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**CONSONANT ENHANCEMENT EFFECTS  
ON SPEECH RECOGNITION OF HEARING IMPAIRED  
CHILDREN**

**by**

**Lynn Z. Smith**

**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**

**1997**

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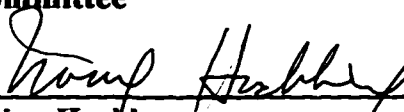
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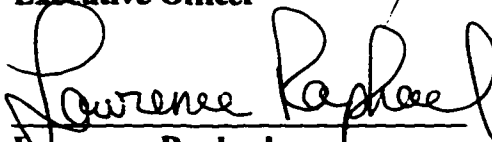
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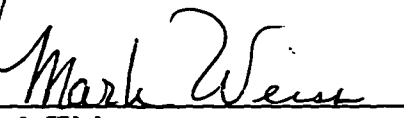
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Harry Levitt  
Chair of Examining  
Committee

May 2, 1997  
Date

  
Irving Hochberg  
Executive Officer

  
Lawrence Raphael

  
Mark Weiss

  
Alan Montgomery

**The City University of New York**

**ABSTRACT****CONSONANT ENHANCEMENT EFFECTS  
ON SPEECH RECOGNITION OF HEARING IMPAIRED CHILDREN**

by

**Lynn Z. Smith****Adviser: Professor Harry Levitt**

This dissertation examined the effects of consonant enhancement on speech recognition by hearing-impaired children. The goal of this research was to determine if there is an optimal consonant amplitude in relation to a neighboring vowel whereby consonant recognition is maximized. The differences in gain required (enhancement, in dB) to optimize the consonant vowel (CV) ratio in nonsense syllables was determined for stops and fricatives, both voiced and voiceless. Twelve children with congenital moderate to severe sensorineural hearing loss acted as subjects. One group of 6 children ranged in age from 5 to 6 years, a second group of 6 children were 8 to 9 years of age. The test stimuli consisted of VC nonsense syllables with various levels of enhancement. The enhancement levels ranged from 0 dB (for the unprocessed stimulus) to 30 dB of gain, in steps of 3 dB. The gain was applied to only the consonant portion of each nonsense syllable. The arc sine transformation was used to stabilize the error variance of the test scores. Curves were fitted to the transformed scores as a function of enhancement level. The maximum value of this curve identified the CV ratio at which consonant recognition was maximized for experimental condition and consonant type. The results showed that significant improvements in consonant recognition can be obtained with individualized adjustment of consonant amplitude for children as young as 5 year of age.

## ACKNOWLEDGMENTS

*“Whoever, in the pursuit of science, seeks after immediate practical utility, may generally rest assured that he will seek in vain.”*

**Hermann von Helmholtz  
Academic Discourse, 1862**

Early education lays the foundation of a lifetime of learning. Its impact must not be underestimated. The Dominican Sisters were my educators from first through twelfth grades. I am grateful to these dedicated women for teaching me to persevere and to always strive for excellence.

As a teacher of young hearing impaired children I learned more about deafness from my students and their families through daily interactions than could ever be gained through books. I thank all my former students for sharing their lives with me.

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## **CHAPTER I. INTRODUCTION AND STATEMENT OF NEED**

Understanding speech is difficult for individuals with sensorineural hearing loss. Comprehending what has been said can be like fitting pieces of a puzzle. Parts of the spoken message are often missing or distorted. The hearing-impaired listener must sort through the input using contextual information and language experience to arrive at meaning. Hearing-impaired children may have more difficulty sorting information than adults because they have limited experience with language and a weaker base of world knowledge upon which to build contextual cues. Additionally, children may process auditory information differently than adults. However, both adults and children with sensorineural hearing impairment must deal with an incoming speech signal comprising features of mixed degrees of clarity.

In an attempt to determine what features of speech are difficult for hearing-impaired listeners, Picheny, Durlach, and Braida (1981) found that talkers use different strategies when speaking to the hearing-impaired. It was observed that speakers spontaneously adapt their speech when talking to individuals with hearing impairment. This type of “clear” speech is more easily understandable to hearing-impaired listeners than “conversational” speech or speech that has not been adapted for the benefit of the hearing-impaired. Picheny, et al. (1981) analyzed both types of speech to determine what characteristics had been changed in clear speech. In general, three changes occurred: (a) the duration of the consonants and vowels increased; (b) the phonemes were articulated as if the words were in isolation; (c) the consonant/vowel intensity ratio (CVR) increased. Very little change in formant frequencies was observed from conversational to clear speech.

Efforts to utilize Picheny, et al.'s findings have been proposed in the form of speech enhancement using digital technology (Montgomery and Edge, 1988). Whereas automatic adjustment of duration or processing speech to alter articulatory patterns is unlikely to be accomplished in a wearable hearing aid in the near future, automatic adjustment of the consonant vowel intensity is a viable possibility (Preves, et al 1994). Speech characteristics that are weak, distorted, or imperceptible to hearing-impaired listeners may be enhanced through hearing aid circuitry that alters the gain for selected portions of the speech signal. For example, in normal conversational speech, /a/ is relatively intense as compared to /f/. The difference in intensity between these two phonemes may be as much as 20-25 dB, making /f/ barely perceptible, especially when the strong /a/ precedes the weak /f/, as in /af/.

