ABSTRACT
        Material for teacher-users of a computer-based system
of speech training aids for the deaf is offered. Research on the
types of deficiencies found in the speech of the deaf is reviewed; a
philosophy concerning training which emphasizes the role of
diagnosis, is presented; and suggestions are made concerning use of
the displays produced by the system to facilitate diagnosis and
training. (Author/SK)

DRAFT CURRICULUM MANUAL:

A REVIEW OF SPEECH PROBLEMS OF THE DEAF

AND A PRELIMINARY GUIDE TO THE USE OF

THE BBN SYSTEM OF SPEECH-TRAINING AIDS

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Abstract

Our primary purpose in writing this document was to
provide some material that would be helpful to teacher-users
of the BBN computer-based system of speech-training aids for
the deaf. Research on the types of deficiencies that are found
in the speech of the deaf is reviewed; a philosophy concerning
training, and emphasizing the role of diagnosis, is presented;
and suggestions are made concerning how the displays that can
be produced by the system may be used to facilitate diagnosis
and training. The tentativeness of the ideas that are presented
in this document concerning training is acknowledged by the use
of the word "draft" in the title.

1. INTRODUCTION

For over two years we have been attempting to develop, use
and evaluate a computer-based system of speech-training aids for
the deaf. The purpose of this document is to set forth what we
think we have learned as a result of this effort concerning how
such a system might be used to help teach speech to deaf children.
Although the proposed training exercises and illustrations are
all based on the capabilities of this particular system, it should
not be inferred from this that we view this system as the ultimate
in computer-based speech-training aids. Our feeling is quite to
the contrary. We view this system as a very modest step in the
direction of bringing computing technology to bear on the extra-
ordinarily difficult problem that teaching speech to deaf children
represents.

Our experience to date has convinced us of the validity of
the assumption that computer technology has the potential to
impact favorably and significantly on this problem, but it is also
clear that a long time and considerable effort may be required to
exploit that potential fully. The major difficulties are not
technological limitations, but pedagogical uncertainties. Even
with a relatively small computing machine such as the one in our
system, we are able to generate more displays than we know how to
use effectively. We take this not as cause for discouragement
but as support for a point of view that was expressed at the
beginning of this project; namely, that a system of the sort
toward which we are working cannot be <u>designed</u>. Such a system
must be <u>evolved</u>, and the evolutionary process must be guided by
a close interaction between developers and users. This is the
approach that has been taken in the development of the system
with which this manual is concerned. We consider the system

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to be still in an early stage of evolution, but it has evolved
to a point at which it can, we think, be used to advantage in the
day-to-day training of speech.

2.   PROBLEMS WITH SPEECH OF THE DEAF

It may be somewhat misleading to talk about specific
problems, or specific deficiencies, in the speech of the deaf,
because it can create the impression that these problems are
independent and can be dealt with individually. Independence
is almost certainly not the case. No matter how one categorizes
the various deficiencies that have been focused upon, one dis-
covers that one cannot say much about any given category without
implicating others. Nevertheless, some structuring is necessary.

In this report the discussion of speech problems is
organized around five topics: timing and rhythm, pitch and
intonation, velar control, articulation, and voice quality.
This selection reflects nothing more than the fact that we
find it convenient to structure our own thinking in this way.
No claim is made for the superiority of this organization
over others that might be used.

2.1   Timing and Rhythm

Poor timing has been considered by several investigators
to be a major cause of the generally poor intelligibility of
the speech of the deaf (Bell, 1916; Hood, 1966; Hudgins & Numbers,
1942; John & Howarth, 1965; Houde, 1973; Nober, 1967; Stratton,
1973).

Precise specification of timing deficiencies is not possible
simply because not enough is yet known about the temporal charac-
teristics of "normal" speech. The results from a number of
studies permit several tentative assertions, however, that are
at least suggestive of ways in which the speech of the deaf

may differ, in the aggregate, from that of hearing speakers with respect to temporal aspects. Many of these findings have been reviewed in greater detail by Nickerson, Stevens, Boothroyd, and Rollins (1974).

Deaf speakers tend to speak at a much slower rate than do hearing speakers (Boone, 1966; Colton '   )oker, 1968; Hood, 1966; John & Howarth, 1965; Martony, 1966; Mason & Bright, 1937; Nickerson, et al., 1974; Voelker, 1938). It has been estimated that hearing speakers emit speech at the rate of about 3.3 syllables (Pickett, 1968) or 10 to 12 phonemes (Miller, 1962) per second on the average; although speech rate can deviate considerably in either direction from these norms and still be highly intelligible (Abrams, Goffard, Kryter, Miller, Sanford, & Sanford, 1944). Deaf speakers tend to speak more slowly than the slowest hearing speakers, however, and when the deaf and hearing speakers have been studied under similar conditions, the measured rates have often differed by a factor of two or three, or more (Hood, 1966; Mason & Bright, 1937; Voelker, 1938).

Deaf speakers fail to make the difference between the durations of stressed and unstressed syllables sufficiently large (Angelocci, 1962; Nickerson, et al., 1974). This is because, although deaf speakers prolong the durations of both stressed and unstressed syllables relative to the hearing, the increase tends to be proportionally greater for unstressed than for stressed sounds. Hearing speakers lengthen stressed syllables and syllables in word-final and sentence-final positions (Parmenter & Trevino, 1935; Fry, 1958; Lindblom & Rapp, 1973; Klatt, 1974). A stressed syllable in final position is likely to be three to five times as long as a preceding

unstressed syllable; for deaf speakers the ratio is typically
much smaller than this. It is almost as though the deaf speaker
produces only stressed syllables; and, in fact, some investigators
have suggested that this problem is in part a result of training
that puts great emphasis on the articulation of individual speech
sounds in isolation or in isolated consonant-vowel syllables
(Boone, 1966; John & Howarth, 1965).

Deaf speakers tend to insert more pauses, and pauses of
longer duration, in running speech than do hearing speakers
(Hood, 1966; Hudgins, 1946; John & Howarth, 1965; Nickerson,
et al., 1974). Moreover, these pauses often are inserted at
inappropriate places, such as within phrases (Nickerson, et al.,
1974).

Closely related to the problem of excessive and inapprop-
riately placed pauses is that of poor rhythm. When listeners are
asked to rate the adequacy of the rhythm or syllable grouping of
the speech of deaf speakers, the ratings are below those for
hearing speakers (Hood, 1966; Hudgins, 1946). The importance
of speech rhythm for intelligibility has been demonstrated by
Hudgins and Numbers (1942).

Both the problem of pauses and that of poor rhythm are
related to, or perhaps result at least in part from, inadequate
breath control during speech production (DiCarlo, 1964; Hudgins,
1934, 1936, 1937, 1946; Scuri, 1935; Rawlings, 1935, 1936).
Apparently, deaf speakers expel much more breath while speaking
than do hearing speakers (Hudgins, 1934, 1937, 1946; Rawlings,
1935, 1936), and consequently are likely to interrupt the speech
flow more frequently in order to permit the intake of air.

Apparently, too, deaf speakers tend to use more breath during
speaking than when not speaking; whereas hearing speakers use
about the same amount in both cases (Scuri, 1935). Scuri's
data suggest that the deaf sometimes seem to lack the ability
to close the glottis completely, which could help account not
only for the excessive expenditure of breath as a factor in
producing poor timing and rhythm, but also for the quality
problem of "breathy" voice.

Some timing problems that have been noted by investigators
of the speech of the deaf are associated with the production of
certain types of speech sounds. Fricative consonants, for
example, may have an inordinately long duration for deaf speakers
(Angelocci, 1962; Calvert, 1961, 1962), as may the closure periods
of plosive consonants (Angelocci, 1962; Calvert, 1962).

Finally, speech sounds that require the precise coordination
of the timing of different articulatory movements or the rapid
transition from one articulatory position to another may be
problematical for the deaf speaker. The timing of voice onset
relative to release for a voiceless stop consonant (Angelocci,
1962), and that of the onset of nasalization for a nasal consonant
(Stevens, Nickerson, Boothroyd, & Rollins, 1974) are cases in
point, as is the timing of the movements required to produce
consonant blends or diphthongs, or that of the transitions
represented by the junctions between fricative or nasal
consonants and vowels (Martony, 1966).

To teachers of speech to the deaf, timing problems can be
particularly frustrating. Although timing deficiencies are
widely considered to be especially important as causes of
the lack of speech intelligibility, there is no well-developed

theory of timing from which performance objectives and evaluation
criteria can be inferred. One may be able to say with confidence
that the timing of a given utterance is grossly deficient, but
it does not follow that one will be able to say with the same
assurance precisely how it should be modified to make the timing
right. Until an adequate theory of timing is developed, attempts
to rectify timing deficiencies will, of necessity, be somewhat
ad hoc.

Some progress toward a theory of speech timing is being made
(Klatt, 1974; Lindblom & Rapp, 1973; see Nickerson, Stevens,
Boothroyd, & Rollins, 1974, for a brief summary). It is probably
important, however, to distinguish between a theory that is
descriptive of the speech of the hearing and one that will provide
the basis for establishing training goals for the deaf. It is not
necessarily the case that normative timing patterns derived from
statistical representations of the speech of hearing speakers
constitute reasonable targets toward which all deaf children
should be encouraged to strive. What is needed is a much better
understanding of how intelligibility and quality of speech depend
on various temporal features. Such understanding can only come
from extensive studies of the speech of the deaf as well as of
that of the hearing, designed to answer precisely this question.

2.2 Pitch and Intonation

The fundamental frequency (F_0) of voiced speech sounds
varies considerably in the speech of a given speaker, and the
average, or characteristic, F_0 varies over speakers. Average
F_0 decreases with increasing age until adulthood for both
males and females, as shown in Fig. 1. The average drop for

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(a)

(b)

ADOLESCENT VOICE BREAK

AGE (YEARS)
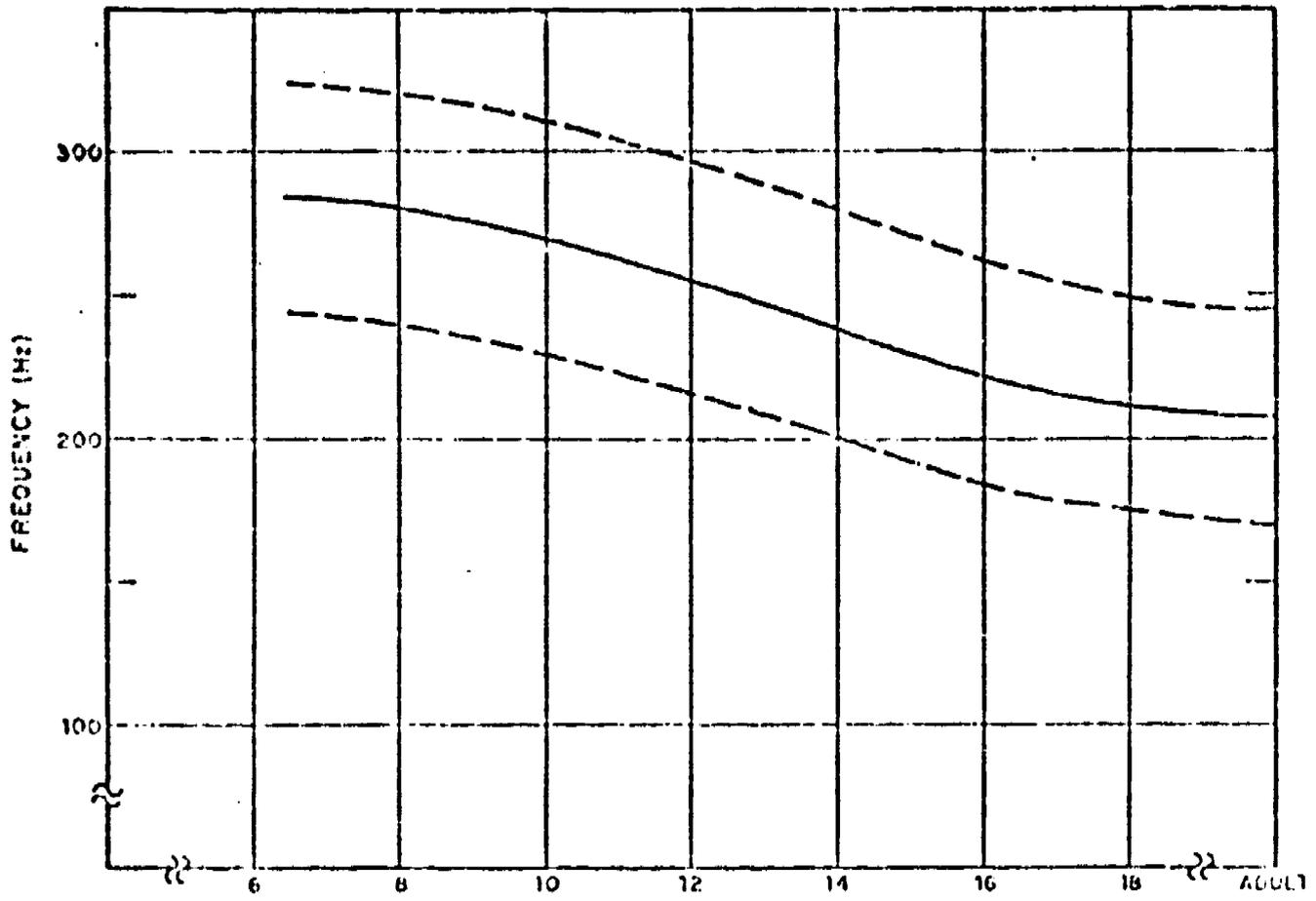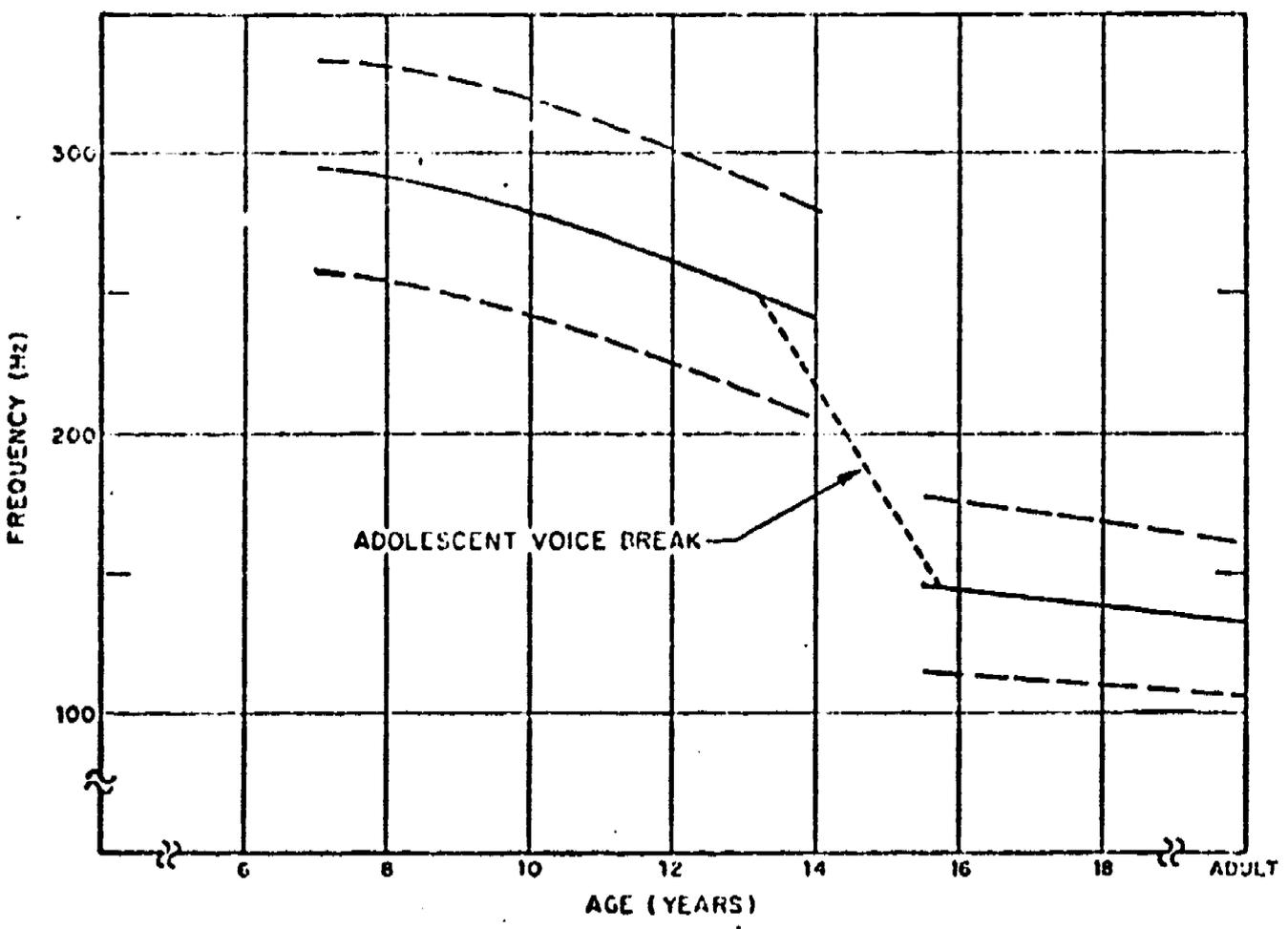
Figure 1. Legend on following page.

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Legend to Fig. 1 (previous page)

Figure 1.   (a) The solid line shows mean fundamental frequency
             used by normally-hearing female speakers at different
             ages.   Mean frequencies of 90 percent of speakers
             are expected to lie within the range indicated by
             dashed lines.   (b) Same as (a), except for male
             speakers.   The adolescent voice break can occur at
             different ages for different individuals.
             (Data from Fairbanks, 1940; Fairbanks, Herbert, &
             Hammond, 1949; Fairbanks, Wiley, & Lassman, 1949;
             Hollien & Paul, 1969).

females is roughly 75 Hz (from about 275-300 Hz to about 200-225 Hz) during the time from prepubescence to adulthood. For males the drop over the same period is likely to be about 150 Hz (from about 275-300 Hz to about 100-150 Hz), about 100 Hz of which may occur abruptly as a result of the adolescent voice break (Curry, 1940; Fairbanks, 1940). Several studies of voices of males between 20 and 30 years of age have placed mean or median F_0 for this group between 119 and 132 Hz (Hanley, 1951; Hollien & Shipp, 1972; Philhour, 1948; Pronovost, 1942). There is some evidence that, at least in the case of males, F_0 may again increase by as much as 30 or 40 Hz with advancing age (Hollien & Shipp, 1972; Mysak, 1959). Of course, for any given age, average F_0s span a considerable range, but about 90% of them would be expected to be within plus or minus 30-40 Hz of the population norms (Fairbanks, 1940; Fairbanks, Wiley & Lassman, 1949; Hollien & Paul, 1969). These ranges of average F_0 for female and male speakers are shown in Figs. 1a and 1b.

Pitch varies in the speech of an average speaker over a range of 1 to 1-1/2 octaves (Fairbanks, 1940). This variation is used to indicate stressed and unstressed vowels, to add emphasis to what is being said, and to carry information about the structure and meaning of a sentence. Stressed syllables are usually spoken with higher pitch than are unstressed syllables, although it may be more accurate to say that stressed syllables are accompanied by pitch change, either within the stressed vowel or in an adjacent vowel. The way in which pitch, amplitude, and duration interact to establish stress is still not fully understood.

Linguistic and semantic information is carried by pitch in several ways. A falling F_0 is used, for example, to signal the end of the final stressed vowel in a declarative sentence. At a

major syntactic break within a sentence, such a fall is followed
by a rise in F_0 to indicate that the sentence is to continue. For
certain types of questions, a rise in F_0 occurs in the final
stressed syllable. Sentences which are ambiguous when printed
(e.g., "Does he speak French or German?") can be spoken in an
unambiguous way because, in part, of the intonation pattern that
is imposed on the words. Also, messages beyond the words, sometimes
subtle, sometimes poignant, can be conveyed by the way the utterance
is inflected. Consider how many ways one can say "Isn't that nice?"

The difficulties that the deaf speaker has with pitch are
of two general types: inappropriate average pitch and improper
intonation. Intonation problems may in turn be divided into two
major types: monotone voice and excessive or erratic pitch
variation.

Several investigators have noted that deaf speakers are apt
to have a relatively high average F_0, or to speak in falsetto
voice (Angelocci, Kopp, & Holbrook, 1964; Boone, 1966; Engelberg,
1962; Martony, 1968). There is some evidence that this problem
is greater for teenagers than for preadolescents, and particularly
troublesome for adolescent boys (Boone, 1966). The results of the
study by Angelocci, Kopp, and Holbrook (1964) suggest that not
only are the fundamental frequencies of deaf speakers higher than
those of hearing speakers, on the average, but the average F_0 for
different speakers spans a wider range.

Deaf speakers often tend to vary the voice pitch much less
than do hearing speakers, and the resulting speech has been de-
scribed as flat or monotone (Calvert, 1962; Hood, 1966; Martony,
1968). A particular problem is that of inappropriate, or insuf-
ficient, pitch change at the end of a sentence (Sorenson, 1974).

A terminal pitch rise--such as that that tends to occur at the
end of some questions--may be even more difficult for a deaf child
to produce than a terminal fall (Phillips, Remillard, Bass &
Pronovost, 1968). Deaf speakers who tend to produce each syllable
with equal duration may also generate a similar pitch contour on
each syllable. Such speakers may fail to indicate variations in
stress either by changing the syllable durations or by modifying
the pitch contours on the syllables. Thus, for example, a common
error would be to fail to shorten an unstressed syllable and to
lower the pitch on such a syllable.

That pitch problems vary considerably from speaker to speaker
is well illustrated by the fact that, whereas insufficient pitch
variation has been noted as a problem for some speakers, excessive
variation has been reported for others (Martony, 1968). Such
variations are not simply normal variations that have been some-
what exaggerated, but, rather, pitch breaks and erratic changes
that do not serve the purpose of intonation.

It has been suggested that some of the unusual pitch varia-
tions that occur in the speech of the deaf may result from attempts
by the speaker to increase the amount of proprioceptive feedback
that he receives from the activity of producing speech. Martony
(1968) and Willemain and Lee (1971) have observed that deaf
speakers sometimes tend to begin a breath group with an abnormally
high pitch, and then to lower the pitch to a more normal level.
Willemain and Lee also noted that the average pitch of the deaf
sometimes increases with the difficulty of the utterance. Inas-
much as the production of high pitch requires increased vocal
effort (such as increased tension in the cricothyroid muscle and
increased subglottal air pressure), they hypothesized that deaf
speakers generate high-pitched tones as a way of providing

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kinesthetic cues concerning the onset and progress of voicing.
A similar conjecture was put forth by Angelocci, Kopp, and
Holbrook (1964) who found that F_0 varied more from vowel to vowel
when the vowels were produced by some deaf speakers than when
produced by hearing speakers, while the reverse relationship held
for first- and second-formant frequencies. These investigators
attributed this type of abnormal pitch variation to efforts by
the deaf speaker to differentiate vowels by varying F_0 and ampli-
tude rather than the frequency and amplitude of the formants.
"In physiological terms he is achieving vowel differentiation by
excessive laryngeal variations with only minimal articulatory
variations" (p. 169).

Some of the pitch variation from vowel to vowel may be the
consequence of improper use of the muscles or use of inappropriate
muscles or muscle groups in controlling the vowel articulations.
These inappropriate muscle contractions may result in inadvertent
tensing or slackening of the vocal cords, resulting in excessive
variations in pitch.

Pitch has been described as a particularly difficult property
of speech for deaf children to learn to control (Boothroyd, 1970).
One possible reason for the difficulty is that deaf children may
lack a conceptual appreciation of what pitch is (Anderson, 1960;
Martony, 1968). Hearing people describe it in terms of a high-low
dimension, but the description is somewhat arbitrary, and it is not
clear that it is meaningful to an individual who has not had an
opportunity to learn, by hearing, what "high" and "low" refer to
in the auditory domain. A lack of intuitive grasp of the concept
may help explain why deaf children often attempt to raise their
pitch by increasing their vocal intensity (Phillips, Remillard,
Bass, & Pronovost, 1968).

2.3 Velar Control

The velum or soft palate functions as a gate between the oral
and nasal cavities. It is lowered to open the passage to the nasal
pharynx when a sound such as one of the nasal consonants is made,
which requires that the air be emitted through the nose. It is
raised, thus sealing off the passage, for sounds that do not make
use of nasal resonances, and in particular for those requiring the
build-up of pressure in the mouth (obstruent consonants). Improper
control of the velum has long been recognized as a source of
difficulty in the speech of the deaf (Brehm, 1922; Hudgins, 1934).
If the velum is raised when it should be lowered, the speech may be
described as hyponasal; if it is lowered when it should be raised,
hypernasality is the result. Miller (1968) has speculated that
type of hearing loss may be a causative factor in connection of some
nasalization problems. Hyponasality, he suggests, may be more
prevalent among people with conductive loss than among those with
sensorineural loss, because nasal sounds may appear excessively
loud to the former, due to the transmittability of nasal resonances
via bone conduction. Individuals with sensorineural loss, on the
other hand, may welcome the additional cues provided by the nasal
resonances, and therefore tend to nasalize sounds that should not
be nasalized.

Nasality is often described as a "quality" problem because
inappropriate velar control may give the overall speech a character-
istic sound. In addition to affecting quality, however, inappropriate
control of the velum can also lead to articulatory problems. There
are three nasal consonants (m, n, and ng) which, in combination,
account for about 11-12% of the occurrences of speech sounds in
English (Denes, 1963; Dewey, 1923). A primary difference between
the articulatory gestures involved in the production of these nasal

consonants and those that are used to produce the three stop con-
sonants (b, d, g) is that the velum is lowered in the former case
and raised in the latter. If the velum is raised when it should
be lowered, or lowered when it should be raised, confusions between
pairs of these sounds may occur. Not surprisingly, such substi-
tutions are found in the speech of the deaf (Stevens, Nickerson,
Boothroyd, & Rollins, 1974).

Learning appropriate velar control may be particularly
difficult for a deaf child for two reasons: (1) raising and lower-
ing the velum is not a visible gesture and therefore not detectable
by lipreading; (2) the activity of the velum produces very little
proprioceptive feedback. Normally-hearing persons are relatively
insensitive to the activity of this part of the articulatory
apparatus, and may be quite unable, without practice, to manipulate
it as an act of conscious control, say while making a steady vowel
sound. Obviously, the movement of the velum must be timed fairly
accurately when producing words with abutting nasal and stop con-
sonants if the appropriate sounds are to be produced and the
resulting speech is to be fluent. Deaf speakers often have con-
siderable difficulty producing such clusters (Stevens, et al., 1974).

Improper velar control is difficult to judge subjectively, in
part because the distinctive perceptual features of nasalization are
not clearly defined and in part because the perception of nasality
may be affected by factors in addition to the activity of the
velum. A deliberate constriction of the nasal pathways, for
example, can modify the resonant characteristics of nasal consonants
and adjacent vowels, thus producing a type of "nasal speech" which
does not necessarily involve improper velar control. Also, some
researchers have suggested that the perception of nasality may be
influenced by such factors as malarticulation, pitch variations,

and speech tempo (Colton & Cooker, 1968). For these reasons,
objective measures that correlate with velar activity are of
considerable interest to investigators of speech. Acoustic
properties of nasal sounds that have been investigated include
shifted and "split" first formant (Fujimura, 1960; House, 1961)
and enhanced amplitude of the lowest harmonics (Delattre, 1955).
Attempts to detect nasalization directly have included the measurement
of the flow of air through the nose (Lubker & Moll, 1965; Quigley,
Schiere, Webster, & Cobb, 1964), the acoustic energy radiated from
the nostrils (Fletcher, 1970; Shelton, Knox, Arndt, & Elbert,
1967), and the vibration on the surface of the nose (Holbrook &
Crawford, 1970: Stevens, Kalikow, & Willemain, 1974).

