In: Bell-Berti, F., & Raphael, L. J. (1995). Producing Speech: Contemporary Issues. For Katherine Safford Harris. AIP Press: New York.

29 Ephphatha[1]: Opening Inroads to Understanding Articulatory Organization in Persons with Hearing Impairment

Nancy S. McGarr
St. John's University
Haskins Laboratories

Melanie McNutt Campbell
The Graduate School and University Center of
The City University of New York
Haskins Laboratories

INTRODUCTION

In 1968, Dorothy Huntington, Katherine Harris, and George Sholes published a seminal paper entitled "An Electromyographic Study of Consonant Articulation in Hearing-Impaired and Normal Speakers" in the *Journal of Speech and Hearing Research.* This collaborative study was Harris' first in the area of speech production of hearing-impaired persons. It was also the very first to employ electromyographic (EMG) techniques to investigate articulatory

[1]"Ephphatha" is a transliteration of an Aramaic word meaning "Be opened." It appears in the New Testament book of Mark as the word used by Jesus when he performed a miracle by opening the ears of a man who was deaf and enabling him to speak.

movement in deaf speakers. Yet in ways other than technique it was also unlike many of the investigations of the speech of the hearing impaired that preceded it.

Some of the earliest known studies of the speech of the deaf were conducted in the 1930s, using kymographic recordings of air pressure inside and outside of the mouth or nose and movement tracings of the contacts of the lips, the tongue with the palate and the movements of the breathing muscles (Hudgins, 1934, 1937; Rawlings, 1935). Those investigations were largely limited to observations of speech rate, breath management (syllables per breath), and speech rhythm. One of the most famous studies, conducted in 1942 by Hudgins and Numbers, determined the relative effects of speech errors on the intelligibility of deaf students by obtaining phonographic recordings, presenting the recorded samples in intelligibility tests to listeners, and phonetically transcribing the productions. From pressure measures, movement tracings, and transcriptions, these early investigators made insightful speculations about the nature of the underlying articulatory behaviors, but had no means to directly observe such.

In the decades that followed, studies were conducted that used more direct measurement techniques. They included use of the oscillograph (Lindner, 1962), the sound spectrograph (Angelocci, Kopp, & Holbrook, 1964; Calvert, 1961), the glossal transducer (Brannon, 1964), cinefluorography (Crouter, 1963), and EMG (Huntington, Harris, & Sholes, 1968). Huntington, Harris, and Sholes (1968), however, employed a paradigm that has become a hallmark of work by Harris and her colleagues: collecting multiple channels of information simultaneously. In this particular study both audio and EMG signals were recorded from multiple repetitions of utterances by each subject. The audio recordings enabled the researchers to administer perceptual tests of intelligibility as well as to analyze of muscle activation. Observing multiple repetitions of tokens, allowed EMG patterns to emerge, and accorded the researchers an opportunity to examine the consistency of productions, rather than to rely on only one or two illustrative tokens from many speakers.

The paper was distinguished also by its perspective. As Harris wrote on another occasion, "studies of pathological phoneme production are generally directed towards treatment. We might be able to gain considerable insight into the function of various parts of the nervous system in controlling articulation, if we used clinical material on damage at different levels and sites in the sensorimotor system" (Harris, 1971, p. 208). The Huntington, Harris, and Sholes paper (1968) was just such a study: "Our immediate interest was to clarify, if possible, some of the factors which give deaf speech its perceived pathological quality; our more general goal was the better understanding of the organization of normal speech by considering the effects of various types of malfunction of the whole speech chain" (p. 147).

In that spirit, it is the aim of this paper to understand better the importance of auditory feedback to the organization of speech by adopting a specific perspective for a brief review of some literature about the speech of hearing-impaired persons and for a discussion of some research in progress. From this perspective, the intent of the literature overview will not be to list deaf speech errors, but to delineate broader parameters of speech motor control dependent on auditory feedback. This perspective incorporates a central assumption: that the speech production system of a hearing-impaired person is intact, save the benefit of complete and undistorted auditory feedback, and thus seeks and uses any available visual, vibrotactile, kinesthetic, proprioceptive, and residual auditory feedback to organize itself. The speech produced by such a system, while communicating with more variable success than one served by normal hearing, will still resemble it. The overview of the literature will show that the chances for successful, intelligible speech production will be higher when a speech target has inherent possibilities for visual and/or vibrotactile feedback, when the articulators involved have fewer degrees of freedom of movement, and when the timing of the movement of one articulator is not tightly interrelated to the movement of another. Such factors will affect all hearing-impaired talkers and thus contribute to similarities in their speech production. The availability and quality of auditory feedback and the ability to use that and other types of feedback will, however, vary from one hearing-impaired individual to another. Any two intact speech production systems seeking to organize themselves around different auditory information, or around secondary visual, vibrotactile, kinesthetic or proprioceptive cues in its absence, will vary in production strategies and thus contribute to differences among hearing-impaired speakers.

Huntington, Harris, and Sholes built the line of inquiry for their paper from Calvert's (1961) results. Calvert had shown that experienced listeners could not discriminate isolated vowels spoken by hearing speakers from those spoken by hearing-impaired talkers, but could discriminate them when they were in CV syllables. Huntington, Harris, and Sholes reasoned, then, that deaf speech quality was caused neither by simple abnormal control of vocalization nor by abnormal communication of suprasegmental phonemes. They considered that possible contributing factors could be assigned arbitrarily to either topological or dynamic categories. While the 1968 study addressed only questions about topology, this paper will begin with topology, discuss dynamics, and proceed to two additional areas that have emerged as relevant from later work mirroring the original Huntington, Harris, and Sholes methodology. A brief overview of some facts that are known about each will be provided and brought to bear on some current research concerning the articulatory organization of hearing-impaired talkers. While deaf speech quality most certainly includes aspects of respiration (reviewed in Metz & Schiavetti, this volume) and voice quality, the goal here is to focus on articulatory parameters, beginning with the question that Huntington, Harris, and Sholes addressed. When compared to hearing speakers, do hearing-impaired speakers:

1. use different articulatory configurations (Topology);
2. demonstrate movement patterns to and from consonants (Dynamics and Timing);
3. show less consistent speech patterns in multiple productions of a given target (Variability Among and Within Hearing-Impaired Talkers);
4. exhibit different interarticulatory coordination properties (Interarticulatory Organization)?

TOPOLOGY

In attempting to determine what factors "give deaf speech its pathological quality," Huntington, Harris, and Sholes (1968) speculated, "On the one hand, dynamic features may be distorted—that is, transitions from consonant articulatory configuration to vowel may be strange. On the other hand, purely topological features may be abnormal—that is, the 'wrong' articulatory configurations may be commonly produced by deaf talkers" (p. 148). They investigated the latter for both tongue and lip configurations. The lip data are presented first.