A linear hearing aid can increase CVR by providing increased gain in the high frequencies. This is important for two reasons. One is that hearing-impaired individuals often have greater difficulty hearing high rather than low frequency sounds. Another reason is that many consonants are represented by high frequency components in the speech signal. Braida, Durlach, Lippman, Hicks, Rabinowitz and Reed (1979) suggest that the problem with this approach is that although the linear hearing aid with appropriate frequency gain characteristics can provide a boost to the high frequencies, it does not deal well with input level changes.

Another method for improving CVR comes from compressing intense sounds and amplifying weak consonants. Referred to as syllabic compression, this method for increasing speech recognition has yielded ambiguous results (Braida, et al. 1979). Boothroyd, Springer, Smith and Schulman (1988) suggest that amplitude

compression is by no means necessary or desirable for all profoundly hearing-impaired individuals since amplitude envelope information may be lost through compression. Gross amplitude and temporal features of the waveform are important in speech recognition by the profoundly hearing-impaired as suggested by Erber (1979). On the other hand, modification of the CVR, thereby approximating some of the acoustic modifications found in naturally produced clear speech, can improve speech recognition by hearing-impaired adults or by hearing adults in adverse listening conditions (Gordon-Salant, 1986; Montgomery and Edge, 1988; Revoile, Holden-Pitt, Edward, and Pickett, 1987; Freyman, Nerbonne, and Cote, 1991; and Kennedy, 1994).

Whereas, modification of CVR has been shown to produce improved consonant recognition with hearing-impaired adults, it is not yet known whether this technique will yield similar benefits for hearing-impaired children. There is evidence of increase in auditory abilities with age (Allen, et al. 1989, Irwin, et al., 1986, Siegenthaler, 1969, Abromovitz, 1971, Maxon, 1977 and Neuman, 1982). Hearing-impaired children may have amplification needs that require developmental considerations.

This work focuses on the effects of CVR alterations on consonant identification by hearing-impaired children. It will determine if there is an optimal consonant amplitude in relation to a neighboring vowel whereby consonant recognition is improved. The optimal CVR (for maximizing consonant recognition) will be determined for children for the two most common consonant types (stops and fricatives, both voiced and voiceless) in the syllable-final position, since this is the condition that is most difficult for consonant perception by hearing-impaired listeners.

## **CHAPTER II. REVIEW OF THE LITERATURE**

This review will cover three areas relevant to the proposed investigation. The first area of interest is previous research on CVR adjustment including the benefit of consonant enhancement as it relates to degree of hearing loss and audiometric configuration. The second area examines the psychoacoustic abilities of normal hearing children and how these abilities differ from adults with focus on both frequency and temporal resolution and identification and discrimination abilities. The third area of interest is speech perception by severely hearing-impaired children. This area focuses on identification and discrimination of consonants and speech perception in noise.

### ***Previous Research on CVR Adjustment***

Gordon-Salant (1986) investigated the effects of duration and consonant-vowel ratio (CVR) enhancements on speech perception. The stimuli consisted of 1.) baseline CV's, with no acoustic modification; 2.) CV's in which consonant duration was increased by 100%; 3.) CV's in which consonant energy relative to the vowel energy was increased by +10 dB; and 4.) combined increase CV's, which incorporated both the consonant duration increase and consonant energy increase modifications. She examined the effects of these acoustic modifications and listener age on speech recognition. Subjects were divided into 2 groups: ten young adults (21-33 years) and ten elderly adults (65-72 years). Her findings indicated that increasing the CVR improved the performance of both young and older subjects. However, the older subjects exhibited poorer performance than younger subjects in most conditions.

In a similar investigation, Montgomery and Edge (1988) attempted to reproduce acoustic characteristics of changes that occur in articulation when a talker differentiates between conversational speech and highly intelligible or clear speech. They examined the effects of two types of processing on the intelligibility of speech; amplitude enhancement of consonants and increased duration of consonants. Hearing-impaired listeners identified consonants in CVC stimuli at 65 dB and 95 dB presentation levels. The consonant portion of the CVC was either amplified or lengthened to approximate either the amplitude or the duration of the adjacent vowel. Their findings indicated that amplitude processing (i.e., increasing the CVR) produced a 10-12% improvement in intelligibility for moderately hearing-impaired adults, but that increasing consonant duration provided no benefit to these subjects when presented at 65 dB SPL. When presented at 95 dB SPL amplitude processing showed no benefit but increasing duration indicated a slight improvement in speech recognition.

Gordon-Salant (1987) found hearing-impaired subjects improved their recognition of nonsense syllables at both low and high signal levels. There is agreement, however, between her findings and those of Montgomery and Edge regarding increased consonant duration at the 95 dB SPL presentation level. That is, a modest improvement in speech recognition among hearing-impaired listeners was found at the higher signal level when consonant duration was lengthened. However, Montgomery and Edge suggested that duration changes in clear speech are primarily a byproduct of articulatory effort and do not contribute directly to greater intelligibility.

Revoile, et al., (1987) evaluated the effect of CVR adjustment on severely-to profoundly hearing-impaired subjects. Her test stimuli consisted of /baeC/

syllables in which C = /f, s, v, z/. The stimuli were presented at each listener's Most Comfortable Level (MCL) and at an enhanced level whereby the consonant portion of the stimuli was amplified by approximately 18 to 21 dB to approximate the level of the preceding vowel. A significant improvement in recognition of fricative voicing was obtained with increased amplification of the fricative consonants.