Procedures have not yet been developed for quantitatively
assessing the severity of nasalization problems. Indeed, normative
data are lacking that would provide the necessary baseline measures
in terms of which deviance could be judged. Moreover, what may
be more important--at least for intelligibility--than the overall
nasality of an individual's speech is the difference in the degree
of nasalization of sounds that should be nasalized and those that
should not be, and the adequacy of the velar adjustments that are
required in order to produce nasal consonants in the context of
other sounds. Stevens, Nickerson, Boothroyd, and Rollins (1974)
have defined for this purpose an index based on detection of
vibration by an accelerometer attached to the surface of the
speaker's nose. The index is intended to indicate how well the
speaker differentiates nasal consonants and nonnasal vowels in
running speech. It is defined as the difference between the
average amplitude of the accelerometer signal (in decibels)
for nasal consonants and the amplitude for vowels that should be
produced without nasalization. Measurements obtained from normally-
hearing speakers produced values of this index in the range

10-20 dB. Values close to zero would suggest a failure to
differentiate nasal from nonnasal sounds. Such failure could
result from either excessive hyper- or hyponasality.

2.4 Articulation

Articulatory problems of a variety of types have been
identified. Failure to develop certain phonemes, failure to
differentiate between others, substitution of one sound for another,
use of the neutral schwa /ə/ (as in about) as a general-purpose
vowel, and other distortions of pronunciation of various sorts
are all articulatory difficulties that are encountered in the
speech of the deaf. Unfortunately, the information that exists
concerning these problems is fragmentary and not easily integrated
into a self-consistent whole. No large-sample study has been
conducted for the express purpose of cataloging the various
articulatory problems that are found in the speech of the deaf,
or of determining either the prevalence of individual problems or
their relative importance vis-a-vis intelligibility and speech
quality. Several investigators have reported specific articulatory
difficulties that they have observed among particular groups of
deaf children, and it is these reports that will be summarized
here. It will be apparent that an intensive study of a large
enough sample of the speech of the deaf to provide some reliable
prevalence data, and a concerted attempt to relate articulatory
problems to intelligibility and quality measures, could increase
greatly our understanding of the speech problems of the deaf.

The failure to produce appropriate vowel sounds has been
noted as a problem by several investigators (Angelocci, Kopp, &
Holbrook, 1964; Boone, 1966; Hudgins & Numbers, 1942). The problem
may take the form of a failure to differentiate one vowel sound
from another, or that of producing diphthongs in place of vowels.
Typically, vowel errors tend to involve spectrally similar sounds
(Smith, 1973).

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Inasmuch as the formant frequencies--and perhaps especially F_2 (Boothroyd, 1972; Licklider & Pollack, 1948; Thomas, 1968)-- apparently provide the information that is needed to distinguish among different voiced speech sounds, one might guess that the speech of the deaf would tend to show some deficiencies in this respect. Some such deficiencies have been noted. Boone (1966), for example, found that the second-formant frequency tended to be lower for deaf than for hearing children, a fact which he attributed to the tongue being too far back toward the pharyngeal wall. (The inappropriate tongue position was also considered by Boone to be responsible for the "cul de sac" resonance that has been ascribed to some deaf speakers.) This observation is consistent with Mangan's (1961) identification of faulty front vowel production as one of the major contributors to the errors that listeners made in transcribing a list of 50 PB words read by deaf speakers.

Angelocci, Kopp and Holbrook (1964) have also focused on formant frequencies in a comparison of the speech of another sample of deaf and hearing children. In this case, the range of mean values of F_1 was much smaller for the deaf than for the hearing children, and the difference between F_0 and F_1 was smaller for the former group. The range of the means of F_2 was also smaller for the deaf children than for those with normal hearing, and the dependence of the frequency and amplitude of F_3 on which vowel was being spoken seemed to differ considerably for the two groups. As we have already noted in the discussion of pitch and intonation, F_0, in contrast to F_1 and F_2, varied more with vowels for the deaf than for the hearing speakers.

Angelocci, et al. present several coordinate plots of F_2 against F_1, showing the scatter of these coordinates for each vowel for both deaf and hearing speakers. What is clear from the plots

is that the degree of overlap among the areas representing different vowels is much greater in the case of the speech samples obtained from the deaf. For the hearing speakers, the easiest and most difficult vowels to identify were, respectively, /i/ (98 %) and /æ/ (48%); /æ/ was frequently misidentified as /ɛ/. The best and worst vowels produced by the deaf speakers were, respectively, /u/ (46%) and /ə̂/ (21%).

Several investigators have claimed that as a rule deaf speakers are better at producing consonant sounds than at producing vowel sounds (Huntington, Harris, Shankweiler, & Sholes, 1968; Joiner, 1922; Jones, 1967; for a counter example, see Nober, 1967). Nevertheless, many difficulties associated with consonant sounds have been noted. Stewart (1969) identifies the production of fricatives and affricates as one difficulty and points out that /s/ and its voiced cognate /z/ are often omitted altogether, particularly from the final syllable position. Other investigators have also identified /s/ as a special difficulty (Borrild, 1968; Brehm, 1922; Nober, 1967), as well as the failure to distinguish between /s/ and /š/ (shoe). This is perhaps not surprising inasmuch as most of the energy of the /s/ sound is concentrated at the high end of the frequency range, where the hearing deficit of many hearing-impaired individuals, particularly those with sensorineural loss, tends to be most severe. (Apparently, even people with close-to-normal low-frequency hearing may have difficulty producing good sibilants if they have severe hearing loss above about 1 kHz [Miller, 1968] or speech difficulties not related to hearing [Irwin, 1966].) Also, the articulatory gestures involved in producing /s/ and /š/ are relatively invisible.

Failure to distinguish between voiced and voiceless consonants is another problem that has been noted (Calvert, 1961, 1962; Mangan, 1961; Smith, 1973). One form of this problem is the "surd-sonant

error" (Calvert, 1962, 1964; Mangan, 1961) in which intended voiced plosives are perceived as voiceless plosives, or the reverse. Calvert (1962) measured the durations of closure and release periods of consonants and found that when a plosive was intended to be unvoiced (e.g., p, t) and was heard as voiced (e.g., b, d), the duration of the release period was about the same as that of the voiced consonant when produced by a hearing speaker. Similarly, when a voiced consonant was intended and its unvoiced cognate was perceived, the measured duration of the release period was appropriate to the perceived form. Another form of the voice-voiceless problem is continuous phonation, a defect which, according to Millin (1971), is observed in a "sizeable segment" of the hearing-impaired population and contributes significantly to reducing the intelligibility of the speech. Millin notes that the fact that the phonation is continuous is not necessarily perceived immediately; listeners are more likely to be aware of severe misarticulation of phonemes as a result of it, but not of the underlying continuous phonation itself.

Another articulatory difficulty that has been observed is the omission of arresting and releasing consonants (Hudgins & Numbers, 1942). In particular, Stewart (1969) has noted as problems both the introduction of intrusive stop elements into the pronunciation of fricatives and the omission of stop elements when they should be there. The pronunciation of sheep as cheap is an example of the first type of problem, and the pronunciation of chair as share is an example of the second. He notes that intrusive stop elements can give the speech a somewhat "clipped" quality if they occur frequently enough.

There is some evidence from electromyographic data that the articulatory behavior of deaf speakers is more nearly like that of

hearing speakers with respect to lip movements than with respect
to tongue movements (Huntington, Harris, Shankweiler, & Sholes,
1968), and, consequently, labial consonants produced by the deaf
tend to be more intelligible than lingual consonants and vowels.
This could be due either to the greater visibility of lip movements,
or to the possibly greater inherent complexity of tongue gestures;
however, Huntington et al. concluded against attributing the dif-
ference to the greater difficulty of tongue movements on the
grounds that a similar greater intelligibility of labial sounds
was not found for hearing individuals who had speech difficulties
stemming from central nervous-system disorders. The importance of
the relative visibility of articulatory gestures in determining the
ease with which the deaf learn to produce specific sounds is further
suggested by Guttman, Levitt, and Bellefleur's (1970) finding of a
positive correlation between the quality of a speaker's articulation
and his lipreading ability. In the same vein, Levitt (1974) has
pointed out that the speech production errors that were documented
by Smith (1973) show patterns of confusions among phonemes that
are similar to those found by Erber (1974) in studies of lipreading.

Perhaps the most compelling evidence concerning the importance
of visibility as a determinant of articulatory competence has been
reported by Nober (1967). He found that when consonants, classified
in terms of place of articulation, were rank-ordered in accordance
with the relative frequency with which they were correctly articu-
lated by the 46 deaf children in his study, the resulting order
(from best to worst: bilabial, labiodental, glottal, linguadental,
lingua-alveolar, linguapalatal, linguavelar) was very similar to
the order that would represent relative visibility. (Nober also
reported the following order for articulatory competence in terms
of manner of articulation, again from best to worst: glides, stops,
nasals and fricatives.) That visibility is not the only factor,

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however, is suggested by the fact that several studies of consonant
articulation problems arising from causes other than hearing loss
(retardation, cleft palate) have shown similar trends with respect
to the rank ordering of consonants in terms of how problematic
they appear to be.   Such consistency, Nober notes, is suggestive
of the importance of maturational factors, and of differences in
the inherent difficulty of articulating and of discriminating
different phonemes.

It is important in discussing articulatory problems to dis-
tinguish between the ability to produce appropriate individual
speech sounds in isolation and the ability to combine those sounds
in such a way as to produce fluent speech.   Deaf children often
have the former ability, but not the latter (Borrild, 1968; Jones,
1967).   Difficulties in executing smooth transitions between speech
sounds (e.g., consonant-vowel transitions) (Jones 1967) and
malarticulation of compound and abutting consonants (Hudgins &
Numbers, 1942) are examples of articulation problems that probably
affect fluency detrimentally.   These difficulties may also help
to account for the finding that consonants occurring in initial
sound position tend to be articulated better than those occurring in
medial position, which in turn tend to be better than those in final
position (Nober, 1967).   Durational aberrations in transitional
sounds (Jones, 1967) would be especially detrimental to smoothly
flowing speech, as would many of the timing deficiencies discussed
in the section of this paper dealing with timing problems.

A few investigators have attempted to determine how the
spontaneous development of speech sounds differs between deaf and
hearing children.   Some have suggested that during the first year
of life deaf and hearing children do not differ greatly in their
spontaneous vocalizing and babbling (Carr, 1953).   However, recent

findings have provided evidence of differences in babbling of deaf
and normal-hearing infants as early as 22 weeks (Murai, 1961;
Malvilya,1970 [cited in Menyuk, 1972]). In general, the relatively
"easier" sounds appear to be the more prevalent, e.g., middle as
opposed to extreme front and back vowels, and voiced labial con-
sonants as opposed to unvoiced and lingual consonants (Heider,
Heider, & Sykes, 1941; Neas, 1953 [cited in Carr, 1964]), although
there is some evidence that most of the sounds that occur in
standard English can be found in the spontaneous vocalizations of
deaf children (Sykes, 1940; Carr, 1953; Fort, 1955 [cited in Carr,
1964]). According to Carr (1953), children's speech shows a
greater frequency of vowel sounds than of consonant sounds (see
also Neas, 1953), of front vowels than of back vowels; and, at
least in the case of deaf children, front consonants occur more
frequently than back consonants. In addition, voiced consonants
are more prevalent than their unvoiced cognates. Carr points out
that the differences between the speech sounds of deaf and hearing
children become increasingly more apparent with increasing age, and
suggests that the differences are best characterized by saying that
the spontaneous development of sounds by deaf children does not
continue much beyond one year. He suggests that the higher fre-
quency of front consonants among deaf children may be attributed
to the greater visibility, and, hence, imitatability of the arti-
culatory gestures involved. It is believed that the articulatory
maturation of children with normal hearing is complete by about
the eighth year (Templin, 1957).

2.5 Voice Quality

It seems to be generally agreed that deaf speakers have a
distinctive voice quality (Bodycomb, 1946; Boone, 1966; Calvert,
1962); however, what exactly is meant by voice quality is not
entirely clear. More specifically, the question arises whether

it is more appropriate to think of the speech of the deaf as having
a distinctive voice quality, or as having a variety of qualitative
properties which characterize the speech of different individuals
to different degrees. Unfortunately, data relating perceived
quality to the acoustic properties of speech are sparse, almost
to the point of nonexistence.

The term "quality" is sometimes used in contrast with "intel-
ligibility," the idea being that the quality and intelligibility
of speech may vary somewhat independently. Sometimes the term
also appears to be used to connote steady-state, as opposed to
dynamic, properties of speech. In this sense, hypernasality and
hyponasality might be considered qualitative properties of speech,
whereas rhythm and timing aspects probably would not. Another
example of a steady-state characteristic that could contribute to
qualitative distinctiveness is the "cul de sac" resonance described
by Boone. Still another is breathiness (Hudgins, 1937; Peterson,
1946; Scuri, 1935, reviewed by Hudgins, 1936), a characteristic
that Hudgins attributed, in large measure, to inappropriate
positioning of the vocal cords and poor control of breathing during
speech. In particular, too large a glottal opening may be pro-
duced by failure to close properly the vocal folds: "the result
is a large expenditure of air and a voice of poor quality"
(Hudgins, 1937, p. 345).

This list of problems relating to speech quality could be
extended considerably. Calvert (1962), in fact, was able to find
52 different adjectives that had been used as descriptors of deaf
speech in the literature. When fifteen teachers of the deaf were
asked to select from these 52 words those that they considered to
be the most accurate, the words most often chosen were "tense,"
"flat," "breathy," "harsh," and "throaty."

Calvert (1962) also attempted to determine empirically whether
in fact the speech of the deaf is distinguishable on the basis
of quality from that of speakers with normal hearing. He had
teachers of the deaf attempt to determine by listening whether
recorded speech sounds (vowels and diphthongs in isolation, non-
sense syllables, words, and sentences) had been produced by pro-
foundly deaf speakers, speakers imitating deaf speech, speakers
simulating harsh and breathy voice, or normally-hearing speakers.
Isolated vowels, from which onset and termination characteristics
had been clipped, could not be distinguished as to source; however,
the sources of the sentences were identified with 70% accuracy.
Calvert concluded that deaf voice quality is not identified on the
basis of relative intensity of the fundamental frequency and the
harmonics alone, but on the dynamic factors of speech such as the
transition gestures that change one articulatory position into
another.

Although it is questionable whether inappropriate "loudness"
or "volume" of speech is best thought of as a quality deviation,
it is perhaps as reasonable to mention it here as under any of
the other categories in terms of which this review is organized.
The problem, which has been noted by several investigators
(Carhart, 1970: Martony, 1968; Miller, 1968), may take several
forms: voicing may be too soft, or too loud, or the volume may
vary erratically. Miller (1968) points out that the way in which
the volume of a speaker's voice is affected by hearing loss may
depend on the nature of the impairment. An individual with a
sensorineural loss may tend to speak in an abnormally loud voice
because he does not receive feedback via bone conduction, whereas
an individual with a conductive loss may tend to speak very softly,
because his own voice, which he may hear via bone conduction, may
appear very loud as compared with the speech of persons with whom

he is talking. Carhart (1970) advocates that deaf people be
trained to talk at each of four or five general levels of loudness,
and to shift from one to the other, depending on kinesthetic cues
and reactions from listeners to judge the appropriateness of the
level at which they are talking at any given time.

How important voice quality is for intelligibility is really
not known. One can find a variety of views on this issue in the
literature. Peterson (1946), for example, considers voice quality
to be relatively unimportant as a determinant of intelligibility.
Adams (1914), on the other hand, points out that while it may have
little effect on intelligibility in a technical sense, it can play
a very important role in determining whether what a deaf speaker
is saying will in fact be understood by an unfamiliar listener.
She claims that people who are unfamiliar with the deaf may find
their speech so disagreeable when they first encounter it that,
even if it is quite adequate for effective communication, the
listener may not make the effort necessary to understand it.

2.6   Interrelatedness of Problems

As has already been noted, the topical organization of the
foregoing discussion of problems encountered in the speech of the
deaf was used as a writing convenience, and, while it is not an
unreasonable organization, there are doubtlessly others that would
serve as well. It is important to emphasize, however, that any
problem taxonomy has an element of arbitrariness about it. And
the impression that any taxonomy can create that the subject is
really partionable into several independent classes is, in this
case, certainly false. The problems that have been discussed under
separate headings interrelate in many ways.

The importance of accurate timing at the phonetic level for correct articulation is intuitively apparent, for example, as is the necessity for accurate velar control.

Calvert (1962) makes the point that the types of durational distortions that impair the intelligibility of the speech of the deaf (e.g., extension of unstressed vowels, fricatives and closure periods of plosive consonants) may also contribute to perceived speech quality. He notes that deaf speakers are more easily distinguished from speakers with normal hearing, the greater the articulatory complexity of the utterance, and concludes that distortions in phoneme durations may be significant determinants of what is commonly called "deaf voice."

Hudgins (1934, 1936, 1937, 1946) has extensively documented the interrelationship between the problem of inappropriate control of breathing during speech and that of poor timing and rhythm.

Peterson (1946) speaks of the lack of pitch variation as one of the three major quality problems in the speech of the deaf. (The other two that he identifies are breathiness and nasality.) We have classified lack of pitch variation, or monotone speech, as a pitch control problem, but it clearly could easily be discussed under the topic of speech quality. Furthermore, the inappropriate laryngeal posture that seems to be a concomitant of breathy voice quality undoubtedly has an influence on the control of laryngeal muscles that produce changes in pitch.

Colton and Cooker (1968) have suggested that the perception of nasality may be influenced by such factors as articulatory errors, pitch variations and slower than normal tempo.

While conceptually distinct, the problems of volume control
and pitch control are probably closely related in practice. There
is some indication that a deaf child has difficulty gaining sepa-
rate control over volume and pitch: often he tends to increase
vocal effort when trying to increase pitch (Phillips, Remillard, Bass,
& Pronovost, 1968).

That pitch, volume and timing are intimately interdependent
as determiners of stress patterns is well known, but exactly how
they relate is not. In some cases a change of emphasis might be
indicated by a change in any one of these properties. In other
cases, however, changes probably have to occur together. It is
evident, for example, that a vowel that must carry a falling
pitch contour must be lengthened to accommodate this contour.

The list of factors that interrelate could be lengthened;
indeed, one might argue persuasively that each of the problems
that has been discussed here is related in some way to each of the
others. But perhaps the point has been made. While an analytical
approach is undoubtedly necessary in order to make the task of
studying deficient speech tractable, a problem-by-problem approach
to training may be bound to yield only limited success. Perhaps
the most distinguishing characteristic of speech is its integrity,
and it may be that training techniques will continue to produce
disappointing results until methods are developed that will provide
a child with an ever-present visual or tactual representation of
his own and other people's speech that is as rich as the repre-
sentation that the hearing person gets by ear. But exactly what
information should be represented in such a display and how that
information should be encoded, are questions that have yet to be
answered. And until they are answered, an analytic approach to
training is probably the only path that is open.

3. TRAINING PHILOSOPHY

We have found it helpful to distinguish four major aspects
of the problem of teaching speech to the deaf:

1. diagnosis of speech deficiencies,
2. establishment of training objectives,
3. specification of training procedures, and
4. evaluation of progress.

While each of these aspects is essential to a well-rounded speech
training program, it will be apparent from what follows that we
consider objective diagnosis to be basic. Given an adequate
diagnostic procedure, much of the rest follows: without such a
procedure it is questionable whether the other desiderata can be
realized at all.

3.1 Diagnosis

In diagnosing a child's speech problems it is not enough to
say that the speech is unintelligible, or that it does not sound
natural. The goal should be to specify as precisely and quanti-
tatively as possible the nature of the speech deficiencies and how
these deficiencies contribute to the lack of intelligibility or
poor quality of the speech. What is needed is a diagnostic profile
that is to speech what the audiogram is to hearing.

Such a profile has yet to be developed. Moreover, the develop-
ment of a diagnostic procedure that produces a demonstrably valid
and reliable assessment of one's level of competence with respect
to the various skills that make for speech proficiency must undoub-
tedly await a fuller understanding of both "normal" and defective
speech. However, until such a procedure is developed, the other
aspects of speech teaching will necessarily be based on less than

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solid ground. Therefore, we make the assumption that even a crude
diagnostic procedure is better than none, provided that (a) its
limitations are recognized and (b) that it is viewed as a point of
departure for the development of more precise and useful techniques.

It seems likely that any diagnostic profile that is to be
reasonably comprehensive must contain information concerning each
of the problem categories that have been discussed in Section 2.
The findings reviewed in that section suggest the following measure-
ments as candidates for a diagnostic profile.

Timing and rhythm
- Speech rate (rate of word, syllable or phone emission).

- Ratio of durations of stressed and nonstressed syllables
  (probably distinguishing stressed syllables in final and
  non-final word and sentence positions)

- Ratio of pause time to speaking time in utterances of
  varying complexity and rhythmic structure

- Relative frequency of pauses in different contexts
  (between sentences, between phrases, within phrases)

- Durations of specific speech sounds (e.g., fricatives,
  closure periods of stop consonants)

- Timing of coarticulation and transition events (e.g.,
  timing of voice onset relative to release of the closure
  period of plosive consonants, onset of nasalization for
  nasal consonants, timing of glide from one vowel sound
  to another in production of diphthongs, transitions
  between fricative or nasal consonants and vowels)

- Rhythm (subjectively judged)

Pitch and intonation
- Average F_0

- Magnitude of F_0 fall (in octaves) after F_0 maximum in final
  stressed vowel in selected declarative sentence(s)

- Magnitude of F_0 rise on sentence-final stressed vowel in selected interrogative sentence(s)

- Magnitude of F_0 rise from initial unstressed vowel to initial stressed vowel in selected sentence(s)

- Variability of F_0 for selected utterance(s)

- Acceptability of intonation pattern on selected sentences (subjectively judged)

Nasalization

- Nasalization level (measured from an accelerometer attached to the nose) while sustaining /m/ sound

- Nasalization level while sustaining each of several vowel sounds

- Peak nasalization levels when saying selected mono-syllables such as ma, pa, no, toe, song, sock

- Nasalization index for selected sentences and phrases (see Section 2.3, and Stevens, Nickerson, Boothroyd, & Rollins [1974] for a definition of this measure)

Articulation

- Spectral differentiation among vowels, especially /a/, /i/, and /u/

  Spectral distinctiveness of fricatives, especially /s/ and /š/

- Differentiation between voiced consonants and their voiced cognates

- Differentiation between nasal consonants and nonnasals whose production depends upon the same place of articulation

- Appropriate production of consonant clusters and blends

- Smoothness of glide from one vowel sound to another in the production of diphthongs

Quality

- Measure of breathiness

- Measures listed under other categories insofar as they relate to speech quality

Missing from this picture are normative data in terms of which
the normalcy or deviance of measures such as these can be determined.
In some cases, norms can be inferred from the literature; in other
cases, they will have to be developed empirically. If a measure-
ment profile can be developed that can be demonstrated to be de-
scriptive of those aspects of speech that are critical to intelli-
gibility and quality, it will undoubtedly be desirable to develop
norms for the material in the diagnostic procedure itself. This
would mean applying the procedure to a large and representative
sample of speakers in order to obtain accurate estimates of the way
in which the various measures are distributed in the general popu-
lation. The magnitude of such an undertaking is sufficiently great,
however, to be justified only after considerable progress has been
made in establishing what the measures should be.

3.2 Training Objectives

The ultimate training objective, of course, is intelligible,
fluent speech. Such an objective is not very helpful to the speech
teacher, however. What is needed are some interim objectives that
satisfy certain criteria, among which are the following:

Assessability. Interim objectives must be defined in such a
way that one may determine whether or not they have been attained
at any particular time. To the extent possible, they should be
quantitative. Ideally, they should be expressed in terms of the
properties and measurements that comprise the diagnostic profile.
Examples of assessable objectives relating to the diagnostic
measurements listed above would include: modifying average F_0 to
bring it within a specified range, increasing the ratio of durations
of stressed and unstressed syllables, increasing syllable emission
rate, increasing the amount of pitch fall on sentence-final syllables,
improving quantitative measures that relate to adequacy of velar
control.

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Feasibility. Interim objectives should be realistic in the
sense that there is a reasonable expectation of achieving them.
This implies the need for graded objectives that are applicable at
different stages of speech proficiency. It also reinforces the
notion that an effective diagnostic procedure is the sine qua non
of a comprehensive training program. What is a feasible training
objective for one individual may be unrealizable for another. And
the determination of what is feasible and what is not must be made
in the light of an accurate assessment of an individual's current
level of speech proficiency and his specific difficulties.

Validity. Interim objectives should be such that achievement
of them does in fact facilitate realization of the long-term goal
of improving speech intelligibility and quality. It is important
to recognize, however, that achievement of any particular interim
objective will not necessarily, in and of itself, improve intel-
ligibility or quality. It could diminish either or both. Improve-
ment of overall rhythm could, for example, have the immediate effect
of degrading articulation and thereby decreasing intelligibility.
However, working toward an interim goal in such a case might still
be justified providing that it is clear that the long-range gains
more than offset the short-term impairment. How one makes that
determination in any particular case, given the current level of
understanding of speech production and recognition, is not apparent.
However, the existence of a widely used diagnostic profile could
itself help considerably to develop the data necessary to solve
the problem. If one had a large set of speech samples, each of
which had been assessed with respect to intelligibility and overall
quality, and for each of which a diagnostic profile had been ob-
tained, one could begin to determine the relative importance of
various deficiencies as determinants of intelligibility and
quality.

These comments with regard to training objectives must apply
not only to specific vocal exercises and utterances that are
rehearsed and produced in a training situation. Appropriate
objectives must be formulated to encourage carryover of the skills
learned in the tutorial sessions to spontaneous speech. In fact,
it frequently happens that certain specific speech skills can be
acquired rather rapidly in the tutorial sessions, but the carryover
of these skills to everyday speech is a long and difficult process.

3.3 Training Procedures

Training procedures should be designed to reduce the distance
between where one is and where one would like to be. It seems
fairly apparent that such procedures cannot be developed, or at
least not tailored to the needs of individual students, with any
assurance of efficacy in the absence of adequate diagnostic data
and concrete training objectives. This is not to suggest that the
specification of individualized training procedures should be a
trivial task, given acceptable solutions to the diagnosis and
training-objective problems, but rather to suggest that it is
probably an impossible task if these other problems are not at
least partially solved.

In Section 4 of this report we present numerous examples of
how the displays that the system can generate can be used in training.
In particular, many suggestions are made concerning exercises that
may be used in an effort to realize specific objectives. It is
important, of course, that these suggestions be applied in ways
that are consistent with an individual child's diagnosis and the
particular training objectives that have been established for him.

3.4   Evaluation of Progress

The fourth problem, like the third, is greatly diminished by the existence of acceptable solutions to the first two. To the extent that training objectives are expressable in quantitative form, progress vis-a-vis these objectives can be assessed in terms of specific quantitative measurements. Progress in a more global sense can be evaluated in terms of changes in the overall speech diagnostic profile. It would, of course, be necessary to establish norms with respect to the various measurements comprising the profile and such norms would have to reflect different speech characteristics that are found in different groups of speakers. For example, one would want to express pitch norms in terms of age and sex. Given the establishment of such norms, an ultimate goal of training vis-a-vis objectively measurable aspects of speech would be to produce speech for which the values of the parameters represented on the profile would fall within the appropriate normative range with respect to all measurements.

In this section we have been discussing philosophy, and attempting to articulate a point of view concerning speech training. This point of view recognizes four major aspects of the speech-training problem: diagnosis, training objectives, training procedures, and performance evaluation. We recognize the danger of oversimplification in any conceptual scheme of this sort. And we certainly do not wish to suggest by this particular conceptualization that we believe speech training can really be reduced to a by-the-numbers approach. We do, however, want to insist that each of the four factors mentioned is, or should be, an important aspect of speech training, to argue that an effort to develop a program that incorporates each of those aspects explicitly and in an integrated way should be made, and, finally, to suggest that diagnosis is in some sense the fundamental problem.

4. USE OF DISPLAYS FOR SPEECH DIAGNOSIS AND TRAINING

The purpose of this section is to discuss and illustrate ways
in which some of the displays that have been implemented on the
BBN system can be used to facilitate diagnosis of an individual
child's speech problems and to help provide training aimed at
remediation. The discussion here is limited to displays that are
implemented on the system as it currently exists. There is always
the possibility, of course, of adding to the system's capabilities,
and, in particular, of programming new displays for either diagnostic
or training purposes as needs for such additions are identified.

The section is organized in terms of the problem areas that
were discussed in Section 2. It will be clear, however, that it
is often difficult to maintain the separability of the different
problem areas, both because of the fact that many of the displays
provide information on several aspects of an utterance and also
because of the inherent interrelatedness of the problems on which
we have focused. Thus, while a separate subsection is devoted to
each of the major topics, we do not hesitate to violate this
topical arrangement somewhat when it appears reasonable to do so
in order to make optimal use of the illustrative material that is
presented.

