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Obstruent production by hearing-impaired speakers: Interarticulator timing and acoustics[a]

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This study examines the organization of laryngeal control and interarticulator timing in the production of obstruents and obstruent clusters by three severely–profoundly deaf adults. Glottal activity was monitored by transillumination; temporal patterns of oral articulation (lips and tongue–palate) were recorded using an electrical transconductance technique. For each of the deaf speakers, an inappropriate abduction gesture was often found between words, a pattern never observed for hearing speakers. At the same time, the deaf speakers differed from each other with respect to types of errors, variability, and interarticulator coordination. For the most intelligible speaker, the timing of glottal opening with respect to oral articulation was most like that observed for normals. The second deaf speaker often failed to observe voicing contrasts with respect to glottal opening. This subject was nevertheless consistent in producing most plosives without a glottal opening, and all fricatives with an opening gesture. For the third deaf speaker, the pattern of errors was more complex and included both missing and inappropriate glottal opening gestures.

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INTRODUCTION

Production of voiceless obstruents requires intricate coordination of several articulatory systems. At the laryngeal level, an abduction/adduction gesture of the glottis normally occurs to arrest the glottal vibrations and assist in the buildup of oral presure. Movements of the upper vocal tract are also necessary to produce a closure or constriction. Thus the laryngeal and supralaryngeal articulations must be temporally coordinated. Differences in the relative timing of the glottal and oral gestures are used in a wide variety of languages to produce contrasts of voicing and aspiration (cf., Lisker and Abramson, 1964; Löfqvist and Yoshioka, 1981).

Since the glottis is placed in an inaccessible and invisible position, it is reasonable to assume that coordination of interarticulator gestures is learned by auditory monitoring of the acoustic signal. Developmental studies suggest that children master sound contrasts requiring glottal adjustments (e.g., voicing and aspiration) by attending to their acoustic and perceptual consequences (Kewley-Port and Preston, 1974; Zlatin and Koenigsknecht, 1976; Gilbert, 1977; Macken and Barton, 1980). These studies also show that obstruent contrasts emerge relatively late in childrens' speech and that production is more variable in children than in adults. The acoustic cues for obstruents are complex, spread over time, and involve differences in the sound source and the spectral composition of the signal. For example, in the production of a voiceless fricative in a vocalic environment, the sound changes from periodic to aperiodic and then back to periodic. Similarly, a voiceless aspirated stop in the same environment is associated with the following sequence of source changes: periodic voicing during the preceding vowel, silence during the closure, transient noise, aspiration noise, periodic voicing during the vowel. In addition to being spread over time, the acoustic attributes of obstruents often involve short-term spectral changes, where high-frequency components play an important role. Examples of such attributes are release bursts and formant transitions for stop consonants, and the spectra and transitions for fricatives.

Given the complex articulatory and acoustical/perceptual nature of voiceless obstruents, one would expect hearing-impaired speakers to have particular problems with this class of sounds. This is indeed the case, as shown by several descriptive and acoustic studies. For example, hearing-impaired speakers frequently fail to make the voiced-voiceless distinction (Hudgins and Numbers, 1942). In some studies, this substitution is reported as occurring to the voiced member of the pair (Heider *et al.*, 1941; Carr, 1953; Millin, 1971; Smith, 1975), and at other times to the voiceless cognate (Mangan, 1961; Nober, 1967; Markides, 1970). At the acoustic level, several studies report a lack of voice onset time distinction for deaf speakers (Monsen, 1976; Mahshie, 1980), and also that closure or constriction duration is different from normals (Calvert, 1961; Osberger and Levitt, 1979). Production of obstruent clusters is also particularly difficult for hearing-impaired speakers (Hudgins and Numbers, 1942; Brannon, 1964; Smith, 1975). Reported error patterns for these blends include the dropping of one or more components of the cluster, or the addition of an adventitious segment, usually the neutral /ə/, between the elements. Errors in voicing as well as in cluster production have been shown to effect deleteriously the overall intelligibility of deaf speech (Hudgins and Numbers, 1942).

While we may presume that it is some failure of interarticulator coordination that leads to these perceptual and acoustic results, it is not possible to infer the precise nature of

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the laryngeal and supralaryngeal events from the acoustic record. The purpose of the present investigation, therefore, was to make detailed observations of the glottal and upper articulatory events during obstruent and obstruent cluster production in a comparison of hearing-impaired and normal speakers.

I. METHOD

A. Subjects

The subjects were three congenitally and severly–profoundly deaf adults[1] (mean pure tone average for 0.5, 1, and 2 kHz, 90 dB + ISO in the better ear) and a hearing subject who served as a control. All of the hearing-impaired subjects had received at least part of their training in oral schools for the deaf. None had any additional handicaps besides deafness.

Speech samples from each of the hearing-impaired speakers were analyzed in two ways. First, two listeners (the authors) made broad phonetic transcriptions of the test words produced by the deaf subjects. Of particular interest was the voicing status of the obstruents and obstruent clusters. In general, the listeners agreed in their judgments, and the results are summarized in Table I.

Second, speech samples were rated for overall intelligibility by a listener highly experienced with the deaf. Following the format of the rating scale for intelligibility (Subtelny, 1975), deaf speaker 1 could be characterized as 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. Deaf speaker 3 was difficult to understand with only isolated words or phrases intelligible.

