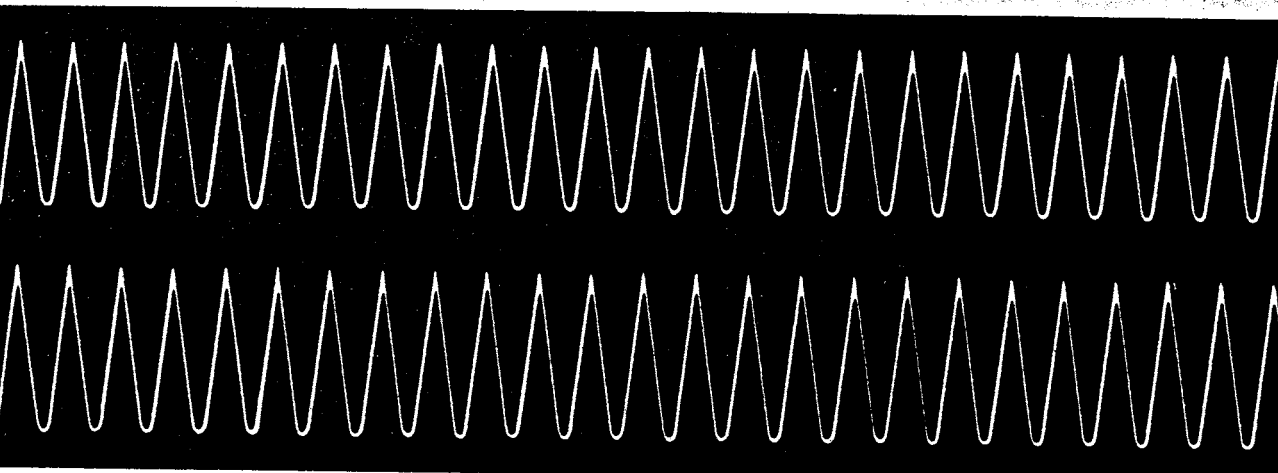# Proceedings of the Conference on the Planning and Production of Speech in Normal and Hearing-Impaired Individuals:

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Chapter 9

THE ROLE OF PRODUCTION VARIABILITY IN NORMAL AND DEVIANT DEVELOPING SPEECH

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The idea of an underlying structure which is given some kind of imperfect surface manifestation is, of course, a rather common one in description of behavioral phenomena in general, and linguistic systems in particular. Following the lead of Jakobson's (1968) famous monograph investigations of child language have been couched in terms of underlying phonological systems, related to a child's phonetic output by rewrite rules, like the rules governing morphophonemic alternations in adult speech. Thus, a child who omits the final /g/ in the word "dog," but will produce the diminutive "doggie" may be described as having an underlying representation which includes the /g/, with a rule which deletes it in syllable-final position.

Many scholars, notably Smith (1973) and Ingram (1976), have asserted that the underlying phonology of normal children at the time of beginning vocabulary development is that of the ambient community. This belief rests in part on old anecdotal evidence that children often can recognize words which they cannot produce, and, in part, on more recent evidence regarding the ability of infants to discriminate differing speech sounds (Eimas, 1982). However, as Studdert-Kennedy (in press) points out "I do not doubt that infants can form auditory categories, but there is no evidence that this capacity is either needed for or brought to bear on early speaking."

Much the same view of the relationship of two levels is often taken of the underlying phonology in functionally misarticulating children. For a history of the use of phonological process analysis within speech-language pathology (see Edwards & Shriberg, 1983). That is, it has often been assumed that the misarticulating child has a normal underlying perceptual process, but obeys rule-governed restrictions in output.

Recently, Elbert, Dinssen, and Weismer (1984) and Maxwell (1979) have suggested that misarticulating children differ among themselves in the relationship of underlying and surface forms. While some children give evidence, either by the presence of morphophonemic alternations (e.g., /dɔ/ but /dɔ gɪ/) or by preservation of acoustic differences in output for two forms in which a phone is omitted in transcriptional description, others do not. These authors suggest, therefore, that the nature of a child's phonological structure should be demonstrated on a phone-by-phone basis, rather than assumed.

It is possible to take the more radical position that description of children's early word attempts might be couched in auditory and motoric rather than linguistic terms (Studdert-Kennedy, in press). After all, it is not necessary to assume that the child has internalized phonological categories which conform to the description of adult linguistic behavior (Harris, 1983; Menn, 1980; Menyuk & Menn, 1979). The fact that transcription has been the method of choice for describing children's production has tended to push description toward adult categories. However, Ferguson has presented evidence that early words are learned on a one-by-one basis (Ferguson & Farwell, 1975) and that attempts at an early word are highly variable. While it is extremely difficult to abandon the transcriptional description of words, even transcriptions show that ubiquitous variability is an essential component of the description of the child's categories.

This same variability has been repeatedly shown in instrumental descriptions as characteristic of the speech of children, even when they produce apparently mature forms (Kent, 1976). Eguchi and Hirsh (1969) described the spectral variability of production of vowels in children's speech. While the extent to which their data were affected by measurement error has been the subject of some discussion (Monsen & Engebretson, 1983), there seems to be little doubt about the appropriateness of Eguchi and Hirsh's characterization of the variability phenomenon itself. Similar production variability has been shown to characterize temporal aspects of developing speech production capabilities (see Smith, 1978).

We emerge, then, from the description of normal child phonology with two general principles. First, a phonological

inventory description must be supported by production data of some sort which demonstrates the differentiation of units which are presumed to be phonologically distinct. Often, forms distinct in the adult model are collapsed in the child's output, or are differentiated on a basis which is different from the adult. Second, it may be that the description of a child's speech in terms of an underlying phonological structure fails to capture at least the important variability aspect of performance.

