of the voiceless cognate for the voiced. Using the Templin–Darley Test of Articulation, Nober (1967) analyzed production of phonemes by 46 severely and profoundly hearing-impaired children. He also reported that voiceless phonemes were produced correctly more often than voiced phonemes. Data obtained by Mangan (1961) can also be interpreted to show the difficulty that hearing-impaired children have with voicing contrasts. Subjects in this study were reported to devoice final voiced consonants.

Taken together, these studies suggest that coordination of the articulators necessary for voicing contrast is an exceedingly difficult task for hearing-impaired speakers, and that voicing errors are a common segmental problem. Some investigators (McGarr & Löfqvist, 1982; Whitehead & Barefoot, 1980; among others) have begun to examine the physiological manifestations of some typical errors in the speech of the hearing impaired. Their data suggest that voicing errors may be far more complex than represented in the descriptive literature. In fact, some hearing-impaired speakers fail to coordinate the timing of respiration, phonation, and articulation in attempting to produce voicing contrasts. More will be discussed about these findings in a later section.

b. Substitution Errors: Place of Articulation. Another common articulatory error in the speech of the hearing impaired involves the substitution of one phoneme for another; frequently, the substitution is to a phoneme with a similar place of articulation. There is general agreement that phonemes produced in the front of the mouth are more often produced correctly than are phonemes produced in the back of the mouth. This makes sense when one considers that the relative visibility of articulatory gestures should be important to hearing-impaired persons for whom there is reduced auditory information.

Substitution errors involving the same place of articulation have been noted in several studies. Nober (1967) analyzed correctly articulated consonants according to place of articulation and then ranked them from highest to lowest scores as follows: bilabials, 59%; labiodentals, 48%; glottals, 34%; linguadentals, 32%; lingua-alveolars, 23%; linguapalatals, 18%; and linguavelars, 12%. Similar patterns of correct production have been reported by Smith (1975) and Gold (1978); however, these investigators found that sounds produced in the middle of the mouth were more prone to error than were sounds produced in the back of the mouth.

This general trend, better production for more visible phonemes, has been found not only for production of isolated words and sentences (Huntington, Harris, & Sholes, 1968; Geffner & Freeman, 1980; Levitt *et al.*, 1976; Levitt, Stromberg, Smith, & Gold, 1980; Smith, 1975) but also for spontaneous speech (Carr, 1953; Geffner, 1980; Heider *et al.*, 1941).

Some caution should be exercised, however, in interpreting the importance of visibility in and of itself as a key factor in production. Some articulators, such as the lips, although quite visible, are also relatively more constrained and thus permit fewer possibilities for errors than other articulators such as the tongue. Later, we shall discuss some physiological data obtained by Huntington *et al.* (1968) and McGarr and Harris (1982) which are pertinent to this issue.

c. Substitution Errors: Manner of Articulation. A common observation arises from an analysis of consonant errors according to place of articulation. Hearing-impaired speakers tend to position their articulators fairly accurately, especially for those places of articulation that are highly visible, but fail to coordinate properly the movement of the articulators (Huntington *et al.*, 1968; Levitt *et al.*, 1976). The type of consonant substitution that occurs in these cases is often described as one resulting from incorrect timing. These errors are also described as involving an inappropriate manner of articulation.

One example of a common error involving manner of articulation is the nasal–oral substitution. According to Hudgins and Numbers (1942), errors in nasality may be considered to be a segmental problem as well as a problem affecting voice quality, although here we are interested primarily in the former. Nonnasal phonemes were reported by Hudgins and Numbers to be nasalized and nasal consonants were often produced as stops. Similar findings have also been noted by Markides (1970), Smith (1975), and Stevens, Nickerson, Boothroyd, and Rollins (1976).

Other errors in manner of articulation have also been noted. Smith's hearing-impaired children were most often in error when producing the following: palatal plosives, fricatives, affricates, and the nasal/ŋ/. Glottals were frequently substituted for stops and fricatives showed a high rate of substitution to, but not from, the plosives. Affricatives were never substituted for other consonants but tended to be substituted by one of their components, usually the plosive component. However, bilabial plosives, the glides, and the fricatives /f/ and /v/ were often produced correctly. Nober's (1967) results also followed the general pattern reported by Smith: glides were most often correct, followed by stops, nasals, and fricatives. Similar findings were obtained by Geffner and Freeman (1980) for 67 6-year-old severely and profoundly hearing-impaired children attending schools for the deaf throughout the state of New York.

The articulatory movements for both alveolar and velar sounds are visually obscure. One reason why alveolar sounds may be more prone to error than velar sounds is that more sounds are produced in the middle than in the back of the mouth. Because of this, precise positioning of the articulators is necessary in order to differentiate correctly all the sounds with a medial place of articulation. Thus, greater variability in articulatory placement can be tolerated before the velar sounds are misperceived by the listener. In any event, a consistent finding is that hearing-impaired children correctly produce the highly visible phonemes (i.e., those produced in the front of the mouth) more often than those phonemes which are not articulated with a high degree of visibility (i.e., those produced in the middle or back of the mouth).

d. Omission Errors. By far the single most frequently reported error in the speech production of the severely and profoundly hearing impaired is the omission of a phoneme (Hudgins & Numbers, 1942; Markides, 1970; Smith, 1975). Omission of consonants may occur in the initial and/or final position of words, also reported as nonfunction of releasing or arresting consonants, respectively.

Hudgins and Numbers reported that omission of initial consonants was more common than omission of final consonants. The consonants most frequently omitted from the initial position of words included /h, l, r, y, th, s/. Turning to final consonants, the authors point out several error patterns: dropping of the consonants completely, releasing the consonants into the following syllable, or incomplete production whereby the phoneme loses its dynamic properties and becomes merely a passive gesture. Among the final consonants most frequently omitted in the Hudgins and Numbers study were /l, t, s, z, d, g, k/. These results are in agreement with those reported by Geffner (1980) who analyzed the spontaneous speech samples of young hearing-impaired children.

Others (Nober, 1967; Markides, 1970; Smith, 1975) have also observed similar consonants omitted from the speech of hearing-impaired children. In contrast to Hudgins and Numbers, however, these studies reported a greater number of consonants omitted from the final position of words than from either the initial or medial positions.

e. Consonant-Cluster Errors. Not many investigators have reported data for production of consonant blends. This is surprising since Hudgins and Numbers suggested that these errors had an important and deleterious effect on intelligibility. In their study, these errors involved two forms: one or more components of the cluster were dropped or an adventitious phoneme, usually the /ə/, was added between the elements. This latter error may be particularly detrimental to the timing or rate and rhythm of speech. Brannon (1966) also found that misarticulation of consonant blends was a significant error in the speech of hearing-impaired children. Smith (1975) tested consonant blends /p, t, k/ and /s/ in the speech production of older hearing-impaired children (13–15 years old). Here again, there was frequent omission of one or more elements of the cluster. In fact, a phoneme in the blend environment was more likely to be omitted than the same phoneme occurring in a nonblend environment.

B. Acoustic Characteristics of Consonant Production

We now turn to a discussion of the acoustic patterns of consonant production. Whereas these consonantal features have been extensively studied in normal speech as well as with synthetic speech (cf. Borden & Harris, 1980; Pickett, 1980, for a review of this work), there have been far fewer studies of the acoustic characteristics of consonants produced by hearing-impaired speakers. This is in part because spectral measurements of hearing-impaired speech are particularly difficult to make, either because of the mismatch between spectrograph filter and fundamental frequency (cf. Huggins, 1980) or because of source function abnormalities (Monsen, Engebretson, & Vemula, 1979).

In normal speech production, the acoustic consequences of consonant production are complex and spread over a period of time. They involve differences in the sound source and the spectral composition of the signal. For example, in the production of a voiceless fricative in a vocalic environment (e.g., VCV, *I see*), the sound source is changed from a periodic to an aperiodic one and then back to the periodic source. Similarly, a voiceless aspirated stop in a similar VCV environment (e.g., *a pie*) is associated with the following sequence of source changes: periodic voicing during the preceding vowel, silence during the consonantal closure, transient noise, aspiration noise, and periodic voicing during the vowel. In addition to being spread across time, the acoustic attributes of many consonants often involve short-term spectral changes, where high-frequency components play an important role. Examples of such attributes are release bursts and formant transitions for stop consonants and spectra and transitions for fricatives. These characteristics provide considerable information as to the identity of segments. In the speech of the hearing impaired, acoustic analysis of consonant production has been made only for voice onset time (VOT), formant transition, or closure and constriction duration, and these patterns give ample evidence for the great perceptual difficulty that listeners to the speech of the hearing-impaired experience.

1. Voiced–Voiceless Distinction

At the acoustic level, contrasts such as *voiced* versus *voiceless* or *aspirated* versus *unaspirated* are manifested as complexes of acoustic cues (Slis & Cohen, 1969a,b). In the classic study of Lisker and Abramson (1964), release of the oral occlusion relative to the onset of glottal pulsing (i.e., VOT) was one of the salient cues that distinguished voiced from voiceless stops. As was previously discussed, errors in voicing are common in the speech of the hearing impaired, and some acoustic studies of the speech of the hearing impaired provide evidence that a lack of VOT contributes to the perception of the voiced–voiceless confusion.

Perhaps the most careful study in this area has been conducted by Monsen (1976b). Spectrographic measurements of VOT were made of word-initial stops /p, t, k/ and /b, d, g/ produced by 36 profoundly hearing-impaired children. Some of the children distinguished the cognates in the normal manner. VOT values were longer for the voiceless than voiced segments and VOT contrasts were longer for velars than for alveolars and bilabials, respectively. However, most of the hearing-impaired speakers did not observe the voiced–voiceless distinction and deviated from normal speakers in a similar way. Typically, VOT values for voiceless segments were lower than those for voiced and also overlapped with the measurements for voiced. This pattern was noted for /p–b/ and /t–d/ although measurements for /k–g/ were more complex. Furthermore, these subjects did not distinguish VOT among stops based on place of articulation. Hearing-impaired speakers who observed the voiced–voiceless distinction typically had high speech intelligibility, probably because they were capable of producing other aspects of speech normally as well. Hearing-impaired speakers who did not observe these contrasts tended to collapse the voiced–voiceless categories, producing most segments as voiced, and these speakers were considerably less intelligible than those speakers who produced the voicing distinction.

Findings similar to Monsen's have been shown in the earlier work of Calvert (1961) and Irvin and Wilson (1973), and more recently as part of measurements made in studying the acoustic and articulatory correlates of the speech of the hearing impaired (Mahshie, 1980; McGarr & Löfqvist, 1982; Stein, 1980). In the McGarr and Löfqvist study, the authors noted that VOT values for some of their hearing-impaired speakers fell in the range of 20–30 msec, which is close to the perceptual boundary where interactions and shifts in the perception of voicing have been shown to occur. This may be one reason why listeners to the speech of the hearing impaired have difficulty making judgments of particular phonetic segments. We will return to these physiological studies later.

2. *Formant Patterns of Transition*

Hearing-impaired speakers have often been described as having difficulty in moving their articulators correctly from one phoneme to the next (Calvert, 1961; John & Howarth, 1965; Martony, 1965; Smith, 1975). One manifestation of this problem at the acoustic level is distortion of formant frequency transitions.

Changes in the formant frequencies, particularly the direction, extent, and duration of the second formant transition, have been shown to be important acoustic cues for the place of articulation (Delattre, Liberman, & Cooper, 1955; Liberman, Delattre, Gerstman, & Cooper, 1956). As discussed above, hearing-impaired speakers characteristically produce many errors involving the place of articulation.

Whereas there have been only a few acoustic analyses of formant transition of hearing-impaired speakers, these studies are nonetheless in general agreement (Martony, 1966; Monsen, 1976c; Rothman, 1976). In general, this work shows that formant transitions were exceedingly short in duration or missing altogether, that the extent of the frequency range of the transitions was limited in part because the formant frequencies for vowels were greatly neutralized, and that transitions varied little with respect to phonetic context. In addition, the slope of the transitions frequently remained fairly flat when either a rising or falling pattern was dictated. Thus, F2 transitions in the speech of the hearing impaired may be reduced in both time and frequency. These patterns, together with deviations in the steady-state formant frequencies for vowels (to be discussed later), suggest that hearing-impaired speakers have reduced articulatory movement and an absence of the coarticulatory effects observed in the speech of normal-hearing speakers.

C. Production of Vowels and Diphthongs

1. Overview

Hudgins and Numbers (1942) were again among the first investigators to study systematically the production of vowels and diphthongs in the speech of the hearing impaired. They classified the errors according to five major types. These included:

1. Substitution of one vowel for another
2. Neutralization of vowels
3. Diphthongization of vowels
4. Nasalization of vowels
5. Errors involving diphthongs: either the diphthong was split into two distinctive components or the final member of the diphthong was dropped

In their study, substitutions and neutralization of vowels as well as difficulty with the production of diphthongs were among the most common errors. Essentially the same pattern has been replicated in other studies of hearing-impaired speakers regardless of whether the vowel was produced in a CVC framework (Angelocci, Kopp, & Holbrook, 1964; Calvert, 1961), in test words (Geffner, 1980; Mangan, 1961; Markides, 1970; Nober, 1967), or in sentences (Smith, 1975).