TABLE I. Summary of listener judgments of the productions by the hearing-impaired speakers. The percentage of correct productions, the percentage of errors, and the error categories are shown.

	Deaf speaker 1		Deaf speaker 2		Deaf speaker 3	
Single Obstruents	% Corr.	% Err.	% Corr.	% Err.	% Corr.	% Err.
peal	100		17	83 /b/	83	17 /b/
beak	100		100		33	67 /p/
teal	100		100		100	
deal	83	17 /t/		100 /t/		100 /t/
seal	100		100		100	
zeal	17	50 /dʒ/ 33 /d/		100 /s/	67	33 /s/
paper	100			100 /b/		100 /b/
paper	100			100 /b/		100 /b/
chicken	50	33 /s/ 17 /t/		100 /s/		67 /ʃ/ 17 /z/ 17 /ʒ/
jester	50	33 /ʃ/ 17 /d/		100 /s/		67 /ʒ/ 17 /t/ 17 /ʃ/
Obstruent Clusters						
steal	83	17 /s/	83	17 /s/		83 /t/ 17 /s/
jester	17	50 /ht/ 33 /t/	17	33 /t/ 33 /h/ 17 /ht/		100 /ʃ/
less tea	100		33	67 /sd/	100	
messtent	100		100		100	

B. Procedure

Laryngeal activity was monitored by transillumination (Sonesson, 1960). A flexible fiberscope inserted through the nose and held in position by a headband provided illumination of the larynx. The amount of light passing through the glottis was sensed by a phototransistor placed on the surface of the neck just below the cricoid cartilage and coupled to the skin by a light–tight enclosure. The transillumination signal was recorded on one channel of a multichannel instrumentation tape recorder. During the recording session, the view of the larynx was monitored through the fiberscope in order to detect movements and fogging of the lens.

Temporal information on laryngeal articulatory movements obtained by transillumination has been shown to be practically identical to similar information obtained by fiberoptic filming of the larynx (Yoshioka *et al.*, 1981; Löfqvist and Yoshioka, 1980). Transillumination is thus an excellent tool for studying laryngeal behavior in speech. It has a better temporal resolution than fiberoptic filming and video recording. Data collection and processing are quick and easy, and larger amounts of material can be handled than with any other method available for laryngeal investigations.

Temporal patterns of oral articulation were recorded using an electrical transconductance technique (cf., Karlsson and Nord, 1970). The electrodes of a modified laryngograph were placed on the upper and lower lips, respectively. Onset and offset of lip or tongue–palate contact could then be identified from changes in the electrical signal. The signal was recorded on another channel of the instrumentation recorder.

Conventional acoustic recordings were obtained simultaneously using a direction-sensitive microphone. The voice signal was recorded in direct mode on the tape recorder. As described above, the recordings of all productions by the hearing-impaired speakers were later used to obtain listener judgments.

For each token, a number of measurements were made, relevant from the point of view of motor control. Measurements of closure and constriction duration were made from the transconductance signal representing labial or tongue–palate contact. Implosion was defined as the onset of labial/tongue–palate contact; release as the offset of contact. Defining these events in physiological terms is particularly helpful in the case of deaf speakers, since closure or constriction duration may be very difficult to measure in the acoustic waveform.

For laryngeal articulation, the occurrence of peak glottal opening served as the reference point. This point marks the end of the abduction and the beginning of the adduction of the vocal folds, and is under motor control. EMG recordings from internal laryngeal muscles have indicated a reciprocal pattern of activation for the posterior cricoarytenoid and the interarytenoid muscles in the control of glottal opening in single voiceless obstruents (cf., Hirose, 1976; Hirose *et al.*, 1978; Löfqvist and Yoshioka, 1980). This justifies the use of peak glottal opening as a reference point in studies of laryngeal articulation in speech.

Measures of interarticulator timing were defined in two ways. First, the interval from onset of labial or tongue–palate contact to peak glottal opening was calculated. This measurement provides an estimate of the relationship between onset of constriction or closure and the beginning of the adduction of the vocal folds. It is useful since it highlights differences in timing between obstruents, e.g., stops and fricatives (Löfqvist and Yoshioka, 1981). A second measurement of interarticulator timing was the interval from peak glottal opening to offset of labial or tongue–palate contact. This measure shows the relationship between onset of glottal adduction and release, and is particularly useful in examining timing differences between different stop categories (Löfqvist, 1980). The physiological measurements were supplemented by acoustic measurements of voice onset time for stops. All measurements were made interactively on a computer.

C. Linguistic material

The linguistic material is presented in Table II. It consisted of voiced and voiceless obstruents, and also of obstruent clusters. Since the transillumination technique requires a free passage for the light from the fiberscope to the glottis, front vowels and labial and dental consonants were chosen. The subjects read the material from randomized lists in the carrier phrase "Say...again." Six repetitions of each token were obtained.

II. RESULTS

A. Single obstruents

Figure 1 shows records of representative tokens of the hearing subject's production of voiced and voiceless stops. A glottal abduction/adduction gesture is seen for the voiceless stop but not for the voiced cognate. Patterns of interarticulator timing are noted by the relationship between events recorded in the signals representing labial/tongue–palate contact and glottal opening, respectively. For the voiceless plosive, peak glottal opening occurs at the oral release, indicated by the offset of lip contact and the release burst. The pattern is the same as that found for other speakers of American English (Löfqvist and Yoshioka, 1981).