Surface EMG recordings were made of upper, lower, and corner lip muscle activity for 11 common consonants in a disyllabic frame (hə'CVk) spoken by two deaf and two hearing speakers. The 11 consonants included a set of visible segments, /p, b, m, w, f/. Upper lip and corner lip peak activity showed high positive correlations between the hearing and deaf subjects. The facial muscle postures of the deaf were generally correct, though usually exaggerated. Huntington, Harris, and Sholes concluded, "Deaf speakers are more likely to be like normal speakers where there is a possibility of getting visual feedback" (p. 157). Other evidence that visual information enhances accurate lip configuration was provided by Carr (1953). She recorded the spontaneous productions of 48 five-year-old children with congenital deafness and observed that the labial sounds /p,b,m,w,f,v/ occurred more frequently in the deaf than has been observed for hearing infants. However, as Locke (1980) points out in his review of Carr's study, it would be imprudent to conclude that deaf children display a different course of speech development based on visual information. They may use more labial sounds, but these consonants are also used frequently by hearing babies and are also found in many of the world's languages. The hearing-impaired child's pattern of use of such consonants then, still resembles the speech development pattern of a hearing child, but his successful and more frequent use of the labials is made more probable because visual cues are available.

Another visible aspect of articulation, jaw opening, appears to be correct in the speech of the hearing impaired, as shown in a cineflourographic study by Crouter (1963) of six hearing and six deaf talkers producing four vowels in target words in a carrier sentence. From film tracings of incisal opening (i.e., jaw lowering) she determined that the deaf used greater jaw lowering for the close vowels /u/ and /i/ than did the hearing, but maintained the jaw height distinction between high and low vowels. More recent studies using optical tracking (McGarr, Löfqvist, & Story, 1987), strain gauge (Tye-Murray & Folkins, 1990) and cinefluorography plus X-ray microbeam techniques (Tye-Murray, 1991) have suggested that deaf and hearing speakers use similar magnitudes of jaw displacement in vowel production (though ratios of tongue-to-jaw displacement may be different).

Conversely, the tongue, an articulator with not easily seen and one with many degrees of freedom for movement, appears to be less accurately shaped. Huntington, Harris, and Sholes (1968), also examined tongue EMG activity for production of /t,s,ʃ,r,l,k/. Electrodes were placed at tongue-tip, mid-tongue, and back-tongue positions. Peak values were correlated for various consonants for pairs of hearing and hearing-impaired subjects, one electrode at a time. All correlations were positive and only a few were not statistically significant, indicating that "the topology of deaf articulation is not totally uncorrelated to [the] normal pattern" (p. 157). Still, hearing speakers were more like each other than they were like the hearing-impaired speakers. The hearing-impaired subjects exhibited some configurations that were different from those of the hearing speaker. For example, one hearing-impaired talker used more tongue-tip activity for /s/ and /ʃ/ than for /t/, the reverse of the pattern for the hearing. More recently Waldstein and Baum (1991), in an acoustic study, have provided corroborative centroid and F_2 evidence that hearing-impaired children produce incorrect consonantal tongue configurations. Hearing-impaired children were shown to produce points of constriction for /ʃ,t,k/ farther back in the mouth than did hearing children.

Tongue configurations were also less accurate in vowels produced by hearing-impaired speakers. In addition to cinefluorographic tracings of incisal opening, described earlier, Crouter (1963) traced tongue shape at the middle frame of vowels. Despite great individual differences in tongue contour among all subjects, overall differences were evident between the hearing and the hearing impaired. Measurements were made of the minimal distance between the posterior pharyngeal wall and the base of the tongue. The airway was greater for high versus low vowels in both subject groups, but the hearing subjects had greater opening for high vowels. In other words, the hearing speakers moved their tongues farther forward and out of the pharyngeal cavity than did deaf speakers. Consistent retraction of the tongue root and a lowered tongue body in vowel production by the hearing impaired have also been reported by Subtelny, Li, Whitehead, and Subtelny (1989).

Angelocci et al. (1964) provided acoustic measures that further indicate that hearing-impaired subjects frequently employ vowel configurations that are topographically incorrect. Examining the production of 10 vowels by hearing and hearing-impaired 11-to-14-year-old boys, they showed that F_1 and F_2 frequency means revealed a tendency for deaf speakers to follow the normal progression of a rising F_1 moving from close to open vowels and a lowering F_2 going from front to back vowels, but over a far more *limited* frequency range. On the other hand, drawing enclosures around plots of F_1 by F_2 values of tokens from deaf subjects for each vowel resulted in large areas entirely overlapping each other, indicating great variability across subjects and a high degree of inaccuracy in placement of articulators. Enclosures for the vowels of the hearing children were smaller, suggesting more accuracy. These findings have been supported by several acoustic (Monsen, 1976a; Monsen, 1976b; Shukla, 1989), cinefluorographic (Stein, 1980; Tye, Zimmermann, & Kelso, 1983), cinefluorographic plus X-ray microbeam (Tye-Murray, 1991), and intelligibility studies (Suonpää & Aaltonen, 1981). All indicate that hearing-impaired talkers exhibit a reduced articulatory space, resulting in vowel confusions for listeners. Monsen (1976a) suggests that the deaf may differentiate vowels primarily on the basis of F_1, which is greatly affected by height of the jaw, a visible articulator, and which carries acoustic information at lower frequencies, more often within the residual hearing of hearing-impaired listeners. F_2, on the other hand, is primarily affected by forward and backward movements of the tongue that are largely invisible and carry acoustic information at higher frequencies, often beyond residual hearing.

Do hearing-impaired speakers use different articulatory configurations than hearing speakers? The answer appears to be yes and no, depending upon the articulators involved and the inherent possibilities for visual, auditory or other feedback. The evidence that the configurations are not dissimilar in kind from those of hearing speakers, together with the great differences across deaf subjects, suggest that speech production systems of hearing-impaired talkers are sensitive to and are organized around any feedback available, including residual hearing.

DYNAMICS AND TIMING

A frequent observation about hearing-impaired speech is that it is slow (Boothroyd, Nickerson, & Stevens, 1974; Voelker, 1938). Closure durations of plosives and constriction durations of fricatives are extended (Calvert, 1961), vowel durations are longer (Zimmermann & Retaliata, 1981), repetitive syllables are uttered at a slower rate (Robb, 1985), and segmental shortening with increased length of utterance is not consistently exhibited (Tye-Murray & Woodworth, 1989). Rothman (1976), Stein (1980), and Zimmermann and Retaliata (1981) have observed slower consonant-to-vowel transitions. If speech production of hearing-impaired talkers is guided in part by vibrotactile cues, it is possible that articulator contacts, approximations and constrictions, and movement to and from such points, might be prolonged to maximize feedback, resulting in slower production overall. Conversely, with visible articulators, such as the lip and jaw, vision may augment and, in fact, reduce dependence on vibrotactile cues. Some evidence suggests that this is true. Open vowel posture durations (Tye-Murray, 1984) and opening and closing durations of the jaw (McGarr, Löfqvist, & Story, 1987; Tye-Murray & Folkins, 1990) and the lower lip (Tye-Murray & Folkins, 1990) have been found to be similar in hearing and hearing-impaired subjects. Jaw and lip peak velocities (McGarr et al., 1987; Tye-Murray & Folkins, 1990) have also been shown to be comparable for the two groups. Some have found these velocities to be faster in hearing-impaired subjects (Stein, 1980; Zimmermann & Retaliata, 1981). It is difficult to explain the findings of faster velocities of the lip and jaw other than to speculate that, because they are visible, their movements could serve to return the articulators from open postures with fewer sources of feedback to points of closure or constriction where vibrotactile feedback is abundant.