When we turn to deaf children, we find that the same kind of phonological structure approach has been used in describing their speech, especially by Monsen (1976, 1983) and by Fisher, King, Parker, and Wright (1983). For hearing-impaired children there is, of course, no question that the representations supporting the phonological structure must be very different from that of the hearing community, since we presume that the sensory information on which such children base any structure and maintain differentiation between items is very different from that for normals. Thus, in Fisher's et al. (1983) description, a single form is produced by deaf children for forms which are differentiated in the adult model, or a given contrast, while preserved, is preserved in phonetically different terms. One of the most interesting points made by Fisher and his colleagues (op. cit.) is that intelligibility for those deaf speakers who maintain a system of deviant contrasts may be reduced by a speech training regime which moves some phones towards the normal model, but removes certain contrasts that are preserved on a deviant basis.

What kind of evidence might be marshalled in support of the point of view that the oral deaf preserve contrasts between phones as normals do? We can examine, carefully and systematically, the variability of production of some class of sounds. A deviant phonology would be indicated by normal production variability, co-occurring with a failure to differentiate pairs of sounds, or an abnormally based distinction.

An indirect form of evidence for the "deviant phonology" hypothesis could be provided by the listener effect, an effect which has been investigated by several researchers at the Central Institute for the Deaf. If deaf speakers differentiate between sounds in production in a way that is different from normal, then teachers, who are experienced in listening to hearing-impaired talkers, might be able to invoke a special listening strategy, based on the use of cues which naïve listeners ignore. For example, if it were true that some deaf speakers systematically substitute fundamental frequency variation for formant variation (Angelocci, Kopp, & Holbrook, 1964), then an experienced listener might simply focus on this characteristic as a way of differentiating vowels (or classes of vowels). The listeners would then show a heavier dependence on F_0 than on spectral characteristics of individual tokens. Alternatively, if deaf speakers simply overlay some abnormal characteristic (Stevens, Nickerson, & Rollins, 1983), such as too high or too low pitch on their speech, experienced listeners might learn to ignore the deviant overlay, and focus on vowel cues. In this case, the pattern of differentiation would be the same for experienced and inexperienced listeners, although experienced listeners would show superior performance.

An essential component of the listener effect is that listeners must be able to identify speakers as deaf. Some time ago, Calvert (1961) demonstrated very convincingly that experienced teachers of the deaf can identify speakers as deaf, but that the teachers' performance depends very heavily on the presence of articulatory movement in the samples judged—that is, the time-dependent deviance of deaf articulatory patterns is detectable, and hence, might serve as the basis of a detection strategy. Moreover, the fact that sustained vowels produced by deaf talkers are less readily identified than vowels produced in context suggests that such identification does not depend on an overlaid characteristic, such as voice quality.

In what follows, we will discuss three studies that bear on the issues above. The first is a doctoral dissertation by Judith Rubin (1984). Obviously, there is a great deal more detail in her study than can be reported here. We will then go on to discuss some physiological work on interarticulator timing in the productions of deaf talkers (McGarr & Gelfer, 1983; McGarr & Harris, 1983; McGarr & Löfqvist, 1982) and also in normal speakers (Harris, Tuller, & Kelso, 1984; Tuller & Kelso, 1984; Tuller, Kelso, & Harris, 1982, 1983).

The object of Rubin's study was first, to make a direct test of the hypothesis that deaf speakers produce vowels with the same variability as normal talkers. Beyond that, she wanted to compare the strategies that experienced and inexperienced listeners use in decoding deaf and normal vowels.

The subjects of her study were six orally trained, severely or profoundly hearing-impaired high school students and two age-matched normals. The speakers were asked to say "You got me the /bvb/" with any of seven test vowels in the vowel slot. Each token was produced 15 times. The results were analyzed acoustically, using an LPC algorithm; F_0, F_1, F_2 and duration were measured.

In the perceptual part of the study, experienced and inexperienced listeners were asked to make two judgments—first, they were asked to identify each vowel token as to whether it was produced by a deaf or a normal talker. Second, they were asked to identify the vowel. Stimuli were presented in three conditions—first, the whole utterance; second, the /bvb/ syllable alone; and third, a short, more-or-less steady state segment gated out of the middle of the /bvb/ syllable. The stimuli were grouped by condition, but not by speaker.

We will first describe the results of the acoustic formant analysis. First, on average, deaf talkers show a reduced range of average F_1 and F_2 values, relative to normals—durations are prolonged as has been previously reported, and fundamental frequency is a little higher on average. (Note that the talkers were preselected to avoid subjects with such severe source problems that LPC analysis would become problematic). However, when we look at individual talkers, comparing mean plots and variability plots, a different and more complicated picture emerges.

While individual differences are not discussed here in detail, some of the speakers showed small variability for the point vowels (/i/, /ɑ/, and /u/), with much greater variability for intermediate vowels such as /ɛ/. Some showed overlap between front and back vowels while some showed a great deal of variability for all vowels. Thus the placement of the average values in F_1-by-F_2 space does not predict the relative variability of the tokens around average values.

This point is illustrated in the average data for two hearing-

impaired speakers. Average vowels for the first speaker shown in Figure 1 are more or less appropriately distributed in formant space.

