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Contemporary Issues in Phoneme Production By Hearing-Impaired Persons: Physiological and Acoustic Aspects

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The purpose of this chapter is to review and present a cohesive interpretation of the current literature relative to the physiologic correlates of speech production by individuals who are hearing impaired. It focuses specifically on the production of phonemes. This review includes contemporary data on respiration for speech production, phonation, speech aerodynamics, and articulation. The chapter also presents a similar review and interpretation regarding current acoustic analyses of speech produced by hearing-impaired persons. This includes acoustic data relative to features such as speech intelligibility and coarticulation. Theories of production are also considered with reference to reframing some of the issues that underlie our assumptions of speech training protocols.

Overview of Speech Production

The physiological or biomechanical process for the production of speech and voice in humans involves complex and sophisticated interactions between the respiratory system, the larynx, and the structures contained within the oral cavity, particularly the tongue. The segmental features of speech, classified as vowels, diphthongs, and consonants, are produced by modification of the exhaled breath stream at the level of the vocal folds in the larynx and/or by the articulators within the pharynx and oral cavity. Vowels are produced by modification of the voiced signal which originates at the level of the vocal folds with concomitant changes in the upper articulators, e.g., changes in tongue position, velopharyngeal closure, and/or lip position. Consonants are produced by modification of the breath stream by the articulators and are classified in a variety of ways according to the manner of articulation (plosives, fricatives, nasals, affricates, etc.), the place of articulation, or whether the phoneme is voiced or voiceless (i.e., produced with an accompanying voiced signal from the vocal folds or without such a signal).

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Obviously, to produce a correct and intelligible sequence of vowels and consonants which is to be interpreted as spoken language requires critical coordination and timing among the physiological mechanisms used to modify the breath stream. Any biomechanical and/or aeromechanical aberrations within this process may well result in phonemic errors which affect the intelligibility of the speaker. There is substantial perceptual literature that describes some of the typical segmental errors of speakers who are hearing impaired (Hudgins & Numbers, 1942; Smith, 1975). These include: voicing errors for consonants as well as vowel and consonant distortions, omissions, and substitutions, among others. In order to obtain a clearer understanding of the cause(s) of such segmental errors, a considerable amount of acoustic and physiological research has been undertaken over the last two decades concerning speech produced by individuals who are hearing impaired.

The goal of speech production is obviously an acoustic one. In speech produced by hearing persons, movements of the various parts of the speech production system give rise to elegant, complex, and redundant acoustic signals that the listener uses to decipher the message. Acoustic and physiological analyses of speech produced by hearing-impaired talkers have been impelled by the technology that provides speech researchers with the instrumentation to study the fine-grained details of speech production. Some of this instrumentation has been successfully developed to allow speech teachers to employ computerized displays, thus rendering invisible aspects of the speech signal visible. Ideally, acoustic and physiological analyses of speech permit both the researcher and the teacher to understand better the organization of speech produced by persons who are hearing impaired and, with that understanding, to effect changes in speech training protocols. The study of acoustics and of physiology certainly has relevance, then, as a window for viewing the organization of the speech production system and assisting in the development of more valid assessment tools regarding speech associated with deafness as well as with the pedagogy that motivates our speech training protocols.

The literature on production of speech by persons with normal hearing is replete with detail. Theoretical models of the physiological and the acoustic aspects of speech production impel future research. With respect to studies of speech produced by persons with hearing impairment, a survey of the literature is certainly less detailed when compared to the significant literature on speech production in persons with normal hearing. Formation of theoretical models of speech organization in persons with various degrees of hearing loss is only in germinal phases of development. Such models would provide important impetus to research studies and would impact considerably on the development of speech training curriculum. That work remains the challenge of researchers and teachers alike.

The purpose of this chapter is to present, interpret, and discuss some of the research findings regarding the physiological studies of speech; the respiratory, laryngeal biomechanic, aerodynamic, and temporal coordination that occur during speech production by individuals who are hearing impaired; and the acoustic manifestations of these events. It is anticipated that such information will assist in developing a rationale for the existence of some of the segmental errors exhibited by persons who are hearing impaired and suggest issues for future consideration.