The system itself and the displays that it is capable of
generating have been described elsewhere (Nickerson & Stevens, 1973;
Nickerson, Kalikow, & Stevens, 1974). Details concerning the
mechanics of loading display programs, setting display parameters,
and so forth, may be found in Rollins, Kalikow, and Nickerson (1974).

Finally, we wish to stress that the suggestions in this section
are suggestions only. They are offered as working hypotheses about
how best to proceed, and as points of departure for future research.

4.1 Timing_and_Rhythm .

The diagnosis and training of speech timing and rhythm require
the assessment of the temporal properties of several types of
utterances, ranging from monosyllables through short phrases and
sentences that contain syllables with various patterns of stress.

The first step in the diagnosis of timing problems is to
measure the length of a single-syllable consonant-vowel utterance
produced by the student. The student should be able to limit the
length of the voicing in this syllable to 500 msec. or less, with
a reasonably abrupt rise and fall in loudness. In assessing the
timing for monosyllables and for other more complex utterances, it
is appropriate to select words containing consonants and vowels
that do not present serious articulation problems, i.e., articula-
tion problems that might interfere appreciably with timing.
Examples of time-plot displays for the syllable paw produced with
acceptable duration and loudness contour are shown in Fig. 2.
The solid horizontal line indicates the presence of voicing, and
the contour is a measure of intensity of the signal (with a par-
ticular kind of frequency weighting). This display has been called
the voicing-loudness (VL) display. The kinds of problems that are
likely to be encountered at this stage include: (1) too long a
duration of voicing (Fig. 3), (2) a gradual reduction in amplitude
toward the end of the vowel indicating a possible breathiness in the
vowel offset (Fig. 3a), and (3) too abrupt an onset of loudness of
the vowel, as indicated by a brief peak in loudness at the beginning
of the vowel (Fig. 3c).

The gradual reduction in amplitude at the end of the syllable,
possibly accompanied by a cessation of the voicing line well before
the final drop in loudness (as in Fig. 3a) is often observed when
the utterance is judged to have a breathy termination. Under these
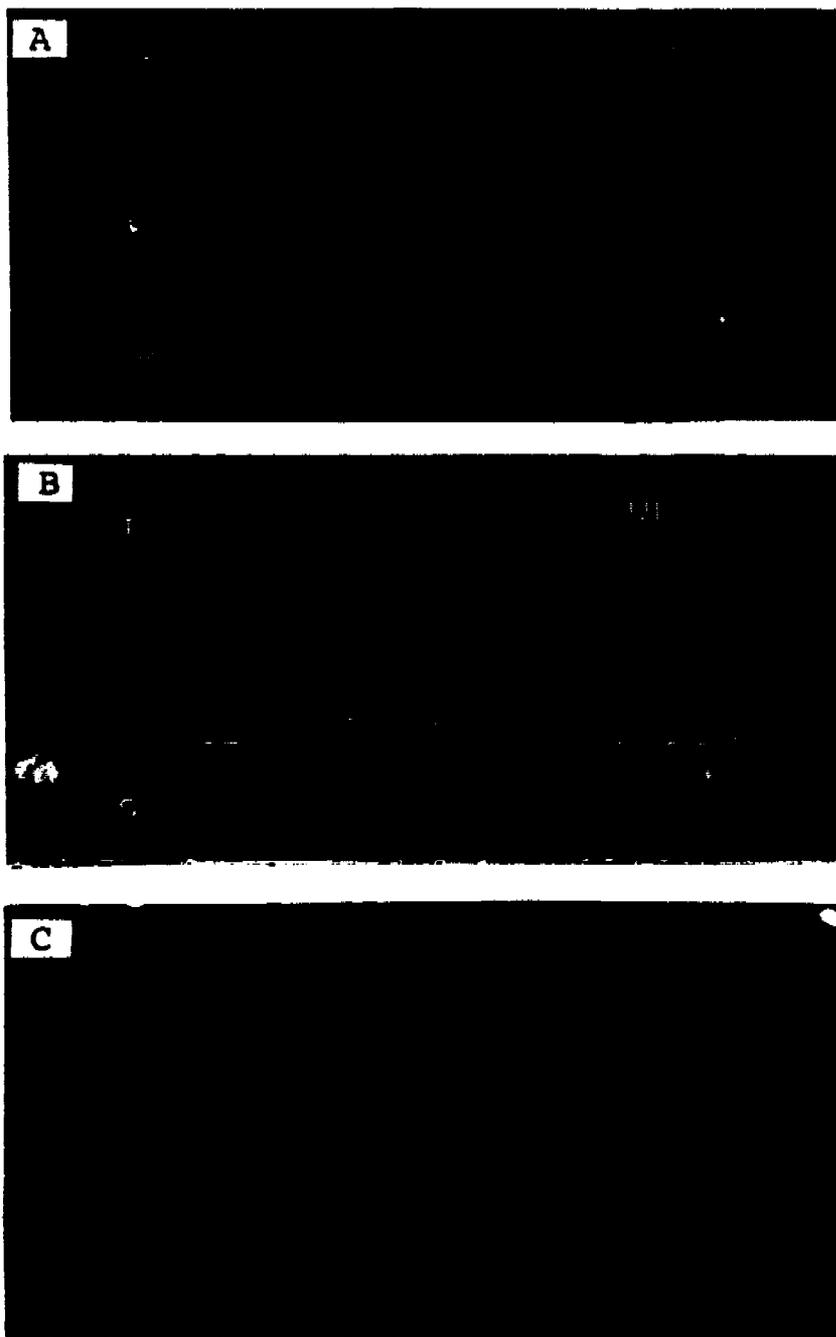
Figure 2. Voicing-loudness (VL) display for the monosyllabic word <u>paw</u> produced in an acceptable fashion by three different normally-hearing speakers. The total width of the display is about 2 sec. in this and in all subsequent time-plot displays.
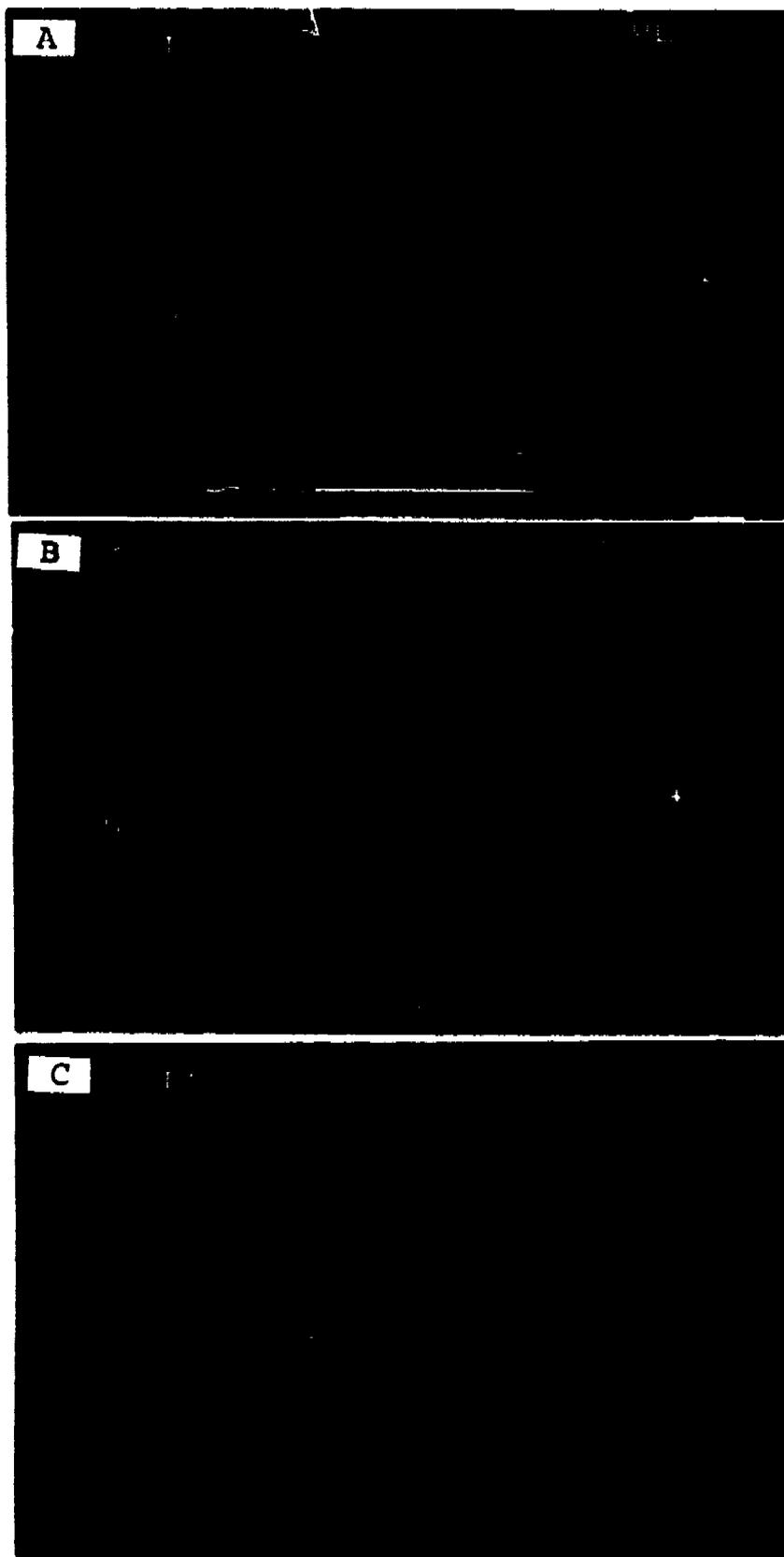
Figure 3. VL display for the monosyllabic word paw produced in an unacceptable way by three different deaf students. See text.

circumstances, the gradual decay is probably a consequence of a
gradual and premature abduction of the vocal cords toward the end
of the syllable--a premature return of the vocal-cord configuration
to a position appropriate for normal breathing. The abduction
maneuver is accompanied by a decreased amplitude of vocal-cord
vibration, an increase in airflow, and an increase in the ampli-
tude of turbulence noise generated at the glottis, resulting in
the impression of breathy voice. Normally-hearing speakers often
produce this kind of aspiration in the final syllable of an utte-
rance, particularly if the syllable is an open syllable (i.e., no
final consonant), but this gesture is much more marked for many
deaf speakers, and leads to an unnatural sound.

The overly abrupt syllable onset (as in Fig. 3c) is probably
a consequence of too great an effort in producing the initial con-
sonant in the syllable. This increased effort--possibly reflected
in a raised lung pressure--leads to a strong consonantal release,
and a peak in loudness at the vowel onset. The rather "forced"
or "tense" sound that results may in some cases stem from a pre-
occupation with the training of consonant articulation in isolated
monosyllables.

For a student who produces a monosyllable with a time pattern
that is too long or that has an inappropriate decay in loudness,
the emphasis in training should be on forming a proper termination
of the syllable. In the case of an open syllable, the voicing
should be terminated relatively abruptly, avoiding the slow decay
in amplitude noted above.

After monosyllables are assessed, the next step in the diagnosis
is to examine the timing of simple two-syllable utterances with a

reduction in stress for either the first or the second vowel.
Timing can be measured more easily with these two-syllable utter-
ances if the consonant (or consonants) that separates the two
syllabic nuclei is voiceless, since a break in voicing can then
be observed, and the relative durations of the voiced portions of
the two syllables can be determined. If there is no break in
voicing, as in an utterance like the man, or sinner, then the
relative durations of the syllables must be evaluated from the
positions and durations of the peaks in the loudness contour.

For an utterance with an initial unstress d syllable (such as
a car, the tree), the duration of voicing for the second (stressed)
syllable should be 4 to 8 times the duration for the unstressed
syllable (Nickerson, Stevens, Boothroyd, & Rollins, 1974). Examples
of normal variation are given in Fig. 4. Usually the amplitude of
the unstressed syllable (as indicated by the loudness contour)
should be less than that of the stressed syllable. (There may be
occasions when this amplitude relation does not apply, however,
particularly when the stressed syllable contains a high vowel such
as /i/ or /u/, which has an inherently lower amplitude than a non-high
vowel such as /a/, /e/, /o/.) The VL display for the stressed
vowel in these two-syllable utterances should satisfy the require-
ments indicated above for a monosyllable. It is important to note,
however, that when the same stressed syllable occurs within an
utterance and is not the final syllable before a pause, its duration
should be less than the duration in utterance-final position.

For a two-syllable utterance with stress on the initial syllable
(such as puppy, sister), the temporal pattern is quite different.
Here the duration of voicing in the initial stressed syllable should
be 1/2 to 3 times the duration of voicing in the unstressed syllable.
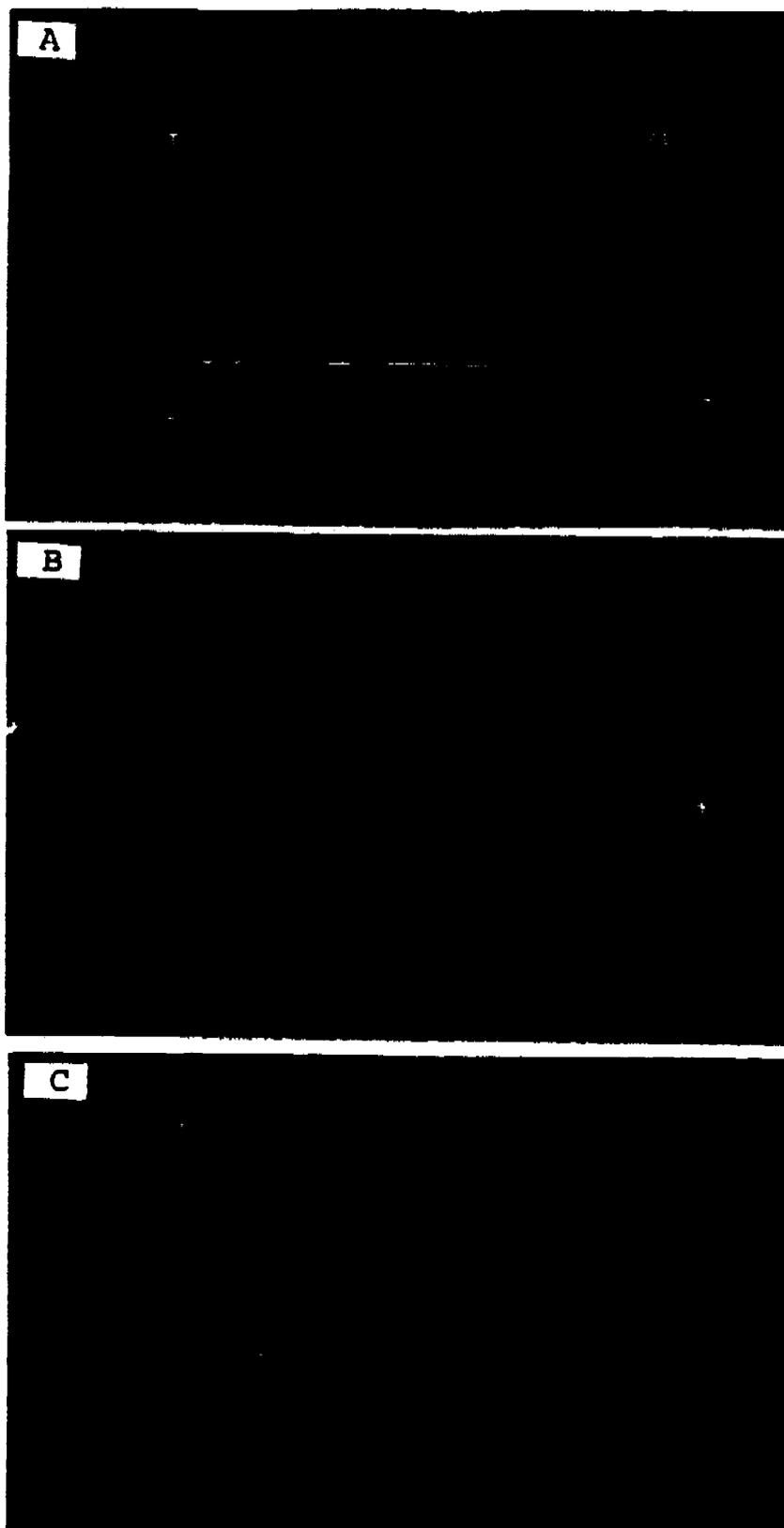Furthermore, both the stressed and the unstressed syllables should be

Figure 4. VL display for the utterance <u>a car</u> produced by three different normally-hearing speakers. The final stressed syllable is much longer than the initial unstressed syllable.

shorter than a single monosyllable. The amplitude of the stressed
syllable (as indicated by the loudness contour) should usually be
greater than that of the unstressed syllable. Examples of the
normal timing pattern for the word puppy are shown in Fig. 5.

It is common for deaf students to tend to put equal stress on
both syllables of these two-syllable utterances. Thus, the un-
stressed syllables are usually not sufficiently shortened relative
to the stressed syllables. Examples are shown in Fig. 6 for final
stress and Fig. 7 for initial stress. Another error that is fre-
quently made is to insert too long a pause between the two syllables,
as in Figs. 6b and 7a. Work with the students should be aimed at
correcting these two problems. Figure 7c is another example
illustrating the gradual drop in loudness in the final syllable,
leading to a breathy termination. The utterances with final stress
should be regarded in some sense as monosyllabic words with a brief
initial syllable appended, rather than a concatenation of two
syllables that have equal status. An utterance with initial stress
should have about the same total duration as a monosyllable, but
it is separated into two parts by one or more consonants.

If a student is having difficulty in producing these two-
syllable temporal patterns, it may be convenient to practice with
nonsense utterances such as pa pá, or pá pa, so that problems with
articulation do not stand in the way of achieving the appropriate
timing. When the proper rhythm is mastered with this nonsense
material, then these patterns should be practiced with meaningful
two-syllable sequences involving a variety of vowels and consonants.
The student should be encouraged to maintain reasonable vowel and
consonant articulation while producing acceptable timing patterns.

The diagnosis and training of timing for longer utterances
involves concepts similar to those introduced in moving from
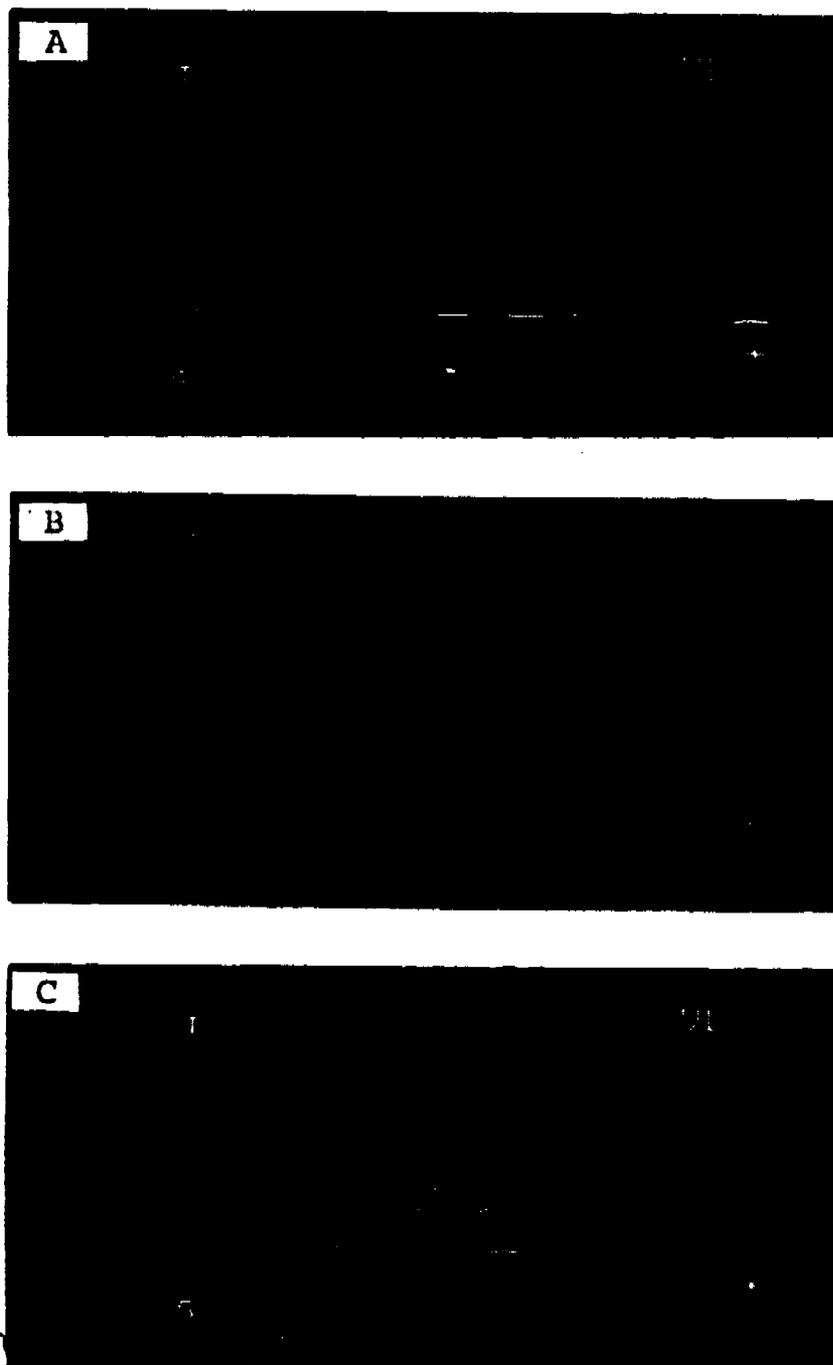
Figure 5.   VL display for the word _puppy_ produced by three
            different normally-hearing speakers. The two
            syllables are comparable in length for these
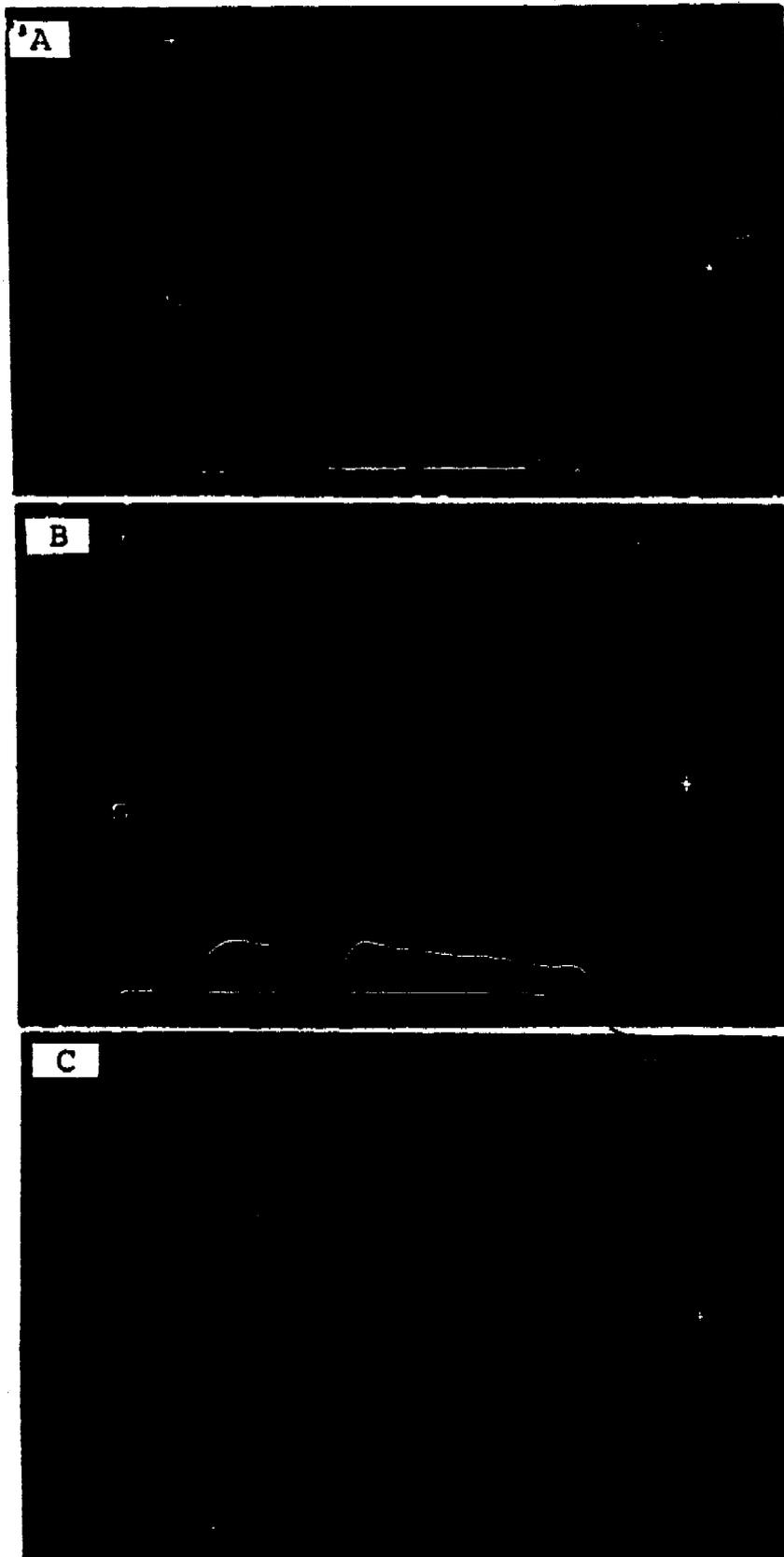   examples.

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Figure 6. VL display for the utterance a car produced in an unacceptable fashion by three different deaf students.
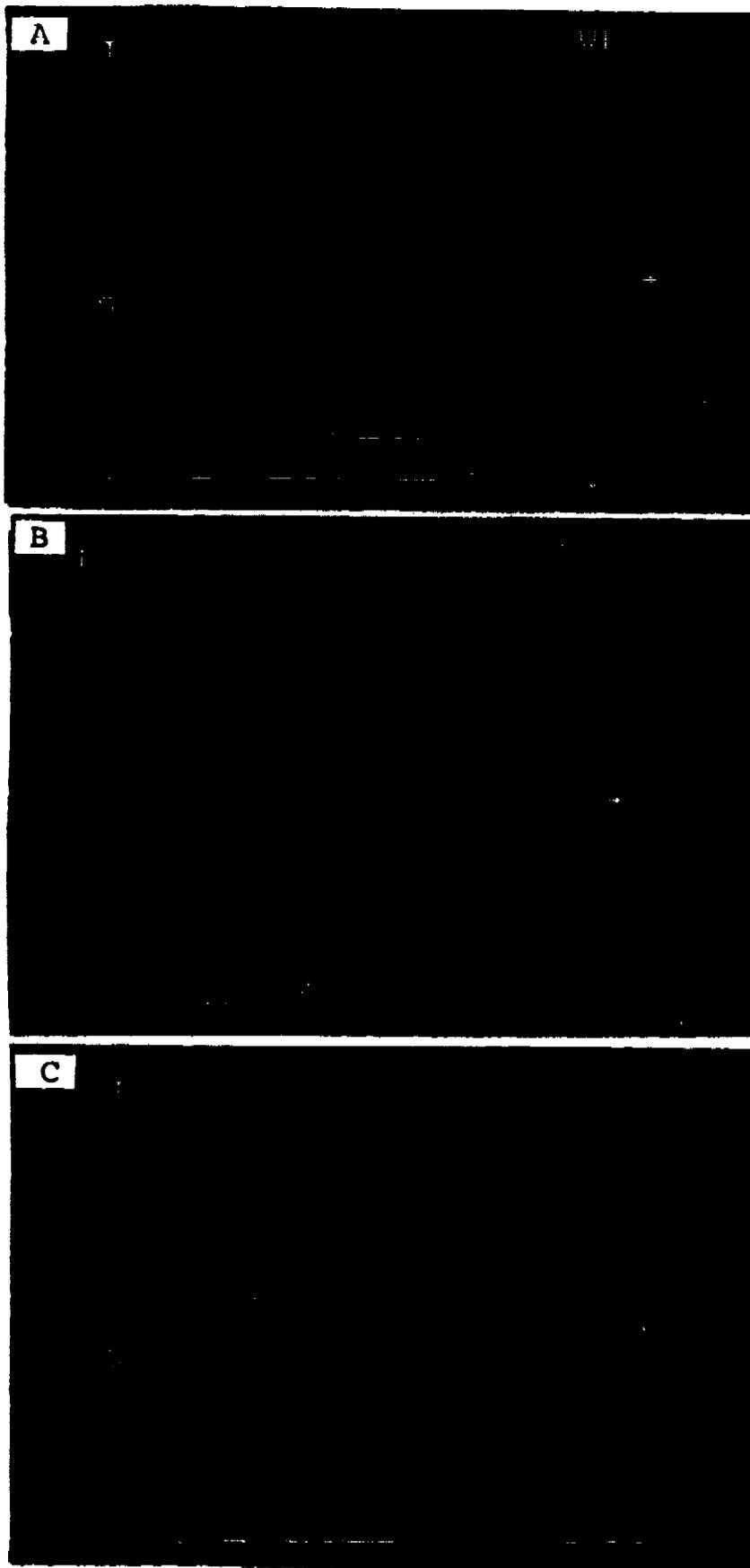
Figure 7. VL display for the word puppy produced in an unacceptable fashion by three different deaf students.

monosyllables to two-syllable utterances. For example, one can
append an additional unstressed syllable at the beginning of the
utterance the park to produce the phrase at the park. The first
syllable should have a duration similar to (perhaps slightly longer
than) that of the second unstressed syllable, and both unstressed
vowels should be considerably shorter than the final stressed vowel.
Examples of the timing pattern for normally-hearing speakers pro-
ducing this phrase are given in Fig. 8. Voicing for the very brief
second syllable sometimes does not register on the display. Again,
the tendency of some deaf students is to produce each syllable with
approximately the same duration, as illustrated in Fig. 9 (especially
Fig. 9c). Training for these students should concentrate on pro-
ducing a shorter syllable in the unstressed position, with an
amplitude that is lower than that of the stressed syllable. Initial
work with these stress patterns may be facilitated by the use of
nonsense utterances such as pa pa pá. Figures 9a and 9b also
illustrate another common problem: the introduction of an inad-
vertent syllable between two abutting consonants, in this case
between at and the.