The literature is also in agreement concerning the frequency of vowel versus consonant errors. Overall, fewer errors in vowel production have been reported, although it should be noted that this finding may be influenced by variables in both production and perception. For example, Brannon (1966) claimed that vowels were in fact easier for hearing-impaired speakers to produce than consonants since vowels were supposed to require less precise articulatory position, although surely one might argue otherwise. Perceptually, Hudgins and Numbers (1942) and later Monsen (1976c) suggested that listeners will tolerate a greater degree of distortion in vowels than in consonants, hence the report of fewer vowel errors. Furthermore, acoustic information conveyed in the vocalic position of the stimulus also provides information of consonants and, thus, if erroneous (as we will discuss later), may directly affect the perception of the consonant. In general, it should also be noted that fewer vowels than consonants are produced in running speech and thus there is less opportunity for error.

2. Vowel Errors

Traditional classification schemes for vowels employ such categories as tongue position (high–low, front–back), tongue tension (tense–lax), and degree of lip rounding. These refer to articulatory events and are important to our subsequent discussion of the acoustic characteristics of vowels. In general, hearing-impaired speakers have been found to produce back vowels correctly more often than front vowels (Boone, 1966; Geffner, 1980; Mangan, 1961; Nober, 1967; Smith, 1975) and low vowels correctly more often than those with mid or high tongue positions (Geffner, 1980; Nober, 1967; Smith, 1975). In fact, Boone (1966) suggests that hearing-impaired speakers tend to keep their tongue retracted in a low back position, generating resonances that further interfere with the perception of front vowels. In contrast, Stein's (1980) cinefluographic study of vowels produced by hearing-impaired speakers showed *fronting* of back vowels.

With respect to errors of substitution, hearing-impaired speakers often confuse the tense–lax distinction (e.g., i–I) or substitute a vowel that is clearly related in articulatory position (Mangan, 1961; Monsen, 1974; Smith, 1975), although there is evidence to the contrary (Hudgins & Numbers, 1942; Markides, 1970). The commonly observed error of neutralization, a problem akin to substitution, has been noted in the descriptive literature (Heider *et al.*, 1941; Markides, 1970; Smith, 1975) as well as in acoustic studies (Angelocci *et al.*, 1964; Monsen, 1976a, 1978). This work suggests that the hearing-impaired speaker tends to produce all vowels approaching the pattern for the neutral vowel /ə/. This error has implications at the segmental as well as the suprasegmental level since in the latter case the syllable is shortened and often not given the appropriate stress.

Other commonly reported errors in vowel production include inappropriate nasalization of vowels (Martony, 1966; Stevens *et al.*, 1976) and diphthongization of pure vowels (Boone, 1966; Markides, 1970; Smith, 1975). With the exception of the study by Hudgins and Numbers (1942), very little additional data have been collected on production of diphthongs, the error patterns reported being essentially the same (Levitt *et al.*, 1980; Nober, 1967).

D. Acoustic Characteristics of Vowels

The acoustic characteristics of vowels and diphthong production, like those of consonants, have been studied in great detail in normal speech production, but again little in the speech of the hearing impaired. We will concentrate here primarily on studies of vowel formants, leaving a discussion of timing characteristics (i.e., duration) and segmental influences on fundamental frequency until later in this article.

The formant frequencies, especially the first (F_1) and second (F_2) formants, are traditionally used to provide an acoustic description of vowels. Usually, these formant values are plotted against each other and the data points for each vowel cluster into fairly distinctive regions (cf. Peterson & Barney, 1952). Interestingly, the acoustic vowel plot of F_1 and F_2 closely resembles the articulatory vowel map. Although the relationship between acoustic and articulatory correspondence is not simple, it has been suggested that F_1 (which increases and then decreases as the vowels go from /i/ to /u/) represents tongue height, and that F_2 (which decreases from /i/ to /u/) represents the constriction of the tongue in the front–back plane. Of course, events such as degree of lip rounding, pharyngeal constriction, as well as individual speaker differences, must also be considered.

Analysis of spectrograms of this population is not without problems. In many cases, the fundamental frequency (F_0) of hearing-impaired speakers is often quite high. This may create a mismatch between the source and the bandwidth of the spectrogram filter, thus obscuring important harmonics. This problem is the same as one faced in the spectrographic analysis of young hearing children's speech (cf. Huggins, 1980). Spectrographic analysis of hearing-impaired persons' speech is further complicated by perturbations in the source, inappropriate management of intensity, and/or inappropriate nasalization that introduces additional and often unusual harmonics in the spectra. This often precludes easy and straight-forward analysis. Some of these problems may be circumvented by the use of digital analysis techniques such as Linear Predictive Coding (LPC). Even with the use of LPC, determination of formant frequency location may still be difficult, particularly if the child has a high fundamental frequency.

There have been several studies that have examined the acoustic characteristics of vowels produced by hearing-impaired children using spectrographic analysis (Angelocci *et al.*, 1964; Monsen, 1974, 1978), and one study in which the speech was digitized and subjected to LPC analysis (Osberger, Levitt, & Slosberg, 1979). Besides instrumentation differences, these studies are distinguished in that the latter work includes only productions perceived as correct in hearing-impaired children's speech, whereas the other studies are not clear with respect to this point. Nonetheless, the results of these studies show that the formant frequencies of deaf children's vowels tend toward that of the neutral vowel /ə/. This result is of further interest since the hearing-impaired subjects in both the Monsen and the Osberger *et al.* studies produced vowels in sentence context, whereas subjects in the Angelocci *et al.* study produced vowels in CVC monosyllables. The data from these studies are interpreted to suggest that hearing-impaired speakers use a restricted amount of tongue movement to achieve vowel differentiation. Indeed, several investigators (Angelocci *et al.*, 1964; Martony, 1968) have suggested that differences in vowels produced by hearing-impaired speakers are achieved primarily by means of variation in fundamental frequency.

In addition to reduced phonological space for all vowels and extensive overlapping of vowel areas, Monsen (1976a) also noted that the second formant of vowels remained around 1800 Hz rather than varying as different vowels were articulated. This *immobility of* F_2 not only deleteriously affects perception of the vowel but also interferes with transmission of consonantal information. The difficulty with F_2 is not surprising since many hearing-impaired speakers have residual hearing only in the frequency range of F_1 and not in the range of F_2. Another factor is the relative invisibility of tongue constriction from a front-to-back position that is primarily responsible for the second formants. Articulatory movements such as jaw lowering associated with F_1 are certainly more visible.

Very little is known about the acoustic aspects of diphthong production in the hearing impaired. Monsen (1976d), using spectrographic measurements of the diphthong /aI/, has classified deviant acoustic patterns on the basis of frequency change during production of the diphthong. One deviant pattern is characterized by a large change in the frequency of F_1 with an immobility of F_2. Monsen hypothesized that this pattern results when the appropriate jaw movement is not accompanied by appropriate movement of the tongue. Minimal movement of both F_1 and F_2 was another pattern observed which Monsen attributed to a generally stable vocal tract throughout production of the diphthong with minimal jaw movement. A third pattern was a reversal of the direction of movement of F_2 with respect to normal. Monsen hypothesized this to be the acoustic consequence of the diphthong being produced with the tongue lowered and retracted.

IV. NONARTICULATORY PATTERNS IN THE SPEECH OF SEVERELY AND PROFOUNDLY HEARING-IMPAIRED SPEAKERS

This section will present information on the nonarticulatory aspects of hearing-impaired children's speech. These patterns are also referred to as *suprasegmental* because they involve characteristics of speech that extend over units composed of more than one phonetic segment. Included in this category are characteristics such as timing, intonation, and stress assignments. These areas, as well as the acoustic correlate of pitch (fundamental frequency) and factors affecting perceived voice quality will be described in this section.

A. Timing Patterns

1. Overall Speaking Rate

With few exceptions, the speech of the severely and profoundly hearing impaired is perceived as being too slow and sounding very labored. Physical measures of speaking rate have shown that profoundly hearing-impaired speakers, on the average, take 1.5 to 2.0 times longer to produce the same utterance as do normal-hearing speakers (Boone, 1966; Heidinger, 1972; Hood, 1966: John & Howarth, 1965; Voelker, 1935, 1938). The reduced speaking rate is due to the excessive prolongation of speech segments and the insertion of pauses.

Prolongation of speech segments may be present in the production of phonemes, syllables, and words. Calvert (1961) was among the first to obtain objective measurements of phonemic duration in the speech of the hearing impaired by spectrographic analysis of bisyllabic words. The results of this study showed that hearing-impaired speakers extended the duration of vowels, fricatives, and the closure period of plosives up to 5 times the average duration for normal speakers. In a later study, Osberger and Levitt (1979) observed that syllable prolongation in the speech of the hearing-impaired was due primarily to prolongation of vowels.

Figure 1 shows data obtained by Osberger (1978) on mean syllable duration in a sentence produced by six normal-hearing and six profoundly hearing-impaired children. The data show a distinct pattern of syllable durations for the two groups of speakers. The line connecting the data points of the hearing-impaired speakers lies above and is approximately parallel to that of the hearing children. The exception to this is the sixth syllable where the mean syllable duration is shorter for the hearing-impaired than for the normal speakers. This was due to the omission of

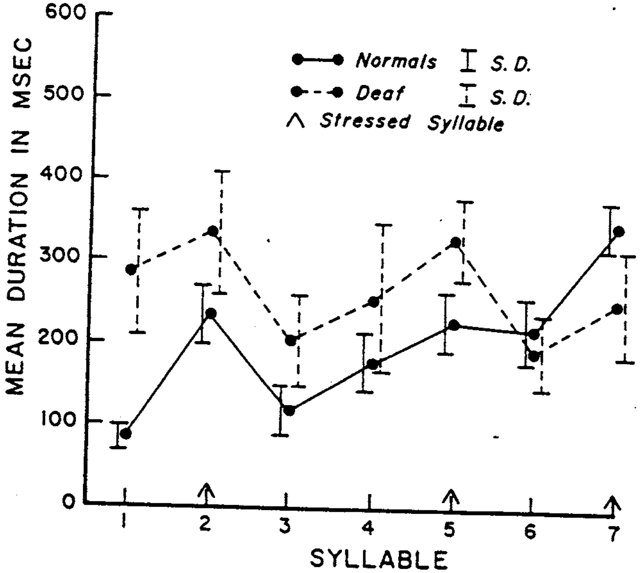

Figure 1. Mean duration (in milliseconds) for syllables in the sentence *I wish I could read that book* produced by six normal-hearing children and six hearing-impaired children. The standard deviation is represented by the vertical bars. (After Osberger, 1978.)

some of the phonemes in the syllable by the hearing-impaired speakers, making the duration of the syllable shorter than would be expected if all of the intended segments had been produced. The size of the standard deviations, shown by the vertical bars, indicates that there is greater variability in syllable duration among the hearing-impaired than among the normal speakers.

Profoundly hearing-impaired speakers typically insert more pauses and pauses of longer duration than do speakers with normal hearing (Boone, 1966; Boothroyd, Nickerson, & Stevens, 1974; Heidinger, 1972; Hood, 1966; John & Howarth, 1965; Stevens, Nickerson, & Rollins, 1978). Pauses may be inserted at syntactically inappropriate boundaries such as between two syllables in a bisyllabic word or within phrases. The greatest difference between normal-hearing and hearing-impaired speakers has been observed in the durations of inter- and intraphrase pauses (Stevens *et al.*, 1978). The results of Hudgin's (1934, 1937, 1946) early investigations indicate that the frequent pauses observed in the speech of the hearing impaired may be the result of poor respiratory control. Specifically, Hudgins found that deaf children used short, irregular breath groups often with only one or two words, and breath pauses that interrupted the flow of speech at inappropriate places. In addition, there was excessive expenditure of breath on single syllables, false groupings of syllables, and misplacements of accents. Later, we shall discuss the propensity of hearing-impaired speakers to use inappropriate breath groups.

2. *Segmental Timing Effects*

Acoustic analyses of normal speech have shown that the duration of vowels is systematically influenced by effects operating at the level of phonetic segments. Since vowels form the nuclei of the larger segments of speech, these differences in vowel duration exert substantial effects on both the production and perception of the temporal and segmental aspects of speech. Vowels have been described as having an intrinsic duration (Peterson & Lehiste, 1960) and, in comparable contexts, some vowels are consistently shorter than other vowels (House, 1961). Hearing-impaired speakers with severe and profound losses have been found to distort this relationship between the vowels. For example, Monsen (1974) observed that /i/ was relatively longer than /I/ in monosyllabic words in the speech of normal-hearing subjects, but in the speech of profoundly hearing-impaired children there was a tendency for these vowels to occupy mutually exclusive duration ranges. McGarr and Harris (1980), on the other hand, found that the profoundly hearing-impaired speaker in their study did not show consistent differences in intrinsic vowel duration.

There is a substantial literature showing that the average duration of vowels also varies markedly as a function of phonetic context in normal speech. When different phonetic contexts are considered, the voicing characteristic of the following consonant has been shown to have one of the most dramatic effects on vowel duration. Acoustic measurements have consistently shown that for normal speakers, the duration of a vowel preceding a voiceless consonant is, on the average, less than the vowel duration preceding a voiced consonant in stressed syllables (Denes, 1955; House, 1961; House & Fairbanks, 1953; Peterson & Lehiste, 1960). This systematic change in vowel duration has been found to be a significant perceptual cue to the voicing characteristic of the following consonant or consonant cluster (Raphael, 1972). Results obtained by Calvert (1961) and Monsen (1974) have shown that the hearing impaired fail to produce the appropriate modifications in vowel duration as a function of the voicing characteristic of the following consonant. Thus, the frequent voiced–voiceless confusions which have been observed to occur in the speech of the deaf may actually be due to vowel duration errors (Calvert, 1961).

