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THE EFFECT OF TIMING ERRORS ON THE  
INTELLIGIBILITY OF DEAF CHILDREN'S SPEECH

by

MARY JOSEPH OSBERGER

A dissertation submitted to the Graduate Faculty in Speech and Hearing Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

1978

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## CHAPTER I

## INTRODUCTION

It is well known that congenital deafness imposes severe communication handicaps on a child. Throughout their educational training, most deaf children must be taught the speech skills which the normal hearing child readily acquires during the first few years of life. Even with years of intensive training, most deaf children fail to acquire speech skills comparable to those of their hearing peers. Of particular interest to educators of the deaf is the development of improved training procedures to facilitate the acquisition of those speech skills necessary for the production of intelligible speech. Studies which have quantified the intelligibility of deaf children's speech have consistently shown that intelligibility is severely reduced, and therefore, only a small proportion of what a child says can be understood by persons not familiar with the speech of the deaf.

One approach to developing more effective speech training strategies is to determine quantitatively the ef-

fect that specific types of errors have on the intelligibility of deaf children's speech. Given this information, those errors which are found to have the greatest effect on intelligibility could be corrected first in a child's speech. Correction of these errors would thus yield the greatest improvements in intelligibility.

The majority of past research efforts has been devoted to identifying the types of errors that occur in the speech of the deaf. As a consequence, we now have a better understanding of the types of errors that exist in the speech of the deaf. However, there is a relatively small amount of quantitative data which demonstrates how these errors render the deaf child's speech unintelligible.

Since the early 1900's, investigators have repeatedly shown that the speech of deaf children contains numerous timing errors. Studies which have attempted to determine the effect of deviant timing patterns on intelligibility have produced conflicting results. The results of these studies indicate that the effect of incorrect timing patterns on the intelligibility of deaf children's speech has not yet been clearly established. The purpose of the present study was to quantify the effect that

certain timing errors, uncontaminated by other variables, have on the intelligibility of deaf children's speech. This was accomplished by means of computer simulation in which the speech waveform was modified to correct timing errors only, leaving all other aspects of the speech unchanged. The timing adjustments involved the correction of pauses and segment duration. The latter type of modification primarily involved the correction of vowel duration errors and for some conditions the duration of other continuant sounds (semivowels, glides, nasals) were also corrected. Using a six-stage approximation procedure, these errors were corrected to systematically approach timing patterns typical for normal hearing children. The original and the computer-modified utterances were then played to persons unfamiliar with the speech of the deaf. Measures of speech intelligibility were then obtained. The data were analyzed in an attempt to answer the following questions:

1. Is the systematic correction of deviant timing patterns accompanied by systematic improvements in intelligibility?
2. Does the correction of different types of

of timing errors have different effects on intelligibility?

3. Does the correction of deviant timing patterns have a greater effect on improving the intelligibility of some children's speech than others?

## CHAPTER II

## REVIEW OF RELATED LITERATURE

Some Timing Characteristics in Normal Speech

During the past few years, there have been numerous investigations of the temporal organization of speech. Such studies have attempted to define those variables which influence duration at all levels of speech production, ranging from the level of the phonetic segment to large linguistic units. The intent of the following section is not to provide an exhaustive review of these studies, but rather to present information on those temporal aspects of speech deemed to be relevant to the understanding of deviant timing patterns in deaf children's speech which are of direct interest to the present study.

Segmental Effects on the Duration of Syllabic Nuclei

Acoustic analyses of normal speech have shown that the duration of vowels is systematically influenced by effects operating at the level of phonetic segments. Since vowels form the nuclei of the larger segments of speech, these changes in vowel duration exert substantial effects

on both the production and perception of the temporal and segmental aspects of speech. Unlike other speech segments, vowels have been described as having an intrinsic duration (Peterson and Lehiste, 1960). In comparable contexts, some vowels are consistently shorter in duration than other vowels. The durational difference between the "short" and the "long" vowels is on the order of 100 msec (House, 1961).

The average duration of vowels varies markedly as a function of phonetic context. When different phonetic contexts are considered, the voicing characteristic of the following consonant appears to have the most dramatic effect on vowel duration. Acoustic measurements have consistently shown that the duration of a vowel preceding a voiceless consonant is on the average less than the vowel duration preceding a voiced consonant (House and Fairbanks, 1953; Denes, 1955; Peterson and Lehiste, 1960; House, 1961). The average duration of a vowel preceding a voiced consonant is roughly three times longer than the duration of a vowel preceding a voiceless consonant (Denes, 1953). This systematic change in vowel duration has been found to be a significant perceptual cue

to the voicing characteristic of the following consonant or consonant cluster (Raphael, 1972).

The manner of production of adjacent consonants also has a significant effect on vowel duration, although this effect is much less pronounced than that of voicing. When voicing is held constant, vowels are much longer in fricative environments than in stop-plosive environments. Vowels are also longer before nasals, but since nasals are composed of only voiced sounds, it is not possible to separate, in a balanced manner, the individual effects of voicing and manner of production on vowel duration. The place of consonant articulation has been shown to have a negligible effect on the duration of the vowel (House and Fairbanks, 1953; House, 1961).

#### Suprasegmental Effects on Vowel Duration

The duration of vowels is also influenced by effects operating at the level of syllables, words and phrases. In English, changes in the stress pattern have been found to produce systematic changes in vowel duration. When vowels are stressed, they are longer in duration than when the same vowels are unstressed (Parmenter and Trevino,

1936). In addition, the durational variations which accompany changes in linguistic stress have been found to be the most effective cue for the perception of stress (Fry, 1955).

Another suprasegmental effect is the lengthening of final syllables in word-final, phrase-final and sentence-final positions. In English, the lengthening of final syllables has been found to be due primarily to increases in the duration of the vowel (Oller, 1973).

A recent acoustical study by Klatt (1974) examined the systematic changes in vowel duration in the context of connected discourse. The results of this study showed that the magnitude of the vowel duration changes is much smaller in this context than in isolated syllables and words. For example, while the average duration of stressed vowels was longer than that of unstressed vowels in connected discourse, the values obtained for both stressed and unstressed vowels were much smaller than the durations of vowels in words produced in isolation. Also, the large differences in vowel duration conditioned by features of the following consonant were observed only in phrase-final syllables.

Klatt also observed that vowels in word-final

syllables of phrase-final words were significantly longer in duration than vowels in any other position. In fact, the lengthening of sentence-final syllables was no greater than the lengthening of other phrase-final syllables in connected discourse. One of the hypotheses that Klatt poses is that durational increases may provide acoustic cues which serve to mark the ends of major syntactic units for the listeners. That is, speakers typically do not pause, or produce substantial changes in fundamental frequency between units such as noun phrases and verb phrases and, segmental lengthening may be the cue that signals the boundaries of these units.

In summary, many of the large durational effects that occur in speech are primarily due to systematic changes in the duration of vowels. The magnitude of the vowel duration effects is large and these effects may operate at the segmental or suprasegmental level of speech. Thus, errors of vowel timing, such as those which have been found to occur in the speech of the deaf, may severely distort the temporal aspects of speech and result in numerous segmental and suprasegmental misperceptions.

## Timing Patterns in Deaf Children's Speech

### Overall Speaking Rate

The results of numerous investigations have shown that the deaf typically speak at a much slower rate than do normal hearing speakers (Voelker, 1935, 1938; John and Howarth, 1965; Boone, 1966; Hood, 1966; Heidinger, 1972; Nickerson et al., 1974). On the average, deaf speakers take roughly 1.5 to 2.0 times as long to produce the same utterances as do normal hearing speakers. The reduced speaking rate of the deaf appears to be attributed to three types of timing errors: 1) the excessive prolongation of speech segments (phonemes, syllables and words), 2) the insertion of pauses and, 3) the insertion of adventitious segments.

The first type of error, the excessive prolongation of speech segments, is present in deaf speakers' production of phonemes, syllables and words. On the phonemic level, deaf speakers have been observed to extend the duration of vowels, fricatives and the closure period of plosives up to five times the average duration for normal speakers (Calvert, 1961). The lengthened duration of phonemes, in turn, results in the prolongation of

syllables and words (Hood, 1966; Heidinger, 1972; Levitt, Smith and Stromberg, 1976).

The second type of timing error which substantially reduces the speaking rate of the deaf is the insertion of pauses. Deaf speakers typically insert more pauses, and pauses of longer duration than do normal hearing speakers (John and Howarth, 1965; Boone, 1966; Hood, 1966; Heidinger, 1972; Boothroyd, Nickerson and Stevens, 1974; Nickerson et al., 1974). The greatest difference between normal and deaf speakers has been observed in the durations of inter- and intra-phrase pauses (Nickerson, et al., 1974). The results of Hudgins' (1934, 1937, 1946) investigations indicate that the frequent pauses observed in the speech of the deaf may be the result of poor respiratory control. Specifically, Hudgins found that deaf children used short, irregular breath groups often with only one or two words, and breath pauses that interrupted the flow of speech at inappropriate places. In addition, there was excessive expenditure of breath on single syllables, false groupings of syllables and misplacements of accents.

The third type of error, insertion of adventitious

sounds, appears to be the direct result of the slow and imprecise control of articulatory movements. A common error is the insertion of adventitious sounds between two consonants in a cluster or between two abutting consonants (Hudgins and Numbers, 1942). According to Smith's (1975) classification, adventitious sounds may be associated with the formation or release of consonant phonemes. Adventitious sounds associated with the formation of a consonant are inserted before the initial phoneme of a word or in a vowel-to-consonant transition. Those associated with the release of a consonant are inserted after the final consonant of a word or in a consonant-to-vowel transition.

#### Timing Errors at the Phonemic Level

The acoustic analyses of deaf speech have shown that deaf speakers fail to produce the systematic changes in vowel duration that are typical of normal speech. Results obtained by Calvert (1961) and Monsen (1974) indicate that deaf speakers distort the intrinsic differences in vowel duration. The results of these studies have also shown that deaf speakers fail to correctly modify vowel duration as a function of the voicing characteristic

of the following consonant. In fact, the data obtained by Calvert indicate that vowel duration errors may account for the frequent voiced-voiceless confusions which have been observed to occur in the speech of the deaf.

Other frequently occurring segmental errors in the speech of the deaf appear to be caused by incorrect timing of articulatory movements. Such errors include the omission of one or more members of a consonant cluster, the division of a diphthong into two distinct vowels, and the diphthongization of pure vowels (Hudgins and Numbers, 1942). Failure to coordinate the timing of articulatory and laryngeal gestures distorts the voice-onset time and results in the perceptual confusions between word-initial voiced and voiceless stop consonants in the speech of the deaf (Monsen, 1976).

An interesting finding obtained by Calvert (1961) is that deaf speakers' articulatory movements may be responsible for the voice quality that is so typical of their speech. Teachers of the deaf were able to identify reliably speakers as either deaf or normal hearing once the level of articulatory complexity involved some type of articulatory movement, such as that required for the

production of a diphthong or CVC syllable. Productions with negligible articulatory movements, such as sustained vowels, failed to provide the experienced listeners with the necessary information for the correct identification of speakers. On the basis of these findings, Calvert concluded that the distinguishing characteristics of deaf speech are associated with articulatory movement as a function of time, rather than with voice quality per se.

#### Timing Errors at the Syllabic Level

The results of the aforementioned studies have shown that deaf speakers prolong the duration of syllables. In addition to this timing error, deaf speakers also fail to temporally differentiate stressed and unstressed syllables. Nickerson et al. (1974) found that while both deaf and hearing speakers made the average duration of the unstressed syllables shorter than that of stressed syllables, the proportional shortening of the unstressed syllables was smaller on the average for the speech produced by the deaf speakers than for that produced by the hearing speakers.

Nickerson et al. also observed that deaf speakers did not consistently lengthen the duration of phrase-final syllables relative to the duration of the other syllables in the phrase. When there was evidence of prepausal lengthening, the increase in the duration of the final syllable was much smaller, on the average, for the deaf speakers than for the normal hearing speakers.

In summary, the speech of the deaf contains numerous timing errors. Such errors include a reduced speaking rate, excessive prolongation of speech segments, insertion of long pauses, introduction of adventitious sounds between phonemes and syllables, failure to temporally differentiate stressed and unstressed syllables and failure to modify segment duration as a function of phonetic environment. Because of such errors, the speech of the deaf has often been described as slow, labored and lacking in rhythm. Within recent years studies have also shown that poor timing control may result in the perceived segmental as well as the suprasegmental errors in the speech of the deaf.

### The Effect of Timing Errors on Intelligibility

Studies which have attempted to determine the effect of deviant timing patterns on the intelligibility of deaf children's speech can be classified into two major categories: correlational and causal. In the first type of study, a statistical analysis of the association between timing errors and the decrease in intelligibility is performed. The second type of study measures changes in intelligibility after timing errors have been corrected in the speech of deaf children. The causal studies can further be sub-divided into two basic types: studies in which timing errors are corrected after deaf children receive intensive training for the correction of such errors and, studies in which timing errors are corrected in deaf children's speech samples using modern signal processing techniques. The results of the various types of studies will be discussed in the following sections.

#### Correlational Studies

One of the earliest attempts to determine the relationship between deviant timing patterns and intelligibility is found in the Hudgins and Numbers (1942)

study. Although Hudgins and Numbers correlated rhythm errors with intelligibility, many of the rhythm errors which they describe actually appear to be due to poor timing control. In the Hudgins and Numbers study, test sentences recorded by 192 hearing impaired children were transcribed and classified according to three rhythm categories by teachers of the deaf. The three categories were: sentences spoken with normal rhythm, sentences spoken with abnormal rhythm and sentences spoken non-rhythmically. Hudgins and Numbers reported that slightly less than half of all sentences spoken by the children were judged to have normal rhythm. These sentences accounted for 74% of all the sentences correctly understood by the listeners and, the sentences classified as having correct rhythm patterns had roughly a 4 to 1 advantage of being understood over those spoken with incorrect rhythm. In addition, Hudgins and Numbers found that those sentences spoken with correct rhythm were likely to have fewer articulation errors than those spoken with abnormal rhythm. The correlation between speech rhythm and intelligibility was roughly .73. A finding of particular significance was that the total number of

consonant errors correlated  $-.70$  with intelligibility, and the total number of vowel errors  $-.61$ . On the basis of these data, Hudgins and Numbers concluded that the relationship between rhythm and intelligibility was just as great as that between consonant errors and intelligibility and considerably greater than that between vowels and intelligibility.

In a later investigation, Hood (1966) examined the relative importance of the various aspects of speech rhythm on the intelligibility of the speech of students with severe and profound hearing losses. Utterances produced by the subjects were low-pass filtered below 500 Hz and were subsequently played to a group of listeners who rated the rhythm of the filtered sentences with respect to intonation, loudness and temporal factors. Hood observed that high speech intelligibility was associated with speech rhythm better than a certain level and low intelligibility was associated with speech rhythm worse than that level.

Physical measures of fundamental frequency, intensity and timing were made for unfiltered sentences for the six hearing impaired subjects with the best rhythm

ratings and, the six hearing impaired subjects with the poorest rhythm ratings. Of the three types of physical measures obtained, the differences between the hearing and the normal hearing speakers was most pronounced on the measure of duration. In addition, the highest correlations were obtained between duration measures and intelligibility. The largest durational differences between the two groups of speakers were seen in the absolute duration of syllables and the length of pauses between words.

The correlational studies which have been conducted during the past few years have specifically examined the relationship between duration errors and intelligibility. Monsen and Leiter (1975) obtained significant negative correlations between average syllable duration and intelligibility. Their results also showed that there was a higher negative correlation between the average duration of syllabic nuclei of function words and intelligibility than between the average duration of content word nuclei and intelligibility. Monsen and Leiter suggested that the duration of function words rather than the duration of content words may be a more

reliable indicator of intelligibility. The authors further concluded that the excessive prolongation of function words, which are usually unstressed and of short duration, is more detrimental to intelligibility than the prolongation of the normally long, stressed content words.

Levitt, Smith and Stromberg (1976) observed a relationship between poor intelligibility and deviant timing patterns. In this study, acoustic measures were obtained of timing patterns in deaf and normal hearing children's speech. The results showed that excessive prolongation of segments and excessive pause times were generally present in the deaf children's speech. It was assumed by the authors that excessive prolongation of those segments and pauses which showed the least variation between the normal hearing speakers would have the greatest effect on intelligibility. An overall measure of deviant duration was derived in which pauses and excessive prolongation of voiced segments were weighted in inverse proportion to the variation in duration for corresponding sections in the hearing children's speech. The unit of deviant duration was the total number of

standard errors in excessive duration between the deaf and normal speech. The data showed that as intelligibility increased, the measure of deviant duration decreased. Of particular significance was the observation that intelligibility fell markedly as the deaf children's durations exceeded the durations exhibited by the normal hearing children.

In a recent study by Parkhurst and Levitt (1978), a multiple linear regression was performed relating intelligibility to four types of prosodic errors that were judged to occur in the speech of a group of deaf children. The four types of prosodic errors included: adventitious sounds, excessive phoneme duration, pauses and, pitch breaks. The prosodic errors that showed the greatest negative regression with intelligibility were unexpected adventitious sounds, i.e., adventitious sounds other than those linked to normal articulatory movements, very long prolongation of individual sounds and unexpected changes in pitch. Excessive or prolonged pauses, including prolonged closure in plosives, had a secondary effect (in a correlational sense) on intelligibility. In contrast, short pauses were found to have a positive effect

on intelligibility and may have actually helped to improve intelligibility. The authors interpreted this latter finding as an indication that the presence of pauses in deaf children's speech may provide listeners with additional time to process the distorted speech that has been heard.

The results of the above studies indicate that there is a high correlation between deviant timing patterns and intelligibility. In addition, it appears that certain types of timing errors may have a more detrimental effect on intelligibility than others. In fact, the results of Parkhurst and Levitt (1978) indicate that one timing error, the insertion of short pauses at syntactically appropriate boundaries, may actually have a positive effect on the intelligibility of deaf children's speech.

### Causal Studies

#### 1. Training Studies

These studies have attempted to quantify the changes in intelligibility that occur after deaf children have received intensive training to correct timing errors in their speech. The first study of this type was performed

by John and Howarth (1965). In their study, pre- and post-training intelligibility measures were compared for a group of severely hearing impaired and profoundly deaf children after the children had received intensive training which focused on the correction of timing errors only. Intelligibility, which was based on the number of words correctly understood by persons not familiar with the speech of the deaf, was 19% for the pre-training samples and 30% for the post-training samples. Thus, the training resulted in an 11% increase in word intelligibility. The data showed no significant difference in the amount of improvement exhibited by the children on the basis of either age or degree of hearing loss.

Heidinger (1972) also observed a significant improvement in the intelligibility of a group deaf children's speech following the correction of timing errors. Heidinger found that following training there was a significant decrease in word duration but there was no significant change in the occurrence of pauses or intrusive sounds. Thus, the improvements reported by Heidinger appear to be due to changes in segment duration.

One problem with the studies of this nature is that

although the training procedures emphasized the correction of only timing errors, concomitant correction of other errors may also have occurred. In fact Heidinger (1972) reported a decrease in the number of consonantal omissions in the children's speech following training. Because of this confounding problem, it is difficult to determine whether or not the observed improvements in intelligibility were due only to the correction of timing errors.

Studies of a similar nature were performed by Houde (1973) and Boothroyd, Nickerson and Stevens (1974). However, the results of these investigations failed to support those of John and Howarth (1965) and Heidinger (1972). Houde observed that while training procedures were effective in reducing the number of syllabic stress errors and pause errors in the speech of four deaf students, there was a substantial decrease in intelligibility for those two subjects who showed the greatest improvement in the correction of deviant timing patterns. Houde hypothesized that the decrement in intelligibility could have resulted if the increased attention to the rhythmic aspects of speech was accompanied by a decreased atten-

tion to the articulatory aspects. In other words, the training procedures could have resulted in an increase in the number of segmental errors in the deaf students' speech.

In the Boothroyd, Nickerson and Stevens (1974) study, a group of deaf children received training which focused on the correction of relative timing errors in their speech. This involved attempts to reduce the duration of unstressed syllables while retaining the long duration of stressed syllables and reduction or elimination of with-in phrase pauses while retaining the longer pause durations between phrases. Following training, spectographic measurements revealed significant reductions in the duration of unstressed syllables and within-phrase pauses. For some of the deaf students there were statistically significant changes in the pre- and post-training intelligibility scores; three of the students showed an increase in intelligibility and three showed a decrease in intelligibility. For two of the students the difference between the scores was not statistically significant.

In summary, the results of the various training

studies have yielded mixed results. The improvements in intelligibility reported by John and Howarth (1965) and Heidinger (1972) may have been due to the concomitant correction of other types of errors. On the other hand, the decrements in intelligibility reported by Houde (1973) and Boothroyd, Nickerson and Stevens (1974) may have resulted because additional articulatory errors were introduced in the children's speech when emphasis was placed on the temporal aspects of speech production.

Another explanation for the conflicting results is that in each study, different types of timing errors were corrected. It is possible that different timing errors may produce different effects on intelligibility. Correction of some timing errors may lead to an improvement in intelligibility whereas correction of other types of timing errors may actually have a detrimental effect on intelligibility. In fact, the correlational data obtained by Parkhurst and Levitt (1978) indicate that this indeed may be the case.

## 2. Studies Using Signal Processing Techniques

In these studies, speech is either synthesized with timing distortions or, synthesized versions of deaf

speech are modified so that timing errors are corrected. An advantage to this type of approach is that it is possible to eliminate some of the confounding factors which can occur in the training studies.

Lang (1975) employed analysis-synthesis techniques in order to correct the deviant timing patterns in the recorded speech samples of one profoundly deaf student. The speech samples were first converted to digital form and Fast Fourier subroutines were used to compute short term spectra of a sequence of 10 msec segments of the waveform. Timing modifications were accomplished by deleting or duplicating a specified number of these 10 msec short-term spectra from the speech. In the synthesis stage, the short-term spectral windows of the re-timed speech were then transformed back into time waveforms, converted to analog form and recorded on audio tape.

Using the analysis-synthesis approach, the timing characteristics in 10 sentences produced by a deaf subject were modified to approach the timing characteristics of a normal hearing speaker. In addition, the timing patterns in 10 sentences produced by the normal hearing speaker

were altered so as to resemble those timing patterns of the deaf subject. The original sentences and the computer-modified versions were then played to six teachers of the deaf. Several measures of intelligibility were obtained but the largest differences between the altered and unaltered versions were observed when identification of key contextual words was scored. Four of the 10 sentences showed an improvement in the intelligibility of key contextual words when the deaf speech was retimed to the rhythmic patterns of the normal hearing subject. Three sentences showed an equal intelligibility score before and after the retiming, and three sentences showed a decrease in intelligibility. When the rhythmic patterns of the normal hearing subject were modified to resemble those of the deaf subject, the overall intelligibility of key contextual words decreased by 12%.

It should be noted that Lang reported distortions in the computer-generated versions of some of the speech samples. Although the severely distorted words were deleted from the intelligibility analyses, it is difficult to assess the overall quality of the computer-processed sentences. It is not known exactly how much distortion

was produced as a result of the type of processing that was employed in this study.

Bernstein (1977) attempted to determine the relative effect of 1) consonant errors of omission and substitution, and 2) suprasegmental timing errors on the intelligibility of a deaf child's speech. In this study, sentences were synthesized so that the segmental and suprasegmental characteristics matched those of the same sentences produced by a normal hearing adult. The synthesized sentences were modified to approximate the consonantal articulation and suprasegmental timing of the deaf child. Following the synthesis procedures, intelligibility measures were obtained. The results revealed that consonant errors had a detrimental effect on intelligibility whereas the timing errors had essentially no effect on intelligibility. However, Bernstein commented that some normal aspects of timing, such as the intrinsic durational differences between syllables, were retained in the synthesized versions. It is possible that had all timing errors been synthesized, the errors would have produced a more noticeable effect on intelligibility.

Huggins (1977) attempted to determine the relative

effect that inappropriate duration and fundamental frequency changes had on speech intelligibility. In this study, sentences were synthesized and either the timing assignment rules, or the pitch assignment rules, or both were made to operate on incorrect stress assignments. Specifically, the stress assignments were changed so that the normally stressed syllables were unstressed and the normally unstressed syllables were stressed in the synthesized versions. The greatest reductions in intelligibility occurred when both the pitch and timing were inappropriate. When either occurred alone, inappropriate timing had a more detrimental effect on intelligibility than inappropriate pitch.

### Conclusions

A review of the related literature has shown that the speech of the deaf contain numerous timing errors. However, the effect that these errors have on intelligibility has yet to be clearly established. A number of studies have attempted to quantify the effect of timing errors on intelligibility by measuring changes in intelligibility after deaf children receive intensive training

for the correction of these errors. A problem encountered with this technique is that the training may result in the concomitant correction of errors other than those involving timing or, alternatively, in attempting to correct timing errors, other articulatory errors may be introduced in a child's speech. Because of these confounding factors, it is difficult to determine if measured changes in intelligibility are due to the correction of timing errors only.

More recent investigations have attempted to eliminate this confounding variable by using modern, computer processing techniques. This type of approach appears promising but to date, there have been few, comprehensive studies of this nature.

One problem with the previous research is that there has been no attempt to determine the relative effect of different types of timing errors on intelligibility. The usual approach has been to correct several types of timing errors and generalize the findings, whether they be positive or negative, to include the effect of all types of timing errors on intelligibility. A review of past research findings indicates that different types of

timing errors may have different effects on intelligibility.

In summary, the review of the literature reveals that there is a need for further investigation of the effect of timing errors on the intelligibility of deaf children's speech. If the exact gain in intelligibility due specifically to the correction of timing errors can be determined, then perhaps this information can be used to formulate more effective speech training procedures for deaf children.

## CHAPTER III

## EXPERIMENTAL PROCEDURES

As previously stated, the primary purpose of this study was to quantify the effect that the correction of deviant timing patterns have on the intelligibility of deaf children's speech. The procedures used to accomplish this purpose consisted of the correction of specific timing errors in the recorded samples of deaf children's speech by computer processing techniques and, quantifying the effect of the time modifications through intelligibility measures.

Before the above mentioned procedures could be carried out, a number of preliminary procedures were necessary in order to: 1) select a small group of deaf children's recorded speech samples which were to be manipulated, ii) determine exactly how the timing patterns in the deaf children's speech deviated from the timing patterns in normal hearing children's speech, iii) determine precisely the timing modifications to be made in the deaf children's speech. Thus, the chapter has been divided into major sections. The first section consists of a preliminary study which presents the

following information: i) the subject selection procedures, ii) the segmentation procedures used to obtain measures of duration in the deaf children's speech and in the speech of a group of normal hearing subjects, iii) a detailed analysis of the timing patterns in the deaf children's speech and, an analysis of the extent to which these timing patterns differed from those in the normal hearing children's speech, iv) determination of those timing adjustments which were to be made in the deaf children's speech.

The second part of the chapter is devoted to the description of those techniques which were used to actually correct the deviant timing patterns in the children's speech and the measurement of the effect that the timing modifications had on the intelligibility of their speech.

It should be noted that in this chapter the major emphasis has been placed on describing those aspects of the procedures which were directly applicable to the purposes of this study. A more detailed description of some of the procedures will be found in the stated appendices.

### Preliminary Investigation

#### Subjects and Sentence Material

The deaf children's utterances which were eventually

manipulated were ones which were previously collected by Smith (1972). The population consisted of 40 deaf children from the Lexington School for the Deaf in New York City. Twenty children were in the 8-10 year old age range and 20 children were in the 13-15 year old age range. Her criteria for subject selection were:

1. Some measurable audiometric response according to previous testing, at least to 750 Hz in at least one ear.
2. Congenital deafness.
3. No other presently apparent physical or psychological anomalies other than deafness.
4. Enrollment in the school for at least 3 years.

Each child read a list of 20 sentences or sentence pairs which were recorded on magnetic tape. The number of segmental (phonemic) errors in each child's speech was determined from the broad phonetic transcriptions which were made by a group of trained phoneticians. An intelligibility score was obtained for each child, based on the proportion of words correctly understood by persons not familiar with the speech of the deaf.

In the present study, 6 sentences produced by 6

children were selected from the recordings obtained by Smith (Smith, 1972, 1975). Figure 1 illustrates the relationship between phonemic errors and intelligibility for the 40 children in the study. On the average, intelligibility decreases as the frequency of segmental errors increases. The solid curve is a quadratic polynomial fitted by the method of least squares which approximates the relationship between the two variables. However, the data show a fair degree of dispersion and children with roughly the same frequency of segmental errors have speech intelligibility scores differing by as much as 30 percentage points. In the same study, it was shown that differences in intelligibility among those children with the same frequency of segmental errors correlated with certain suprasegmental errors. In the present study an attempt was made to select those children whose measured intelligibility scores were poorer than the intelligibility score that would be predicted only on the basis of the number of segmental errors present in their speech. This approach was based on the assumption that the speech of these children would show the greatest improvement in intelligibility if timing

Fig. 1. Percent intelligibility as a function of segmental errors

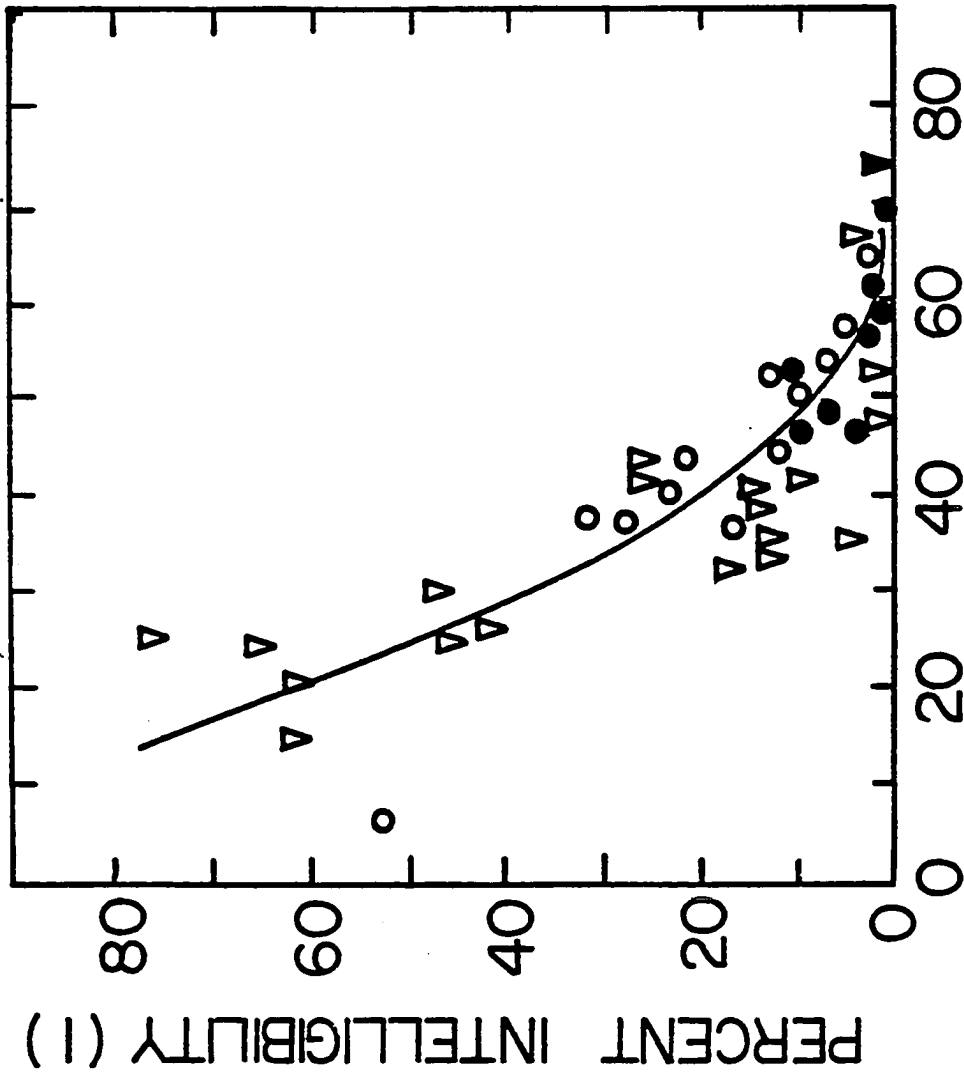
▽ : older group, hearing parents.