Figure 2 shows selected tokens of the same utterances produced by deaf speaker 2. Several patterns are different from normal. First, closure duration is considerably longer for the deaf than the hearing speaker's production. Second, there is evidence of an inappropriate glottal gesture. The deaf speaker makes a glottal abduction/adduction gesture immediately preceding the test word, before onset of lip closure for the initial stop. Thus for both productions, glottal adduction starts before lip closure, and the glottis is in a position suitable for voicing at the relase of the oral closure. The abduction/adduction gesture between words in an utterance was fairly typical of the other deaf speakers as well, but was never observed for the hearing speaker.

TABLE II. The linguistic material.

peal	paper	chicken	steal
beak		jester	less tea
teal			messtent
deal			
seal			
zeal			

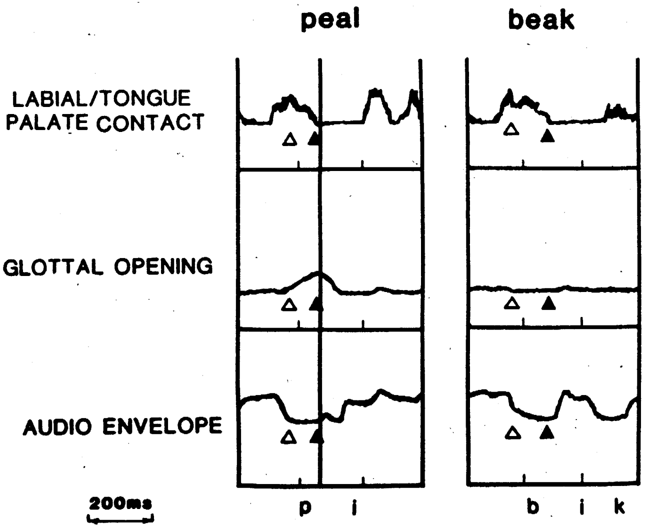

FIG. 1. Records of the hearing speaker's productions of the utterances "peal" (left), and "beak" (right). Curves represent labial/tongue palate contact (top), glottal opening (middle), and audio envelope (bottom). Onset of labial closure for the word-initial labial stops in "peal" and "beak" is marked by △, release or oral closure by ▲. The vertical line indicates the time at which peak glottal opening occurs.

From these raw data, a number of measurements were made that are summarized in Figs. 3 and 4 and also 6–9. Line 1 in these figures shows mean duration of closure or constriction. Line 2 shows, as a histogram, the number of instances of glottal opening associated with the obstruent production. The third row shows the first measure of interarticulator timing—the interval between implosion and peak glottal opening. The second measure of interarticulator timing is the interval from peak glottal opening to release, indicated in numerals below the third row. A negative value here implies

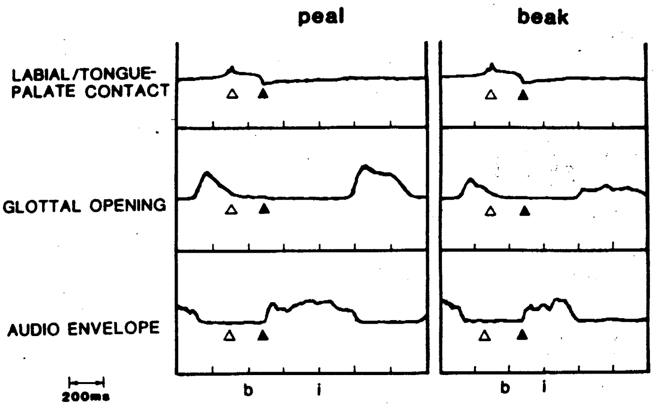

FIG. 2. Records of deaf speaker 2's productions of the utterances "peal" (left), and "beak" (right). Symbols as in Fig. 1.

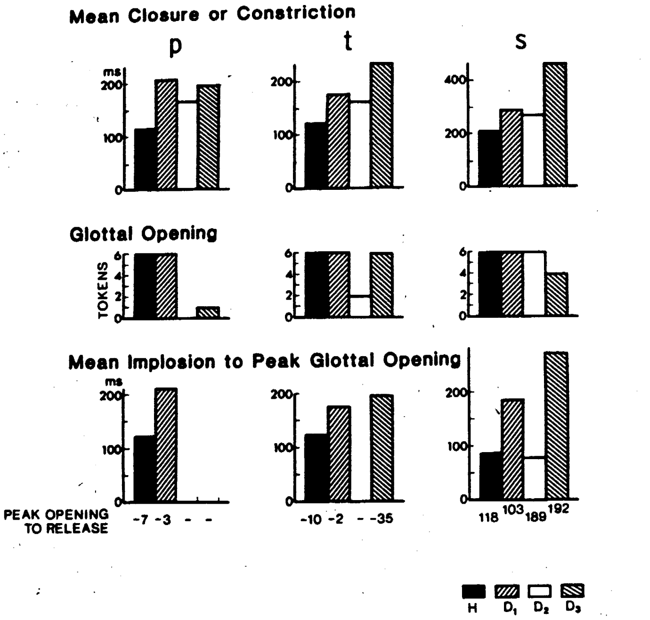

FIG. 3. Summary of measurements for single voiceless obstruents. See text for further details on measurements.

that peak glottal opening occurred after release. The presentation follows our general impression of overall speaker intelligibility in rank order: the hearing speaker, followed by deaf speaker 1, felt to be the most intelligible, and deaf speakers 2 and 3, less intelligible, respectively.