3. *Suprasegmental Timing Effects*

The duration of segments is also influenced by effects operating at the level of syllables, words, and phrases. In English, changes in contrastive stress have been found to produce systematic changes in vowel duration. When vowels are stressed, they are longer in duration than when the same vowels are unstressed (Parmenter & Trevino, 1936). This durational variation has also been found to be an important cue for the perception of stress (Fry, 1955, 1958).

Several investigations have shown that whereas hearing-impaired speakers make the duration of unstressed syllables shorter than that of the stressed syllables, the proportional shortening is smaller, on the average, in the speech of the hearing impaired than in the speech of normal subjects (Stevens *et al.*, 1978; Osberger & Levitt, 1979). In contrast to this finding, Reilly (1979) found larger than normal duration differences between vowels in primary- and weak-stress syllables produced by a group of profoundly hearing-impaired children. These data are shown in Fig. 2. In this figure, duration has been calculated for the vowels /i, I, u/ produced in both primary- and weak-stress syllables by hearing and hearing-impaired children. For /i/ and /u/, longer average durations were measured for greater stress for both groups, with the hearing-impaired durations being longer overall, and the difference between the primary and weak syllables being more extreme than in the samples produced by the hearing children. There was almost no difference in duration between the primary and weak /I/ in the normal children's samples, whereas the hearing-impaired speakers produced longer durations of /I/ in weak syllables than in primary stress syllables.

Exactly how a hearing-impaired speaker uses temporal manipulations to convey differences in syllabic stress pattern is not clear. In a recent study, McGarr and Harris (1980) found that, although intended stressed vowels were always longer than unstressed vowels in the speech of one profoundly hearing-impaired speaker, the intended stress pattern was not always perceived correctly by a listener. Thus, the hearing-impaired speaker was using some other suprasegmental feature to convey contrastive stress. Variation in fundamental frequency would be a likely alternative; but McGarr and Harris also found that while the hearing-impaired speaker produced the systematic changes in fundamental frequency associated with syllable stress, perceptual confusions involving stress pattern were still observed.

Another suprasegmental temporal effect which occurs in normal speech is prepausal lengthening. When a syllable occurs before a pause that marks a major syntactic boundary, it is longer in duration than when it

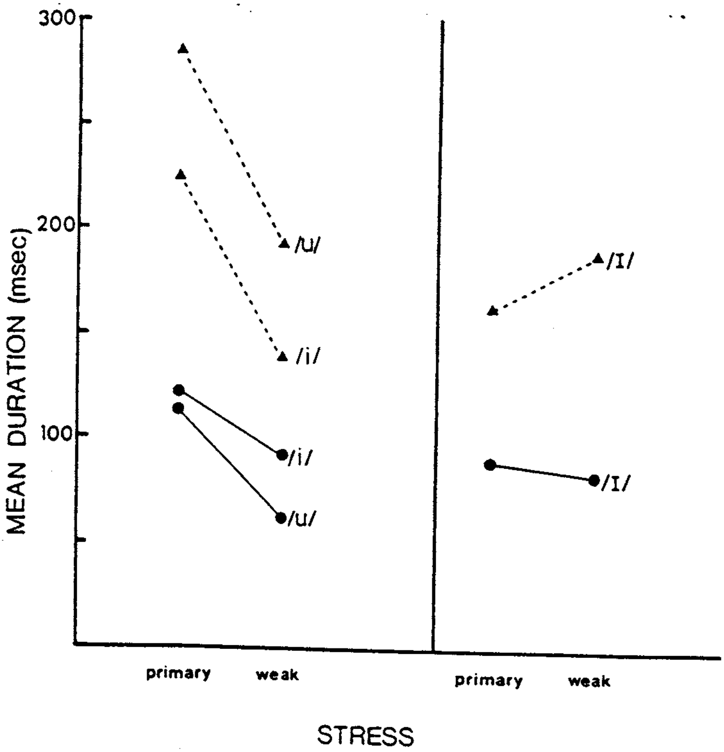

Figure 2. Mean vowel duration (in milliseconds) in primary- and weak-stress syllables produced by a group of normal-hearing (●) and a group of profoundly hearing-impaired (▲) children. (After Reilly, 1979.)

occurs in other positions in a phrase (Klatt, 1975). It has been observed that hearing-impaired speakers do not always lengthen the duration of phrase-final syllables relative to the duration of the other syllables in the phrase. Stevens *et al.* (1978) observed that when there was evidence of prepausal lengthening in the speech of profoundly hearing-impaired talkers, the increase in the duration of the final syllable was much smaller, on the average, for the hearing-impaired speakers than for the normal-hearing speakers. In contrast to this finding, Reilly (1979) found that the group of profoundly hearing-impaired speakers she studied used duration to differentiate prepausal and nonprepausal syllables. As was the case for primary- and weak-stress syllables discussed above, Reilly observed a larger than normal difference between the duration of syllables in the prepausal and nonprepausal position in the samples produced by the hearing-impaired children.

The information presented above clearly shows that profoundly hearing-impaired speakers distort many temporal aspects of speech. These distortions, such as excessively prolonged speech segments and the insertion of both frequent and lengthy pauses, are perceptually prominent and disrupt the rhythmic aspects of speech. However, in spite of these deviancies, there is evidence that suggests the hearing-impaired talker manipulates some aspects of duration, such as those involving relative duration, in a manner similar to that of speakers with normal hearing.

B. Fundamental Frequency Patterns

1. *Average Fundamental Frequency*

Among the most noticeable speech disorders of the hearing impaired are those involving fundamental frequency (F_0). In normal speech, there are differences in average fundamental frequency depending on the sex and age of the speaker. Reported fundamental frequency values range from 100 to 175 Hz for adult males and from 175 to 250 Hz for adult females (Fairbanks, 1940; Fairbanks, Wiley, & Lassman, 1949b; Fairbanks, Herbert & Hammond, 1949; Hollien and Paul, 1969). Recent data (Hasek, Singh, & Murry, 1981) suggest that a significant difference between the average F_0 of preadolescent male and female children with normal hearing begins to emerge by 7 or 8 years of age, with the sex difference attributable to a reduction in F_0 for male children only, beginning around age 7. No significant preadolescent age-related change in F_0 in females was observed.

If there is a problem with a hearing-impaired speaker's average fundamental frequency, more often the voice pitch is characterized as too high rather than too low (Angelocci *et al.*, 1964; Boone, 1966; Martony, 1968). Some differences in average F_0 have been found as a function of the age or sex of the hearing-impaired speaker. The results of several studies have shown that there are no significant differences in average F_0 between young hearing and hearing-impaired children in the 6–12 year age range (Boone, 1966; Green, 1956; Monsen, 1979). Differences have been reported between groups of older children but it is not clear if pitch deviation is greater for hearing-impaired females or males. Boone (1966) found a higher average F_0 for 17- to 18-year-old males than females. Osberger (1981) found that the difference in F_0 between hearing and hearing-impaired speakers in the 13–15 year age range was greater for females than for males. This finding is illustrated in Fig. 3 which shows the F_0 values averaged across sentences for six subjects with normal hearing and 10 hearing-impaired subjects. As can be seen, the F_0 for the female hearing-impaired speakers ranged between 250 and 300 Hz. This value is

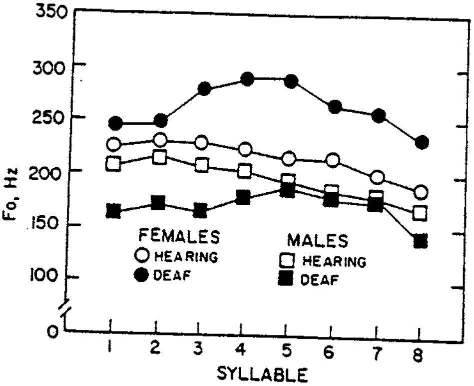

Figure 3. Fundamental frequency values (in hertz) measured at the center of the vowel in each syllable in the sentence, *I like happy movies better*, for groups of normal-hearing and profoundly hearing-impaired males and females.

about 75 Hz higher than that observed for the normal-hearing females. The average F_0 value of the utterances of the male hearing-impaired speakers is slightly lower than that of the hearing males for the first part of the utterance. The F_0 values for the hearing and hearing-impaired male speakers overlap for the last half of the utterance. Bush (1981) observed excessive segmental variations in F_0 for a small group of profoundly hearing-impaired females in the same age range as those in the Osberger study. Age-related factors such as laryngeal growth accompanied by adolescent voice change or similarities in speech training were suggested by Bush as reasons for the problems of the females in controlling F_0.

Up to this point, we have limited all our discussion to physical measures of fundamental frequency. In a clinical or school situation, the examiner will not have, in most cases, the equipment necessary to make such measurements. In these settings, the clinician will have to rely on his or her perceptual abilities to evaluate the appropriateness of the child's pitch. The pitch deviancy of profoundly hearing-impaired children has been evaluated perceptually by McGarr and Osberger (1978) using a five-point rating scale. The profile rating of pitch register (Subtelny, 1975) and the descriptors are shown in Table I. The scale was used with approximately 50 children 10–11 years of age. The results of this study showed that a large number of the children received pitch ratings that were either appropriate for their age and sex or differed only slightly from optimal level. Thirty-two of the children received an average rating higher than 4.0. There was, however, a small group of children who could not sustain phonation and whose speech was characterized by pitch breaks or large

Table I. Rating Scale Used to Evaluate Pitch[a]

Profile rating	Functional descriptor
1	Cannot sustain phonation
2	Much above (+) or much below (−) optimal level
3	Moderately above (+) or moderately below (−) optimal level
4	Slightly above (+) or slightly below (−) optimal level
5	Appropriate for age and sex

[a] From Subtelny (1975).

fluctuations in pitch. On the whole, these findings are in agreement with earlier studies which indicate that the pitch of many preadolescent hearing-impaired children is within the normal range. However, it is not clear to what extent the average F_0 of a hearing-impaired child's speech can differ from that of a normal child before it is perceived as deviant. It is possible that rather large differences in F_0 can exist between normal and hearing-impaired speakers before pitch is perceived as deviant and remedial training is indicated.

2. *Intonation Patterns*

Intonation is the perceived pattern of change in fundamental frequency within a phrase or sentence. Reference is made, even in the very early literature, to the difficulties that hearing-impaired speakers experience in controlling this aspect of speech. Haycock (1933), Rawlings (1935), Russell (1929), Scripture (1913), and Story (1917) all describe the speech of congenitally deaf persons as *monotonous* and *devoid of melody*. Later investigations showed that hearing-impaired speakers did produce pitch variations, but the average maximum pitch changes were more reduced than those of speakers with normal hearing (Green, 1956; Hood, 1966; Voelker, 1935).

Some hearing-impaired speakers may demonstrate an intonation problem in the form of excessive and inappropriate changes in fundamental frequency. These speakers may raise or lower F_0 100 Hz or more within the same utterance. Often, after a sharp rise in fundamental frequency, the hearing-impaired speaker loses all phonatory control and there is a complete cessation of phonation. These excessive and erratic changes in F_0 have been described by several investigators (Monsen, 1979; Smith, 1975; Stevens *et al.*, 1978).

Figure 4 shows the intonation contour of a simple, declarative sentence spoken by a normal, 14-year-old female. There is a rise in F_0 at the

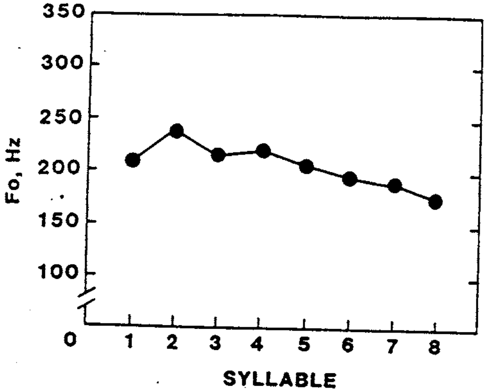

Figure 4. The intonation contour of the simple declarative sentence, *I like happy movies better,* spoken by a normal-hearing child. Each data point is the fundamental frequency value (in hertz) measured at the center of the vowel in each syllable in the sentence.

beginning of the sentence with a peak on the first stressed syllable (the second syllable in the sentence). As the sentence is produced, there is a gradual reduction in F_0, known as *declination*. The sharp drop that occurs in F_0 at the end of the sentence is referred to as the *terminal fall*. Figure 5 shows the contour of the same sentence spoken by a hearing-impaired male speaker, 14 years of age, judged to have insufficient variation in intonation. Note that the extent of the change in the F_0 throughout the

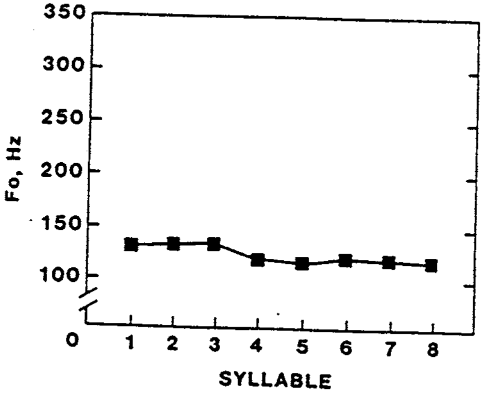

Figure 5. The intonation contour of the sentence, *I like happy movies better,* spoken by a profoundly hearing-impaired speaker judged to produce insufficient variation in intonation. Each data point is the fundamental frequency value (in hertz) measured at the center of the vowel in each syllable of the sentence.