Consistent with the hypothesis that vibrotactile cues are a primary source of information for the hearing-impaired talker and that segments may be prolonged to maximize that feedback, is the evidence that hearing-impaired talkers exhibit less coarticulation than hearing speakers. Metz, Whitehead, and McGarr (1982) provided figures from high speed film data of laryngeal configurations by two women, one hearing and one hearing-impaired, during /h/ production of an /ihi/ syllable. The normal speaker placed the vocal folds in a semi-adducted posture in the medial glottal plane. The folds oscillated slightly during production of the /h/, but did not contact nor vibrate periodically. The hearing-impaired speaker, on the other hand, separated the vocal folds widely and did not position them in the medial glottal plane, making it difficult to make a smooth transition to the following vowel. Data from Whitehead and Metz (1980) had previously demonstrated that this subject had both extremely high air flow rates during the /h/ segment and perceptual discontinuities between individual segments of the /ihi/ syllable. At the acoustic level Waldstein and Baum (1991) and Baum and Waldstein (1991) examined both anticipatory and perseveratory coarticulation in hearing and hearing-impaired children. They measured duration and spectral characteristics of /ʃ,t,k/ when preceded or followed by the vowels /i/ and /u/. Both anticipatory and perseveratory lip rounding for /u/ affects the spectral characteristics of consonants and thus served as a measure of coarticulation. The highly intelligible hearing-impaired children in their studies showed evidence of both anticipatory and perseveratory liprounding, though the effects were not as robust as for the hearing children. Tye-Murray (1987) observed that hearing subjects lowered the jaw more during bilabial closure for "ba" and "pa" than for "bi" and "pi," but the deaf did not move in such an anticipatory fashion. The upper articulator studies just discussed are especially interesting because coarticulatory liprounding and jaw opening, while available visually, were not demonstrated at all or to the same degree as in hearing speakers. It may be that vibrotactile feedback for segment-by-segment production is used as a primary monitoring device even when visual information is available.

Acoustic studies have shown that formant transitions are more restricted in spectral range in hearing-impaired speech (Monsen, 1976b; Rothman, 1976). These studies offer still more data that different movement patterns are exhibited by hearing-impaired speakers. In the "Topography" section of this paper, evidence was presented that F_2 carries acoustic information often beyond the residual hearing of hearing-impaired talkers and that those speakers have a tendency to keep the tongue in a more retracted and low position during vowel production. Monsen (1976a) observed that F_2 "floats" around 1800 Hz regardless of the vowel produced. As Monsen pointed out, the lack of F_2 movement precludes the transmission of important consonant and vowel information. The restricted formant transitions presumably arise, then, from (1) movements to consonants from less accurate tongue configurations for vowels, and (2) from movements altered in order to exploit vibrotactile cues.

It was suggested in the "Introduction" of this paper that the probability for intelligible speech production in hearing-impaired speakers is diminished when rapid and precise temporal alignment of two or more articulatory events is required. McGarr and Harris (1983) studied the timing of the lips with the tongue for production of nonsense VCVCV utterances (e.g., /əˈpɑpip /). EMG techniques were employed to study orbicularis oris and genioglossus activity in one hearing and one deaf speaker. Lip muscle activity was similar for both, but the timing of tongue activity relative to lip muscle activity was different for each subject. The hearing speaker consistently displayed peak tongue muscle activity for /i/ coincident with the acoustic /p/ burst. The deaf speaker exhibited changing patterns of timing from token to token, and peak muscle activity for /i/ occurred frequently after lip release for /p/. Thus, the behavior of a visible articulator, the lips, appeared near-normal, but that of the invisible articulator, the tongue, with many degrees of freedom for possible movement, was shown to be variably timed with respect to the lips.

Another example of a particular problem for hearing-impaired speakers is the temporal alignment of activity of the larynx and upper articulators. Rothman (1977) showed with EMG and spectrographic data that deaf speakers frequently initiated or terminated voicing for a given segment incorrectly, either before or after tongue gestures were in place. Cinefluorographic data from Stein (1980) indicated that deaf speakers timed voice onset incorrectly in syllable-initial consonant production. Aerodynamic data from Whitehead and Barefoot (1980) showed that hearing and intelligible deaf speakers had greater average airflow during voiceless consonant production than voiced, but that unintelligible deaf speakers did not differentiate airflow for voiceless and voiced consonants. It was hypothesized that the unintelligible group did not employ normal glottal abductory gestures for voiceless consonants. Transillumination and transconductance data from McGarr and Löfqvist (1982) as well as fiberscopic evidence from Mahshie and Conture (1983) have provided further details. Both studies found that hearing-impaired speakers were variably successful in terms of voice onset timing. Some hearing-impaired talkers produced some coordinated gestures comparable to those of normals, whereas other productions differed in a variety of ways. A laryngeal gesture was sometimes used when none was required, or there was a failure to use an adductory or abductory gesture when expected, and patterns varied among the hearing-impaired speakers. Several studies have also shown that hearing-impaired speakers frequently time voice offset for vowels inappropriately late relative to the production of voiceless final consonants (Stein, 1980). Consequently they do not display normal, systematic differences in vowel duration as a function of the voiced or voiceless status of postvocalic consonants (Calvert, 1961; Monsen, 1974; Whitehead & Jones, 1977).

VARIABILITY AMONG AND WITHIN HEARING-IMPAIRED TALKERS

Hudgins and Numbers' classic study in 1942 of the speech intelligibility of the deaf revealed "recurrent" errors made by 192 deaf and partially deaf students. Seven categories of consonant errors and five of vowel errors were identified from the 5,701 total errors recorded. Clearly, speakers with hearing loss exhibit a certain commonality in speech errors. Furthermore, given a speech sample as small as a CV syllable (Calvert, 1961) or a vowel (Rubin, 1985), listeners can discriminate utterances spoken by hearing-impaired talkers from those spoken by hearing talkers. To the ear of the listener, then, hearing-impaired speakers make characteristically similar, if not stereotypical, articulation errors.

