636

Journal of Speech and Hearing Research, Vol. *31*, 234–239, June 1988

LARYNGEAL KINEMATICS IN VOICELESS OBSTRUENTS PRODUCED BY HEARING-IMPAIRED SPEAKERS

NANCY S. McGARR
Haskins Laboratories, New Haven, CT,
and Graduate Center, The City University of New York

ANDERS LÖFQVIST
Haskins Laboratories, New Haven, CT, and Lund University, Sweden

During normal production of voiceless consonants several events occur simultaneously in the vocal tract. These events must be temporally coordinated. Earlier work has indicated that a breakdown in interarticulator timing can contribute to the characteristic voiced-voiceless errors produced by hearing-impaired speakers. The present study examines kinematic details of the laryngeal articulatory gesture in 2 deaf speakers and a control subject using transillumination of the larynx. Results indicate that hearing-impaired speakers often do not produce differences between stops and fricatives in the kinematic details of the gesture. That is to say, although hearing speakers commonly use a larger laryngeal gesture for fricatives than for stops and also show durational differences of the abduction and the adduction phases between phonetic categories, the hearing-impaired subjects did not make them. Also, the deaf speakers participating in this study were more variable in the kinematic measures.

In a series of studies, we have investigated the timing and coordination of laryngeal and oral articulations in the production of voiceless consonants. These studies examined how interarticulator timing is used in a wide variety of languages to produce contrasts of voicing and aspiration (e.g., Löfqvist & Yoshioka, 1981a, 1984) and also showed that a breakdown in interarticulator timing contributes to the characteristic voiced-voiceless errors produced by hearing-impaired speakers (McGarr & Löfqvist, 1982).

During normal production of voiceless stops and fricatives, several events occur simultaneously in the vocal tract. At the laryngeal level, an abduction-adduction gesture of the glottis is made to arrest glottal vibrations. This gesture also contributes to the aerodynamic conditions necessary to increase oral pressure behind a constriction or closure in the oral cavity. In the production of voiceless stop consonants, a transient noise source occurs at the release of the oral closure. For fricatives, the oral pressure drives the air through a narrow constriction and a turbulent noise source is created. These laryngeal and supralaryngeal events in voiceless consonant production must be temporally coordinated.

It is well documented that hearing-impaired speakers have great difficulty preserving temporal aspects of speech (cf., Osberger & McGarr, 1982). For example, in a study of obstruents produced by hearing-impaired speakers (McGarr & Löfqvist, 1982), we showed both similarities and dissimilarities in the speech of 3 deaf talkers with respect to normal production. In some cases, the hearing-impaired subjects preserved the correct pattern of interarticulator timing between the larynx and the upper articulators described above. In other cases, the speakers omitted the glottal abduction-adduction gesture for voiceless consonants or produced such a gesture where none was required. This failure in interarticulator coordination accounts for some perceptual results reported in the literature on the speech characteristics of the hearing impaired: the voiced for voiceless substitutions (Carr, 1953; Heider, Heider, & Sykes, 1941; Hudgins & Numbers, 1942; Millin, 1971; Smith, 1975), and the converse patterns—voiceless for voiced substitutions, (Mangan, 1961; Markides, 1970, Nober, 1967). In the acoustic domain, it also explains the lack of appropriate voice onset time (Mahshie & Conture, 1983; Monsen, 1976) that characterizes the speech of this population.

In our earlier work on the deaf, we were concerned with the presence or absence of the glottal gesture and its timing relative to the upper articulators. In this paper, we extend this research by examining some kinematic details of the laryngeal gesture. Only recently has this area been investigated in speech produced by hearing subjects (cf., Löfqvist & McGarr, 1986; Löfqvist & Yoshioka, 1981b; Munhall, Ostry, & Parush, 1985). The results of these studies may be summarized as follows: There is a high positive relationship between peak amplitude (i.e., maximum displacement of the vocal folds) and peak velocity of laryngeal articulatory movements. The overall duration of the abduction and adduction gesture is similar for both fricatives and stops. The durations of the opening and closing phases of the laryngeal gesture are identical or very similar. Peak amplitude is generally larger for fricatives than for stops. A corresponding kinematic analysis of laryngeal gestures produced by hearing-impaired talkers has not been made.