▼ : older group, deaf parents.

○ : younger group, hearing parents.

● : younger group, deaf parents.

(From Smith, 1975.)



PERCENT SEGMENTAL ERRORS

PERCENT INTELLIGENCE (I)

errors were corrected.

In order to identify these children, scatter plots similar to that of Figure 1 were generated by computer for each of Smith's 20 sentences. On each plot, the data point for each child was identified and a quadratic equation was fitted relating the intelligibility score to the proportion of segmental errors. The children who were of interest to the present study were those whose data points fell below the fitted curve, i.e., those children whose measured intelligibility scores were less than those predicted by the fitted curve for a given frequency of segmental errors.

Approximately 20 children were eliminated either because there was evidence of very large variations in pitch in their speech or because their speech consistently contained too many segmental errors. The children with large variations in pitch were excluded since this was considered to be a problem of some deaf speakers which was not applicable to the present study. In addition, the excessive variations in pitch would result in marked aperiodicities in the speech waveform which would have made direct manipulation of the waveform extremely difficult.

Also excluded were children with a high frequency of segmental errors, i.e., more than 50-60%. These children were excluded because their speech did not contain a sufficient number of identifiable phonemes to segment and manipulate.

For the remaining children, several problems were encountered in using the original subject selection procedures. First, the children's intelligibility scores were inconsistent; that is, for any given child the intelligibility score varied from one sentence to the next. Secondly, the frequency of segmental errors varied considerably from sentence to sentence, and exceeded the criterion value of 50-60% on some of the sentences. Therefore, the criteria for subject selection had to be modified. The children who were utilized in the present study were those whose speech contained less than the 50-60% criterion value of phonemic errors.

The 6 children, 3 males and 3 females, were selected from the older age group since the speech of the younger children typically contained too many segmental errors. The subject numbers of the 6 children in Smith's study were: 6, 7, 8, 9, 10, and 17. In the

present study, the children's identification numbers were changed from 6, 7, 8, 9, 10, 17 to 1, 2, 3, 4, 5, 6, respectively. Five (1, 2, 3, 5, 6) of the 6 children were in Smith's first quartile of intelligibility; one child (#4) was in the second quartile of intelligibility. Relevant background information and audiological data for the 6 children appear in Appendix A.

The following sentences were the ones selected to meet the above criteria as best as possible:

1. I think he'd better keep away from here.  
He can't behave himself.<sup>1</sup>
2. Did Jack find the orange ball? I need it.
3. I wish I could read that book.
4. The wagon has food and dishes on it.
5. The zipper on my coat is no good anymore.
6. Who will feed the cat today?

The sentences contained a representative sample of the phonemes of English. Each of the front, mid and back vowels, the diphthongs /əɪ/, /ou/, /eɪ/, the glides /r/, /l/ and the semivowel /w/ occurred at

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<sup>1</sup>For the present study, only the first sentence of the pair was used.

least once. The fricatives occurred a total of 21 times (9 voiced, 12 voiceless); the plosives 30 times (17 voiced; 13 voiceless); the nasals 13 times and the affricate /dʒ / once.

The measured intelligibility of the children's speech on the 6 sentences ranged from 0 to 97.2%; the percentage of segmental errors ranged from 5.9 to 60%. Table 1 shows the percentage of phonemic errors and the measured intelligibility scores as obtained by Smith for the 6 children on each of the 6 sentences.

It should be noted that there were differences in the phonetic transcriptions available from Smith and those transcriptions made by this author. For a summary of the major differences, see Appendix B. The author's transcriptions were used in all subsequent analyses involving phonemic errors in the children's speech. Confusion matrices showing the pattern of phonemic errors in the deaf children's speech can be found in Appendix C.

In the 36 sentences, there was a total of 14 intrusive sounds. Using Smith's (1975) classification, 4 of the intrusive sounds were associated with the release of a consonant. These errors involved the insertion

TABLE 1.--Percentage of Phonemic Errors and Speech Intelligibility for the Six Children on Each of the Six Sentences (From Smith, 1972)

Subject #	Sentence 1		Sentence 2		Sentence 3	
	% Phonemic Errors	% Intell.	% Phonemic Errors	% Intell.	% Phonemic Errors	% Intell.
1	27.9	33.3	42.3	44.4	11.8	85.7
2	19.6	94.4	30.8	37.0	29.4	80.9
3	30.2	97.2	26.9	52.8	47.1	57.1
4	34.9	8.3	50.0	14.8	17.7	0
5	11.6	88.9	15.4	33.3	53.0	57.1
6	20.9	50.0	30.8	29.6	47.1	33.3

TABLE 1--Continued

Subject #	Sentence 4		Sentence 5		Sentence 6	
	% Phonemic Errors	% Intell.	% Phonemic Errors	% Intell.	% Phonemic Errors	% Intell.
1	8.0	25.0	23.1	23.3	11.8	72.2
2	32.0	41.7	23.1	30.0	5.9	27.8
3	60.0	41.7	30.8	90.0	11.8	83.3
4	44.0	25.0	26.9	26.7	5.9	66.7
5	36.0	12.5	23.1	16.7	35.3	94.4
6	36.0	4.2	34.6	90.0	29.4	94.4

of a vowel after the final consonant of a word. There were no intrusive sounds associated with the formation of a consonant. Of the remaining intrusive sounds, 7 consisted of the insertion of aspiration following the production of an unaspirated stop consonant in the word-final position. The other 3 intrusive sounds occurred as isolated segments interjected in the middle of a pause.

Speech samples were obtained from 6 normal hearing children. The children were in the same age group and lived in the same geographical area as the deaf children used in this study. Recordings were obtained of the children reading the list of 20 sentences. The normal hearing children's speech samples were subjected to the same type of analyses as the deaf children's speech samples in order to obtain normative data.

### Equipment

The speech samples were segmented and subsequently manipulated using an interactive computer system. The system consisted of the DEC PDP 8/E computer (core memory of 16k 12 bit words) and the peripheral devices neces-

sary for the speech analysis. The analog devices included the following equipment:

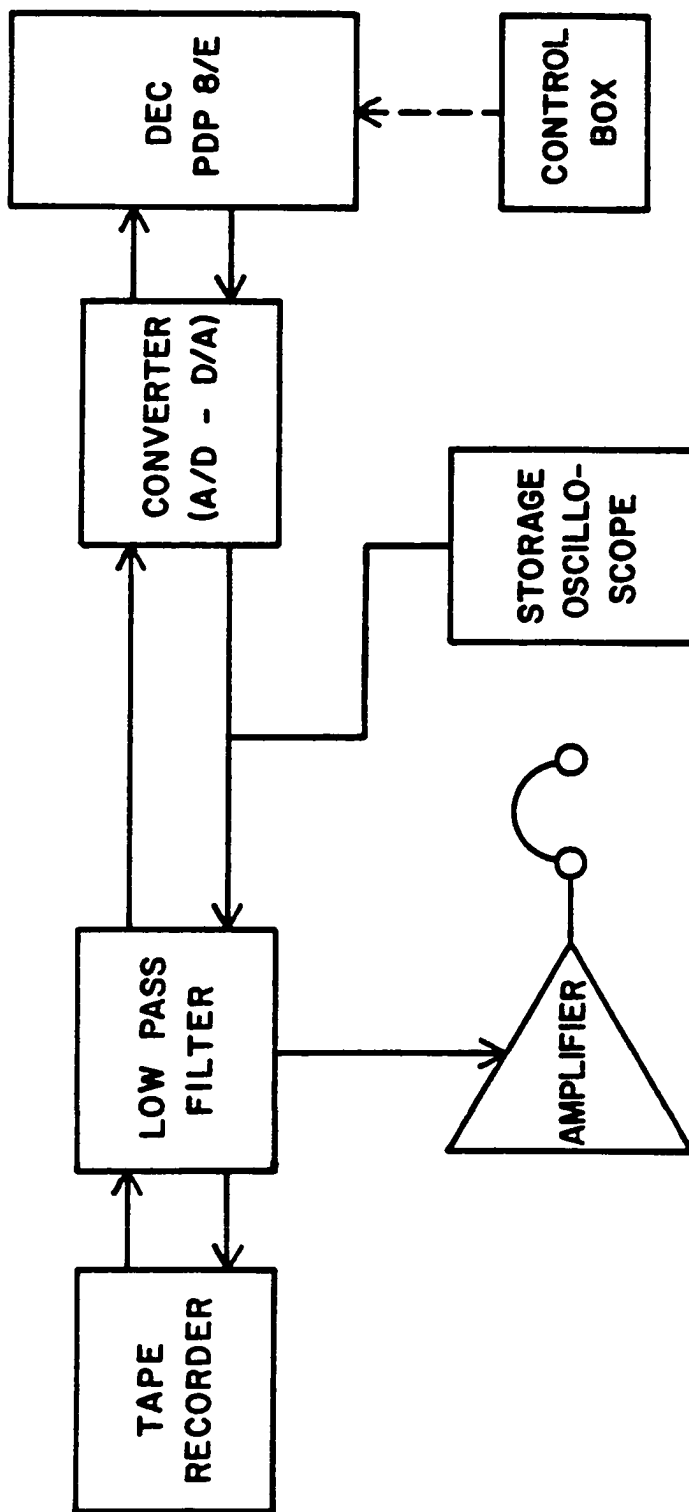
- tape recorder (Ampex 440)
- earphones (TDH-49)
- filter (Allison A124B Variable Filter)
- storage oscilloscope (Nicolet Digital Oscilloscope Model 1090)
- keyboard (Digital DEC Scope)
- control box (custom built)

The digital devices included the following:

- digital tape unit (DEC tape)
- disk unit (DEC RK05 Disk Drive with RK8-E cartridge 1.6 million 12 bit words)

Figure 2 shows a block diagram of the computer hardware. Signals in analog form on audiotape were first read into the digital computer and converted into digital form by means of an analog-to-digital converter. The signals were digitized at a sampling rate of 20k Hz and each sample was quantized to 12 bits. The sampling rate of 20k Hz was selected because it was the highest, most practical sampling rate that could be used with the system. Although 20k Hz was not ideal (40k Hz would

Fig. 2. A block diagram of the interactive computer system.



be ideal), it was adequate for the present study. The speech was then filtered to a nominal frequency of 9k Hz. Actually, there was some energy above 9k Hz because of the filter slope, but the frequency response of the headphones used in the final testing was no better than 9k Hz.

The speech to be sampled was low-pass filtered below approximately 9k Hz in order to avoid aliasing errors. Aliasing errors occur when frequencies are present in the speech which are higher than half the sampling rate (Blackman and Tukey, 1958). In the present study, frequencies higher than 10k Hz would have been read by the computer as separate low frequency components resulting in a noisy signal. Low pass filtering below 10k Hz prevented the occurrence of aliasing errors and, consequently the presence of any unwanted noise. After the signals were digitized, they were then transferred to the disk and later stored on DEC tape.

Any signal on the disk could be played back and heard through earphones and, if desired, recorded on audiotape. The speech waveform could also be viewed

on the storage oscilloscope. The system was designed<sup>2</sup> so that any portion of the speech could be heard and its corresponding waveform could be displayed simultaneously. Raising a switch on the front panel of the computer permitted a continuous digital-to-analog conversion which allowed a specified portion of speech to be played back repeatedly until the switch was lowered.

The length of the speech segment could be manipulated by means of a continuously variable manual adjustment on the control box. Using this manual control, it was possible to adjust the start and stop times of the segment of speech independently. The control box contained 6 knobs, 3 each for the adjustment of the start and stop times of the speech. The 3 knobs for the start and stop times permitted timing adjustments of the speech signal in steps of .05 msec, 15 msec, or 3 sec. It should be noted that with a sampling rate of 20k Hz, the interval between samples is  $1/20,000$  or .05 msec. It was thus possible, using the manual control, to adjust the

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<sup>2</sup>The system was designed for the present study by Richard White, Ph.D., Doctoral Program in Speech and Hearing Sciences, CUNY, New York, N. Y.

duration of the speech segment with an accuracy equal to the sampling interval of the digitized signal. The start and stop times corresponding to the knob settings were displayed on the keyboard monitor and the values could be read directly from the screen.

### Segmentation Procedures

The 6 sentences produced by each of the 6 deaf children and the 6 normal hearing children were digitized using the interactive computer system. The 72 utterances were then segmented on a phoneme-by-phoneme basis. Before proceeding with a description of the procedures used in this study, a few comments regarding the difficulties encountered in segmenting speech are necessary. The traditional approach to segmenting speech has been to determine the phoneme boundaries by eye from visual inspection of the speech spectrogram. The problem encountered with this approach is that there is not necessarily a one-to-one correspondence between the phonetic segments and the acoustic segments which are displayed on the spectrogram. The reason for this lack of one-to-one correspondence is that the phonemes of a language

are not represented as discrete sounds which are transmitted to the listener in serial order (Liberman et al., 1967). Rather, the phonemic message is a complex perceptual code which is restructured at the level of sound. The spectrogram provides a visual representation of the acoustic signal, but it does so in its unencoded form. As a consequence, definable acoustic segments do not necessarily correspond to segments at the perceptual level.

Although a particular segment does not correspond to a particular phoneme, it can be argued that certain acoustic segments represent the primary, though not complete, acoustic characteristics of a phoneme. Rather than trying to locate these acoustic segments on a spectrogram, an alternative approach is to determine the phoneme boundaries by ear. With this approach, the acoustic signal is segmented in its encoded form and phoneme boundaries are determined on the basis of what is heard by the listener.

In the present study, the primary purpose of the segmentation was not to obtain physical measures of duration per se, but rather to determine what timing adjustments should be made in the deaf children's speech. Since

the timing adjustments would eventually be evaluated auditorily, the specifications for these adjustments were determined, as far as possible, by ear. The phoneme boundaries were specified in terms of the acoustic features heard by the listener. These specifications were then applied to the speech waveform in order to achieve the desired timing adjustments.

The majority of phoneme boundaries (roughly 75%) were established by ear using the interactive computer system. A potential problem exists with this procedure in that audible transients can be introduced as the speech is turned on and off. However, the use of modern computer processing techniques helped to minimize this problem in the present study.

The segmentation was achieved by playing a segment of speech, usually a short phrase and, while keeping the stop time constant, systematically adjusting the start time with the fine manual adjustment on the control box, until the last evidence of the phoneme of interest was heard. A bracketing procedure was used to determine each boundary by repeatedly adjusting the start time in small steps and crossing back and forth over the boundary until the boundary

had been established such that no portion of the adjacent phoneme was heard. Once the final boundary of the phoneme had been established, the start time of the adjacent phoneme was taken as the smallest increment permitted by the resolution of the knob, i.e., .05 msec. Thus, if the final boundary of one phoneme was 585.60 msec, the onset of the boundary for the adjacent phoneme was 585.65 msec. This degree of precision was necessary in defining the phoneme boundaries for the subsequent computer manipulation of the waveform. The degree of precision used in specifying the phoneme boundaries should not be interpreted as representing the accuracy of segmentation. Allowing for uncertainties due to differences in criteria, the accuracy of segmentation is more likely to be on the order of 30 msec. Repeated estimates of the boundary locations revealed that the repeatability of the auditory measures was on the order of 10 to 30 msec.

Segmentation was always accomplished by "cutting off" one phoneme at a time progressing from the initial phoneme of the sentence to the final phoneme of the sentence. In the majority of cases, the phoneme boundaries could be easily established by ear with the aid of contextual

information. For example, Sentence 5 began with the words /ʒə zɪpəʃ /. This portion of the sentence was played and the start time was adjusted until the frication of /ʒ / was no longer audible and only /ə zɪpəʃ / was heard. Adjacent phoneme boundaries were established in the same manner by systematically adjusting the start time until the vowel /ə / was no longer heard and only the segment /zɪpəʃ / was audible. This procedure was continued until all boundaries for the segment of interest had been established.

No attempt was made to segment the two adjacent vowels in Sentence 1 (/ɪə /) and Sentence 5 (/ɔə /). When the timing adjustments were made in the children's speech, each pair of vowels was treated as a single segment. The boundary between glides and vowels was established by listening for a change in vowel color. In the deaf children's speech, these segments were produced more like stressed vowels and the determination of these boundaries was relatively easy.

For roughly 20% of the phonemes, the boundaries could not be accurately determined through audition. These difficult cases were most commonly encountered

when the phoneme of interest was preceded or followed by a silent interval. In these cases, the phoneme boundaries were determined with the visual display of the waveform. A description of these procedures appears in Appendix D.

Occasionally, there were certain problems inherent in attempting to use the same set of rules to segment speech samples produced by the two different groups of speakers. These problems were particularly evident because the speech material consisted of sentences rather than isolated words or syllables. The deaf children frequently paused between words and the normal coarticulatory effects between phonemes of adjacent words was absent. Because of this confounding problem, the criteria for a boundary differed between the normal and deaf speakers. Whenever possible, the differences in the measurement procedures were taken into account when the segment durations were adjusted.

Also there were some ambiguous boundaries in the normal hearing children's speech samples that were not present in the speech of the deaf children. Again, these difficulties arose because the deaf speakers produced

the sentences differently than the normal hearing speakers. For these special cases (roughly 5% of the boundaries) rules were developed so that certain segments could be isolated in the normal speakers utterances which could later be compared to the deaf subjects segments for the timing adjustments. The rules appear in Appendix E.

#### Determination of Syllable Stress

Since failure to temporally differentiate stressed and unstressed syllables is a common problem in the speech of the deaf, the ratio of the duration of stressed to unstressed syllables was examined. The author first listened to the normal hearing children's productions of the 6 sentences and assigned a degree of stress. Two degrees of stress were assigned: stressed or unstressed to each syllable in the sentence. Table 2 shows the stress assignments made.

In order to obtain a stressed/unstressed ratio, each unstressed syllable was then grouped with a stressed syllable in the same phrase. In the majority of cases, the two syllables were adjacent. However, there were some instances in which a stressed syllable was preceded by two or more unstressed syllables in the same phrase.

TABLE 2.--Stress Assignments for the Syllables in Each Sentence. A Syllable which is Stressed is preceded by "'".

æɪ 'θɪŋk hɪd 'bet ə kɪp ə 'weɪ frəm 'hɪrə

dɪd 'dʒæk 'faɪnd ði 'ɔr əndʒ bɔl? æɪ 'nɪd ɪt

æɪ 'wɪʃ aɪ kʊd 'rɪd ðæt 'bʊk

ðə 'wæg ən hæz 'fʊd ænd 'dɪʃ əz ən 'ɪt

ðə 'zɪp ə ən maɪ kʊt ɪz nʊv 'gʊd ən ɪ 'mɔr

hʌ wɪl 'ɪf ðe 'kæt tu 'deɪ

When this happened, the stressed syllable could be paired with more than one unstressed syllable. Table 3 shows the stressed/unstressed syllable pairs.

### Results of the Preliminary Study

#### Sentence Duration

Measures of sentence duration were obtained from the segmentation data for both groups of children. The data are summarized in Table 4. On the average, the deaf speakers took roughly 1.8 times as long to produce the sentences as did the normal hearing speakers and they were more variable on this measure than the normals. Table 5 shows the mean sentence duration for each sentence for each of the deaf subjects ranked in order of duration production. The mean duration for the fastest speaker (#5) is roughly 1.5 times that of the mean sentence duration for the normal hearing speakers while the sentence duration of the slowest deaf speaker (#3) is roughly 2.0 times that of the average normal duration. For all deaf speakers, the increased sentence duration was due both to the prolongation of speech segments and to the insertion of pauses.

TABLE 3.--Stressed and Unstressed Syllable Pairs in Each Sentence

Sentence 1		Sentence 2		Sentence 3	
<u>Stressed</u>	<u>Unstressed</u>	<u>Stressed</u>	<u>Unstressed</u>	<u>Stressed</u>	<u>Unstressed</u>
θŋk	ɑɪ	dʒæk	dɪd	wɪʃ	ɑɪ
bɛt	hɪd	ɔr	ðɪ	rɪd	ɑɪ
bɛt	ɜ	ɔr	ændʒ	rɪd	kʊd
wɛɪ	kɪp	ɔr	bɔl	bʊk	ðæɪ
wɛɪ	ə	nɪd	ɑɪ		
hɪə	fɹəm	nɪd	ɪt		
Sentence 4		Sentence 5		Sentence 6	
<u>Stressed</u>	<u>Unstressed</u>	<u>Stressed</u>	<u>Unstressed</u>	<u>Stressed</u>	<u>Unstressed</u>
wæʒ	ðə	zɪp	ðə	fɪd	hʊ
wæʒ	ən	zɪp	ɜ	fɪd	wɪl
fʊd	hæz	kɔʊt	ən	kæt	ðə
dɪʃ	ænd	kɔʊt	mɑɪ	dɛɪ	tʊ
dɪʃ	ɛz	gʊd	ɪz		
ɪt	ən	gʊd	nɔʊ		
		mɔɜ			

TABLE 4.--Duration of the Sentences, in Seconds, Produced by the Deaf and Normal Hearing Subjects

		Sentence 1			Sentence 2		
Subject	Normal Duration	Deaf		Normal		Deaf	
		Subject	Duration	Subject	Duration	Subject	Duration
1	1.9968	1	3.1931	1	2.1906	1	4.1340
2	1.9072	2	4.8643	2	2.7670	2	3.8565
3	1.8272	3	5.1641	3	2.1432	3	5.5602
4	1.9012	4	2.8932	4	2.1285	4	3.4018
5	1.7210	5	3.3291	5	2.2183	5	3.5410
6	1.6397	6	2.8016	6	2.8168	6	3.4170
Mean	1.8321		3.7075		2.3774		3.9850

		Sentence 3			Sentence 4		
Subject	Normal Duration	Deaf		Normal		Deaf	
		Subject	Duration	Subject	Duration	Subject	Duration
1	1.2928	1	2.6198	1	1.9561	1	3.3381
2	1.6287	2	2.8223	2	1.8989	2	3.8285
3	1.3778	3	3.0976	3	1.6384	3	5.0855
4	1.2951	4	2.4153	4	1.9073	4	3.3199
5	1.4693	5	2.2515	5	1.6938	5	2.8479
6	1.4393	6	2.2207	6	1.6794	6	3.2431
Mean	1.4171		2.5712		1.7956		3.6105

TABLE 4.--Continued

	Sentence 5		Sentence 6	
	Normal Subject Duration	Deaf Subject Duration	Normal Subject Duration	Deaf Subject Duration
1	2.2273	4.5871	2.2154	2.9184
2	2.3394	4.3030	1.2844	3.2238
3	2.1376	5.1486	1.3457	3.6074
4	2.0224	3.5347	1.2732	2.2776
5	1.9818	3.2432	1.3382	1.7175
6	2.0737	4.1687	1.3569	2.0752
Mean	2.1304	4.1642	1.4689	2.5166

TABLE 5.--Mean Sentence Duration for Each of the Deaf Subjects. The children are ranked in order of duration of production.

<u>Subject</u>	<u>Mean Sentence Duration</u>
5	2.82 sec.
6	2.98 sec.
4	2.99 sec.
1	3.46 sec.
2	3.81 sec.
3	4.23 sec.

### Syllable Duration

Data on syllable durations were also obtained for the two groups of children. Figures 3 through 8 show the mean durations and the standard deviations for each of the syllables in the 6 sentences. The syllable duration for the deaf children is the sum of the durations of the speech segments that were actually produced by the children. If phonemes in a syllable were omitted, the syllable duration was computed by summing any portion of the syllable that was produced. Thus, some of the syllable durations are actually shorter than would be expected if all segments in the syllables had been present in the deaf children's speech.

The data show that, on the average, the duration of syllables is longer in the speech of the deaf subjects than in the speech of the normal hearing subjects. Of the total sample of 56 syllables, 48 (85%) of the syllables produced by the deaf children are longer. For the majority of cases (43 of the 56 syllables), the syllable duration of the deaf subjects fails to fall within one standard deviation of the normal hearing group. There is also greater variability among the deaf speakers as evidenced

Fig. 3. Mean duration and standard deviation of the syllables in Sentence 1 for the two groups of subjects.

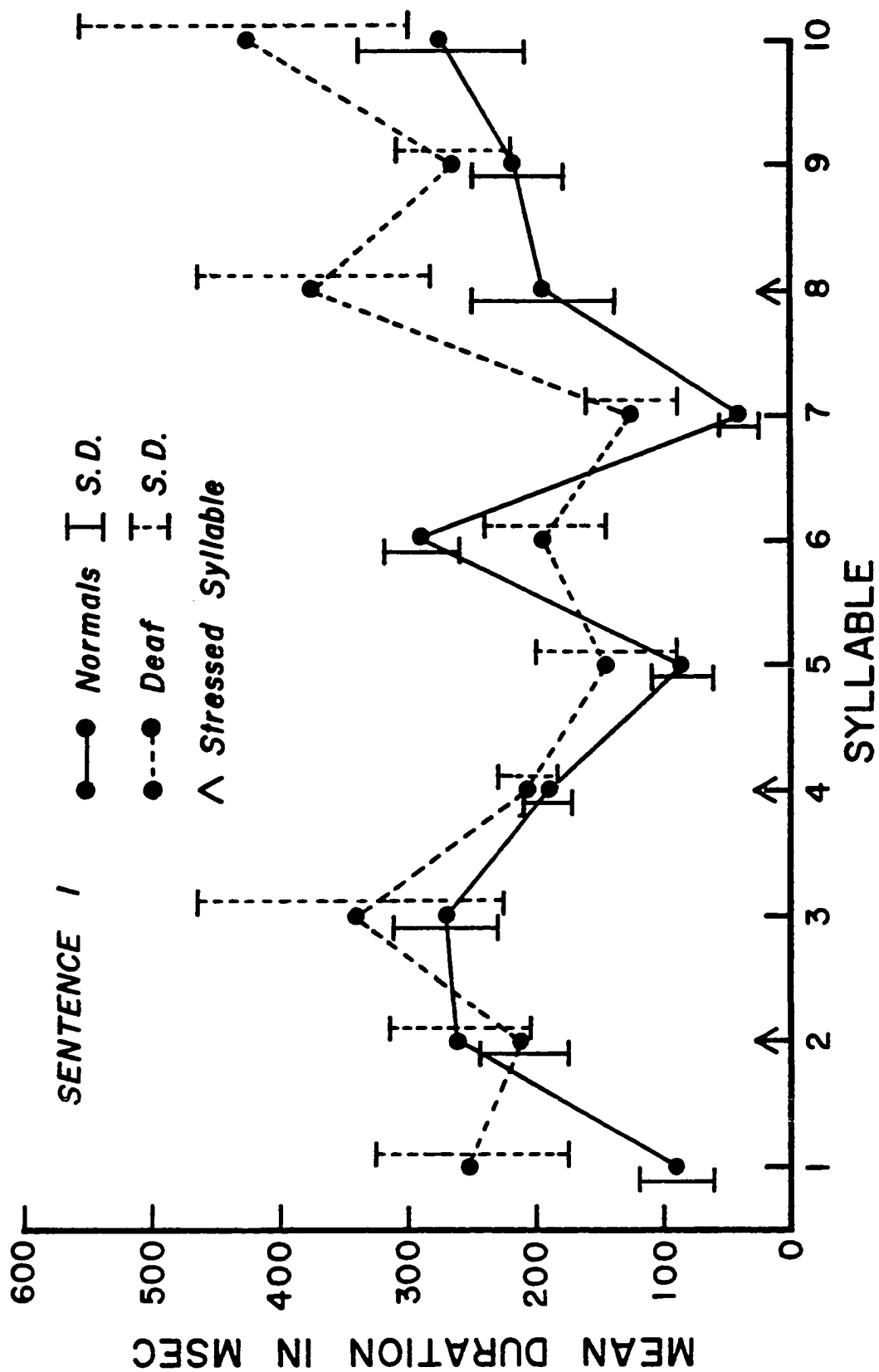


Fig. 4. Mean duration and standard deviation of the syllables in Sentence 2 for the two groups of subjects.

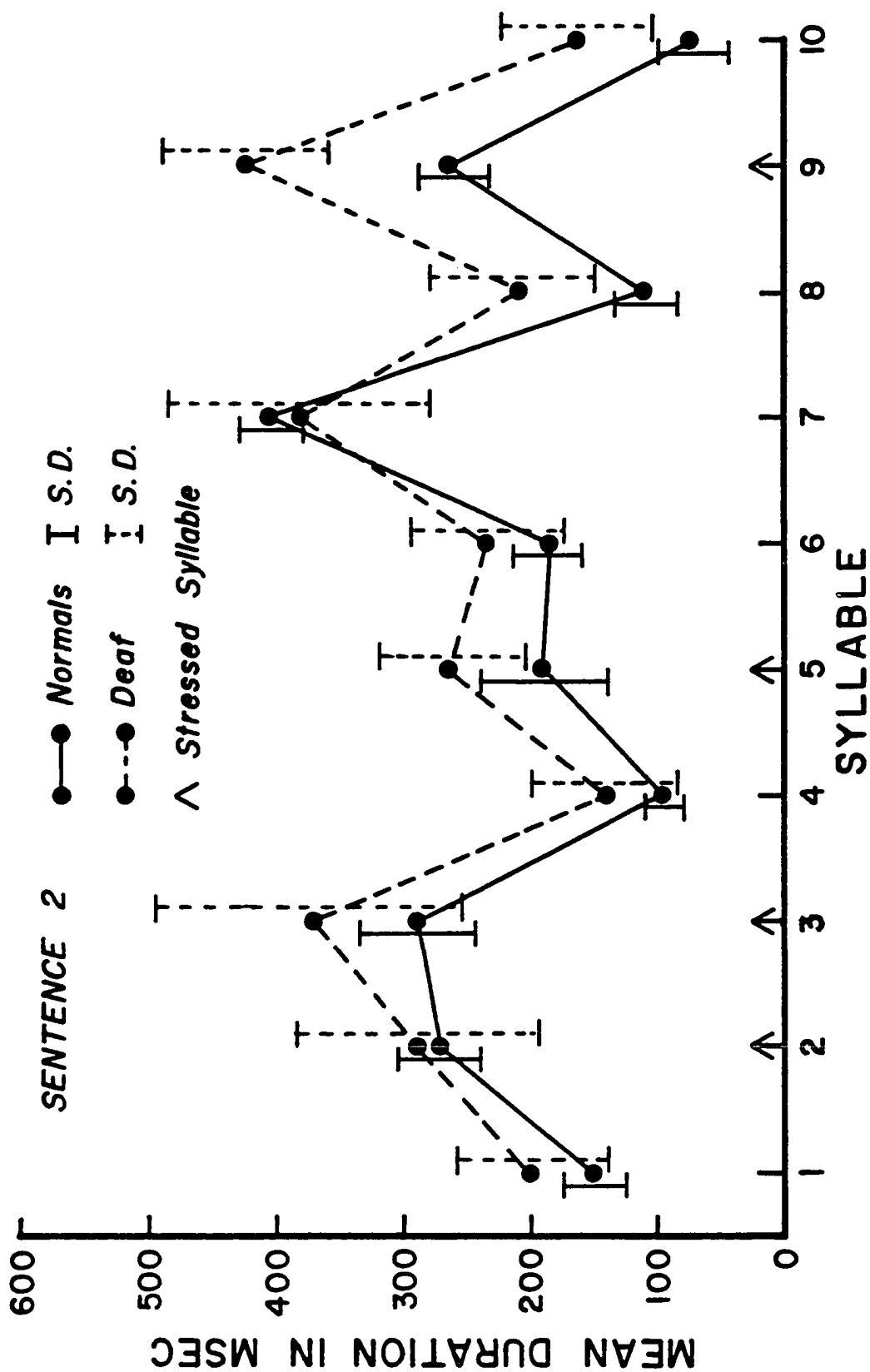


Fig. 5. Mean duration and standard deviation of the syllables in Sentence 3 for the two groups of subjects.