Nevertheless, many of the studies discussed in the preceding sections of this paper have revealed a great deal of variability *among* hearing-impaired talkers. Crouter (1963) obtained cineflourographic tongue shape tracings of vowels produced by hearing and hearing-impaired speakers. Great variability in tongue contour was seen in both groups, but the greatest differences were seen among deaf speakers. In their acoustic measures of vowels spoken by hearing and deaf subjects, Angelocci et al. (1964) plotted F_1 by F_2 values and found that the distributions of values for the vowels of the hearing were more limited, suggesting more consistency and accuracy in production. The greater dispersal of values for vowels spoken by the hearing-impaired children indicated a high degree of inconsistency and inaccuracy across speakers. Robb (1985) studied diadochokinetic syllable rates of 30 hearing-impaired high-school students. Results revealed large variability around durational means. Huntington, Harris, and Sholes (1968) found EMG patterns for tongue movement in consonant production by deaf subjects that differed both from those of the hearing controls and from each other. They concluded, "Deaf speakers are no more like each other than they are like normal speakers" (p. 157). Indeed, Monsen (1974) studied vowel duration preceding various final consonants in monosyllabic words spoken by hearing and hearing-impaired talkers. He concluded that deaf talkers were more different from the hearing than from other deaf talkers, yet stated that patterns of production varied so much from deaf speaker to deaf speaker as to be "idiolectal" in nature (p. 393).

Evidence suggests that reduced or absent auditory feedback results in both stereotypic productions common to most hearing-impaired talkers *and* differences from speaker to speaker. Most certainly, the kind and amount of residual hearing available to a talker influences production. Boothroyd's observations (1984) of varying speech perception abilities among hearing-impaired individuals with similar audiograms supports that conclusion. Though the following quotation is taken from Tye-Murray's (1992) observations about hearing-impaired children, it most certainly applies to hearing-impaired speakers of all ages: "The existence of idiosyncrasies suggests that latitude exists in how children compensate for deafness" (p. 255).

Production patterns by *any one* hearing-impaired speaker from speech sample-to-speech sample also appear to reflect the dichotomous form of stereotypicality and variability seen *among* speakers. Few early studies shed light on this question, since they sampled only one or two productions each of a variety of phonemes produced by multiple talkers (e.g., Crouter, 1963; Angelocci et al., 1964). Even when subjects produced several tokens of a particular phoneme, these phonemes were often spoken in different phonetic environments or only a few tokens were selected for analysis (e.g., Crouter, 1963; Hudgins and Numbers, 1942; Monsen, 1976a; Suonpää & Aaltonen, 1981). The Huntington, Harris, and Sholes study (1968) required that multiple tokens be collected in order to reveal any consistent EMG patterns and to "calibrate" the speech production of an individual. For clear patterns to emerge, movements had to be quite regular. Huntington, Harris, and Sholes commented that the results differed from observations they had made of repeated utterances by dysarthrics, which were extremely variable and displayed a tendency for all of the articulators to move at the same time. "In contrast, the deaf have well-organized habits, which may be 'correct' or 'incorrect' by comparison with normals, but are not dissimilar in kind" (pp. 157-158). They found that visible articulations were generally correct. They also found that tongue muscle patterns were "stereotyped," though frequently wrong, for production of the consonants /t,s,ʃ,r,l,k/. Vibrotactile cues might reasonably have allowed for the stability seen in the production of those consonants. Monsen's 1974 study of the durations of /i/ and /I/ before final consonants in monosyllables produced by hearing-impaired talkers revealed that the normal pattern of modification according to final consonant, seen in hearing speakers, was replaced by a different pattern in which the duration of /i/ and /I/ were almost mutually exclusive rather than more naturally overlapping as in the hearing. Monsen noted, "Although the variation is different from normal speech, in any one subject it appears systematic to a considerable extent" (pp. 393-394). He suggested that durational cues were more accessible to hearing-impaired talkers than spectral cues. Use and exploitation of durational differences may have competed with attention to and production of more subtle duration and timing differences of vowels with respect to final consonants. McGarr et al. (1987) used optical tracking to study the vertical dimension of jaw movement duration, displacement, and velocity for utterances such as "And Pa peals it" and "And Bea pops it." They found no good evidence of variability in any of the kinematic measures of the jaw, a visible articulator with relatively few degrees of freedom of movement.

On the other hand, several studies have provided evidence that there is also great variability in some articulatory gestures of deaf speakers. Bush (1981) examined the relations among fundamental frequency, formant frequency, and vowel intelligibility in monosyllabic words produced by deaf and hearing children and adolescents. Results revealed that the amount of change in fundamental frequency from vowel-to-vowel was greater in the deaf than in the hearing, but that these changes were a consequence of vowel height effects and not systematically used as a substitute for F_1 and F_2 movement to differentiate these vowels. McGarr and Löfqvist (1982, 1988) provided dramatic evidence of variability in laryngeal timing in relation to tongue and lip movements in hearing-impaired adults during obstruent and obstruent-cluster production. Even for phonemes judged by listeners as correct, considerable physiological variability from token-to-token was evident. As discussed previously, McGarr and Harris (1983) studied tongue-tip and lip coordination using bilabial-vowel-bilabial sequences such as /ə'pɑpip/. In both hearing and hearing-impaired speakers orbicularis oris peaks of activity for /p/ were well defined, though more prolonged in the hearing-impaired. However, the activity of the genioglossis for /i/ was variable, occurring too early, slightly late, or very late, relative to the release burst of the second /p/. Similar interarticulator variability has also been described by McGarr and Gelfer (1983), who found one deaf speaker with high token-to-token variability in onset and offset of genioglossus EMG activity relative to onset of voicing in six vowels in a [hVd] environment.

Rubin (1985) conducted a study to test directly whether deaf speakers produce vowels with the same variability as normal talkers. Her subjects were six orally trained, severely and profoundly hearing-impaired high school students and two age-matched normals. The subjects produced "You got me the /bVb/" with any of seven test vowels, and each of the seven types was said 15 times. Deaf talkers were significantly more variable than normals on measures of fundamental frequency, vowel duration, and F_1 and F_2 frequency. However, the pattern of variability varied from talker to talker. Some speakers showed small variability for point vowels but greater variability for half-close vowels like /ε/. Others showed overlap between front and back vowels. Still others showed a great deal of variability for all vowels.