In Figure 2, the ranges of the tokens for the same speaker are shown by adding lines drawn to enclose the points representing all tokens. For this speaker, the three point vowels /i, a, u/ are reasonably well defined; however, intermediate vowels are much more variable.
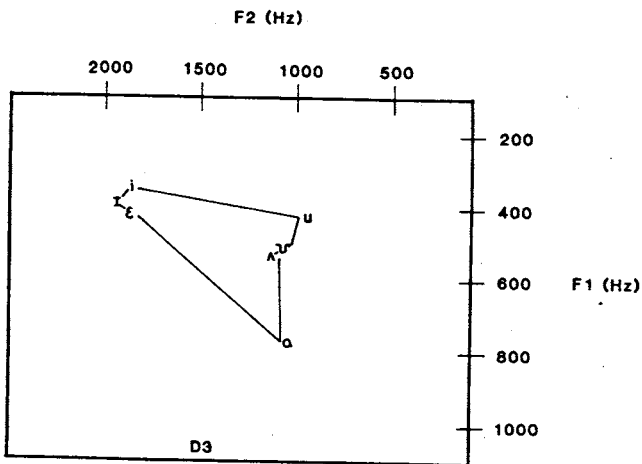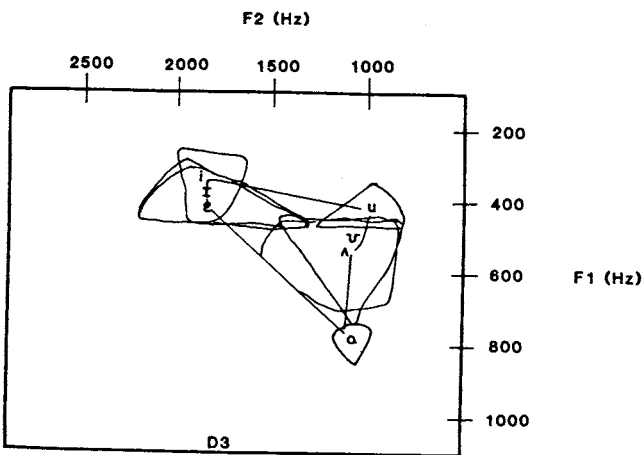

FIGURE 1. Average vowels for Talker D3.
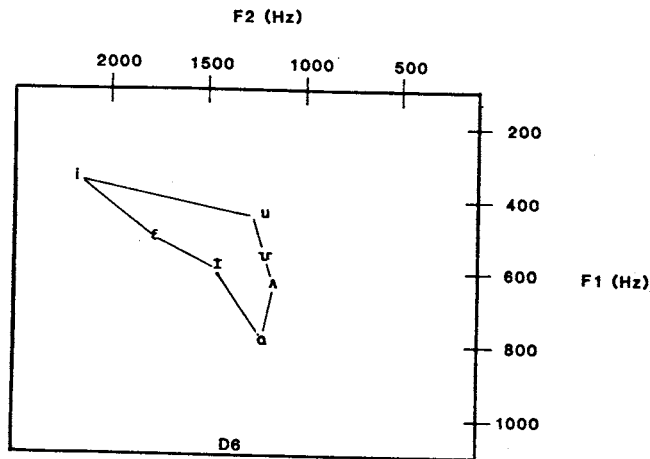

FIGURE 2. Range of vowels for Talker D3.

Average values for a second deaf speaker are similar to those for the first, as shown in Figure 3, but when we examine the distribution around the average values, as shown in Figure 4, we find a great deal of smear for all vowels. That is, the average values do not give a clear picture of the token-to-token variability.

Figure 5 shows the standard deviations of F_1 and F_2 for the six talkers, while Figure 6 shows standard deviations for the four acoustic measures summarized in a somewhat different fashion. The important point here is that deaf talkers are statistically significantly more variable than normals on every acoustic dimension. Thus, a description of average formant values fails to capture differences between vowel systems.
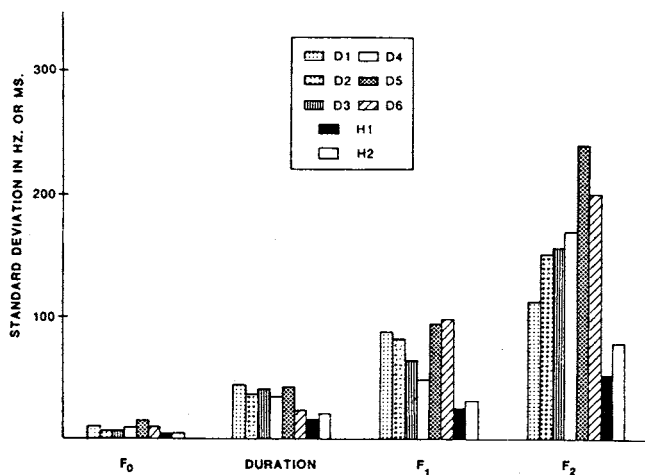