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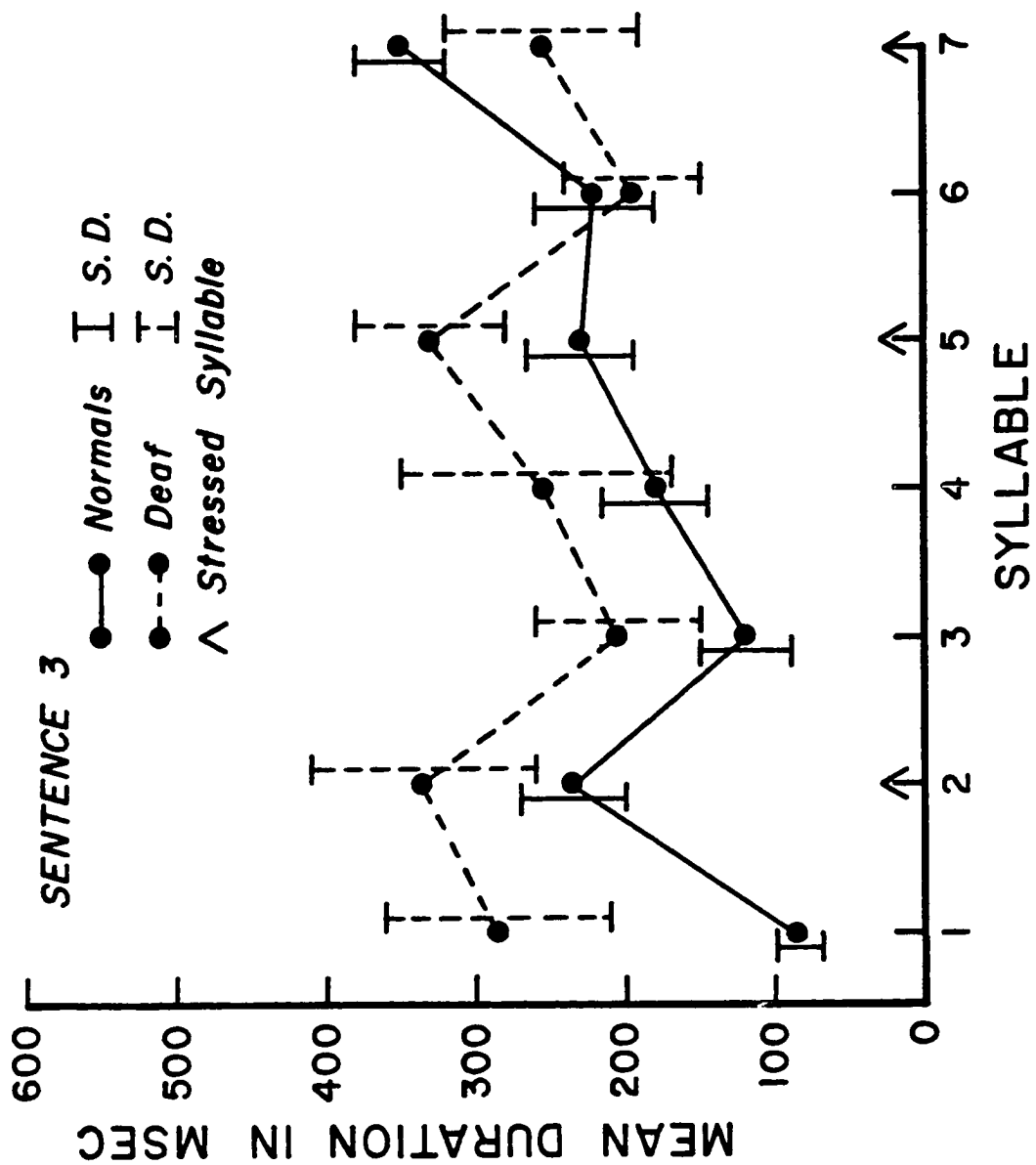


Fig. 6. Mean duration and standard deviation of the syllables in Sentence 4 for the two groups of subjects.

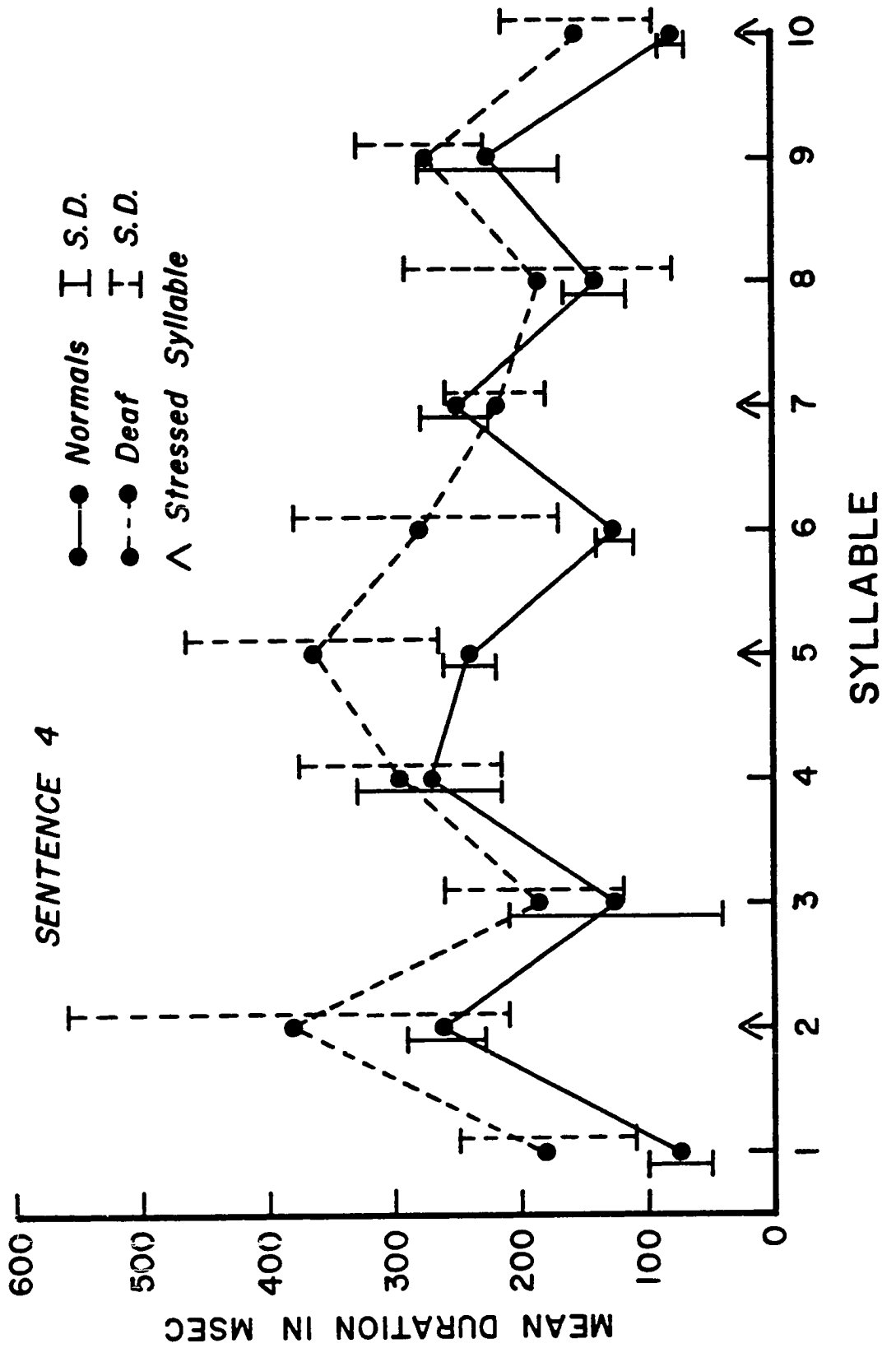


Fig. 7. Mean duration and standard deviation of the syllables in Sentence 5 for the two groups of subjects.

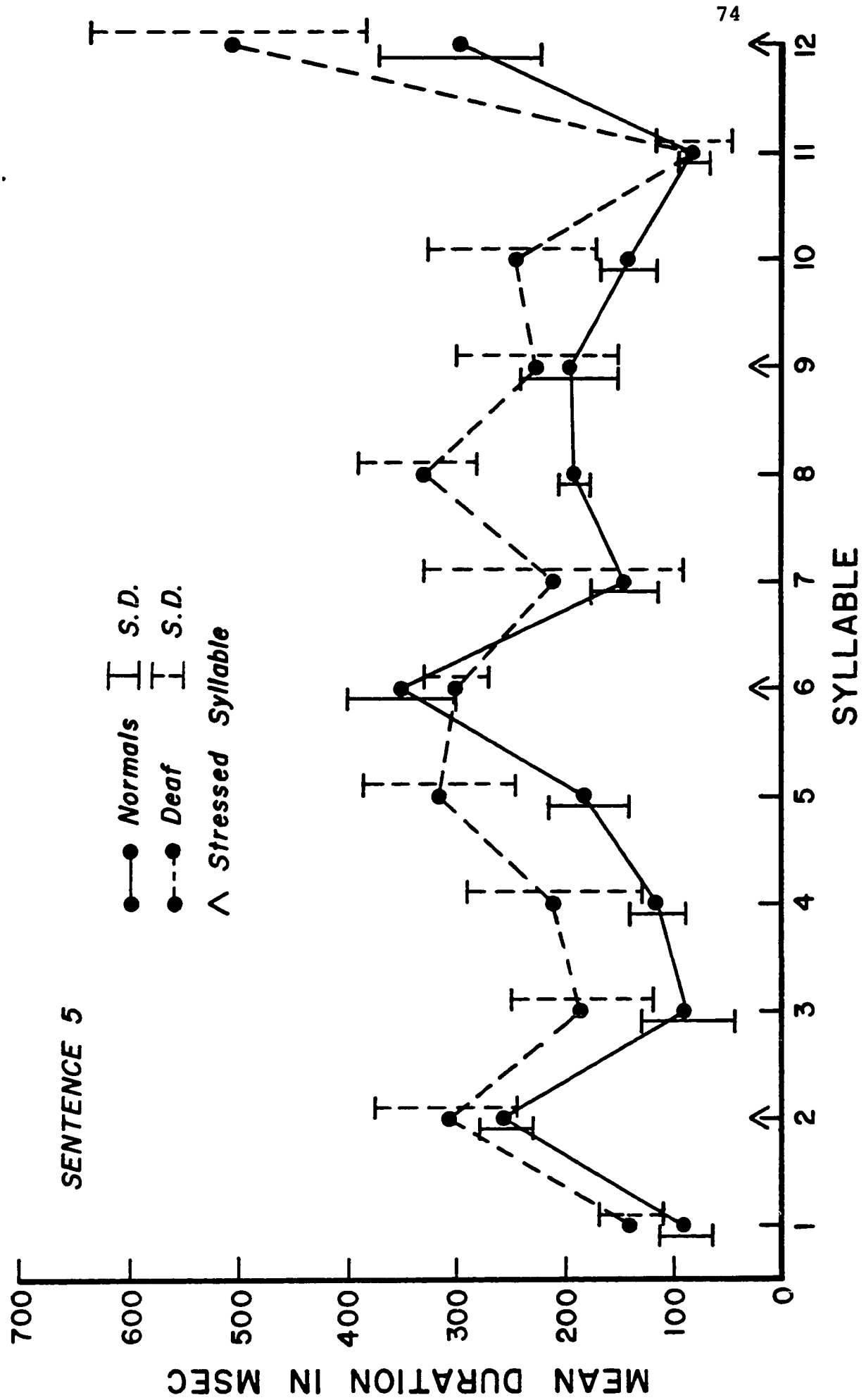
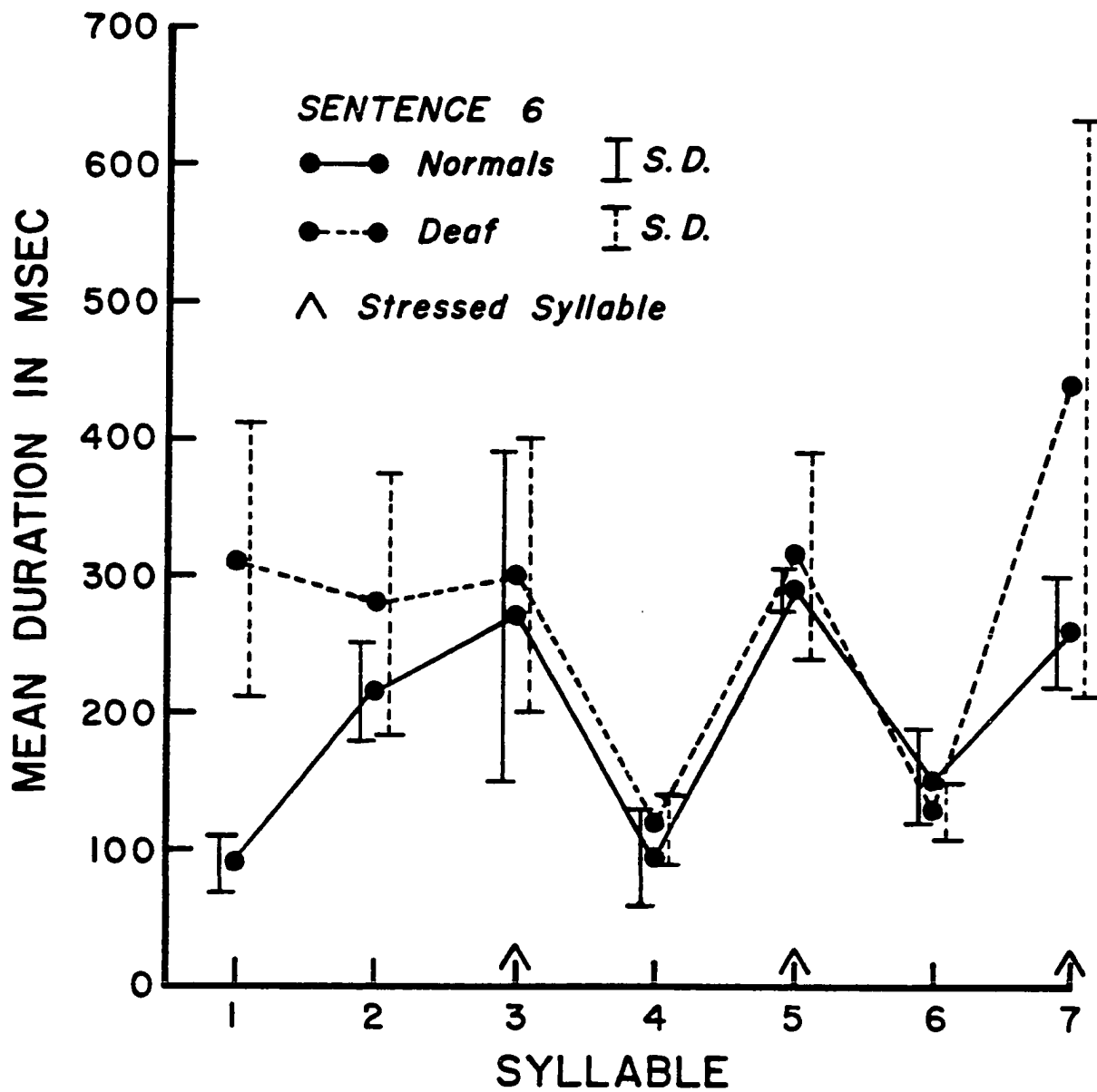


Fig. 8. Mean duration and standard deviation of syllables in Sentence 6 for the two groups of subjects.

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by the larger standard deviations. Even for those syllables in the deaf children's speech which are shorter in duration than those of the normal hearing group, the standard deviations are generally larger for the deaf speakers.

An examination of those syllables in the deaf children's speech which were shorter in duration than those of the normal hearing group revealed that this probably occurred for one of two reasons. First, phonemes were omitted in all but one of these syllables. When the two groups were compared on the basis of vowel duration, the duration of the vowels in these syllables was substantially longer in the deaf children's samples than in the normal hearing children's samples. Thus, the reduced duration of these syllables appears to be due, in part, to the omission of phonemes.

Secondly, the syllable durations in the deaf children's speech may have been shorter because of a measurement artifact. Five of the 7 syllables contained a word-initial plosive and the segmentation procedures used to measure the durations of these segments was different for the two groups of children. The deaf children

paused between words and it was not possible to differentiate the termination of a pause from the onset of the plosive closure. Because of this ambiguity, only the duration of the noise burst was used to represent the duration of plosives in the deaf children's speech. However, the duration of word-initial plosives in the normal hearing children's speech was measured to include both the duration of the closure period and the noise burst. Because of the differences in the segmentation procedures, the duration of plosives was substantially shorter in the deaf children's speech than in the normal hearing children's speech. Whereas the duration of the plosives contributed substantially to the overall syllable duration in the normal hearing children's speech, the reverse was true for the deaf children.

The syllable duration data was examined using a two-way analysis of variance with the following factors: Group (Hearing and Deaf) and Syllable. The results of the analysis of variance are shown in Table 6. The data reveal significant differences in syllable duration between the two groups of speakers on all 6 sentences. Significant differences are present in the

TABLE 6.--Analysis of Variance: Syllable Duration (Group by Syllable)

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance
Sentence 1					
Group (G)	16118.813	1	16118.13	34.48	0.000
Syllable (S)	666910.75	9	74101.19	15.86	0.000
G x S	249414.25	9	27712.69	5.93	0.000
Residual	467331.00	100	4673.31		
Total	1544744.00	119	12981.29		
Sentence 2					
Group (G)	124921.94	1	124921.94	30.63	0.000
Syllable (S)	1045980.56	9	116220.06	28.49	0.000
G x S	74219.12	9	8246.57	2.00	0.044
Residual	407906.00	100	4079.06		
Total	1653027.00	119	13890.98		
Sentence 3					
Group (G)	83562.25	1	83562.25	25.62	0.000
Syllable (S)	217968.63	6	36328.10	11.14	0.000
G x S	160236.31	6	26706.05	8.19	0.000
Residual	228287.81	70	3261.25		
Total	690055.13	83	8313.91		

TABLE 6.--Continued

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance
Sentence 4					
Group (G)	161938.44	1	161938.44	25.25	0.000
Syllable (S)	566648.94	9	62960.99	9.82	0.000
G x S	82201.19	9	9133.47	1.42	0.188
Residual	628575.00	98	6414.03		
Total	1448315.00	117	12378.76		
Sentence 5					
Group (G)	226768.00	1	226768.44	53.08	0.000
Syllable (S)	1118648.00	11	101695.25	23.80	0.000
G x S	155333.31	11	14121.21	3.31	0.001
Residual	512698.00	120	4272.48		
Total	2013448.00	143	14080.06		
Sentence 6					
Group (G)	112376.38	1	112376.38	13.63	0.000
Syllable (S)	571509.38	6	95251.56	11.55	0.000
G x S	153646.44	6	25607.74	3.11	0.009
Residual	577121.75	70	8255.59		
Total	1414654.00	83	17044.02		

duration of syllables within a given sentence and there are significant interactions between the two factors for 4 (Sentences 1, 2, 3, 5) of the 6 sentences. The syllable durations for the two groups of speakers appear in Appendix F.

### Phoneme Durations

The speech of the two groups of children was also compared on the basis of phoneme duration. The deaf children typically prolonged the duration of vowels, glides and nasals whereas the duration of fricatives and affricates were typically shorter in the deaf children's speech than in the normal hearing children's speech. Accurate comparison of plosive duration could not be made because of the different segmentation procedures used to measure the boundaries of these segments in the speech of the two groups of children. On the basis of these findings, it appears that the increased syllable duration in the speech of the deaf children is primarily due to the increase in vowel duration and, the duration of consonants appears to contribute very little to the overall prolongation of syllable duration. The phoneme

durations for the 12 children appear in Appendix G.

### Relative Duration of Stressed and Unstressed Syllables

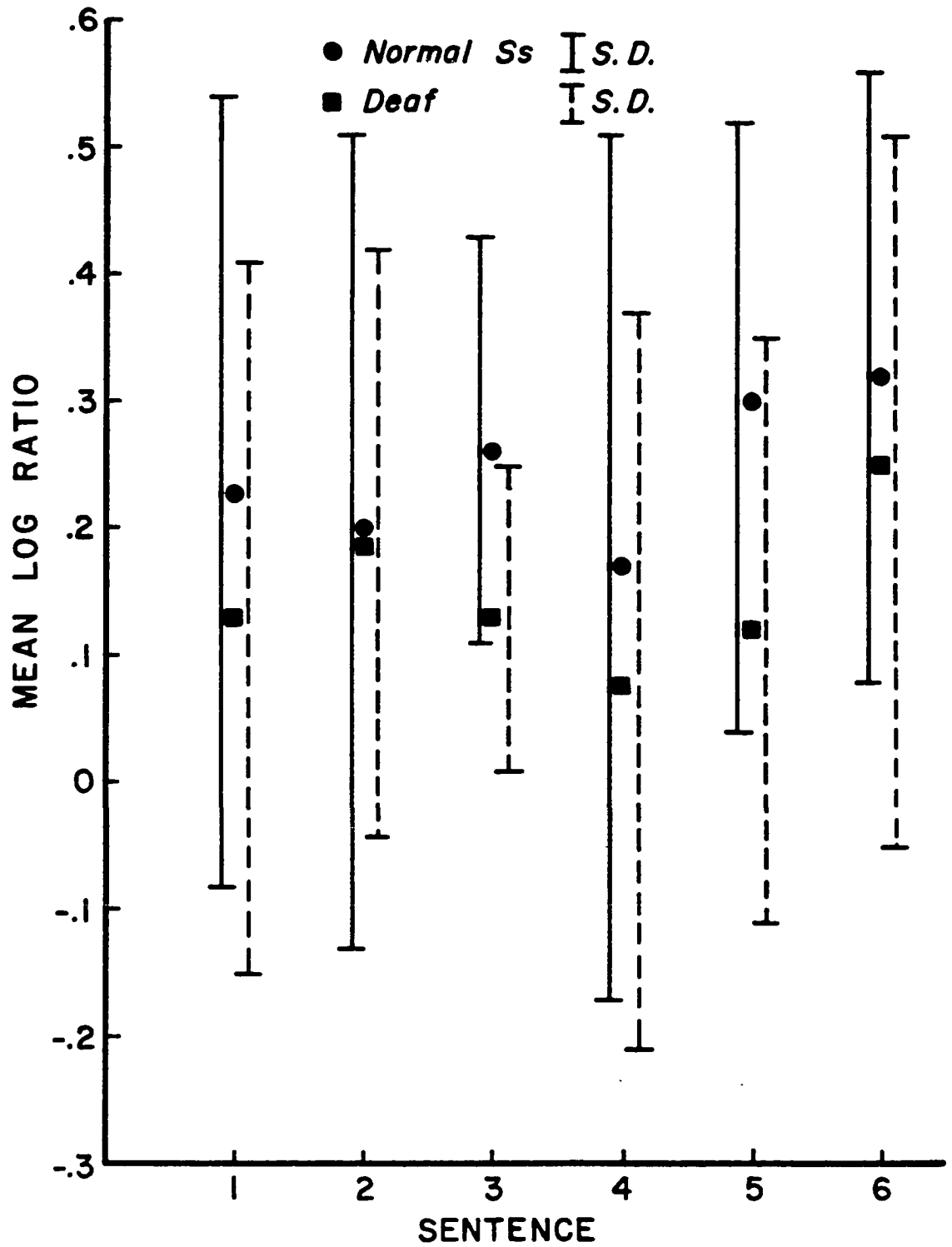
As shown in Figures 3-8, the duration of the stressed syllables is generally longer than the duration of the unstressed syllables in the speech of the normal hearing children. There are, however, some stressed syllables which are shorter in duration than the unstressed syllables. In these cases, the stressed syllables consist of fewer speech segments than the unstressed syllables or, the vowels in the stressed syllables are intrinsically shorter in duration than those in the unstressed syllables.

The temporal relationship between stressed and unstressed syllables in the deaf children's speech approximates that of the normal speakers for some of the syllables. This is particularly evident for some of the syllables in Sentences 2, 4, and 6. In these sentences, the line connecting the data points of the deaf subjects lies above that of the normal subjects but the shape of the curves is very similar. In order to more closely examine the relative timing in the children's

speech, the ratio of the duration of each stressed syllable to the duration of the unstressed syllable of each syllable pair was computed for all the sentences. The data are summarized in Figure 9 which shows the mean ratio for the syllable pairs in each sentence. Also, the analysis included all syllables produced by the deaf children even if some phonemes were omitted from the syllables. The ratios have been converted to logarithmic units (base 10) to reduce the spread of the data points.

The data show that, on the average, the duration of unstressed syllables is shorter than the duration of stressed syllables in the sentences produced by both groups of children. However, the syllable ratios are much smaller in the deaf children's speech than in the speech of the normals. The differences in the size of the ratios between the two groups of children is particularly evident on Sentences 1, 3, and 5. The reduced ratios indicate that while the average duration of unstressed syllables is shorter than the duration of stressed syllables in the speech of the deaf children, the proportional shortening of unstressed syllables is

Fig. 9. Mean duration ratio in logarithmic units (base 10) and standard deviation of the syllable pairs in each sentence for the two groups of subjects.



smaller, on the average, in the deaf children's speech than in the normal hearing children's speech. The variability of the ratios is quite large for both groups of children as evidenced by the large standard deviations. For some of the sentences, the standard deviation for the normal group is larger than that of the deaf group. The ratios of the syllable pairs in each sentence for all 12 children appear in Appendix H.

A two-way analysis of variance was performed on the syllable ratios with the following factors: Group (Hearing and Deaf) and Syllable Pair. The results are shown in Table 7. Significant differences are present in the syllable ratios between the two groups of children for Sentences 1, 3, and 5. With the exception of Sentence 3, there are significant differences in the syllable ratios within a given sentence. Significant interactions between the two factors are present for Sentences 1, 3, 4 and 6.

#### Syllable Durations in the Speech of Each Child

An additional analysis was performed in order to obtain more specific information about the timing patterns in each deaf child's speech. In this analysis, the

TABLE 7.--Analysis of Variance: Syllable Ratios (Group by Syllable Pair)

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance
Sentence 1					
Group (G)	0.16	1	0.16	5.16	0.027
Syllable Pair (SP)	2.70	5	0.54	17.23	0.000
G x SP	1.76	5	0.35	11.20	0.000
Residual	1.88	60	0.03		
Total	6.50	71	0.09		
Sentence 2					
Group (G)	0.00	1	0.00	0.11	0.745
Syllable Pair (SP)	4.31	5	0.86	44.36	0.000
G x SP	0.24	5	0.05	2.48	0.042
Residual	1.17	60	0.02		
Total	5.72	71	0.08		
Sentence 3					
Group (G)	0.22	1	0.22	17.20	0.000
Syllable Pair (SP)	0.17	3	0.06	4.61	0.007
G x SP	0.24	3	0.08	6.45	0.001
Residual	0.50	40	0.01		
Total	1.13	47	0.02		

TABLE 7.--Continued

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance
Sentence 4					
Group (G)	0.09	1	0.09	3.24	0.007
Syllable Pair (SP)	4.56	5	0.91	31.86	0.000
G x SP	0.63	5	0.13	4.43	0.002
Residual	1.63	57	0.03		
Total	6.93	68	0.10		
Sentence 5					
Group (G)	0.55	1	0.55	19.76	0.000
Syllable Pair (SP)	2.31	6	0.39	13.94	0.000
G x SP	0.36	6	0.06	2.16	0.058
Residual	1.93	70	0.03		
Total	5.14	83	0.06		
Sentence 6					
Group (G)	0.09	1	0.09	3.13	0.082
Syllable Pair (SP)	1.17	3	0.39	13.76	0.000
G x SP	0.89	3	0.30	10.42	0.000
Residual	1.13	40	0.03		
Total	3.28	47	0.07		

syllable durations in each deaf child's speech was plotted as a function of the average syllable duration of the normal hearing children, excluding syllables with phoneme omissions. The data are summarized in Figures 10 through 15. The straight line represents the relationship that would be observed if the syllable durations in the deaf child's speech were identical to the average normal syllable duration. The distance between the data points and the straight line shows the extent that the syllable durations in each child's speech deviated from the average normal syllable duration.

It should first be mentioned that the data points which fell below the straight line for all children typically represented the durations of syllables with initial plosives, probably because different segmentation rules were used to measure the durations of these phonemes in the speech of the two groups of children.

The syllable durations of Subjects 1, 2 and 3 show the greatest deviation from the mean normal durations. As shown by the dispersion of data points, only a few syllables in these children's speech approximates the average duration of the normal hearing speakers. In

Fig. 10. Syllable durations of Deaf Subject 1 plotted as a function of the mean normal syllable duration.