Results for the single voiceless and voiced obstruents are found in Figs. 3 and 4, respectively. Closure or constriction duration was always longer for the deaf subjects than for the hearing subject, consistent with previous reports. As is typical for hearing speakers, closure or constriction duration was longer for voiceless than for voiced segments. For the deaf speakers, the duration measurements for the voiceless and voiced segments overlapped (see Fig. 5).

The number of tokens for which a glottal abduction gesture occurred are shown in line 2. These gestures were always correct for the hearing speaker and deaf speaker 1. That is, for single voiceless obstruents, each token was characterized by a single abduction/adduction gesture; for single-voiced obstruents, there was no glottal gesture. For the other deaf speakers, the pattern varied. Deaf speakers 2 and 3 used an appropriate glottal gesture more often for the voiceless alveolar than for the voiceless bilabial obstruents. We will discuss the voiced obstruents of these speakers below.

With respect to interarticulator timing, both the hearing speaker and deaf speaker 1 showed nearly similar patterns for all segments. For voiceless stops, the interval from implosion to peak glottal opening tends to be similar to closure

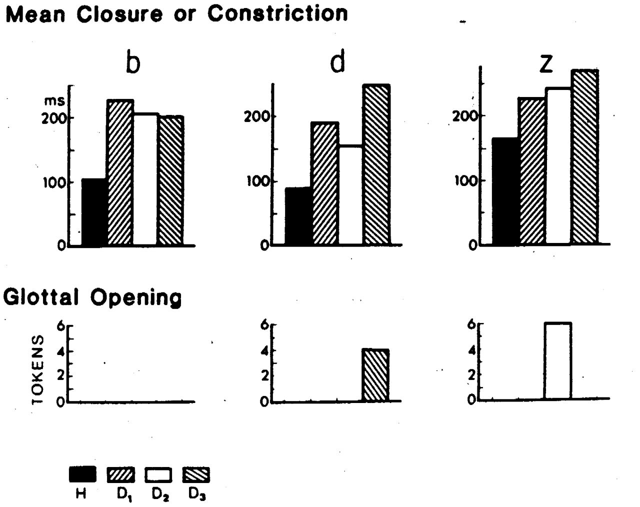

FIG. 4. Summary of measurements for single-voiced obstruents.

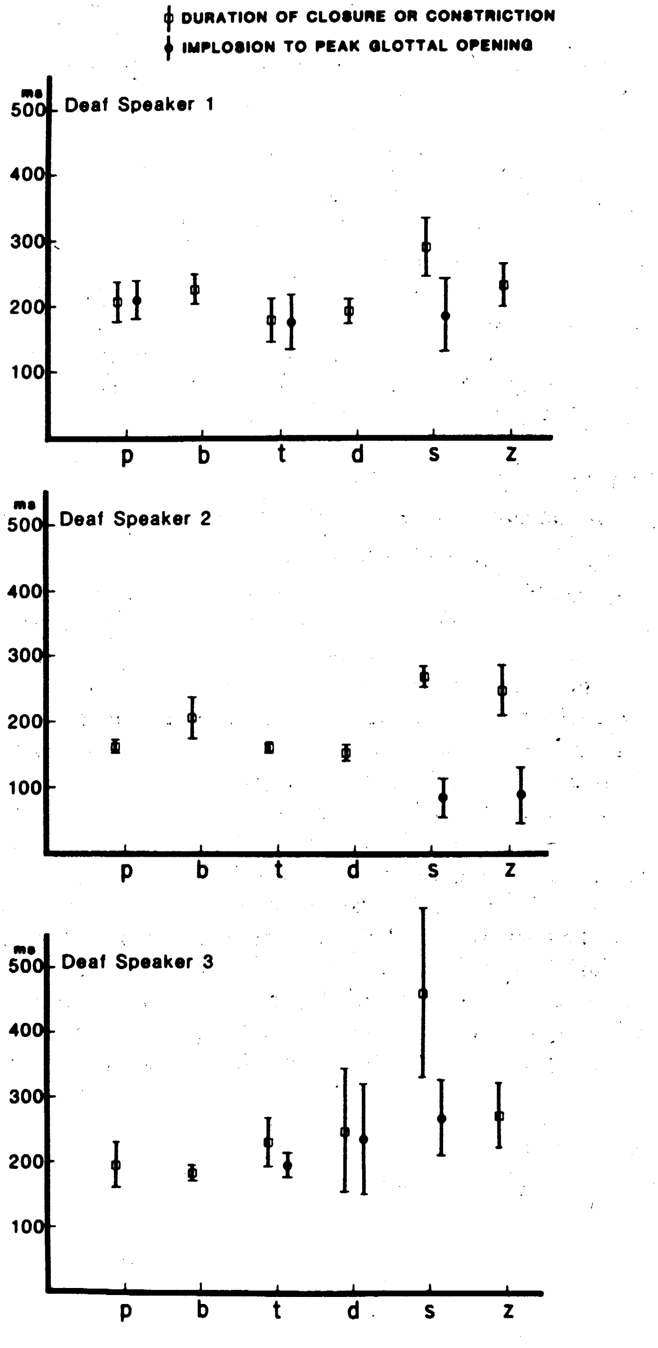

FIG. 5. Plot of articulatory measurements for the three deaf speakers' productions of single obstruents. Means and standard deviations are shown.

duration. This means that peak glottal opening and oral release almost coincide. Thus these two speakers both show a small negative number for the second measure of interarticulator timing, i.e., the interval from peak glottal opening to release. Even though the closure durations for the deaf speaker are prolonged overall, the relative timing of oral and glottal gestures is indistinguishable from normal. For the voiceless fricatives of these two speakers, the interval from implosion to peak glottal opening is roughly half of the duration of the oral constriction. Peak glottal opening thus occurs about 100 ms before release.