Freyman, et al., (1991) investigated the effect of CVR modification on amplitude envelope cues for consonant recognition. One group of normal hearing adult subjects listened to VCV's at various signal to noise ratios, while a second group of normal hearing adults listened to the stimuli with the consonant portion amplified by 10 dB. The findings show that consonant recognition decreased in the amplified-consonant condition for some consonants presumably because waveform envelope cues were distorted. For example, many of the manner errors were substitutions of glides in place of voiced fricatives. This substitution was explained by noting that the amplification of voiced fricatives, in this experiment, produced a flatter waveform envelope that was similar to that of the glide productions.

Another example of decreased consonant recognition occurred with recognition of amplified glides. This result was explained by noting that glides are vowel-like sounds with levels roughly equal to that of the adjacent vowel. Recognition of other consonants, however, especially voiced stops, was found to increase with increased consonant gain.

Kennedy (1994) examined the amount of improvement in consonant recognition that is possible through adjustment of the CVR. Three groups of hearing-impaired

adults participated in the experiment. One group had a relatively flat hearing loss, a second group had a mildly sloping high frequency loss and the third group had a precipitous high frequency loss. A balanced set of 48 VC nonsense syllables (16 consonants x 3 vowels) was used as test stimuli. The consonant portion of each nonsense syllable was amplified in steps of 6 dB. The CVR generating the maximum score was determined for each consonant in each vowel environment for each subject. Under these conditions, improvement in consonant recognition scores was found to be greater than that obtained in previous research on consonant enhancement. Presumably, the greater improvements in consonant recognition found in this study were a result of individualizing the amount of consonant enhancement for each subject..

### **The Benefit of Consonant Enhancement As It Relates To Degree of Hearing Loss And Audiometric Configuration**

The benefit of consonant amplification is largely determined by degree of hearing loss. For Montgomery and Edge's moderately hearing-impaired subjects consonant recognition improved by 10-15% when consonants were amplified by 10 to 21.5 dB above their normal level relative to vowels in words. Gordon-Salant (1987) found similar results with nonsense syllables among elderly mild-to-moderately hearing-impaired listeners. In contrast, severely hearing-impaired subjects have not shown similar improvements in performance from consonant amplification. Revoile's severely-to-profoundly hearing-impaired subjects performed at chance levels for identification of amplified stops and amplified fricatives. There was no benefit for place distinctions of amplified consonants. However, these listeners did show improved recognition in consonant voicing distinction for fricatives and even more so for stops.

The findings of Dubno, Dirks, and Schaefer (1989) are consistent with those of Revoile, et al. Dubno examined the association between place perception and audibility. The purpose was to make predictions of stop-consonant recognition for hearing-impaired listeners by examining the sensation levels of specific portions of the speech signal. If only a narrow spectral region is presented at suprathreshold levels, then poor performance would be expected. In contrast, if the sensation level of speech is high for several spectral regions, then relatively good consonant recognition would be expected. This speech recognition prediction strategy is based on Articulation Index theory (French and Steinberg, 1947). Articulation Index theory suggests that speech intelligibility can be predicted from a weighted sum of speech-to-noise or speech-to-threshold ratios over the audio frequency range. Calculations are made using 20 contiguous frequency bands, each of which

contributes the same proportion (5%) to overall speech intelligibility. The speech-to-noise (or speech-to-threshold) ratios in these frequency bands are combined into a single number from 0 to 1.0. The result, referred to as the Articulation Index (AI), has a monotonic relationship to the speech recognition score.

Dubno, et al. (1989) found that among listeners with high frequency hearing loss, prediction of stop consonant recognition using the AI was less accurate for those with severe hearing loss than those subjects with more hearing. Therefore, poor speech recognition is not completely explained by signal audibility for all levels of hearing impairment. This is consistent with Revoile's findings that there are differences in the effectiveness of consonant amplification based on the extent of hearing loss.

Kennedy (1994) examined the benefits of consonant amplification among three groups of hearing-impaired adult subjects, those with either flat, sloping, or precipitous audiometric configurations. Although the data did not show a significant main effect of audiometric configuration, a significant interaction involving audiometric configuration was observed at the CVR corresponding to the maximum score. Subjects with flat and sloping audiometric configurations performed similarly while those with precipitous losses performed relatively poorly on high frequency consonants. Listeners with flat or sloping losses, she explained, have access to more acoustic cues than those with precipitous losses, even under conditions of optimum acoustic amplification for each type of loss.

## ***The Psychoacoustic Abilities of Normal Hearing Children***

### **Frequency Resolution**

Relatively little is known about the differences between the auditory systems of adults and children. Experiments in frequency resolution have revealed information concerning the auditory capabilities of normal adult hearing mechanisms. Frequency resolution is the ability of the human ear to separate incoming sound into its spectral constituents and is typically explained in terms of an internal auditory filter. Irwin, Stillman, and Schade (1986), using a notched-noise paradigm, found that the bandwidth of this auditory filter is still developing during the school-aged years. Their data suggest that the auditory filters of 6-year-old children are wider in bandwidth than those of 10-year-old children and adults at 500, 1000, and 3000 Hz.

Allen, Wightman, Kistler, and Dolan (1989), using a variation of the notched-noise paradigm, reported similar findings on frequency resolution in children. In this forced-choice masking experiment, children ranging in age from 3 years 8 months to 9 years 9 months, as well as several adults, acted as subjects. Thresholds for pure-tone signals at 500 Hz, 2000 Hz, and 4000 Hz in two masking conditions were obtained. A 4000 Hz-wide band of noise centered at the signal frequency was the masker in one condition. The masker in the second condition was a notch in the noise spectrum, approximately one-half octave wide and 50 dB deep, centered at the signal frequency. The difference in signal threshold between the two masking conditions determined frequency resolving ability. Their data suggest that the frequency resolving ability of children improves at all frequencies with increasing age.