Physiological Studies of Speech: Respiration

The initial work regarding respiratory patterns during speech produced by individuals who are hearing impaired was undertaken by Hudgins (1934) and Rawlings

(1935). The general conclusions from these investigations were that speech of hearing-impaired individuals was primarily characterized by an excessive amount of air expenditure such that for a single exhalation of air, only a few syllables would be uttered. Thus, it was initially concluded that air wastage during speech production was one major contributing factor to segmental speech errors exhibited by individuals who are hearing impaired. Later Hudgins and Numbers (1942) suggested that speech errors of persons who are hearing impaired may well be the result of a lack of coordination between respiration and articulation.

More recent investigations by Forner and Hixon (1977) and by Whitehead (1983) provided additional insight regarding speech breathing patterns of persons who are hearing impaired. In general, these authors found that hearing-impaired persons with reduced overall speech intelligibility, i.e., numerous segmental and suprasegmental errors, failed to take in sufficient amounts of air prior to initiating a speech sequence, attempted to produce speech using air within the functional residual capacity (FRC), uttered four to six syllables per exhalation phase, and/or exhaled a quantity of air prior to the actual onset of speech.

More specifically, these authors reported that their hearing-impaired speakers with poorer speech intelligibility would take in 300cc-400cc of air above FRC prior to initiating a speech sequence, while normal-hearing speakers and intelligible hearing-impaired speakers would inhale approximately 1000cc of air. Further, it was found that normal-hearing speakers and intelligible hearing-impaired speakers would usually terminate the speech sequence at a phrase or sentence boundary which occurred slightly above or below FRC, and then inhale for the next phrase or sentence. The hearing-impaired speakers with reduced intelligibility would continue to speak well below FRC before inhaling for the next speech sequence. This act of attempting to speak on air while in FRC for some hearing-impaired speakers would create an excessive strain and tension on the respiratory structures as they attempted to force out air, and also limit the availability of air to overcome the biomechanical resistance of the vocal folds and articulators through aerodynamic forces. Further, while normal-hearing and intelligible hearing-impaired individuals would use 800cc to 1000cc of air to speak 14-16 syllables before inhaling for the next speech segment, some hearing-impaired speakers would use 600cc to 800cc of air to speak four to six syllables before inhaling. Finally, some of the hearing-impaired speakers with poor speech intelligibility would exhale 100-300cc of air prior to the actual initiation of speech in comparison to the normal-hearing and intelligible hearing-impaired speakers who would begin speech immediately upon the exhalation of air.

The general results of this research have led to the conclusion that respiratory dysfunction alone does not account for the physiological causes of segmental speech errors in hearing-impaired persons. The data on respiratory patterning, however, do indicate the need for therapeutic intervention to correct respiratory patterning errors, such as inhaling larger volumes of air, not attempting speech within FRC, and initiating speech at the onset of exhalation.The data also suggest, however, the need for a better understanding of how hearing-impaired speakers with speech intelligibility deficiencies valve the air stream at the level of the vocal folds and articulators during speech production and also how the vocal folds function during the critical coordination between respiration and upper airway valving during speech production.

Laryngeal Valving of Phonemes

As noted previously, one of the deficiencies exhibited by some hearing-impaired individuals is a wastage of air that is used to produce speech and voice. The vocal folds are one of the air stream valving mechanisms within the human vocal tract and are used to produce the sound source for vowels and voiced consonants. Further, during speech, it is requisite that the vocal folds separate, or abduct, as the speaker moves from the production of voiced phonemes (vowels and consonants) to the production of voiceless consonants. Thus, from a laryngeal perspective, speech production is a highly coordinated process which includes closure, or adduction, of the vocal folds for voicing purposes, abduction for a following voiceless consonant, adduction for the next voiced segment(s), etc.