There is much yet to be learned about the stability of articulatory movement in hearing-impaired populations. Observations and data presented by Metz, Schiavetti, Sitler, and Samar (1990) illustrate this well. First, they pointed out that Mahshie and Conture (1983) showed that lateral excursion of the arytenoid cartilages during abduction and adduction (observed using a fiberoptic nasolaryngoscope) and oral patterns coordinated with laryngeal movements (revealed from associated spectrograms) were more variable for two of four hearing-impaired subjects than for four hearing speakers. The other two hearing-impaired subjects exhibited consistent aberrant laryngeal articulatory patterns over multiple tokens. The two subjects whose productions were unstable had higher overall speech intelligibility ratings than the two whose productions were consistent, but wrong. Metz et al. noted that those findings are in contrast to those of McGarr and Löfqvist (1982) who also examined laryngeal articulatory behaviors and interarticulator timing patterns in obstruents produced by hearing and hearing-impaired adults. McGarr and Löfqvist reported that one subject who showed high production instability was their least intelligible speaker. Second, Metz et al. provided data in which they examined the relation between measures of the speech intelligibility of 40 hearing-impaired speakers and production stability as indicated by standard deviation calculations for eight acoustic measures including voice onset time, range of F_2 transitions, and difference in formant values between high and low vowels or between front and back vowels measured in a variety of utterances. Equal numbers of subjects were drawn from each of five groups representing five intelligibility ratings ranging from low to high. Results indicated that hearing-impaired subjects who were rated as having high intelligibility also exhibited high stability for the acoustic measures. Subjects rated as having low intelligibility, however, exhibited either of two overall patterns: highly stable, but aberrant patterns of acoustic values or highly variable patterns. The first may represent those who have learned a stable, yet wrong, set of production rules and consistently use them. The latter may represent those who did not learn a consistent set of speech production rules and who lack consistent underlying speech production motor strategies.

Harris, Rubin-Spitz, and McGarr (1985) have drawn comparisons between findings of greater variability in the speech of the hearing-impaired and that of the motorically immature young hearing speaker. It would appear that auditory feedback, just as speaking experience, constrains production variability. The accumulated data do not indicate that hearing-impaired talkers have a deviant phonology, reliably produced, but a partially correct phonology with varying patterns of variability. Correct and more stable production may occur when a speech target has inherent possibilities for visual, vibrotactile, and auditory feedback, when the articulators involved have fewer degrees of freedom, and when timing of the movement of one articulator is not highly dependent on another. Partially correct and less stable production may occur when these conditions are not met. From the perspective taken in this paper, examples of both stable and variable articulatory movement in hearing-impaired talkers are both explainable and expected.

INTERARTICULATORY ORGANIZATION

Monsen (1976a) proposed that the differences in speech between the hearing and the hearing-impaired can be explained by the characteristics of the feedback they receive. In his words, "the audiogram tends to imprint itself upon speech" (p. 197). Monsen supported this proposal with vowel data from hearing and hearing-impaired talkers. He examined five tokens each of the vowels /i/, /ɑ/, and /ɔ/ from words in sentences in order to map the rough dimensions of each individual's vowel triangle. Drastic reductions in articulatory space were seen in the productions of hearing-impaired subjects, yet differentiated regions of production in the vowel space were preserved. Monsen stressed that the hypothesis that hearing-impaired subjects do not have clearly defined vowel target areas was unsupported. To prove such "one would have to show that there is a nearly random relation between the formant frequency pattern and the intended vowels" (p. 197). Monsen suggested that hearing-impaired talkers distinguish vowels on the basis of the first formant, since a resonance peak in the lower frequency region is more often within the residual hearing of hearing-impaired speakers. (The second formant is in higher frequency regions, often beyond residual hearing, and has been shown to be more restricted in range in hearing-impaired talkers.) F_1 is most affected by tongue height. Jaw position greatly influences tongue height and, as a visible articulator, is observable by a hearing-impaired talker.

If vowel targets for the hearing impaired are formed in terms of visual and partial auditory information, the nature of the targets must be quite different than those for the hearing. These different targets might or might not marshal the neuromuscular articulatory system in the same way. In a study currently underway to explore some of these questions, Campbell (in preparation) is examining the coordination between the tongue and the jaw for vowel production in the hearing impaired, using a bite-block.

Previous studies have shown that hearing talkers speak normally in a variety of conditions in which normal movement has been disrupted. Thus, for example, articulatory compensation has been shown to occur when a speaker's jaw is artificially fixed in an open position by a bite-block placed between the teeth (e.g., Fowler & Turvey, 1980; Lindblom, Lubker, & Gay, 1979; Lindblom & Sundberg, 1971a, 1971b; Nooteboom & Slis, 1970). When the jaw is not free to move normally, the tongue displays greater movement to achieve vowel targets. Vowel formant frequencies in bite-block speech of hearing speakers have been shown to approximate those in normal speech. Because formant measures have usually been made at the onset of the vowel, many have assumed that auditory feedback plays no role in on-line speech motor control. Furthermore, it has also been speculated that while acoustic feedback may play some role in coordinating reciprocal movements of articulators, it may not be a substantial component. Testing for the presence or absence of articulatory compensation in hearing-impaired talkers probes the importance of acoustic feedback to compensation and the nature of neuromuscular articulatory coordination in speakers whose vowel targets have been developed around little or no reliance on audition. If hearing-impaired speakers use visual and kinesthetic feedback from jaw displacement as a primary means to differentiate one vowel from another and if they use little difference in tongue positioning (Stein, 1980; Stevens, Nickerson, & Rollins, 1983; Monsen, 1976a, 1976b), it may be that the jaw and tongue complex are not functionally linked in the same manner as in the hearing, and there may be no compensatory movements of the tongue. One cinefluorographic and perceptual study (Tye et al., 1983) has suggested that hearing-impaired speakers with acquired and congenital hearing losses exhibit articulatory compensation for a bite-block while an acoustic study (Osberger, Netsell, & Goldgar, 1986) indicated that prelingually deafened subjects do not.

Campbell's subjects were hearing-impaired adults with hearing loss onset before two years of age and an average hearing loss in either the severe or profound range. All were graduates of an oral school and had received consistent speech training throughout their school years. A group of hearing subjects, age and sex-matched to the hearing-impaired group, served as controls. Subjects produced repetitions of one of three vowels /i/, /ɪ/, or /æ/ in the carrier phrase "Say /hVt/ again." Each vowel was produced 16 times in random order in each of four, also randomized, conditions:

1. a normal condition;
2. a bite-block condition in which subjects wore bite-blocks custom-made to produce an interincisal distance of 20 mm. Hearing-impaired subjects wore their hearing aids.
3. a bite-block-plus-masking condition in which subjects wore the bite-block and were deprived of auditory feedback. Hearing-impaired subjects removed their hearing aids and both hearing and hearing-impaired subjects listened to masking noise delivered via headphones from a pink noise generator at a measured output of 81 dB SPL.
4. a masking noise condition in which hearing-impaired subjects removed their hearing aids and both hearing and hearing-impaired subjects listened to masking noise, as in #3, above.

Compensation was determined by measuring the formants of vowels and comparing the formant frequencies spoken in test the conditions with those obtained in the normal condition.