An example of a different three-syllable stress pattern appears
in Fig. 10, for the phrase the father. In this case, the final
word should have a temporal pattern similar to that of other two-
syllable utterances with initial stress, and the initial unstressed
syllable should be appended in much the same way as before, as
shown in Fig. 10a for a normally-hearing speaker. The utterance
by the deaf student (Fig. 10b) has much too long a final syllable.

As one increases the number of syllables beyond three, the
number of possible patterns greatly increases. The same general
timing principles apply, however, and the diagnosis and training
of timing should focus on these principles. These include: (1)
unstressed syllables should be shortened relative to stressed
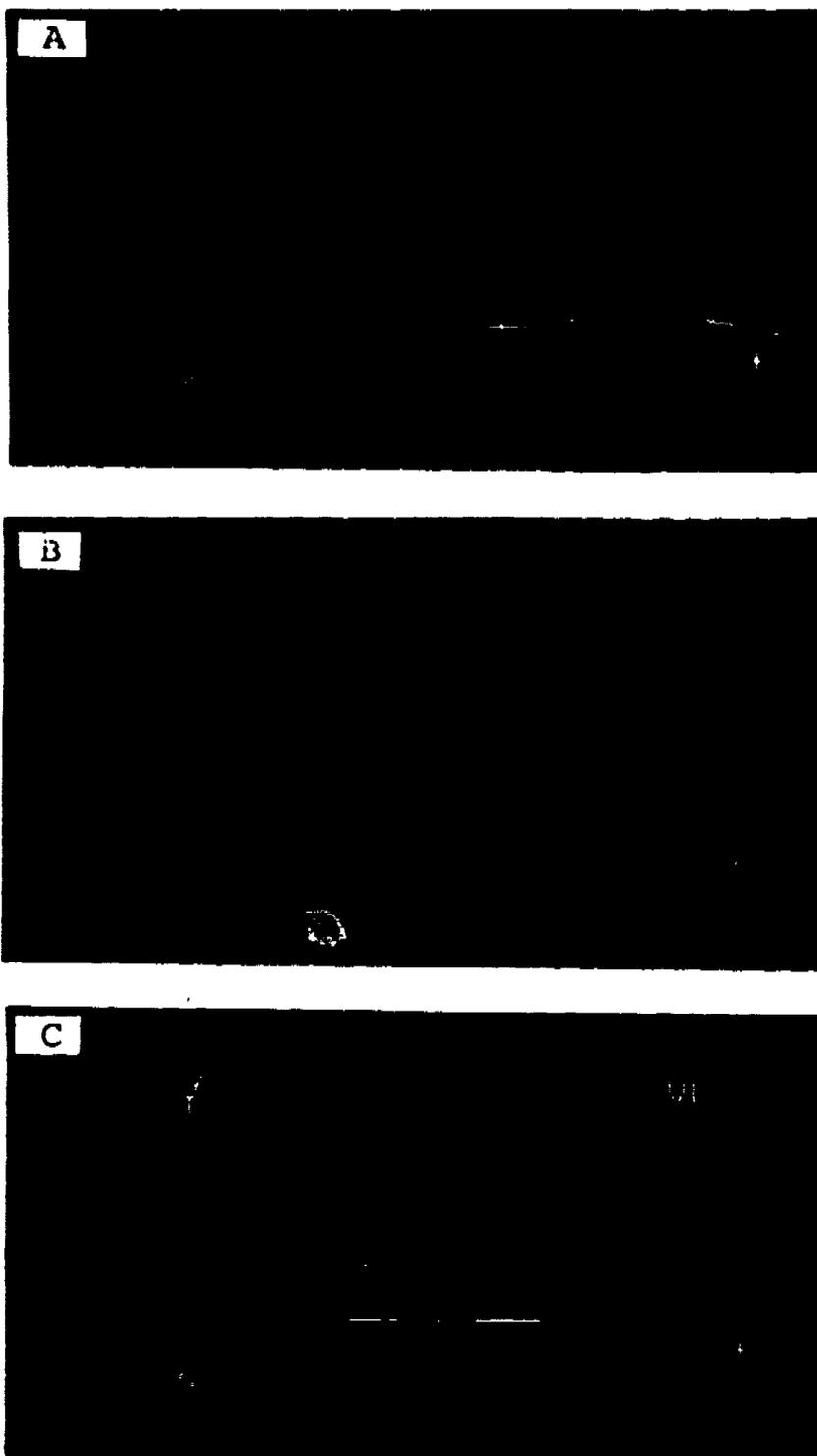
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Figure 8. VL display for the phrase <u>at the park</u> produced by three different normally-hearing speakers.

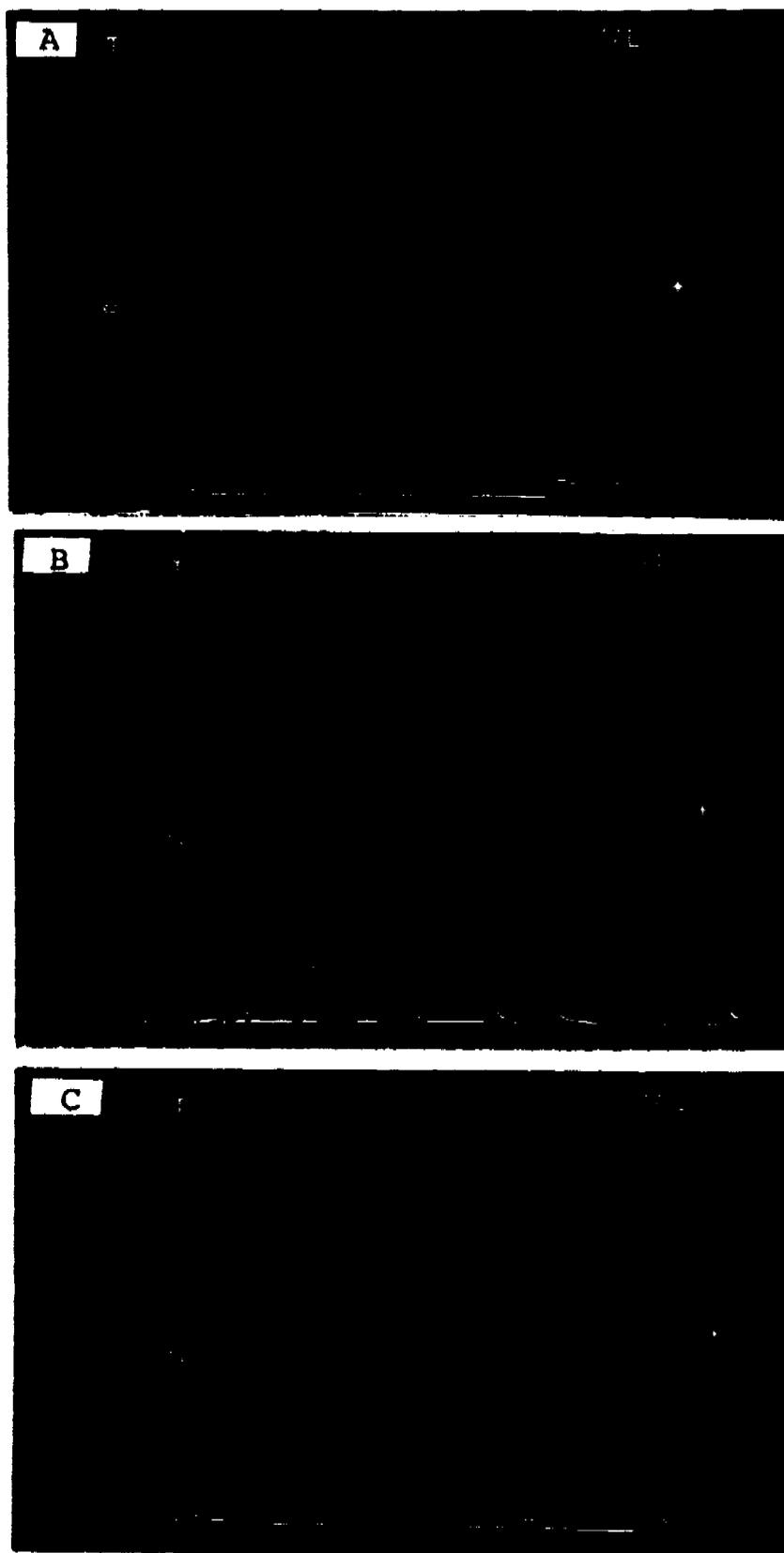**BEST COPY AVAILABLE**

Figure 9.   VL display for the phrase at the park, produced in
             an unacceptable fashion by three different deaf
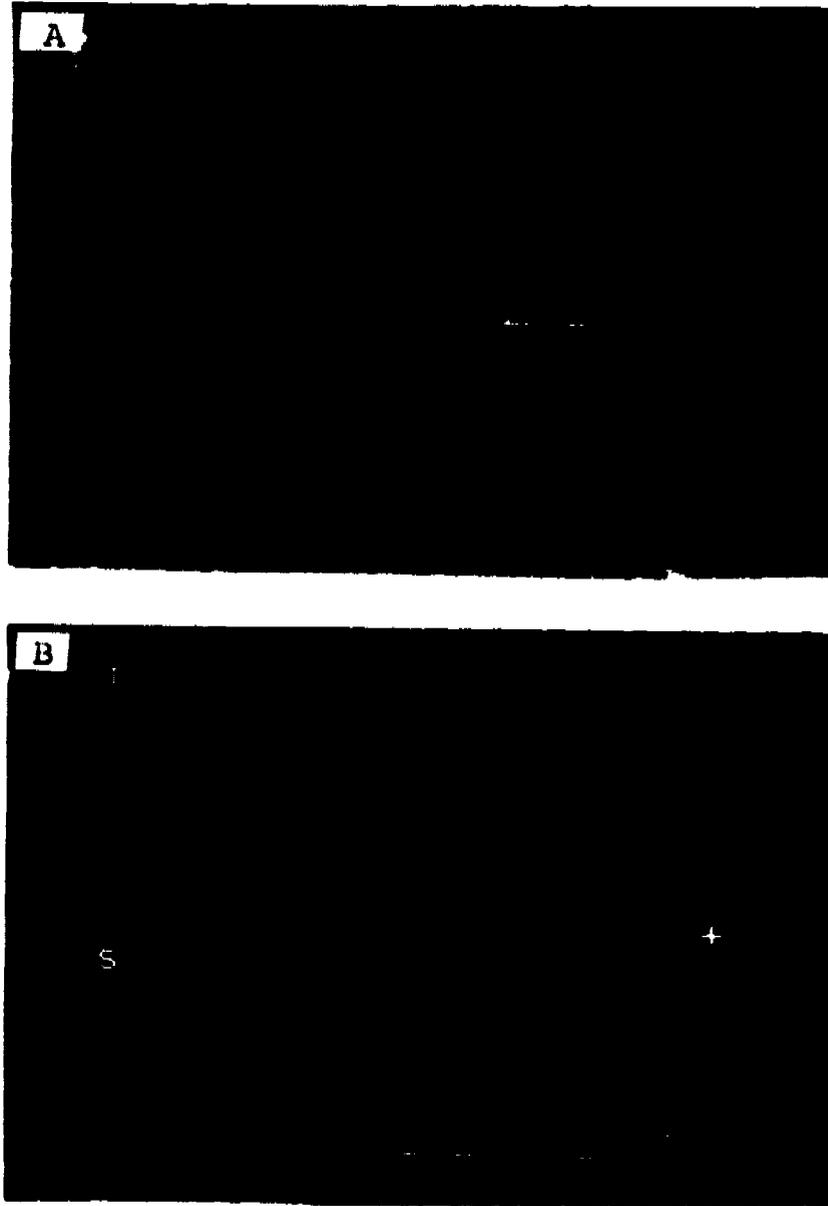   students.

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Figure 10.   VL display for the phrase the father, produced by a
              normally-hearing speaker (top) and produced with
              unacceptable timing by a deaf student (bottom).

syllables; (2) syllables at the end of an utterance, or syllables
occurring before a pause, should be lengthened relative to syllables
that occur within an utterance; (3) inadvertent pauses within a
phrase should be avoided. The second of these rules can result in
an utterance-final unstressed syllable that is comparable in
length to a preceding stressed syllable, as noted earlier. Rules
(2) and (3) introduce the idea of a pause and a phrase. Longer
utterances can be divided into phrases, and these phrases can
(optionally) be separated by pauses. Thus in the sentence "My
sister has a fish," a phrase boundary occurs after sister. The
speaker has the option of inserting a pause at this point, in which
case sister occurs before the pause, and the final syllable is
lengthened. A gap at any other point in the sentence would con-
stitute an inappropriate pause.

The above discussion indicates that the timing of the syllables
in an utterance is closely tied to the stress pattern and to the
syntactic composition of the utterance. The contour of fundamental
frequency (F_0) is also closely related to these aspects of a phrase
or sentence. In fact, it is probable that the timing and the F_0
contour are organized in such a way that the appropriate F_0 contour
can be accommodated within the temporal pattern. Thus the assess-
ment and the training of timing and of pitch control for deaf
students cannot be separated. As a deaf student acquires skill in
producing simple timing patterns, it could be appropriate during
training to switch to a display of pitch, and to train the student
to produce an appropriate pitch contour that is consistent with the
timing objective. Comments on the diagnosis and training of pitch
control are given in the next section.

4.2 Control of Fundamental Frequency (F_0)

The initial step in the assessment of fundamental-frequency (F_0) control for a student is to measure the habitual F_0 and the range of F_0 in a short sentence and in several monosyllabic words containing various vowels and consonants. The pitch display is used, with the accelerometer attached to the throat. The habitual F_0 can be approximated by asking the student to say a phrase or sentence (e.g., "My name..."), and obtaining an estimate of the average F_0 by setting the horizontal line on the time-plot display so that it is straddled by the pitch contour. The range is obtained by finding the maximum and minimum F_0 within the sentence. The habitual F_0 should be compared with the range of average F_0 values found for normally-hearing children in the same age range, as shown in Fig. 1. If the average F_0 for the student deviates appreciably from the normal range, consideration should be given to training that would cause the student to modify his habitual F_0.

The F_0 deviations measured in the manner described should be roughly 2:1 for normally-hearing speakers. If the range is less than about 1.5:1 for a student, some training aimed at broadening the range should be carried out. If the range is significantly greater than 2:1, there is the possibility of inadvertent jumps or other discontinuities in F_0, such as shifts to falsetto or to some other deviant mode of vocal-cord behavior.

At this stage in the diagnosis, the pitch contour should be examined and the student's utterances should be judged for the presence of abnormal jumps or discontinuities in the pitch pattern. Several types of abnormalities are possible. One example (AK), shown in Fig. 11, is a jump in F_0 that occurs within a vowel. In this case, this kind of discontinuity takes place toward the
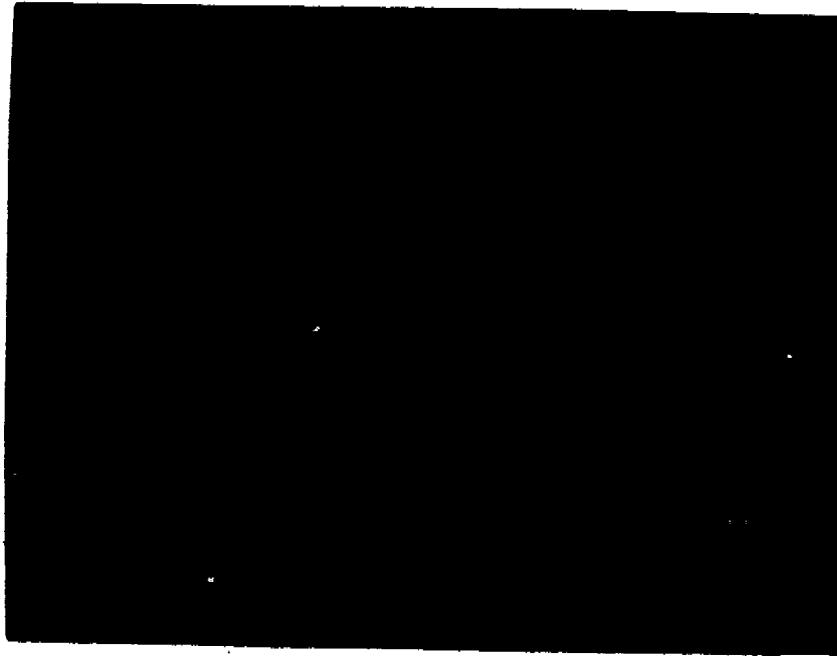
Figure 11.   This photograph shows the presence of a sudden pitch
             rise at the termination of the utterance "Audrey,"
             an abnormality which characterized this student's
             speech.

end of many of the vowels produced by the student. Even though
the discontinuous shift in F_0 is not large, it gives an abnormal
quality to the speech. Another example is a jump to falsetto for
some vowels, but use of F_0 within the normal range for others.
The pitch display has proved effective in the process of training
students to avoid producing these abnormal jumps in pitch.

The pitch contour within a phrase or sentence should have
smooth rises and falls of F_0 on appropriate vowels within the
utterance, depending on the stress pattern and the grammatical
structure. For many utterances, there is some room for variation
in the shape of the contour, depending on the meaning the speaker
is trying to convey. Diagnosis of the ability of the student to
execute these pitch .nges involves assessment at two levels:
(1) Is the student .pable of producing the requisite changes in
F_0 with the proper physiological gestures? (2) If he is capable
of actualizing the F_0 variations, does he insert these changes
at appropriate points within an utterance?

Interpretation of the F_0 contours on the pitch display is
sometimes complicated by the fact that some consonants can produce
shifts or possible irregularities in F_0 at the onset or offset of
an adjacent vowel. Irregularities or "noise" in the contour can
also be observed for some speakers who have a particular kind of
harsh or breathy voice quality. Example of such aberrations can
be seen in contours for both normally-hearing and deaf speakers.
Illustrations of these phenomena are in Fig. 12a (final syllable),
Fig. 12b (final syllable), Fig. 12c (final syllable), Fig. 13b
(artifacts in each syllable, and Fig. 13a (end of first syllable).
If a contour has excessive "noisiness," there could be a problem
with accelerometer attachment or location on the speaker, or the
speaker could have an excessively breathy or harsh voice, rendering

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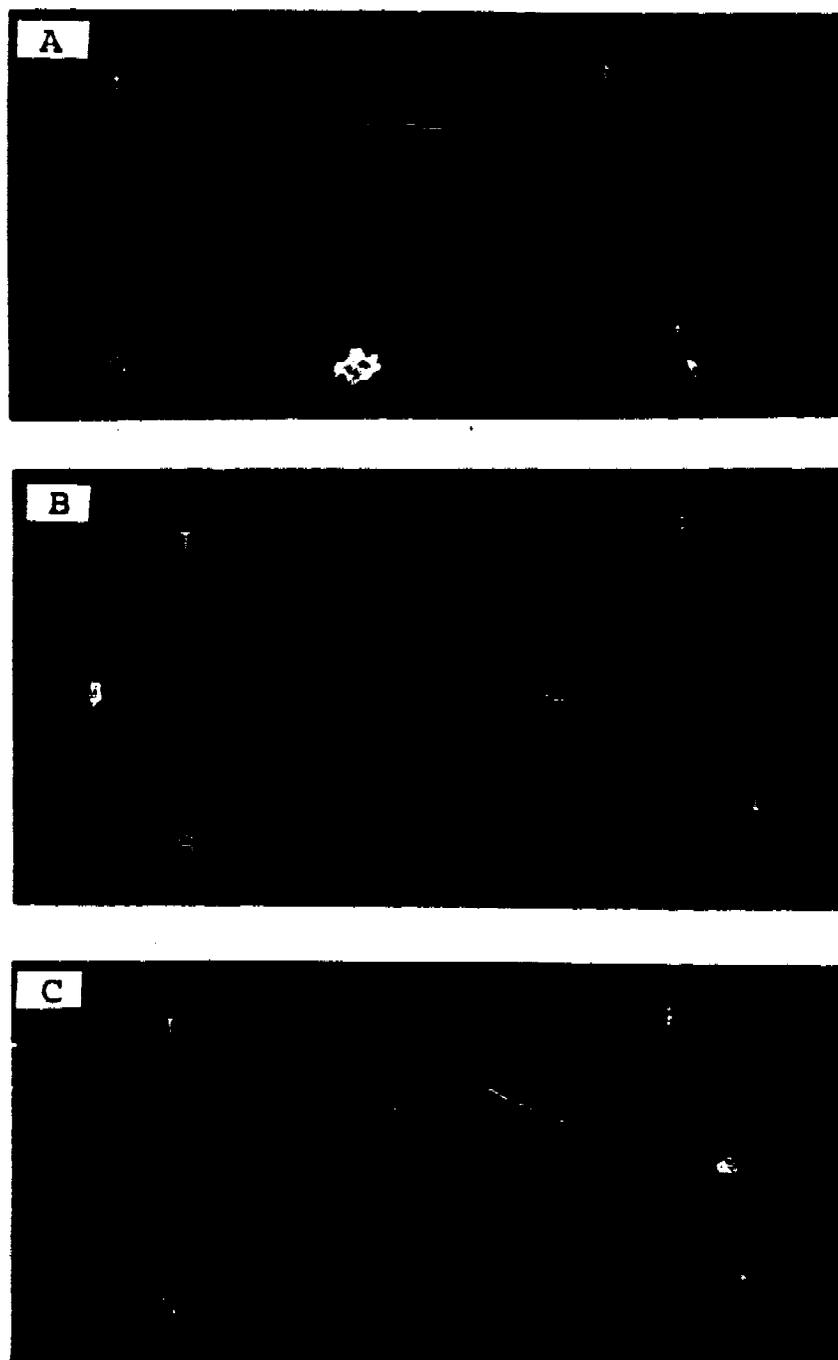

Figure 12. Pitch display for phrases produced by normally-hearing
            speakers. The top and bottom displays represent
            the phrase It's a pie; the middle display represents
            It's a pencil.
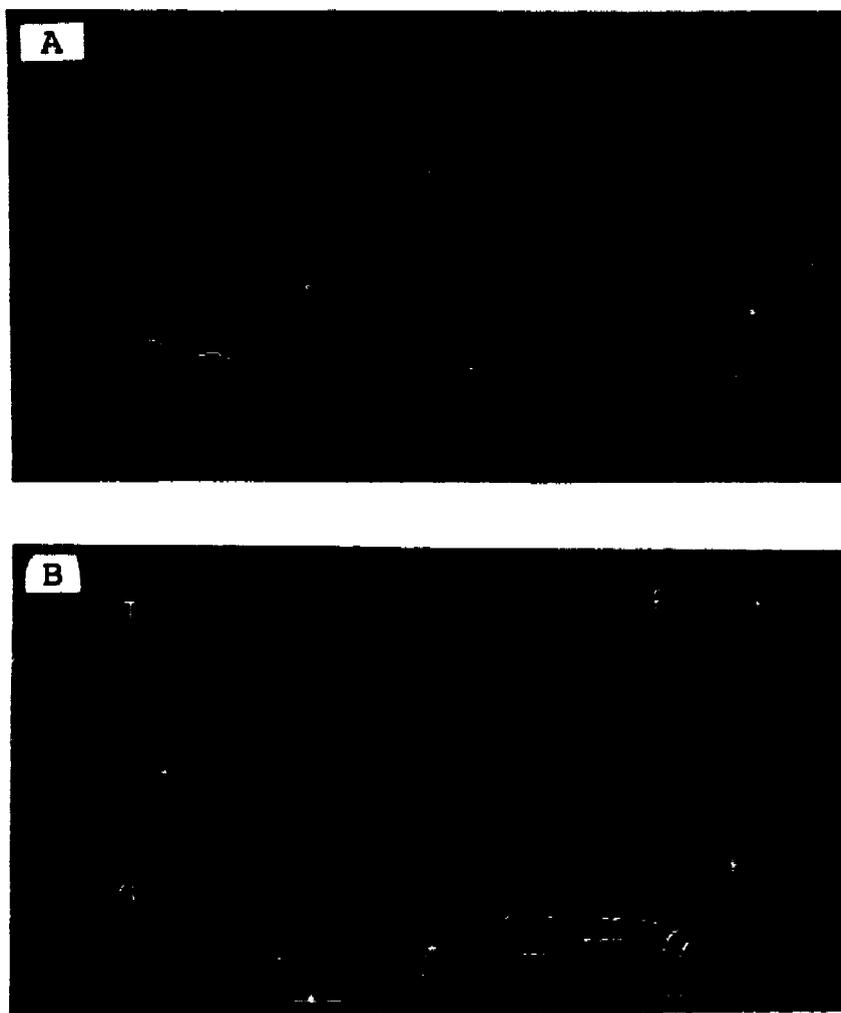
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Figure 13. Examples of pitch displays for utterances produced
            by deaf students with inappropriate pitch contours.
            The phrases are It's a pie (upper) and the paper
            (lower).

the measurement of pitch difficult. In assessing the gross changes
in pitch to be discussed below, local aberrations in the display of
the type just illustrated can usually be ignored.

One of the more basic aspects of a normal pitch contour is the
fall in F_0 that must occur at the end of a sentence. If the final
vowel in the sentence is stressed, the F_0 fall must occur within
the vowel. If the final stressed vowel does not occur at the end
of the sentence, the F_0 fall must occur within the unstressed
vowel or vowels that follow the stressed vowel.

This terminal fall for utterances produced by normally-hearing
speakers is illustrated in Fig. 14. In the phrase "It's a pie,"
the F_0 fall occurs on the final vowel, which, of course, is
lengthened because it occurs before a pause. For each of the
phrases "the paper" and "It's a pencil," the final vowel is un-
stressed, and F_0 on this vowel is lower than on the preceding
stressed vowel. Usually the final F_0 fall begins toward the end of
the stressed vowel and continues through the following unstressed
vowel.

Several kinds of abnormal terminal F_0 contours can be ob-
served in the displays for deaf students in Figs. 15 to 17. One
of the most common difficulties is simply failure to produce a
significant change in F_0 on or following the final stressed syllable.
This problem is illustrated for a final stressed vowel in Figs.
13a, 15a, and 15b, where F_0 remains more or less constant through-
out the final vowel. Figure 13b is an example of a level contour
for a final unstressed vowel.