METHODS

Stimuli

The linguistic material consisted of the words "seal, peal, teal, chicken, steal," which formed part of the

0022-4685/88/3102-0234$01.00/0

TABLE 1. Summary of listener judgments of the productions by the deaf speakers. The percentage of correct productions, the percentage of errors, and the error categories are shown. (after McGarr and Löfqvist, 1982)

	Deaf Speaker 1		*Deaf Speaker 2*	
Obstruents	*Percent correct*	*Percent error*	*Percent correct*	*Percent error*
*p*eal	100		17	83 (b)
*t*eal	100		100	
*s*eal	100		100	
*ch*icken	50	33 (s) 17 (t)		100 (s)
*st*eal	83	17 (s)	83	17 (s)

corpus of our previous study. These words were placed in the carrier phrase "Say . . . again" and were repeated six times by each of the subjects.

Subjects[1]

The production of 3 subjects—the hearing control and deaf subjects 1 and 2 of McGarr and Löfqvist (1982)—were reanalyzed. The data from Deaf Subject 3 could not be used in this study due to technical problems. Both hearing-impaired subjects were congenitally deafened and sustained severe-profound hearing losses (mean pure tone average for 0.5, 1, and 2 kHz = 90 dB+ ISO in the better ear). The hearing-impaired subjects had received at least part of their training in oral schools for the deaf, and had no other handicaps. Speech samples obtained from each subject were rated for overall intelligibility by an experienced listener. Following the format of the rating scale for intelligibility (Subtelny, 1975), Deaf Speaker 1 could be characterized as highly intelligible with the exception of a few words or phrases. The speech of Deaf Speaker 2 could be characterized as difficult to understand although the gist of the content could be understood. The authors also made broad phonetic transcriptions of the test words. In general, the listeners agreed in their judgments, and the perceptual results are summarized in Table 1.

Because the kinematic measures depend on the execution of a glottal abduction/adduction gesture, not all tokens could be used for analysis. Although all 30 stimuli of both the hearing control and Deaf Speaker 1 were produced with a glottal gesture associated with the obstruent, Deaf Speaker 2 produced only 18 appropriate glottal gestures (see McGarr & Löfqvist, 1982). Of these, 3 tokens were not analyzable for this study due to technical reasons. This resulted in 1 token of teal, 6 tokens each of seal and chicken respectively, and 2 tokens of steal for which kinematic measures could be made.

Procedure

Laryngeal articulatory movements were recorded using transillumination of the larynx. Comparisons between transillumination and fiberoptic films (Löfqvist & Yoshioka, 1980) and also between transillumination and high-speed films (Baer, Löfqvist, & McGarr, 1983) have shown good agreement. A fiberscope provided illumination of the larynx, and the light passing through the glottis was sensed by a phototransistor placed on the neck at the level of the crico-thyroid membrane. During the recording session, the view of the larynx was monitored in order to control for movements of the light source as well as fogging of the fiberscope lens. The transillumination signal was recorded on FM-tape for subsequent computer processing. A microphone signal was recorded simultaneously in direct mode. For processing, the transillumination signal was digitized at 200 Hz. After smoothing using a 15 ms (3-point) triangular window, the signal was differentiated to obtain a measure of movement velocity. From these records of the normal and differentiated transillumination signals, a number of measurements were made. These included the peak amplitude of the abduction-adduction gesture, peak velocity of abduction and adduction, and the duration of the abduction and adduction phases. Onset and offset of movement were defined as points of zero velocity. All measurements were made interactively on a computer. Because the transillumination signal cannot be calibrated *in vivo*, the measurements were made in arbitrary units. It is assumed that these units are constant within an experiment although not comparable between different sessions. Thus comparisons can be made within subjects but not across subjects. This procedure is the same as employed in studies of hearing speakers (Löfqvist & McGarr, 1986).

RESULTS

Figures 1 and 2 plot movement amplitude versus peak velocity (of the same movement) for the abduction and adduction phases, respectively. For the hearing speaker, the following points can be made. First, there is a high positive correlation between movement amplitude and peak velocity. This is apparent for both abduction and adduction ($r = .96$, $y = .91x + 95.8$ and $r = .83$, $y = .051x + 143.1$, respectively, where y = peak velocity and x = movement amplitude). Second, laryngeal gesture is influenced by phonetic category. There is a positive relationship between movement amplitude and peak velocity for both fricatives and stops. Fricatives and the cluster /st/ are produced with a larger glottal opening than the stops and the affricate. In both Figures 1 and 2, the data points for the fricatives and the stops occupy almost non-overlapping regions in the plot.