Deaf speaker 2 is inconsistent in interarticulator timing, since in most cases there was no active glottal opening gesture for the stops. For the fricative, there was an appropriate glottal gesture, and interarticulator timing is more normal. For deaf speaker 3, we again find an inconsistent pattern. For the labials, there are no glottal openings, and hence no evidence of interarticulator coordination, whereas for the alveolars, a glottal opening gesture was made. The interarticulator timing in these cases is similar to normal. For /t/, the glottis did not begin to close until about 35 ms after the oral release, which is somewhat long, although not totally unusual. For the fricative, although the durations are long overall, the relative timing pattern was normal.

Usually one does not discuss laryngeal–oral coordination for voiced obstruent production, but since deaf speakers are known to produce voiceless for voiced segments, we have also examined these productions. Figure 4 shows these data. Here, we again find evidence that deaf speakers may use an inappropriate abduction gesture for the production of some voiced sounds, but as before, the speakers are inconsistent in this aberrant pattern.

When the deaf speakers produced the appropriate glottal gestures for voiceless stops, their overall pattern of interarticulator timing resembled that of normals. Specifically, the oral release and peak glottal opening tend to correspond in time. For fricatives, peak glottal opening precedes offset of tongue–palate contact as has been observed for normals. But a rather unexpected finding was obtained for these deaf subjects. In general, the laryngeal gesture for the voiceless fricative /s/ was produced correctly more often than for the voiceless plosives. For example, as shown in Figs. 3 and 4, deaf speaker 2 consistently contrasted stops and fricatives at the glottal level—the former were nearly always produced with a closed glottis, while for the latter, the glottis was always open. However, as shown in Fig. 5, the deaf speakers were unlike the normal in that they were highly variable in their production from token to token. Standard deviations for the deaf speakers were, in many cases, fairly large. For the hearing speaker, the standard deviations were quite small—on the order of 10–25 ms, and therefore not included in the figure.

For all test words described above, obstruents were produced in the word-initial position. An allophonic variation in American English is that voiceless stops following a stressed vowel are typically heard as unaspirated. Therefore we also examined stops produced in two different positions of a bisyllabic word—"paper," where p_1 is stressed and p_2 is unstressed. These data are shown in Fig. 6. The timing pattern for the initial stops in this test word was essentially the same as that described above for all speakers' production of a single voiceless stop. For p_2, the pattern is similar for the hearing subject and deaf speakers 2 and 3. Closure duration was shorter in these cases and there was a tendency not to use an abduction gesture in production. However, deaf speaker 1 produced both initial and medial stops in an almost identical way, with aspiration in both cases.

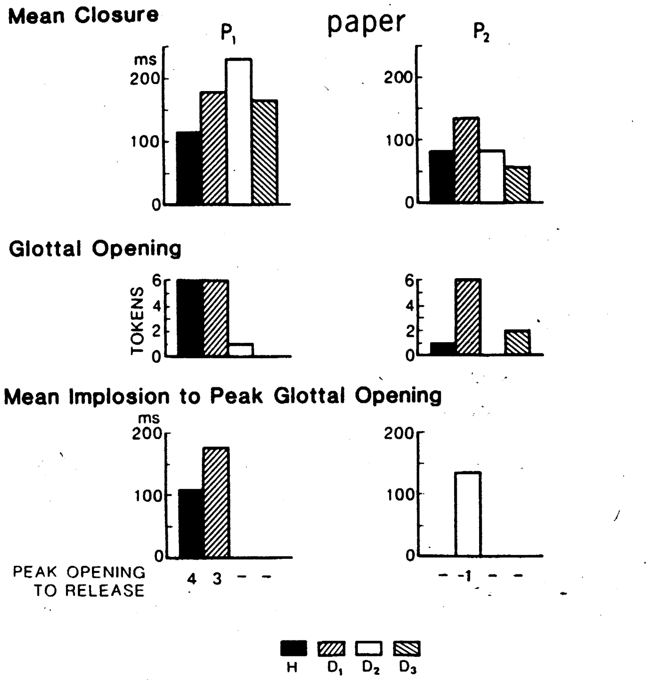

FIG. 6. Summary of measurements for the two stops in "paper."

Table III shows measurements of voice onset time for single stops. These acoustical measurements match fairly well with the physiological data, i.e., voice onset time was generally longer when a glottal gesture was found. However, in contrast to the physiological data, the standard deviations for the acoustic measurements were fairly small.

Data for affricates are shown in Fig. 7. These segments are

TABLE III. Measurements of voice onset time for single stop consonants (ms, n = 6).