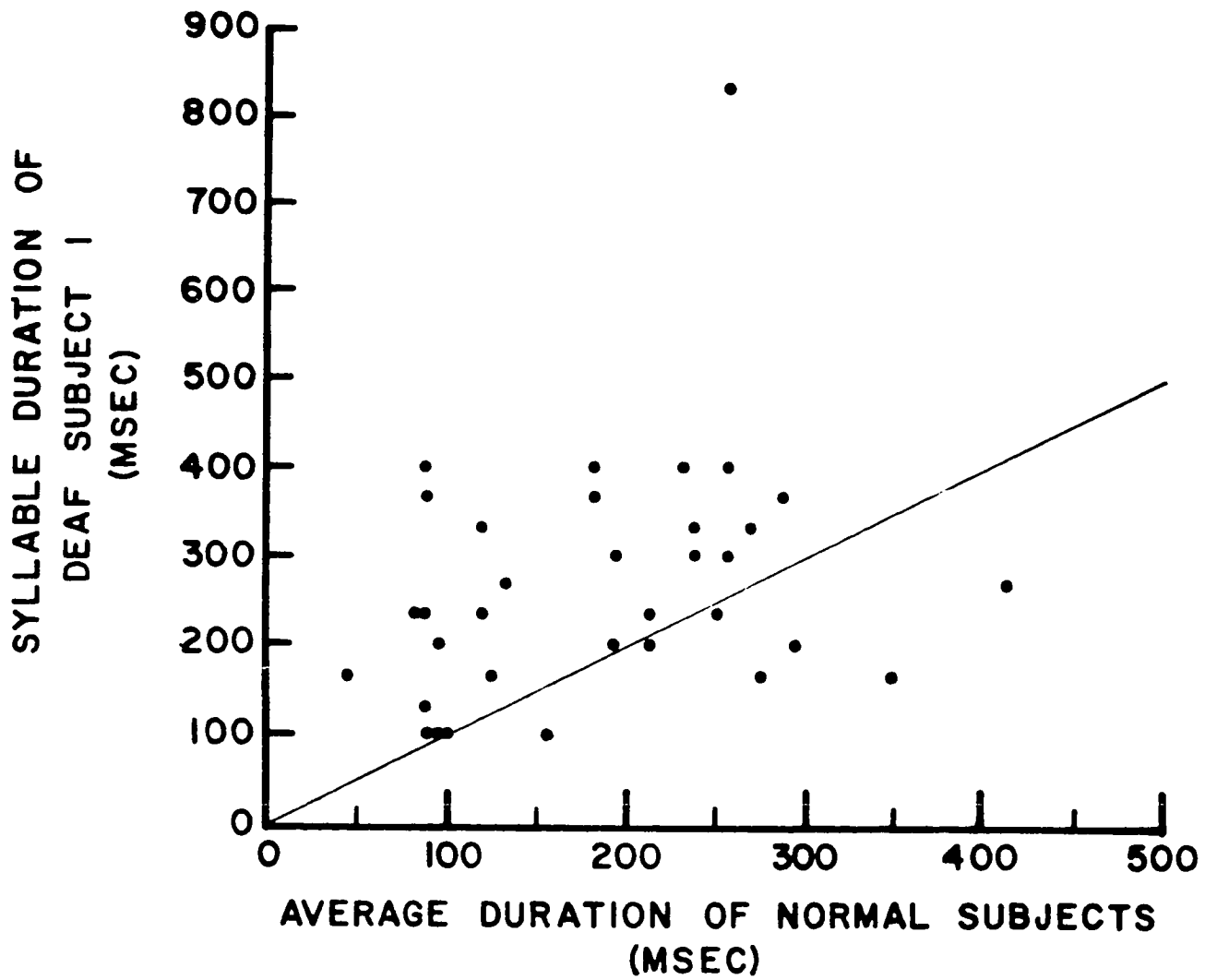


Fig. 11. Syllable durations of Deaf Subject 2 plotted as a function of the mean normal syllable duration.

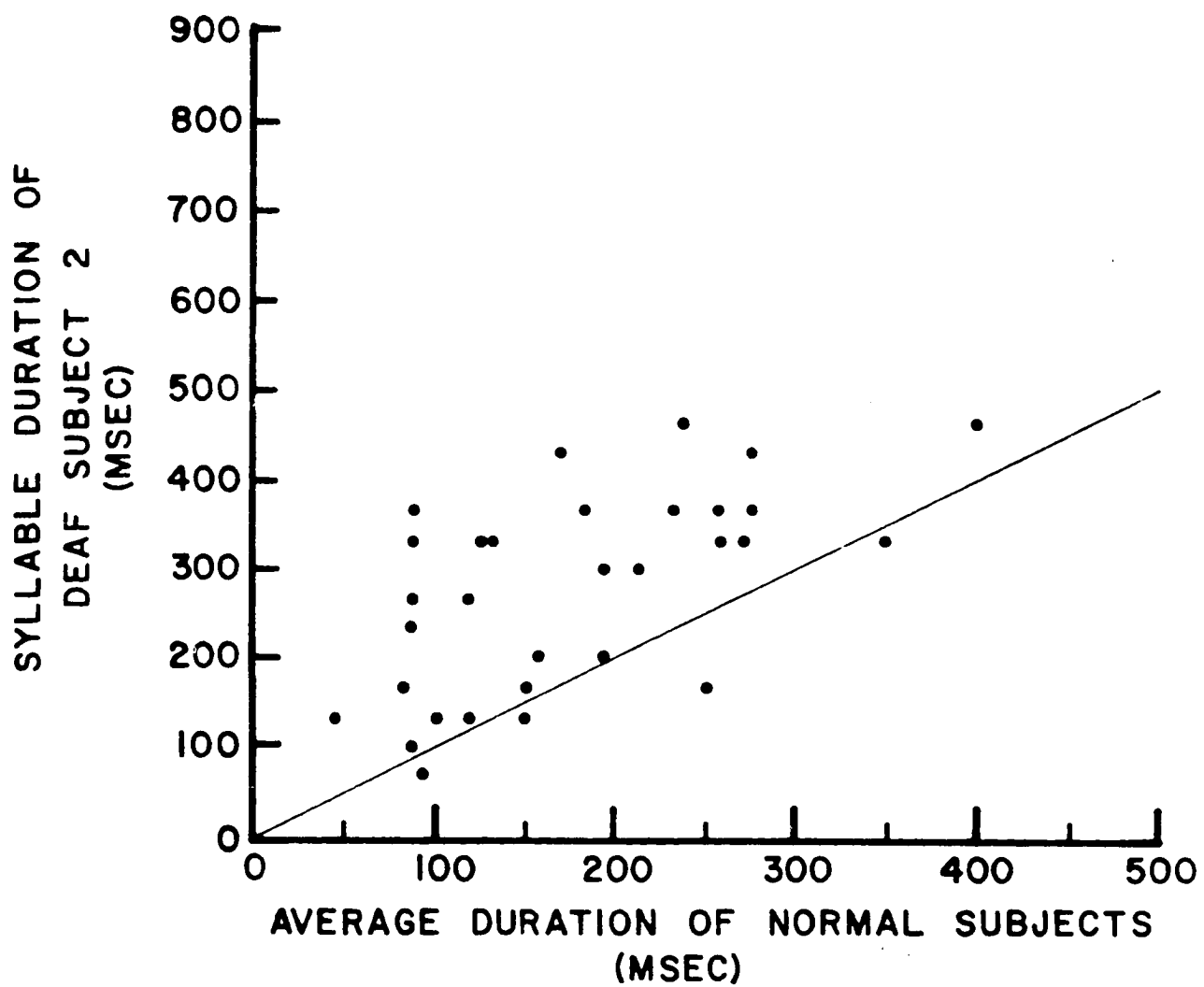


Fig. 12. Syllable durations of Deaf Subject 3 plotted as a function of the mean normal syllable duration.

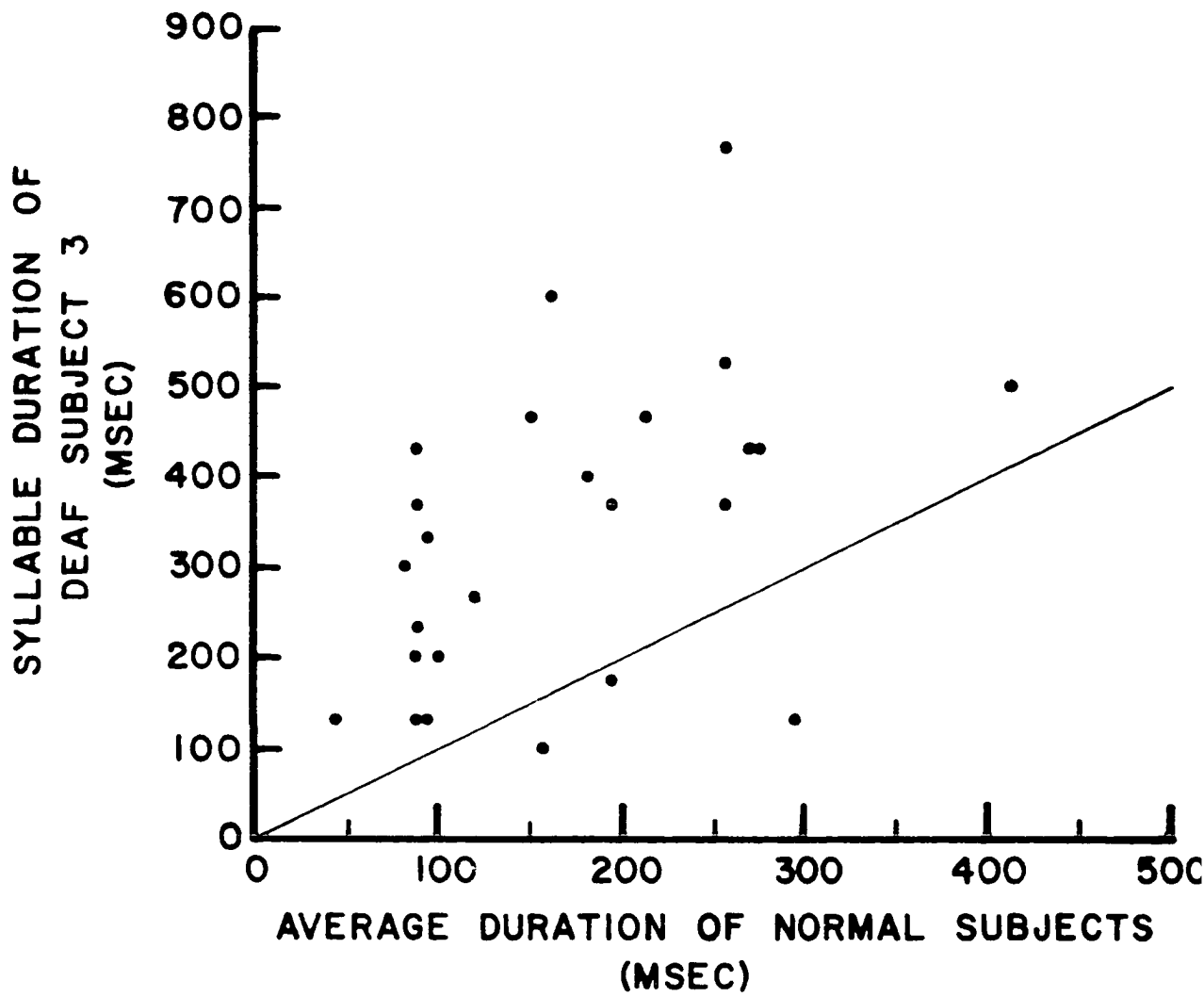


Figure 13. Syllable durations of Deaf Subject 4 plotted as a function of the mean normal syllable duration.



Fig. 14. Syllable durations of Deaf Subject 5 plotted as a function of the mean normal syllable duration.

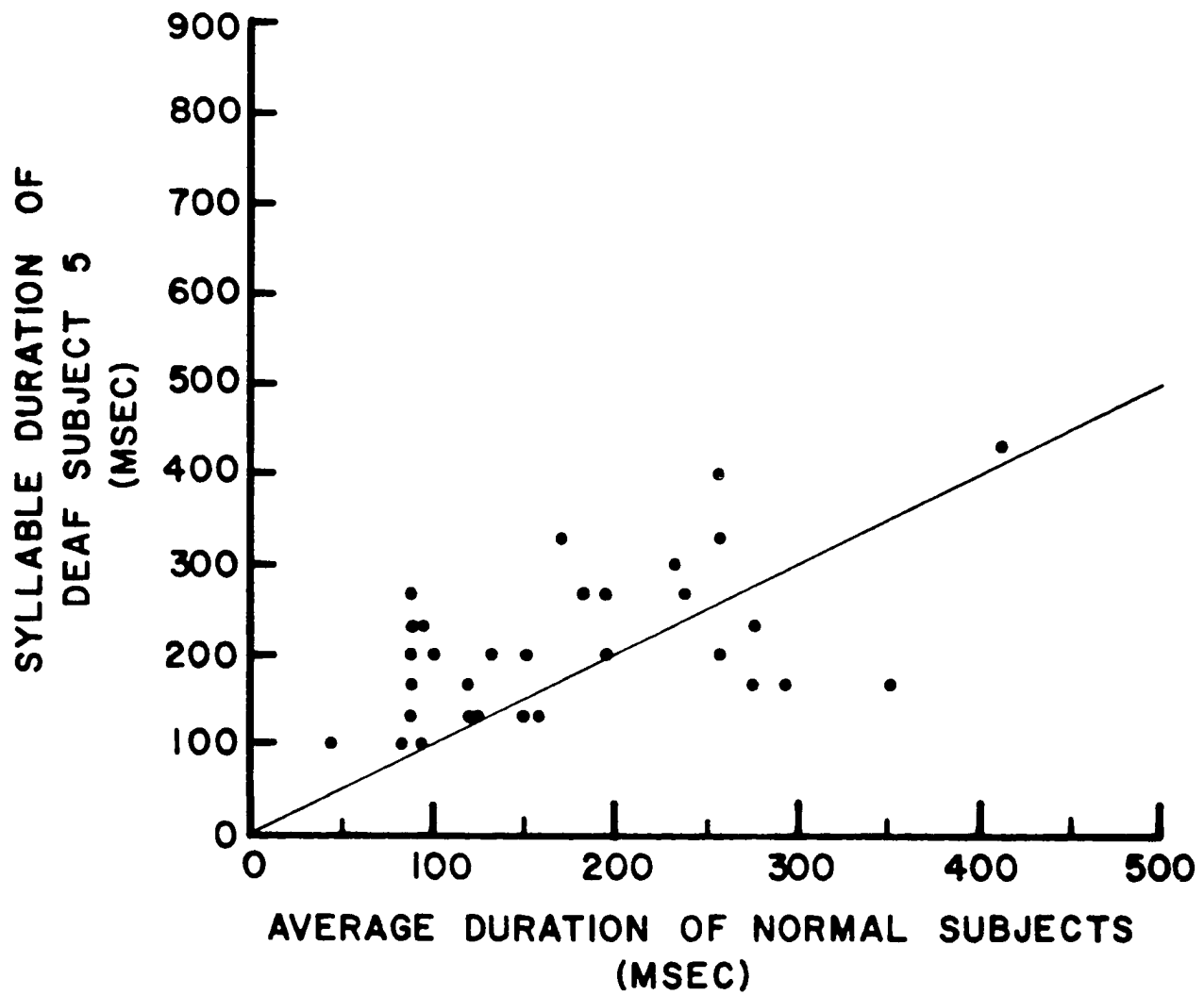
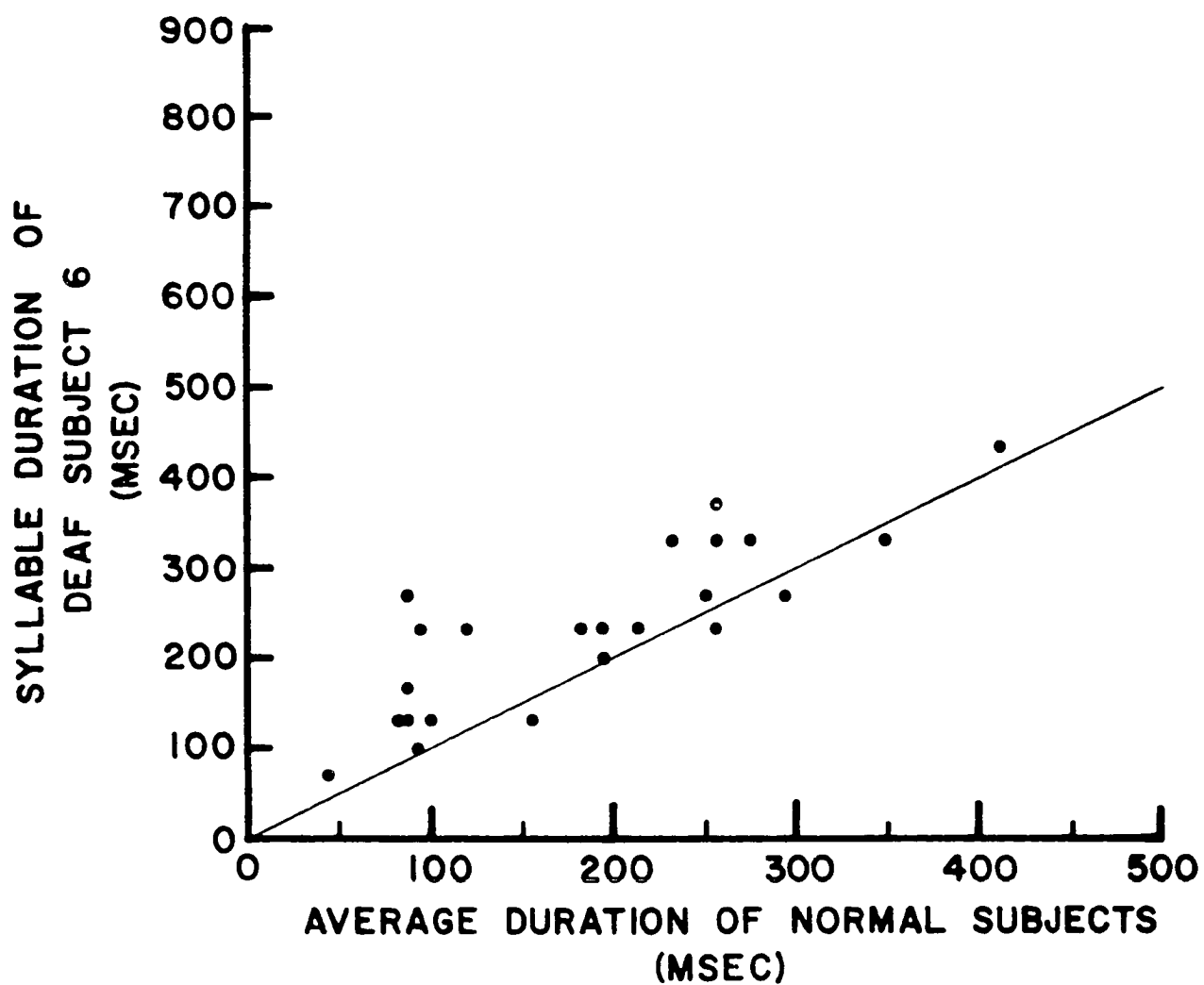


Fig. 15. Syllable durations of Deaf Subject 6 plotted as a function of the mean normal syllable duration.



contrast to this, the syllable durations for Subjects 4, 5 and 6 more closely approximate the average normal syllable duration. The greatest deviation from the average normal duration in these children's speech appears to be for syllables of short duration. That is, when the average normal syllable duration is roughly 150 msec or less, the three subjects show a greater prolongation of syllable duration than if the average normal syllable duration exceeds roughly 150-200 msec.

#### Pauses

There was no evidence of within-phrase or within-sentence pauses in the speech of the normal hearing children. For the deaf, the number of pauses present in each of the sentences produced by each of the deaf children are summarized in Table 8. The data show that the greatest number of pauses occur in Sentences 1, 2, 4 and 5 and relatively fewer pauses are present in the other two sentences. This is not an unexpected finding since Sentences 1, 2, 4 and 5 contain more words and, therefore, there is more opportunity for the deaf children to pause. Subject 4 pauses more often than the other subjects, followed by Subjects 1, 3, 2, 5 and 6.

TABLE 8.--Number of Pauses in Each Deaf Child's Speech

Subject Number	Sentence						Subject Average
	1	2	3	4	5	6	
1	6	7	5	8	6	5	6.2
2	6	5	4	7	6	5	5.5
3	6	8	5	5	6	5	5.8
4	8	6	6	8	7	6	6.8
5	6	6	3	6	7	4	5.3
6	3	6	4	5	6	5	4.8
Sentence Average	5.8	6.3	4.5	6.5	6.3	5.0	

The number of pauses was examined using a two-way analysis of variance with the following factors: Child and Sentences. The results of the analysis of variance are shown in Table 9. The data show that the differences in the number of pauses produced by the children is significant. In addition, there are significant differences between sentences in the number of pauses.

An examination of the pause data also showed that the number of pauses for a sentence is conditioned by phonetic factors. If the initial and final phonemes of adjacent syllables is a plosive, fricative or affricate, the deaf children generally pause between the two syllables. They typically do not pause between syllables if the adjacent phonemes of the two syllables consist of either a vowel, semivowel, glide or nasal. The location of the pauses in each sentence and the duration of the pauses appear in Appendix I.

Table 10 shows the average pause duration for all 6 sentences for each of the 6 children. The children are ranked in order of the length of the pause duration. On the average, there is very little difference in the duration of the pauses for Subjects 6, 5, 1, and 4. However,

TABLE 9.--Analysis of Variance: Number of Pauses  
(Subject by Sentence)

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance
Subject (R)	14.58	5	2.92	3.33	0.019
Sentence (S)	20.25	5	4.05	4.62	0.004
R x S	21.92	25	0.88		
Total	56.75	35			

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TABLE 10.--Mean Duration of Pauses in the Deaf Children's Speech. The children are ranked in order of pause duration.

Subject Number	Mean Pause Duration
6	130.9 msec
5	145.2 msec
1	151.9 msec
4	165.1 msec
2	216.5 msec
3	224.1 msec

the duration of the pauses in the speech of Subjects 1 and 2 is considerably longer than the duration of the pauses in the speech of the other four subjects. Subjects 5 and 6 not only have fewer pauses (as shown in Table 8) in their speech, but the pauses are of shorter duration than those in the speech of the other four children.

#### Identification of the Median Normal Speaker

In addition to the above analyses, an additional analysis was performed in order to identify the median normal speaker. The median normal speaker for a given sentence was defined as that speaker whose phoneme durations were the closest to the average for all six children. This analysis was performed because it was decided at this stage of the study that the timing patterns of the median normal speaker were to be used to determine the desired durations for the deaf children's speech segments. Initially, adjustment of the deaf children's speech samples so that the altered segment durations matched the average durations for the normal hearing children was considered. However, the resulting timing

patterns in the deaf children's speech would have represented the timing patterns of a hypothetical rather than a real speaker.

In order to identify the median normal speaker, the squared deviation from the mean duration for each phoneme was computed for each phoneme in each sentence for each normal hearing child. The child with the smallest mean squared deviation was taken as the median normal speaker for each sentence. Table 11 shows the median normal speaker for each of the sentences.

#### Summary of the Results of the Preliminary Study

The results show that, on the average, the deaf children took longer to produce the utterances than did the normal hearing subjects. The increased sentence duration was both due to the prolongation of speech segments and to the insertion of pauses. On the average, the syllables produced by the deaf children were longer in duration than those produced by the normal hearing subjects. The deaf children typically prolonged the duration of vowels, semivowels, glides and nasals whereas the duration of consonants were usually shorter in the deaf children's speech than in the normal hearing children's

TABLE 11.--Mean Squared Deviation for the Six Normal Hearing Children for the Six Sentences

Subject Number	Sentence					
	1	2	3	4	5	6
1	515.9	2843.3	340.3*	1316.3	1734.3	2072.0
2	373.2	1415.5	1142.7	286.6	899.6	359.4
3	337.8*	1921.5	396.4	352.7	656.1	439.9
4	667.5	1455.0	416.3	1273.9	308.8*	303.9
5	1392.3	756.3*	340.6	236.9*	704.1	255.7*
6	703.2	6421.0	437.8	446.9	498.0	693.3

\* Median Normal Speaker

speech. The increased duration of syllables in the deaf children's speech appeared to be due primarily to the increased duration of vowels or vowel-like segments.

The deaf children distorted the duration ratio of stressed/unstressed syllables by extending the duration of the unstressed syllable. On the average, the durational differences between the stressed and unstressed syllables was much smaller in the deaf children's speech than in the normal hearing children's speech.

An examination of the data for individual children revealed that the syllable durations of Subjects 1, 2, and 3 showed the largest deviation from the mean normal duration.

The deaf children paused frequently with-in and between phrases. Some children paused significantly more often and, the duration of the pauses was substantially longer in some children's speech than in others.

The results of this study are consistent with those reported by other investigators. The most common timing errors involve the prolongation of speech segments, the distortion of the temporal relationship between stressed and unstressed syllables and the insertion of

pauses. On the basis of these findings a decision was made to correct the following timing errors in the children's speech: 1) absolute syllable duration 2) relative timing errors (stressed/unstressed ratio and 3) pauses.

### Experimental Procedures for the Main Study

#### Manipulation of the Speech Waveform

The interactive computer system was used to alter the timing patterns of the children's speech samples. The timing adjustments were accomplished by direct manipulation of the speech waveform. Once the phoneme boundaries had been established, each pitch period in the segment of interest (a vowel, diphthong, glide, semi-vowel or nasal) was identified using a semi-automatic technique. In order to accurately identify the periods, the fine manual adjustment on the control box was used to locate the region of the zero crossings for each of the periods. Initially the knobs on the box were adjusted until the peak of the first pitch period of interest was display on the storage oscilloscope. The zero crossing just before the major peak was determined auto-

matically by the computer.<sup>3</sup> This information (the time location of the zero crossings) was then automatically stored for subsequent use in the speech processing stage. The zero crossings for successive pitch periods were located and stored in the same manner (one at a time) until the end of the speech segment was reached.

Once the zero crossings had been located and stored, the speech segments were shortened (or lengthened) by eliminating (or adding) whole pitch periods and rejoining the waveform at the zero crossings. Since all changes were made at the zero crossings, it was possible to make the timing adjustments in the speech samples with only minor audible distortions. Computer sub-routines were developed so that a specified percentage of pitch periods in the waveform could be deleted automatically. In order to lengthen a segment, a specified percentage of periods could be duplicated. Using this procedure it was possible to alter the duration of each segment individually.

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<sup>3</sup>The user programs for this system were developed by Mr. Harvey Stromberg, computer programmer, Doctoral Program in Speech and Hearing Sciences, CUNY, New York, N. Y.

Attempts were made to manipulate the waveform only during the relatively steady state portions. A pilot study was conducted to determine the percentage of the total duration of the speech segments that could be manipulated without introducing any audible distortions. Using the durations obtained from the segmentation study, the midpoint of each vowel in one of the sentences was located. Pitch periods were then systematically deleted from 50%, 75%, 90%, 95% and 100% of the vowel in either direction from the midpoint. Two listener's evaluations of the altered segments indicated that the speech contained no audible distortions if periods were deleted from no more than 90% of the vowel in either direction from the midpoint. If periods were deleted from 95% or 100% of each half of the vowel, the altered speech produced an audible distortion much like that of low-level additive impulse noise. In the present study, manipulation of the waveform was performed on no more than 90% of each segment in either direction from the midpoint.

Pause times in the sentences also were corrected by direct manipulation of the waveform. This was ac-

completed by eliminating (or adding) silent intervals.

#### Correction of Deviant Timing Patterns

The absolute syllable duration, relative timing and pause errors were corrected in the deaf children's speech so as to systematically approach the timing patterns of the median normal speaker. The procedures for identifying the median normal speaker were presented in the preliminary study.

Correction of the relative timing errors involved modification of vowel (including diphthongs) duration while correction of absolute syllable duration involved modification of the duration of vowels, diphthongs, semivowels, glides and nasals. The majority of timing modifications involved the correction of vowel duration. This decision was based on the results of the preliminary investigation which showed that the increased duration of syllables was due primarily to increases in the duration of vowels.

A six-stage approximation procedure was used to correct the timing patterns in the deaf children's speech. The stages of approximation were:

1. Original utterance
2. Correction of pauses only
3. Correction of relative timing (stressed/  
unstressed ratio)
4. Correction of absolute syllable duration
5. Correction of relative timing and pauses
6. Correction of absolute syllable duration  
and pauses

The six-stages of approximation were applied to each of the 6 sentences produced by each of the children resulting in a total of 36 sentences for each child and 216 sentences for the group of children.

The first stage consisted of the original, unaltered utterances. No adjustments were made in the utterances except for the deletion of adventitious segments (phonemes or syllables) when the adventitious segment was preceded or followed by a pause. If such an adventitious segment was eliminated from the original utterance, it was deleted from all of the other altered versions. When an adventitious segment was not bounded by pauses, the segment was left alone in all versions. Adventitious segments were eliminated from the following

utterances: Sentence 1 (Subject 5), Sentence 4 (Subject 3) and Sentence 5 (Subject 6).

### 1. Correction of Pauses

Pauses were corrected in Stages 2, 5 and 6. In the latter two stages, there was concomitant correction of pauses and segment duration.

Since the median normal speaker did not pause between words in any of the sentences, all pauses between words were eliminated, as far as possible, from the deaf children's speech samples. The only time that a pause was found to occur in the median normal speaker's samples was between the pair of sentences in Sentence 2. In fact, the pause time of the normal speaker was longer than that of 4 of the deaf children's. In this case, the pause time was lengthened in the 4 deaf children's utterances until it matched the duration of the median normal speaker's pause. In addition to the elimination of pauses between words, pauses which occurred between syllables in bisyllabic words in the deaf children's utterances were eliminated.

Complete elimination of pauses between words and

syllables was not possible because the waveform could not be re-joined between two distinct speech segments without producing audible clicks. Therefore, the waveform was rejoined approximately 5-10 msec after the pause began and approximately 5-10 msec before the termination of the pause.

As mentioned previously, it was difficult to determine the termination of a pause and the onset of closure for initial and medial plosives. In order to avoid eliminating closure time, a silent interval equal to the median normal speaker's closure time was left in the altered version. Table 12 shows the closure durations for the median normal speaker's plosives in the sentences. If the pause time preceding the plosive in the deaf children's samples was equal to or less than the closure duration for the normal speaker, the pause was considered to represent closure and was left alone.

## 2. Correction of Relative Timing

Relative timing errors were corrected in the 3rd and 5th stages of approximation. For this type of timing correction, the ratio of the duration of vowels in

TABLE 12. Closure durations for Initial and Medial Plosives in the Median Normal Child's Speech Samples

<u>Plosive</u>		<u>Closure Duration</u>
/b/	/buk/	70 msec
/b/	/bet/	40 msec
/k/	/kip/	57 msec
/b/	/bol/	100 msec
/k/	/kæt/	55 msec
/t/	/kæt/	42 msec
/t/	/tu/	42 msec
/k/	/kout/	52 msec
/p/	/z ip/	65 msec

stressed/unstressed syllables was corrected to approximate the ratio of the duration of stressed/unstressed vowels in the median normal speaker's utterances. The procedures used to identify the stressed and unstressed syllables and to determine the ratio of the syllable pairs was described in the preliminary study.

Usually, the ratio was corrected by altering the duration of the vowel in the unstressed syllable while leaving the stressed vowel duration unchanged. Since the duration of stressed vowels was shorter than the duration of unstressed vowels in some of the normal speaker's syllable pairs, it was often necessary to lengthen rather than shorten the duration of the unstressed vowels in the deaf children's speech samples in order to achieve the desired ratio. The only case in which the unstressed vowel was unaltered was when the duration of the original segment was so long that it was impossible to reduce the segment sufficiently to achieve the desired duration or, when correction of the unstressed segment would have resulted in the lengthening of that segment to 500 msec. Segments could not be expanded to 500 msec or longer because the resulting speech sounded

unnatural and distorted. For those cases when it was impossible to alter the duration of the unstressed vowel, the duration of the stressed vowel was changed. Of the 193 syllables altered, 13 involved correction of the stressed/unstressed ratio by manipulating the duration of the stressed vowel.

Substitution of one phoneme for another was a common error in the deaf children's speech. Since many of the vowel and diphthong substitutions involved poor timing control, e.g., tense-lax error, vowel diphthongized, vowel and diphthong distortions, the duration of the substituted vowel or diphthong was corrected to the duration of the intended phoneme. All other substitutions were left alone.

For the 5th stage of approximation, pauses were corrected in the altered versions of the sentences which had been generated in the 3rd stage of approximation.