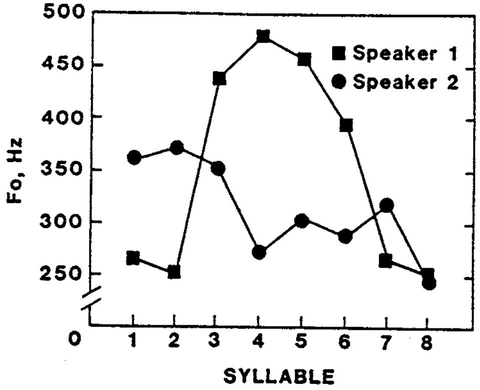

Figure 6. The intonation contour of the sentence, *I like happy movies better*, spoken by two profoundly hearing-impaired females judged to produce excessive and inappropriate changes in fundamental frequency. Each data point is the fundamental frequency value (in hertz) measured at the center of the vowel in each syllable of the sentence.

utterance is more restricted than that observed for the child with normal speech in Fig. 4. In contrast to this pattern, Fig. 6 shows contours for two females, 14 years old, who produced the sentence with excessive and inappropriate changes in F_0. Speaker 1 produced the first part of the sentence with a sharp rise in F_0, followed by a sharp fall in F_0 over the last half of the utterance. Speaker 2 produced inappropriate fluctuations in F_0 throughout the entire utterance.

There have been few attempts to arrive at a quantitative classification of intonation contours produced by hearing-impaired children. Monsen (1979) has described the following four types of contours which he found to occur in the production of CV syllables by 3- to 6-year-old hearing-impaired children: (1) a falling contour, characterized by a smooth decline in F_0 at an average rate greater than 10 Hz per 100 msec; (2) a short-falling contour, occurring on words of short duration, and the F_0 fall may be more than 10 Hz per 100 msec but the total change may be small; (3) a falling-flat contour, characterized by a rapid change in frequency at the beginning of a word, followed by a relatively unchanging, flat portion; (4) a changing contour, characterized by a change in frequency, the duration of which appears uncontrolled and extends over relatively large segments.

Monsen (1979) found that the type of contour appeared to be an important characteristic in separating the better from the poorer hearing-impaired speakers. The classification scheme developed by Monsen (1979) represents a substantial step forward in describing the intonation patterns of the hearing impaired. However, it remains to be determined if such a classification scheme can be used to describe objectively the intonation patterns of entire sentences as well as isolated syllables.

One factor that strongly influences F_0 changes is the degree of stress placed on syllables within a breath group. Typically, stressed syllables are spoken with a higher fundamental frequency than are unstressed syllables (Fry, 1955). Thus, the contour consists of peaks (rises) and valleys (falls) in F_0 which correspond to the stressed and unstressed syllable pattern of the sentence. This pattern has been observed to be distorted in the speech of the hearing impaired. An example of this distortion is apparent in the F_0 contours of the two speakers in Fig. 6.

3. *Segmental Influences on Fundamental Frequency Control*

A common clinical observation is that some hearing-impaired children produce the vowels /i, I, u/ on a higher F_0 than the other vowels of English. It has been shown that there is a systematic relationship between vowel production and F_0 in normal speech. High vowels are produced on a higher F_0 than low vowels, resulting in an inverse relationship between F_0 and the frequency location of the first formant of the vowel (House & Fairbanks, 1953; Peterson & Barney, 1952). Angelocci *et al.* (1964) first examined some of the vowel changes in F_0 in the speech of the hearing-impaired. Their results showed that the average F_0 for all vowels was considerably higher for the hearing-impaired than for normal-hearing subjects. Measures of vowel amplitude were also found to be higher in the samples of the hearing-impaired speakers than in those of the normal-hearing children's. In contrast, the range of frequency and amplitude values for the vowel formants was greater for the normal-hearing than for the hearing-impaired speakers. This finding, combined with the high F_0 and amplitude values, led Angelocci *et al.* to suggest that the hearing-impaired subjects attempted to differentiate vowels by excessive laryngeal variations rather then with articulatory maneuvers, as do normal-hearing speakers.

A recent study by Bush (1981) does not support a simple trade-off between F_0 variability and articulatory skill. Bush observed for the majority of profoundly hearing-impaired subjects in her study a close relationship between vowel-related variability in F_0 and articulatory skill. In general, greater F_0 variability was observed for the hearing-impaired speakers who produced a wide range of vowel sounds (in terms of F_1 and F_2 values) than for speakers whose articulatory skills were more limited. The large vowel-to-vowel variations in F_0 also tended to be associated with better speech intelligibility. Bush also noted that, although the amount of F_0 variation used by the hearing-impaired speakers was greater, on the average, than that used by the hearing speakers, the direction in which F_0 varied as a function of vowel height was similar for the two groups of speakers.

On the basis of the above observations, Bush concluded that the vowel-to-vowel variations produced by the hearing-impaired speakers were, in some way, a consequence of the same articulatory maneuver used by normal speakers in vowel production. The mechanism proposed by Bush to explain the segmental variations in F_0 by the hearing impaired was an extension of a vocal fold tension mechanism developed by Honda (1981) to account for normal vowel-related variations in F_0. Briefly, Honda's mechanism assumed that moving the tongue root forward for the production of high vowels causes the thyroid bone to move forward, tilting the cartilage anteriorly. As a result of these maneuvers, there is increased tension on the vocal folds, resulting in an increase in F_0. Bush has postulated that because of the nonlinear nature of the stress–strain relationship for vocal fold tissue, increases in vocal fold tension may be greater in magnitude when the tension on the vocal folds is already relatively high (as is the case with hearing-impaired speakers), resulting in somewhat larger increases in F_0 during the articulation of high vowels.

In summary, as was observed for some of the temporal patterns of speech, it appears that profoundly hearing-impaired speakers encode and organize some aspects of fundamental frequency with respect to syntactic considerations in much the same manner as do normal speakers. There are obvious deviations in fundamental frequency control in the speech of the hearing impaired, but there is evidence to suggest that they know and use some of the same rules applied by normal-hearing speakers.

C. Production Patterns Affecting Voice Quality

1. *Voice Quality*

It is not unusual to find people who, after working with the profoundly hearing impaired, claim that the speech of this population has a distinctive quality that differentiates it from other speakers. Calvert (1961) found that teachers of the hearing impaired could reliably differentiate the voices of profoundly hearing-impaired speakers from normal speakers, provided that the speech samples contained articulatory movement, such as that required for the production of a diphthong or a CVC syllable. Productions with negligible articulatory movements, such as sustained vowels, failed to provide the experienced listeners with the necessary information for the correct identification of speakers. On the basis of these findings, Calvert concluded that the distinguishing characteristics of the speech of the profoundly hearing impaired are associated with articulatory movement over time rather than with voice quality per se.

In the same study, Calvert (1961) also found that there was a great deal of variability among teachers in choosing the characteristics which were felt to describe most closely the voice quality of the hearing impaired. Thus, although the deviant voice quality of the hearing impaired can be recognized easily, the characteristics which contribute to the perceived deviation are difficult to define.

In a recent study, Monsen (1979) quantified some of these characteristics. Acoustic analyses of duration, fundamental frequency, and phonatory control were correlated with ratings of voice quality for monosyllables produced by young hearing-impaired children. The results of this study showed that the fundamental frequency contour appeared to be the most general acoustic characteristic which differentiated the children with better voices from those with poorer voices. Children with good voice quality ratings had fundamental frequency contours which fell within an appropriate range and which varied over time in an appropriate manner. In contrast to this finding, children with poor voice quality produced intonation contours which were excessively flat or excessively changing. Monsen (1979) concluded that while other deviations such as poor vowel quality, breathiness, and duration errors may exert a strong influence on perceived voice quality in individual cases, these do not appear to be the major factors in determining the quality of the voice. From the results of this study and those of Calvert (1961), it appears that the distinctive voice quality of the hearing impaired may be due to both poor articulatory timing control and inadequate control of fundamental frequency.

2. *Nasalization*

Proper control of the velopharynx has been recognized as a source of difficulty for hearing-impaired speakers for many years (Hudgins, 1934). If the velopharyngeal port is opened when it should be closed, the speech may be perceived as hypernasal; if it is closed when it should be opened, hyponasality will result. Problems in nasalization control are often described as affecting voice quality because hyper- or hyponasality affects the resonant properties of speech. Improper velopharyngeal control may also result in articulatory errors, a problem which was addressed earlier in this article.

In a clinical setting, the evaluation of velopharyngeal control is usually made on the basis of qualitative judgments, which are often difficult to assess because they may be influenced by the presence of other deviations. Stevens *et al.* (1976) have attempted to overcome this problem by developing a procedure to quantify the degree of nasalization for nasal and nonnasal sounds in the speech of hearing-impaired children. Measurements of nasalization have been obtained with an accelerometer attached to the surface of the nose. The accelerometer picks up vibrations of the nose when there is velopharyngeal opening during a voiced sound. The output from the accelerometer is then processed and analyzed. Stevens *et al.* have evaluated adequacy of velar control by comparing the amplitude of the accelerometer signal (in decibels) for nasal consonants to the amplitude of vowel sounds which should be produced without nasalization. For normal-hearing speakers, the amplitude difference between these measures is in the range of 10–20 dB. Using amplitude difference as an index of nasalization, Stevens *et al.* found that 76% of the profoundly hearing-impaired children studied had excessive nasalization in at least half of the vowels produced in monosyllablic words. Excessive nasalization on at least 8 of the 10 vowels studied was observed for 36% of the children. The greatest difficulty in velopharyngeal control was evidenced in the hearing-impaired children's production of nasal-stop clusters which required closely coordinated movements of the velopharynx and oral articulators. Almost half of the hearing-impaired children made an error on at least one word with a nasal-stop cluster.

3. Breathy Voice and Glottalization

These problems are caused by improper adjustment of the vocal folds. Breathiness occurs when there is excessive airflow during voicing, resulting in generation of turbulence noise at the glottis. In addition, the vocal folds do not come together rapidly, which affects the shape of the volume–velocity waveform, resulting in an acoustic waveform with enhanced energy in the low frequencies and deficient energy in the high frequencies (Stevens *et al.*, 1978).

Glottalization involves the insertion of the glottal stop between syllables or words. It is caused by tightly adducting the glottal folds and then abruptly releasing them. Profoundly hearing-impaired children often substitute glottal stops for consonants produced in the center and back of the mouth (Levitt *et al.*, 1976). There is also a tendency for hearing-impaired children who insert many glottalizations in their speech to have lower intelligibility than those who do not (Stevens *et al.*, 1978).

V. PRODUCTION PATTERNS IN THE SPEECH OF HARD-OF-HEARING CHILDREN

A. Articulatory Patterns

Until only recently, little attention has been paid to the speech of the hard-of-hearing child. This is probably largely due to the fact that the majority of these children are integrated into regular schools and they are not as accessible for study as the students attending day schools for the deaf. In addition, researchers traditionally have viewed the communication and education problems of the profoundly hearing impaired as more serious than those of the hard of hearing and, thus, the majority of research effort has been devoted to the children who appeared to have the greatest need. We now know that the presence of even a mild hearing loss can affect speech and language development and interfere with academic performance. Often, hard-of-hearing children are neglected in the public school system. They frequently fail to receive the support services from appropriately trained professionals that they require in order to perform successfully in a regular class (Davis, 1977).

The majority of information available on the speech of hard-of-hearing children involves analyses of articulatory skills. Relatively few studies have quantified suprasegmental production patterns and, for this reason, only the segmental aspects of the speech of hard-of-hearing children will be discussed.

If it is assumed that the major difference between hard-of-hearing and profoundly hearing-impaired children is the degree of hearing loss, it is to be expected that hard-of-hearing children would have better speech skills than children with profound hearing losses. This notion has, in fact, been supported by the results of several studies which have shown that, on the average, the frequency of vowel and consonant errors is less in the speech of hard-of-hearing children than in the speech of profoundly hearing-impaired children (Gold, 1978; Hudgins & Numbers, 1942; Markides, 1970; Nober, 1967).