To discuss whether a subject compensates for a bite-block, one must first consider what would happen if he did not. That is, one must consider what would happen to formant values of vowels if they were produced with a lowered jaw, as for a bite-block, and if the rest of the vocal tract did not vary. Such measures are not possible to obtain with humans, so they are provided by computer simulation. Such simulations predict the direction and degree of change in F_1 and F_2, whose values go in opposite directions. A bite-block lowers the jaw and opens the mouth, thus raising F_1. The tongue rocks back in the mouth, thus lowering F_2. For the vowel /i/, the only vowel that will be discussed here, simulated values predict a rise in F_1 of approximately 250 to 275 Hz and a lowering of F_2 of approximately 375 to 400 Hz, when the jaw is lowered for a bite-block and there is no compensatory change in the vocal tract.

Returning to Campbell's study, preliminary results for one profoundly hearing-impaired subject and one subject with normal hearing, matched for age and gender, are illustrated in Figure 1. The hearing-impaired male subject (P3M) sustained a profound bilateral sensorineural hearing loss present since birth, possibly of genetic origin. His pure tone average threshold in the better ear was 107 dB HL.

Compared to the hearing speaker (N1M), the hearing-impaired subject (P3M) produced tokens of /i/ in a lower and more backed position in the vocal tract, reflected in higher first formant and lower second formant values. These values were also dramatically more variable.

In general, subject N1M showed a very small but systematic effect of test conditions in the direction, but not the degree, predicted by simulation. The most disrupting condition, bite-block plus masking, resulted in mean F_2 values that were decreased by 3.6% and F_1 values that were raised by 7.6%. Standard Deviations for F_2 doubled for the bite-block-plus-masking condition (SD=59.8) compared to the normal condition (SD=24.12).

The form of P3M's adjustments was quite different. In Figure 1 it can be seen that the tokens in the four conditions separate, revealing the effect of each condition in the direction, but not to the degree, predicted for F_1. The greatest change was seen in the bite-block-plus-masking condition in which F_1 increased 12.6% from a mean of 342 Hz in the normal condition to 385 Hz and the Standard Deviation went from 16.05 to 53.63. Clearly this subject made adjustments in upward movement of the tongue to adjust for a fixed open jaw. A surprising effect on F_1 was shown in the masking condition where mean F_1 (371 Hz) increased 8.5%. That effect was greater than the bite-block condition that produced a mean F_1 (359 Hz) 5% higher than the normal condition. Removal of the hearing aid and the application of masking noise affected this subject's productions in the F_1 dimension more than the bite-block. These results suggest that this profoundly hearing-impaired subject used residual hearing to monitor his production of this vowel and made upward adjustments of the tongue for a bite-block that were more successful with his hearing aid than without.

There was a surprising reversal from the predicted change in F_2. Mean F_2 was increased, rather than decreased, by 7.5%, 12.7%, and 14.8% in the masking, bite-block, and bite-block-plus-masking conditions, respectively, compared to the normal condition. It appears that the subject's response to each test condition was to move the tongue farther forward in the mouth. These adjustments may have been an attempt to maximize tactile feedback in the presence of a bite-block by bunching the tongue at the front of the vowel space.

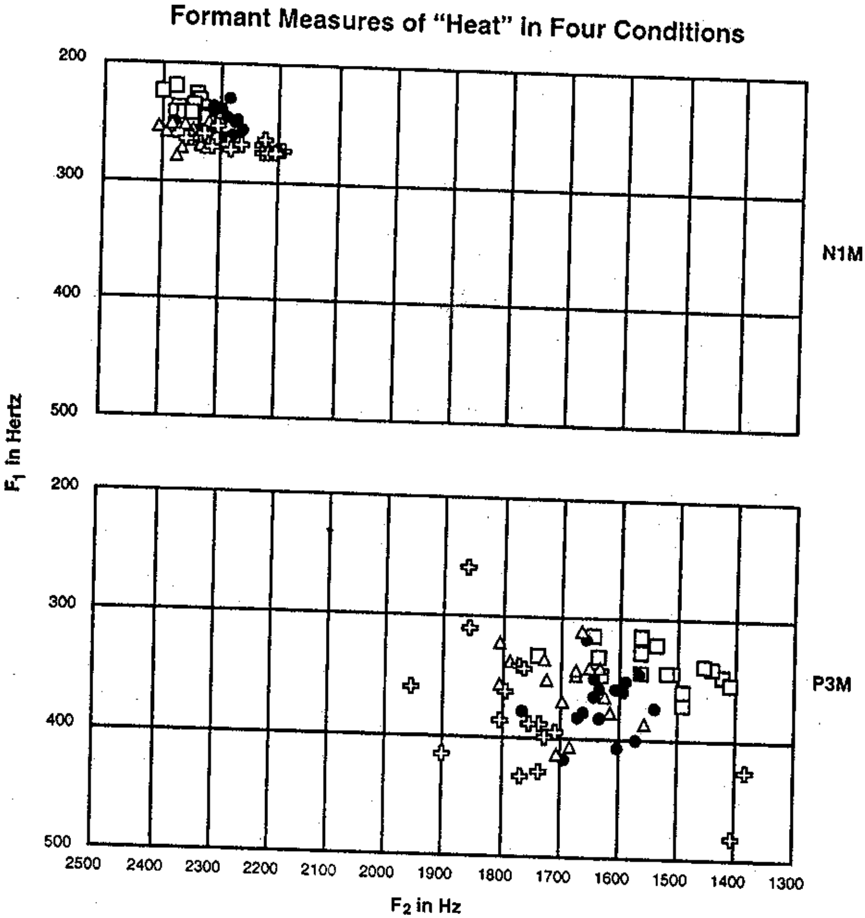

FIGURE 1. Formant measures for the vowel /i/ in the word "heat" spoken by one hearing subject, NIM, and one profoundly deaf subject, P3M, in four conditions:

- □ Normal Condition.
- ● Masking Condition (Hearing Aids Removed).
- △ Bite-Block Condition.
- ✣ Bite-Block-Plus Masking Condition (Hearing Aids Removed).

However, removal of the hearing aid and the application of masking noise with or without a bite-block also resulted in an increase in F_2. Furthermore, accuracy in the combined condition was greatly disrupted compared to the normal condition (SD=185.68 Bite-Block-plus-Masking; SD=63.25 Normal Condition) and was also more disrupted than in the bite-block alone condition (SD=55.99), again suggesting forward adjustments of the tongue for a bite-block that were more consistent with the hearing aid than without.

In response to a fixed jaw, this hearing-impaired speaker exhibited adjusted movements of the tongue for the vowel /i/ that resembled articulatory compensation in hearing speakers. Those adjustments appeared to be aided by residual hearing. However, the adjustments were less successful than, and different from, those of the hearing subject, perhaps, in part, as a result of attempts to maximize tactile feedback.