### 3. Correction of Absolute Syllable Duration

Absolute syllable duration was corrected in the 4th and 6th stages of approximation. For this type of timing correction, the duration of all phonemes was matched, as far as possible, to the segment durations of

the median normal speaker. The fricatives, affricates and plosives were not manipulated since the duration of these phonemes was typically shorter in the deaf children's speech. If a phoneme was omitted by the deaf child and the preceding or following segment was altered, the duration of the omitted phoneme was accounted for in the duration of the altered segment. Normative durations for the omitted phonemes were obtained from the median normal speaker's samples. For this stage, as for the third stage, the duration of a substituted vowel or diphthong was corrected to the duration of the intended phoneme. All other substitutions were left unaltered.

Stage 6 involved the correction of pauses in those utterances in which the absolute syllable duration had been corrected.

#### Accuracy of the Timing Adjustments

After the segment durations were altered in the 3rd stage (correction of the stressed/unstressed vowel duration ratio) and the 4th stage (correction of absolute syllable duration) of approximation, the sentences were resegmented in order to check the accuracy of the

timing adjustments. Table 13 summarizes the extent to which the altered segment durations deviated from the target durations. As shown in the table, the largest proportion of altered durations for both stages of approximation were within 20 or 30 msec of the target duration. A somewhat smaller proportion of the altered segment durations were within 10 msec of the target duration. Relatively few of the altered segments were identical in duration to that of the target duration.

For both stages of approximation a small proportion of the altered segments were more than 30 msec longer than the target duration. In these cases, it was impossible to achieve a closer approximation to the target duration for one of two reasons. First, some of the segments to be altered were almost 100 percent longer in duration than the segments in the speech of the median normal speaker. In these cases it was impossible to reduce sufficiently the duration of the altered segment. Secondly, some of the segments contained aperiodic portions which could not be manipulated. These aperiodicities limited the range in which manipulations could be performed thereby making it impossible to achieve some of the target

TABLE 13.--Accuracy of the Timing Adjustments. The samples and the proportions within the listed error ranges are cumulative in the first four columns. Absolute sample size and proportions are listed for the fifth error range.

<u>Stage of Approximation</u>	<u>Error Range</u>				
	<u>0</u>	<u>Within 10 msec</u>	<u>Within 20 msec</u>	<u>Within 30 msec</u>	<u>Over 30 msec</u>
Correction of Absolute Syllable Duration (N=426)					
Number of Samples	68	305	404	413	13
Proportion	.160	.716	.948	.969	.031
Correction of Relative Timing (N=193)					
Number of Samples	12	158	189	191	2
Proportion	.062	.819	.979	.990	.010

durations. Whenever either of the above two problems occurred, the segment was shortened as much as possible in the steady state, periodic portion of the waveform.

### Measures of Speech Intelligibility

The 36 utterances generated for each child were recorded on audiotape and randomized using a 6 x 6 Latin Square design. Since it was impossible to construct a 6 x 6 Graeco-Latin Square (Johnson and Leone, 1964), different rotations of the Latin Square, balanced as far as possible, were used for each child. Six tapes were made for each child with 6 sentences on each tape; each tape contained each of the 6 different sentences with each of the 6 stages of approximation occurring on a different sentence. A sentence or stage of approximation never occurred more than once on a tape.

Six different protocols were used to a) randomize the order in which listeners heard each of the 6 stages of approximation and, b) randomize the 6 different sentences on which the stages of approximation occurred. Because the Graeco-Latin Square could not be used, some of the sentences occurred in the same ordinal position on different tapes. When this happened, the sentence

never appeared in the same spot with the same stage of approximation.

Intelligibility measures were obtained by playing the tapes to persons with no significant previous experience in listening to the speech of the deaf. Three different listeners heard each of the tapes, totaling 18 listeners for each child's speech samples (3 listeners for each child's 6 tapes) and 108 listeners for the entire 36 tapes.

The listeners were all volunteers and the majority of them were recruited from colleges in the New York City area. The age of the speakers ranged from 18 to 40 years. They were all native speakers of English and reported no history of ear pathology or hearing problems.

The tapes were played to one listener at a time. Each listener was shown a sheet with a typed set of instructions (see Appendix J) which described the nature of the listening task. The listeners were permitted to hear each sentence played twice and they were required to write down as much as they could of what the child was saying. They were encouraged to make use of contextual information and, if they were unsure of what the

child had said, to take a guess. The tapes were played on either a Wollensak 1500 SS tape recorder or a Uher 4200 tape recorder. The speech was presented monaurally through a TDH-49 earphone.

The responses of the 108 listeners were scored word by word. Intelligibility scores were obtained for each child based on the proportion of words correctly understood in each sentence.

## CHAPTER IV

## RESULTS

Analysis of the Intelligibility Data

The listener responses were scored on a word-by-word basis so that the measure of intelligibility for each sentence was the proportion of words correctly understood averaged over the three listeners. In further analyses, the proportions were transformed to inverse sine units, in order to stabilize the binomial sampling variability that is inherent in estimating a proportion from a finite number of items (in this case the number of words in each sentence).<sup>4</sup>

After transformation, the intelligibility data were analyzed using a three-way analysis of variance. The factors were: Stage of Approximation (1 through 6), Subject (1 through 6), and Sentence (1 through 6).

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<sup>4</sup>The transformation used is  $y=2 \arcsine \sqrt{p/100}$  where  $p$  is the percent words correct and the transformed variable,  $y$ , is a measure of intelligibility in inverse sine units. Whereas the variance of  $p$  is a function of the value of  $p$ , the variance of  $y$  is roughly constant and is approximately  $1/n$  where  $n$  is the total number of words in each sentence (Brownlee, 1965).

Between-listener effects were not analyzed as a separate factor since it was not possible to construct a 6 x 6 Graeco-Latin Square (Johnson and Leone, 1964). Between-listener effects are included in the residual of the sum of squares, which in this analysis includes any three-way interactions of the main effects.

The results of the analysis of variance are shown in Table 14. From the table it can be seen that each of the three factors was significant. There were significant differences in intelligibility scores between Stages of Approximation, between Subjects and between Sentences. Significant Subject-Sentence interactions were also present. There were no significant interactions between Subjects and Stage of Approximation, or between Sentences and Stage of Approximation.

The intelligibility data for the Stages of Approximation are summarized in Table 15 and plotted in Figure 16. The average values were obtained from the analysis of variance in inverse sine units and were then transformed back to proportions. On the average, the highest intelligibility score was obtained when relative timing errors only were corrected. The correction of these

TABLE 14. Analysis of Variance of Intelligibility Data  
(Subject by Sentence by Stage of Approximation)

Source of Variation	Sum of Squares	DF	Mean Square	F	Significance Level
Subject (R)	3.88	5	.78	5.6	.001
Sentence (S)	11.15	5	2.23	16.2	.001
Stage of Approximation (A)	4.20	5	.84	6.1	.001
R x S	26.45	25	1.06	7.7	.001
R x A	3.02	25	.12	.9	.635
S x A	4.40	25	.18	1.3	.190
Residual*	17.23	125	.14		
Total	70.34	215			

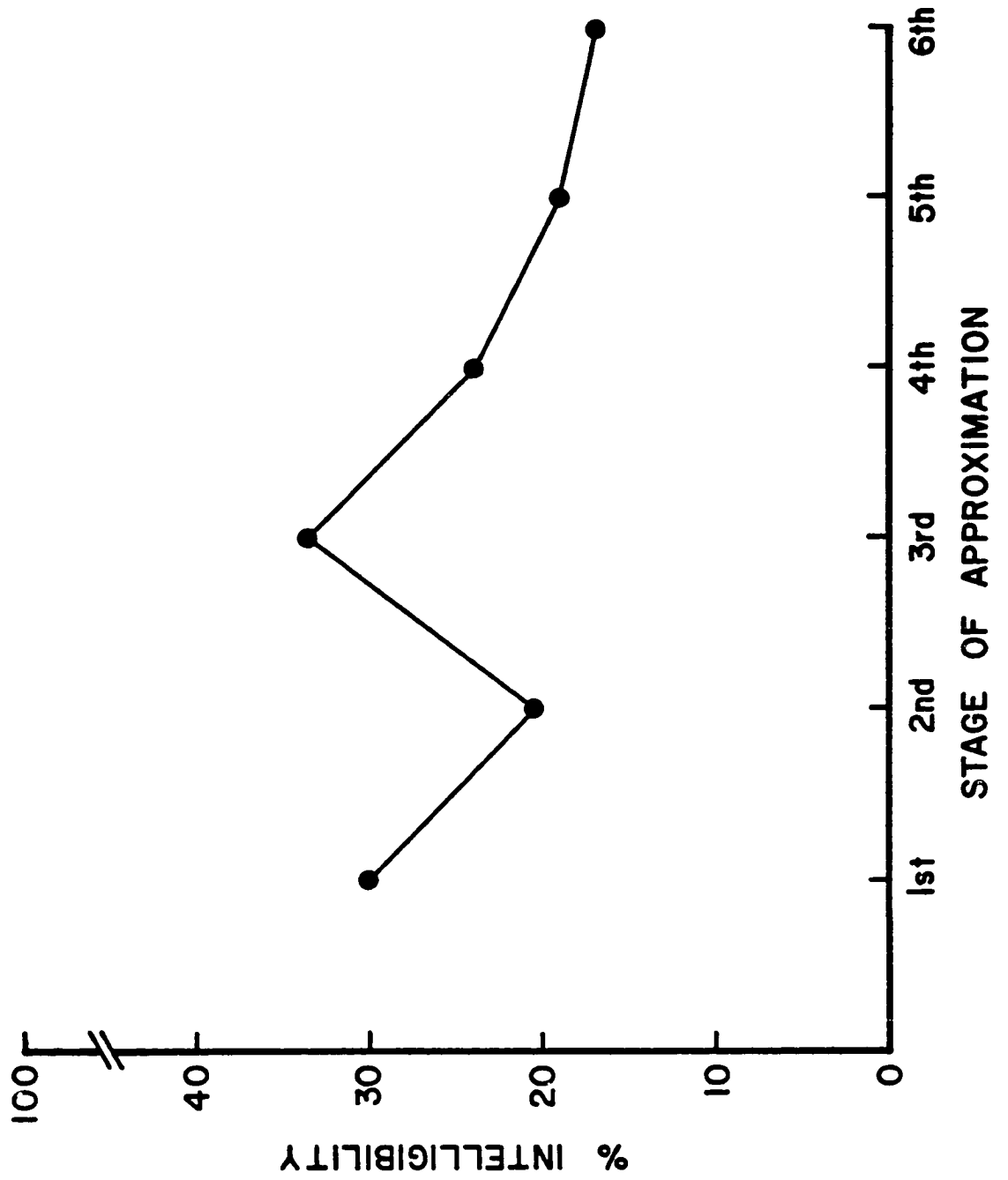
\*The expected variance (assuming that the binomial sampling variability is the only source of variation) is  $1/8$ , i.e., 0.125, where 8 is the average number of words per sentence.

TABLE 15. Average Scores (Transformed Back from Arc Sine Units) for Each Stage of Approximation for Each Child

Stage of Approximation	Subject Number					
	1	2	3	4	5	6
Original	29.0	24.6	48.1	20.5	26.8	34.7
Correction of Pauses	21.1	21.1	35.6	9.8	24.1	15.7
Correction of Relative Timing	33.1	35.9	47.0	21.8	34.0	32.6
Correction of Absolute Syllable Duration	32.6	16.9	33.0	23.6	14.9	25.8
Correction of Relative Timing and Pauses	16.5	16.6	31.0	18.3	12.0	22.3
Correction of Absolute Syllable Duration and Pauses	14.8	10.6	20.6	19.1	8.8	33.5
Means:	24.1	20.4	35.6	18.6	19.3	27.1

\* Average scores for each stage of approximation and for each child were computed, in inverse-sine units, as part of the analysis of variance. The entries in this table are those average values transformed back to percentages. Had the inverse-sine transformation not been used, the average scores would be very similar, but not identical.

Fig. 16. Intelligibility scores averaged across subjects and sentences for the six stages of approximation. The average values were transformed back to percentages from arcsine units.



errors resulted in an intelligibility score of 33.9%. The next highest intelligibility score was 30.3%, obtained for the original, unaltered utterances. Average intelligibility scores of 24.1%, 20.7%, 19.1% and 17.2% were obtained for the 4th, 2nd, 5th and 6th stages of approximation, respectively.

The data revealed that an improvement in intelligibility occurred for only one type of timing adjustment, e.g., when relative timing only was corrected. On the average, the correction of these errors resulted in a small but statistically significant improvement (approximately 4%) in intelligibility. The other forms of timing modification resulted in systematic decreases in intelligibility. Of these four forms, the correction of absolute syllable duration produced the smallest decrement in intelligibility. The other three forms, each of which involved the correction of pauses, had the most detrimental effect on intelligibility. As shown in Figure 16, the correction of absolute syllable duration produced a smaller decrement in intelligibility than did the correction of pauses only. Intelligibility was significantly poorer, on the average, when absolute

syllable duration was corrected with pauses corrected than when either of these timing errors was corrected in isolation. Also, the improvement in intelligibility that resulted when relative timing errors only were corrected was no longer evident when pauses were corrected in addition to the correction of relative timing errors. Not only was the gain in intelligibility lost when relative timing errors were corrected with pauses, but intelligibility was significantly poorer when these corrections were present than for the original unaltered utterances.

The data are summarized in Table 16 for the other two main effects, Subject and Sentence, and the one interaction effect, Subject by Sentence, which was found to be statistically significant. While these effects are significant, no hypothesis suggests itself about the pattern of effects observed.

The speech of Subject 3 was more intelligible, on the average, than the speech of the other five subjects. The average intelligibility score for this child, across all conditions, was 35.6%. The next highest intelligibility score was obtained for Subject 6 (27.1%),

TABLE 16.--Average Scores for Subject, Sentences and Subjects by Sentences Interaction. All entries are percentages, transformed back from arc sine units (see footnote to TABLE 15).

Subject Number	Sentence						Subject Average
	1	2	3	4	5	6	
1	20.1	30.7	41.9	2.8	61.3	35.6	24.1
2	35.7	32.2	50.2	31.1	11.8	18.4	20.4
3	53.6	20.4	43.9	7.1	27.9	62.5	35.6
4	5.2	13.3	32.7	17.2	8.8	0.0	18.6
5	1.0	8.8	23.5	31.2	8.3	25.4	19.3
6	53.9	21.4	23.5	34.2	10.4	47.7	27.1
Sentence Average	29.8	29.1	34.3	10.1	14.2	30.8	

followed by Subjects 1 (24.1%), 2 (20.4%), 5 (19.3%) and 4 (18.6%).

An analysis of the improvements in intelligibility for the individual subjects showed that for three of the six subjects (#'s 1, 2, 5), the highest intelligibility score was obtained when relative timing errors only were corrected. Improvements in intelligibility of 4.0%, 9.3% and 7.2% were obtained for Subjects 1, 2, and 5, respectively. For one subject (#4), the highest intelligibility score was obtained when relative timing errors and pauses were corrected. The next highest score for this subject was obtained when relative timing errors only were corrected. The highest intelligibility score for Subjects 3 and 6 was that of the original, unaltered utterances. Thus, for these two subjects, the timing corrections reduced rather than improved intelligibility.

The data also show that, on the average, Sentence 3 was the most intelligible sentence. Sentence 6 was slightly less intelligible than Sentence 3 followed by Sentences 1 and 2. Sentences 4 and 5 were significantly less intelligible than the other sentences.

The interactions between Subjects and Sentences

did not appear to follow a simple, systematic pattern. The largest component of the interaction occurred with Sentence 4 in that one of the children whose intelligibility was low on the average, obtained a high intelligibility score on this sentence and two children, who had obtained high scores on the other sentences, performed poorly on this sentence.

#### Evaluation of a Simple Fixed-Effects Model

The intelligibility data were further analyzed to determine the individual effects of the timing modifications on the measured intelligibility scores. In order to quantify these effects, a simple fixed-effects model was developed. The model has two basic components, an effect of correcting pause errors and an effect of correcting either the relative or absolute duration of each syllable, i.e.,

$$Y_{ij} = O_{ij} + P_{ij} + (R_{ij} \text{ or } A_{ij}) + e_{ij}$$

where  $Y_{ij}$  is the test score (in inverse sine units) for each child  $i$  on sentence  $j$

$O_{ij}$  is the intelligibility score prior to any timing adjustments

$P_{ij}$  is the change in the intelligibility score resulting from the correction of pauses

$R_{ij}$  is the change in the intelligibility score resulting from the correction of relative timing

$A_{ij}$  is the change in the intelligibility score resulting from the correction of absolute syllable duration

$e_{ij}$  is the error term

Since there may be an interaction between P and R or between P and A, each of these effects was estimated separately for each combination of conditions, i.e., in analyzing the effect of the pause corrections,  $P_1$ ,  $P_2$  and  $P_3$  were calculated for each child and each sentence, where  $P_1$  represents the effect of correcting pauses alone,  $P_2$  represents the effect of correcting pauses with relative timing errors corrected and  $P_3$  represents the effect of correcting pauses with absolute syllable duration corrected. Similarly, in analyzing the effects of correcting relative or absolute syllable duration,  $R_1$  and  $R_2$  were calculated, where  $R_1$  represents the effect of correcting relative timing alone,  $R_2$  represents the effect of correcting relative timing

with pauses corrected and, A1 and A2 were calculated, where A1 represents the effect of correcting absolute syllable duration alone and A2 represents the effect of correcting absolute syllable duration with pauses corrected.

Table 17 summarizes the components of the model, showing how the values of these components were calculated from the intelligibility scores. For example P1 (the effect of pause corrections alone) was calculated for each sentence and each child by subtracting the intelligibility score (in inverse sine units) of the original sentences from the intelligibility score (in inverse sine units) of those sentences with only pauses corrected. As in the analysis of variance, the inverse sine transformation was used in order to stabilize the error variance. After the components had been estimated from the intelligibility data, the component values were analyzed statistically.

The first major component of the model, the effect of correcting pauses in the presence of other corrections, was examined using a three-way analysis of variance. The factors were: Subject (1 through 6), Sentence (1 through 6), and Correction of Pauses (P1:

TABLE 17.--Components of the Fixed-Effects Model

Nomenclature

- O = Intelligibility score for the unaltered sentences
- P = Intelligibility score obtained with only pauses corrected
- R = Intelligibility score obtained with only relative timing corrected
- A = Intelligibility score obtained with only absolute syllable duration corrected
- RP = Intelligibility score obtained with relative timing and pauses corrected
- AP = Intelligibility score obtained with absolute syllable duration and pauses corrected

All of the above scores are specified in inverse sine units.

Effect of Correcting Pauses

- P1: Effect of correcting pauses alone =  $P - O = P$
- P2: Effect of correcting pauses with relative timing corrected =  $RP - R = P$
- P3: Effect of correcting pauses with absolute syllable duration corrected =  $AP - A = P$

TABLE 17.--Continued

Effect of Correcting Syllable Duration

- R1: Effect of correcting relative timing alone  
= R - O = R
- R2: Effect of correcting relative timing with pauses  
corrected = RP - P = R
- A1: Effect of correcting absolute syllable duration  
alone = A - O = A
- A2: Effect of correcting absolute syllable duration  
with pauses corrected = AP - P = A

the effect of correcting pause errors only; P2: the effect of correcting pause errors with the concomitant correction of relative timing; P3: effect of correcting pause errors with the concomitant correction of absolute syllable duration).

The second major component of the model was examined using a four-way analysis of variance with the following factors: Subject (1 through 6), Sentence (1 through 6), Correction of Syllable Duration (relative, R1, or absolute, A1), Effect of Pause Correction on Syllable Duration Correction (R1 or A1 vs R2 or A2).

#### The Effect of Correcting Pauses

The results of the three-way analysis of variance are shown in Table 18. The data show that one of the main effects, Sentence, and one interaction effect, Subject x Sentence, was statistically significant. The effect of other corrections on the correction of pauses (P1, P2, P3) was of borderline significance (at the .055 level). The effect of Subjects and the two interaction effects (Sentence x Pause Corrections and Subjects x Pause Corrections) was not statistically significant.

Table 19 summarizes the data for the factors

TABLE 18.--Analysis of Variance: Pause Component of the Model (Subject by Sentence by Correction of Pauses)

Source of Variation	Sum of Squares	DF	Mean Squares	F	Significance Level
Sentence (S)	2.55	5	.51	5.1	.001
Subject (R)	.14	5	.03	.3	.917
Pause (P)	.61	2	.31	3.0	.055
S x R	6.41	25	.26	2.5	.003
S. x P	1.27	10	.13	1.3	.277
R x P	1.34	10	.13	1.3	.239
Residual	5.03	50	.10		
Total	17.36	107			

TABLE 19.--Effect of Pause Corrections on Intelligibility. Each entry is the contribution to intelligibility in arc sine units, as derived from the fixed-effects model.

Correction of Pauses	
Pauses Only Corrected (P1)	-.19
Pauses and Relative Timing Corrected (P2)	-.29
Pauses and Absolute Syllable Duration Corrected (P3)	-.11

Subject Number	Contribution to Intelligibility for Each Sentence-Subject Combination					
	1	2	3	4	5	6
1	-.28	.10	-.03	-.20	-.08	-.86
2	-.44	.37	-.80	-.46	-.02	.09
3	-.97	-.03	-.22	-.31	-.28	.26
4	.12	.15	-.06	-.56	-.29	-.33
5	-.35	.08	-.08	-.17	-.26	-.11
6	-.41	.02	-.19	.00	-.35	-.24
Sentence Average	-.39	.11	-.23	-.28	-.21	-.20

which were found to be statistically significant. The values which appear in the table are in arcsine units. A positive value indicates that the effect resulted in an improvement in intelligibility whereas a negative value indicates that the effect resulted in a decrement in intelligibility.

The data show that, on the average, the correction of pauses always had a detrimental effect on intelligibility. Correction of pauses with the correction of relative timing errors (P2) produced the largest, negative effect on intelligibility, followed by the correction of pauses alone (P1) and the correction of pauses with the correction of absolute syllable duration (P3). The differences, however, between P1, P2 and P3 were small.

The data also show that there was a significant difference between sentences in that the correction of pauses had a negative effect on the intelligibility of five of the six sentences. In contrast to this, there was an improvement in intelligibility when pauses were corrected in the remaining sentence (Sentence 2: "Did Jack find the orange ball? I need it.").

The results of the analysis of variance showed a

statistically significant interaction between Subjects and Sentences. The data for this interaction also appear in Table 19. As in the previous analysis, the interaction between Subjects and Sentences did not appear to follow a systematic pattern.<sup>5</sup> From Table 19 it can be seen that for all children, the correction of pauses had a positive effect on intelligibility for one or two sentences, but a negative effect on intelligibility for others.

#### The Effect of Correcting Syllable Duration

The results of the analysis of variance for this component of the model appear in Table 20. Because of the large number of F tests performed in this analysis, only those factors with a significance level of .01 or smaller were considered to be statistically significant. The data show that three of the main effects (Sentences, Subjects, Correction of Syllable Duration) were statistically significant. The other main effect, the Effect of Pause Correction on Syllable Duration Correction, was

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<sup>5</sup>The two analyses of variance should not be regarded as independent since they were derived from the same data.

TABLE 20.--Analysis of Variance: Syllable Duration Component of the Model  
(Subject by Sentence by Effect of Pause Corrections on Syllable Duration  
Corrections by Syllable Duration Correction)

Source of Variation	Sum of Squares	DF	Mean Squares	F	Significance Level
Effect of the Correction of Pauses on Syllable Duration Correction (P)	.01	1	.01	.1	.808
Sentence (S)	3.53	5	.71	12.0	.001
Subject (R)	1.42	5	.28	4.8	.003
Syllable Duration Correction (E)	.45	1	.45	7.6	.010
P x S	1.22	5	.24	4.1	.007
P x R	1.48	5	.30	5.1	.003
P x E	.31	1	.31	5.2	.030
S x R	10.85	25	.43	7.4	.001
S x E	.38	5	.08	1.3	.296
R x E	.65	5	.13	2.2	.084
P x S x R	3.14	25	.13	2.1	.031
P x S x E	.23	5	.05	.8	.576
P x R x E	.18	5	.04	.6	.704
S x R x E	3.72	25	.15	2.5	.012
Residual	1.47	25	.06		
Total	29.03	143			

not statistically significant.

The data are summarized in Table 21 for the main effects which were found to be statistically significant. There were significant differences between sentences. On the average, four of the sentences showed an improvement in intelligibility as a result of the timing corrections and two of the sentences showed a large decrement in intelligibility.

The average values for the individual subjects showed that the timing corrections had a negative effect on the intelligibility of three of the children's speech and a positive effect on the intelligibility of the other three children's speech.

The data for the other main effect, Correction of Syllable Duration showed that the correction of relative timing errors resulted in a small but statistically significant increase in intelligibility whereas the correction of absolute syllable duration produced a detrimental effect on intelligibility.

As shown in Table 20, three of the six two-way interactions were significant. The average values appear in Table 22. Again, there appeared to be no clear

TABLE 21.--Effect of Syllable Duration Correction on Intelligibility. Each entry is the contribution to intelligibility in arc sine units, as derived from the fixed-effects model.

	Sentence					
	1	2	3	4	5	6
Average Contribution	.03	-.29	-.22	.07	.13	.02

	Subject Number					
	1	2	3	4	5	6
Average Contribution	-.03	-.29	-.22	.07	.13	.02

	Correction of Syllable Duration	
	Relative	Absolute
Average Contribution	.01	-.10

TABLE 22.--Interactive Effects for the Syllable Duration Component of the Model. Each entry is the contribution to intelligibility in arc sine units, as derived from the fixed-effects model.

Contribution to Intelligibility for Each Sentence-Subject Combination						
Subject Number	Sentence					
	1	2	3	4	5	6
1	-.41	.01	-.72	-.04	.06	.12
2	-.21	.01	-.14	.18	.08	-.31
3	-.31	-.69	.18	.30	-.21	-.27
4	.13	-.19	-.04	-.25	.86	-.22
5	-.18	-.55	-.62	-.21	-.06	.27
6	.35	-.35	.01	.00	.07	.56

TABLE 22.--Continued

Contribution to Intelligibility  
for Each Subject -- Pause Correction Effect on  
Syllable Duration Correction Combination

	Subject					
	1	2	3	4	5	6
Correction Alone (R1 + A1)	.01	.03	-.17	.01	-.03	-.08
Correction with Pauses (R2 + A2)	-.06	-.16	-.17	.08	-.28	.29

Contribution to Intelligibility  
for Each Sentence -- Pause Correction Effect on  
Syllable Duration Correction Combination

	Sentence					
	1	2	3	4	5	6
Correction Alone (R1 + A1)	.13	-.36	-.23	.05	.28	-.10
Correction with Pauses (R2 + A2)	-.07	-.22	-.21	.08	-.01	.15

cut pattern to the Sentence-Subject interaction. As shown by the data the children performed differently on different sentences

A significant interaction was also present between Subjects and the Effect of Pause Corrections on Syllable Duration Correction. The data showed that for two of the children (#'s 1 and 2), the correction of syllable duration alone improved intelligibility, but when pauses were also corrected, there was a reduction in intelligibility, i.e.,  $R1+A1$  was positive but  $R2+A2$  was negative. For one child (#5), the correction of syllable duration, both with and without pauses corrected, resulted in a reduction in intelligibility, i.e.,  $R1+A1$  and  $R2+A2$  were negative. Unlike the other children, Subjects 4 and 6 showed an improvement in intelligibility when pauses were corrected with syllable duration. One of these children (#4) had shown a slight improvement in intelligibility when only syllable duration was corrected while the other child (#6) had shown a decrement in intelligibility for this correction. For the remaining child (#3), the correction of syllable duration alone reduced intelligibility and intelligibility was

unchanged when pauses were also corrected.

The two-way interaction between Sentences and Effect of Pause Correction on Syllable Duration Correction was also significant. As shown in Table 22, correction of only syllable duration had a detrimental effect on the intelligibility of three of the six sentences (#'s 2, 3, 6). For two of these three sentences (#'s 2, 3), there was an even greater reduction in intelligibility when pauses were also corrected with relative timing corrected. When syllable duration was corrected with pauses in Sentence 6, there was a large increase in intelligibility. Sentences 1 and 5 showed an improvement in intelligibility when syllable duration was corrected but a decrement in intelligibility when pauses were also corrected. Sentence 4 showed a slight improvement in intelligibility when syllable duration alone was corrected and a larger improvement in intelligibility when pauses were also corrected.

#### The Relationship Between Segmental Errors and Changes in Intelligibility

The data were further analyzed to determine if there was a relationship between segmental errors and

changes in intelligibility following the timing modifications. Specifically, the analysis was performed to determine if changes in intelligibility were related in any way to the frequency of segmental errors of various types. It was hypothesized that such a relationship might be present because the timing modifications involved the correction of duration errors on the segmental level. Since only the correction of relative timing resulted in an average improvement in intelligibility, it was reasoned that if a relationship existed between segmental errors and improvements in intelligibility, it would be most apparent in this condition.

The author's phonetic transcriptions were used to calculate the percentage of vowel errors and consonant errors in each sentence produced by each deaf child. The percentage of errors was based on the number of perceived vowel (or consonant) errors of the total number of occurrences of vowels (or consonants) in each sentence. The percentage of errors was then compared with the change in intelligibility that occurred when relative timing errors alone were corrected, calculated by subtracting the intelligibility score of the original

sentence from the intelligibility score with relative timing errors corrected.

Figure 17 shows the results for vowels. Generally, when relative timing was corrected and there were no perceived vowels errors, intelligibility decreased; however, when there were vowel errors present, intelligibility improved.

Figure 18 shows the results for consonants. All of the sentences contained some consonant errors and there were more consonant errors than vowel errors. There appears to be no systematic relationship between number of errors and intelligibility.

In order to analyze this effect in another way, the percentage of vowel and consonant errors were examined for the six individual sentences which showed the greatest improvement in intelligibility and the greatest reduction in intelligibility. These data appear in Table 23. On the average, those sentences which showed the greatest improvement in intelligibility contained more total vowel and consonant errors than those sentences which showed a decrement intelligibility. In addition, those sentences which showed improvements in intelligibility

Fig. 17. Percentage of vowel errors as a function of the change in intelligibility when relative timing only is corrected. The percentages are based on the number of vowel errors of the total number of occurrences of vowels in each sentence.