		H	D_1	D_2	D_3
p	$\bar{x}$	84	87	8	29
	s	8.1	5.6	3.9	6.9
b	$\bar{x}$	15	16	11	25
	s	3.5	4.0	3.3	6.8
t	$\bar{x}$	121	83	20	69
	s	13.8	16.1	3.0	6.3
d	$\bar{x}$	23	47	21	59
	s	4.3	19.6	3.5	6.7
p_1	$\bar{x}$	68	77	11	25
	s	7.4	4.5	4.8	6.8
p_2	$\bar{x}$	14	71	20	
	s	6.7	3.4	3.8	

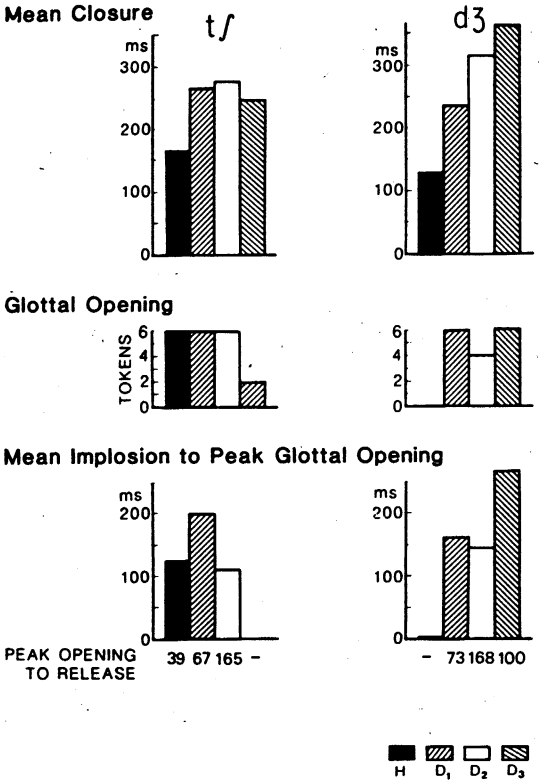

FIG. 7. Summary of measurements for the affricates.

known to be particularly difficult for deaf speakers to produce. For the hearing subject, the stop closure and the fricative portion of the voiceless affricate were 39 and 126 ms, respectively, with peak glottal opening occurring during the fricative portion. In contrast, for the deaf speakers there was in most cases no stop component. Consequently, the timing pattern resembled that of a fricative. All deaf speakers produced the voiced affricates with a laryngeal abduction gesture.

B. Clusters

Clusters have not been studied much in the speech of the hearing impaired. The common /st/ cluster was examined in the word-initial position and in the medial unstressed position of a two-syllable word. Figure 8 shows only one component of the cluster since we were often unable to identify two separate gestures for the hearing-impaired speakers. Consequently, these productions mostly resemble patterns described above for the single voiceless fricatives. For the hearing speaker, when a voiceless unaspirated stop followed a fricative, peak glottal opening is timed during the fricative segment and the glottis begins to close before the stop component begins. Deaf speaker 1 tended to use a timing pattern for an aspirated stop with peak glottal opening at release. In some cases, two opening gestures occurred—one for the fricative and one for the stop. For deaf speakers 2 and 3, in most cases, interarticulator timing for the word-initial cluster more closely resembled that observed for single fricatives. These timing patterns were similar to the normal in that peak glottal opening occurred during the fricative portion. No clear pattern emerges for these speakers' productions of /st/ in "jester."

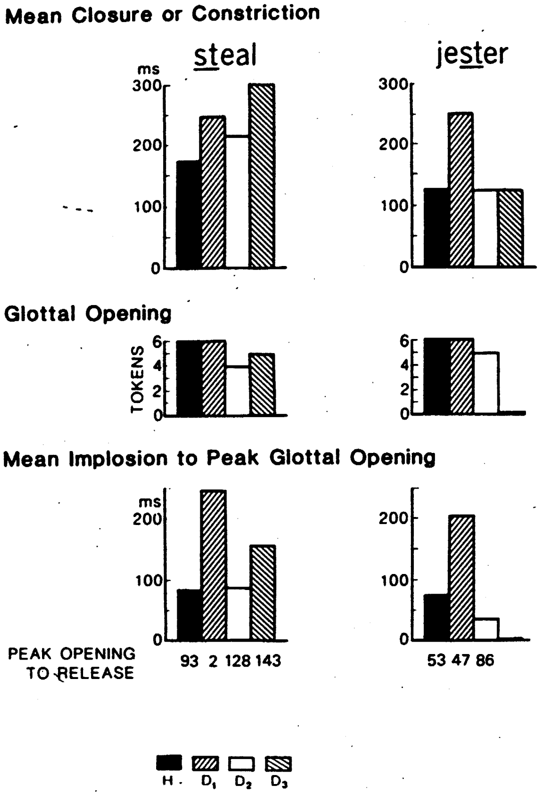

FIG. 8. Summary of measurements for /st/ clusters.

We finally turn to clusters with either a word or morpheme boundary within the cluster, see Fig. 9. In the first case, that of the word boundary ("less tea"), we would expect that the word-initial stop /t/ would be aspirated since aspiration here is a way of signaling that a word boundary occurs between the /s/ and the /t/. In fact, all of the speakers, with