When the final syllable should be unstressed, some deaf
students inadvertently produce stress on the vowel, Thus, in Fig.
16 there is a terminal fall on the final vowel, but F_0 in the

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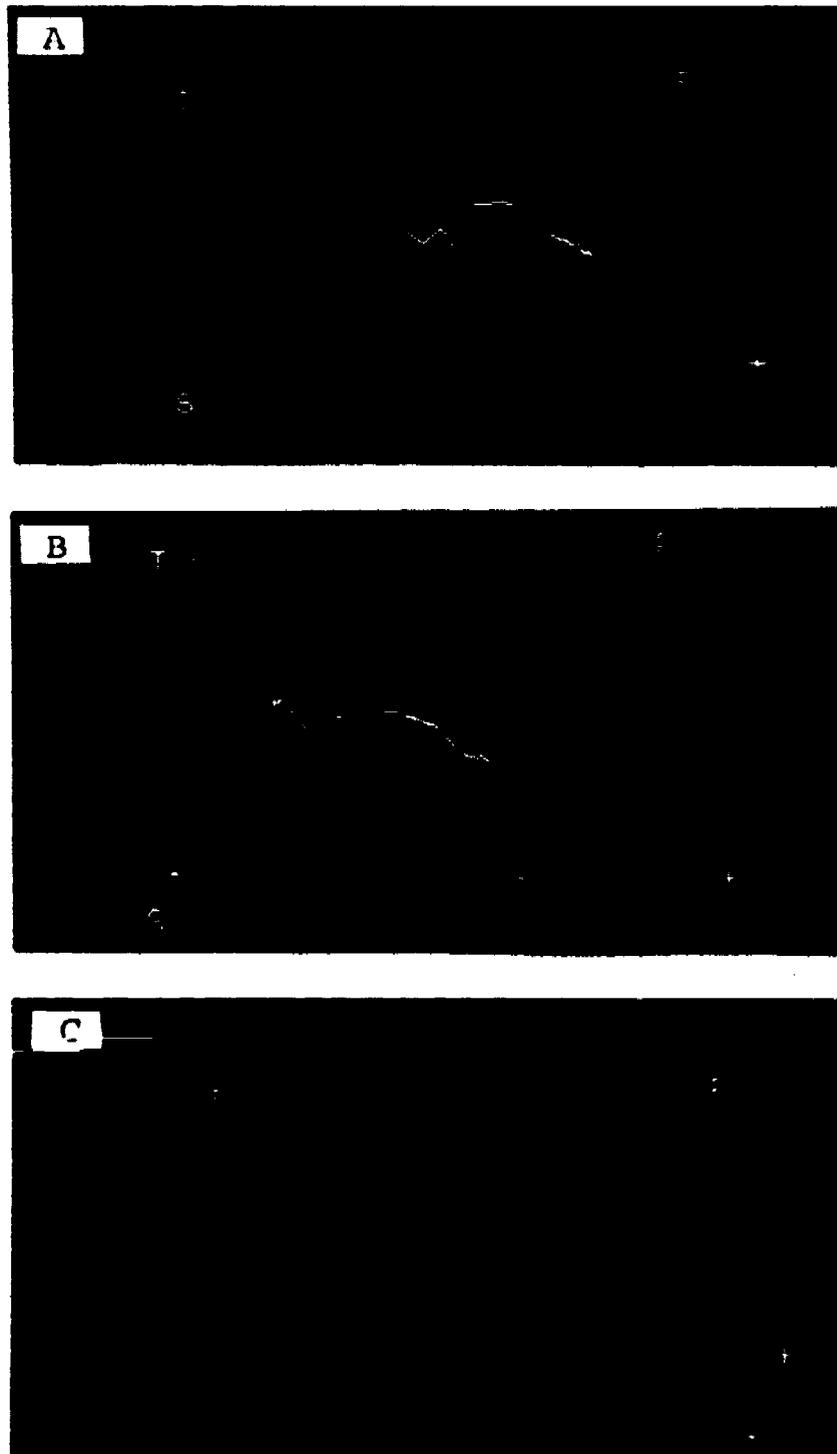

Figure 14.   Pitch displays for normally-hearing individuals
             producing the phrases the paper (top), It's a pie
             (middle), and It's a pencil (bottom). These
             contours illustrate the terminal fall in F_0.
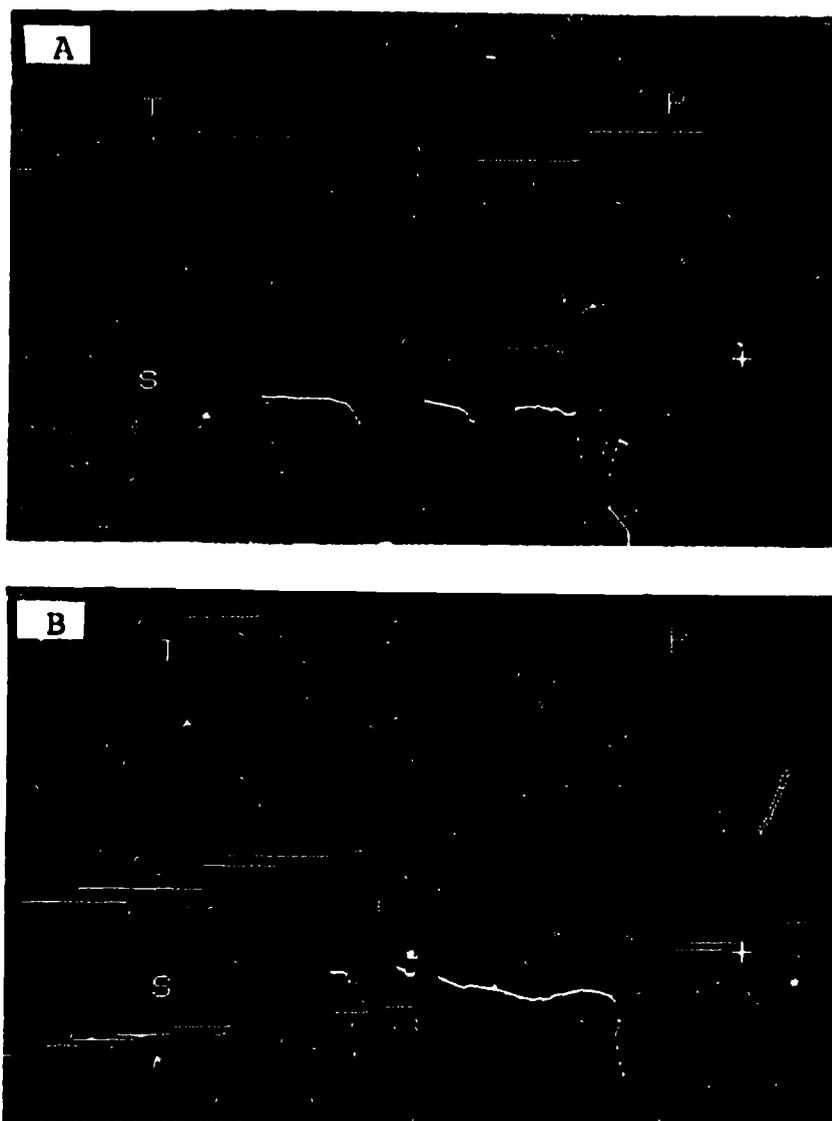
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Figure 15.   Pitch display for the phrase It's a pie, produced
             with unacceptable F_0 contour by two deaf students.

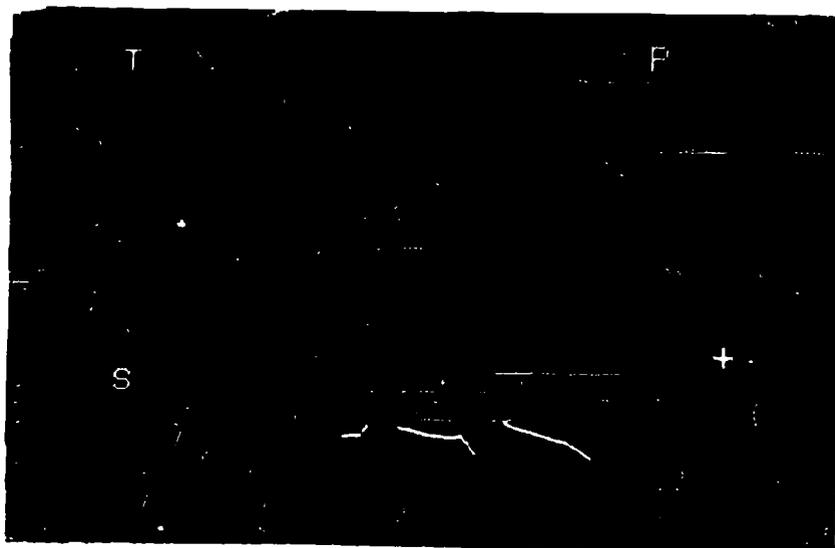**BEST COPY AVAILABLE** ·

Figure 16.   Pitch display for the phrase the paper, produced
              with unacceptable F_0 contour by a deaf student.
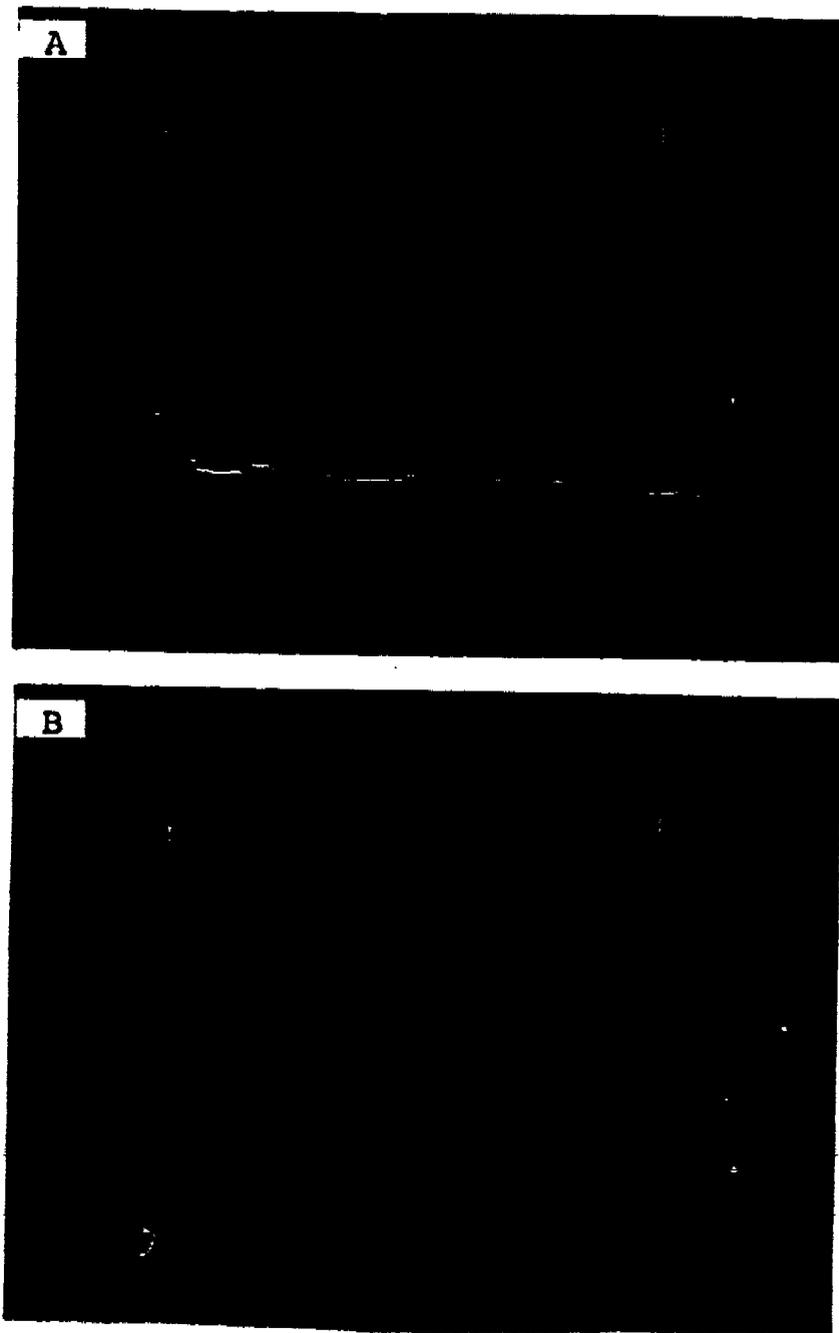
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Figure 17. Pitch display for the phrase It's a pencil, produced with unacceptable F_0 contour by two deaf students.

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vowel begins above F_0 for the previous vowel. In this example, then, the student apparently has the capability of producing a final fall, but begins this fall on the wrong syllable.

Some deaf students tend to produce each syllable with equal stress, and to place the same pitch contour on each syllable. Examples are given in Fig. 17. In Fig. 17b there is an F_0 fall on each syllable, including the final one, and the problem is the lack of a rise in F_0 on any syllable.

Exercises aimed at training a deaf student to produce a terminal F_0 fall should begin with a simple monosyllabic word or with an isolated vowel. The syllable should be generated with a duration of 500 msec. or less and with an F_0 contour that falls throughout the voiced interval. An F_0 fall of at least 40 Hz (for low-pitched voices, i.e., for older boys) to 80 Hz (for higher-pitch voices) should be set as an objective. A contour that is concave downward is most appropriate (e.g., Fig. 14b), but a brief final levelling of the contour is acceptable, as this example shows. Practice in producing this falling contour on a stressed monosyllable should include syllables with various vowels and with different initial and final consonants.

The next logical step in work with a final F_0 fall is to shift to two-syllable utterances with stress on the first syllable (paper, pencil, baby, etc.). For these words, F_0 should be higher on the first syllable than on the second, and there should be a fall on the second vowel, as in Fig. 14a or 14c. The relative durations of the syllables should be in accordance with the rules for timing discussed in Section 4.1.

Probably the next most basic aspect of the F_0 contour for a sentence is the relatively high F_0 that must occur on the first

stressed syllable in a phrase or sentence. If the first stressed
syllable is preceded by one or more unstressed syllables, then F_0
on the unstressed syllables should be lower than that on the
stressed vowel. Examples that show a strong initial F_0 rise of
this kind are shown in Figs. 12b, 12c and 14a. Such utterances
can, however, be produced with a different style, as in Fig. 18a,
where the second unstressed syllable is produced with a raised F_0.
(In this case, however, the high F_0 on this syllable may be a
local influence of the adjacent consonants.)

Speech training aimed at producing a pitch rise from an initial
unstressed syllable to a following stressed syllable should utilize
initially two-syllable utterances of the type papá, a pie, good-bye,
etc. At some point the student should be constrained not only to
produce an initial rise to the stressed vowel but also to generate
an appropriate final pitch fall as discussed above. The fundamental
frequency for the initial unstressed syllable should be greater than
the terminal F_0; the highest F_0 should, of course, occur on the
stressed syllable. Exercises could also include two-syllable words
that are voiced throughout, such as helló, a man, police, etc.
With such utterances, however, it may be difficult to determine
where each syllable occurs from observations of the pitch display
alone. The locations of the syllable peaks can be determined by
switching to the loudness display.

A logical next step in training would be to work with utter-
ances containing more than two syllables, but with only one of the
syllables being stressed. Examples of such utterances have been
given above.

The next stage of complication in the training sequence would
be to work with utterances that require an F_0 fall followed by a
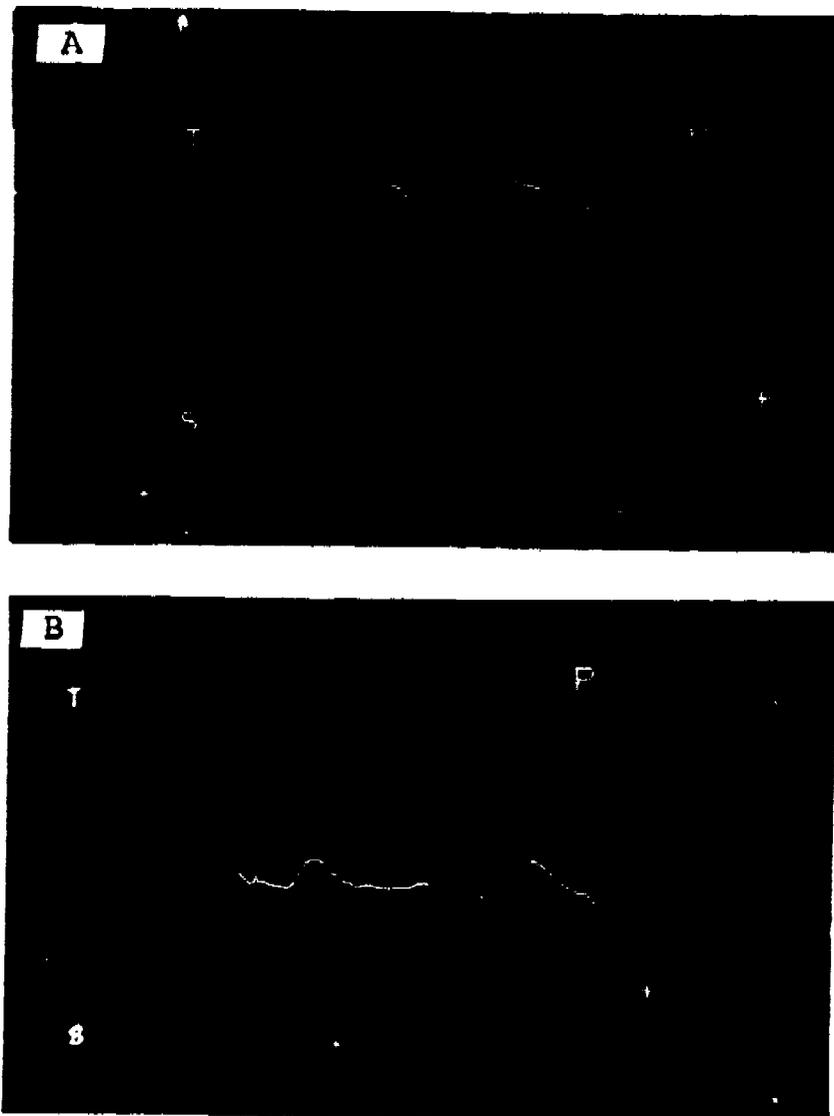
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Figure 18. Examples of pitch displays for normally-hearing
speakers. (A) The phrase is It's a pencil. The
contour shows a rise in F_0 on the second syllable--
a somewhat atypical but acceptable way of producing
the phrase. (B) The sentence is The boy went to
school. The contour shows the rise for the first
stressed syllable (boy), followed by a fall,
followed by a rise for the word school, with a
terminal fall.

rise. Such a sequence of gestures would occur in a sentence with an appropriate syntactic structure containing two stressed syllables separated by one or more unstressed syllables. Examples are: My sister is at home; the boy went to school. In these sentences there is a final F_0 fall on the final stressed syllable, as before, and an initial rise to the first stressed syllable. In addition, most people would produce these sentences with an F_0 fall following the first stressed syllable, an interval of lowered F_0 during the intervening unstressed syllables, and then a rise to the final stressed syllable. An example of such an F_0 pattern is shown in Fig. 18b.

4.3 Velar Control

Diagnosis of the adequacy of velar control consists of assess-ment of the ability of the student to maintain the velum in a raised position for nonnasal vowels and consonants, to lower the velum for nasal consonants, and to exercise appropriately timed dynamic control of the velum during sequences that involve both nasal and nonnasal sounds.

An initial step is to examine the nasality, using the voicing nasality (VN) display, for monosyllabic words. This assessment is accomplished by first obtaining a reading of nasalization on the display when the student is sustaining a nasal consonant such as m at his normal voice effort. This reading should be in the range 200-300 for most individuals. When a nonnasal word is produced, the peak nasalization should be less than the reading for the nasal con-sonant by an amount that depends to some extent on the vowel. Mini-mum difference values that should be achieved for several vowels if they are to have an acceptable degree of nasalization are given in Table 1 (see Stevens, Nickerson, Boothroyd, & Rollins, 1974).

Table 1.   Difference in nasalization reading (VN display) for
           various nonnasal vowels produced in isolated mono-
           syllabic words.   These differences are obtained for
           normally-hearing speakers.

Vowel	Difference in Nasalization Reading*
i	110
a	200
æ	200
u	150

---

*These numbers are in units of approximately 1/10 dB.

There may be some individuals who produce vowels with an acceptable
degree of nasality (as judged by listeners) when the difference
values are somewhat less than those in Table 1. Thus the values
in Table 1 should be used as guidelines that may be modified up
or down as much as 50 units, based on the subjective impression
of the teachers.

In many situations, particularly for low vowels (e.g., /a/
and /æ/), the nasalization reading in a nonnasal word is, in effect,
zero, and the VN display for the word is simply a horizontal line
indicating the voicing interval (as in Fig. 19a). In other cases,
the nasalization trace is visible above the voicing line (Figs. 19b
and 19c), sometimes for only a portion of the vowel. When an open
syllable is produced in utterance-final position, a hearing speaker
often lowers the velum toward the end of the vowel in a sort of
relaxation gesture that terminates a breath group. Thus, a slight
rise in the nasalization reading at the end of a final vowel should
not be regarded as an abnormality that requires correction. An
example is shown in Fig. 19c.

For the examples given in Figs. 20 and 21, the peak nasality
within the word exceeded the criterion given in Table 1 by a sub-
stantial amount. The word pad begins and ends with an obstruent
consonant (a consonant that requires buildup of pressure in the
mouth). Pressure buildup in the mouth requires, of course, a
closed velum. In the examples in Figs. 20 and 21, there is evidence
in the display to indicate that velar closure was achieved during
the consonants, since the nasalization trace was low in the voiced
portions adjacent to the consonants. Shortly after the consonant
release, however, velar opening occurred, and there was excessive
nasalization throughout much of the vowel. These students were ap-
parently able to raise the velum during the consonants, and may have
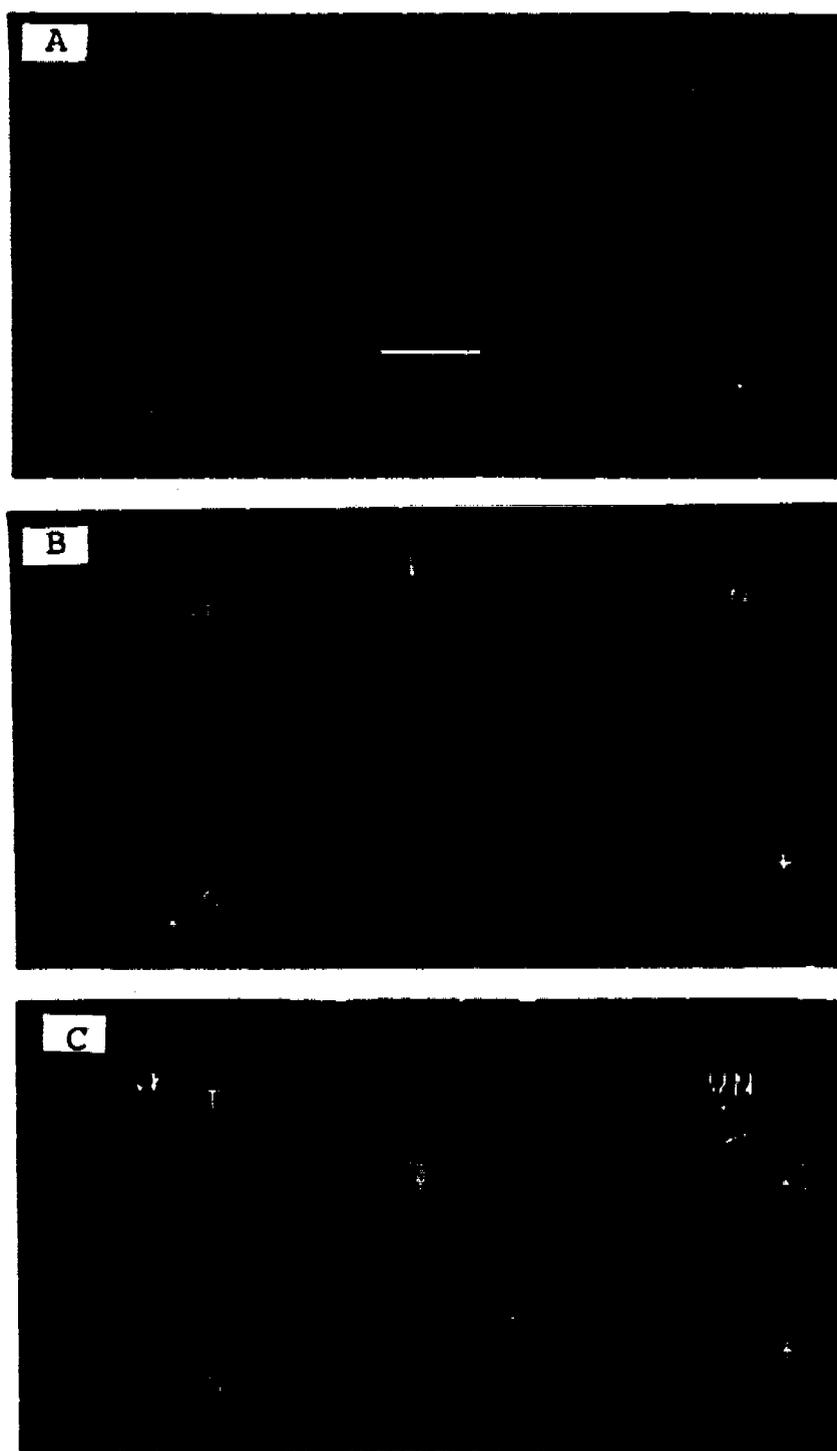managed to maintain a raised velum through forces resulting from

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Figure 19. Voicing-nasalization (VN) display for monosyllabic
words produced with acceptable velar control by
normally-hearing speakers. For the top trace (word pad),
the nasalization trace does not show above the baseline,
whereas for the middle (pad) and bottom (fee) displays,
the nasalization trace can be observed, but it is below
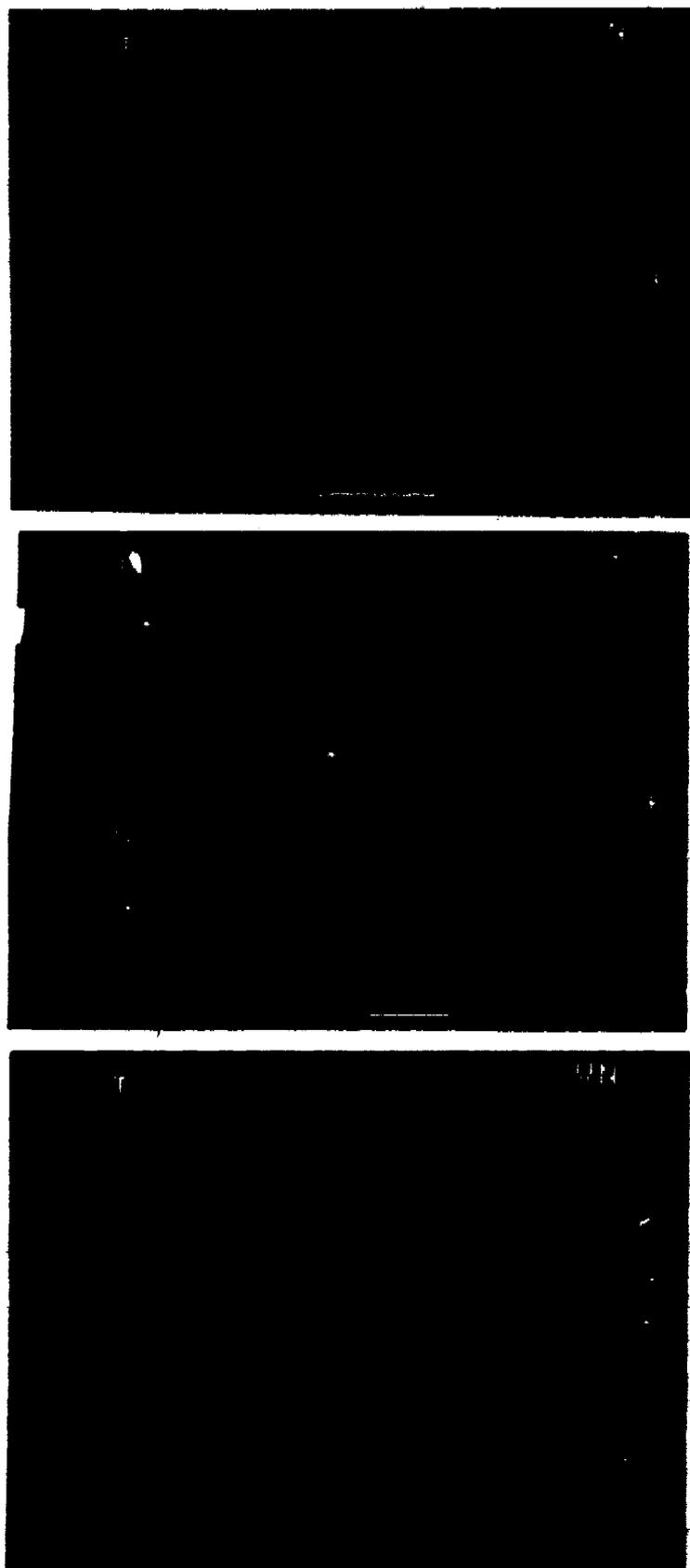the criterion given in Table 1.