---

[1] For convenience in the following discussion, we call the speech characteristics of the group "deaf speech" and the speakers of "deaf speech" will be called "deaf." By making this identification, we acknowledge that not all persons who sustain severe to profound hearing losses produce this characteristic speech.

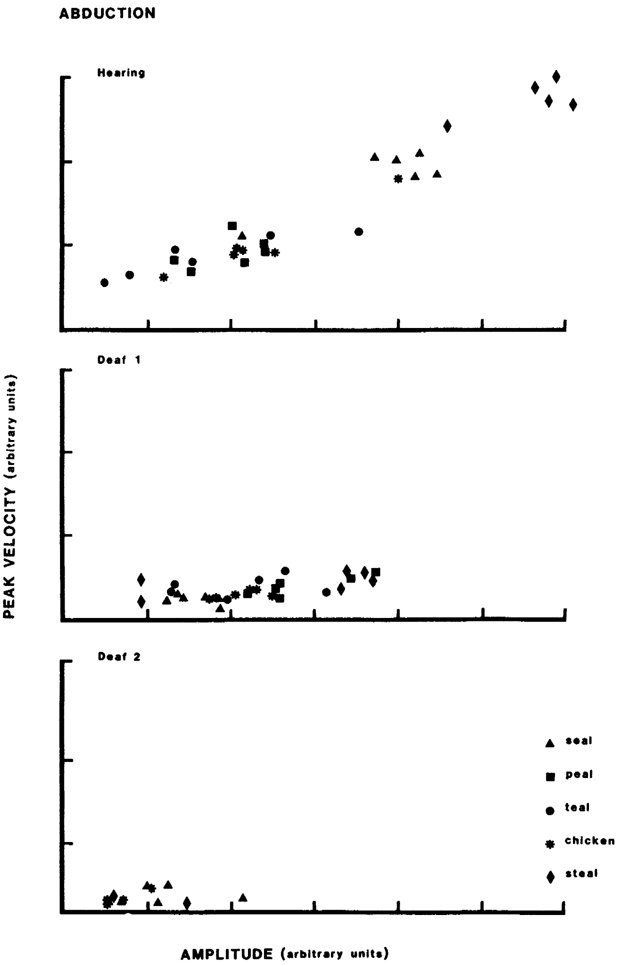

FIGURE 1. Plot of amplitude and peak velocity of glottal abduction.

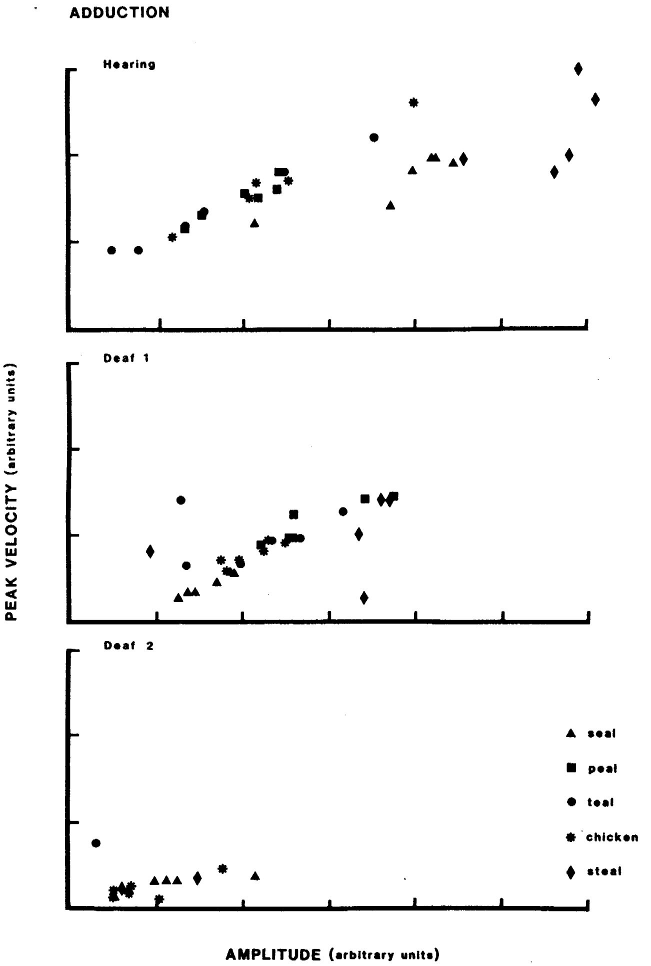

FIGURE 2. Plot of amplitude and peak velocity of glottal adduction.