Olsho, Koch, and Halpin's (1987) study of frequency discrimination in infants used 500, 1000, and 4000 Hz tones at 40 and 80 dB SL to elicit responses from infants aged 3, 6, and 12 months and adults regarding change in frequency. The infants did not perform as well as the adults. The interesting aspect of this study is that the effect of frequency on the difference threshold varied according to the infant's age. All of the infants were poorer than the adults at 500 and 1000 Hz. However, the 6 and 12 month-olds approximated adult performance at 4000 Hz. These results show that there is a developmental aspect to frequency discrimination at high and low frequencies.

### **Temporal Resolution**

Temporal resolution refers to the tracking of time-domain changes in a sound. Developmental studies in temporal resolution have used the paradigm of temporal gap detection. This technique involves the detection of the smallest interval of silence in an otherwise continuous sound. Irwin, Ball, Kay, Stillman, and Rosser (1985) measured gap detection as a function of age. Three groups of listeners, 6 year-olds, 6 through 10 year-olds, and 10 year-olds through adult, listened to broadband noise and octave bands of noise centered at 500, 1000, and 2000 Hz. Thresholds for temporal gap detection were measured for each of these noises. In all cases, the 6 year-olds performed poorest; the listeners 10 years or older performed like adults; and listeners between 6 and 10 years performed somewhere between these extremes.

Grose, Hall, and Gibbs (1993) measured temporal resolution as a function of frequency region and listener age. Rather than gap detection, this study used a masking paradigm. The threshold for a pure-tone in a modulated masker was determined. Detection of the tone depends upon the ability to process the modulation: the lower the threshold, the better the temporal resolution. The

listeners in this study included children divided into three groups: 4-5 year-olds, 6-7 year olds, and 8-10 year olds, and adults. The results indicated that temporal resolution improves with age, although at high frequencies, 6 year olds and adults perform similarly. In summary, Grose, et al. found developmental effects for temporal resolution and that these effects are more pronounced in the lower frequencies.

Marean and Werner (1991) examined forward masking in 3 month-olds in efforts to measure the temporal resolving power of the auditory system. The infants were trained to detect a 1000 Hz tone, referred to as the probe, when it was preceded by a noise masker at 65 dB SPL. The temporal separation of the masker and probe determined the amount of forward masking. In this experiment, the probe detection thresholds were measured at 5, 10, and 25 ms. In a control condition, the detection threshold was measured at 200 ms, in which no forward masking was expected to occur due to the relatively long length of the stimulus. In this condition, there was no difference between the infants and the adults, which was evidence that the masking itself did not have a detrimental effect on performance. However, the shorter probes presented more difficulty for the infant. Marean and Werner concluded that infants have poorer temporal resolution than do adults.

### **Identification and Discrimination**

An increase in auditory perceptual abilities with age was reported by Abromowitz (1971). The ability of children ranging in age from 5 to 10 years to recognize environmental sounds, discriminate speech intonation, identify simultaneous environmental sounds, and discriminate tone pairs varying in duration, pitch, interval, and loudness was examined. A significant difference was found between the performance of the 5 year-old children and that of the 10 year-old children.

Siegenthaler (1969) found evidence for improvement in auditory ability with age by testing children aged 3 to 12. Changes in performance as a function of age were observed for pure tone thresholds, localization, reaction time to a tone, speech reception thresholds, speech-in-noise thresholds, and perception of interrupted speech. For children older than 8 years performance on pure tone threshold, speech reception threshold, and speech discrimination did not improve. However, for the speech-in-noise task, improvement continued until age 11 and for the reaction time task, improvement in performance continued until age 12. Although the subtests were not administered to all age groups and no adult norms were available, these findings suggest that auditory perceptual ability increases from age 3 to age 12.

Maxon (1977) measured pure tone thresholds, and difference limens for intensity and frequency and temporal integration of loudness abilities of children ages 4 to 12 years. Test methods and schedules of reinforcement appropriate for each age group were used. The data revealed a significant decrease in the size of the difference limens for intensity, for frequency and a significant decrease in temporal integration thresholds as a function of age.

Neuman (1982) investigated the effect of reverberation on the phoneme identification of normal-hearing children age 5, 7, 9, 11, and 13 years and a group of adults. Discrimination of nonsense disyllables was measured under three conditions of reverberation. The results showed that children made more errors than adults. Children over 9 made the same type of errors as adults, but the younger children produced a wider range of errors including substitutions involving voicing, affrication, and consonantal features.

## ***Speech Perception by Severely Hearing-impaired Children***

### **Identification And Discrimination Of Consonants**

Boothroyd, (1984) examined auditory perception of speech contrasts by children with varying degrees of sensorineural hearing loss. The three frequency (500, 1000, and 2000 Hz) average hearing losses for the listeners in this study ranged from 55-123 dB HL. The purpose of this study was to find out how much of the acoustic information in amplified speech is accessible to children with severe and profound hearing loss. The stimuli were context- varying, forced choice tests of speech perception containing the following speech pattern contrasts:

1. vowel height (high vs. low, e.g. /bu-bʊ/ )
2. vowel place (front vs. back, e.g. /uʃ-ɪʃ/ )
3. initial consonant voicing (e.g. /si-zi/ )
4. initial consonant continuance (e.g. /tu-su/ )
5. talker gender (male talker vs. female talker)
6. intonation (natural vs. monotone)

Results indicated the following average hearing levels up to which a given contrast is accessible:

- > 115 dB HL for vowel height
- 115 dB HL for syllabic pattern (intonation)
- 105 dB HL for talker gender
- 100 dB HL for vowel place
- 90 dB HL for initial consonant voicing
- 85 dB HL for initial consonant continuance

These results indicated the ability to perceive segmental and suprasegmental contrasts in connected speech by subjects with sensorineural hearing losses as high as 105-114 dB HL.