Using high-speed laryngeal photography, Metz, Whitehead, and Whitehead (1984) reported that during production of an initial vowel in the CVC syllable /ihi/, some hearing-impaired speakers exhibited a lack of complete closure along the margins of the vocal folds. This incomplete closure during voicing would result in the needless escape of air, and thus contribute to air wastage. Similar results have been reported for some hearing-impaired speakers by Mahshie and Oster (1991) using electroglottagraphy and glottal air flow measurements. The perceptual result of incomplete vocal fold closure and escape of air during voicing is identified as breathiness and is one quality present in the speech of some hearing-impaired individuals (Subtelny, Whitehead, & Orlando, 1980).

Metz et al. (1984) also noted that when separating the vocal folds for production of the voiceless phoneme /h/ following the initial vowel /i/, some of the hearing-impaired speakers would separate the vocal folds excessively wide when compared to normal hearing speakers, and/or maintain the abduction for a substantially long period of time before initiating vocal fold adduction for the final vowels in the /ihi/ test syllable. Obviously, if the vocal folds are separated too widely or are held in their abductory position for a lengthy duration, large amounts of air will escape. Thus, possible contributing factors to the air wastage reported by numerous investigators for hearing-impaired speakers are: the lack of complete approximation of the vocal folds during voicing and/or appropriate laryngeal valving during devoicing gestures.

Mahshie and Contour (1983), using fiberoptics to observe and videotape the action of the vocal folds during speech, reported that some hearing-impaired speakers would inappropriately devoice, or abduct the vocal folds, when attempting to produce a voiced consonant. Such voiced-voiceless confusions or substitutions are common segmental errors in the speech of some hearing-impaired individuals. Thus air wastage by hearing-impaired speakers could also be the result of inappropriate voiceless for voiced consonant substitution and would be particularly costly, in terms of respiratory efficiency, if the substitutions were produced in conjunction with abnormally large separations of the vocal folds, as observed by Metz et al. (1984).

More recently, McGarr and Lofqvist (1982, 1988), using transillumination of the larynx, studied the voiced-voiceless laryngeal gesture for different phonetic categories. These authors reported that for normal hearing speakers, voiceless fricative consonants were produced with larger glottal openings than were voiceless plosives. For one hearing-impaired speaker in their study, the authors reported the lack of a similar systematic segmental differentiation regarding abductory width. Obviously more research in this area with additional hearing-impaired speakers may provide greater insight regarding other laryngeal valving factors which could contribute to excessive air wastage in the speech of hearing-impaired persons.

Articulatory Valving of Phonemes

The production of the consonants of English involves the manipulation of the stream of exhaled air by articulation of some of the structures located within the oral and pharyngeal cavities. This is accomplished primarily, but not totally, by the movement and placement of the tongue. Plosive consonants are produced by a blockage of the air flow from the lungs by the lips /p,b/, the tongue and alveolar ridge /t,d/, the tongue and the velum /k/g/, etc. The outgoing flow of air is stopped, the air pressure increases behind the articulators, and the articulators are then released producing a sudden burst of air which creates the sound wave essential for the perception of a plosive consonant. With respect to fricative consonants, air flow is forced through a narrow constriction created by the articulators, such as the tongue and teeth /θ, ð/, tongue and alveolar ridge /s,z/, etc.

For the production of English consonants, it is necessary to establish and maintain requisite amounts of air flow and air pressure in order to create or produce intelligible phonemes. The aerodynamics of speech involves the measure of these air flow and air pressure rates and can provide information relative to how effectively the breath stream is being modified during speech production. Ineffective manipulation may lead to air wastage and inaccurate consonant production.

Hutchinson and Smith (1976) reported on the air flow and air pressure rate for plosive and fricative consonants produced by adult hearing-impaired speakers. These authors reported that in many instances there was a blurring of the voiced-voiceless distinction for hearing-impaired speakers. That is, normally voiceless consonants are produced with greater air flow and air pressure rates than are voiced consonants because of the lack of impedance of the vocal folds. As noted previously, voicing errors are common problems in the speech of some hearing-impaired individuals. Hutchinson and Smith (1976) also noted the existence of inefficient air stream valving by hearing-impaired speakers. For some speakers there would be high flow rates where low flow rates would normally be expected, and low flow rates where higher rates would usually occur.