For Deaf Speaker 1, there is an overall positive relationship between amplitude and peak velocity for adduction (Figure 2) but not for abduction ($r = .59$, $y = .051x + 76.9$ and $r = .62$, $y = .022x + 31.5$ respectively, where y = peak velocity and x = movement amplitude). We reported in McGarr and Löfqvist (1982) that this speaker's productions were characterized by two linked abduction-adduction gestures. However, the interarticulator timing of the second glottal event with respect to upper articulators was like normal. The results for abduction and adduction in the present study refer to the first and second gesture, respectively. In both Figures 1 and 2, the data points associated with different phonetic categories show overlap.

For Deaf Speaker 2, the number of tokens is often less than six because this speaker did not always make the appropriate abduction-adduction gesture. There is no clear relationship between movement amplitude and peak velocity for either abduction or adduction ($r = .19$, $y = .006x + 18.4$ and $r = .18$, $y = .011x + 33.6$ respectively, where y = peak velocity and x = movement amplitude). Also for this speaker, there is no segmental differentiation.

Figures 3 and 4 present the relationship between movement amplitude and the duration of the abduction and adduction phases, respectively. There is no clear relationship between amplitude and duration of abduction and adduction. For the hearing speaker, duration of abduction is similar for each token irrespective of movement amplitude ($r = -.311$, $y = -.004x + 126.2$, where y = peak velocity and x = movement amplitude); however, the duration of the adduction gesture shows a slight positive relationship to amplitude ($r = .79$, $y = .018x + 110.5$, where y = peak velocity and x = movement amplitude). For both deaf speakers, there is considerable scatter in the plots; none of the slopes of the regressions for amplitude and duration deviated from zero.

Figure 5 plots the duration of the abduction phase versus the duration of the adduction phase. For the hearing speaker, the fricatives and the stops form two distinct clusters. For the fricatives, abduction is shorter than adduction, $M = 116$ ms ($SD = 8.61$) compared to $M = 141$ ms ($SD = 12.4$), $t(10) = 5.49$, $p < .001$. For the stops and the affricate, the reverse is true, $M = 129$ ms ($SD = 10.70$) compared to $M = 107$ ms ($SD = 8.6$), $t(17) = 6.77$, $p < .001$. For Deaf Speaker 1, there is no such clear

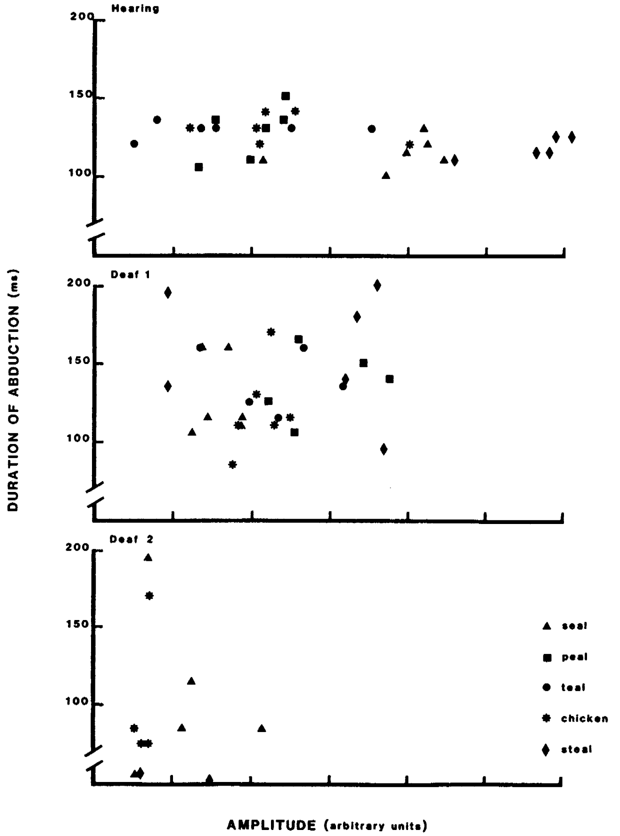

FIGURE 3. Plot of amplitude and duration of glottal abduction.

pattern. For all segment types, abduction is longer than adduction, $M = 143$ ms ($SD = 36.15$) and $M = 127$ ms ($SD = 26.41$) for the fricatives [$t(11) = 1.24, p < .05$]. For the stops and the affricate the corresponding values for abduction and adduction are $M = 131$ ms ($SD = 24.6$) and $M = 112$ ms ($SD = 115.15$), $t(15) = 2.63$, $p < .05$. This subject shows more variable durations than the hearing subject as evidenced by the greater standard deviations. Deaf Speaker 2 is even more variable.