Probably the most comprehensive study on the speech of hard-of-hearing children has been conducted by Gold (1978). In this study, a comparison was performed on the articulatory errors made by mainstreamed hard-of-hearing [pure tone average (PTA) of 80 dB HTL or less] and deaf (PTA of 80 dB HTL or greater) children. Phonemic transcriptions were made of sentences read by the children which contained all the phonemes of English. The data were analyzed to determine if the types of articulatory errors were the same for the two groups of children. An analysis of the results in terms of overall error rate revealed, not unexpectedly, that the deaf group had significantly more segmental errors than the hard-of-hearing group. An analysis of the data further revealed that the types of errors were similar for the two groups of children. These data are summarized in Table II. Two calculations were made for each of the eight error types for both groups of children. The first calculation, error type as the proportion of intended phonemes, which is shown in the first column of Table II for each of the two groups, was derived from the frequency of the error type relative to the total number of phonemes in the sample. The

Table II. Relative Frequency of Articulatory Errors for Hard-of-Hearing and Deaf Children[a]

	Hard-of-Hearing		Deaf	
Type of error	Proportion of intended phonemes	Proportion of errors	Proportion of intended phonemes	Proportion of errors
Omissions	.076	(.392)	.116	(.405)
Vowel–vowel substitutions	.050	(.258)	.065	(.227)
Consonant–consonant substitutions	.035	(.180)	.060	(.210)
Recognizable distortions	.019	(.098)	.023	(.080)
Unrecognizable distortions	.007	(.036)	.013	(.045)
Non-English substitutions	.002	(.010)	.004	(.014)
Diphthong errors	.004	(.021)	.004	(.014)
Other	.001	(.005)	.001	(.007)
Total proportion of error	.194	(1.000)	.286	(1.000)

[a] From Gold (1978).

second calculation, error type as a proportion of all of the errors, which is shown in the second column, was performed to take into account the higher error rate of the deaf group. Thus, the proportion of errors was based on the relative frequency of the error type out of the total proportion of errors made by the group. Once the overall rate was taken into account, the data showed striking similarities in the frequency of an error type for the hard-of-hearing and deaf children. For example, the most frequent type of error for both groups was that of omission. As the data show, differences between the two groups were not substantial.

The results of the Gold study showed that although profoundly hearing-impaired children produce more segmental errors than hard-of-hearing children, the relative proportion of errors for each error type is similar for both groups of children. Only a small number of phonemes showed any significant differences in the pattern of confusions between groups. Gold has concluded, at least for children in the same type of educational setting, that the degree of the hearing loss is more strongly related to the overall frequency of errors than to the kinds of errors which will be made.

B. Pattern of Speech Errors of Different Populations of Children

From the preceding discussion it becomes evident that the pattern of articulatory errors is remarkably similar in the speech of different populations of hearing-impaired children. Two studies, those of Smith (1975) and Gold (1978), lend themselves to cross-population comparison because the same test materials and procedures were used by the two investigators. The major difference between the studies is the groups of children studied. Smith examined the segmental errors in the speech of profoundly hearing-impaired children in an oral day school for the deaf. Gold, as mentioned above, examined the segmental errors in mainstreamed hard-of-hearing and profoundly hearing-impaired children. Some of the data from these two studies have been plotted in Fig. 7. In this figure, correct production of consonants is plotted as a function of place of production for the three groups of hearing-impaired children. Comparison of the data shows distinct patterns across groups of children. As might be expected, the hard-of-hearing children most often produced the consonants correctly, followed by the mainstreamed profoundly hearing-impaired children; the children in the school for the deaf produced the consonants correctly the least often. Note also that sounds produced in the front of

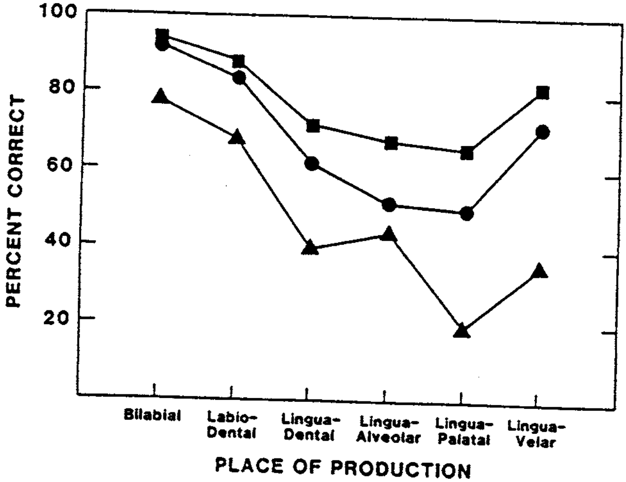

Figure 7. Percentage correct production of consonants plotted as a function of place of production for three groups of hearing-impaired children. (■) Hard of hearing (Gold, 1978); (●) integrated (Gold, 1978); and (▲) school for the deaf (Smith, 1975).

the mouth were most often correct, followed by the back sounds; sounds produced in the middle of the mouth were most prone to error, a finding discussed earlier in this article.

Gold did find some significant differences in the pattern of confusions made by the mainstreamed hearing-impaired children and the children in the school for the deaf. The children in the school for the deaf used more neutral vowel substitutions and omitted more consonants than did the mainstreamed children. They also substituted the glottal stop for /t/ and /k/ and /b/ for labial sounds more often than the profoundly hearing-impaired children who were mainstreamed.

The results of the above study show that although the nature of the confusions did not differ significantly between the hard-of-hearing and deaf children in the same educational setting, there were significant differences between the deaf children in schools of the deaf and those in the regular public schools. Similarities in segmental error pattern were also apparent across groups of children. It should be mentioned that although the mainstreamed children had better speech skills than the children in the school for the deaf, a causal relationship between speech skills and school setting cannot be concluded. Although it is possible that a hearing-impaired child's speech may improve as a result of daily exposure to hearing children, the children in Gold's study may have been mainstreamed because of their good speech skills.

VI. MECHANISMS OF PRODUCTION CONTROL

As we have described earlier, speech production skills of the hearing impaired have been examined using listener judgments, phonetic transcriptions, and acoustic analyses. Whereas the descriptive literature is fairly detailed, there have been few physiological studies on the speech of the hearing impaired. This is surprising since technology is available and because speech production skills in normal-hearing speakers have been studied fairly extensively. Indeed, close to 50 years ago, researchers attempted objective measurements of hearing-impaired speech production in such areas as breath control (Hudgins, 1936; Rawlings, 1935; Scuri, 1935), voice production (Hudgins, 1937; Voelker, 1938), and articulation (Brehm, 1922; Hudgins, 1934). Although by today's technological standards the instrumentation in these studies was not very sophisticated, these researchers deserve our admiration for their ingenuity and creative insight. Their intuition and observations are clearly not dated. Consider the following:

> The most obvious fault in the speech-breathing of deaf children is that they have little or no control over the breath supply so that a great deal more breath than is necessary is allowed to escape on each syllable. They do not speak with normal chest-abdominal action. They have not learned to group their syllables into breath groups and phrases. Instead, they often expend an entire breath on a single word. The reasons for this excessive use of breath is two-fold: The inco-ordinated (sic) movements of the breathing muscles and the maladjusted glottis. (Hudgins, 1937, p. 348)

The observations of Hudgins and his contemporaries might be taken today as evidence for a breakdown in interarticulator coordination. That is, hearing-impaired speakers fail to coordinate the complex activity of respiration, phonation, and articulation, and the resultant errors in timing occur at the segmental and suprasegmental levels of speech production.

Admittedly, there has been a long hiatus between the early research efforts and contemporary rekindled interest in speech physiology of the deaf. Whether the time lapse represents a period of preoccupied interest with that of describing the error patterns of hearing-impaired talkers, or reflects a lag in applying the technology and ideas of speech production in normal-hearing speakers to speech production of the hearing impaired, can only be conjecture. There may be some truth in each, but in any event, we now turn to some recent studies on the physiological characteristics of deaf speech.

A. Respiration

Studies on the respiratory patterns of profoundly hearing-impaired speakers have shown that they evidence at least two kinds of problems. The first is that they initiate phonation at too low a level of vital capacity and produce a reduced number of syllables per breath (Forner & Hixon, 1976; Whitehead, 1982). The second problem is that they mismanage the volume of air by inappropriate valving at the laryngeal level.

Hixon and his associates have provided some objective data on respiratory behavior both in normal (Hixon, Goldman, & Mead, 1973; Hixon, Mead, & Goldman, 1976) and hearing-impaired speakers (Forner & Hixon, 1977). In these studies, magnetometers were used to measure changes in the anterior–posterior dimensions of the chest wall during respiratory maneuvers and speech. Hearing-impaired speakers were found to be like hearing speakers in some respects but not in others. For example, respiratory activity for nonspeech activities such as tidal breathing was similar to normal. This has also been noted for other nonspeech respiratory activities such as coordinative demands on the breathing mechanism for athletics. In addition, Forner and Hixon (1977) showed that the mechanical adjustments of the respiratory mechanism in preparing to speak (i.e., the relative posture of the ribcage versus the abdomen) were often correct. These findings do not support the suggestions of the early researchers that hearing-impaired speakers evidence inappropriate posture problems such as ribcage–abdominal asynchronization. However, like the early researchers, Forner and Hixon reported that hearing-impaired speakers paused at inappropriate linguistic boundaries either to inspire or alternatively to waste air, and thus they produced fewer syllables per breath unit. Hearing-impaired speakers were also found to initiate phonation at inappropriate lung volumes and to speak within a fairly restricted lung volume range.

These results have been reconfirmed by Whitehead (1982) who has extended the findings of Hixon by examining different respiratory patterns with respect to the speech intelligibility of hearing-impaired talkers. Not surprisingly, Whitehead showed that profoundly hearing-impaired speakers who were more intelligible had respiratory patterns similar to those of normal speakers. For example, both groups initiated speech well above functional residual capacity (FRC) and terminated production well within the mid-volume range. In contrast, hearing-impaired speakers who were characterized as semiintelligible initiated speech at substantially lower lung volumes and continued speaking well below FRC. Speech attempted at such reduced lung volumes is exceedingly difficult because the speaker is working against the natural recoil forces of the respiratory mechanism. Furthermore, this aberrant respiratory pattern will also directly affect phonation, as is obvious to anyone who has tried to sustain speech at the end of the respiratory cycle.

Control of the expiratory cycle for speech is crucial for phonation and is particularly important in producing events such as changes in vocal intensity, accommodating different aerodynamic patterns associated with consonant production, as well as linguistic phrasing. To achieve such speech events, the volume of expired air must be appropriately managed and this usually occurs at the laryngeal level. Thus, during speech production, one might think of the relationship of the larynx to the respiratory mechanism as analogous to that of an air valve whereby the valve must be open at certain times to let the air escape (e.g., when producing a voiceless segment) and must be closed at the other times to preserve the breathstream.

There are data that suggest that hearing-impaired speakers have difficulty in coordinating the events of respiration and laryngeal valving. For example, consider some aerodynamic studies of consonants produced by hearing-impaired speakers (Hutchinson & Smith, 1976; Whitehead, 1982; Whitehead & Barefoot, 1980). The method of data collection in these studies was similar: air flow rate was measured using a face mask coupled to a pneumotachograph. Air flow measurements are taken to reflect the relative open or closed state of the vocal tract. For normal-hearing speakers, voiceless plosives would be produced with greater peak airflow than their voiced cognates; fricatives would be produced with greater airflow than plosives. Overall, Whitehead and others cited previously have shown that hearing-impaired speakers do produce, although inconsistently, plosives and fricatives with normal airflow patterns, suggesting that at least some hearing-impaired speakers are relatively successful in coordinating respiration and laryngeal valving. Not surprisingly, these speakers were among the more intelligible in the Whitehead study. Less intelligible hearing-impaired speakers were often quite variable in management of airflow and they did not differentiate voiced and voiceless cognates aerodynamically. Data from these subjects suggest inappropriate laryngeal gestures that could reduce airflow or, in other words, an inability of some hearing-impaired speakers to coordinate respiration and laryngeal valving.

Another example of laryngeal valving problems can be gleaned from a study of laryngeal–supralaryngeal coordination in the speech of the hearing impaired (McGarr & Löfqvist, 1982). In this experiment, laryngeal activity was monitored by means of transillumination, whereby a flexible fiberscope is used to illuminate the larynx and a phototransistor, placed on the surface of the subject's neck below the cricoid cartilage, senses the light passing between the vocal folds. Figure 8 shows selected tokens of an utterance produced by one profoundly hearing-impaired speaker. Information about laryngeal abduction/adduction is shown in the transillumination records. Evidence of inappropriate glottal abduction/adduction gestures is noted preceding each test word as well as between words in the carrier phrase. Figure 9 shows representative samples from a second profoundly hearing-impaired speaker's production of the same test words. Similar inappropriate glottal gestures between words are again observed. Leaving interarticulator timing for a later discussion, this pattern supports the notion of valving problems at the laryngeal level consistent with previous discussions. During pauses between words, these hearing-impaired speakers inappropriately opened the glottis, a pattern never observed in the production of normal-hearing speakers. Whether these hearing-impaired speakers actually took a breath or simply wasted air cannot be directly ascertained from these data since simultaneous monitoring of respiratory activity was not conducted. However, the authors argue that the latter is more likely since the glottal abduction gesture was smaller and shorter in duration between words than between utterances. This pattern of aberrant laryngeal valving differs from one hypothesized by Stevens, Nickerson, and Rollins (1982). Based on a spectrographic study of deaf

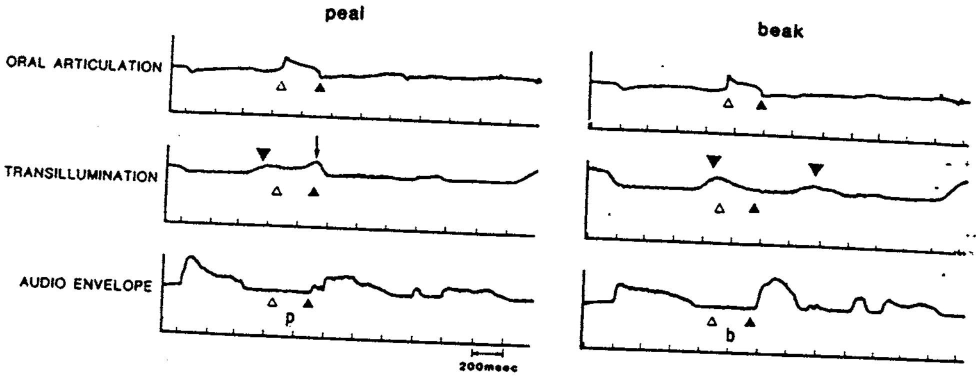

Figure 8. Records of a profoundly hearing-impaired speaker's production of the utterance, *Say peal again* (left) and *Say beak again* (right). Curves represent oral articulation (top), transillumination (middle), and audio envelope (bottom). Onset of labial closure for the word initial stops in *peal* and *beak* is marked by △, release of oral closure by ▲; ↓ marks peak glottal opening. Examples of inappropriate abduction/adduction gestures are noted in the transillumination record by ▼.

children's productions, they hypothesized that the glottis is closed during pauses between words.