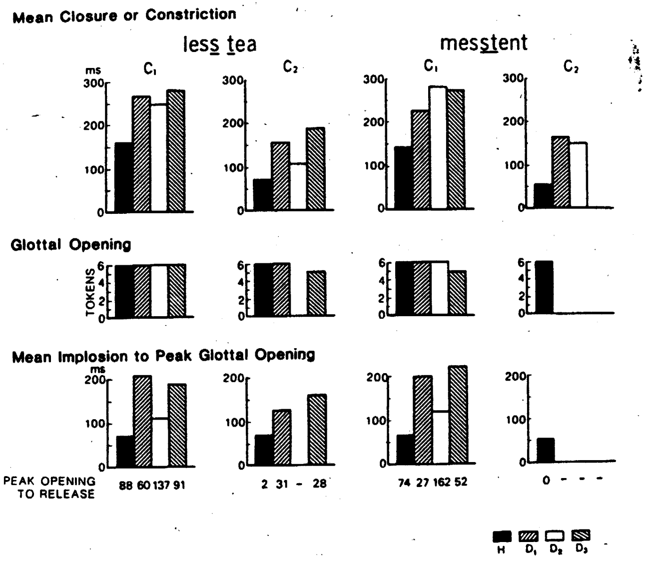

FIG. 9. Summary of measurements for clusters with word and morpheme boundary within the cluster.

the exception of deaf speaker 2, produced these tokens with two separate glottal gestures—one for the fricative and one for the stop. The patterns of deaf speaker 2 are consistent with the previous observation that this deaf speaker produced most stops without glottal opening, although for these test words, he nevertheless respected the word boundary. The pattern of interarticulator timing is similar to that observed for other tokens of fricatives and aspirated stops.

Turning now to the effect of the morpheme boundary, the pattern for the fricative segment is similar to that for other single fricatives. For the stop segment, only the hearing speaker shows evidence of a separate laryngeal adjustment. Deaf speakers 1 and 2 did not use a glottal opening. For deaf speaker 3, no stop segment could be identified.

III. DISCUSSION

Normal speakers consistently use different patterns of laryngeal–oral coordination for stops and fricatives (Löfqvist and Yoshioka, 1981). Onset of glottal abductions generally tends to coincide with onset of oral closure or constriction, unless preaspiration occurs, in which case glottal abduction precedes implosion. For aspirated stops, peak glottal opening occurs at the release of the oral closure. This ensures a delay in voice onset time and also allows a substantial airflow for generation of frication noise immediately after the release. In fricatives, the peak glottal opening occurs closer to the onset of the oral constriction. The velocity of the abduction gesture is higher for fricatives than for stops and the size of the glottal opening also tends to be larger for the fricatives. The differences in laryngeal control and interarticulator timing are most likely related to different aerodynamic requirements at implosion and release for fricatives and aspirated stops, respectively. The hearing speaker in this study followed these patterns.

The deaf subjects showed both similarities and dissimilarities with respect to normal speakers. The most obvious dissimilarity was failure to produce the voiced–voiceless distinction. The deaf speakers either made a glottal gesture when none was required or omitted the glottal gesture. Furthermore, even when a glottal gesture was produced, its timing relative to oral articulatory events only sometimes resembled normal. This pattern varied considerably among deaf speakers.

Not surprisingly, deaf speaker 1, the most intelligible, closely followed the normal pattern. For aspirated stops, peak glottal opening consistently occurred at the oral release. The same strategy was used in production of the second stop in the word "paper," although in this case, the phonological rules of American English dictate that aspiration is not necessary. On the other hand, while the timing for single fricatives was often produced correctly, the /st/ clusters showed different patterns of interarticulator timing. One example is the /st/ cluster in "steal" for which relative timing was observed to be like that for an aspirated stop. Again, this speaker uses an aspirated stop inappropriately—in this example as part of a segment cluster.

Deaf speaker 2 differs from normal in still a grosser fashion. Stops were consistently produced without laryngeal activity while fricatives were usually produced with an appropriate glottal gesture. For these latter cases, the interarticulator timing was relatively correct. Turning to deaf speaker 3, we note both incorrect and highly variable productions. However, when the relative timing is preserved between the articulators, the absolute duration of articulatory events is longer than those found for hearing speakers. This pattern of increased duration has often been noted in the speech of the deaf (Hudgins and Numbers, 1942; Calvert, 1961; Osberger and Levitt, 1979). In relation to these findings, it is interesting to note that hearing speakers, when deprived of auditory feedback, also show evidence of increasing duration (Borden, 1980).

Another characteristic that marks the speech of the deaf as different from normal is variability in production at the physiological level. This variability appears to be an important factor in the speech of the deaf, indicating that deaf speakers, even the less intelligible, do not produce an utterance in quite the same way each time it is perceived to be in error. However, we also observed that even when speakers were judged to be correct in their productions, there was considerable physiological variability from token to token. These results are consistent with electromyographic data obtained for oral articulatory timing (tongue–lips) of a deaf talker (McGarr and Harris, in press). Variability in production was noted less at the acoustic level (VOT measurements), although fairly large standard deviations for deaf speakers' productions have been reported (Monsen, 1976). Such inconsistencies in production may be one reason why listeners find the speech of the deaf difficult to understand.

As mentioned above, all deaf speakers were more successful in producing fricatives than stops. These results differ from those reported in the literature (Nober, 1967; Smith, 1975; Levitt *et al.*, 1980). On one hand, we find our results perplexing since one would expect that fricatives, because of their high-frequency spectra and articulatory invisibility, would be difficult for severely–profoundly deaf speakers to perceive and thus to produce. Alternatively, on the physiological level, one might postulate that voiceless fricatives, for example, require less precise interarticulator timing than voiceless stops. At the laryngeal level, the deaf speaker need only open the glottis, even if in a fairly stereotypic way as demonstrated by our subjects, and then direct the airstream in an outward direction. The distortion of the /s/ in the speech of the hearing impaired may thus more accurately reflect poor placement of the upper articulators rather than inappropriate laryngeal adjustments. Indeed, it is well known that normally the /s/ is produced at the level of the upper articulators with both channel and wake turbulence, the former being generated by the grooved portion of the tongue, and the latter generated when the airstream strikes the teeth. Deaf speakers are known to have difficulty positioning the tongue for correct place of articulation (Huntington *et al.*, 1968; McGarr and Harris, in press). Plosives, on the other hand, demand particularly fine interarticulator coordination between the glottis and the upper articulators and more precise management of the airstream.