FIGURE 3. Average vowels for Talker D6.
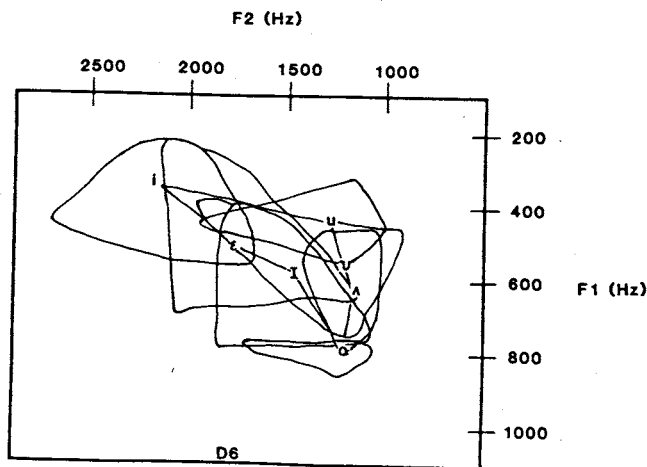
FIGURE 4. Range of vowels for Talker D6.
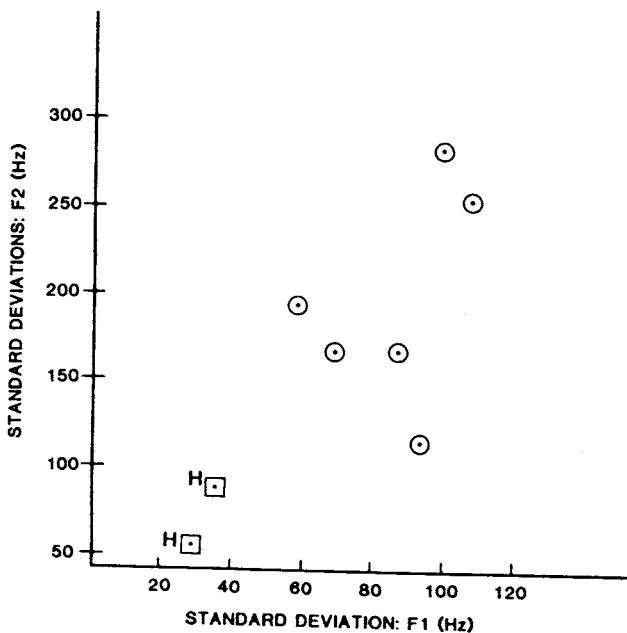
FIGURE 5. Standard deviations of F_1 vs. F_2 for all subjects.

FIGURE 6. Standard deviations of F_0, duration, F_1 and F_2 for all subjects.

There remains the possibility that hearing-impaired talkers were using F_0, or duration, alone or in combination with F_1 and F_2 in their attempt to discriminate between vowels. This possibility was checked by comparing two linear discriminant analyses, to see how many vowel targets can be discriminated using F_0 and duration, which were not discriminated by F_1 and F_2 alone. We find that for the most part, adding F_0 and duration information does not change the number of vowels which can be discriminated statistically, on a talker by talker basis. This provides additional support for Bush's (1981) finding that deaf talkers do not substitute F_0 differentiation for formant differentiation in vowel production.

Finally we turn to the perceptual part of the study. As we discussed above, a strong listener effect would be indirect evidence suggesting that deaf unintelligibility is, in part, due to a systematic, but deviant production strategy.

As Figure 7 shows, there was no statistically significant difference between experienced and inexperienced listeners. The
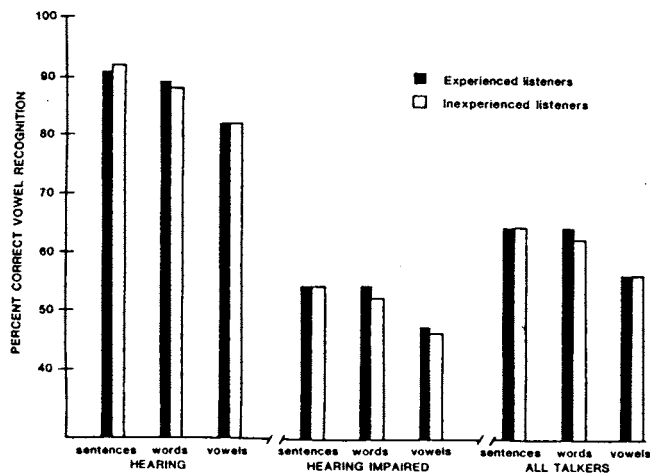
listener effect for vowel identification has been reported by McGarr and Gelfer (1983), but not by Gulian and Hinds (1981). A listener effect for word identification has been found by Mangan (1961), Markides (1970), McGarr (1978), Nickerson (1973), and Thomas (1963).

Let us turn now to an examination of the effects of context. While the effects of context on vowel identification in normals has been the subject of debate in voluminous literature (see Ochiai & Fujimura, 1971; Pisoni, Carrell, & Simnick, 1979; Verbrugge, Strange, Shankweiler, & Edman, 1976), studies have at least suggested that phonetic context aids in recognition. That is the case here. Listeners, whether experienced or inexperienced, were most successful with sentences and syllables and least successful with gated segments excised from the vowel.

Context also was important in the other judgment the listeners made, that is, whether the speaker was deaf or normal. Since there were two normal and six hearing-impaired speakers in the study, d' was used as a measure of the ability of listeners to identify the speakers as hearing or deaf, as shown in Figure 8. Again, the effects of experience were minimal. However, the listeners were increasingly correct in judging the speaker to be deaf as they had more dynamic information. This result qualitatively confirms Calvert's thesis result (1961). However, at a quantitative level, listeners in the present study could be shown to behave statistically slightly above
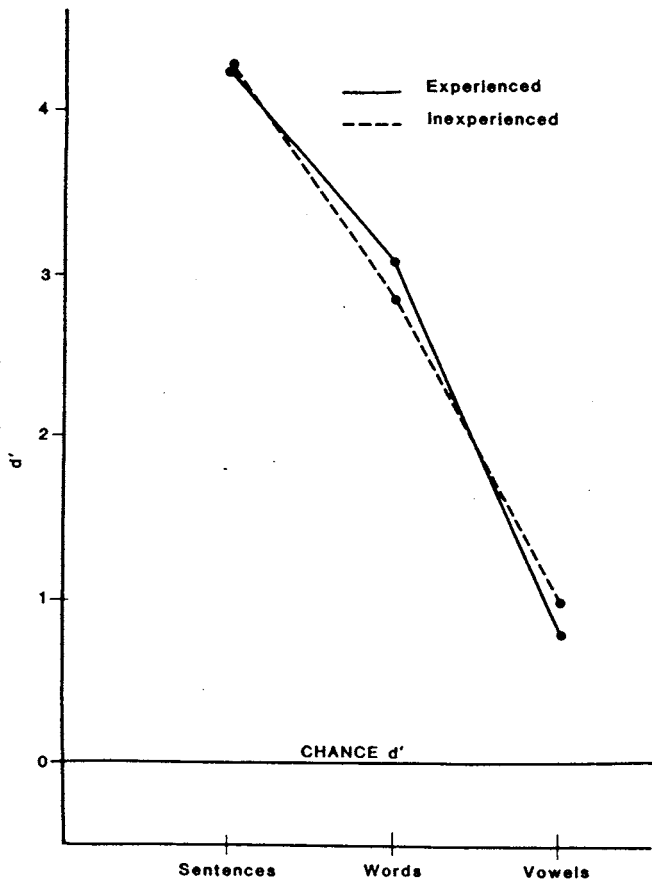