Bennett and Ling (1973) examined the ability to label voiced and voiceless stops in natural speech. Two groups of listeners, normal hearing and severely

hearing-impaired children, acted as subjects in this study. The stimuli consisted of 54 CV's of bilabial and alveolar stops with /a/, /u/, or /i/. The task was to identify the consonant. For the hearing group, voice onset time less than or equal to 20 ms. signaled a voiced stop, while voice onset times from 40 to 120 ms. were usually associated with the voiceless stops. The hearing-impaired listeners needed a longer voice onset time, that is, greater than or equal to 60 ms. to perceive a voiceless consonant. The hearing-impaired group showed no clear-cut voicing boundary and evidenced confusion about place of articulation.

### **Speech Perception in Noise**

A continuing interest in speech perception by severely hearing impaired children lead Smith and Boothroyd (1990) to examine speech perception in noise. The purposes of this study were to measure perception of speech pattern contrasts by hearing-impaired children as a function of signal to noise ratio; to compare findings with those of normal hearing subjects; and to evaluate the differential effect of noise on various speech pattern contrasts.

Two groups of listeners participated in this study. One group comprised hearing-impaired children between 8 and 14 years of age with pure tone averages ranging from 82 dB to 98 dB. The other group consisted of normal hearing adults. A three-interval forced choice test, referred to as THRIFT (Boothroyd, et al., 1988), was used to evaluate speech perception. THRIFT provides an estimate of probability of perception of phonologically significant contrasts using an oddity procedure specifically developed for work with subjects lacking good phonological knowledge, reading skills, and vocabulary. THRIFT consists of 9 subtests. In each subtest the odd-man-out differs from the other two stimuli along

a single phonologically contrastive dimension. Each subtest represents a different contrast. These subtests are as follows:

1. intonation (constant/changing fundamental frequency) -
2. vowel height /bu-bʊ/
3. vowel place /ʊz-iz/
4. initial consonant voicing /si-zi/
5. final consonant voicing /is-iz/
6. initial consonant continuance /tu-su/
7. final consonant continuance /ɪf-itʃ/
8. initial consonant place /tʰ-kʰ/
9. final consonant place /ad-ab/

In addition, a composite score was obtained by averaging the 9 contrast scores.

Stimuli were generated from laser disc recordings of a female talker. A computer was used both to control stimulus presentation and to record responses. Acoustic presentation was under headphones via a master-hearing aid developed for this and related work. Output was controlled in 2 dB steps and was set to the highest comfortable level for the hearing-impaired subjects and the most comfortable level for the normal hearing subjects. The frequency response was adjusted to provide a high frequency boost (thereby “whitening” the average speech spectrum). For the hearing-impaired subjects, the high frequencies were further boosted to provide equal speech awareness thresholds in the low and high frequency bands of the hearing aid, (70 Hz - 1 KHZ and 1KHz - 7KHz). The noise consisted of white noise added to the speech signal before any frequency shaping.

Mean scores were obtained by the 5 hearing-impaired subjects at signal to noise ratios of 0, 10, and 20 dB and also in quiet for each contrast and for the mean of 9 contrasts. The mean vowel, voicing, and intonation scores were at better than chance levels in quiet. Of these, only vowel height remained at better than chance levels for a signal to noise ratio of 0 dB.

Similar data for the normal subjects was obtained at 0 dB and 10 dB signal to noise ratios. It was concluded that in order to preserve the average perception of speech contrasts at a given level in relation to performance in quiet, hearing-impaired subjects may need signal to noise ratios as much as 20 dB better than those required by normal hearing subjects.

### ***SUMMARY***

Adjustment of the CVR appears to be a promising technique for improving speech recognition in hearing-impaired listeners. Most of the studies in consonant enhancement presented in this literature review have been similar in the use of stimuli. That is, adjustment of CVR was the same for all subjects in each experiment. Individual differences were considered in the work of Kennedy (1994). Individualized adjustment of CVR for different consonants in different vowel environments for each subject can yield even greater improvements in consonant recognition than that obtained previously.

All of the data obtained thus far on CVR adjustment have involved adult subjects. The auditory abilities of children, however, are different from those of adults. Hearing-impaired children have amplification needs that require developmental considerations. Although consonant enhancement techniques have proven successful with hearing-impaired adults, it is not yet known whether the techniques would yield similar benefits for hearing-impaired children. A need exists to obtain information regarding the effects of consonant enhancement on speech recognition of hearing-impaired children. Such a study would have important implications regarding hearing aid requirements specific to children based on developmental capabilities.

## **CHAPTER III. EXPERIMENTAL PROCEDURE**

This chapter describes the subjects, the stimuli, the instrumentation, and the procedures used to obtain data.