CONCLUSIONS

This brief overview of evidence from a variety of studies of the speech patterns of hearing-impaired persons and the discussion of research in progress suggest that the speech production system of a hearing-impaired speaker seeks and uses any available visual, vibrotactile, kinesthetic, proprioceptive, and residual auditory feedback to organize itself. The speech produced by such a system, while communicating with more variable success than that produced by a system served by normal hearing, still resembles it. Chances for successful, intelligible production are greater when a speech target has inherent possibilities for visual and/or vibrotactile feedback, when the articulators involved have fewer degrees of freedom of movement, and when the timing of the movement of one articulator is not highly constrained by the movement of another. These factors result in similarities among hearing-impaired talkers. However, the great contrasts among hearing-impaired subjects in many of these studies point to the possibility of large differences in availability, quality, and use of feedback by individuals within the categories of severe or profound deafness. Research addressing the organization and control of speech produced by hearing-impaired subjects clearly is warranted to increase knowledge and to provide the important data bases necessary to improve the efficacy of training.

EPILOG

As a Distinguished Professor at the Graduate School and University Center of the City University of New York, Katherine Safford Harris has served on the doctoral thesis committees of many of its students. Noted especially here are those students who studied aspects of the speech and language skills of persons with hearing impairments, students who profited from the wit and wisdom of Katherine Harris as a member of their thesis committees:

Clarissa R. Smith	(1972)	Residual Hearing and Speech Production in Deaf Children
Sr. Rosemary Helen Gaffney	(1977)	Assessing Receptive Language Skills of Five- to Seven-Year-Old Deaf Children
Nancy Steinmuller McGarr	(1978)	The Differences Between Experienced and Inexperienced Listeners in Understanding the Speech of the Deaf
Mary Joseph Osberger	(1978)	The Effect of Timing Errors on the Intelligibility of Deaf Children's Speech
Abigail Peterson Reilly	(1979)	Syllable Nucleus Duration in the Speech of Hearing and Deaf Children
Judith A. Rubin	(1983)	Static and Dynamic Information in Vowels Produced by the Hearing Impaired
Melanie McNutt Campbell	(in progress)	Articulatory Compensation in Hearing and Hearing-Impaired Speakers
Areti Okalidou	(in progress)	Coarticulation in Deaf Speakers

ACKNOWLEDGMENT

This manuscript and the research conducted as Campbell's thesis was supported by NIH Grant DC-00121 to Haskins Laboratories.

REFERENCES

Angelocci, A. A., Kopp, G. A., & Holbrook, A. (1964). The vowel formants of deaf and normal-hearing 11- to 14-year-old boys. *Journal of Speech and Hearing Disorders, 29*, 156-170.

Baum, S. R., & Waldstein, R. S. (1991). Perseveratory coarticulation in the speech of profoundly hearing-impaired and normally hearing children. *Journal of Speech and Hearing Research, 34*, 1286-1292.

Boothroyd, A. (1984). Auditory perception of speech contrasts by subjects with sensorineural hearing loss. *Journal of Speech and Hearing Research*, *27*, 134-144.

Boothroyd, A., Nickerson, R., & Stevens, K. (1974). Temporal patterning in the speech of the deaf. *SARP Report #7*. Northampton, MA: Clarke School for the Deaf.

Brannon, J. B., Jr. (1964). *Visual feedback of glossal motions and its influence upon the speech of deaf children*. Unpublished doctoral dissertation, Northwestern University.

Bush, M. A. (1981). *Vowel articulation and laryngeal control in the speech of the deaf*. Unpublished doctoral dissertation, Massachusetts Institute of Technology.

Calvert, D. R. (1961). *Some acoustic characteristics of the speech of profoundly deaf individuals*. Unpublished doctoral dissertation, Stanford University.

Campbell, M. M. (in preparation). *Articulatory compensation in hearing and hearing-impaired speakers*. Unpublished doctoral dissertation, City University of New York.

Carr, J. (1953). An investigation of the spontaneous speech sounds of five-year-old deafborn children. *Journal of Speech and Hearing Disorders, 18*, 22-29.

Crouter, L. (1963). *A cinefluorographic comparison of selected vowels spoken by deaf and hearing subjects*. Master's thesis, University of Kansas.

Fowler, C. A., & Turvey, M. T. (1980). Immediate compensation in bite-block speech. *Phonetica, 37*, 306-326.

Harris, K. S. (1971). Children's language development and articulatory breakdown. In D. L. Horton & J. J. Jenkins (Eds.), *The perception of language* (pp. 207-215). Columbus, OH: Chas. E. Merrill.

Harris, K. S., Rubin-Spitz, J., & McGarr, N. S. (1985). The role of production variability in normal and in deviant developing speech. In J. Lauter (Ed.), *Proceedings of the conference on the planning and production of speech in normal and hearing-impaired individuals: A seminar in honor of S. Richard Silverman* (pp. 50-57). ASHA Reports 15. Rockville, MD: American Speech-Language-Hearing Association.

Hudgins, C. V. (1934). A comparative study of the speech co-ordination of deaf and normal subjects. *Journal of Genetic Psychology, 44*, 1-48.

Hudgins, C. V. (1937). Voice production and breath control in the speech of the deaf. *American Annals of the Deaf, 82*, 338-358.

Hudgins, C. V., & Numbers, F. C. (1942). An investigation of the intelligibility of the speech of the deaf. *Genetic Psychology Monographs, 25*, 289-392.

Huntington, D. A., Harris, K. S., & Sholes, G. N., (1968). An electromyographic study of consonant articulation in hearing-impaired and normal speakers. *Journal of Speech and Hearing Research, 11*, 147-158.

Lindblom, B. E. F., Lubker, J. F., & Gay, T. (1979). Formant frequencies of some fixed-mandible vowels and a model of speech motor programming by predictive simulation. *Journal of Phonetics, 7*, 147-161.

Lindblom, B. E. F., & Sundberg, J. (1971a). Acoustical consequences of lip, tongue, jaw, and larynx movement. *Journal of the Acoustical Society of America, 50*, 1166-1179.

Lindblom, B. E. F., & Sundberg, J. (1971b). Neurophysiological representation of speech sounds. *Papers from the Institute of Linguistics - University of Stockholm, 7*, 16-21.

Lindner, G. (1962). Über den zeitlichen Verlauf der Sprechweise bei Gehörlosen. *Folia Phoniatrica, 14*, 67-75.

Locke, J. L. (1980). The prediction of child speech errors: Implications for a theory of acquisition. In G. H. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson (Eds.), *Child phonology, Volume 1: Production* (pp. 193-209). New York: Academic Press.

Mahshie, J. J., & Conture, E. G. (1983). Deaf speakers' laryngeal behavior. *Journal of Speech and Hearing Research, 26*, 550-559.

McGarr, N. S., & Gelfer, C. E. (1983). Simultaneous measurements of vowels produced by a hearing-impaired speaker. *Language and Speech, 26*, 233-246.