More recently, Whitehead and Barefoot (1980; 1983) studied the air flow rates for plosive and fricative consonants produced in the initial and medial syllable environments (CV and VCV) by hearing-impaired individuals with overall intelligible and semi-intelligible speech. Further, all the subjects were able to produce correctly the test consonants with respect to voicing and manner of articulation. These authors reported that for initial plosives and fricatives, the semi-intelligible hearing-impaired speakers exhibited significantly higher air flow rates for both voiced and voiceless phonemes than did the normal-hearing speakers and the intelligible hearing-impaired speakers. Further, for the medial plosives and fricatives, the semi-intelligible hearing-impaired speakers demonstrated significantly lower air flow rates for the voiced and voiceless phonemes when compared with the normal-hearing and intelligible hearing-impaired speakers.

There are several possible reasons to explain the elevated and reduced air flow rates for the semi-intelligible hearing-impaired speakers reported by Whitehead and Barefoot (1980; 1983). First of all, with respect to the initial plosives and fricatives, the elevated flow rates may have been due to increased respiratory muscular effort during speech production, as reported by Hutchinson and Smith (1976). It might well be that such a phenomenon is partly the result of previous speech training exercises which encourage the larger expenditure of air to produce consonants, particularly plosives, through such activities as repeatedly "blowing out a candle." Secondly, elevated air flow rates for plosives may have been due to prolonged closure durations of the articulators as has been reported by Whitehead (1991) and Brown and Goldberg (1990). If plosive closure durations are longer than necessary, there would be a subsequent increase in the air pressure behind the articulators and a greater amount of air flow upon the release of the articulators. Thirdly, for fricatives, greater air flow may have been the result of reduced articulator constriction, thereby allowing larger than normal amounts of air to flow through and creating perceptually distorted fricatives. Fourth, for voiceless consonants, an excessive abduction of the vocal folds in terms of glottal area and/or duration would result in larger amounts of air escaping to the articulators. Finally, for voiced consonants, greater air flow rates would occur when there was incomplete closure of the vocal folds during voicing, as observed by Metz et al. (1984).

With respect to the medial plosives and fricatives, there are also several possible reasons to explain the reduced flow rates. First, it is possible that air wastage occurred on the initial vowel in the VCV, due to a lack of complete closure of the vocal folds, excessively long vowel durations, and/or a failure to initiate voicing immediately upon exhalation, and that there would be a limited amount of air available to produce the medial consonant. Thus, it is possible that in order to conserve air, particularly for the final vowel because of its inherent longer duration, the semi-intelligible hearing-impaired speakers attempted to produce the medial consonant with the smallest amount of air possible in order to have sufficient air for final vowel production. Second, for the plosives, shorter closure durations, as a result of timing errors, would result in reduced air flow upon the release for the articulators. Thirdly, during the production of the fricatives, there may have been an increase in the amount of articulatory constriction, thereby, reducing air flow, as reported by Hutchinson and Smith (1976). Finally, for voiceless consonants, some of the hearing-impaired speakers may have shut off the air flow at the level of the vocal folds by constriction of the laryngeal structures. Such a phenomenon has been reported by Metz et al. (1984) as occurring in the speech of some hearing-impaired individuals.

Acoustic Analysis of Vowels

Acoustic analysis of vowels and diphthongs produced by hearing-impaired speakers have followed closely studies of persons with normal hearing although the work on speech of hearing-impaired persons is not as detailed. With respect to vowels, formant frequencies values (F_0, F1, F2 and F3) for productions by men, women, and children with normal hearing have been obtained (e.g., Peterson & Barney, 1952) The measured formant frequency values, traditionally F1 and F2, are plotted against each other; data points for each vowel tend to cluster in distinct regions although there may be some overlap in measures with adjacent vowels. Obviously the different formant values, obtained for men, women, and children, reflect variations in the size of the vocal tract. Interestingly, the acoustic vowel space mapped by F1 and F2 resembles the articulatory domain. While the relationship between articulation and acoustics is not straightforward, changes in F1 are generally said to reflect variation in tongue height, while changes in F2 represent the degree of constriction of the tongue in the front-back plane. Obviously, interspeaker anatomical differences, the degree of lip-rounding, the pharyngeal constriction, and, in particular, variations in the source at the laryngeal level, are some factors that will effect vowel production and the resultant acoustic measures.