FIGURE 7. Effects of context on vowel recognition by experienced and inexperienced listeners, listening to hearing and hearing impaired talkers.

FIGURE 8. d' for vowels in various contexts.

chance levels in judging even isolated vowels. The ability of listeners to judge a vowel correctly was statistically independent of their ability to judge it as produced by a hearing or deaf child, whether the listener was experienced or inexperienced. This result again suggests that there is no special strategy which is effective in decoding deaf vowels.

Still another analysis was made of whether listeners were using conventional information in making vowel identity judgments for deaf talkers. Figures 9 and 10 show the acoustic data for the two individual deaf talkers discussed earlier, with circles around those vowels which are judged correctly at least 70% of the time. The effect of context is to enlarge the "correct vowel" area. Thus, we can speculate that placing a vowel within a consonant transition context allows the listener to be less dependent on precisely appropriate specification of vowel formant information.

Let us summarize these results, and go on to say a bit about production. First, these analyses fail to provide any evidence that deaf speakers were using a substitution strategy in vowel production, or that experienced listeners were better than inexperienced, because of a different way of judging deaf speech. Deaf speakers were more variable than normals, although the pattern of variability was different from talker to talker. One interpretation of the results presented is that it is
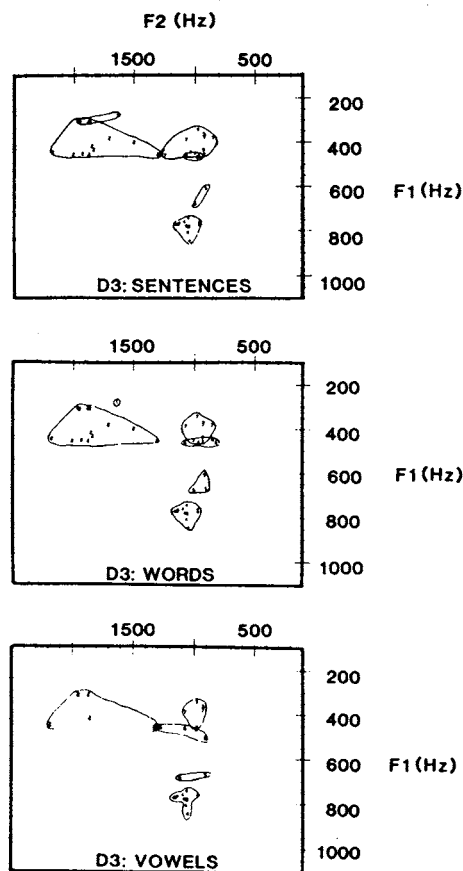

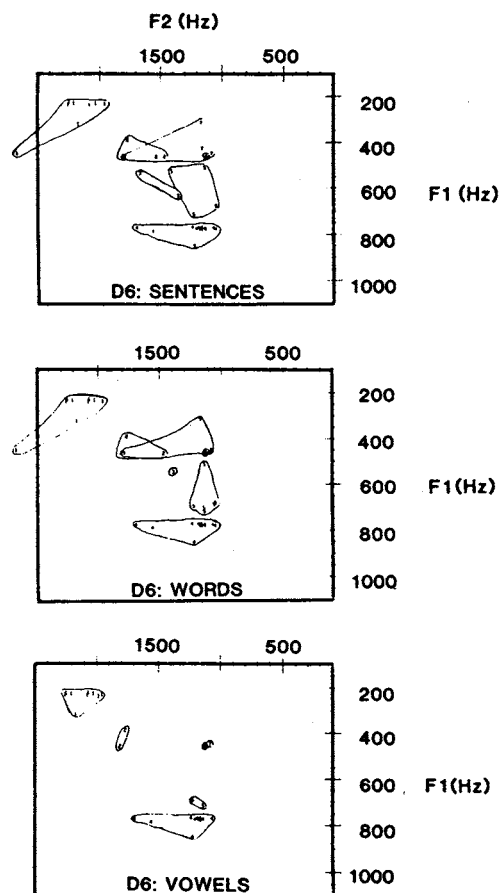FIGURE 10. $F_1 \times F_2$ plots of vowel tokens perceived correctly in the three experimental contexts, for Speaker D6.

FIGURE 9. $F_1 \times F_2$ plots of vowel tokens perceived correctly in the three experimental contexts, for Speaker D3.

not appropriate to describe these talkers as presenting a deviant phonology. Indeed, we would argue that a "deviant phonology" description of their production does not capture essential aspects of their performance. The results we have seen for these children suggest that they are behaving, in a more extreme way, like normal children, as Kent (1976) describes them. Performance variability is an essential characteristic of all the speech of children as they learn to talk, and as they attain control of the production apparatus.