Figure 20.   VN display for the word pad, produced with
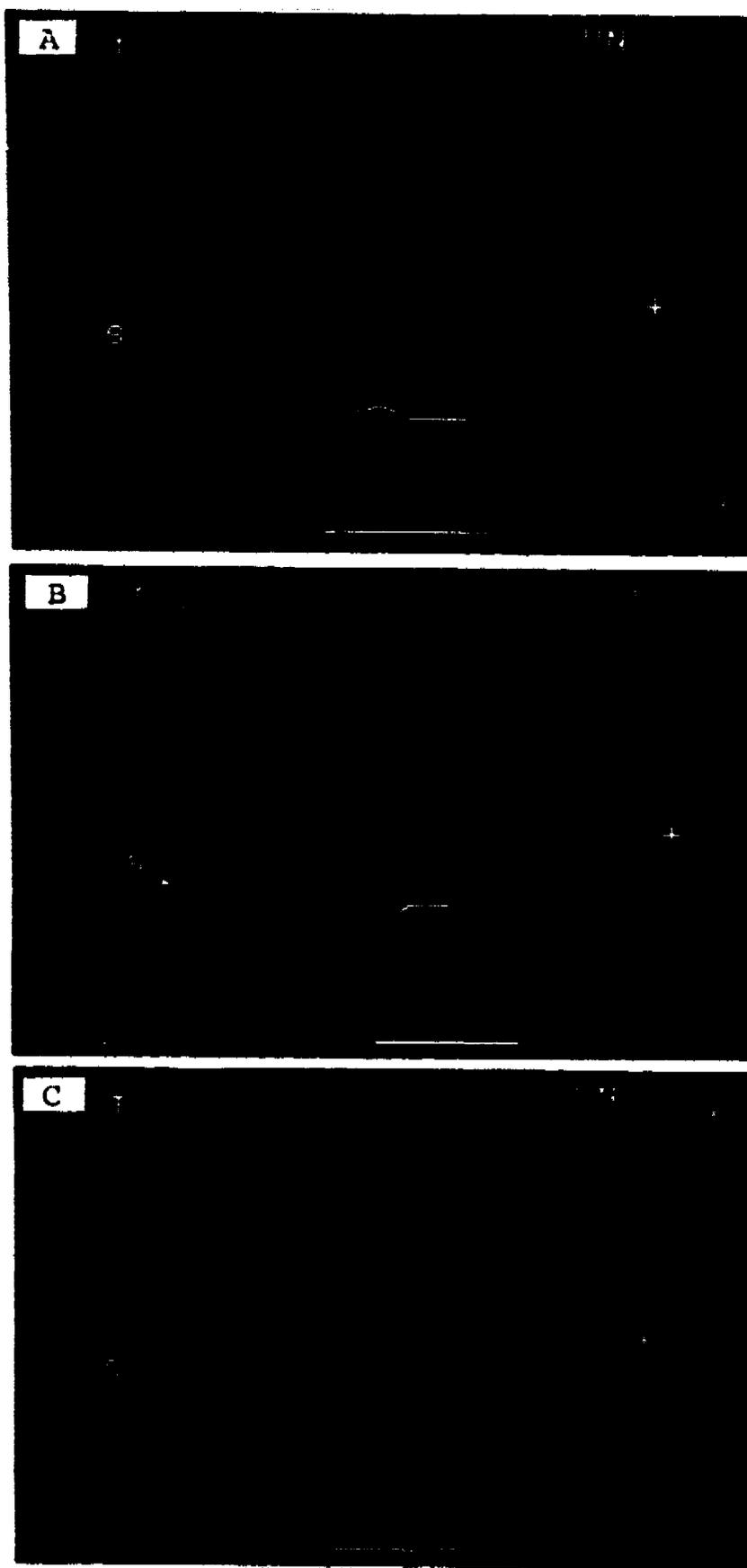unacceptable nasalization by three deaf students.

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Figure 21. VN display for the word _fee_, produced with unacceptable nasalizatic ι by three deaf students.

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the increased pressure in the mouth. A raised velum could not be maintained, however, during the vowel, when there was no increased intraoral pressure.

The initial diagnosis with monosyllabic words should be carried out with words containing several different vowels, such as those listed in Table 1. It frequently happens that deaf students can produce some vowels with an acceptably low degree of nasalization, but not others.

For students who are producing monosyllabic words with excessive nasalization, the initial training should be directed toward achieving control of the velum during vowels. Since the velar position cannot easily be "felt" by the student, some experimentation on the part of the student is needed, with the display operating in real time. Several different strategies can be tried--the strategy that proves to be successful may differ from one student to another.

One strategy is to work initially with isolated vowels, attempting to reduce the nasalization reading during the course of a long vowel of several seconds' duration. Different vowels can be tried. If success is achieved with one vowel, the student should attempt a shift to another vowel while maintaining a closed velum. Goals can be set for the student--a certain number of successes at a particular task being required before proceeding to the next.

Another strategy is to work with monosyllables rather than with sustained vowels. If, for example, the student can raise the velum to produce an initial stop consonant such as p, he should then try to maintain the low nasalization reading throughout the vowel. Exercises with a sequence of syllables such as pa pa pa may be helpful in learning this task.

A next step in the diagnosis of adequacy of velar control is
to examine monosyllabic words containing nasal consonants. The dis-
play for these words should show a substantial peak in nasalization
for the nasal consonant, and usually a lesser degree of nasalization
in the adjacent vowel. It is not necessary for the nasalization
reading in the vowel to satisfy the criteria in Table 1 if the
vowel is adjacent to a nasal consonant.   Some deaf students may
exhibit hyponasality in the utterances containing nasal consonants,
as manifested by low nasalization readings within the consonant.
That is, the nasal consonant is inadvertently produced with a raised
velum, resulting in a stop consonant rather than a nasal. Training
materials designed to aid in the correction of this problem should
consist initially of monosyllables with nasal consonants in initial
position and in final position in the syllable.

The ability of a student to produce velar opening and closing
with acceptable timing should be assessed initially with simple
utterances containing both nasal consonants and obstruents. The
simplest utterances of this type are monosyllabic words such as
nap and Sam. The first of these words requires a lowered velum
at the onset of the word, and the velum must then be raised at some
time during the vowel, in preparation for the final obstruent con-
sonant. A raised velum is, of course, essential if mouth pressure
is to be built up in the final consonant. The second word is
produced with the reverse sequence of gestures: i.e., a raised
velum during the first consonant, and a lowering gesture during
the vowel in preparation for the final nasal consonant. Figure 22a
shows an example of the normal sequence, with initial low nasalization
(immediately following the onset of the vowel), a somewhat nasalized
vowel, and a peak in the nasalization contour for the final consonant.
Some of the deviations from this prototype pattern that might be
expected for normally-hearing listeners are illustrated in Figs.
22b and 22c. In the former case, the peak in nasalization in the

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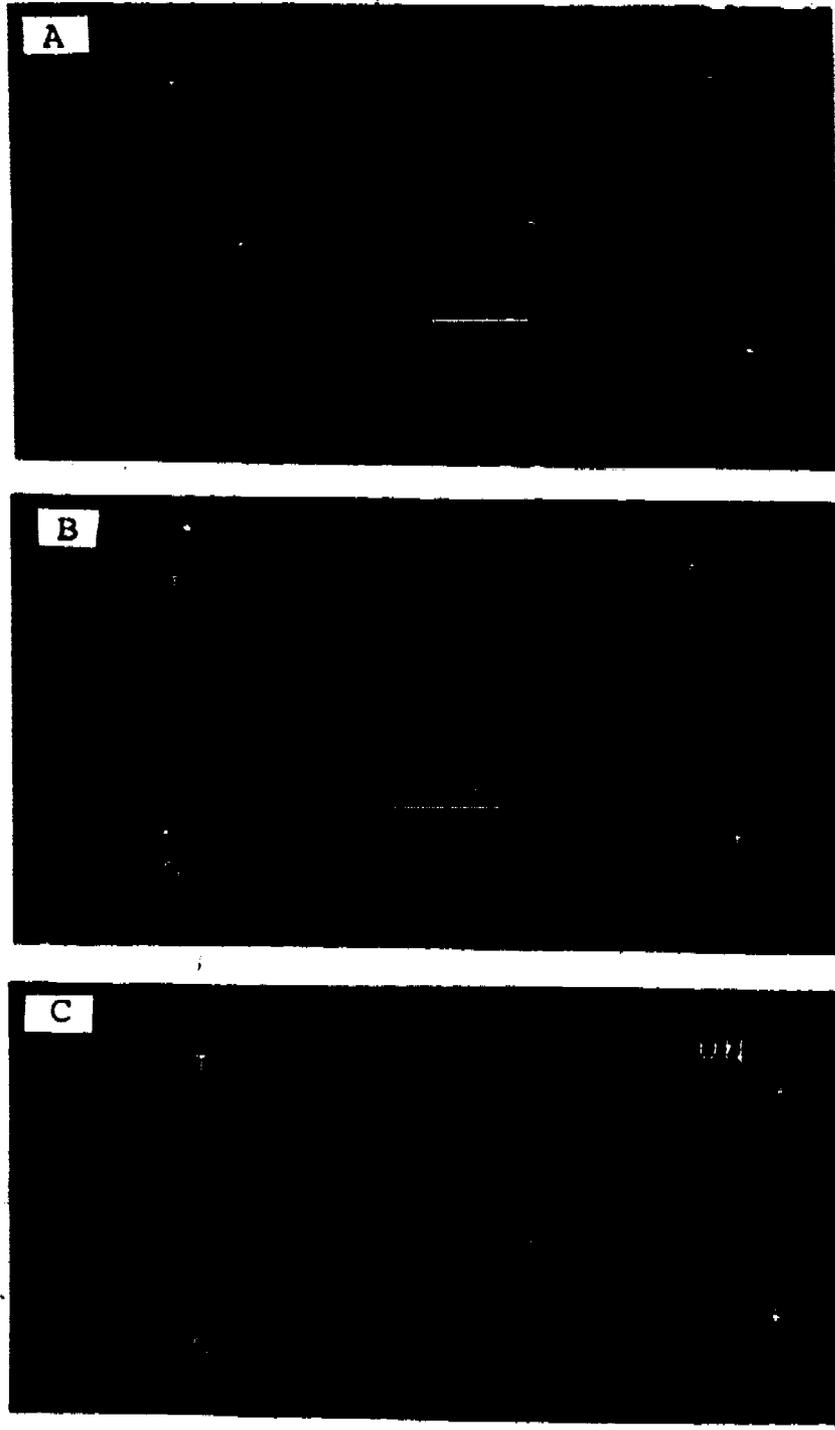

Figure 22. VN display for the word <u>Sam</u>, produced by three
           normally-hearing speakers. The example in (A)
           is most typical of such speakers.

consonant is rather small, indicating that the final consonant was
not fully nasalized. The latter display shows strong nasalization
of the vowel, and an apparent drop in amplitude at the end of the word.
(Note that the /s/ sound should not be visible on the VN display.)

Monosyllabic utterances that involve a more complex sequence
of velar movements consist of words with consonant clusters con-
taining nasals--words such as snap, Smith, drink, jump. In these
words, the velum must undergo a raised-lowered-raised sequence of
movements, since the initial and final consonants are both ostruents.

Control of the velum becomes slightly more complex in two-
syllable words containing both nasals and obstruent consonants.
An example is the word Monday, illustrated in Fig. 23. For the
normally-hearing speakers, nasalization peaks are observed for the
two nasal consonants in the first syllable, and the intervening
vowel is usually produced without velar closure. The velum must
close rapidly in preparation for the stop consonant d, and then
remain closed during the final syllable, as the display in Fig. 23
shows. The deaf students represented in Fig. 24 produced adequate
nasalization in the first syllable, and apparently raised the velum
to produce the stop consonant d. However, there was excessive
nasalization in the final syllable, which should, of course, be
produced with velar closure. In Fig. 25 the student apparently
failed to open the velum in the first syllable--an example of
hyponasality.

For the word Monday, the velum is lowered during the first
syllable, and then must be raised for the second syllable. The
reverse sequence must be produced in words such as happen and
patting. Both types of words should be included in a training
sequence aimed at the development of improved control of the velum.
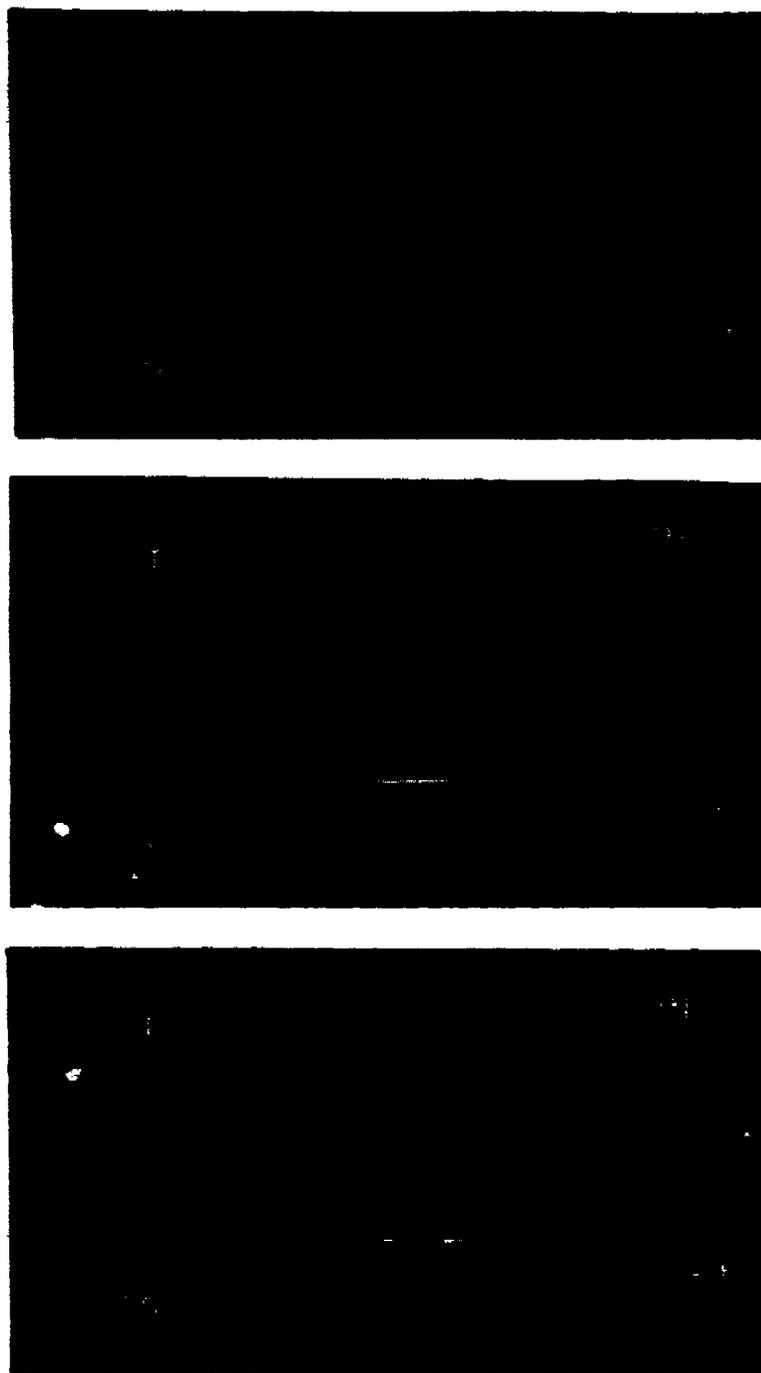
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Figure 23.   VN display for the word <u>Monday</u>, produced by
             three normally-hearing speakers.
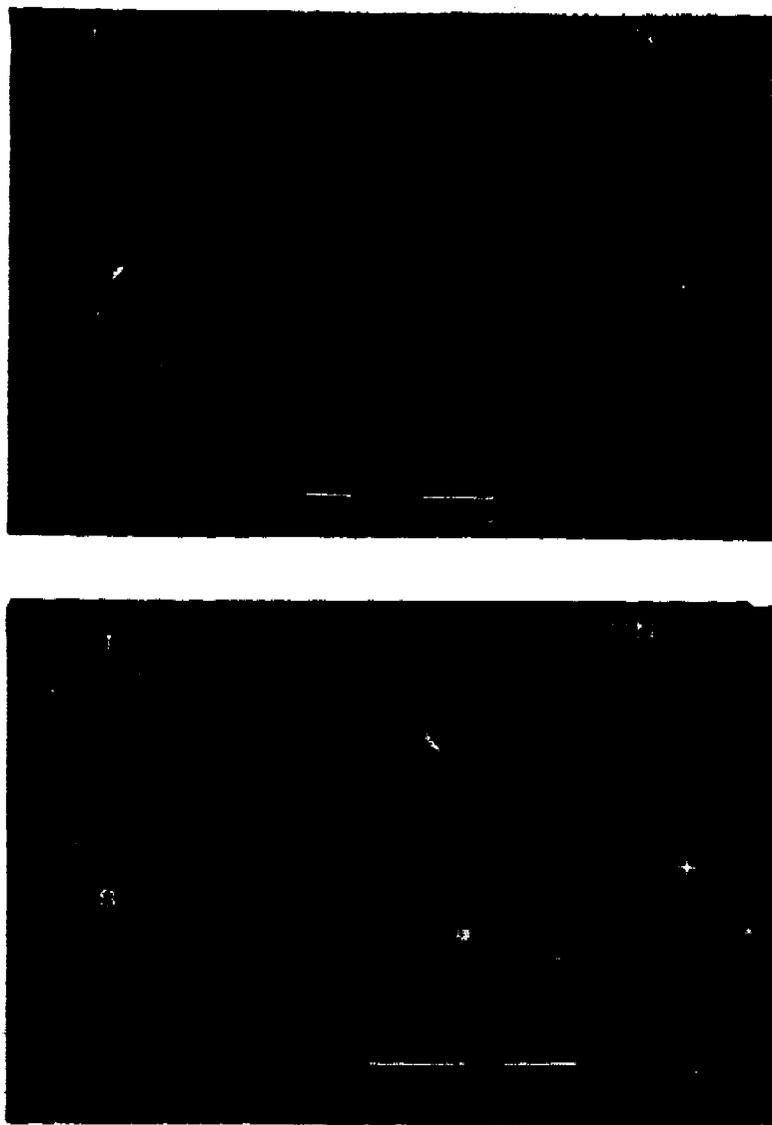
Figure 24.   Examples of VN display for deaf students producing
             the word Monday with excessive nasalization on the
             second syllable.
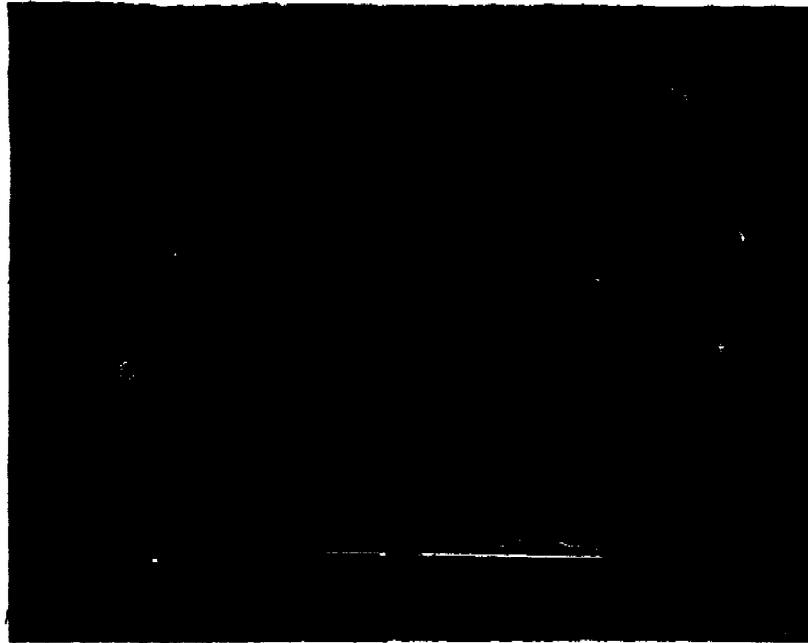
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Figure 25. VN display for a deaf student producing the word
Monday with hyponasality. The velum apparently
remains raised throughout the word.

Diagnosis and training of velar control for longer utterances
should include phrases containing no nasals and phrases containing
mixed nasal and obstruent consonants. Examples are the short
sentences "Be my baby" and "You can drink your milk," for which
displays for normally-hearing speakers are shown in Figs. 26 and 27.
For the first of these sentences, the vowel in the word be is
nasalized because it precedes a nasal consonant, but the two syl-
lables of the last word show no nasalization. The second sentence
(Fig. 27) contains three nasal consonants, and only the first word,
which is separated from a nasal consonant by a stop consonant, is
free of nasalization. The unacceptable samples for the first of
these sentences include cases where the velum remains raised during
the nasal consonant (Fig. 28a) and where nonnasal vowels are inad-
vertently nasalized (Figs. 28b and 28c). Similar examples of
hyponasality and hypernasality can be seen in Fig. 29. In this
sentence, the word you should not be nasalized since it is separated
from the nasal consonants by an obstruent, for which the velum
must be raised. Other vowels, such as the vowel in your, may
become nasalized since the velum is lowered in anticipation of the
nasal consonant in the following word. It is not uncommon for a
given student to denasalize some nasal consonants and to inadver-
tently nasalize some vowels within the same utterance--i.e., the
inability to control the velum with the proper timing results in
both hyponasality and hypernasality. An example is given in Fig.
29a, where the first vowel is inadvertently nasalized, and the /m/
in milk is produced as a stop consonant.

4.4 Articulation

The training of deaf children to achieve improved articulation
involves work with many different types of articulatory gestures.
The displays that have been implemented to date are not sufficiently
versatile to be used to indicate a wide variety of articulation
problems. This inadequacy is due in part to our lack of knowledge
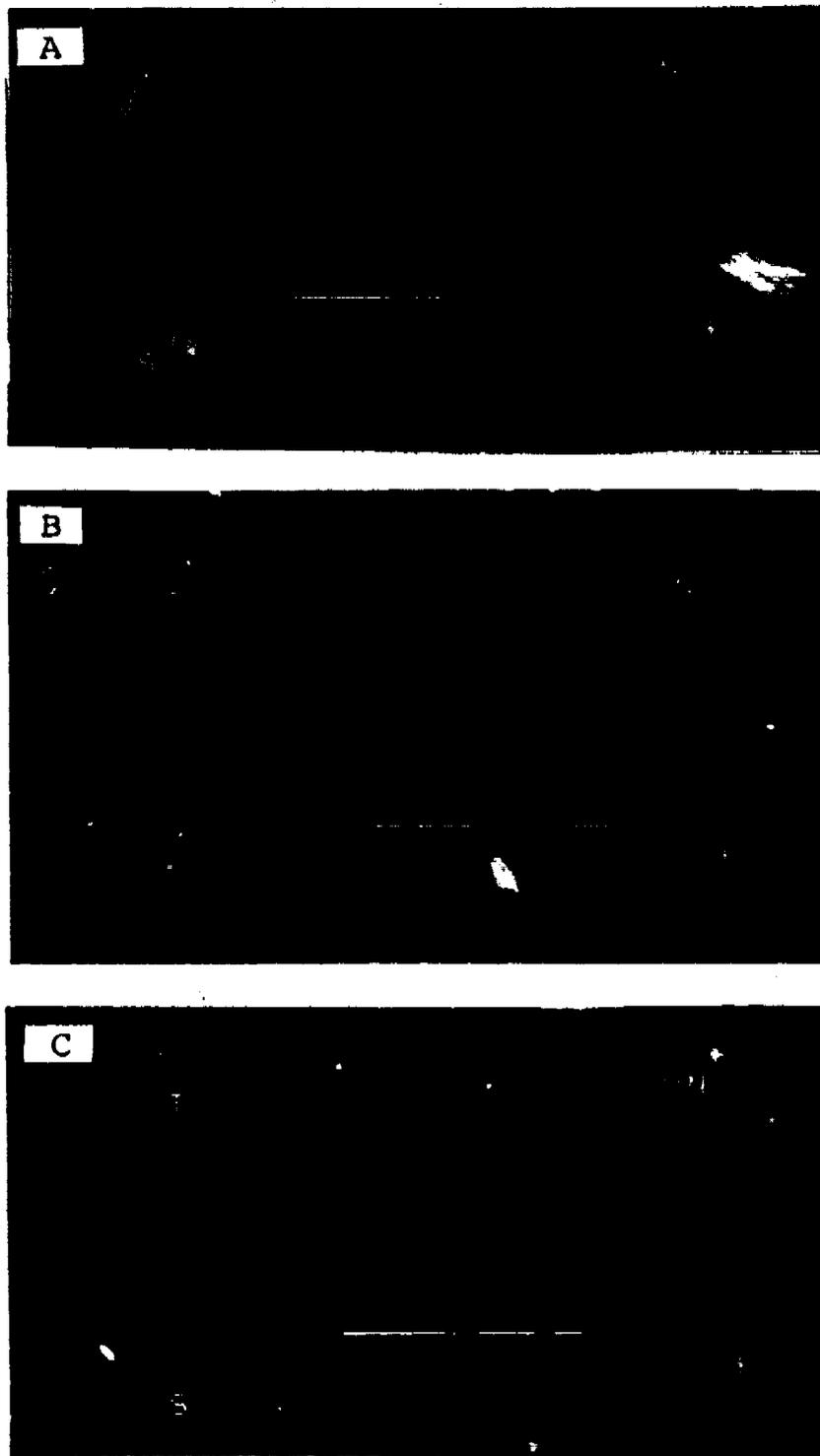
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Figure 26.   VN display for the sentence "Be my baby" produced
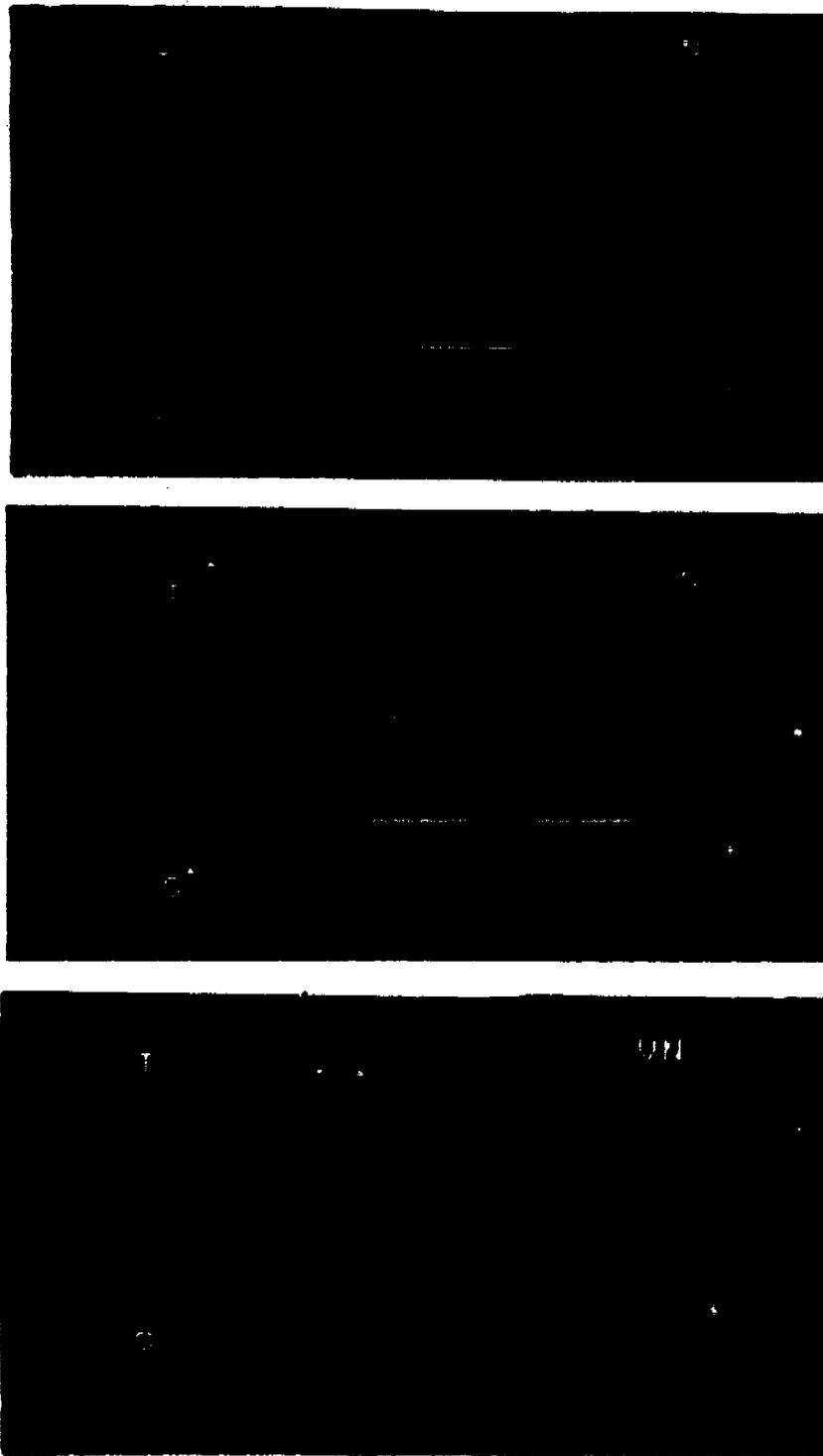   by three normally-hearing speakers.