B. Phonation

The larynx serves as the primary source of acoustic energy for speech and plays an integral role in changes of stress and intonation as well as in voicing information. Whereas we have noticed earlier in this article that

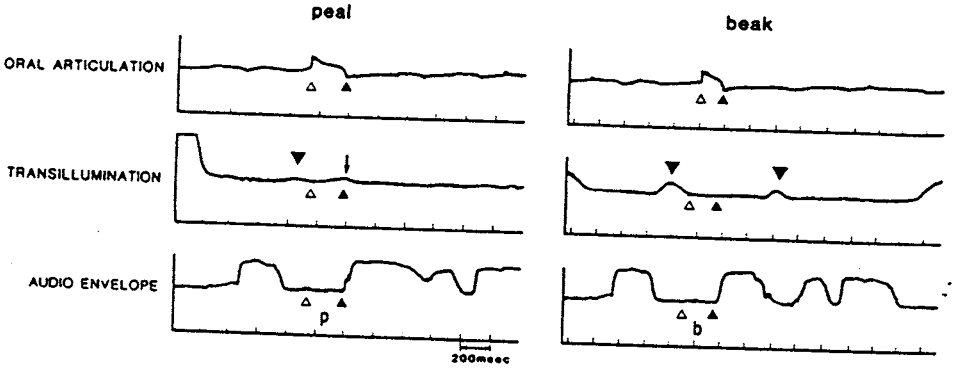

Figure 9. Record of a second profoundly hearing-impaired speaker's productions of the utterances *Say peal again* (left) and *Say beak again* (right). The symbols are the same as in Fig. 8.

hearing-impaired speakers exhibit great difficulty in controlling these phonatory parameters, there are few physiological studies of laryngeal function in the hearing impaired. For convenience of discussion, we will divide laryngeal function into two areas: phonatory and articulatory.

To date, there are few studies that have examined the basic phonatory mechanism in hearing-impaired speakers. One study (Monsen, Engebretson, & Vemula, 1979) examined the glottal volume–velocity waveforms of hearing-impaired speakers using a reflectionless (Sondhi) tube. In this procedure, the subject phonates a neutral vowel into the tube and a microphone positioned in the tube records a pressure waveform that is considered to be an approximation of the glottal waveform. It should be noted that the use of the Sondhi tube presents some problems in the study of both normal and pathological voice production. In order to provide an accurate estimate of the source waveform, several conditions must be met. For example, the vocal tract itself must have a uniform area function and not contain any side resonators such as the nasal passages. Since inappropriate nasal resonance is a common problem in the speech of the hearing impaired, data obtained using this measurement technique should be interpreted cautiously. Monsen *et al.* (1979) reported that an individual glottal pulse for a hearing-impaired speaker was not abnormal per se, but that differences between hearing-impaired and hearing subjects were seen for successive changes of the glottal waveform from one period to another. Glottal waveforms of hearing-impaired speakers also showed evidence of diplophonia and *creaky* voice. Thus, the authors hypothesized that hearing-impaired speakers have difficulty controlling overall tension of the vocal folds and subglottal pressure.

Second, high-speed laryngeal films have also provided evidence of abnormal laryngeal function in hearing-impaired speakers (Metz, Whitehead, & Mahshie, 1982). Films of several profoundly hearing-impaired speakers show evidence of inappropriate positioning of the vocal folds prior to the onset of phonation and subsequent patterns of abnormal vocal fold vibration. For example, an abnormally high amount of medial compression on the arytenoid cartilages was observed in the films of one hearing-impaired speaker and only the anterior one-third of the folds vibrated freely. The analysis of these films also revealed that some hearing-impaired speakers do not use appropriate abduction/adduction gestures in producing VCV utterances where C was a voiceless consonant. These data speak to the point of difficulty in laryngeal articulation, that is, the production of segments requiring control and coordination of the larynx.

Laryngeal articulation in the speech of the hearing impaired has been examined in two physiological studies, the first a fiberoptic study of voiced and voiceless segments (Mahshie, 1980) and the second a transillumination study of obstruent production described previously (McGarr & Löfqvist, 1982). We have noted in other sections of this article that there is considerable evidence from the descriptive and acoustic literature to suggest that hearing-impaired speakers have great difficulty coordinating laryngeal and oral articulatory gestures. One common problem that illustrates this difficulty is confusion of the voiced–voiceless distinction.

Let us consider what is required in the production of a voiceless obstruent (a plosive, fricative, or affricative) in the speech of normals. In addition to the supralaryngeal adjustments used to make the closure or constriction, a laryngeal abduction/adduction gesture normally occurs to stop glottal vibration and assist in the build-up of oral pressure. Production of these segments thus involves simultaneous activity at both laryngeal and supralaryngeal levels, and the laryngeal and oral articulations must be coordinated in time. Variations in this timing are used in a wide variety of languages to produce contrasts of voicing and aspiration (cf. Löfqvist & Yoshioka, 1981).

An example of how this interarticulator timing might be manifested in the speech of a hearing subject is shown in Fig. 10. Data are taken from the transillumination study of McGarr and Löfqvist described earlier. At this time, we focus on the temporal relationship between the oral and laryngeal events. Peak glottal opening for the voiceless /p/ in *peal* shown in the transillumination signal (middle record) occurs at about the same time as the end of lip closure (top record) and the burst-release in the acoustic envelope (bottom record). The pattern for this plosive is essen-

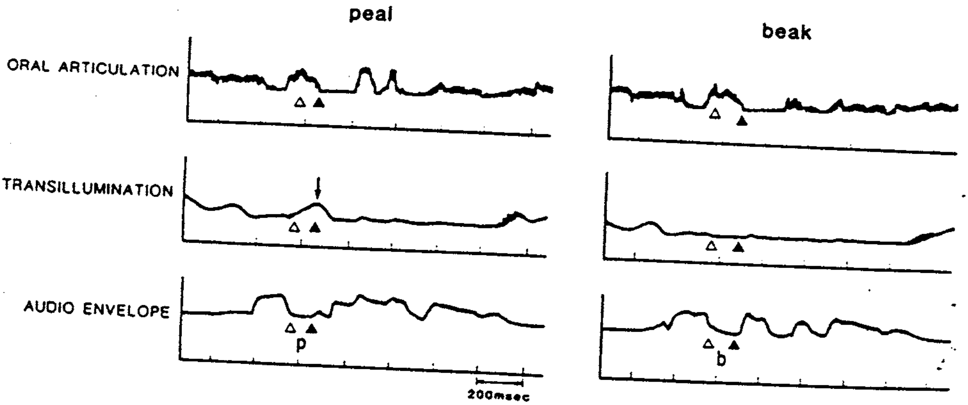

Figure 10. Records of a hearing speaker's productions of the utterances, *Say peal again* (left) and *Say beak again* (right). The symbols are the same as in Fig. 8. (After McGarr & Löfqvist, 1982.)

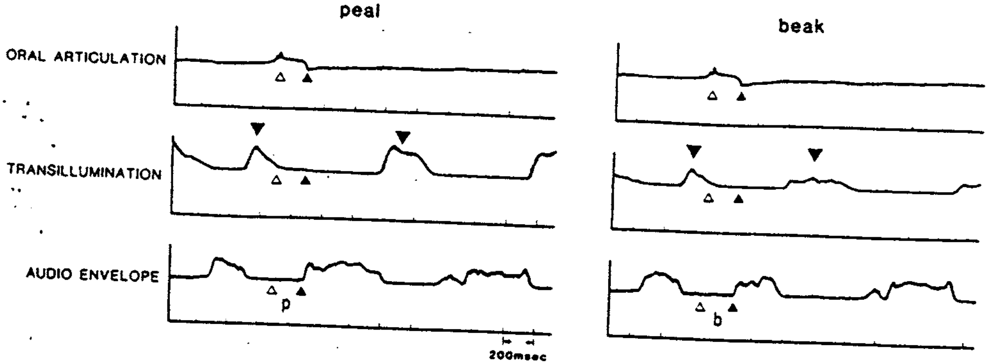

Figure 11. Records of a third profoundly hearing-impaired speaker's production of the utterances, *Say peal again* (left) and *Say beak again* (right). The symbols are the same as in Fig. 8. This example illustrates the common b/p substitution. (After McGarr & Löfqvist, 1982.)

tially the same as that obtained for other hearing speakers' production of obstruents in different and unrelated languages (Löfqvist & Yoshioka, 1981). For production of the voiced /b/ in *beak*, there is no evidence of glottal opening in the transillumination signal as would be expected for a correct production of this segment.

Figure 11 is an example of a common voiced for voiceless substitution in the speech of a hearing-impaired talker. In this example, the error is due to inappropriate positioning of the vocal folds. For production of the /p/, the transillumination signal shows no evidence of a glottal opening following the onset of lip closure, or any evidence of a burst-release in the acoustic signal. Indeed, listeners judged this production to be a /b/ for /p/ substitution. McGarr and Löfqvist reported that hearing-impaired speakers differed from normal-hearing speakers by either omitting the glottal gesture entirely as illustrated above, or by producing a glottal gesture when none was required (see also above, Figs. 8 and 9). In fact, one speaker consistently differentiated plosives from fricatives by producing the former without a glottal gesture but the latter with an opening gesture. However, even when an appropriate laryngeal gesture was made by the hearing-impaired subjects, the timing relative to the oral articulatory events was not always like normal. Similar observations on the nature of laryngeal articulation have been made by Mahshie (1980). The data from these two studies suggest that hearing-impaired speakers have difficulty in coordinating the temporal and spatial demands of different articulators. We now turn to some evidence that shows that this difficulty in coordination also occurs at the articulatory level.

C. Articulation

Articulatory errors in the speech of the hearing-impaired have been reviewed above. The error patterns described in the literature suggest several hypotheses concerning the physiological *underpinnings* of articulation in the hearing impaired. One hypothesis, derived primarily from studies of consonant production, suggests that hearing-impaired speakers place their articulators fairly accurately but fail to coordinate interarticulator movements. These errors may be broadly characterized as errors in timing. Another hypothesis primarily concerned with vowel articulation is that hearing-impaired speakers move their articulators through a relatively restricted range, thereby *neutralizing* vowels. Again, there have been relatively few physiological studies of articulation in hearing-impaired speakers, three electromyographic investigations (Huntington *et al.*, 1968; McGarr & Harris, 1980; Rothman, 1977) and two cinefluographic studies (Stein, 1980; Zimmerman & Rettaliate, 1981). These investigations provide some insight into the complex nature of articulatory errors in the hearing impaired.

For example, electromyographic studies of the speech of hearing-impaired persons give ample evidence of instability of production and failure to achieve the tight temporal coupling in articulatory muscles. McGarr and Harris (1980) have shown that for normal speakers, the relationship between two articulators, the lips (orbicularis oris) and the tongue (genioglossus), is closely coordinated in time, and that even changes in stress from one syllable to another do not disrupt this temporal relationship. Indeed, this closely timed interarticulator relationship seems to be characteristic of normal speech production and is evidenced in many articulatory muscles across changes in stress as well as speaking rate (Tuller, Harris, & Kelso, 1981).

Figure 12 provides an illustrative example of this temporal relationship taken from electromyographic records of a normal-hearing speaker in the McGarr and Harris experiment. These productions are contrasted in Fig. 13 to several examples taken from the records on a hearing-impaired speaker. Clearly, these tokens demonstrate considerable variability on the part of the hearing-impaired speaker in coordinating the activity of the tongue with the lips. Occasionally, tongue activity was timed relatively correctly with respect to lip activity. Most often, the hearing-impaired speaker initiated this tongue activity either too early or too late relative to the lips. These samples suggest that the hearing-impaired speaker does not produce a *wrong* pattern in a stereotypic way; rather, productions are variable from token to token not only for utterances perceived as correct but also for utterances perceived as incorrect. It is interesting that this

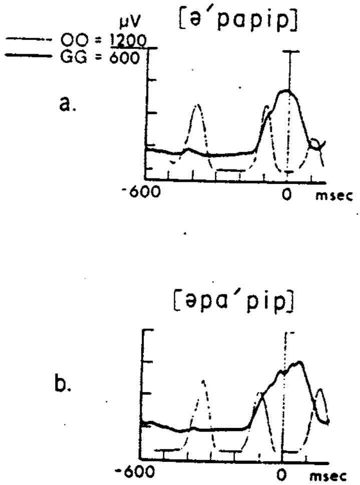

Figure 12. Ensemble average of the EMG potentials for genioglossus (GG) and orbicularis oris (OO) for the utterance (əpapip) produced by a hearing speaker (FBB). Stress occurs on V_1 in (a) or V_2 in (b), respectively. The vertical line indicates the acoustic release of the /p/ closure. Peak genioglossus activity for the vowel occurs at about the same time as the acoustic burst release. (After McGarr & Harris, 1980.)

variability in production is observed primarily in the lingual rather than the labial component; that is, it is the less visible aspect of articulation that varies. Similar observations have been made regarding phoneme visibility in earlier EMG studies (Huntington *et al.*, 1968; Rothman, 1977). However, observations on the variability in both perceptually correct and incorrect productions clearly provide new insights into the organization of the speech of hearing-impaired talkers.