Making accurate acoustic measure of vowels produced by hearing-impaired speakers can be problematic. Often hearing-impaired speakers will produce vowels with inappropriately high pitch, with pitch breaks, or with other pertubations in the phonatory source such as breathiness or hoarseness, or with nasalization. These phenomena may create a mismatch between the source and the bandwidth of the spectrogram filter and obscure important harmonic information. Even with the advent of digital analysis techniques such as Linear Predictive Coding (LPC), determination of the formant frequencies may be difficult especially if the fundamental frequency (F_o) is high. These problems not withstanding, several studies (Angelocci, Kopp & Holbrook, 1964; McGarr & Gelfer, 1983; Monsen, 1976a;1978; Rubin-Spitz, 1983) have examined the acoustic characteristics of vowels produced by hearing-impaired persons All studies report similar results: formant frequency values of vowels may not be distinct and may tend toward the frequency values for the neutral vowel /ə/. These acoustic data have been interpreted to suggest that hearing-impaired speakers use restricted tongue movements to achieve vowel differentiation or, alternatively, may attempt to achieve differences in vowels by varying the degree of jaw opening. These ideas have been substantiated in a series of physiological studies by Tye-Murray (1992). Moreover, electromyographic studies (McGarr & Gelfer, 1983; McGarr & Harris, 1982) of the genioglossus tongue muscle used in production of high vowels (e.g., /i/), have shown inappropriate tongue posture and timing relative to other articulators. Occasionally, formant frequency values for a back vowel such as /u/ resembled the values for a high front rounded vowel /y/ as found in French suggesting that the hearing-impaired speaker was using visual cues (lip rounding), and not tongue position, to effect a vowel distinction (McGarr & Gelfer, 1983). Such results reported in the acoustic domain have been often noted in the classic perceptual studies (Hudgins & Numbers; 1942; Smith, 1975).

At issue is how the results gathered from perceptual, acoustic, and physiological studies of vowel articulation can be shaped to form a model of vowel production in persons with hearing loss. For example, do the reported results of vowel neutralization suggest there is an "absent vowel target"? This hypothesis implies that hearing-impaired speakers do not have precise articulatory and acoustic representations of vowels because of hearing loss. Moreover, there would be systematic differences in production of phonemes with respect to degree of loss. Such a hypothesis might be supported by evidence from physiological studies showing static tongue body posture (Tye-Murray, 1992), and /or from acoustic studies showing relatively restricted formant frequencies (Angelocci et al., 1964). However, one would expect to find somewhat different error patterns in vowel production as a function of hearing loss although this is not the case. While there is a difference in the quantity of errors as a function of hearing loss, research (Levitt, McGarr, & Geffner, 1987) has shown that there are no differences in error patterns for subjects with different degrees of hearing loss, of different ages, or whose educational placement is in a mainstream environment or in a school for the deaf. It is important to note that with few exceptions (McGarr & Gelfer, 1983; Rubin-Spitz, 1983), the data from most studies are obtained from a single token of each vowel and the results are averaged across talkers. Thus, Monsen (1976a) argues that to advance an "absent vowel target theory," one would have to show that the productions were random with respect to the vowel target. This is not deducible from studies with a single repetition of each target vowel. Alternatively, one might espouse Monsen's theory that hearing-impaired speakers produce their vowel targets in a well-defined but deviant phonological space. Again, this linguistic theory requires analysis of multiple repetitions of tokens as supporting evidence. More recently Harris, Rubin-Spitz and McGarr (1985) have argued in both acoustic and physiological investigations that hearing-impaired subjects may be highly variable in their production of repeated tokens. That is, hearing-impaired speakers may fail to marshall their articulators consistently as would normal-hearing speakers and thus their productions resemble the unskilled or emerging patterns of new learners. The consistency of normal hearing talkers to produce speech intelligibly even under a variety of novel situations (e.g., pipe smoking, pencil in mouth, novocaine, or bite blocks) is well documented and speaks to this consistency in organization. Preliminary data (Campbell, Boothroyd, McGarr, & Harris, 1992) of the vowel productions of hearing-impaired speakers in a variety of bite-block conditions indicate that they are able to make articulatory compensatory adjustments but cannot do so consistently. Taken together, these data do not support the theory of an absent vowel target or the notion of deviant phonology. However, data supporting any theory are limited. Clearly, each of these theories would impel a different organization of speech training protocols. And neither the research nor the pedagogy currently exist to test these models.