### ***Subjects***

Twelve congenitally hearing-impaired children with moderately-to-severely and gradually sloping sensorineural hearing loss acted as subjects. Moderately to severely hearing-impaired listeners were chosen for this study since they have shown to benefit from consonant enhancement (Gordon-Salant, 1987 and Montgomery and Edge, 1988). One group ranged in age from 5 to 6 years and the other group was aged from 8 to 9 years. The younger group attended a pre-school for the hearing-impaired where emphasis was placed on the development of aural/oral communication skills. The older group attended mainstream programs in public schools and used oral communication. None of the subjects had any other handicapping conditions. All of the twelve subjects were experienced hearing aid users.

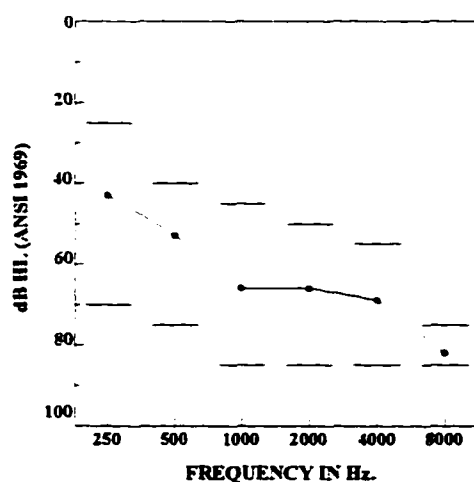
Given the difficulty in obtaining a subject pool that met the age, audiometric, and parental consent requirements it was not possible to have an equal number of boys and girls participate in this study. Both the younger and older groups consisted of five girls and one boy, equaling a total of ten girls and two boys. Tables 1 and 2 show gender, age, pure tone thresholds and pure tone averages for the test ears of both groups of subjects. Figures 1 and 2 show composite audiograms of the mean threshold levels and ranges for the better ear (test ear) for each group.

School records of the prospective subjects were examined to confirm the status of current audiologic evaluations and the absence of other handicapping conditions.

Prior to testing parent permission was obtained (see Appendix A for form). There were instances in which parents required further explanation regarding the testing of the children. This was accomplished by telephone conversations with the parents and or conferences with the school contact person, such as the principal or speech pathologist.

**Table 1. Subject characteristics and audiometric data for the best/test ear in the younger population.**

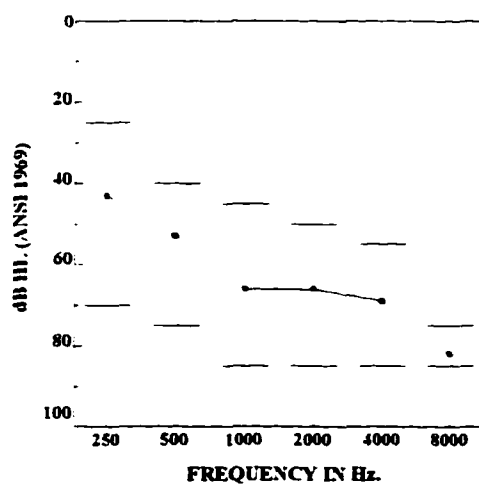
Subject	Gender	Age (yr.-mos.)	Pure Tone Thresholds (dB HL)						PT
			250	500	1000	2000	4000	8000 Hz.	
KG	F	5.1	35	30	40	50	40	60	40
BD	F	5.7	35	40	55	65	60	70	53
CD	F	5.7	55	50	65	90	80	75	68
AJ	F	5.6	35	65	65	75	75	90	68
EM	F	6.3	65	80	90	85	85	100	85
VL	M	6.6	50	50	50	85	110		62
	Mean	5.8	46	53	61	75	75	79	63



**Figure 1. Mean thresholds and ranges for best/test ears in the younger population.**

**Table 2. Subject characteristics and audiometric data for the best/test ear in the older population.**

Subject	Gender	Age (yr./mos.)	Pure Tone Thresholds (dB HL)						PTA
			250	500	1000	2000	4000	8000 Hz.	
AM	F	9.6	35	45	60	65	70	85	57
AM	F	8.2	45	60	70	70	70	80	67
LC	M	8.11	25	45	75	60	70	85	60
MK	F	9.6	40	40	45	50	55	75	45
DD	F	9.2	70	75	85	85	85		82
AP	F	9.5	45	55	60	65	65	85	60
	Mean	9.1	43	53	66	66	69	82	62



**Figure 2. Mean thresholds and ranges for best/test ears in the older population.**

## ***Stimuli***

Test items from the Nonsense Syllable Test (NST) developed by Resnick, Dubno, Hoffnung and Levitt (1975) were used as stimuli. An adult male acted as the speaker. Only selected vowel-consonant (VC) syllables from the NST were used in the present investigation. There is evidence that final consonants are particularly difficult to identify or discriminate in speech recognition tasks because of decreased overall intensity when compared to initial consonants. In addition, the intensity of the final vowel is weakened due the temporal masking of the preceding vowel (Picheny, Durlach and Braida, 1986). Furthermore, hearing impaired individuals have demonstrated great difficulty with the recognition of final consonants (Boothroyd, 1984). The VC syllables of interest were digitized using a 20K sampling rate and stored in a PC-AT type computer using a 12-bit analog-to-digital converter (Data Translation 2801-A data acquisition board). The board was also used to provide digital-to-analog conversion for playing back the processed stimuli. To avoid the possibility of aliasing and imaging distortions, both input and output signals were low-pass filtered at 7.5 kHz.