Cinefluographic studies (Stein, 1980; Zimmerman & Rettaliata, 1981) provide additional information on upper articulatory movements in hearing-impaired speakers. These X-ray films have been analyzed for an adventitiously hearing-impaired speaker in the former study as well as for five prelingually hearing-impaired adults in the latter work. Despite differences in onset of hearing loss, these subjects showed patterns of articulatory dynamics similar to each other and not unlike normals in many respects. This is not surprising since all of the hearing-impaired speakers were at least partially intelligible. Some of the differences between normal and hearing-impaired speakers were as follows. Hearing-impaired speakers frequently exhibited faster articulatory speeds for lip, tongue, and jaw movements, and articulatory displacements were often of greater magnitude than for normal-hearing speakers. Vowel height differentiation was

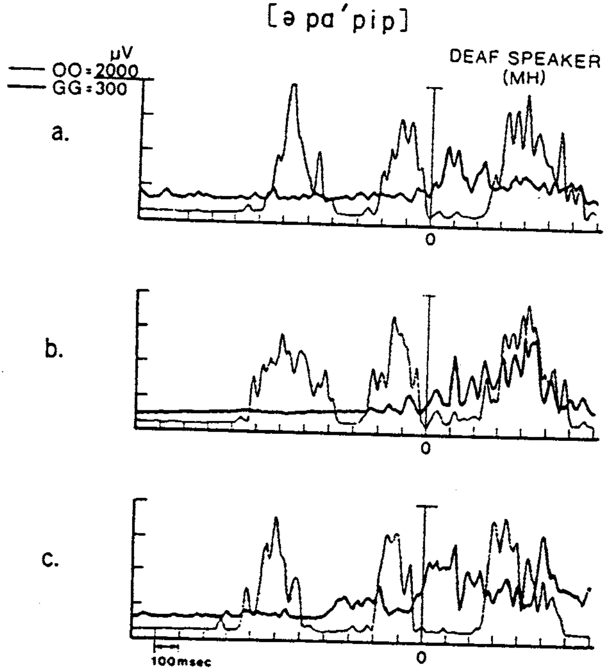

Figure 13. Three selected examples of the electromyographic (EMG) potential for the genioglossus (GG) and orbicularis oris (OO) for the utterance /əpa'pip/ produced by a profoundly hearing-impaired speaker (MH). The vertical line indicates the acoustic release of the /p/ closure. In (a), peak genioglossus activity occurs between the second and third orbicularis oris peaks, but it is late relative to the acoustic event. This pattern was most like normal. In (b) and (c) the single tokens show that genioglossus activity was either too late or too early, respectively. (After McGarr & Harris, 1980.)

achieved primarily by jaw movements and deviant positioning of the tongue with primarily *fronting* of back vowels was noted. A consistent finding of these studies was that onset and offset voicing in consonant production was frequently too long. These physiological data agree with descriptive studies on voicing errors, particularly that of Millin (1971). These results reaffirm the notion that interarticulator coordination is poorly controlled by hearing-impaired speakers.

In summary, these studies suggest that the physiological correlates of segmental and suprasegmental errors in the speech of the hearing impaired are exceedingly complex. Our knowledge of the physiology of speech production by the hearing impaired is still in the germinal stages. While the research described above has included only relatively few hearing-impaired speakers, and caution must be taken not to overgeneralize results, several interesting mechanisms of production are beginning to emerge.

One mechanism is that certain physiological characteristics of the speech production of hearing-impaired speech may span an entire utterance and thus cannot be accurately ascribed to either segmental or suprasegmental attributes of speech. These have been termed *postural characteristics* by Stevens and his colleagues (Stevens *et al.*, 1978, 1982). Examples of postural errors would include inappropriate respiratory control, glottal abduction/adduction gestures, vocal fold tension and mass, tongue position and range of movements, and velopharyngeal posture and movements. These postural characteristics include not only the preparatory state for speaking but also the configuration of the speech production mechanism over time. We have noted several examples in the preceding discussion that suggest that hearing-impaired speakers evidence such inappropriate postures.

The importance of postural characteristics has also been highlighted recently in studies of speech production in normal-hearing speakers. Parallels between coordinated nonspeech and speech activities have been drawn. For example, a nonspeech activity such as locomotion is said to be like speech in that both may be thought of as having a series of rapid, rhythmic, and highly coordinated movements superimposed on a broad posture base. We might think then of speech as a complex and rapidly changing articulatory–phonatory process overlayed on a slowly changing respiratory base. Thus, the hearing-impaired speaker who adopts an inappropriate respiratory posture for whatever reason may preclude the coordination and control of movement elsewhere in the speech production mechanism. An inappropriate respiratory posture may be further exacerbated by inappropriate glottal gestures, or inappropriate tongue position, and so on.

A second problem evidenced by many hearing-impaired speakers is great difficulty in coordinating respiration, phonation, and articulation. In normal speech production, the tight temporal coordination of these events constitutes an important component in any theory of speech production. In the speech production of the hearing impaired, we have ample evidence for a breakdown in interarticulator coordination; for example, in the studies of aerodynamics, laryngeal–supralaryngeal coordination, and articulation cited previously. These data suggest not only difficulty accommodating the demands of speech in space and time but also substantial variation in production from utterance to utterance. Without such coordination, intelligible speech is impossible and, taken together, these factors suggest some reasons why listeners find the speech of the hearing impaired so difficult to understand.

Neither problems of postural characteristics nor those of interarticulatory coordination are mutually exclusive. Physiological research focusing on several levels of speech production may prove fruitful in clarifying many of the errors documented in the descriptive literature. A better understanding of these problems at the physiological level will hopefully lead to the development of more effective assessment techniques and training programs for hearing-impaired speakers.

VII. SPEECH INTELLIGIBILITY

We shall use the term *speech intelligibility* to refer to how much of what a child says can be understood by a listener. On the average, the intelligibility of profoundly hearing-impaired children's speech is very poor. Only about one in every five words they say can be understood by a listener who is unfamiliar with the speech of this group (Brannon, 1964; John & Howarth, 1965; Markides, 1970; McGarr, 1978; Smith, 1975).

Before we proceed to a discussion of factors which have been found to affect intelligibility, some comments on analysis techniques are necessary. First, intelligibility measures in most studies have been based only on a listener's auditory judgments of a child's productions. Whereas this approach may be the most appropriate for quantifying the intelligibility of speech, it does not necessarily provide an accurate assessment of a child's ability to communicate in a face-to-face situation.

A second point which should be made is that the majority of investigators who have attempted to determine the effect of specific variables on intelligibility have done so using a correlational analysis, a statistical analysis of the association between the factor of interest and the reduction in intelligibility. However, correlations should be interpreted carefully because a cause and effect relationship cannot be inferred from the results. Several causal studies that have been performed will be presented in some detail in this section.

A. Hearing Level

A review of the literature indicates that an important factor in determining the intelligibility of a hearing-impaired child's speech is the degree of the child's hearing loss (Boothroyd, 1969; Elliott, 1967; Markides, 1970; Montgomery, 1967; Smith, 1975). Boothroyd (1969) found a correlation between percentage intelligibility scores and hearing level at all frequencies, particularly at 1000 and 2000 Hz, for a population of hearing-impaired children from the Clarke School for the Deaf. In fact, the data formed a bimodal distribution: the children with good speech intelligibility (intelligibility score of 70% or more) had considerable hearing, whereas those children with poor intelligibility (70% or less) had little residual hearing. The median hearing level of the group with good speech intelligibility was 90 dB and, as the hearing loss exceeded 90 dB at 1000 Hz, the median speech scores fell rapidly. In another study that analyzed the speech intelligibility of profoundly hearing-impaired children, Smith (1975) observed a systematic decrease in intelligibility with poorer hearing level until a level of about 85 dB HTL, after which the relationship was not clear. Monsen (1978) found that all the children he studied with hearing losses of 95 dB HTL or less had intelligible speech, but children with losses greater than 95 dB HTL did not always have poor or unintelligible speech. These data indicate that, although a child has a profound hearing loss, he or she still has the potential to develop functional speech skills.

Two studies of interest are those by Smith (1975) and Gold (1978), which were described in the preceding section. Recall that the same test materials and procedures were used in the two studies to assess the speech of different populations of hearing-impaired children. The average intelligibility of the profoundly hearing-impaired children's speech in an oral day school for the deaf was reported by Smith to be about 19%. Gold (1978) reported an average intelligibility score of 39% for the mainstreamed profoundly hearing-impaired children assessed in her study. Thus, children with similar hearing levels in different educational settings showed an average difference of 20% in their intelligibility scores. Not unexpectedly, research has shown that the intelligibility of hard-of-hearing children's speech is substantially higher than that of profoundly hearing-impaired children: average intelligibility scores of 70 to 76% have been reported for the hard-of-hearing (Markides, 1970; Gold, 1978).

Substantially higher intelligibility scores than those mentioned above have been reported by Monsen (1978). His results revealed an average intelligibility score of 91% for severely hearing-impaired children and a score of 76% for profoundly hearing-impaired children in his study. Monsen (1978) has attributed the difference in intelligibility scores between his and other studies to differences in the speech material which the children were required to produce. According to Monsen (1978), the sentences used in his study were shorter, had more familiar vocabulary, and were syntactically less complex than those used by other investigators. In fact, McGarr (1980) has shown that intelligibility scores for hearing-impaired speakers may vary considerably, depending on speech material (sentences or words), amount of context, phonetic composition, and, of course, experience of the listener.

The above studies indicate that, although the degree of hearing loss is an important variable, this measure alone cannot reliably predict the intelligibility of a child's speech. In fact, in a study by Smith (1975), hearing level was found to be only a fair predictor of the speech intelligibility of profoundly hearing-impaired children. The hearing measure found to be most closely correlated with speech intelligibility was performance on an auditory phoneme recognition test. This finding suggests that it is not hearing level per se that is most important for the development of intelligible speech, but rather the ability of the hearing-impaired child to make use of the acoustic cues which are available to him.

B. Segmental Errors

It has generally been found that as overall frequency of segmental or phonemic errors increases in the speech of the hearing impaired, intelligibility decreases (Brannon, 1964; Gold, 1978; Hudgins & Numbers, 1942; Markides, 1970; Smith, 1975). However, the number of segmental errors alone cannot account for reduced intelligibility. Smith (1975), for example, observed that some of the subjects in her study with approximately the same frequency of segmental errors had speech intelligibility scores differing by as much as 30%. She hypothesized that these differences appeared to be related, in part, to certain suprasegmental errors which interacted in a complex manner with the segmental errors to reduce intelligibility.

The relationship between specific types of segmental errors and intelligibility has been examined to some extent by Hudgins and Numbers (1942) and later by Smith (1975). In their classic study, Hudgins and Numbers found a high negative correlation between intelligibility and total number of vowel errors (−.61) as well as total number of consonant errors (−.70). Similar results were reported by Smith except that she found a slightly higher correlation between vowel errors and intelligibility than did Hudgins and Numbers.

Of the seven consonant error categories considered in the Hudgins and Numbers (1942) study, three categories (omission of initial consonants, voiced–voiceless confusions, and errors involving compound consonants) had the most significant effect on intelligibility. The other four categories considered (substitution errors, nasality errors, omission of final consonants, and errors involving abutting consonants) had a lower correlation with intelligibility and contributed to a much lesser extent to the reduced intelligibility of hearing-impaired children's speech.

In a recent study, Monsen (1978) examined the relationship between intelligibility and four acoustically measured variables of consonant production, three acoustic variables of vowel production, and two measures of prosody. A multiple regression analysis showed that the following three variables bore a high multiple correlation (.85) with intelligibility and thus accounted for 73% of the variance: (1) the difference in VOT between /t/ and /d/; (2) the difference in second formant location between /i/ and /I/; and (3) acoustic characteristics of the nasal and liquid consonants. The first two variables accounted for almost 69% of the variance.

Other segmental errors which have been observed to have a significant negative correlation with intelligibility are omission of phonemes in the word-initial and medial position, consonant substitutions involving a change in the manner of articulation, substitutions of non-English phonemes such as the glottal stop, and unidentifiable or gross distortions of the intended phoneme (Levitt *et al.*, 1980).

C. Suprasegmental Errors

The suprasegmental errors which have been examined most extensively in relation to intelligibility have been those involving timing. One of the earliest attempts to determine the relationship between deviant timing patterns and intelligibility is found in the Hudgins and Numbers (1942) study. Although Hudgins and Numbers (1942) correlated rhythm errors with intelligibility, many of these errors appear to be due to poor timing control. They found that sentences spoken with correct rhythm were substantially more intelligible than those that were not. The correlation between speech rhythm and intelligibility was .73, which was similar to the correlation between total consonant errors and intelligibility, and higher than the correlation found between vowel errors and intelligibility.