Acoustic Analysis of Consonants

Production of consonants such as sonorants and obstruents are made with different constrictions and pressures in the vocal tract and a number of acoustic measures have been used to characterize aspects of these productions. Spectral changes have been studied in some detail in speech produced by hearing persons. However, in studies of the acoustic properties of consonants produced in the speech of hearing-impaired persons, most work has been either an analysis of voice onset time (Monsen, 1976b; McGarr & Lofqvist, 1982) or of formant frequency transitions (Monsen, 1976c; Rothman, 1976). For example, an extremely common problem in speech produced by hearing-impaired talkers is a failure to observe the voiced-voiceless distinction. In their classic study of normal talkers, Lisker and Abramson (1964) noted that release of the oral occlusion relative to the onset of the glottal pulse (i.e., voice onset time, VOT) is one of the salient acoustic cues that distinguish the voiced and the voiceless stops. VOT values are longer for voiceless than voiced segments, and VOT contrasts are characteristically longer for velars than for alveolars and bilabials, respectively. Acoustic studies (Monsen, 1976b; McGarr & Lofqvist, 1982) of phonemes produced by hearing-impaired talkers indicate that values for voiced and voiceless segments often overlap. The range of these values in some hearing-impaired talkers (roughly 20-30msec.) are close to the perceptual boundaries reported in synthetic speech studies. At these ranges, interactions and shifts in the perception of voicing are known to occur. Thus, when the VOT values of segments produced by hearing-impaired speakers fall within this range, listeners have great difficulty making segmental judgments. The result is a "blur" in the voicing distinction and poorer intelligibility than for those speakers who produce voiced and voiceless phonemes. Wherein does this error pattern originate? Earlier in this chapter, we discussed several physiological studies of laryngeal articulation

(Mahshie & Contour, 1983; McGarr & Lofqvist, 1982; 1988) which show that the hearing-impaired speaker may use inappropriate laryngeal gestures when producing stops and fricatives. That is, they may fail to abduct the vocal folds, thus using a gesture appropriate for a a voiced phoneme, or they may fail to observe the demand that voiceless fricatives are produced with a greater opening than voiceless stops (to accommodate the airflow for fricatives). Still, in other instances, the speaker may not temporally coordinate the laryngeal gesture with the oral articulation, and so the production fails.

In still another view of segmental production problems, hearing-impaired speakers will be characterized as placing the articulators fairly accurately, especially for highly visible aspects of articulation, but show great difficulty in moving the articulators correctly from one position to the next. The manifestation of this problem at an acoustic level is a severe distortion in formant frequency transitions. Changes in formant frequency transitions, including the direction, extent and direction especially of the second formant frequency (F2), are critical acoustic cues for identifying the place of articulation. Work (e.g., Monsen, 1976c; Rothman, 1976) indicates that formant transitions produced in speech by many hearing-impaired persons are exceedingly short in duration, are missing altogether, or are limited because the formant frequencies of the surrounding vowels are severely neutralized. The second formant may hover in the 1800Hz range with a slope that is fairly flat when the linguistic demands of the language require either a rising or falling transition. These few acoustic studies imply the absence of coarticulation in speech of hearing-impaired speakers—a topic of considerable speculation in the literature.