DISCUSSION

The results for the hearing subject in this study show agreement with previous investigations in that a positive relationship between peak velocity and peak amplitude was noted for both abduction and adduction (Löfqvist & McGarr, 1986). This relationship has also been described for other articulators, for example the lips and the jaw (Kelso, Vatikiotis-Bateson, Saltzman, & Kay, 1985), and the tongue (Ostry, Keller, & Parush, 1983; Ostry & Munhall, 1985) and is also considered to be a basic property of nonspeech motor systems, for example limb movements (Cooke, 1980), and eye movements (Carpenter, 1977; Henriksson, Pykkö, Schalen, & Wennmo, 1980). This relationship was also noted for Deaf Speaker 1, particularly for adduction (see Figure 2) although the data for this deaf subject show more scatter than those of the normal talker. For the second deaf speaker, the relationship is not as clear, but the range of movement amplitudes is very restricted compared to the other subject.

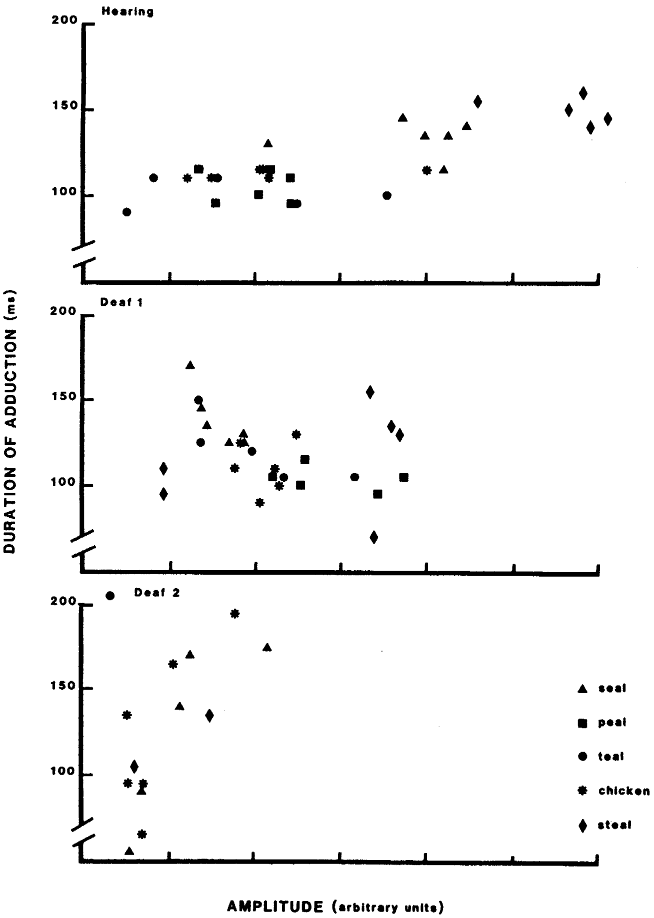

FIGURE 4. Plot of amplitude and duration of glottal adduction.

With respect to segmental effects, for the hearing subject, the fricatives were produced with a larger glottal opening and hence higher peak velocity than the stop and the affricates. However, for fricatives, the duration of the abduction gesture was shorter than the duration of the adduction gesture. For the stops, the reverse was true. These results can be accounted for in terms of different aerodynamic requirements for stop and fricative production. A large glottal gesture not only prevents glottal vibrations but also reduces laryngeal resistance to air flow and assists in the build-up of oral pressure necessary for driving the noise source in fricative production. For the deaf speakers, there was no systematic segmental differentiation in amplitude and duration measures. Also, the overall duration of the abduction-adductions was highly variable from production to production.