The nature of the articulator routines underlying the variability in acoustic output is unresolved by the study just described. However, we might note that the sequence of upper articulator movements in producing the utterance /bvb/ is fairly simple. The subject closes the lips for the initial and terminal bilabial consonants, and between these two gestures, s/he must produce an appropriate tongue configuration. If these gestures are produced in an inappropriately timed sequence, the acoustic result will be inappropriate, but the consequences of changing the relative timing of the gesture sequence is not directly represented in the acoustic signal.

One of the observations made by Ferguson and Farwell (1975) was that a normal child, in attempting to produce the word "pen," engaged in attempts which were variable pre-

cisely because she did not output the required sequence of articulatory gestures in the correct order. We believe that the characteristic variability in deaf speech may arise in part from the same sources (cf. McGarr & Gelfer, 1983; McGarr & Harris, 1983; McGarr & Löfqvist, 1982).

We illustrate this point with data from a tongue-tip coordination study of McGarr and Harris (1983) in which stimuli not unlike Rubin's, (i.e., a bilabial-V-bilabial sequence) were used. Articulatory timing was monitored by electromyographic techniques. When muscle fibers contract, a change in potential is generated in the surrounding medium and these changes in potential can be measured by appropriately placed electrodes. Lip closure (e.g., in bilabial production) is accomplished in part by the contraction of the orbicularis oris muscle, a muscle whose fibers ring the lips. For production of a high vowel such as [i], the tongue body is bunched and raised by contraction of the genioglossus, a muscle whose fibers radiate through the center of the tongue mass. The EMG record then indicates gesture sequencing.

Results are shown for a hearing speaker producing the utterance /əpɑpip/ in Figure 11. These data represent the ensemble average of about 20 repetitions or tokens of each utterance, with each token on the average showing essentially the same pattern of activity (see Harris & McGarr, 1980; McGarr & Harris, 1983). The line-up point, indicated by the vertical line at 0 ms, is the release burst of the second /p/.

The data for the orbicularis oris (00) show three well-defined peaks of activity corresponding to the lip gestures for the three /p/ closures in /papip/. The line-up point falls between the second and third peaks. For the genioglossus (GG), there is a peak of activity associated with /i/ but not /a/, because genioglossus is active in raising and bunching the tongue. Peak genioglossus activity occurs approximately at the acoustic line-up. This is not surprising because EMG activity typically precedes the articulatory event to which it is attached by about 50 to 100 ms. Shifting of stress from the first (Figure 11A) to the second vowel (Figure 11B) does not disrupt this temporal relationship.

Figure 12 shows similar data for an oral deaf adult. The EMG pattern for 00 shows, as for the hearing subject, three well-defined peaks of activity. The duration of the peaks is prolonged, however. In Figure 12A, peak GG activity occurs between the second and third orbicularis oris peaks but is late relative to the acoustic event. This pattern was most like normal. In Figure 12B the GG activity was too late. In Figure 12C, activity begins during what should be /a/ production, when the GG should be silent. Thus, the EMG pattern for GG is quite variable from token to token. This variability is reflected in a less well-defined average pattern (see McGarr & Harris, 1983, for more details).

While this evidence is fragmentary, it suggests precisely the sort of production variability we might expect; that is, while the behavior of a visible articulator is more or less normal, activity for one of the muscles associated with tongue movement is variable in its temporal alignment with the ac-

HEARING SPEAKER
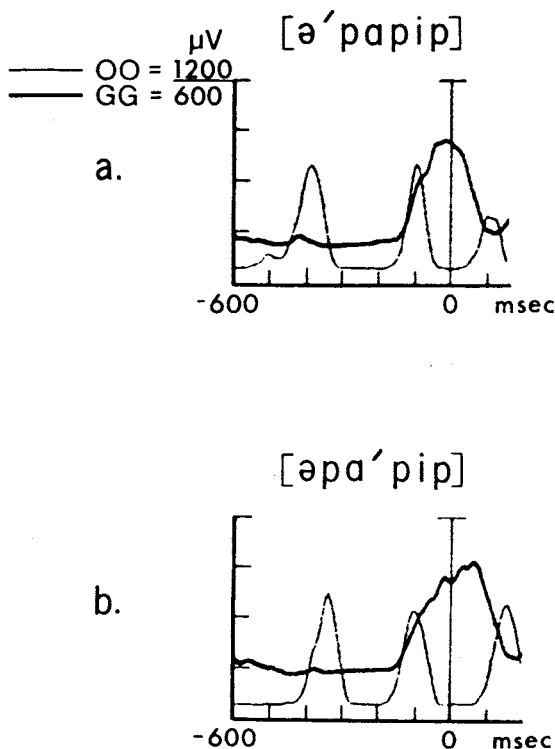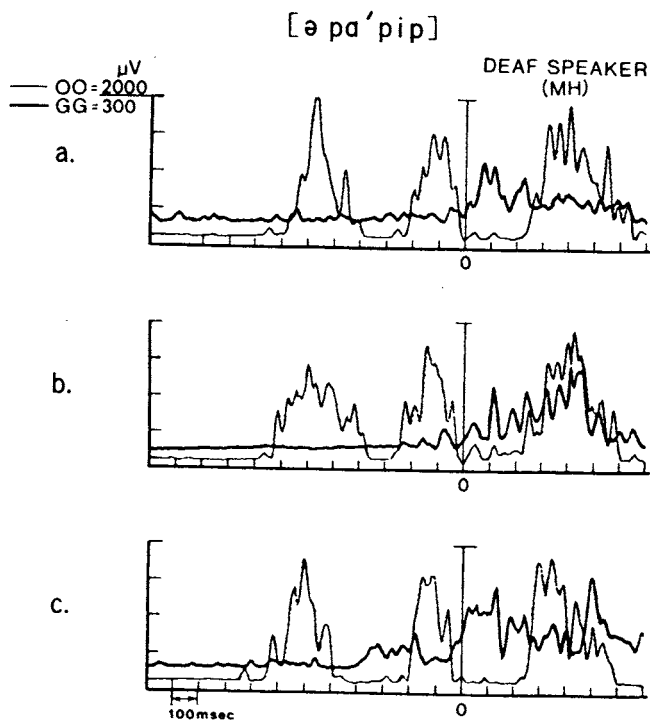(FBB)