The frication noise portion of fricatives and the burst portion of stops in each VC of the digitized speech signal were isolated using a waveform editing procedure as described by Weiss (1992). The vowel portion of each VC was adjusted to equal intensity. The precise start and stop times for each fricative or burst and vowel in each VC was determined using methodology similar to that described in Dubno and Levitt (1981). The CVR of the unmodified (natural) speech input was arbitrarily given the value of 0 dB and acted as a baseline for increasing levels of consonant amplitude. Test stimuli were then generated having CVR ranging in value from 0 dB baseline to a maximum of +24 dB in steps of 3 dB.

Two sets of consonants were used:

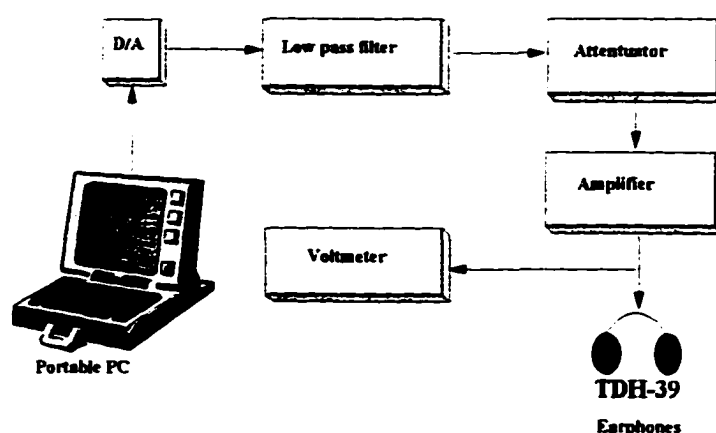
1. Voiceless and voiced fricatives - /s, f, θ, z, v, ð/
2. Voiceless and voiced stops - /p, t, k, b, d, g/

Each consonant followed an /a/ vowel in a VC (vowel consonant) format. The VC format was chosen since hearing-impaired listeners typically have greater difficulty recognizing consonants in syllable final position.

### *Instrumentation*

A portable computer with a hard drive containing the test programs and experimental stimuli was used. The digitized experimental stimuli were stored in computer memory and presented to the subject as required by the experimental design. In doing so, the digitized test stimulus was converted to analog form via a data translation 2801-A data acquisition board and low pass filtered to remove any aliasing or imaging errors. The signals were then passed through a Realistic amplifier to TDH 39 earphones. Output was monitored by a voltmeter as the signal was sent out through the earphones.

Figure 3 shows a block diagram of the instrumentation used for data collection.



**Figure 3. Instrumentation used for data collection**

## ***Procedure***

The following terminology will be used:

- A trial = 1 presentation of a test syllable
- A subtest = a group of 6 consonants (i.e., 6 voiced or 6 voiceless)
- A set = a maximum of 5 subtests, one subtest at each of a maximum of 5 consonant enhancement levels
- A session is made up of 3 replications of a set
- An experiment consists of 8 sessions

Six sessions, one per subject, were planned to take place during each visit to the school. Due to unforeseen absences, school trips, special classroom activities, and school closings due to inclement weather, flexibility in the scheduling of testing sessions was required. Each session consisted of a maximum of 5 consonant enhancement levels for one set of stimuli (6 consonants, voiced or unvoiced) with 3 replications. Eight 1/2 hour sessions per subject were necessary to complete the experiment for each child. This allowed for 12 replications of each consonant at each level.

A split paired design was used in the collection of data. Older subjects were randomly assigned odd numbers and younger subjects were randomly assigned even numbers.

The order of presentation was:

<u>Session:</u>	<u>Subjects 1 through 6</u>	<u>Subjects 7 through 12</u>
1	voiced set	voiceless set
2	voiceless set	voiced set
3	voiced set	voiceless set
4	voiceless set	voiced set
5	voiced set	voiceless set
6	voiceless set	voiced set
7	voiced set	voiceless set
8	voiceless set	voiced set

The advantage of this design is that, if a learning effect occurs, the effect will be balanced across the voiced and the voiceless sets of consonants and across younger and older subjects.

All trials within a set were randomized, i.e., all of the nonsense syllables at the various enhancement levels within a set were presented in random order during each session.

All testing took place in a quiet room in the school setting. The better ear served as the test ear. Stimuli were presented through earphones.

The first test determined the Most Comfortable Loudness Level (MCL) for each subject. The purpose of this test was to find and maintain a level of loudness that is most comfortable for listening. The stimuli used were the same as described in the Stimuli section. A lower level and an upper level of MCL was determined in order to obtain a range of levels appropriate for individual subjects. The level of the speech signal was controlled by the up and down keys on the computer keyboard. To find the lower MCL, the subject pressed the home key to begin the test. If the speech was quieter than comfortable (the starting condition), the subject pressed the up key. When the speech was at a comfortable loudness level the subject pressed the down key. Testing continued until the lower MCL boundary was crossed at least 6 times. To find the upper level of loudness comfort the subject pressed the home key to begin again. This time the starting level was at MCL. When speech was at MCL the subject pressed the up key. When speech was louder than comfortable the subject pressed the down key. Subjects pressed either key to continue the test. The average of the upper and lower MCL values was used as the listening level in subsequent testing.

The experimenter trained each subject in the above procedure prior to testing. Materials appropriate for children were used for instruction. Picture cards developed by Cochlear Corporation to teach concepts of loudness and loudness scaling were used to find comfort levels (see Appendix B for instructions and materials used in obtaining loudness comfort levels.)

Individual MCL values for both groups of subjects are listed below.