Although deaf speakers are frequently able to execute the laryngeal gesture necessary to achieve perceptually correct productions of voiceless obstruents (McGarr & Löfqvist, 1982), the kinematics of this gesture may differ from normal in several ways. In particular, there was no segmental differentiation noted in any of the measures. The results of the present study raise an interesting

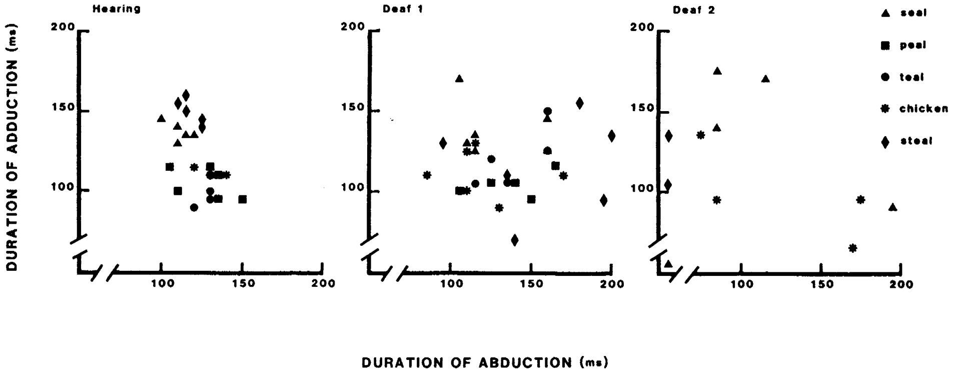

FIGURE 5. Duration of abduction plotted against duration of adduction.

question in speech research, namely, the relationship between perceived phonetic categories and the kinematics of the articulatory gestures producing the acoustic signal. This relationship is far from transparent. Indeed, there are a number of possible relationships between the articulatory dynamics and the resulting acoustic signal. In some cases, variations in the articulatory domain will give small or no acoustic results; while in other cases, quite small articulatory variations will have large acoustic effects (cf. Perkell & Nelson, 1982, 1985; Stevens, 1972). Examples of these instances might include variations in the location and the size of the maximum constriction during vowel production. Variations in movement kinematics will also affect formant transitions. In the present case, it is quite conceivable that small variations in the degree of glottal opening during voiceless consonant production will have limited effects on the acoustic qualities of voiceless consonants. Such variation would mainly affect the glottal resistance to air-flow, and hence the buildup of oral air pressure. The acoustic consequences would be found in the intensity and the spectrum of the release burst for stops and the noise spectrum for fricatives. With respect to the kinematics of the glottal gesture, it remains to be shown that the reported differences between stops and fricatives are crucial. We should also note that several aspects of articulation in the hearing impaired may deviate simultaneously from normal speech production. It is thus difficult or impossible to determine the contribution of a single articulator to the overall quality of the speech of the hearing impaired.

A further problem concerns the appropriate methodology for perceptual evaluation of disordered speech. It is well known that within-category discrimination of speech sounds is rather poor (Liberman, Harris, Hoffman, & Griffith, 1957). Thus, utterances produced with deviant articulatory kinematics and/or timing would not necessarily be judged as incorrect *if* the evaluation consisted solely of an identification task. In this case, the correct utterance would be reported if acoustic deviations did not cross a category boundary. Thus, evaluation based on identification, as is frequently the case, would not provide a sufficiently sensitive measure of articulatory deviancy. Rather, more stringent perceptual tests would be required.

Further research on the kinematics of articulatory events produced by hearing-impaired speakers, and the perceptual consequences, is clearly warranted. Speech produced by these subjects is so often characterized in terms of aberrant timing relationships; however, the nature of movement control in this population still remains largely unspecified.

ACKNOWLEDGMENTS

We thank Thomas Baer and Kevin Munhall for their helpful comments. This work was supported by NINCDS Grant NS-13617 and NS-13870, and NIH Biomedical Research Support Grant RR-5596 to Haskins Laboratories.

REFERENCES

BAER, T., LÖFQVIST, A., & MCGARR, N. S. (1983). Laryngeal vibrations: A comparison between high-speed filming and glottographic techniques. *Journal of the Acoustical Society of America, 73,* 1304–1308.

CARPENTER, R. H. S. (1977). *Movement of the eyes.* London: Pion.

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

COOKE, J. (1980). The organization of simple, skilled movements. In G Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 199–212). Amsterdam: North-Holland.