The operation of the glottis in speech is analogous to that of an air valve, whereby the valve must be opened for voiceless sounds to let some air escape, and must also be closed at the appropriate times in order to preserve the breath stream. Studies of the respiratory patterns of deaf speakers have shown that these subjects evidence at least two kinds of problems. The first is that they initiate phonation at too low a level of vital capacity, and, also that they produce a reduced number of syllables per breath (Forner and Hixon, 1977; Whitehead, in press). A second problem is mismanagement of the volume of air by inappropriate valving at the laryngeal level. Laryngeal valving has two functions: articulatory and phonatory. For the former, aerodynamic studies of deaf speech production do not consistently show that hearing-impaired speakers produce obstruents with abnormally high airflow rates (Whitehead, in press). One might infer phonatory valving problems from some descriptive studies that often ascribe breathy voice quality to deaf speakers (Hudgins and Numbers, 1942; Monsen *et al.*, 1978; Stevens *et al.*, in press). The results of the present study suggest valving problems of a somewhat different nature. That is, during pauses between words, each of the deaf speakers in this study inappropriately opened the glottis. Whether they actually took a breath, as is suggested in the early work of Hudgins (1937) or simply wasted air cannot be ascertained directly from our data. However, we would argue that the latter is more likely since the glottal abduction gesture was smaller and shorter in duration between words than between utterances. This pattern differs from one hypothesized by Stevens *et al.*, (in press). Based on spectrographic analysis of deaf children's productions, these authors proposed that the glottis is closed during pauses between words.

Turning to acoustics and perception, we find a rather straightforward relationship between physiological records and acoustic measurements for stops. The relationship between the physiological measurements and the listener judgments were not always direct. Perception of both voiced and voiceless obstruents could be found for tokens with and without a correct laryngeal gesture. For example, for the productions of deaf speaker 2, listeners heard /b/ for /p/, the common voiced-for-voiceless substitution, when no glottal opening was found, cf., Table I and Fig. 3. However, for the alveolar stops of the same speaker, listeners reported a voiceless sound in all cases, including those without glottal abduction. From Table III it appears that VOT was only 20 ms for these stops.

These results are not too surprising, since a straightforward relationship between physiology and listener judgments is unlikely in such a complex phenomenon as the voiced/voiceless distinction. This mismatch between physiological records and listener judgments of deaf speakers has also been noted by Mahshie (1980). Although in controlled studies using synthetic speech, VOT has been shown to be an important determiner for the voiced–voiceless distinction, in real speech there are a host of acoustic cues that may be co-responsible for this perception. Measurements along one single acoustic dimension cannot be readily expected to predict listener responses when other acoustic variables are not held constant, since interactions have repeatedly been shown to occur. Examples of such interactions that affect the perception of the voiced–voiceless distinction in stops are amplitude and duration of aspiration (Repp, 1979), and speech tempo and closure duration (Port, 1979; Fitch, 1981; see also Miller, 1981). Our VOT values for the deaf speakers were in the range of 20–30 ms, where interactions and boundary shifts are most likely to occur. This may be another reason why listeners to deaf speech have difficulty making judgments of particular phonetic segments.

Earlier, we argued that because the larynx is placed in an inaccessible and invisible position, mastery of glottal articulation is arrived at by the acoustic signal. The deaf speakers in this study all sustained severe–profound hearing losses suggesting that oral–glottal articulation would be exceedingly difficult in light of reduced auditory acuity. In fact, deaf speakers are often said to place their articulators fairly accurately especially for those places of articulation that are highly visible, but fail to coordinate the movements between several articulators. Our data show that this notion of deaf speech is in part correct, yet our subjects were also capable of executing appropriate glottal gestures. We would argue that this is in part due to low-frequency residual hearing that conveys some voicing information as well as tactile feedback.

There are other findings in studies of deaf speech that are also perplexing and not satisfactorily accounted for by either residual hearing or taction: prepausal lengthening (Reilly, 1979) and pitch declination (Breckenridge, 1977). If auditory monitoring of speech was the sole prerequisite for the establishment of these phenomena, one would not necessarily expect to find them in profoundly deaf speakers. Quite possibly, they may be due to intrinsic factors of the speech production system. This idea may also account for why interarticulator timing was sometimes correct for the hearing-impaired subjects of this study. Laryngeal articulatory movements overall are rather stereotypic and restricted to abduction and adduction. For example, production of a voiceless fricative involves opening the glottis and letting air through. This bears some resemblance to nonspeech activities such as blowing and respiration. For the latter, it is reasonable to assume that there exist respiratory–laryngeal linkages whereby glottal abduction and adduction are automatically coordinated with respiratory activity. Speech production in both normals and the deaf most likely utilizes such given linkages, although the details are unknown at present.

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[1] For convenience in the following discussion, we will 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.

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