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Figure 27. VN display for the sentence "You can drink your
milk" produced by three normally-hearing speakers.
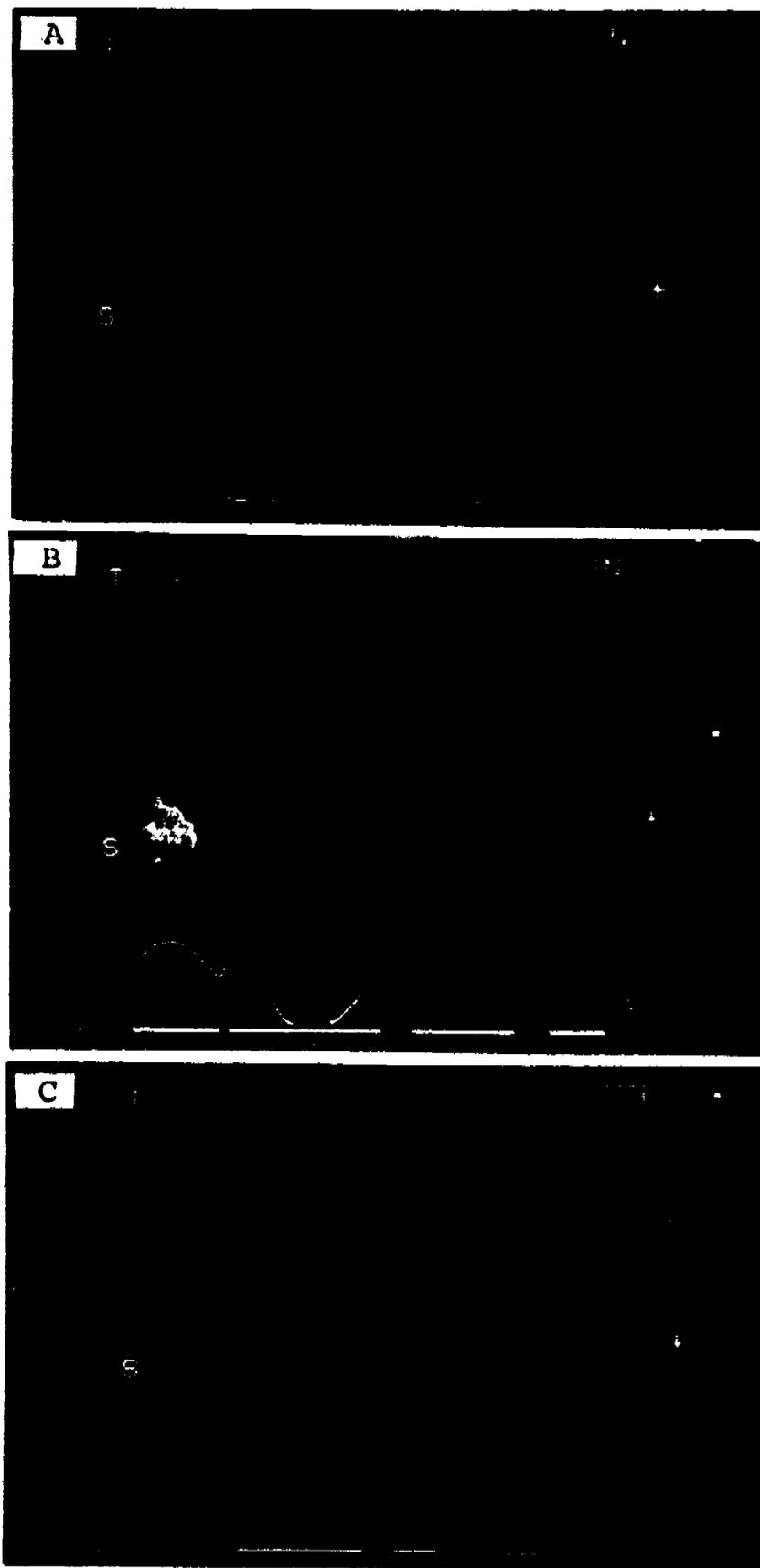
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Figure 28. Examples of VN display for deaf students producing the sentence "Be my baby" with improper control of the velum.
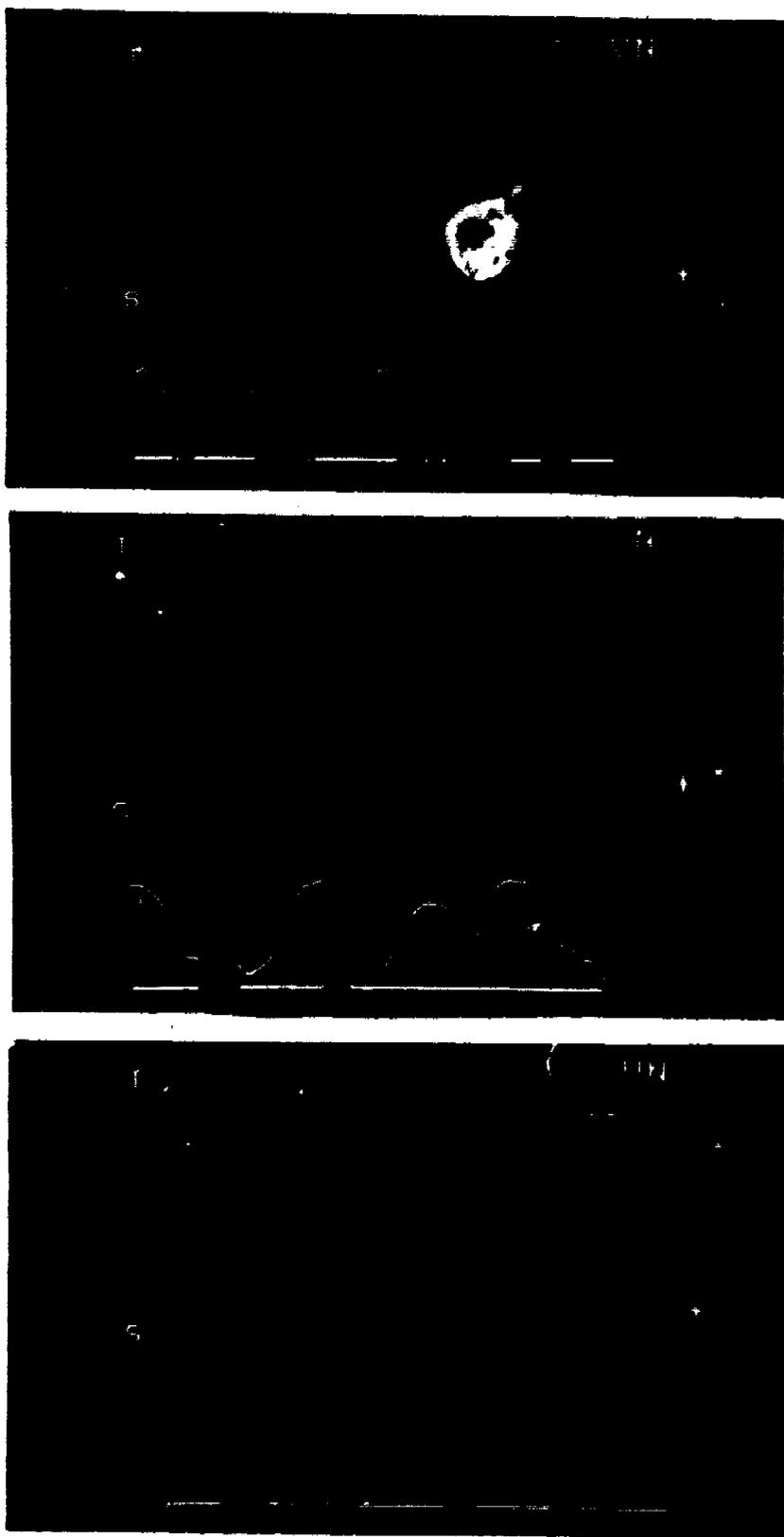
Figure 29. Examples of VN display for deaf students producing
the sentence "You can drink your milk" with improper
control of the velum.

as to what acoustic parameters can be extracted to give reliable
indications of articulation problems and in part to difficulties
with providing a display that can be properly interpreted by an
observer.

The dual spectrum display is useful for assessing the adequacy
of sounds that can be sustained and can be produced in isolation.
It can also be used (with somewhat reduced facility) for displaying
such sounds in brief monosyllabic words and for examining sounds
that are characterized by a relatively slowly changing spectrum,
such as diphthongs. The slow-motion replay option provides the
capability for examining the spectral changes in a captured speech
sample after the fact, and can be helpful in identifying missing,
spurious, or misarticulated sounds.

All of the spectrum displays shown in this section can be
generated with a normalization feature that sets a maximum width
for the display when the intensity of the sound exceeds a certain
threshold. For a sound intensity above this threshold, the shape
of the pattern for a given sound should be relatively independent
of intensity. When the intensity is below this threshold, the width
at all points along the height of the pattern is reduced by the
same amount. This can alter the appearance of the pattern, par-
ticularly when the width becomes very narrow or reduces to a single
vertical line in some regions of the pattern.

4.4.1 Fricative Consonants

The vertical spectrum display gives rather distinctive patterns
for the fricative consonants /s/ and /š/. Initial work with these
consonants should involve producing them in isolation with the
appropriate shape for the display.

Examples of patterns of /s/ produced by normally-hearing
speakers are shown in Fig. 30. The distinguishing feature of
this pattern is a wide top, narrowing down rapidly to a rather thin
"stem." The usual type of inadequacy in the production of /s/ by
deaf students is for the pattern to be too wide in the stem im-
mediately below the wide top. An example is shown in Fig. 31a.
For some unacceptable examples, there may be no abrupt widening
at the top of the pattern, as in Fig. 31b.

Deaf students should be instructed to adjust the position of
the tongue tip and to shape the tongue blade while producing a
continuous noise, in an attempt to obtain the desired pattern shape.
If an adequate continuous sound can be produced, then the next
step is to generate a series of brief versions of the sound in
isolation, each with the proper shape of the vertical spectrum.

Work should then shift to simple monosyllabic words that
begin or end with /s/. Unlike the time-plot displays that are
used in the training of pitch, timing, and nasality, the vertical
spectrum display does not show a trace of some aspect of an utter-
ance over time. When a fricative consonant is produced in a word,
therefore, the spectrum display changes very quickly during the
utterance. The display can, however, be replayed and "frozen" at
any point throughout a 1-second utterance. In working with mono-
syllabic words, therefore, the procedure is to store the spectral
information for the word (produced by the student or by the teacher)
by depressing the appropriate control button, and then to replay
the spectrum sequence in slow motion, stopping the replay within
the sound that is being worked with--in this case, the /s/. The
details of the spectrum can then be examined by teacher and student,
and the adequacy of the production can be assessed. A successful
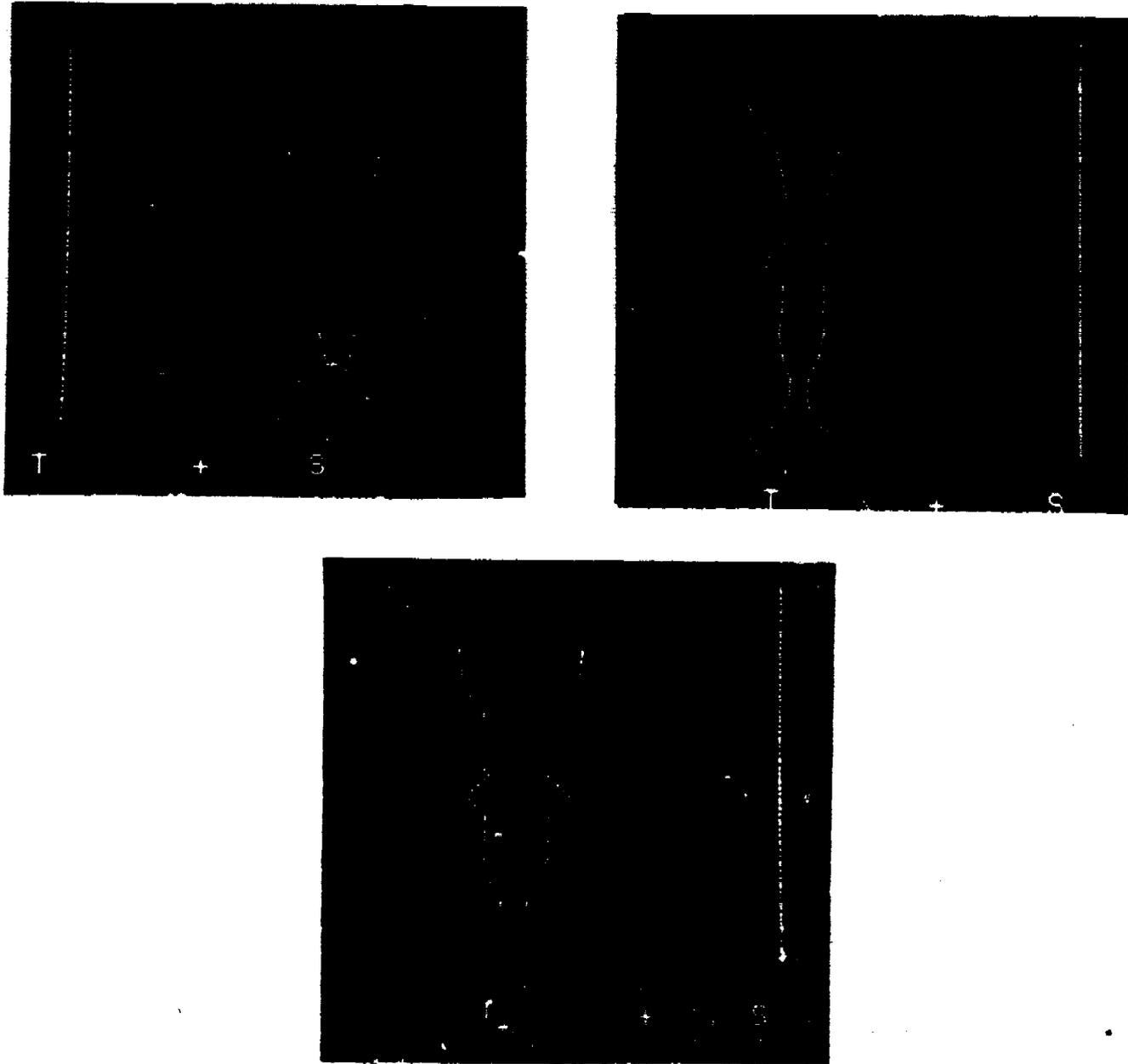version of the student's utterance can, if desired, be shifted to

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Figure 30.   Examples of vertical spectrum display for
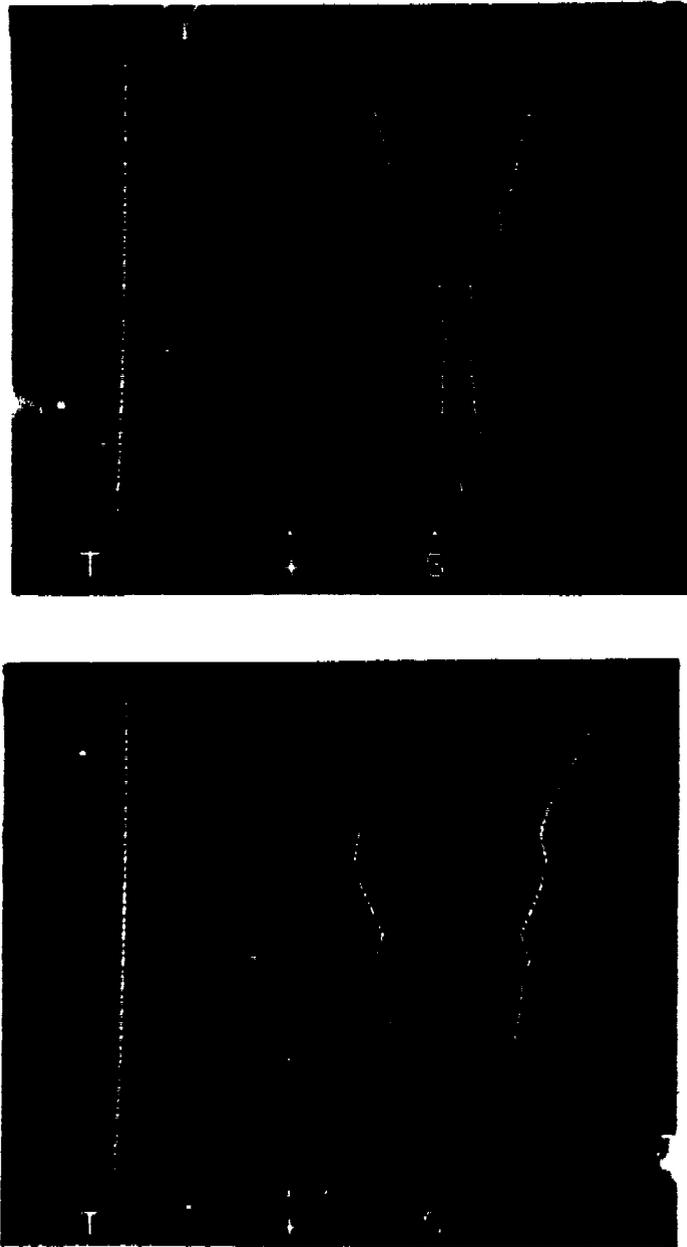   acceptable versions of the sound /s/.

Figure 31. Examples of vertical spectrum display for two deaf
children producing unacceptable versions of the
sound /s/.

the teacher's side of the display, where it can serve as a target
against which future utterances of the student can be compared.

In addition to having the proper spectrum shape, the /s/ in a
monosyllabic word should have an appropriate duration in the range
100-150 msec. This means that the s-duration should generally be
somewhat less than the duration of the vowel in such a word. The
adequacy of the timing of the fricative can be assessed using the
VL display, which shows the voiceless fricative as a trace with
appreciable loudness but with no voicing.

A next exercise for the deaf student is to produce the /s/ in
an intervocalic position such as /asa/ or /isi/, with proper spec-
trum shape and duration. Work with other phonetic environments
should then move to /s/ in initial consonant clusters (e.g., spot,
small) and in final consonant clusters (pots, mask). Until an
adequate fricative consonant is produced with words such as these,
the dual spectrum display should be used. Proper timing of the
/s/ production in relation to other aspects of the word should be
examined using the VL time-plot display.

A similar sequence of exercises should be followed with /š/.
Examples of adequate versions of this sound are shown in Fig. 32.
The pattern for both /s/ and /š/ has a wide top which narrows
toward the bottom. The upper half of the pattern for /š/ is,
however, considerably wider than it is for /s/. A typical dif-
ficulty for /š/ is a pattern that is too wide in the middle and
lower regions, as in Fig. 33.

Extensive experience with training with other classes of
fricative consonants, such as the voiceless /f/ and /θ/, the
various voiced fricatives, and the affricates, has not yet been
obtained.
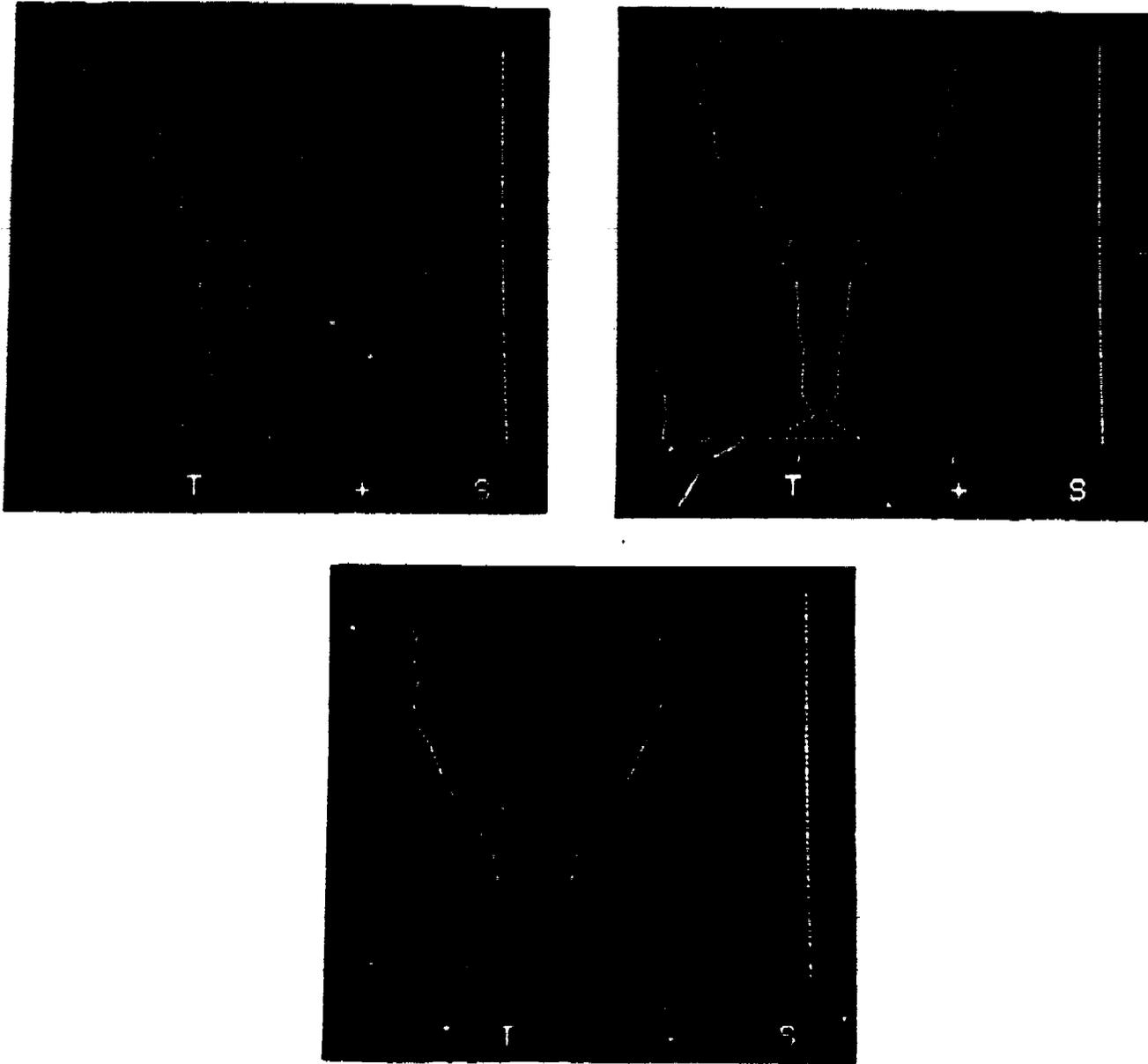
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Figure 32.   Examples of vertical spectrum display for acceptable
              versions of the sound /š/.
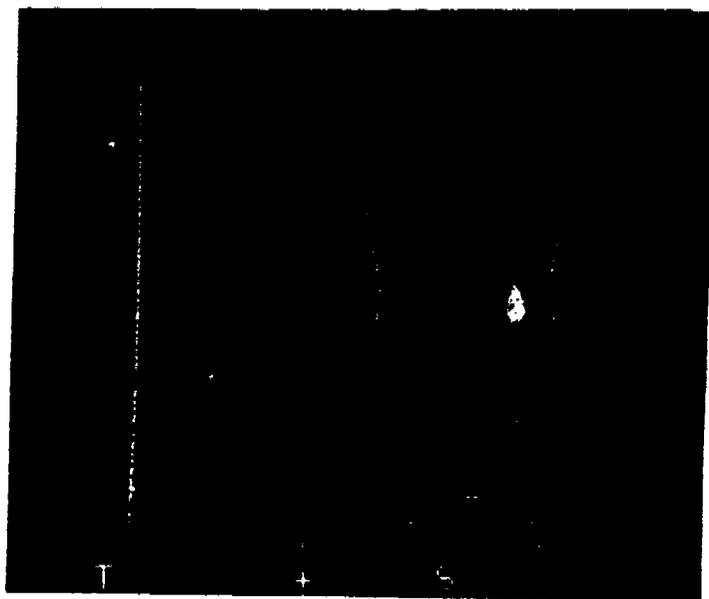
Figure 33. Vertical spectrum display for an unacceptable
            version of /š/, produced by a deaf student.

4.4.2 Vowels and Diphthongs

The dual spectrum display can indicate the gross acoustic attributes of vowel , and thus can be used to aid in the training of some aspects of vowel production. Examples of this display for the three vowels /a/, /i/, and /u/ produced by normally-hearing speakers are shown in Figs. 34, 35, and 36.

The distinguishing attributes of the pattern for /a/ include: (a) the pattern is pinched in at the bottom; (b) the lower one-third of the pattern is characterized by a wide bulge; (c) the pattern is pinched in somewhat at about the middle or slightly above the middle (Fig. 34c is slightly atypical), but is not too narrow at this point (in comparison with the displays for /i/ and /u/; and (d) the pattern fattens out to produce another bulge in the upper half.

Examples of deviations from this normal pattern for /a/ are shown in Fig. 37. Typical problems include a lack of narrowing of the pattern at the low end (Fig. 37a), two well-separated bumps instead of one wide bump in the lower half or two-thirds of the pattern (Fig. 37b), and a narrowing of the display too far above the middle (Fig. 37c).

In the case of /i/, the pattern begins wide at the bottom and then narrows down to a rather small width within the lower one-third of its height. The region of narrowing may extend over some distance. The pattern then widens in the upper half, so that the width is comparable to, or even greater than, the width at the bottom. The large bump in the upper half may have various detailed fluctuations, as the examples in Fig. 35 indicate. Examples of poor productions of /i/ have patterns with insufficient or even no narrowing in the middle (Figs. 38a and 38c), a narrowing too high

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Figure 34.   Vertical spectrum display for the vowel /a/, produced
             by three normally-hearing speakers. The horizontal
             lines indicate that the sound is voiced.   The height
             of the vertical "lollipop" within the pattern
             indicates the pitch of the sound.