Coarticulation of Speech Segments

What is coarticulation? A basic definition considers the temporal overlap of articulatory movement for different phones. It is co-production. Coarticulation enables the speaker to transmit redundant information in less time than if segments were produced sequentially. Coarticulation thereby maximizes communication and reduces the load on the listener. Coarticulation skills are influenced by anticipatory events; that is, a phoneme is influenced by the characteristics of preceding segment(s). An often cited example is the anticipation of liprounding that occurs in consonants preceding /u/ relative to /i/. On the other hand, perseveratory coarticulatory or carry-over effects can also occur. This is defined as the influence of a given sound segment on a following sound segment. For example, postvocalic consonants are strongly influenced by the preceding vowel. Perseveratory or carry-over coarticulation may more reflect the mechanical properties of the articulatory system.

Coarticulation has been studied to a considerable degree in physiological and acoustic studies of the speech of adults and a number of coarticulation models or theories have been promulgated. Anticipatory coarticulation, as a speech production strategy, is apparently learned and the development of coarticulatory skills in young normally developing children has recently become a focus of considerable research. Some researchers (e.g., Sereno, Baum, Marean, & Liberman, 1987; Sereno & Liberman, 1987) argue that children coarticulate less than adults because the phoneme size elements are not appropriately blended. Thus, the coarticulatory effects become more precise and adult-like with increasing age. Others (e.g., McGowen & Nittrouer, 1988; Nittrouer & Studdert-Kennedy, 1987) argue that there are greater coarticulatory effects across syllable size units in children than in adults citing evidence that the units are not well differentiated. In this consideration, the syllabic units decrease and become more adult-like as skills develop.

Historically, hearing-impaired speakers have been described as articulating on a segment-by-segment basis (Calvert, 1961). The analogy "as beads on a string" has been used to describe the productions. As noted above in discussion of vowel and consonant studies, evidence to suggest a lack of coarticulatory skills in hearing-impaired talkers can be derived from numerous sources. Recent research (Baum & Waldstein, 1991; Waldstein & Baum, 1991) directly addresses some issues concerning coarticulatory speech skills produced by hearing-impaired persons. Apart from how well the specified phonemes are produced *per se*, data on coarticulation of speech segments in this population have been sparse. In the Waldstein and Baum work, temporal (duration) and spectral measures (centroids and F2) of hearing-impaired children's productions of obstruents were made to study both anticipatory and carry-over coarticulation effects. These data were also analyzed with respect to developmental trends of age-matched normal hearing controls. The acoustic analysis showed evidence of anticipatory coarticulation in the production of CVs by the hearing-impaired children but to a lesser degree than the coarticulation effects evidenced by the normal hearing controls. Statistically significant differences between the two age groups of subjects (averages of 7 years and 10 years, respectively) were found only for the measures of F2. With respect to carry-over coarticulation, again both normal hearing and hearing-impaired children evidenced coarticulatory effects, but the results were less robust in the hearing-impaired groups. Similar results were reported for a group of hearing-impaired adults and matched controls in an electropalatographic and acoustic study of sibilant production (McGarr, Raphael, Kaloustian, Kollia, & Harris, 1991). Taken together, these limited data do not support the absence of coarticulatory effects in speech produced by hearing-impaired persons, but they do lend credence to the notion that such speakers exhibit fewer context effects in their productions.

The work of Whitehead (1986) further suggests that hearing-impaired adults with poor speech intelligibility have not learned some of the coarticulatory timing rules of speech. In his acoustic study of the effect of final consonant on the durations of preceding vowels, it was found that normal hearing speakers and semi-intelligible hearing-impaired speakers produced vowels longer before voiced consonants, as compared with voiceless consonants, and longer before fricative consonants, as compared with plosives. Hearing-impaired speakers who demonstrated semi-intelligible speech, however, failed to demonstrate any vowel durational differences related to the following consonant voicing and manner of production. This, of course, lends credence to the suggestion by Calvert (1961) that hearing-impaired speakers articulate on a segment-by-segment basis.

Obviously, the data regarding coarticulatory effects in speech produced by hearing-impaired persons are limited. Nonetheless, they support the notion that such speakers exhibit fewer context effects in their productions. The effects of reduced or absent coarticulatory features on the overall speech intelligibility of hearing-impaired persons remains to be determined. It is, however, a necessary component, along with the physiologic and acoustic features of segmental speech production, for the eventual development of valid and reliable speech assessment measures and also instructional strategies for hearing-impaired persons.

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