[ə′pɑpip]

[əpɑ′pip]

FIGURE 11. Average 00 and GG outputs as a function of time, of simple nonsense utterances, for a normal talker. (Reproduced with permission from McGarr & Harris, 1983.)

[ə pɑ′pip]

FIGURE 12. Three individual tokens of a simple nonsense utterance, showing 00 and GG outputs as a function of time, for a hearing-impaired talker. (Reproduced with permission from McGarr & Harris, 1983.)

tivity of the visible articulator. This could produce the kind of acoustic variability analyzed in Rubin's work. Similar inter-articulator variability has also been described in our work with deaf speakers for larynx-upper articulators (McGarr & Löfqvist, 1982) and tongue-lip (McGarr & Gelfer, 1983) coordination.

One final result illustrates the extraordinary stability of interarticulator timing in normal adult speech production. Harris, Tuller, and Kelso, (in press); Tuller & Kelso, 1984; Tuller, Kelso, and Harris, (1982, 1983) have performed a series of experiments in which normal adult subjects produce simple nonsense syllables (again, of the form /papap/), with stress on either the first or second syllable and at two self-selected speaking rates. In a typical experiment, lip and jaw movements were monitored by fixing light-emitting diodes on these articulators. In an utterance such as /babab/, downward jaw movements can be associated with vowels, while upward lip movement can be associated with consonants. Tuller was thus able to examine the relationship of the temporal onset of the medial consonant to the duration of a vowel-to-vowel interval.

Figure 13 shows the data plots with the values of $\underline{r}$ and the slopes for a linear regression for four utterance types, /bapab/, babab/, /bawab/, and /bavab/ for a single speaker. The $\underline{r}$ values do not vary systematically with consonant. For the various measures analyzed, the Pearson product-moment correlation values range from $+.84$ to $+.97$ across the four subjects of the experiment. While the values of $\underline{m}$ show a trend towards flatter slopes, and thus, earlier consonant onsets for /v/ and /w/ as compared to /p/ and /b/, the ordering of slopes was not identical across subjects.

The substantial size of the linear correlations suggests that stability of the ratio over changes in vowel duration produced by stress and speaking rate changes is a characteristic of mature normal speech production. If we were to examine similar data for normal children, we would expect a systematic decrease in the scatter around the line of best fit with increasing articulatory maturity. For deaf speakers, we would expect even lower correlation values and we are presently analyzing data from a comparative study of deaf and normal speakers.

Finally let us return to the beginning of this paper and point to the moral. Although "deaf speech" may have distinctive characteristics, the striking thing about the results reported here is the link between deaf speech and motorically immature speech. This relationship will in part be obscured by any description which ignores production variability as an essential characteristic of the speech production capabilities.

ACKNOWLEDGMENTS

REFERENCES

ANGELOCCI, A., KOPP, G., & HOLBROOK, A. (1964). The vowel formants of deaf and normal hearing eleven to fourteen year old boys. *Journal of Speech and Hearing Disorders, 29,* 156–170.

BUSH, M. (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.

EDWARDS, M. L., & SHRIBERG, L. D. (1983). *Phonology: Applications in communicative disorders.* San Diego: College-Hill Press.

EGUCHI, S., & HIRSH, I. J. (1969). Development of speech sounds in children. *Acta Otolaryngologica Supplement 257.*

EIMAS, P. D. (1982). Speech perception: A view of the initial state and perceptual mechanics. In J. Mehler, E. C. T. Walker, & M. Garrett (Eds.), *Perspectives on mental representation* (pp. 339–360). Hillsdale, NJ: Erlbaum.

ELBERT, M., DINNSEN, D. A., & WEISMER, G. (1984). Phonological theory and the misarticulating child. *ASHA Monograph 22,* 1–4.

FERGUSON, C. A., & FARWELL, C. B. (1975). Words and sounds in early language acquisition. *Language, 51,* 419–439.

FISHER, J., KING, A., PARKER, A., & WRIGHT, R. (1983). Assessment of speech production and speech perception as a basis for therapy. In I. Hochberg, H. Levitt, & M. J. Osberger (Eds.), *Speech of the hearing impaired: Research, training and personnel preparation* (pp. 195–214). Baltimore, MD: University Park Press.

GULIAN, A. B., & HINDS, J. (1981). Response bias in the perception of deaf speech by experienced and naïve listeners. *British Journal of Audiology, 15,* 165–171.

HARRIS, K. S. (1983). A review of *Phonological interventions: Concepts and procedures. Applied Psycholinguistics, 4,* 294–297.