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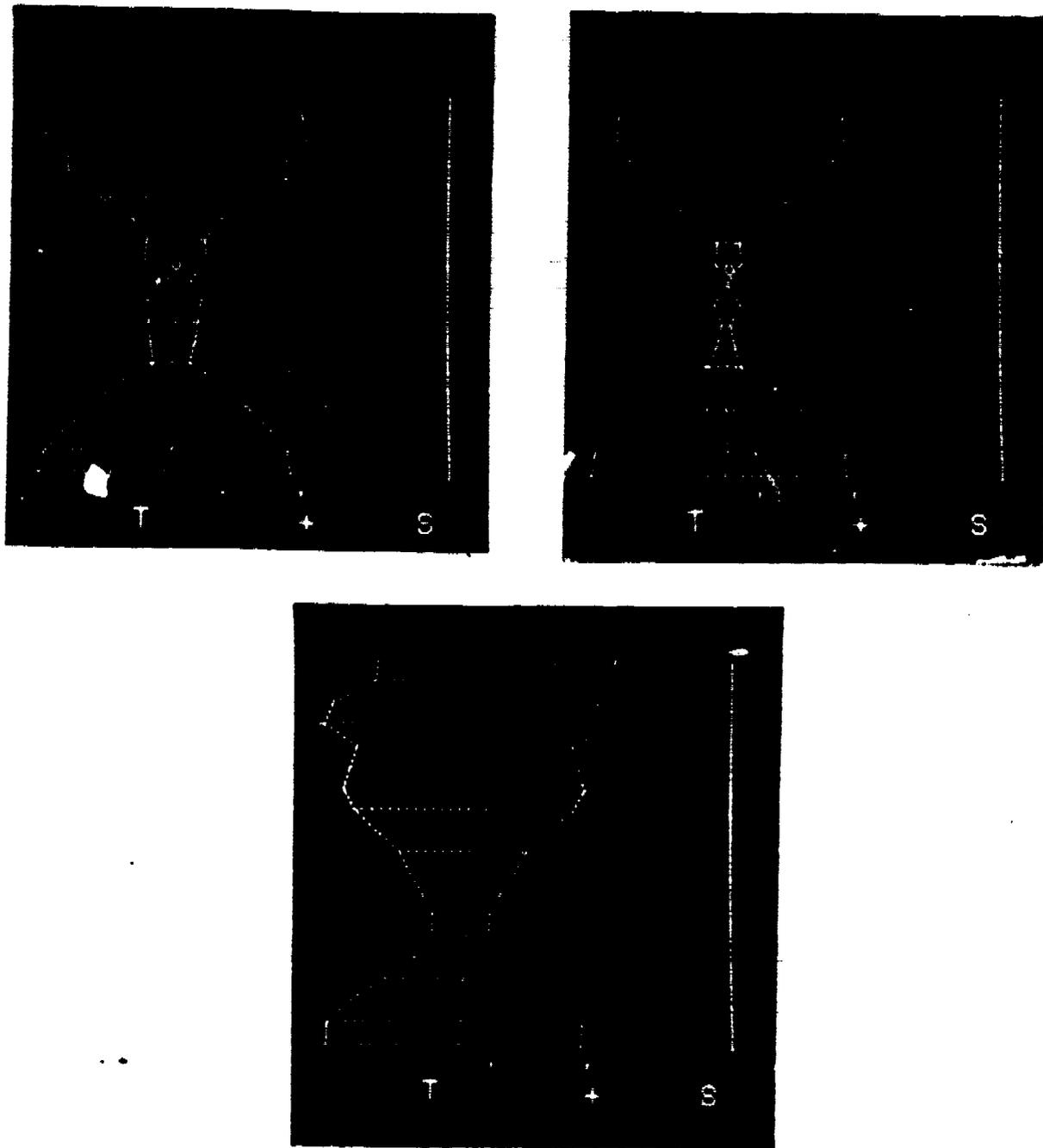
Figure 35.   Vertical spectrum display for the vowel /i/, produced
              by three normally-hearing speakers.   The horizontal
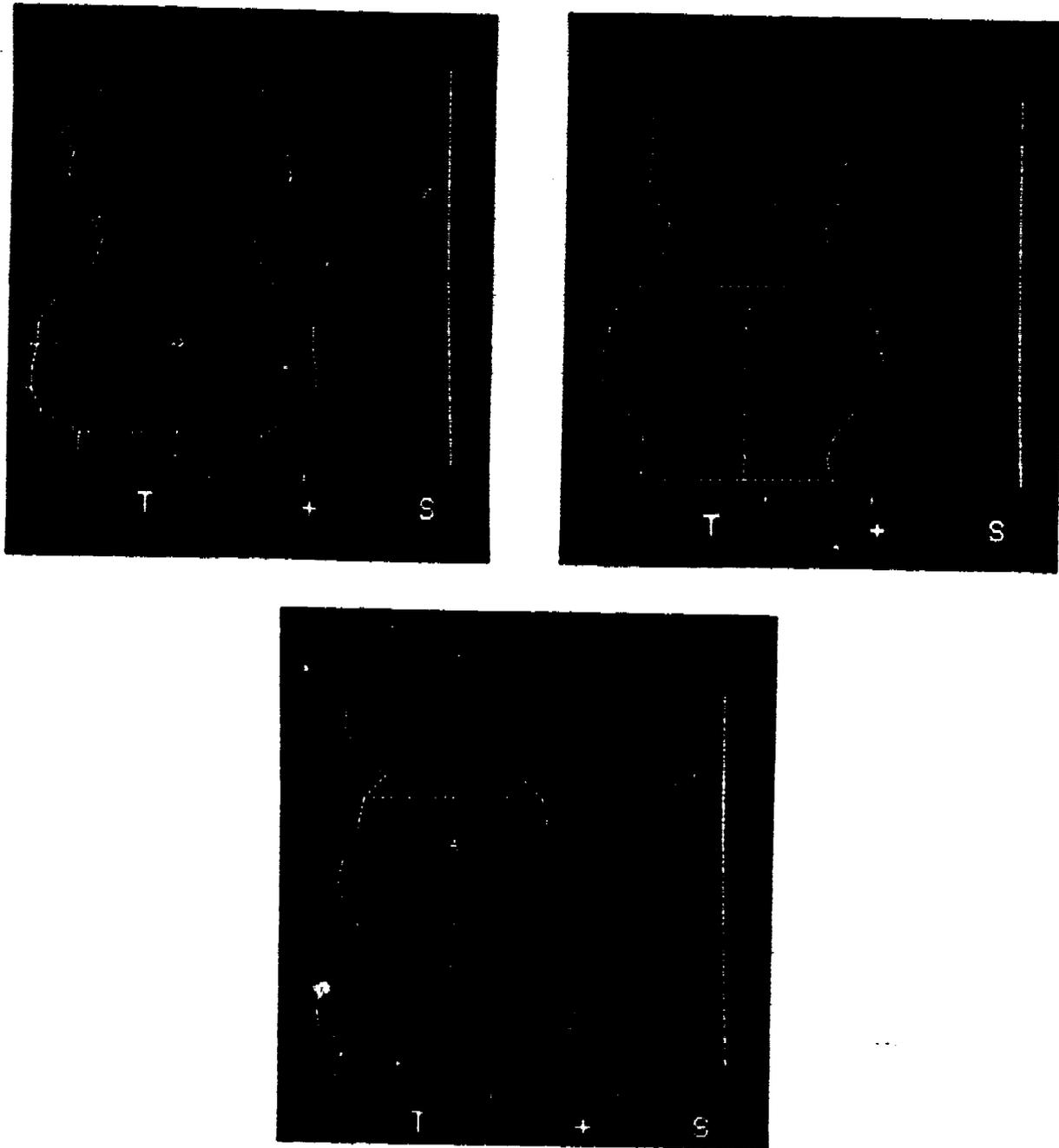   lines indicate that the sound is voiced.
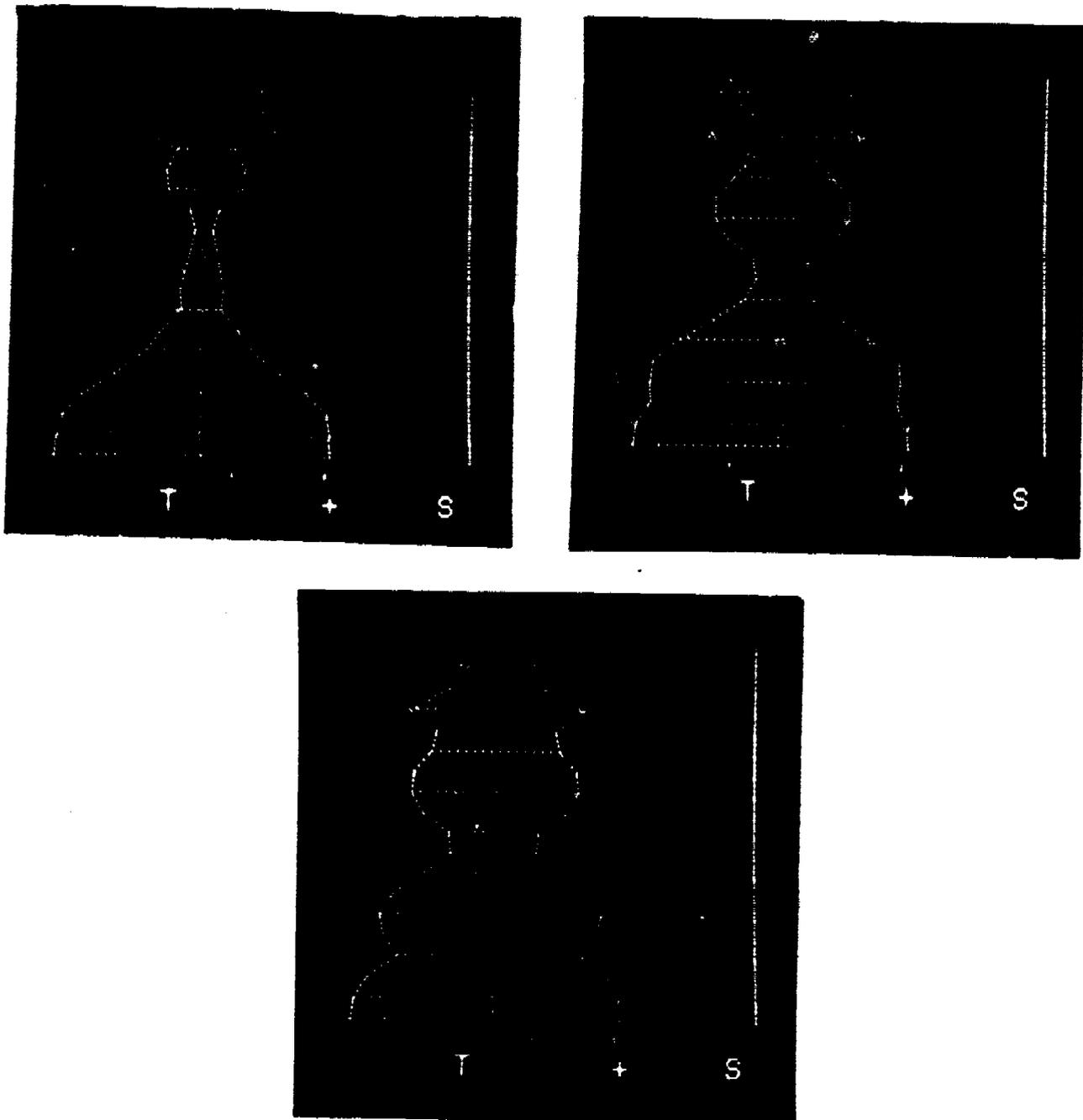
Figure 36.   Vertical spectrum display for the vowel /u/, produced
by three normally-hearing speakers. The horizontal
lines indicate that the sound is voiced.

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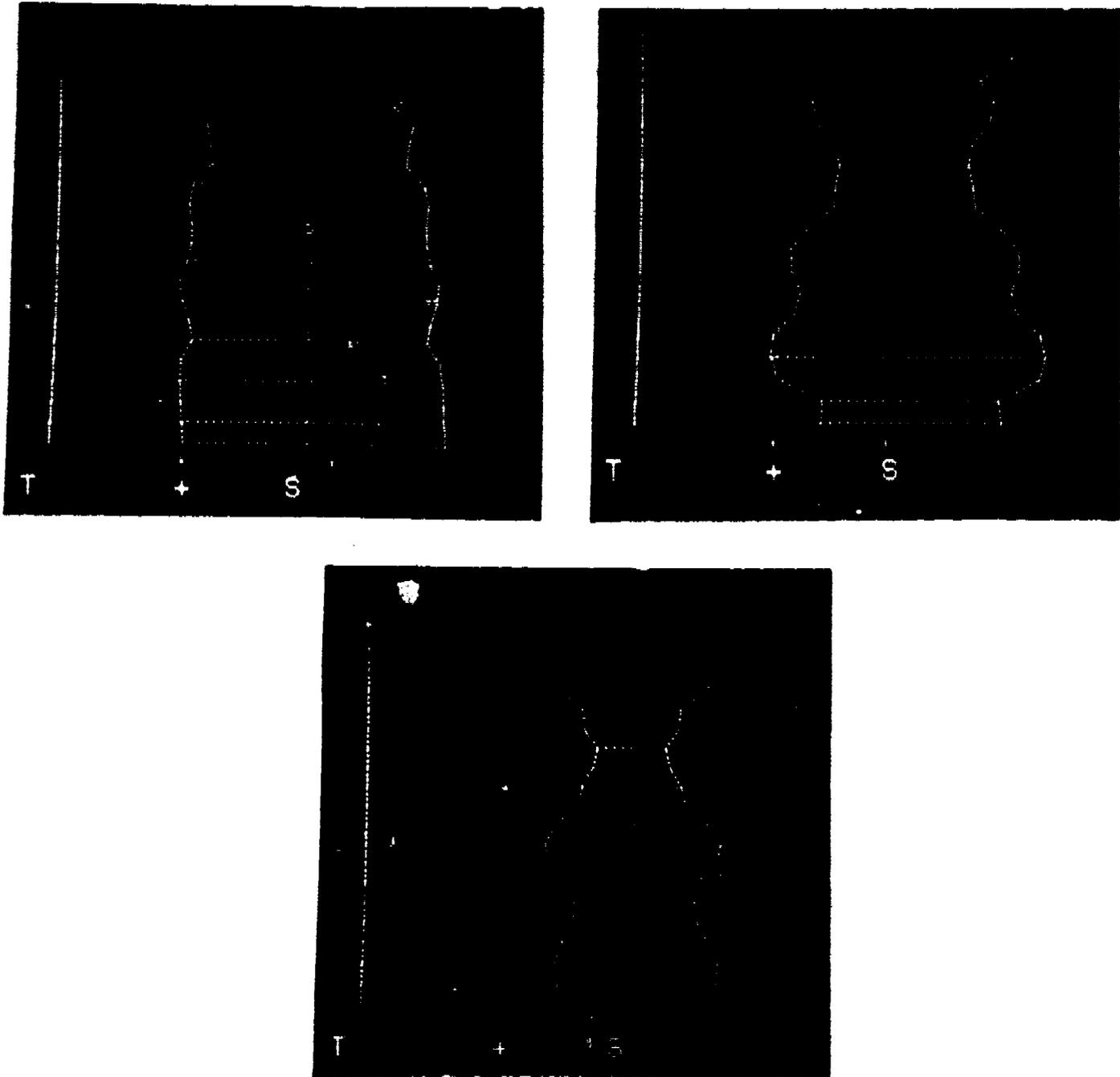

Figure 37. Examples of vertical display for the vowel /a/,
produced improperly by deaf students.
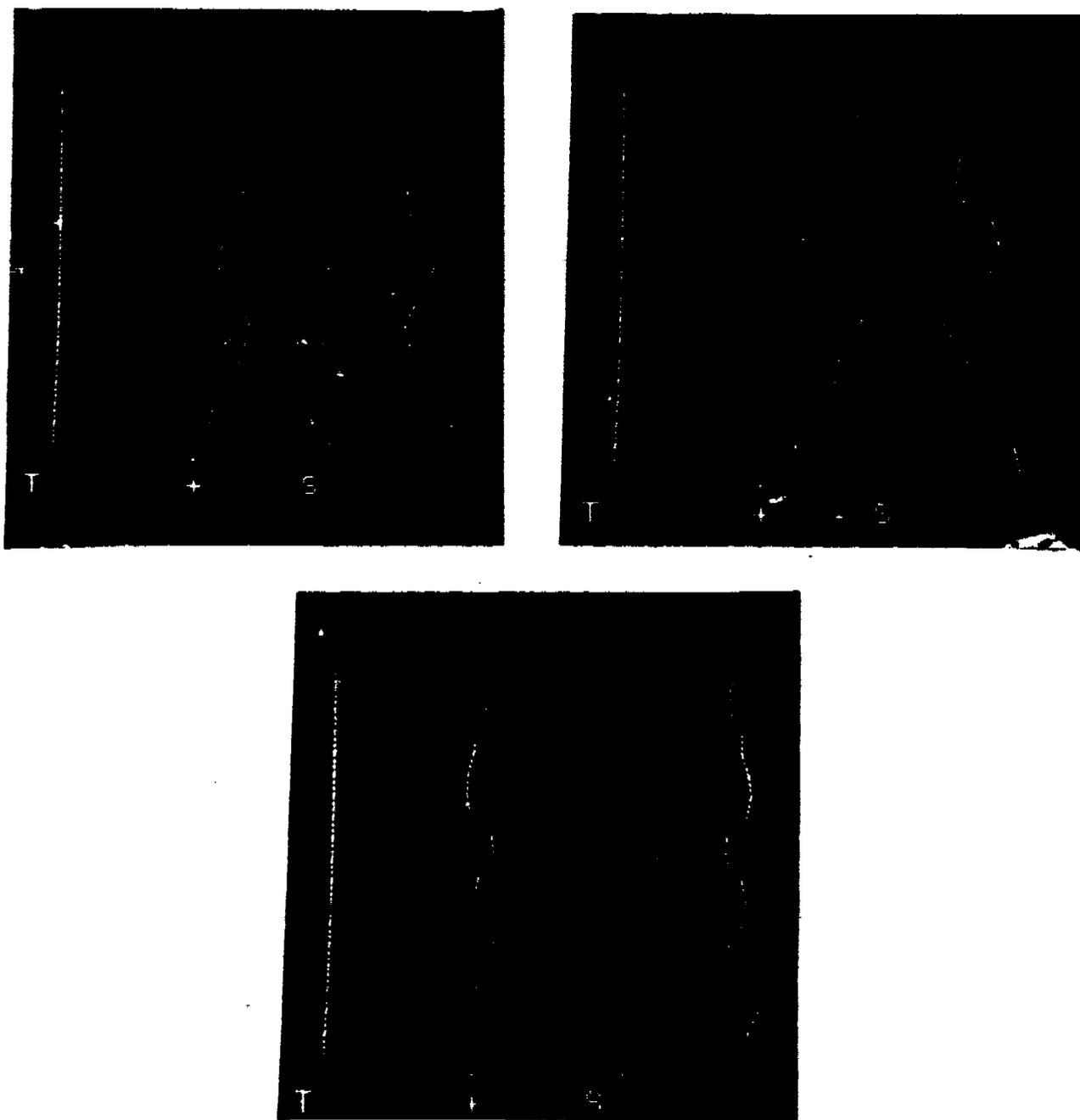
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Figure 38.   Examples of vertical display for the vowel /i/,
             produced improperly by deaf students.

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in the pattern (Fig. 38b), or a maximum width in the lower part
that is not at the bottom of the pattern (Fig. 38c).

The normal patterns for /u/ all have their widest point at
the bottom. There is a broad section in the lower part of the
pattern that narrows down gradually, yielding a minimum width near
the middle. The lower half may sometimes include two bumps (Fig.
36c) and sometimes just one (Fig. 36a). There is a widening above
the middle constriction, but the maximum width in the upper half
is usually appreciably less than the width at the bottom. Typical
errors in production (Fig. 39) lead to insufficient narrowing in
the middle, and the widest point not at the bottom of the pattern.

These comments can be used as guides in working with students
to produce approximations to these vowels produced in isolation.
The normal procedure would be for the teacher to generate a display
of the vowel, and point out the main distinctive attributes of
the display. The student then attempts to produce a display with
these attributes. If he is successful after some trials, the
display of his own utterance can replace that of the teacher, and
can be used by the student as a pattern to be matched on subsequent
attempts.

The next logical step after work with isolated vowels is to
shift to monosyllabic words produced in isolation. The procedure
to be followed here is similar to that discussed above for frica-
tive consonants in words. The word is produced, and the display
during the vowel is observed, although this initial real-time
impression is fleeting. The display for the word may then be
replayed in slow motion and stopped during the vowel, thus per-
mitting both student and teacher to examine the attributes of the
pattern. A new utterance should then be made in an attempt to
correct any inadequacies in the display.
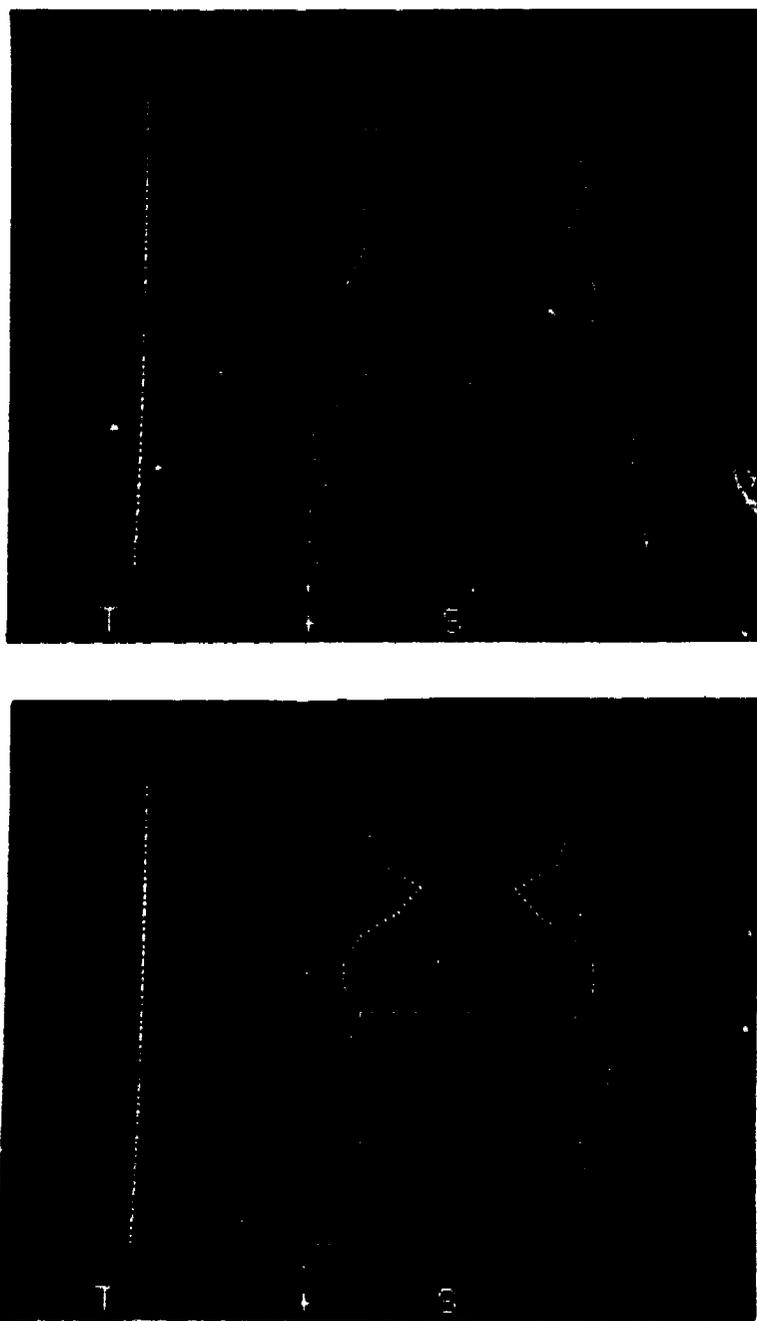
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Figure 39. Examples of vertical display for the vowel /u/, produced improperly by deaf students.

Care must be exercised in following this procedure in working
with vowel articulation in words. During the vowel portion of a
consonant-vowel-consonant word, the articulation of the vowel may
be influenced by the adjacent consonants, especially in regions
of the vowel close to the consonants. Thus, observation of the
vowel display should be made close to the middle of the vowel.
For words with some types of consonants (e.g., /l, r, w, y/), the
display does not show a well-defined boundary between vowel and
consonant, with the result that the middle of the vowel may be
difficult to find. When a word contains a nasal consonant (par-
ticularly in final position), the vowel may be nasalized, and the
spectral patterns shown above for normal vowels will be modified.
Training with vowel articulation in words should avoid words con-
taining these classes of consonants.

The dual spectrum display can also be used to assist training
in the production of diphthongs. When a diphthong like /ai/ (as
in the word bite) is produced, for example, the display should
change smoothly from /a/ toward /i/. Initial work with diphthongs
should use diphthongs in isolation, first produced slowly and then
more rapidly. Training can then be extended to diphthongs in
isolated monosyllabic words.

4.5 Voice Quality

Study of the acoustic correlates of "voice quality" has not
yet reached the point where deficiencies in voice quality can be
diagnosed reliably solely on the basis of objective acoustic
measurements. That is, there is no single acoustic measurement
that shows good correlation with listener judgments of such quali-
ties as breathiness or harshness. This difficulty may be due in
part to the lack of agreement among listeners as to what con-
stitutes a harsh or a breathy voice.

In spite of this lack of reliable acoustic correlates of
breathy or harsh voice quality, a combination of listener judgments
and objective measurements can be used with some success in the
diagnosis of breathy voice quality and in the specification of
training goals. Deaf students who are judged to have a very
breathy voice quality also show a relatively high reading of the
HL parameter for low vowels such as /a/, /æ/ and /ʌ/. Our data
suggest that if the average HL in words containing these vowels
is above 120, then the speech of that talker is judged by listeners
to have a breathy voice quality. For these students, a display
of the HL parameter for words with these vowels can be used to
assess performance after some training.

A reasonable approach to the speech training of these students
is to begin with the isolated vowel /a/. It should first be
established that this vowel can be produced without excessive
nasalization, following the guidelines indicated in Section 4.3.
If there is excessive nasalization, it is appropriate to begin
training to reduce nasalization before approaching the problem of
breathy voice.

After it has been established that the nasalization is within
normal limits, the HL reading for the isolated vowel /a/ should
be determined. Let us assume that this reading is above 120 units
for the HL display. The student should then be encouraged to
experiment with manipulation of his larynx in order to reduce the
HL reading for this vowel. Several approaches are possible. The
student might be instructed to let the air flow out of his lungs
without effort and without forcing or tenseness in the muscles,
letting the phonation occur on a natural exhalation produced by
the elastic recoil of the lungs. He may also be encouraged to
prepare for phonation with a closed glottis and with an initial
pressure build-up behind the glottis. Phonation is then initiated

by a slight relaxation of this glottal closure, so that the glottal
opening remains small. This kind of exercise should be carried out
for a series of brief phonations, while the student is observing
the result of his efforts on the HL display. He should aim for
an HL reading well below 100.

Once the student has mastered the production of brief isolated
vowels without excessive breathiness, he should shift to isolated
monosyllabic words containing low vowels. Again, an HL criterion
value well below 100 units should be set. The HL pattern for the
teacher's utterance can be used as a guide for the student.

Some students tend to terminate an utterance with a breathy
voice, probably as a consequence of premature abduction of the
vocal cords before phonation ceases. This problem has been dis-
cussed in the section on timing and rhythm (Section 4.1), and
examples of "loudness" displays for utterances with this problem
were given. Work with students having this difficulty can also
utilize the HL display, at least for low vowels. Training would
utilize monosyllabic utterances with low vowels (such as /pa/),
and students would be instructed to maintain a low HL reading
throughout the utterance. Abnormal breathiness toward the end of
the utterance would be manifested by an HL contour that curves up
at the end of the vowel.

Only a few deaf students with breathy voice quality have
worked with the HL display. Thus, it is not possible at this time
to specify training procedures in greater detail. The teacher
who has an opportunity to gain experience with this display should
attempt to develop his own training procedures beyond those out-
lined briefly here.

5. ACKNOWLEDGMENTS

The contributions of several people to the development of
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located many of the references that are cited in Section 2.
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that is included in Section 4. Helpful suggestions concerning
training procedures came from several individuals, notably
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teaching staff. Finally, both the patience of the Clarke School
students and their consistent enthusiasm are acknowledged with
pleasure; it is from the students that the real inspiration for
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