The results of other correlational studies have typically shown a moderate, negative correlation between excessive prolongation of speech segments and intelligibility (Monsen & Leiter, 1975; Parkhurst & Levitt, 1978). In a recent study, Reilly (1979) found that relative duration (stressed : unstressed syllable nuclei duration ratio) demonstrated a systematic relationship with intelligibility. Reilly (1979) suggested that the better able the profoundly hearing-impaired speaker was to produce the segmental, lexical, and syntactic structure of the utterance, the more intelligible the utterance was likely to be. Data reported by Parkhurst and Levitt (1978) indicate that another type of timing error, the insertion of short pauses at syntactically appropriate boundaries, had a positive effect on intelligibility and the presence of these pauses actually helped to improve intelligibility.

Studies which have attempted to determine the cause and effect relationship between speech errors and intelligibility have dealt primarily with timing. These causal studies can be subdivided into two major categories:

studies in which hearing-impaired children receive intensive training for the correction of timing errors, and studies in which timing errors are corrected in hearing-impaired children's recorded speech samples using modern signal-processing techniques.

The classic training study that attempted to determine the causal relationship between timing errors and intelligibility was conducted by John and Howarth (1965). These investigators reported a significant improvement in the intelligibility of profoundly hearing-impaired children's speech after the children had received intensive training focusing only on the correction of timing errors. In contrast to this finding, Houde (1973) observed a decrement in intelligibility when timing errors of hearing-impaired speakers were corrected, and the results of a similar study by Boothroyd *et al.* (1974) were equivocal.

A major problem with the training studies is that the training may result in changes in the child's speech other than those of interest. Recent investigations have attempted to eliminate this confounding variable by using computer processing techniques. In these studies, speech is either synthesized with timing distortions, or synthesized versions of the speech of the hearing impaired are modified so that timing errors are corrected. Lang (1975) used an analysis–synthesis approach to correct timing errors in the speech samples produced by hearing-impaired speakers as well as to introduce timing distortions in the samples of normal speakers. Minimal improvements in intelligibility were observed for the speech of the hearing impaired while minimal decrements in intelligibility were obtained for the normal-hearing speakers. Bernstein (1977), however, showed no reduction in the intelligibility of speech samples produced by normal speakers when synthesized with timing errors. On the other hand, Huggins (1978) found that when normal speech was synthesized with the durational relationship between stressed and unstressed syllables reversed, there was a substantial reduction in intelligibility. Even greater reductions in intelligibility occurred when the stress assignments for both pitch and duration were incorrect.

In an attempt to resolve some of the conflicting information in this area, Osberger and Levitt (1979) quantified the relative effect of timing errors on intelligibility by means of computer simulation. Speech samples produced by hearing-impaired children were modified to correct timing errors only, leaving all other aspects of the speech unchanged. Three types of corrections were performed: relative timing, absolute syllable duration, and pauses. Each error was corrected alone and together with one of the other timing errors. An average improvement in intelligibility was observed only when relative timing errors alone were corrected. The improvement, however, was very small (4%). Since the timing modifications for this condition involved only the correction of the duration ratio for stressed-to-unstressed vowels, the overall durations of the vowels (and syllables) were still longer than the corresponding durations in normal speech. These data indicate that the prolongation of syllables and vowels, which is one of the most obvious deviancies of the speech of the hearing impaired, does not in itself have a detrimental effect on intelligibility.

Attempts have also been made to determine the relationship between errors involving fundamental frequency (F_0) control and intelligibility. Monsen (1978) found that there was no clear cut relationship between mean F_0 and mean amount of F_0 change and intelligibility. In their study, McGarr and Osberger (1978) found that for the majority of the children studied, there seemed to be no simple relationship between pitch deviancy and intelligibility. Some children whose pitch was judged appropriate for their age and sex had intelligible speech whereas others did not. The exception to this pattern was the children who were unable to sustain phonation and whose speech contained numerous pitch breaks; their speech was consistently judged to be unintelligible. Smith (1975) also found that errors involving poor phonatory control (intermittent phonation, spasmodic variations of pitch and loudness, and excessive variability of intonation) were highly correlated with intelligibility.

Data obtained by Parkhurst and Levitt (1978) also suggest that excessive variations in pitch may reduce intelligibility. In this study, a multiple linear regression analysis was performed, relating intelligibility to various prosodic distortions judged to occur in the speech of hearing-impaired children. Breaks in pitch was one of the prosodic errors showing a significant negative regression with intelligibility. The effect of the less deviant patterns, such as elevated F_0, has not been clearly established, although preliminary data suggest that these problems will not have a serious effect on intelligibility.

In summary, we have relatively little information regarding the effect of errors, or combination of errors, on the intelligibility of hearing-impaired children's speech, nor are we able to predict reliably if a child has the potential to develop intelligible speech. Some background variables, such as the hearing status of the parent, appear to be important, while others, such as age of identification of hearing impairment, hearing aid use, start of special education, IQ, and the hearing status of siblings, show little or no correlation with speech intelligibility (Smith, 1975).

VIII. CONCLUDING COMMENTS

We shall now summarize some of the major points made in this article and discuss the implications of the available data for the development of assessment and training techniques. On the basis of the data which have been presented, the following statements can be made regarding the speech production skills of hearing-impaired children.

1. Rate of vocal output cannot be used to describe accurately the differences in the vocalization behavior between normal-hearing and hearing-impaired children. Striking differences between the vocalizations of normal-hearing and hearing-impaired infants do emerge at any early age, but the differences are seen in phonemic production rather than rate of vocal output. Specifically, hearing-impaired infants tend to produce stereotypic vocalization patterns with a reduced phonemic retertoire relative to hearing infants.

2. The developmental stages of speech acquisition in the hearing impaired appear to be similar to those of normal-hearing children in some respects but not in others. Moreover, the speech production patterns of older hearing-impaired children show many similarities to the patterns of the younger hearing-impaired children.

3. Segmental errors, as determined by phonetic transcriptions of hearing-impaired children's speech, can be classified by the following two categories:

   a. Omission errors. This type of error most often involves consonants, particularly those in the world-final position. Omission of vowels is infrequent and usually does not occur unless the entire syllable has been omitted.

   b. Substitution errors. Frequent errors in this category involve confusion between voiced–voiceless cognates, substitution of a consonant with the same place of production but a different manner of production as the intended consonant (and vice versa), and substitution of non-English sounds, particularly the glottal stop for the intended phoneme. Vowel errors in this category typically involve tense–lax substitutions, substitutions toward a vowel which is more central than the target vowel, and substitution of the schwa vowel for the intended vowel. Diphthong errors frequently involve substitutions of one of the elements of a closely related vowel.

4. Errors are less frequent for consonant phonemes produced at the front of the mouth (the labial and labiodental consonants) as compared to phonemes with a place of articulation at the middle or back of the mouth. Traditionally, this pattern of production has been attributed to the greater visibility of phonemes produced in the front of the mouth. Other articulatory considerations, such as the relatively constrained movements of the most visible articulators (i.e., the lips) may also account for this production pattern.

5. Similar error patterns have been found to occur in the speech of

different groups of hearing-impaired children. The largest difference between children is in the frequency of errors; type of error may also vary, but to a lesser extent than frequency of errors.

6. At the suprasegmental level of production, poor timing control produces the following deviations: (a) prolongation of speech segments; (b) distortion of temporal relationship between speech segments; (c) insertion of frequent and lengthy pauses often at syntactically inappropriate boundaries; (d) distortion of phonetic context effects; and (e) insertion of adventitious phonemes. Poor control of fundamental frequency can result in problems such as: (a) average pitch level too high; (b) intonation with insufficient variability; (c) intonation with excessive variability. Abnormal voice characteristics such as harshness, breathiness, and hyper- and hyponasality may also be present.

7. Acoustic analyses have shown manifestations of the above perceptual errors in the distortion of VOT, format frequency transitions, frequency location of the formants, and segmental durations.

8. Recent studies have begun to detail the physiological correlates of segmental and suprasegmental errors. These studies show that the underlying causes of error patterns are more complex than has been alluded to in the descriptive literature. Some of the production mechanisms responsible for the perceptual and acoustic distortions are poor respiratory control, evidenced by initation of phonation at too low a level of vital capacity and production of a reduced number of syllables per breath; abnormal laryngeal function, evidenced by laryngeal valving problems and failure to coordinate laryngeal and respiratory events; and a breakdown in interarticulator programming, evidenced by poor control and poor coordination of articulatory gestures, both at the laryngeal and supralaryngeal levels of production. Improper postural characteristics of the speech mechanism may affect many aspects of speech production and result in segmental and suprasegmental misperceptions.

9. Although there are many deviations in the speech of the hearing impaired, these deviations do not generally occur in a random way. There is evidence that many of the deviations are phonetically and phonologically consistent albeit the systems may not be the same as those used by normal-hearing talkers. However, the use of a deviant phonological system will still pose problems for the listener who must decode the intended message. Data are also available which suggest that hearing-impaired talkers manipulate some segmental, lexical, and syntactic aspects of speech in the same manner as normals.

10. The intelligibility of the speech of children with profound hearing losses in day schools for the hearing impaired has been reported to be about 20%. This figure is based on the percentage of words correctly

understood through audition alone by persons who are unfamiliar with the speech of the hearing impaired. Under the same conditions, the intelligibility of the speech of children with profound losses who are mainstreamed has been found to be about 40%. The intelligibility of the speech of hard-of-hearing children is substantially higher than that of severely and profoundly hearing-impaired children.

11. The intelligibility of hearing-impaired children's speech has been found to be influenced by the degree of linguistic context and the experience of the listener with the speech of the hearing impaired.

12. The relationship between specific error types and intelligibility has not been clearly established. Correlational studies show a high degree of association between the frequency of segmental errors and reduction in intelligibility. Of the various error types that have been studied, the highest correlations have been reported for overall frequency of phonemic errors, errors of omission in the world-initial and medial positions, substitutions involving a change in the manner of articulation, substitution of non-English phonemes, and unidentifiable or other gross distortions of the intended phonemes. At the suprasegmental level, timing errors and errors involving poor phonatory control have been found to have a negative effect on intelligibility.

Although our knowledge about the speech of the hearing impaired is far from complete, implications for assessment and training strategies can be gleaned from the aforementioned findings. First, hearing-impaired children show distinct error patterns, and unless appropriate assessment instruments are used, some errors may go undetected. Second, in addition to assessing speech structures, clinicians and teachers must attempt to evaluate the adequacy of respiratory, laryngeal, and articulatory maneuvers essential for normal speech production. By this we do not mean to imply that physiological measures should be performed routinely in the clinic. Rather, through clinical observation and perceptual measures, inferences can be made about the underlying speech production mechanism. Third, a phonological analysis of an individual child's sound system will enable the clinician to determine if a child's speech deviates from normal in a systematic way or if the errors are random.

Following the evaluation, the clinician or teacher should raise pertinent questions regarding each child's error patterns and production skills. Such questions include the following:

1. Does the child have a diverse sound system?
   a. Are the basic contrasts present in the child's sound system? That is, oral–nasal, stop–continuant, fricative–nonfricative
   b. Are these contrasts present for the different places of articulation? That is, front, mid, back

   c. Is there vowel differentiation? That is, front–back contrast, high–low contrast
   d. Are non-English sounds (glottal stop) or unidentifiable sounds frequently substituted for the intended phoneme?
2. Is there adequate control of the speech mechanism?
   a. Is there adequate breath management? That is, Is the feature of frication absent or distorted? Is there evidence of phrase structure with or without a terminal fall in pitch?
   b. Is there poor velopharyngeal control which results in segmental errors (substitution of oral sounds for nasal sounds) and an abnormal voice quality (hypernasality)?
   c. Is there adequate laryngeal control? That is, Are there excessive changes in pitch? Are there inappropriate changes in pitch? Are there localized changes in fundamental frequency which are not linked appropriately to changes in lexical stress?
   d. Is there coordination between laryngeal and supralaryngeal movements? That is, Are there voiced–voiceless errors?
   e. Is there independent control of vowel production and pitch control? That is, Is there a noticeable difference in pitch between productions of low vowels /æ, a/ and high vowels /i, u/?
   f. Is there adequate timing control? Is overall rate too slow? Are there adventitious sounds? Are there distortions of temporal relationships between segments and distortions of phonetic context effects in the temporal domain? Are pauses frequently inserted? Is there glottalization?

Once these areas are addressed, optimal training sequence can be selected to meet the individual needs of each child. The effectiveness of the training strategies can be assessed through careful and objective monitoring of the child's performance in speech therapy.

In summary, great strides have been made in understanding the speech of the hearing impaired, but our knowledge in this area is far from complete. Further research is needed to delineate the developmental stages of speech acquisition in the hearing impaired. Other areas of needed research include determining the effect of specific error types on intelligibility, quantifying the acoustic and physiologic correlates of production patterns, and developing and evaluating remediation strategies.

Acknowledgments

Preparation of this manuscript was in part supported by NINCDS Grant NS-16247 and by NIH Biomedical Research Support Grant # 1S07RR05834 to Boys Town Institute for Communication Disorders in Children; and NINCDS Grants NS-13617 and NS-13870, NIH

Biomedical Research Support Grant # RR-05596 to Haskins Laboratories. The authors wish to thank Drs. Ray Kent and Charles Watson for their helpful comments.

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