McGarr, N. S., & Harris, K. S. (1983). Articulatory control in a deaf speaker. In I. Hochberg, H. Levitt, & M. J. Osberger (Eds.), *Speech of the hearing impaired: Research, training and personnel preparation* (pp. 75-95). Baltimore, MD: University Park Press.

McGarr, N. S., & Löfqvist, A. (1982). Obstruent production by hearing-impaired speakers: Interarticulator timing and acoustics. *Journal of the Acoustical Society of America, 72*, 34-42.

McGarr, N. S., & Löfqvist, A. (1988). Laryngeal kinematics in voiceless obstruents produced by hearing-impaired speakers. *Journal of Speech and Hearing Research, 31*, 234-239.

McGarr, N. S., Löfqvist, A., & Story, R. S. (1987). Jaw kinematics in hearing-impaired speakers. *Proceedings XIth ICPhS: The eleventh international congress of phonetic sciences* (Vol. 4, pp. 173-176). Tallinn, Estonia, USSR: Academy of Sciences of the Estonian S.S.R.

Metz, D. E., Schiavetti, N., Sitler, R. W., & Samar, V. J. (1990). Speech production stability characteristics of hearing-impaired speakers. *The Volta Review, 92*, 223-235.

Metz, D. E., Whitehead, R. L., & McGarr, N. S. (1982). Physiological aspects of speech produced by deaf persons. *Audiology, 7*, 35-48.

Monsen, R. B. (1974). Durational aspects of vowel production in the speech of deaf children. *Journal of Speech and Hearing Research, 17*, 386-398.

Monsen, R. B. (1976a). Normal and reduced phonological space: The production of English vowels by deaf adolescents. *Journal of Phonetics, 4*, 189-198.

Monsen, R. B. (1976b). A taxonomic study of diphthong production in the speech of deaf children. In S. K. Hirsh, D. H. Eldredge, I. J. Hirsh, & S. R. Silverman (Eds.), *Hearing and Davis: Essays honoring Hallowell Davis* (pp. 281-290). St. Louis, MO: Washington University Press.

Nooteboom, S. G., & Slis, I. (1970). A note on the degree of opening and the duration of vowels in normal and "pipe" speech. *IPO Annual Progress Report, 5*, 55-58.

Osberger, M. J., Netsell, R., & Goldgar, D. (1986). Articulatory reorganization in deaf talkers. *Journal of the Acoustical Society of America, 79*, Supplement 1:S37. (A)

Rawlings, C. G. (1935). A comparative study of the movements of the breathing muscles in speech and in quiet breathing of deaf and normal subjects. *American Annals of the Deaf, 80*, 147-156.

Robb, M. P. (1985). Oral diadochokinesis in hearing-impaired adolescents. *Journal of Communication Disorders, 18*, 79-89.

Rothman, H. (1976). A spectrographic investigation of consonant-vowel transitions in the speech of deaf adults. *Journal of Phonetics, 4*, 129-136.

Rothman, H. (1977). An electromyographic investigation of articulation and phonetic patterns in the speech of deaf adults. *Journal of Phonetics, 5*, 369-376.

Rubin, J. A. (1985). *Static and dynamic information in vowels produced by the hearing impaired*. Bloomington, IN: Indiana University Linguistics Club.

Shukla, R. S. (1989). Phonological space in the speech of the hearing impaired. *Journal of Communication Disorders, 22*, 317-325.

Stein, D. M. (1980). *A study of articulatory characteristics of deaf talkers.* Unpublished doctoral dissertation, University of Iowa.

Stevens, K. N., Nickerson, R. S., & Rollins, A. M. (1983). Suprasegmental and postural aspects of speech production and their effect on articulatory skills and intelligibility. In I. Hochberg, H. Levitt, & M. J. Osberger (Eds.) , *Speech of the hearing impaired: Research, training, and personnel preparation* (pp. 35-51). Baltimore, MD: University Park Press.

Subtelny, J., Li, W., Whitehead, R., & Subtelny, J. D. (1989). Cephalometric and cineradiographic study of deviant resonance in hearing-impaired speakers. *Journal of Speech and Hearing Disorders, 54*, 249-263.

Suonpää, J., & Aaltonen, O. (1981). Intelligibility of vowels in words uttered by profoundly hearing-impaired children. *Journal of Phonetics, 9*, 445-450.

Tye, N., Zimmermann, G. N., & Kelso, J. A. S. (1983). "Compensatory articulation" in hearing impaired speakers: A cinefluorographic study. *Journal of Phonetics, 11*, 101-115.

Tye-Murray, N. (1984). *Articulatory behavior of deaf and hearing speakers over changes in rate and stress: A cinefluorographic study.* Unpublished doctoral dissertation, University of Iowa.

Tye-Murray, N. (1987). Effects of vowel context on the articulatory closure postures of deaf speakers. *Journal of Speech and Hearing Research, 30*, 90-104.

Tye-Murray, N. (1991). The establishment of open articulatory postures by deaf and hearing talkers. *Journal of Speech and Hearing Research, 34*, 453-459.

Tye-Murray, N. (1992). Young cochlear implant users' response to delayed auditory feedback. *Journal of the Acoustical Society of America*, *91*, 3483-3486.

Tye-Murray, N., & Folkins, J. W. (1990). Jaw and lip movements of deaf talkers producing utterances with known stress patterns. *Journal of the Acoustical Society of America*, *87*, 2675-2683.

Tye-Murray, N., & Woodworth, G. (1989). The influence of final-syllable position on the vowel and word duration of deaf talkers. *Journal of the Acoustical Society of America*, *75*, 629-632.

Voelker, C. H. (1938). An experimental study of the comparative rate of utterance of deaf and normal hearing speakers. *American Annals of the Deaf*, *83*, 274.

Waldstein, R. S., & Baum, S. R. (1991). Anticipatory coarticulation in the speech of profoundly hearing-impaired and normally hearing children. *Journal of Speech and Hearing Research*, *34*, 1276-1285.

Whitehead, R., & Barefoot, S. (1980). Some aerodynamic characteristics of plosive consonants produced by hearing-impaired speakers. *American Annals of the Deaf*, *125*, 366-373.

Whitehead, R., L. & Jones, K.-O. (1977). Air flow of plosive consonants in the speech of the hearing-impaired. Paper presented at the 94th Meeting of the Acoustical Society of America, Miami Beach, FL.

Whitehead, R., & Metz, D. (1980). Aberrant laryngeal devoicing gestures produced by deaf speakers: Evidence from acoustic, aerodynamic, and glottographic data. Paper presented at the 100th Meeting of the Acoustical Society of America, Los Angeles, CA.

Zimmermann, G., & Rettaliata, P. (1981). Articulatory patterns of an adventitiously deaf speaker: Implications for the role of auditory information in speech production. *Journal of Speech and Hearing Research*, *24*, 169-178.