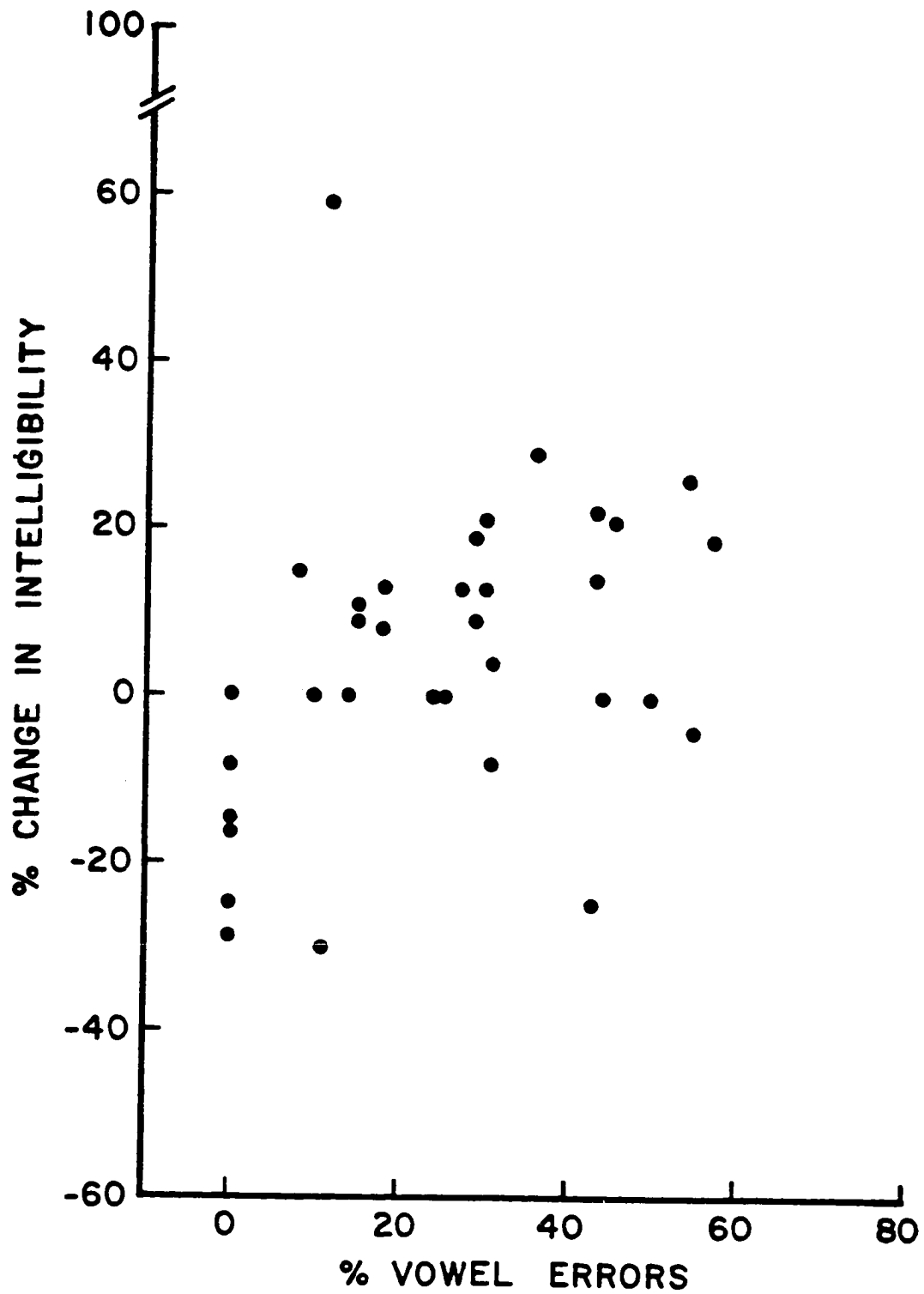


Fig. 18. Percentage of consonant errors as a function of the change in intelligibility when relative timing only is corrected. The percentages are based on the number of consonant errors of the total number of occurrences of consonants in each sentence.



TABLE 23.--Percentage of Vowel and Consonant Errors for the Six Individual Sentences Which Showed the Greatest Improvement in Intelligibility and the Greatest Reduction in Intelligibility When Relative Timing Was Corrected. The percentages are based on the number of vowel or consonant errors of the total number of occurrences of vowels or consonants in each sentence.

Greatest Improvement in Intelligibility

% Vowel Errors	% Consonant Errors
36	43
56	29
11	41
31	23
43	50
14	38
Mean: 32	37

Greatest Reduction in Intelligibility

% Vowel Errors	% Consonant Errors
0	29
22	53
0	20
43	30
0	25
0	10
Mean: 11	28

contained substantially more vowel errors, on the average, than those sentences which showed a reduction in intelligibility.

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## CHAPTER V

## DISCUSSION

Interpretation of the Data

The data obtained in the study revealed several major findings. First, the correction of timing errors affected the intelligibility of the deaf children's speech. Second, the data showed that the correction of different types of timing errors produced different effects on intelligibility. Third, there was an interaction between timing corrections when different types of timing errors were corrected concomitantly. Fourth, the effect of the timing corrections on intelligibility was not the same for all children.

Of the timing modifications performed, an average improvement in intelligibility was observed when relative timing alone was corrected. Since the timing modifications for this condition involved only the correction of the duration ratio of stressed to unstressed vowels, the overall duration of the vowels (and syllables) was still longer in the deaf children's

speech than in the speech of the normal hearing subjects after the corrections were performed. Thus, it appears that the prolongation of syllables, which is so typical of deaf speech, does not in itself have a detrimental effect on intelligibility.

The correction of pauses produced the largest, single effect on intelligibility. However, unlike the correction of relative timing, which improved intelligibility, the correction of pauses alone reduced intelligibility. The analysis of both the intelligibility data and the pause component of the fixed-effects model showed that the correction of pauses always had a detrimental effect on intelligibility. One hypothesis which may account for the negative effect is that the elimination of such errors reduces the amount of time available to the listener to process deaf speech. Since the correction of pauses was accomplished by eliminating only silent intervals from the speech waveform, all other errors were left unchanged. It appears that these errors produced numerous distortions in the children's speech which could not be adequately processed in the time available to the listener. Thus, it appears that the presence of

long pauses may actually provide the listener with additional time with which to process the numerous distortions which occur in the speech of the deaf.

An observation in the study which is consistent with the above hypothesis is the improvement in intelligibility which occurred for Sentence 2 ("Did Jack find the orange ball? I need it.") when pause errors were corrected. Since the normal hearing speaker paused between the pair of sentences, this particular pause was not eliminated from the deaf children's samples. In fact, the duration of the pause was lengthened in the speech of four of the children in order to match the pause time (roughly 400 msec) of the median normal speaker. It is possible that the presence of this long pause, which occurred at a syntactically appropriate boundary, actually improved the intelligibility of the pair of sentences.

Although there are no studies which have directly examined the relationship between processing time and intelligibility of distorted speech, indirect support for the above hypothesis can be found in the studies on the reaction time of normal hearing listeners in speech intel-

ligibility tests. For example, it has been shown (Hecker, et al., 1966) that as speech becomes more distorted, i.e., as the signal-to-noise ratio is increased, it takes listeners a longer period of time to identify speech stimuli than if the speech is free from distortions. Assuming that reaction time and processing time are related, it appears that a listener requires a longer period of time to understand what is said when the speech is distorted than when it is not.

For most of the children, the correction of absolute syllable duration had a detrimental effect on intelligibility. It may be that shortening the overall duration of syllables produces the same effect as eliminating pauses. That is, the shortened syllables may reduce the processing time available to the listener. However, since the modification of absolute syllable duration involved more than just the elimination of a silent interval, as was the case with pause corrections, it is unclear if the reduction in intelligibility is due only to a reduction in processing time. The data do confirm the earlier statement that the prolongation of syllables does not necessarily have a detrimental effect

on intelligibility and, in fact, it is the reduction rather than the prolongation, of syllable duration which adversely affects intelligibility.

The fixed-effects model revealed interactions between the different types of timing corrections on intelligibility. For most of the children, the correction of syllable duration (absolute and relative) resulted in an improvement in intelligibility but, when pause errors and syllable duration were corrected concomitantly, there was a significant reduction in intelligibility. Thus, for these children, the effect of pause corrections exerted a greater influence on intelligibility than did the correction of syllable duration. For two of the children, the reverse was true in that the correction of pauses with syllable duration corrected improved intelligibility.

No obvious explanation, other than that of individual difference, could be found to explain why two of the subjects showed increments in intelligibility when both pauses and syllable duration were corrected. The possibility was considered that the number of pauses in the original utterances may have been a factor, but

no clear cut pattern emerged. An analysis of the number of pauses in the original utterances showed that the speech of one of the subjects contained more pauses than the speech of any of the other children. However, the other subject not only paused less frequently than any of the other subjects, but the average duration of the pauses was shorter in this subject's speech than in the speech of the other five subjects.

The data were also examined in an attempt to explain some of the other individual differences between subjects, without success. The durational aspects of the children's original utterances appeared to have no obvious relationship with the observed changes in intelligibility. For example, the syllable durations of Subjects 1, 2, and 3 showed the greatest deviation from the average normal syllable duration. All forms of timing modification resulted in decrements in intelligibility for Subject 3 while Subjects 1 and 3 showed substantial improvements in intelligibility when relative timing errors were corrected.

The data also showed that sentences with the greatest number of perceived vowel errors showed the

greatest improvement in intelligibility when relative timing was corrected. Since the relative timing modifications involved the correction of vowel duration, it may be that these corrections also improved certain aspects of the children's speech at the segmental level.

In placing the results of the study in perspective, it is important to distinguish between different types of timing errors. The corrections made here were of pauses, absolute and relative syllable duration. These adjustments tapped only a few of the timing errors (both at the suprasegmental and segmental level) occurring in the speech of the deaf. In particular, timing errors involving movement of the articulators were not considered (for technical reasons). The errors that were corrected were perceptually very noticeable and typically associated with deaf speech, i.e., excessively prolonged vowels and insertion of both frequent and lengthy pauses. However, the observed improvement in intelligibility when such errors were corrected was relatively small. It may be that suprasegmental timing errors involving the imprecise control and coordination of articulatory movements over time have a substantial effect on intelligibility. Additional research is needed in order to

determine if the correction of these suprasegmental timing errors improves the intelligibility of deaf children's speech.

#### Comparison with Other Studies

The results of this study showed that while the correction of relative timing errors resulted in an average improvement in intelligibility, the observed improvement was not as large as that reported by either John and Howarth (1965) or Heidinger (1972). As stated previously, the results of these two investigations are difficult to interpret since it is not clear if the improvements in intelligibility were due only to the correction of timing errors.

It was originally postulated that the decrements in intelligibility reported by Houde (1973) and Boothroyd et al. (1974) were caused by the introduction of additional articulatory errors in the children's speech as a result of the training procedures. Another possible explanation is that decrements in intelligibility were observed because of the types of timing errors which were corrected. In both studies, relative timing errors and pauses were corrected concomitantly. As the results of this study showed, there was an interaction between these timing

corrections, which for the majority of children, produced decrements in intelligibility.

The findings of Parkhurst and Levitt (1978), which showed that the presence of pauses at syntactically appropriate boundaries was correlated with improved intelligibility, are substantiated by the results of the present study. Thus, the findings of two independent investigations have shown that the presence of pauses at appropriate boundaries can actually improve the intelligibility of deaf children's speech.

Direct comparison between the results of the present study and those of Bernstein (1977) is difficult since the latter study introduced timing distortions in synthesized speech which did not contain the numerous types of errors which typically occur in the speech of the deaf. Bernstein found that timing errors had no effect on intelligibility. However, the results of the present study suggest that timing errors may interact with other error types to reduce intelligibility. Thus, Bernstein may have found that timing errors had no effect on intelligibility because the timing distortions were not introduced in the presence of other types of errors.

Huggins (1977) also introduced timing distortions in the synthesized versions of normal speech. Unlike the

results of Bernstein's study, Huggins found that the timing errors substantially reduced intelligibility. The results of the present study and those of Huggins are in agreement in that in both studies, relative timing errors were found to have a detrimental effect on intelligibility. However, the effect of these timing errors on intelligibility was much larger in the Huggins study than in the present study. A possible explanation for this difference is that the relative timing errors introduced by Huggins were exaggerations of those that occur in the speech of the deaf. That is, deaf children typically do not reverse the temporal relationship of stressed and unstressed syllables by lengthening unstressed syllables while at the same time shortening stressed syllables.

The only other study which corrected timing errors in deaf children's speech with signal processing techniques, in addition to the present study, was that by Lang (1975). Lang observed an improvement in the intelligibility of key contextual words in 4 of the 10 sentences with timing modifications, 3 of the sentences showed no change in intelligibility after the retiming and 3 sentences showed a decrement in intelligibility. The results of Lang's study are supported by those of the present study in that the correction of deviant timing patterns was

found to improve intelligibility. However, it is not clear from the results of Lang's study why some sentences showed a decrement in intelligibility following the timing corrections. In addition, Lang modified the speech samples of only one deaf speaker and, as shown by the results of this study, the effect of timing corrections can vary among deaf speakers.

It is also possible to explain some of the conflicting findings in the literature on the basis of the data obtained in the present study. As mentioned previously, the results of this study have shown that different types of timing errors have different effects on intelligibility. The approach of previous investigations has been to examine the combined effect of several types of timing errors on intelligibility. Until this time, the individual effects of different timing errors and the interactions between timing errors was not known. It has generally been assumed that one or two types of timing errors reflected the effect of all timing errors on intelligibility. Thus, some of the reported discrepancies may be simply due to the fact that in each study, different timing errors were corrected and, the reported changes in intelligibility varied as a function of those particular errors which had been examined.

### Implications

A number of observations made during the segmentation process lend additional insight into the characteristics of deaf speech. For example, it was observed that the deaf speakers often produced word-final stops as released, aspirated stops rather than unreleased stops. One apparent cause for this is that the deaf speakers paused between words and the stops were produced as if they were in the final position of words spoken in isolation. On the other hand, it may be that deaf children are not taught to produce unreleased stops. If this is the case, then it is not unexpected that they pause after the production of words with final, released stop consonants because it is extremely difficult to produce a final released stop without pausing.

It was also observed that the insertion of pauses interfered with the accurate measurement of the closure duration of word-initial stop consonants. In the present study, different segmentation procedures were used to measure the duration of these segments in the speech of the deaf and hearing children. Regardless of the segmentation procedures used, it appears that accurate measurement of the closure duration for word-initial stop

consonants is extremely difficult (if at all possible) if the stop consonant of interest is preceded by a pause.

The segmentation data also showed that although the syllables produced by the deaf children were longer, on the average, than those of the normal hearing speakers, the deaf children often omitted one or more phonemes from the syllable, and a question was raised as how to compare the duration of such syllables with normal productions. One approach is to measure the duration of any part of the syllable that is produced. An alternative approach is to exclude those syllables with omissions. The type of approach which is selected may vary depending on the type of information that is desired; however, the duration measures obtained will be directly influenced by the method which is used. Previous studies which have examined the duration of syllables and words in the speech of the deaf have not typically addressed this problem in specifying syllable duration.

The results of the preliminary study also revealed new information on the durational aspects of deaf speech. For example, it was found that deaf children not only prolong the duration of vowels, but they also extend the duration of other continuants such as glides, semivowels and nasals. However, contrary to

the results obtained by Calvert (1961), it was found that the duration of fricatives was shorter in the speech of the six deaf children than in the speech of normal hearing subjects. However, Calvert examined the duration of speech segments in isolated syllables and it may be that certain durational aspects of deaf speech change in the context of sentences.

The digital speech processing techniques used in this study appear to have application for future research. The present study has demonstrated that it is possible to manipulate independently specified aspects of the speech waveform. Using this technique made it possible to simulate deaf speech with only timing errors removed. An advantage of this approach was that all other errors remained unchanged and, as a consequence, it was possible to quantify the changes in intelligibility due specifically to the correction of only one type of error. Since the timing adjustments were performed at the zero crossings (or during silent intervals), it was possible to make the various timing modifications with only minor distortions being introduced as a result of the processing technique. As a result, the time-modified utterances were of a very high quality with little or no audible distortion resulting from the signal processing.

The results of the study suggest that additional research is needed to quantify the effect of timing corrections in combination with the correction of other prosodic errors. For example, the changes in fundamental frequency which occur in normal speech were not always present in the speech of the deaf children. In particular, the fall in fundamental frequency which is normally present at the end of a breath group, i.e., preceding a pause, was not always evident. It is possible that the correction of such errors, as well as those of timing, would result in larger improvements in intelligibility than were observed in the present study.

Finally, the findings of the present study have important implications for improving the speech training procedures for deaf children. Since the correction of relative timing errors resulted in an improvement in intelligibility, emphasis should be placed on achieving the correct durational relationship between stressed and unstressed syllables, even if the overall length of the syllables is longer than that of a normal hearing speaker's. According to the results of this study, teaching a deaf child to produce syllables which match the duration of those in the speech of a normal hearing speaker can reduce intelligibility rather than improve it.

The findings with respect to pauses should be interpreted with caution. The results should not be taken to mean that deaf children should be taught to pause after every word they produce. Such a teaching approach is likely to introduce additional distortions in a child's speech and inhibit the development of certain speech skills which may be critical to the development of intelligible speech. If pauses are indeed helpful in improving intelligibility, it would be wiser to concentrate on teaching the child to produce at least one phrase at a time between pauses. Pauses occurring at syntactically appropriate boundaries need not necessarily be corrected by the teacher, even if the length of these pauses appears to be longer than normal. However, attempts should be made to correct those pauses which occur at syntactically inappropriate boundaries, such as those which are inserted between bisyllabic words or during plosive closure.

In summary, the timing errors which were corrected in this study were those which are perceptually prominent in the speech of the deaf. While such errors may distort the rhythmic patterns of deaf speech, their effect on intelligibility is relatively small. The observed interactions between timing modifications suggests that the correction of more subtle timing errors, such as those

occurring at the suprasegmental level, in addition to those of relative syllable duration, may result in larger improvements in intelligibility than were seen in this study. In addition, there may be interactions between timing errors and other prosodic errors in the speech of the deaf. Clearly, additional research is needed to quantify the effects of such errors on intelligibility.

APPENDICES

APPENDIX A

Background Information on the Six Deaf Children (Smith, 1972)

	Subject Number					
	1	2	3	4	5	6
Age at the time of testing	13.5	14.4	14.1	15.0	13.2	13.6
Sex	F	M	F	F	M	M
Parents' Hearing	Both Hearing	Both Hearing	Both Hearing	Both Hearing	Both Hearing	Both Hearing
Hearing of siblings	All Deaf	No Siblings	All Hearing	All Hearing	All Hearing	All Hearing
Language used in the home	English	English	Other	English	English	English
Parental cooperation	Good	Good	Poor	Good	Good	Fair
Socioeconomic level	Lower Middle	Lower Middle	Lower Middle	Middle	Middle	Middle
Age at start of special education	2.9	2.0	4.3	.9	11.0	3.5

	Subject Number					
	1	2	3	4	5	6
Speech grade	4	2	2	2	2	2
Lipreading grade	3	3	1	3	2	4
Score on WISC	114	122	104	125	110	106
Score on Leiter	117	107	100	122	Not Available	Not Available
Age when deafness diagnosed	1 to 2 years	Before 1 year	Before 1 year	Before 1 year	Later than 2 years	Later than 2 years
Age when hearing aid first given	3.6	2.0	3.6	2.5	2.5	5.0
Adequacy of hearing aid	Good	Good	Good	Good	Poor	Poor
Adequacy of use of hearing aid	Good	Good	Good	Good	Good	Good
Evidence of progressive hearing loss	No	No	Yes	No	No	No

Pure Tone Air Conduction Responses of Deaf Children,  
 In dB re: Audiometric Zero (ISO)  
 (Smith, 1972)

Subject Number	Ear	Frequency, in Hz											
		125	250	500	1000	1500	2000	3000	4000	6000			
1	R	80	70	70	95	--	--	--	--	--	--	--	--
	L	75	75	70	100	--	--	--	--	--	--	--	--
2	R	60	80	85	105	--	--	--	--	--	--	--	--
	L	60	75	75	85	100	--	--	--	--	--	--	--
3	R	55	70	85	95	100	105	--	--	--	--	--	--
	L	35	60	85	100	105	110	--	--	--	--	--	--
4	R	80	75	90	105	--	--	--	--	--	--	--	--
	L	70	80	90	110	--	110	--	--	--	--	--	--
5	R	40	50	85	85	95	95	95	100	105	105	100	105
	L	60	70	85	90	100	100	100	105	105	110	110	110
6	R	60	80	90	110	--	--	--	--	--	--	--	--
	L	60	75	95	110	--	--	--	--	--	--	--	--

## Differences in Phonetic Transcriptions

There were some differences in the phonetic transcriptions available from Smith (1972) and those transcriptions made by this author. Disagreements usually involved the stop consonants in the word-final position. Frequently these segments appeared to be present when listening to the entire sentence, but when the word containing the final stop was isolated, the phoneme was perceived as being omitted. Occasionally the reverse occurred and a phoneme which was transcribed as being omitted by Smith was heard, or there was evidence of the segment in the visual display of the waveform.

There was a total of 56 changes (out of a total of 642 phonemes) made in the transcriptions and 41 of these changes involved the transcription of a phoneme which was found to be omitted. In six of the cases the reverse was true. Nine of the cases involved changes in phoneme substitutions. The author's transcriptions were used in all subsequent analyses involving phonemic errors in the children's speech.

APPENDIX C

Confusion Matrices of Phonemic Errors \*  
(Pooled for the 6 children and 6 sentences)

CONFUSIONS	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
11	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	2	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
17	2	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0
19	1	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0
20	1	1	1	1	0	0	0	0	0	39	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0
24	1	1	1	1	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
26	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

\* See page following matrix for key to numerical code.





Key to phoneme confusion matrix:

11	/ɪ/	29	/p/	47	/m/
12	/I/	30	/b/	48	/n/
13	/ɛ/	31	/t/	49	/ŋ/
14	/æ/	32	/d/	50	/w/
15	/ɑ/	33	/k/	51	/ɾ/
16	/ɔ/	34	/g/	52	/ʒ/
17	/ʊ/	35	/f/	53	/l/
18	/u/	36	/v/	54	/ʁ/
19	/ʌ/	37	/θ/	55	/ʃ/
20	/ə/	38	/ð/	56	/ʒ/
21	/ɜ/	39	/s/	57	/ç/
22	/ə/	40	/z/	58	/ʃ/
23	/eɪ/	41	/ʃ/	59	/θ/
24	/aɪ/	42	/ʒ/	60	Intended phoneme distorted.
25	/aʊ/	43	/h/		
26	/oʊ/	44	/hw/	61	Unidentifiable substitution
27	/ɔɪ/	45	/tʃ/	62	Intended vowel diphthongized.
28	/ju/	46	/dʒ/	63	Word misread.
				64	Omission.
				65	Word left out.
				66	Intended diphthong fails.

(From Smith, 1972).

## APPENDIX D

## Visual Segmentation Procedures

The procedures which are described below were employed to determine those boundaries which could not be accurately determined by ear. These procedures were applied relatively infrequently (roughly 20% of the time) and they involved determination of the boundaries with the visual display of the waveform. In these cases, all of the boundaries were determined visually rather than auditorily.

1. Determination of the onset of closure for unreleased stop consonants. In words such as /fid/, the onset of stop closure was defined as the point corresponding to the abrupt change in the waveform of the preceding segment. In cases where this occurred, the preceding phoneme was either a vowel or nasal and the onset of closure for the stop was seen as an abrupt cessation in the periodicity of the vowel or nasal.

2. Determination of the onset of closure for released stop consonants in the initial position of words. In the normal speaker's samples, the onset of closure for stop consonants in the word-initial position was seen as the start of a relatively silent interval in the waveform. The onset of closure for stops in the medial position was most often evidenced by a cessation in the periodicity of the preceding segment. In both cases, the termination of the

stop consonant was defined as the end of the noise burst. Thus, the duration of released stops was defined as the sum of the closure period plus the noise in the speech of the normal hearing subjects. Since the deaf children typically paused between words in a sentence, it was not possible to differentiate pause time from closure duration of word-initial stops. Therefore, the duration of word-initial stops in the deaf children's speech included only the duration of the noise burst. If there was evidence of a silent interval in the waveform preceding the release of a stop in the medial position of a bisyllabic word, this silent interval was defined as a pause. In a word such as /zipə/, it appeared as if some of the deaf children were actually pausing before /p/ thereby breaking the word into two syllables which was heard as /zi pə / rather than /zip ə /. Additional evidence which supports the theory that the deaf children paused at places other than syllable boundaries is provided by their production of other bisyllabic words. In the word /disəz/, a silent interval was observed between the phonemes /ɪ/ and /ʒ/ in the speech of four of the six deaf subjects. Since there is no closure involved in the production of fricatives, it was concluded that the children were actually pausing between the sounds and incorrectly syllabifying the word, i.e., /di səz/ instead of /dis əz /. It was reasoned that this could

also be occurring in the bisyllabic words containing stop consonants.

3. Determination of the initiation and termination of phoneme boundaries when the phoneme of interest was preceded or followed by a pause. This procedure was applied most often when segmenting the deaf children's utterances since they frequently paused between words in the utterances. The onset of vowels, semivowels, liquids and nasals was defined as the first visible evidence of periodicity in the waveform. The termination of these sounds in the word-final position was defined as the last evidence of periodicity. The onset of fricatives was defined as the first visible evidence of turbulence in the waveform and the termination of fricatives was defined as the last evidence of the turbulence. The rules used to determine the initiation and termination of plosives are the same as those described above.

4. Determination of the onset of the initial phoneme of a sentence and the termination of the final phoneme of a sentence (as described above).

## APPENDIX E

## Segmentation of Ambiguous Boundaries

Special procedures were developed for establishing phoneme boundaries for those speech segments which could not be segmented easily. In these difficult cases, the decisions were arbitrary and designed to satisfy an overall objective and not to quantify duration per se.

1. The final syllable in two sentences (Sentences 2 and 4) was /ɛt/. In the normal speaker's utterances the /t/ was produced as an unaspirated stop and determination of the closure was extremely difficult. Therefore, no attempt was made to find the final boundary for this segment. In the deaf children's speech samples, the final /t/ was often produced as an aspirated stop consonant. When this occurred, the aspiration was classified as a special type of adventitious sound.

2. In the normal speaker's samples the two adjacent stop consonants in the segment /kæt tudeɪ/ were typically produced as one phoneme rather than two distinct segments. However, the deaf children typically paused between the two words and produced two distinct segments. In order to compare accurately the syllable durations for the two groups of children, the duration of the two adjacent stops in the sentences produced by the normal hearing

speakers was determined in the following manner. First, the onset of closure for /t/ in /kæt/ was determined in the manner previously described for final unreleased stops. The next measurement obtained was the onset of the noise burst associated with the release of the stop before /u/. The duration of the closure from the termination of /æ/ to the onset of the noise burst was considered to represent the closure period for both stop consonants. This closure period was then halved and half of the total duration was defined as the segment duration of the /t/ in /kæt/. The duration of the /t/ in /tu/ was the sum of half the total closure duration and the duration of the noise burst.

3. Difficulty was encountered in determining the boundaries for the two adjacent stop consonants in the segment /ænd dɪʒz / in Sentence 4. In the normal speaker's utterances, the segment was actually produced as /ændɪʒz / with only one stop consonant being heard for the two words. Since the closure duration was very short (10-20 msec), no attempt was made to account for the duration of /d/ in /ænd/. The closure and the burst were defined as the duration of /d/ in /dɪʒz/. The deaf children typically paused between the two words and omitted the final phoneme of /ænd/. This was still considered an error of omission in their speech because it was assumed that had the normal speakers paused between the words,

there would have been some evidence of the unreleased stop  
at the end of /ænd/.

APPENDIX F

Syllable Durations (in msec)

Sentence 1 Normal Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	128.0	102.4	103.9	73.9	116.2	54.3	96.4	25.0
2:	205.2	332.4	238.4	320.0	197.4	269.0	260.4	52.1
3:	211.3	140.1	191.7	217.3	97.4	169.4	171.2	42.0
4:	196.8	214.3	187.4	213.8	178.9	153.3	190.7	21.1
5:	115.1	114.4	63.9	91.8	63.9	63.9	85.5	22.9
6:	280.3	243.6	321.2	302.4	340.8	268.6	292.8	32.6
7:	38.3	51.4	53.9	38.4	35.6	51.0	44.8	7.4
8:	268.6	191.2	191.4	243.0	75.9	195.7	194.3	60.5
9:	205.4	254.6	242.8	153.2	217.2	204.5	213.8	33.6
10:	345.5	255.8	230.3	245.1	395.4	207.7	280.0	67.2

Sentence 2 Normal Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	180.8	180.7	140.6	138.5	104.7	155.3	150.1	26.4
2:	268.5	269.2	289.3	222.6	253.4	332.5	272.6	33.6
3:	358.0	306.6	319.7	262.0	213.5	294.1	292.3	45.5
4:	89.4	89.4	89.4	109.7	127.8	76.6	97.0	16.8
5:	166.2	281.4	153.4	157.3	153.4	243.0	192.4	50.7
6:	178.7	217.3	220.7	180.3	182.6	153.3	188.8	23.5
7:	433.3	396.5	397.1	465.7	384.2	400.7	412.9	28.0
8:	89.5	153.4	79.0	115.1	102.3	115.1	100.1	23.7
9:	255.7	307.0	278.8	249.4	217.3	268.5	262.8	27.5
10:	89.5	115.1	38.3	75.0	51.1	62.8	72.0	25.3

Sentence 3 Normal Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	102.4	102.3	68.8	76.8	89.5	76.8	86.1	13.0
2:	204.5	297.2	230.1	204.5	235.4	252.4	237.3	31.7
3:	102.3	176.7	113.9	145.1	89.4	91.7	119.8	31.4
4:	166.1	191.7	131.9	138.4	218.8	222.3	178.2	35.7
5:	191.7	258.2	227.0	181.2	250.4	268.5	229.5	33.0
6:	222.3	278.2	225.1	192.4	178.9	171.3	213.0	36.9
7:	301.9	322.8	369.4	355.1	405.3	354.7	351.5	33.0

Sentence 4 Normal Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	63.8	89.5	58.0	64.0	78.4	117.6	78.5	20.4
2:	240.7	304.4	265.8	268.4	268.5	204.5	258.7	30.5
3:	90.5	74.8	127.8	208.9	76.6	76.6	124.2	80.3
4:	370.0	310.1	204.5	251.1	264.9	230.1	271.8	54.6
5:	238.4	246.7	209.2	268.4	230.8	230.0	237.2	18.0
6:	102.5	125.9	127.8	127.8	149.7	140.6	120.0	14.6
7:	252.8	299.3	218.3	238.2	226.4	255.9	248.5	26.3
8:	161.0	144.2	134.5	94.2	127.8	166.2	138.0	23.8
9:	344.0	237.8	192.3	204.6	191.8	179.0	225.1	56.6
10:	89.5	63.9	98.0	80.5	76.7	76.7	82.4	11.2

Sentence 5 Normal Group

Syllable	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	54.4	132.5	63.4	89.5	83.3	115.1	89.8	27.2
2:	270.3	242.6	284.7	204.4	251.6	268.5	253.6	25.8
3:	115.1	172.8	73.8	76.7	43.0	52.6	89.0	43.8
4:	102.2	162.5	102.2	135.5	104.6	89.4	116.1	25.0
5:	129.5	202.1	239.5	171.4	179.1	164.7	181.0	33.9
6:	345.4	370.7	255.4	270.8	418.9	328.9	348.3	50.0
7:	204.5	152.3	144.4	115.0	127.8	140.8	147.5	28.2
8:	182.9	191.8	175.5	195.5	182.2	210.7	191.3	14.3
9:	210.2	246.6	226.0	182.4	114.5	178.9	193.1	42.3
10:	140.6	166.2	148.2	80.4	167.5	138.2	141.7	26.0
11:	58.0	102.5	63.9	76.7	76.7	102.4	80.0	17.1
12:	411.8	191.9	358.2	307.0	230.2	272.1	295.2	74.3

Sentence 6 Normal Group

Syllable	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	112.1	70.6	99.5	57.3	80.7	115.1	89.2	21.3
2:	242.9	267.6	210.4	217.3	191.7	149.0	213.1	37.5
3:	551.1	231.0	168.3	214.6	284.3	213.7	277.2	127.2
4:	51.0	76.6	129.5	60.2	115.0	142.1	95.7	34.9
5:	312.0	270.4	308.3	280.2	285.4	277.7	289.0	15.6
6:	131.1	150.8	188.0	168.0	162.1	125.0	154.2	21.6
7:	264.2	215.6	240.1	274.0	217.4	332.7	257.3	40.1