HEIDER, F., HEIDER, G., & SYKES, J. (1941). A study of the spontaneous vocalizations of fourteen deaf children. *Volta Review 43,* 10–14.

HENRIKSSON, N. G., PYKKO, I., SCHALEN, L., & WENNMO, C. (1980). Velocity patterns of rapid eye movements. *Acta Otolaryngologica, 89,* 504–512.

HUDGINS, C. V., & NUMBERS, F. C. (1942). An investigation of the intelligibility of the speech of the deaf. *Genetic Psychology Monographs, 25,* 289–392.

KELSO, J. A. S., VATIKIOTIS-BATESON, E., SALTZMAN, E., & KAY, B. (1985). A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of America, 77,* 266–280.

LIBERMAN, A., HARRIS, K. S., HOFFMAN, H., & GRIFFITH, B. (1957). The discrimination of speech sounds within and across phoneme boundaries. *Journal of Experimental Psychology, 54,* 358–368.

LÖFQVIST, A., & MCGARR, N. S. (1986). Laryngeal dynamics in voiceless consonant production. In K. Harris, T. Baer, & C.

Sasaki (Eds.), *Vocal fold physiology: Laryngeal function in phonation and respiration,* pp. 391–402. Boston: College-Hill Press.

Löfqvist, A., & Yoshioka, H. (1980). Laryngeal articulation in Swedish obstruent clusters. *Journal of the Acoustical Society of America, 68,* 792–801.

Löfqvist, A., & Yoshioka, H. (1981a). Laryngeal activity in Icelandic obstruent production. *Nordic Journal of Linguistics, 4,* 1–18.

Löfqvist, A., & Yoshioka, H. (1981b). Interarticulator programming in obstruent production. *Phonetica, 38,* 21–34.

Löfqvist, A., & Yoshioka, H. (1984). Intrasegmental timing: Laryngeal-oral coordination in voiceless consonant production. *Speech Communication, 3,* 279–289.

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

Mangan, K. (1961). Speech improvement through articulation testing. *American Annals of the Deaf, 106,* 391–396.

Markides, A. (1970). The speech of deaf and partially hearing children with special reference to factors affecting intelligibility. *British Journal of Disorders of Communication, 5,* 126–140.

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

Millin, J. (1971). Therapy for reduction of continuous phonation in the hard-of-hearing population. *Journal of Speech and Hearing Disorders, 36,* 496–498.

Monsen, R. B. (1976). The production of English stop consonants in the speech of deaf children. *Journal of Phonetics, 4,* 29–42.

Munhall, K., Ostry, D., & Parush, A. (1985). Characteristics of velocity profiles of speech movements. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 457–474.

Nober, H. (1967). Articulation of the deaf. *Exceptional Children, 33,* 611–621.

Osberger, M. J., & McGarr, N. S. (1982). Speech production characteristics of the hearing impaired. In N. Lass (Ed.), *Speech and language: Advances in basic research and practice, Vol. 8* (pp. 221–283). New York: Academic Press.

Ostry, D., Keller, E., & Parush, A. (1983). Similarities in the control of speech articulators and the limbs: Kinematics of tongue dorsum movements in speech. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 622–636.

Ostry, D. J., & Munhall, K. (1985). Control of rate and duration of speech movements. *Journal of the Acoustical Society of America, 77,* 640–648.

Perkell, J., & Nelson, W. (1982). Articulatory targets and speech motor control: A study of vowel production. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), *Speech motor control* (pp. 187–204). New York: Pergamon Press.

Perkell, J., & Nelson, W. (1985). Variability in production of the vowels /i/ and /a/. *Journal of the Acoustical Society of America, 77,* 1889–1895.

Smith, C. R. (1975). Residual hearing and speech production of deaf children. *Journal of Speech and Hearing Research, 18,* 795–811.

Stevens, K. (1972). The quantal nature of speech: Evidence from articulatory-acoustic data. In E. David & P. Denes (Eds.), *Human communication: A unified view* (pp. 51–66). New York: McGraw Hill.

Subtelny, J. (1975). Speech assessment of the deaf adult. *Journal of the Academy of Rehabilitative Audiology, 8,* 110–116.

Received May 12, 1986
Accepted September 3, 1987

Requests for reprints should be sent to Nancy S. McGarr, Haskins Laboratories, 270 Crown Street, New Haven, CT 06511.