HARRIS, K. S., & McGARR, N. S. (1980). Relationships between speech perception and speech production in normal hearing and hearing impaired subjects: Implications for training speech of the hearing impaired. In J. D. Subtelny (Ed.), *Speech assessment and speech improvement for the hearing impaired* (pp. 316–337). Washington, DC: Alexander Graham Bell Association.

HARRIS, K. S., TULLER, B., & KELSO, J. A. S. (in press). Temporal invariance in speech production. In J. Perkell (Ed.), *Invariance and variance in speech processes: Proceedings of Conference at MIT.* Hillsdale, NJ: Erlbaum.
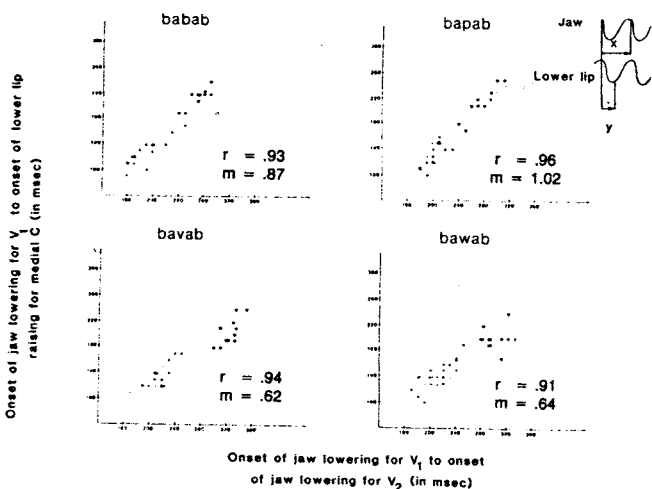

FIGURE 13. Period (jaw lowering) versus latency (lower lip raising) for nonsense disyllables differing in medial consonant for a single subject. Circles indicate utterances spoken at a conversational rate, triangles indicate a somewhat faster rate. Filled symbols have stress on the first syllable, open symbols have stress on the second syllable (Reproduced with permission from Tuller, Kelso, & Harris, in press).

INGRAM, D. (1976). *Phonological disability in children*. New York: Elsevier.

JAKOBSON, R. (1968). *Child language, aphasia, and phonological universals*. The Hague: Mouton.

KENT, R. D. (1976). Anatomical and neuromuscular and maturation of the speech mechanism: Evidence from acoustic studies. *Journal of Speech and Hearing Research, 19*, 421–447.

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.

MAXWELL, E. M. (1979). Competing analyses of deviant phonology. *Glossa, 13*, 181–214.

MCGARR, N. S. (1978). *The differences between experienced and inexperienced listeners in understanding the speech of the deaf*. Unpublished doctoral dissertation, The City University of New York.

MCGARR, N. S., & GELFER, C. (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*. Baltimore: University Park Press.

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.

MENN, L. (1980). Phonological theory and child phonology. In G. H. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson, (Eds.), *Child phonology production* Vol. 1 (pp. 23–41). New York: Academic Press.

MENYUK, P., & MENN, L. (1979). Early strategies for the perception and production of words and sounds. In P. Fletcher & M. Garman (Eds.), *Language acquisition* (pp. 49–70). Cambridge: Cambridge University Press.

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

MONSEN, R. B. (1983). General effects of deafness on phonation and articulation. In I. Hochberg, H. Levitt, & M. J. Osberger (Eds.), *Speech of the hearing impaired: Research, training and personnel preparation*. Baltimore, MD: University Park Press.

MONSEN, R., & ENGEBRETSON, M. (1983). The accuracy of formant frequency measurements: A comparison of spectrographic analysis and linear production. *Journal of Speech and Hearing Research, 26*, 89–97.

NICKERSON, R. (1973). *Computerized speech training aids for the deaf*. Report No. 2633. Bolt, Beranek & Newman.

OCHIAI, K., & FUJIMURA, O. (1971). Vowel identification and phonetic contexts. *Reports of the University of Electro-Communication 22*, 103–111.

PISONI, D., CARRELL, T. D., & SIMNICK, S. S. (1979). Does a listener need to recover the dynamic vocal tract gestures of a talker to recognize his vowels? *Journal of the Acoustical Society of America, 22*, 807–820.

RUBIN, J. (1983). *Static and dynamic information in vowels produced by the hearing impaired*. Bloomington, IN: IULC.

SMITH, B. L. (1978). Temporal aspects of English speech production: A developmental perspective. *Journal of Phonetics, 6*, 37–67.

SMITH, N. V. (1973). *The acquisition of phonology: A case study*. London: Cambridge University Press.

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*. Baltimore, MD: University Park Press.

STUDDERT-KENNEDY, M. (in press). Sources of variability in early speech development. In J. S. Perkell & D. H. Klatt (Eds.), *Invariance and variability of speech processes*. Hillsdale, NJ: Erlbaum.

THOMAS, W. (1963). Intelligibility of the speech of deaf children. *Proceedings of the International Congress on the Education of the Deaf*. Document No. 196.

TULLER, B., KELSO, J. A. S., & HARRIS, K. (1982). Interarticulator phasing as an index of temporal regularity in speech. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 460–472.

TULLER, B., KELSO, J. A. S., & HARRIS, K. S. (1983). Further evidence for the role of relative timing in speech. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 829–833.

TULLER, B., & KELSO, J. A. S. (1984). The timing of articulatory gestures: Evidence for relational invariance. *Journal of the Acoustical Society of America, 76*, 1030–1036.

VERBRUGGE, R. R., STRANGE, W., SHANKWEILER, D. P., & EDMAN, T. R. (1976). What information enables a listener to map a talker's vowel space? *Journal of the Acoustical Society of America, 60*, 198–212.