Sentence 1 Deaf Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	204.8	345.4	347.9	132.7	234.2	230.4	249.2	76.5
2:	156.7	179.0	238.7	135.4	235.0	307.0	208.6	58.0
3:	258.2	436.0	586.8	198.6	326.3	282.8	348.1	129.0
4:	191.7	210.7	170.5	204.6	255.8	204.6	206.3	25.7
5:	110.7	218.3	240.9	95.0	123.8	153.5	158.5	53.4
6:	203.4	252.0	147.9	136.0	183.0	255.8	196.3	46.3
7:	152.0	132.7	127.9	170.1	102.9	63.9	124.9	34.3
8:	490.0	475.2	427.2	205.4	334.3	329.3	378.4	100.5
9:	255.6	204.6	316.0	313.4	263.2	237.2	265.0	39.7
10:	383.8	588.6	553.5	109.2	474.6	364.1	427.3	130.4

Sentence 2 Deaf Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	127.8	120.6	294.5	220.7	195.1	239.2	199.6	61.1
2:	172.8	355.0	446.0	196.4	236.1	328.6	289.3	96.2
3:	329.6	220.4	525.3	230.1	503.0	425.2	372.3	121.4
4:	112.6	134.0	208.5	51.0	201.5	148.1	142.6	53.6
5:	286.5	301.0	358.2	204.6	204.7	240.0	265.8	55.3
6:	243.0	188.0	319.0	246.6	145.3	243.1	231.0	54.2
7:	257.5	465.3	501.3	250.3	422.4	420.2	386.2	97.5
8:	243.1	209.5	332.7	140.6	152.3	191.9	211.7	64.0
9:	453.9	383.7	562.9	305.0	384.1	392.1	428.6	64.7
10:	142.0	127.9	257.5	90.7	153.6	237.7	168.2	59.6

Sentence 3 Deaf Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	358.3	320.0	371.1	170.2	188.7	281.6	283.1	75.8
2:	332.6	460.5	392.1	253.5	252.3	305.4	332.7	74.5
3:	217.6	253.4	254.7	114.8	153.6	218.0	202.0	51.4
4:	363.7	180.3	360.9	170.5	310.7	146.0	258.3	91.6
5:	401.0	370.5	318.6	251.1	295.8	344.3	330.2	49.0
6:	188.7	224.6	233.3	171.2	125.1	246.1	198.2	41.6
7:	173.4	340.1	234.6	255.8	173.8	337.3	252.5	67.9

Sentence 4 Deaf Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	226.8	153.4	303.5	170.0	90.2	140.6	182.2	68.0
2:	295.2	371.2	767.7	216.9	320.5	339.0	385.1	177.6
3:	166.2	319.8	191.9	115.0	140.6	0.0	186.7	71.3
4:	322.6	330.5	422.0	224.3	205.3	249.4	292.3	74.4
5:	309.9	511.9	523.6	305.3	308.8	249.4	368.1	107.9
6:	255.5	319.9	248.2	154.4	200.9	486.4	277.5	106.3
7:	236.0	174.8	244.0	262.9	138.6	252.5	218.1	45.4
8:	156.6	191.8	392.1	78.5	0.0	102.2	184.2	111.3
9:	283.8	332.7	290.7	197.2	242.8	329.0	278.5	49.0
10:	103.1	102.3	294.4	110.9	115.3	215.2	158.4	72.2

Sentence 5 Deaf Group

Syllable	<u>Subject</u>						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	107.9	116.3	200.2	136.7	153.4	137.9	142.1	30.0
2:	391.4	353.2	370.5	289.6	214.9	236.6	309.4	67.1
3:	230.3	276.2	120.0	105.4	233.3	143.3	184.8	64.6
4:	319.8	138.5	281.5	109.1	145.9	294.3	214.8	85.2
5:	384.3	343.1	409.4	279.7	257.1	222.4	316.0	67.9
6:	324.4	243.2	307.4	293.8	304.0	346.1	303.1	31.6
7:	196.9	179.8	473.5	138.1	120.3	171.5	213.3	119.1
8:	379.2	376.7	399.0	236.2	299.4	314.2	334.1	56.6
9:	187.7	181.2	209.8	234.4	168.2	382.9	227.4	72.7
10:	268.7	258.7	388.9	243.1	140.6	188.4	248.1	76.9
11:	140.7	71.6	84.4	76.7	32.4	63.9	78.3	32.4
12:	665.4	606.5	619.8	337.8	370.1	445.6	507.5	128.4

Sentence 6 Deaf Group

Syllable	1	2	3	4	5	6	Mean	Std. Dev.
1:	413.7	358.6	435.0	196.6	259.2	179.2	307.0	101.0
2:	225.0	314.4	474.3	100.4	221.1	245.4	280.1	94.0
3:	268.6	435.1	437.1	258.4	161.0	227.9	298.0	103.5
4:	108.4	81.5	149.7	120.3	102.2	112.9	114.0	21.4
5:	382.3	367.6	371.9	335.1	162.3	270.3	314.9	77.7
6:	110.8	197.4	113.3	90.3	130.0	129.7	130.1	32.0
7:	117.2	338.6	530.8	199.3	394.1	382.4	443.7	193.3

APPENDIX G

Phoneme Durations (in msec)

Phoneme	Normal Group						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	128.6	102.4	103.0	72.0	116.2	54.3	96.4	25.0
2:	38.2	127.0	76.7	86.0	41.1	115.2	81.5	33.0
3:	76.7	76.7	76.7	76.7	51.1	63.0	70.3	9.8
4:	42.5	85.9	59.5	80.5	38.3	38.3	59.2	21.4
5:	46.8	41.0	25.5	63.0	66.9	51.6	49.4	13.9
6:	34.1	41.5	76.7	76.7	20.8	16.1	44.3	24.4
7:	89.5	47.7	63.9	80.5	25.5	63.8	63.3	22.5
8:	87.7	50.9	51.1	51.1	51.1	89.5	63.6	17.7
9:	43.4	60.9	58.6	80.5	63.9	38.3	59.1	16.5
10:	127.9	127.0	77.7	95.8	89.5	89.5	101.9	19.4
11:	25.5	25.5	41.1	25.5	25.5	25.5	20.8	9.5
12:	115.1	114.4	63.9	81.8	63.9	63.9	85.5	22.9
13:	102.3	90.2	124.2	166.3	104.5	115.1	117.1	24.4
14:	63.9	51.1	55.1	51.1	51.1	63.9	62.7	15.6
15:	114.1	102.3	101.0	85.0	185.2	89.6	113.0	33.6
16:	38.3	51.4	53.9	38.4	35.6	51.0	44.8	7.4
17:	102.3	102.3	50.1	53.3	28.2	106.2	73.7	30.9
18:	166.3	88.9	141.3	189.7	47.7	89.5	120.6	49.3
19:	89.5	128.5	140.7	63.0	115.1	115.2	108.8	25.4
20:	38.3	37.3	25.5	25.5	12.7	25.5	27.5	8.6
21:	26.5	26.6	25.5	25.5	28.3	12.7	25.8	7.4
22:	51.1	67.2	51.1	38.3	51.1	51.1	51.6	8.4
23:	89.5	63.9	51.1	51.1	63.9	83.5	67.2	14.7
24:	256.0	191.6	179.2	194.0	331.5	124.2	212.8	65.5

Sentence 2 Normal Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	19.8	25.6	23.9	22.5	21.2	32.7	24.4	4.1
2:	109.9	63.9	48.1	76.6	57.9	31.1	64.6	24.6
3:	51.1	91.2	68.6	38.4	25.6	91.5	61.1	25.0
4:	51.1	39.0	56.4	30.7	36.0	38.3	41.9	8.9
5:	115.1	154.0	179.1	140.7	140.7	179.1	151.4	22.7
6:	102.3	76.2	53.8	51.2	76.7	115.1	79.2	23.3
7:	89.5	102.3	105.7	95.8	73.0	51.1	86.2	18.9
8:	140.7	140.5	95.8	102.3	63.9	140.7	114.0	29.2
9:	76.7	34.1	89.5	51.1	51.1	89.5	65.3	21.1
10:	51.1	29.7	28.7	12.8	25.5	12.7	26.7	12.9
11:	25.5	38.3	25.5	25.5	51.1	12.7	29.8	12.1
12:	63.9	51.1	63.9	84.2	76.7	63.9	67.3	10.6
13:	102.3	204.3	38.3	67.8	89.5	76.7	96.5	52.1
14:	63.9	77.1	115.1	89.5	63.9	166.3	96.0	36.0
15:	38.3	51.1	69.2	34.4	42.0	25.5	43.4	13.9
16:	38.3	87.5	99.2	81.4	100.9	47.5	75.8	24.3
17:	102.1	78.7	52.3	64.5	39.7	80.3	69.6	20.3
18:	115.3	115.1	122.2	95.9	114.1	115.1	112.9	8.1
19:	83.6	127.9	63.4	167.1	90.5	139.8	112.0	35.8
20:	234.4	153.5	211.5	202.7	179.6	145.8	187.9	31.5
21:	89.5	153.4	79.0	115.1	102.3	115.1	109.1	23.7
22:	89.5	89.6	87.0	78.0	51.1	89.5	80.8	13.9
23:	127.9	153.5	153.5	148.9	140.7	153.5	146.3	9.4
24:	38.3	63.9	38.3	22.5	25.5	25.5	35.7	14.1
25:	89.5	115.1	38.3	75.0	51.1	62.8	72.0	25.3

Sentence 3 Normal Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	102.4	102.3	68.8	76.8	89.5	76.8	86.1	13.0
2:	72.6	102.3	88.7	38.5	76.2	102.2	80.1	21.8
3:	29.6	79.9	39.0	63.7	44.0	69.4	54.3	17.9
4:	102.3	115.0	102.4	102.3	115.2	80.8	103.0	11.5
5:	102.3	176.7	113.9	145.1	89.4	91.7	119.8	31.4
6:	76.7	49.2	76.7	48.5	98.5	110.6	76.7	23.0
7:	51.1	55.4	30.5	38.3	51.2	60.6	47.8	10.3
8:	38.3	87.1	24.7	51.6	69.1	51.1	53.6	20.2
9:	59.7	37.6	102.2	44.2	47.2	63.9	59.1	21.2
10:	80.9	128.6	117.9	111.5	119.0	153.5	118.7	21.6
11:	51.1	92.0	6.9	25.5	83.3	51.1	51.6	29.8
12:	59.8	12.7	56.1	30.0	16.5	5.1	30.0	21.1
13:	110.4	115.0	128.7	127.9	111.3	119.5	118.8	7.3
14:	52.1	150.5	50.3	34.5	51.1	46.7	64.2	39.0
15:	100.9	47.4	98.8	114.0	85.4	128.0	95.7	25.3
16:	84.4	143.1	127.9	140.7	146.5	93.9	122.7	24.6
17:	116.6	132.3	142.7	100.4	173.4	132.8	133.0	22.6

Sentence 4 Normal Group

Subject

Phoneme	1	2	3	4	5	6	Mean	Std. Dev.
1:	25.5	25.6	19.7	12.9	25.6	28.1	22.9	5.1
2:	38.3	63.9	38.3	51.1	52.8	89.5	55.6	17.5
3:	38.3	76.7	66.8	51.1	87.6	38.3	63.2	21.3
4:	150.2	191.9	153.5	172.7	142.4	128.2	156.5	20.7
5:	52.2	35.8	25.5	44.6	38.3	38.0	39.1	8.2
6:	38.3	49.3	76.7	76.8	51.1	38.3	55.1	16.1
7:	52.0	25.5	51.1	222.1	25.5	38.3	69.1	69.3
8:	24.6	51.1	46.3	63.9	51.6	25.5	43.8	14.3
9:	217.5	131.1	58.6	89.4	98.2	68.3	110.5	53.1
10:	127.9	127.9	99.6	97.8	115.1	136.3	117.4	14.6
11:	98.1	90.6	68.6	113.5	76.1	72.7	86.6	15.8
12:	114.7	130.6	102.3	142.3	131.7	144.7	127.7	14.9
13:	25.6	25.5	38.3	12.6	23.0	12.6	22.9	8.8
14:	38.6	29.2	38.3	38.3	63.9	38.3	41.1	10.7
15:	63.9	96.7	89.5	89.5	85.8	102.3	87.9	12.0
16:	73.1	111.8	51.1	55.5	45.4	94.0	71.8	24.1
17:	51.1	54.2	63.9	54.8	51.1	33.9	51.5	9.0
18:	128.6	133.3	103.3	177.9	129.9	128.0	125.2	10.0
19:	58.3	58.0	71.0	51.1	63.9	78.3	63.4	9.0
20:	102.7	86.3	63.5	43.1	63.9	87.9	74.6	19.7
21:	306.6	186.7	167.2	153.5	153.5	140.7	184.7	56.4
22:	38.3	51.1	25.1	51.1	38.3	38.3	40.4	8.9
23:	89.5	63.9	98.0	89.5	76.7	76.7	82.4	11.2

Sentence 5 Normal Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	20.9	17.4	12.6	25.5	19.4	25.6	20.3	4.5
2:	33.5	115.1	51.1	64.0	63.9	89.5	69.5	26.4
3:	89.5	89.2	127.9	57.1	91.6	64.4	86.6	22.8
4:	45.5	83.2	51.1	66.9	102.3	114.6	77.3	25.4
5:	135.3	70.2	105.2	80.4	57.7	89.5	89.7	25.2
6:	115.1	172.8	73.8	76.7	43.0	52.6	89.0	43.8
7:	76.7	102.3	38.3	110.0	76.6	63.9	78.0	23.8
8:	25.5	60.2	63.9	25.5	28.0	25.5	38.1	17.0
9:	63.9	71.8	89.5	69.1	89.6	88.0	78.6	10.7
10:	65.6	130.3	150.0	102.3	89.5	76.7	102.4	29.5
11:	153.5	127.9	116.0	124.6	150.4	124.3	132.8	14.0
12:	140.7	154.9	88.4	156.7	179.1	140.8	143.4	27.8
13:	51.2	87.9	51.0	89.5	89.4	63.8	72.1	17.3
14:	102.2	91.1	93.3	63.9	64.0	66.4	80.1	15.8
15:	102.3	61.2	51.1	51.1	63.8	74.4	67.3	17.6
16:	76.7	102.3	97.1	127.3	105.5	79.0	98.0	17.1
17:	106.2	89.5	78.4	68.2	76.7	140.7	93.3	24.3
18:	84.0	123.0	113.8	63.8	67.2	38.3	81.7	29.3
19:	82.0	72.5	74.9	63.9	38.3	102.3	72.3	19.3
20:	44.2	51.1	37.3	54.7	9.0	38.3	39.1	14.9
21:	103.9	102.3	84.3	63.9	118.8	89.5	93.8	17.3
22:	36.7	63.9	63.9	25.5	48.7	48.7	47.9	13.8
23:	58.0	102.3	63.9	76.7	76.7	102.4	80.0	17.1
24:	25.5	63.9	96.6	102.3	102.3	92.9	80.6	27.9
25:	386.3	128.0	261.6	204.7	127.9	179.2	214.6	89.5

Sentence 6 Normal Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	21.1	11.6	22.7	18.9	14.9	21.2	18.4	3.9
2:	91.0	59.2	76.8	38.4	65.8	93.9	70.8	19.1
3:	102.3	76.7	33.6	63.9	38.3	33.9	58.1	25.5
4:	38.3	51.1	38.3	38.3	63.9	38.3	44.7	9.8
5:	102.3	139.8	138.5	115.1	89.5	76.8	110.3	23.5
6:	217.5	52.0	52.3	56.2	105.3	78.3	93.6	58.5
7:	230.3	115.1	89.2	117.5	115.1	113.4	130.1	45.8
8:	103.3	63.9	26.8	40.9	63.9	22.0	53.5	27.6
9:	12.7	25.5	68.1	15.4	48.6	84.6	42.5	27.0
10:	38.3	51.1	61.4	44.8	66.4	57.5	53.2	9.6
11:	127.9	117.7	135.4	116.5	99.8	88.5	114.3	15.9
12:	140.7	102.3	127.9	112.4	143.2	148.8	129.2	16.9
13:	43.4	50.4	45.0	51.3	42.4	40.4	45.5	4.0
14:	87.5	90.2	127.2	122.1	136.6	86.6	108.4	20.7
15:	43.6	60.6	60.8	45.9	25.5	38.4	45.8	12.4
16:	85.1	30.4	35.4	30.8	25.5	51.1	43.0	20.5
17:	179.1	185.2	204.7	243.2	191.9	281.6	214.3	36.6

Sentence 1 Deaf Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	204.8	345.4	347.9	132.7	234.2	230.4	249.2	76.5
2:	12.8	12.7	14.4	12.8	19.7	162.3	29.1	32.8
3:	143.9	166.3	127.9	122.6	127.9	204.7	148.9	28.9
4:	0.0	0.0	96.4	0.0	87.4	0.0	91.9	4.5
5:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6:	12.8	115.1	23.8	26.4	19.3	63.9	43.5	35.9
7:	245.4	269.8	422.3	153.5	234.8	218.9	257.4	81.9
8:	0.0	51.1	140.7	18.7	72.2	0.0	70.7	44.7
9:	12.8	12.8	17.1	12.8	76.8	12.8	24.2	23.6
10:	153.4	157.2	115.1	115.1	140.7	153.5	139.2	17.8
11:	25.5	40.7	38.3	76.7	38.3	38.3	43.0	15.9
12:	119.7	218.3	240.9	95.0	123.8	153.5	158.5	53.4
13:	25.6	71.9	25.5	33.8	68.0	51.2	46.0	19.0
14:	140.7	180.1	98.2	63.9	89.5	140.7	118.8	38.8
15:	37.1	0.0	24.2	38.3	25.5	63.9	37.8	14.3
16:	152.0	132.7	127.9	170.1	102.9	63.9	124.9	34.3
17:	76.7	51.1	120.1	38.3	89.5	102.3	79.7	28.2
18:	422.3	424.1	307.1	167.1	244.8	227.0	298.7	97.0
19:	12.7	25.6	25.9	32.1	20.3	32.7	24.9	6.9
20:	25.5	0.0	38.3	37.9	38.3	38.3	35.7	5.1
21:	102.3	89.5	115.1	113.1	127.9	63.9	102.0	20.7
22:	115.1	89.5	136.7	130.3	76.7	102.3	108.4	21.3
23:	89.5	153.5	152.7	0.0	117.5	0.0	128.3	26.7
24:	294.3	435.1	400.8	109.2	357.1	364.1	341.8	76.9

Sentence 2 Deaf Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	12.7	14.7	10.3	5.7	21.2	24.1	14.8	6.3
2:	115.1	62.1	284.2	99.9	119.8	215.1	149.4	76.0
3:	0.0	43.8	0.0	115.1	54.1	0.0	71.0	31.5
4:	18.5	10.5	41.6	51.9	20.5	18.6	26.9	14.7
5:	77.6	230.3	278.4	144.5	193.3	310.0	205.7	78.6
6:	76.7	115.1	126.0	0.0	22.3	0.0	85.0	40.6
7:	9.7	24.4	13.2	13.1	18.0	69.4	24.6	20.6
8:	319.9	196.0	251.9	217.0	255.9	179.1	236.6	46.3
9:	0.0	0.0	260.2	0.0	229.1	176.7	222.0	34.5
10:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11:	12.7	63.9	18.7	11.2	11.1	12.8	21.7	19.0
12:	99.9	70.1	189.8	39.8	190.4	135.3	120.9	56.8
13:	230.3	230.4	307.1	76.7	166.4	99.3	185.0	80.0
14:	56.2	70.6	51.1	127.9	38.3	140.7	80.8	39.2
15:	179.1	102.3	319.9	246.6	145.3	243.1	206.0	72.1
16:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17:	63.9	85.7	0.0	0.0	0.0	0.0	74.8	10.9
18:	7.7	25.6	26.7	47.7	12.8	20.9	23.6	12.7
19:	127.9	127.9	267.6	202.6	140.7	230.3	182.8	54.2
20:	121.9	311.8	207.0	0.0	268.9	169.0	215.7	68.0
21:	243.1	209.5	332.7	140.6	152.3	191.9	211.7	64.0
22:	85.4	153.5	204.7	153.5	140.7	127.9	144.3	35.5
23:	291.8	191.9	281.5	152.0	218.8	264.2	233.4	50.4
24:	76.7	38.3	76.7	89.5	24.6	0.0	61.2	25.1
25:	142.0	127.9	257.5	90.7	153.6	237.7	168.2	59.6

Sentence 3 Deaf Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	358.3	320.0	371.1	170.2	188.7	281.6	283.1	75.8
2:	127.9	102.3	166.3	39.3	118.3	115.1	111.4	38.2
3:	179.2	204.7	225.8	81.2	102.3	190.3	163.9	53.3
4:	25.5	153.5	0.0	134.0	31.7	0.0	86.2	58.0
5:	217.6	253.4	254.7	114.8	153.6	218.0	202.0	51.4
6:	97.9	39.5	25.5	46.0	127.9	15.0	58.6	40.6
7:	166.3	140.8	335.4	133.5	191.8	131.0	183.1	71.3
8:	99.5	0.0	0.0	0.0	0.0	0.0	99.5	0.0
9:	140.8	127.9	76.8	89.6	102.4	163.2	116.8	30.0
10:	233.8	188.8	241.8	123.2	153.4	134.8	179.3	46.1
11:	26.4	53.8	0.0	38.3	40.0	46.3	41.0	9.1
12:	9.7	11.4	14.0	14.6	13.6	20.1	13.9	3.2
13:	165.1	213.2	219.3	89.5	111.5	174.4	162.2	48.1
14:	13.9	0.0	0.0	67.2	0.0	51.6	44.2	22.4
15:	72.2	7.4	10.2	51.2	25.5	11.1	29.6	24.2
16:	88.5	191.9	224.4	89.5	127.9	179.1	150.2	51.8
17:	12.7	140.8	0.0	115.1	20.4	147.1	87.2	58.7

Sentence 4 Deaf Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	20.7	12.7	22.0	21.8	13.5	12.7	17.2	4.3
2:	206.1	140.7	281.5	157.2	76.7	127.9	165.0	64.7
3:	37.3	63.9	243.1	18.8	120.7	63.9	91.3	74.8
4:	230.3	204.5	499.1	170.1	166.3	204.7	262.3	113.7
5:	27.6	12.8	25.5	10.0	33.5	70.4	31.5	18.6
6:	102.4	76.7	191.9	87.8	43.2	0.0	100.4	49.7
7:	63.8	243.1	0.0	27.2	97.4	0.0	107.9	81.9
8:	51.3	44.9	26.3	19.7	0.0	0.0	35.5	13.0
9:	143.4	196.1	332.7	127.9	205.3	240.4	209.1	68.3
10:	127.9	89.5	63.0	76.7	0.0	0.0	89.3	24.2
11:	15.8	12.8	12.8	22.3	5.0	17.4	14.3	5.3
12:	230.3	409.1	510.8	182.2	303.8	232.0	326.4	131.2
13:	63.8	0.0	0.0	100.8	0.0	0.0	82.3	18.5
14:	166.3	89.6	248.2	64.0	76.8	486.4	188.5	147.5
15:	89.2	230.3	0.0	90.4	124.1	0.0	133.5	57.6
16:	15.6	12.8	0.0	31.6	10.7	9.2	16.0	8.1
17:	204.7	132.9	0.0	144.5	127.9	217.7	165.5	37.9
18:	15.7	29.1	244.0	86.8	0.0	25.6	80.2	85.6
19:	127.9	140.7	216.5	78.5	0.0	76.7	128.1	51.1
20:	28.7	51.1	175.6	0.0	0.0	25.5	70.2	61.6
21:	239.0	217.6	191.9	115.5	153.5	329.0	207.7	67.7
22:	44.8	115.1	98.8	76.7	89.3	0.0	84.9	23.7
23:	103.1	102.3	294.4	119.9	115.3	215.2	158.4	72.2

Sentence 5 Deaf Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	9.2	10.2	12.8	17.1	12.7	16.4	13.1	2.9
2:	98.7	106.1	187.4	110.6	140.7	121.5	129.0	29.3
3:	45.1	12.3	14.7	176.7	14.1	14.2	45.2	57.3
4:	105.1	255.9	174.8	102.4	83.4	167.0	148.1	58.9
5:	241.2	85.0	181.0	16.5	117.4	55.4	116.1	75.8
6:	230.3	276.2	120.0	105.4	233.9	143.3	184.8	64.6
7:	243.1	94.8	166.4	76.8	120.4	294.3	166.0	79.1
8:	76.7	43.7	115.1	32.3	25.5	0.0	58.7	33.3
9:	127.9	135.3	166.3	156.5	80.5	88.6	125.8	31.9
10:	256.4	207.8	243.1	123.2	176.6	133.8	190.1	50.6
11:	16.6	62.9	66.9	29.7	51.1	83.6	51.8	22.7
12:	307.8	180.3	240.5	144.0	252.9	262.5	231.3	54.2
13:	0.0	0.0	0.0	120.1	0.0	0.0	120.1	0.0
14:	196.9	51.9	192.0	138.1	89.5	171.5	140.0	53.6
15:	0.0	127.9	281.5	0.0	30.8	0.0	146.7	103.2
16:	136.1	89.1	0.0	89.6	36.0	134.8	97.1	36.9
17:	243.1	287.6	399.0	146.6	263.4	179.4	253.2	81.1
18:	18.7	19.4	55.2	34.4	47.1	83.6	43.1	22.5
19:	169.0	161.8	154.6	100.5	121.1	299.3	167.7	63.5
20:	0.0	0.0	0.0	99.5	0.0	0.0	99.5	0.0
21:	204.8	153.6	268.7	128.0	102.3	124.5	163.6	56.9
22:	63.9	105.1	120.2	115.1	38.3	63.9	84.4	30.6
23:	140.7	71.6	84.4	76.7	32.4	63.9	78.3	32.4
24:	204.7	197.0	109.7	230.0	108.2	102.3	158.6	52.9
25:	460.7	409.5	510.1	107.8	261.9	343.3	348.9	134.1

Sentence 6 Deaf Group

Phoneme	Subject						Mean	Std. Dev.
	1	2	3	4	5	6		
1:	32.4	64.3	16.1	7.5	14.8	0.0	27.0	20.3
2:	381.3	294.3	418.9	189.1	244.4	179.2	284.5	90.7
3:	58.8	75.8	63.8	36.5	32.6	90.9	63.1	22.4
4:	52.0	115.1	179.2	63.8	188.5	154.5	125.5	53.2
5:	115.1	123.5	211.3	90.1	0.0	0.0	137.2	43.6
6:	20.2	30.2	12.8	21.7	27.9	16.1	23.1	6.8
7:	238.4	390.1	267.1	148.5	100.3	157.1	223.6	100.1
8:	C.C	14.8	117.2	88.2	32.8	54.7	61.5	37.1
9:	17.2	13.9	19.4	15.8	16.3	12.8	15.9	2.1
10:	91.2	67.6	130.3	113.5	85.9	100.1	98.1	20.0
11:	107.4	89.C	84.2	42.7	28.9	50.6	67.1	28.1
12:	104.6	278.6	287.6	164.5	133.4	219.7	213.1	56.2
13:	80.3	C.C	C.C	127.9	0.0	0.0	104.1	23.8
14:	26.2	15.1	12.8	15.5	29.2	10.6	18.2	6.9
15:	84.6	182.3	100.5	83.8	100.8	119.1	111.8	33.7
16:	29.6	6.9	22.7	7.3	51.1	12.7	21.7	15.5
17:	787.6	331.7	508.1	192.0	343.C	369.7	422.0	187.6

## APPENDIX H

## Stressed/Unstressed Ratios for Syllables

Syllable	Phonemes in Syllable	Subject					
Sentence 1	Normal Group	1	2	3	4	5	6
1:	2 TO 5	265.2	332.4	238.4	320.0	197.4	269.0
	1 TO 1	128.0	102.4	103.9	73.9	116.2	54.3
	RATIO:	1.6031	3.2460	2.2945	4.3301	1.6987	4.9539
	LOG10 RATIO:	0.2069	0.5113	0.3606	0.6364	0.2301	0.6949
2:	9 TO 11	196.8	214.2	187.4	213.8	178.9	153.3
	6 TO 8	211.3	140.1	191.7	217.3	97.4	169.4
	RATIO:	0.9313	1.5206	0.9775	0.9838	1.8367	0.9049
	LOG10 RATIO:	-0.0309	0.1845	-0.0098	-0.0070	0.2640	-0.0433
3:	9 TO 11	196.8	214.2	187.4	213.8	178.9	153.3
	12 TO 12	115.1	114.4	63.9	91.8	63.9	63.9
	RATIO:	1.7098	1.8737	2.9327	2.3289	2.7996	2.3990
	LOG10 RATIO:	0.2329	0.2725	0.4672	0.3671	0.4470	0.3800
4:	17 TO 18	268.6	191.2	191.4	243.0	75.9	195.7
	13 TO 15	280.3	243.6	321.2	302.4	340.8	268.6
	RATIO:	0.9582	0.7848	0.5058	0.8035	0.2227	0.7285
	LOG10 RATIO:	-0.0185	-0.1052	-0.2248	-0.0950	-0.6522	-0.1375
5:	17 TO 18	266.6	191.2	191.4	243.0	75.9	195.7
	16 TO 16	38.3	51.4	53.9	38.4	35.6	51.0
	RATIO:	7.0130	3.7198	3.5510	6.3281	2.1320	3.8372
	LOG10 RATIO:	0.8459	0.5705	0.5503	0.8012	0.3287	0.5840
6:	23 TO 24	345.5	255.8	230.3	245.1	395.4	207.7
	19 TO 22	205.4	259.6	242.8	153.2	217.2	204.5
	RATIO:	1.6820	0.9853	0.9485	1.5998	1.8204	1.0156
	LOG10 RATIO:	0.2258	-0.0064	-0.0229	0.2040	0.2601	0.0067

Sentence 2 Normal Group

Syllable	Phonemes in Syllable	Subject					
		1	2	3	4	5	6
1:	4 TO 6	268.5	269.2	289.3	222.6	253.4	332.5
	1 TO 3	180.8	180.7	140.6	138.5	104.7	155.3
	RATIO:	1.4850	1.4897	2.0576	1.6072	2.4202	2.1410
	LOG10 RATIO:	0.1717	0.1730	0.3133	0.2060	0.3838	0.3306
2:	13 TO 14	166.2	281.4	153.4	157.3	153.4	243.0
	11 TO 12	89.4	89.4	89.4	109.7	127.8	76.6
	RATIO:	1.8590	3.1476	1.7158	1.4339	1.2003	3.1723
	LOG10 RATIO:	0.2692	0.4979	0.2344	0.1565	0.0792	0.5013
3:	13 TO 14	166.2	281.4	153.4	157.3	153.4	243.0
	15 TO 17	178.7	217.3	270.7	180.3	182.6	153.3
	RATIO:	0.9300	1.2949	0.6950	0.8724	0.8400	1.5851
	LOG10 RATIO:	-0.0315	0.1122	-0.1580	-0.0592	-0.0757	0.2000
4:	13 TO 14	166.2	281.4	153.4	157.3	153.4	243.0
	18 TO 20	433.3	396.5	397.1	465.7	384.2	400.7
	RATIO:	0.3835	0.7097	0.3863	0.3377	0.3992	0.6064
	LOG10 RATIO:	-0.4162	-0.1489	-0.4130	-0.4714	-0.3988	-0.2172
5:	22 TO 24	255.7	307.	278.8	249.4	217.3	268.5
	21 TO 21	89.5	153.4	79.0	115.1	102.3	115.1
	RATIO:	2.8569	2.0013	3.5291	2.1668	2.1241	2.3327
	LOG10 RATIO:	0.4558	0.3013	0.5476	0.3358	0.3271	0.3678
6:	22 TO 24	255.7	307.0	278.8	249.4	217.3	268.5
	25 TO 25	89.5	115.1	38.3	75.0	51.1	62.8
	RATIO:	2.8569	2.6672	7.2793	3.3253	4.2524	4.2754
	LOG10 RATIO:	0.4558	0.4260	0.8620	0.5218	0.6286	0.6309

## Sentence 3 Normal Group

Syllable	Phonemes in Syllable	<u>Subject</u>					
		1	2	3	4	5	6
1:	2 TO 4	204.5	297.2	230.1	204.5	235.4	252.4
	1 TO 1	102.4	102.3	68.8	76.8	89.5	76.8
	RATIO:	1.9970	2.9051	3.3444	2.6627	2.6301	3.2864
	LOG10 RATIO:	0.3003	0.4631	0.5243	0.4253	0.4199	0.5167
2:	9 TO 11	191.7	258.2	227.0	181.2	250.4	268.5
	5 TO 5	102.3	176.7	113.9	145.1	89.4	91.7
	RATIO:	1.8739	1.4617	1.0929	1.2487	2.8008	2.9280
	LOG10 RATIO:	0.2727	0.1647	0.2994	0.0964	0.4472	0.4665
3:	9 TO 11	191.7	258.2	227.0	181.2	250.4	268.5
	6 TO 8	166.1	191.7	131.9	138.4	218.8	222.3
	RATIO:	1.1541	1.3468	1.7210	1.3092	1.1444	1.2078
	LOG10 RATIO:	0.0622	0.1203	0.2357	0.1170	0.0585	0.0819
4:	15 TO 17	301.9	322.8	369.4	355.1	405.3	354.7
	12 TO 14	222.3	278.2	235.1	192.4	178.9	171.3
	RATIO:	1.3580	1.1603	1.5712	1.8456	2.2655	2.0706
	LOG10 RATIO:	0.1328	0.0645	0.1962	0.2661	0.3551	0.3160

Sentence 4 Normal Group

Syllable	Phonemes in Syllable	<u>Subject</u>					
		1	2	3	4	5	6
1: 3 TO 5 1 TO 2 LOGIO RATIO:		240.7	304.4	265.8	268.4	268.5	204.5
		63.8	89.5	58.0	64.0	78.4	117.6
		3.7727	3.4011	4.5827	4.1937	3.4247	1.7389
		0.5766	0.5316	0.6611	0.6225	0.5346	0.2402
2: 3 TO 5 6 TO 7 LOGIO RATIO:		240.7	304.4	265.8	268.4	268.5	204.5
		90.3	74.8	127.8	298.9	76.6	76.6
		2.6655	4.0695	2.0798	0.8979	3.5052	2.6697
		0.4257	0.6005	0.3180	-0.0467	0.5447	0.4264
3: 11 TO 13 8 TO 10 LOGIO RATIO:		238.4	246.7	209.2	268.4	230.8	230.0
		370.0	310.1	204.5	251.1	264.9	230.1
		0.6443	0.7055	1.0229	1.0688	0.8712	0.9995
		-0.1909	-0.0993	0.0098	0.0288	-0.0598	-0.0002
4: 16 TO 18 14 TO 15 LOGIO RATIO:		252.8	299.3	218.3	238.2	226.4	255.9
		102.5	125.9	127.8	127.8	149.7	140.6
		2.4663	2.3772	1.7081	1.8638	1.5123	1.8200
		0.3920	0.3760	0.2325	0.2703	0.1796	0.2600
5: 16 TO 18 19 TO 20 LOGIO RATIO:		252.8	299.3	218.3	238.2	226.4	255.9
		161.0	144.3	134.5	94.2	127.8	166.2
		1.5701	2.0741	1.6230	2.5286	1.7715	1.5397
		0.1959	0.3168	0.2103	0.4028	0.2483	0.1874
6: 23 TO 23 21 TO 22 LOGIO RATIO:		89.5	63.9	98.0	89.5	76.7	76.7
		344.9	237.8	192.3	204.6	191.8	179.0
		0.2594	0.2687	0.5096	0.4374	0.3998	0.4284
		-0.5860	-0.5707	-0.2927	-0.3591	-0.3981	-0.3681

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## Sentence 5 Normal Group

Syllable	Phoneme In Syllable	Subject					
		1	2	3	4	5	6
1:	3 TO 5	270.3	242.6	284.2	204.4	251.6	268.5
	1 TO 2	54.4	132.5	63.9	89.5	83.3	115.1
	RATIO:	4.9687	1.8309	4.4475	2.2837	3.0204	2.3327
	LOG10 RATIO:	0.6962	0.2676	0.6481	0.3586	0.4800	0.3678
2:	3 TO 5	270.3	242.6	284.2	204.4	251.6	268.5
	6 TO 6	115.1	172.8	73.8	76.7	43.0	52.6
	RATIO:	2.3483	1.4039	3.8509	2.6649	5.8511	5.1045
	LOG10 RATIO:	0.3707	0.1473	0.5855	0.4256	0.7672	0.7079
3:	11 TO 13	345.4	370.7	255.4	370.8	418.9	328.9
	7 TO 8	102.2	162.5	102.2	135.5	104.6	89.4
	RATIO:	3.3796	2.2812	2.4990	2.7365	4.0047	3.6789
	LOG10 RATIO:	0.5288	0.3581	0.3977	0.4371	0.6025	0.5657
4:	11 TO 13	345.4	370.7	255.4	370.8	418.9	328.9
	9 TO 10	129.5	202.1	239.5	171.4	179.1	164.7
	RATIO:	2.6671	1.8342	1.0663	2.1633	2.3389	1.9969
	LOG10 RATIO:	0.4260	0.2634	0.0278	0.3351	0.3690	0.3003
5:	18 TO 20	210.2	246.6	226.0	182.4	114.5	178.9
	14 TO 15	204.5	152.3	144.4	115.0	127.8	140.8
	RATIO:	1.0278	1.6191	1.5650	1.5860	0.8959	1.2705
	LOG10 RATIO:	0.0119	0.2092	0.1945	0.2003	-0.0477	0.1039
6:	18 TO 20	210.2	246.6	226.0	182.4	114.5	178.9
	16 TO 17	182.9	191.8	175.5	195.5	182.2	219.7
	RATIO:	1.1492	1.2857	1.7877	0.9329	0.6284	0.8142
	LOG10 RATIO:	0.0603	0.1091	0.1098	-0.0301	-0.2017	-0.0892
7:	24 TO 25	411.8	191.9	358.2	307.0	230.2	272.1
	21 TO 23	198.6	269.5	212.1	166.1	244.2	240.6
	RATIO:	2.0735	0.7147	1.6888	1.8482	0.9426	1.1309
	LOG10 RATIO:	0.3167	-0.1458	0.2275	0.2667	-0.0256	0.0534

## Sentence 6 Normal Group

Syllable	Phoneme in Syllable	<u>Subject</u>					
		1	2	3	4	5	6
1:	6 TO 8	551.1	231.0	168.3	214.6	284.3	213.7
	1 TO 2	112.1	70.8	99.5	57.3	80.7	115.1
	RATIO:	4.9161	3.2627	1.6914	3.7452	3.5229	1.8566
	LOG10 RATIO:	0.6916	0.5135	0.2282	0.5734	0.5469	0.2687
2:	6 TO 8	551.1	231.0	168.3	214.6	284.3	213.7
	3 TO 5	242.9	267.6	210.4	217.3	191.7	149.0
	RATIO:	2.2688	0.9632	0.7999	0.9875	1.4830	1.4342
	LOG10 RATIO:	0.3557	-0.0638	-0.0969	-0.0054	0.1711	0.1566
3:	11 TO 13	312.0	270.4	308.3	280.2	285.4	277.7
	9 TO 10	51.0	76.6	129.5	60.2	115.0	142.1
	RATIO:	6.1176	3.5300	2.3806	4.6544	2.4817	1.9542
	LOG10 RATIO:	0.7865	0.5477	0.3766	0.6678	0.3947	0.2909
4:	16 TO 17	264.2	215.6	240.1	274.0	217.4	332.7
	14 TO 15	131.1	150.8	188.0	168.0	162.1	125.0
	RATIO:	2.0152	1.4297	1.2771	1.6309	1.3411	2.6616
	LOG10 RATIO:	0.3043	0.1552	0.1062	0.2124	0.1274	0.4251

## Sentence 1 Deaf Group

Syllable	Phonemes in Syllable	Subject					
		1	2	3	4	5	6
1:	2 TO 5	156.7	179.0	238.7	135.4	235.0	307.0
	1 TO 1	204.8	345.4	347.9	132.7	234.2	230.4
	RATIO:	0.7651	0.5182	0.4861	1.0203	1.0034	1.3324
	LOG10 RATIO:	-0.1162	-0.2855	-0.1636	0.0087	0.0014	0.1246
2:	9 TO 11	191.7	210.7	170.5	204.6	255.8	204.6
	6 TO 8	258.2	436.0	586.8	198.6	326.3	282.8
	RATIO:	0.7424	0.4832	0.2905	1.0302	0.7839	0.7234
	LOG10 RATIO:	-0.1293	-0.3158	-0.5368	0.0129	-0.1057	-0.1406
3:	9 TO 11	191.7	210.7	170.5	204.6	255.8	204.6
	12 TO 12	119.7	218.3	240.9	95.0	123.8	153.5
	RATIO:	1.6015	0.9651	0.7077	2.1536	2.0662	1.3328
	LOG10 RATIO:	0.2045	-0.0154	-0.1501	0.3331	0.3151	0.1247
4:	17 TO 18	499.0	475.2	427.2	205.4	334.3	329.3
	13 TO 15	203.4	252.0	147.9	136.0	183.0	255.8
	RATIO:	2.4532	1.8857	2.8884	1.5102	1.8267	1.2873
	LOG10 RATIO:	0.3897	0.2754	0.4606	0.1790	0.2616	0.1096
5:	17 TO 18	499.0	475.2	427.2	205.4	334.3	329.3
	16 TO 16	152.0	132.7	127.9	170.1	102.9	63.9
	RATIO:	3.2828	3.5810	3.3401	1.2075	3.2487	5.1533
	LOG10 RATIO:	0.5162	0.5540	0.5237	0.0818	0.5117	0.7120
6:	23 TO 24	303.8	588.6	553.5	199.2	474.6	364.1
	19 TO 22	255.6	204.6	316.0	313.4	263.2	237.2
	RATIO:	1.5015	2.8768	1.7515	0.6356	1.8031	1.5349
	LOG10 RATIO:	0.1765	0.4589	0.2434	-0.1968	0.2560	0.1860

## Sentence 2 Deaf Group

Syllable	Phonemes in Syllable	Subject					
		1	2	3	4	5	6
1:	4 TO 6	172.8	355.9	446.0	196.4	236.1	328.6
	1 TO 3	127.8	120.6	204.5	220.7	195.1	239.2
	RATIO:	1.3521	2.9510	1.5144	0.8898	1.2101	1.3737
	LOG10 RATIO:	0.1310	0.4699	0.1802	-0.0507	0.0828	0.1378
2:	13 TO 14	286.5	301.0	358.2	204.6	204.7	240.0
	11 TO 12	112.6	134.0	208.5	51.0	201.5	148.1
	RATIO:	2.5444	2.2462	1.7179	4.0117	1.0158	1.6205
	LOG10 RATIO:	0.4055	0.3514	0.2349	0.6033	0.0068	0.2096
3:	13 TO 14	286.5	301.0	358.2	204.6	204.7	240.0
	15 TO 17	243.0	188.0	319.9	246.6	145.3	243.1
	RATIO:	1.1740	1.6010	1.1197	0.8296	1.4088	0.9872
	LOG10 RATIO:	0.0715	0.2043	0.0491	-0.0811	0.1468	-0.0055
4:	13 TO 14	286.5	301.0	358.2	204.6	204.7	240.0
	18 TO 20	257.5	465.3	501.3	250.3	422.4	420.2
	RATIO:	1.1126	0.6468	0.7145	0.8174	0.4646	0.5711
	LOG10 RATIO:	0.0463	-0.1892	-0.1459	-0.0875	-0.3146	-0.2432
5:	22 TO 24	453.9	383.7	562.9	395.0	384.1	392.1
	21 TO 21	245.1	209.5	332.7	140.6	152.3	191.9
	RATIO:	1.8671	1.8315	1.6919	2.8093	2.5219	2.0432
	LOG10 RATIO:	0.2711	0.2628	0.2283	0.4485	0.4017	0.3103
6:	22 TO 24	453.9	383.7	562.9	395.0	384.1	392.1
	25 TO 25	142.0	127.9	257.5	90.7	153.6	237.7
	RATIO:	3.1964	3.0000	2.1860	4.3550	2.5006	1.6495
	LOG10 RATIO:	0.5046	0.4771	0.3396	0.6389	0.3980	0.2173

Sentence 3 Deaf Group

Syllable	Phonemes in Syllable	Subject					
		1	2	3	4	5	6
1:	2 TO 4	332.6	460.5	392.1	253.5	252.3	305.4
	1 TO 1	358.3	320.0	371.1	179.2	188.7	281.6
	RATIO:	0.9282	1.4390	1.0565	1.4146	1.3370	1.0845
	LOG10 RATIO:	-0.0323	0.1580	0.0238	0.1506	0.1261	0.0352
2:	9 TO 11	401.0	370.5	318.6	251.1	295.8	344.3
	5 TO 5	217.6	253.4	254.7	114.8	153.6	218.0
	RATIO:	1.8428	1.4621	1.2508	2.1872	1.9257	1.5793
	LOG10 RATIO:	0.2654	0.1649	0.0971	0.3398	0.2845	0.1984
3:	9 TO 11	401.0	370.5	318.6	251.1	295.8	344.3
	6 TO 8	363.7	180.3	360.9	179.5	319.7	146.0
	RATIO:	1.1025	2.0540	0.8827	1.3988	0.9252	2.3582
	LOG10 RATIO:	0.0423	0.3127	-0.0541	0.1457	-0.0337	0.3725
4:	15 TO 17	173.4	340.1	234.6	255.8	173.8	337.3
	12 TO 14	188.7	224.6	233.3	171.3	125.1	246.1
	RATIO:	0.9184	1.5142	1.0055	1.4932	1.3892	1.3705
	LOG10 RATIO:	-0.0367	0.1801	0.0023	0.1741	0.1427	0.1368

## Sentence 4 Deaf Group

Syllable	Phonemes in Syllable	Subject					
		1	2	3	4	5	6
1:	3 TO 5	295.2	371.7	767.7	216.9	320.5	339.0
	1 TO 2	226.8	153.4	303.5	179.0	90.2	140.6
	RATIO:	1.3015	2.4198	2.5294	1.2117	3.5532	2.4110
	LOG10 RATIO:	0.1144	0.3827	0.4030	0.0833	0.5506	0.3821
2:	3 TO 5	295.2	371.7	767.7	216.9	320.5	339.0
	6 TO 7	166.2	319.8	191.9	115.0	140.6	-1.0
	RATIO:	1.7761	1.1607	4.0065	1.8860	2.2795	0.0000
	LOG10 RATIO:	0.2494	0.0647	0.6021	0.2755	0.3578	-99.0000
3:	11 TO 13	309.9	511.9	523.6	305.3	308.8	249.4
	R TO 10	322.6	330.5	422.0	224.3	209.3	249.4
	RATIO:	0.9606	1.5488	1.2407	1.3611	1.5041	1.0000
	LOG10 RATIO:	-0.0174	0.1899	0.0936	0.1338	0.1772	0.0000
4:	16 TO 18	236.0	174.8	244.0	262.9	138.6	252.5
	14 TO 15	255.5	310.9	246.2	154.4	200.9	486.4
	RATIO:	0.9236	0.5464	0.9830	1.7027	0.6898	0.5191
	LOG10 RATIO:	-0.0345	-0.2624	-0.0074	0.2311	-0.1612	-0.2847
5:	16 TO 18	236.0	174.8	244.0	262.9	138.6	252.5
	19 TO 20	156.6	191.8	392.1	78.5	-1.0	102.2
	RATIO:	1.5670	0.9113	0.6222	3.3490	0.0000	2.4706
	LOG10 RATIO:	0.1781	-0.0403	-0.2060	0.5249	-99.0000	0.3928
6:	23 TO 23	103.1	102.3	294.4	119.9	115.3	215.2
	21 TO 22	283.8	332.7	290.7	192.2	242.8	329.0
	RATIO:	0.3632	0.3024	1.0127	0.6238	0.4748	0.6541
	LOG10 RATIO:	-0.4398	-0.5122	0.0054	-0.2049	-0.3234	-0.1843

Sentence 5 Deaf Group		Phonemes in Syllable					
		1	2	3	4	5	6
1:	3 TO 5	391.4	353.2	370.5	289.6	214.9	236.6
	1 TO 2	107.6	116.3	200.2	136.7	153.4	137.9
	RATIO:	3.6274	3.0346	1.9506	2.1185	1.4009	1.7157
	LOG10 RATIO:	0.5545	0.4824	0.2873	0.3260	0.1464	0.2344
2:	3 TO 5	351.4	353.2	370.5	289.6	214.9	236.6
	6 TO 6	230.3	276.7	170.0	105.4	233.0	143.3
	RATIO:	1.6945	1.2787	3.0875	2.7476	0.9187	1.6510
	LOG10 RATIO:	0.2263	0.1067	0.4896	0.4380	-0.0368	0.2177
3:	11 TO 13	324.4	243.2	307.4	253.8	304.0	346.1
	7 TO 8	319.8	138.5	281.5	109.1	145.9	204.3
	RATIO:	1.0143	1.7559	1.0920	2.6929	2.0436	1.1760
	LOG10 RATIO:	0.0061	0.2444	0.0382	0.4302	0.3188	0.0704
4:	11 TO 13	324.4	243.2	307.4	293.8	304.0	346.1
	9 TO 10	384.3	343.1	409.4	279.7	257.1	222.4
	RATIO:	0.8441	0.7068	0.7508	1.0504	1.1824	1.5562
	LOG10 RATIO:	-0.0736	-0.1494	-0.1244	0.0213	0.0727	0.1920
5:	18 TO 20	187.7	181.2	209.8	234.4	168.2	382.9
	14 TO 15	146.9	179.8	473.5	138.1	120.3	171.5
	RATIO:	0.5532	1.0077	0.4430	1.6973	1.3981	2.2326
	LOG10 RATIO:	-0.0708	0.0033	-0.3535	0.2297	0.1455	0.3488
6:	18 TO 20	187.7	181.2	209.8	234.4	168.2	382.9
	16 TO 17	379.2	376.7	399.0	236.2	200.4	314.2
	RATIO:	0.4949	0.4810	0.5258	0.9973	0.5617	1.2186
	LOG10 RATIO:	-0.3054	-0.3178	-0.2791	-0.0033	-0.2504	0.0858
7:	24 TO 25	665.4	606.5	619.8	337.8	370.1	445.6
	21 TO 23	409.4	330.3	473.3	319.8	173.0	252.3
	RATIO:	1.6253	1.8362	1.3095	1.0562	2.1393	1.7661
	LOG10 RATIO:	0.2109	0.2639	0.1171	0.0237	0.3302	0.2470

## Sentence 6 Deaf Group

Syllable	Phonemes in Syllable	Subject					
		1	2	3	4	5	6
1: 6 TO F 1 TO 2		268.6	435.1	437.1	258.4	161.0	227.9
		413.7	356.6	435.0	196.6	259.2	179.2
	RATIO:	0.6492	1.2133	1.0048	1.3143	0.6211	1.2717
	LOG10 RATIO:	-0.1876	0.0830	0.0020	0.1186	-0.2068	0.1043
2: 6 TO R 3 TO 5		268.6	435.1	437.1	258.4	161.0	227.9
		225.0	314.4	474.3	199.4	221.1	245.4
	RATIO:	1.1140	1.2830	0.9215	1.2958	0.7281	0.9286
	LOG10 RATIO:	0.0751	0.1411	-0.0355	0.1125	-0.1378	-0.0321
3: 11 TO 13 9 TO 10		382.3	367.6	371.9	335.1	162.3	270.3
		108.4	81.5	149.7	129.3	102.2	112.9
	RATIO:	3.5267	4.5104	2.4843	2.5916	1.5880	2.3941
	LOG10 RATIO:	0.5473	0.6542	0.3952	0.4135	0.2008	0.3791
4: 16 TO 17 14 TO 15		817.2	338.6	530.8	199.3	394.1	382.4
		110.8	197.4	113.3	99.3	130.0	129.7
	RATIO:	7.3754	1.7152	4.6849	2.0070	3.0315	2.9483
	LOG10 RATIO:	0.8677	0.2343	0.6707	0.3025	0.4816	0.4695

## APPENDIX I

## Pause Durations (in msec)

## Sentence 1 Between Phoneme Pause Times for Deaf Subjects

Phonemes	Subject:	1	2	3	4	5	6
1 - 2:		211.5	111.0	230.1	126.4	145.8	0.1
2 - 3:		0.1	0.1	0.1	0.1	0.1	0.1
3 - 4:		77.0	0.1	0.1	29.6	0.1	0.1
4 - 5:		-1.0	-1.0	307.2	-1.0	322.0	-1.0
5 - 6:		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
6 - 7:		0.1	0.1	0.1	0.1	0.1	0.1
7 - 8:		149.5	94.4	0.1	113.0	0.1	140.8
8 - 9:		-1.0	537.7	368.7	386.9	192.0	-1.0
9 - 10:		0.1	0.1	0.1	0.1	0.1	0.1
10 - 11:		0.1	0.1	0.1	0.1	0.1	0.1
11 - 12:		0.1	0.1	0.1	0.1	0.1	0.1
12 - 13:		128.0	593.7	539.9	79.6	25.7	192.0
13 - 14:		0.1	0.1	0.1	0.1	0.1	0.1
14 - 15:		0.1	214.7	0.1	89.7	0.1	0.1
15 - 16:		64.1	-1.0	376.5	0.1	58.7	0.1
16 - 17:		0.1	0.1	0.1	76.9	0.1	0.1
17 - 18:		0.1	0.1	0.1	0.1	0.1	0.1
18 - 19:		136.7	269.0	173.8	100.5	50.2	38.6
19 - 20:		0.1	0.1	0.1	0.1	0.1	0.1
20 - 21:		0.1	-1.0	0.1	0.1	0.1	0.1
21 - 22:		0.1	0.1	0.1	0.1	0.1	0.1
22 - 23:		0.1	0.1	0.1	-1.0	0.1	-1.0
23 - 24:		0.1	0.1	0.1	-1.0	0.1	-1.0

## Sentence 2 Between Phoneme Pause Times for Deaf Subjects

Phonemes	Subject:	1	2	3	4	5	6
1 -		0.1	0.1	0.1	0.1	0.1	0.1
2 -		153.6	0.1	205.2	0.1	0.1	79.4
3 -		-1.0	237.7	-1.0	205.8	58.5	-1.0
4 -		0.1	0.1	0.1	0.1	0.1	0.1
5 -		0.1	0.1	116.7	212.5	0.1	38.4
6 -		241.0	214.3	306.5	-1.0	95.0	-1.0
7 -		0.1	0.1	0.1	0.1	0.1	0.1
8 -		508.2	0.1	0.1	356.1	0.1	0.1
9 -		-1.0	-1.0	122.1	-1.0	131.1	40.8
10 -		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
11 -		0.1	0.1	0.1	0.1	0.1	0.1
12 -		409.6	107.3	198.5	0.1	61.8	41.5
13 -		0.1	0.1	0.1	0.1	0.1	0.1
14 -		0.1	0.1	0.1	0.1	0.1	0.1
15 -		0.1	0.1	254.2	122.3	67.9	82.2
16 -		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
17 -		109.1	112.1	-1.0	-1.0	-1.0	-1.0
18 -		0.1	0.1	0.1	0.1	0.1	0.1
19 -		0.1	0.1	0.1	357.2	0.1	0.1
20 -		323.1	677.2	361.5	-1.0	0.1	0.1
21 -		0.1	0.1	0.1	527.1	267.4	267.4
22 -		0.1	0.1	0.1	0.1	0.1	0.1
23 -		0.1	0.1	0.1	0.1	0.1	0.1
24 -		0.1	0.1	187.5	0.1	0.1	-1.0
25 -		19.3	0.1	120.7	120.7	0.1	-1.0

## Sentence 3 Between Phoneme Pause Times for Deaf Subjects

Phonemes	Subject:	1	2	3	4	5	6
1 - 2:		0.1	0.1	0.1	124.1	0.1	0.1
2 - 3:		0.1	0.1	0.1	0.1	0.1	0.1
3 - 4:		0.1	0.1	368.1	0.1	0.1	91.7
4 - 5:		103.8	232.8	-1.0	180.5	576.4	-1.0
5 - 6:		96.9	62.1	117.0	54.1	0.1	62.0
6 - 7:		0.1	0.1	0.1	0.1	0.1	0.1
7 - 8:		0.1	0.1	51.2	221.9	0.1	0.1
8 - 9:		51.2	-1.0	-1.0	-1.0	-1.0	-1.0
9 - 10:		0.1	0.1	0.1	0.1	0.1	0.1
10 - 11:		0.1	0.1	158.7	0.1	0.1	0.1
11 - 12:		107.5	33.7	-1.0	232.8	40.2	72.1
12 - 13:		0.1	0.1	0.1	0.1	0.1	0.1
13 - 14:		0.1	243.3	236.7	0.1	0.1	0.1
14 - 15:		224.0	-1.0	-1.0	186.8	124.8	0.1
15 - 16:		0.1	0.1	0.1	0.1	-1.0	115.2
16 - 17:		0.1	0.1	-1.0	0.1	0.1	0.1
					0.1	0.1	0.1

## Sentence 4 Between Phoneme Pause Times for Deaf Subjects

Phonemes	1	2	3	4	5	6
1 -	0.1	0.1	0.1	0.1	0.1	0.1
2 -	76.8	0.1	0.1	122.0	0.1	0.1
3 -	0.1	0.1	0.1	0.1	0.1	0.1
4 -	54.5	60.4	0.1	83.4	56.1	0.1
5 -	0.1	0.1	0.1	0.1	0.1	0.1
6 -	0.1	0.1	170.3	0.1	0.1	0.1
7 -	82.6	41.0	-1.0	313.1	41.8	-1.0
8 -	0.1	0.1	0.1	0.1	-1.0	-1.0
9 -	0.1	0.1	0.1	0.1	-1.0	-1.0
10 -	189.4	182.1	325.2	473.6	135.2	93.5
11 -	0.1	0.1	0.1	0.1	-1.0	-1.0
12 -	0.1	0.1	0.1	0.1	0.1	0.1
13 -	0.1	205.3	148.5	0.1	311.0	0.1
14 -	0.1	-1.0	-1.0	49.7	-1.0	-1.0
15 -	0.1	0.1	0.1	0.1	0.1	0.1
16 -	188.2	115.2	-1.0	102.5	147.2	130.5
17 -	0.1	0.1	-1.0	0.1	0.1	-1.0
18 -	100.5	115.2	-1.0	0.1	302.6	0.1
19 -	0.1	0.1	0.1	0.1	-1.0	0.1
20 -	0.1	0.1	0.1	249.0	-1.0	0.1
21 -	176.1	209.6	689.1	-1.0	-1.0	513.0
22 -	0.1	0.1	0.1	0.1	0.1	-1.0
23 -	112.9	0.1	64.1	76.9	0.1	-1.0

## Sentence 5 Between Phoneme Pause Times for Deaf Subjects

Phonemes	Subject:	1	2	3	4	5	6
1 - 2:		0.1	0.1	0.1	0.1	0.1	0.1
2 - 3:		173.6	167.6	217.6	0.1	126.7	180.4
3 - 4:		0.1	0.1	0.1	0.1	0.1	0.1
4 - 5:		0.1	0.1	0.1	132.3	0.1	0.1
5 - 6:		0.1	0.1	0.1	0.1	0.1	0.1
6 - 7:		0.1	417.1	448.0	290.1	93.6	77.8
7 - 8:		0.1	0.1	0.1	0.1	0.1	0.1
8 - 9:		0.1	0.1	0.1	0.1	0.1	-1.0
9 - 10:		0.1	0.1	0.1	0.1	0.1	0.1
10 - 11:		115.3	168.6	125.1	97.0	53.8	89.7
11 - 12:		0.1	0.1	0.1	0.1	0.1	0.1
12 - 13:		370.9	255.7	110.9	0.1	374.3	761.7
13 - 14:		-1.0	-1.0	-1.0	296.0	-1.0	-1.0
14 - 15:		51.3	0.1	0.1	92.5	0.1	44.6
15 - 16:		-1.0	0.1	0.0	-1.0	45.4	-1.0
16 - 17:		0.1	0.1	-1.0	0.1	0.1	0.1
17 - 18:		137.0	96.2	271.0	102.0	49.6	0.1
18 - 19:		0.1	0.1	0.1	0.1	0.1	0.1
19 - 20:		140.8	51.2	110.2	0.1	58.1	57.0
20 - 21:		-1.0	-1.0	-1.0	52.6	-1.0	-1.0
21 - 22:		0.1	0.1	0.1	0.1	0.1	0.1
22 - 23:		0.1	0.1	0.1	0.1	0.1	0.1
23 - 24:		0.1	0.1	0.1	0.1	0.1	0.1
24 - 25:		0.1	0.1	0.1	0.1	0.1	0.1

## Sentence 6 Between Phoneme Pause Times for Deaf Subjects

Phonemes	Subject:	1	2	3	4	5	6
1 - 2:		0.1	0.1	0.1	0.1	0.1	0.1
2 - 3:		0.1	0.1	0.1	75.9	0.1	0.1
3 - 4:		0.1	0.1	0.1	0.1	0.1	0.1
4 - 5:		0.1	0.1	0.1	0.1	89.4	71.0
5 - 6:		133.9	120.7	302.6	118.7	0	0
6 - 7:		0.1	0.1	0.1	0.1	0.1	0.1
7 - 8:		112.6	0.1	0.1	0.1	0.1	0.1
8 - 9:		0	294.1	371.3	189.6	60.1	40.1
9 - 10:		0.1	0.1	0.1	0.1	0.1	0.1
10 - 11:		126.5	238.3	169.1	68.7	55.2	51.3
11 - 12:		0.1	0.1	0.1	0.1	0.1	0.1
12 - 13:		0.1	412.5	155.3	0.1	81.9	326.7
13 - 14:		166.6	0	0	286.9	0	0
14 - 15:		0.1	0.1	0.1	0.1	0.1	0.1
15 - 16:		49.9	64.0	96.0	119.4	0.1	37.5
16 - 17:		0.1	0.1	0.1	0.1	0.1	0.1

## Instructions to Listeners

You will hear six sentences recorded by a deaf child. Five of the sentences are single sentences. One of the sentences consists of two consecutive sentences. No sentence is repeated; the child says something different each time. You may hear each sentence played twice.

After you hear each sentence, write down whatever you think the child is saying. If some of the words are unclear, guess what the child is saying. If you can catch an isolated word or two, write them in, indicating their approximate position in the sentence. For example, \_\_\_\_\_ is \_\_\_\_\_ home.

NOTE: Even the best of deaf speakers do not sound like normal hearing speakers.

Any questions?

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