<b>Children age 5 - 6 years</b>		<b>Children age 8 - 9 years</b>	
<b><u>Subjects</u></b>	<b><u>MCL in dBSPL</u></b>	<b><u>Subjects</u></b>	<b><u>MCL in dBSPL</u></b>
BD	79	AM	79
CD	79	VP	92
AJ	89	LC	92
EM	92	MK	89
VL	89	DM	92
KG	79	AP	92

After establishing MCL, a second test determined Uncomfortable Loudness Level (UCL). The same instrumentation and picture cards were used as in determining MCL. Three tokens of a given VC nonsense syllable were presented at MCL and at an enhancement level of 0 dB (i.e., the unenhanced condition). Using the picture cards, the subject indicated whether or not the level was too loud. If the subject indicated that the level was not too loud, three more tokens of the VC syllable were presented with the consonant enhanced by 3 dB. This procedure continued until the subject indicated, by pointing to the appropriate picture card, that the level was too loud. When the subject indicated the level was too loud, the enhancement level for the following presentation was reduced by 6 dB. In cases where only 3 dB of enhancement was too loud, the following presentation was reduced by 3 dB. For cases where UCL was not reached, the highest allowable

level of enhancement was 24 dB. This procedure was repeated until 3 estimates of UCL were obtained for the VC syllable. Testing then continued with another VC syllable until UCL was determined for all of the test consonants. (See Appendix C for instructions on obtaining UCL.)

The CVR for voiced and voiceless test stimuli in the unenhanced condition are listed below.

<b>Voiced Set</b>		<b>Voiceless Set</b>	
<u>Stimuli</u>	<u>CVR in dB</u>	<u>Stimuli</u>	<u>CVR in dB</u>
/ab/	-16.5	/ap/	-26.2
/ad/	-15.1	/at/	-25.9
/ag/	-15.1	/ak/	-25.6
/av/	-15.5	/af/	-28.7
/aδ/	-27.0	/aθ/	-27.0
/az/	-11.0	/as/	-12.8

Possible levels of consonant enhancement were 0, 3, 6, 9, 12, 15, 18, 21, and 24 dB above the unenhanced condition. Of these possible levels, 5 roughly equally spaced levels covering the available dynamic range for each consonant were chosen for testing. If the dynamic range for a given subject on a given consonant was less than 12 dB (i.e., UCL was reached with enhancement levels of 9 dB or lower), then fewer than 5 enhancement levels were used in subsequent testing. Consonant Enhancement (CE) functions were obtained for each subject for each consonant condition.

To maintain consistency across subjects' CE functions, in light of varying tolerance levels, the following parameters were used:

<u>SUBJECT'S UCL</u>	<u>LEVELS OF ENHANCEMENT</u>	<u># of DATA POINTS</u>
3 dB	0	1
6 dB	0 and 3 dB (2 data points)	2
9 dB	0, 3, and 6 dB (3 data points)	3
12 dB	0, 3, 6 and 9 dB (4 data points)	4
15 dB	0, 3, 6, 9 and 12 dB (5 data points)	5
18 dB	0, 6, 9, 12 and 15 dB (*)	5
21 dB	0, 6, 12, 15 and 18 dB (*)	5
24 dB	0, 6, 12, 18 and 21 dB (*)	5
24+dB	0, 6, 12, 18 and 24 dB (*)	5

Test items were generated by the computer based on individual subject tolerances for each test consonant.

The test items were randomized in each of the two sets, voiced and voiceless consonants. The subjects responded by repeating what they heard and pointing to the printed consonant. The response was entered by the tester via a coded keyboard as shown in Figure 4.

### Voiceless Set

F1 f	F2 p	F3 s	F4 t	F5	F6 k
F7 θ	F8	F9	F10	F11	F12

### Voiced Set

F1 z	F2	F3	F4 ð	F5	F6 d
F7 b	F8 g	F9 v	F10	F11	F12

**Figure 4. Coding of the "F" Keys**

Following the entry of a response, one second lapsed before presentation of the next test item. This method of data collection allowed for subject variability in terms of time required to make a response. The computer stored the responses in memory. Upon completion of the experiment, a percent correct score for each consonant at each level of enhancement was computed for each subject.

## CHAPTER IV. RESULTS

This investigation posed three questions:

1. What is the effect of increasing consonant amplitude (i.e., consonant enhancement) on the recognition of these sounds in children?
2. What is the effect of age on consonant enhancement, particularly between the 5-6 year old subjects and the 8-9 year old subjects?
3. What is the effect of consonant enhancement on the pattern of consonant confusions in hearing-impaired children?

In order to answer the first question, the subjects' responses to all VC's at all levels of enhancement were organized and analyzed. The raw scores at each level of enhancement for every subject were organized into tables. Percent correct scores were determined and plotted as a function of consonant enhancement.

A smooth curve was fitted to each set of data using the method of orthogonal polynomials (Bennet and Franklin, 1954; Levitt and Rabiner, 1971). These curves are referred to as Consonant Enhancement functions. Levitt and Oden developed a computer program to fit the curves. The percent correct scores were transformed to arc sine units prior to fitting the curve in order to stabilize the error variance. Once each curve was fitted, the vertical axis was transformed back from arc sine units to percent correct for ease of interpretation. The highest point on the curve identifies the maximum score. The score, in percent correct, is referred to as  $P_{max}$ , or  $Y_{max}$  when arc sine units are used. The enhancement level (in dB) corresponding to  $P_{max}$  is defined as  $CE_{max}$ . The test score in percent for no enhancement (i.e.  $CE = 0$  dB) is defined as  $P_0$ , or  $Y_0$  when arc sine units are used.

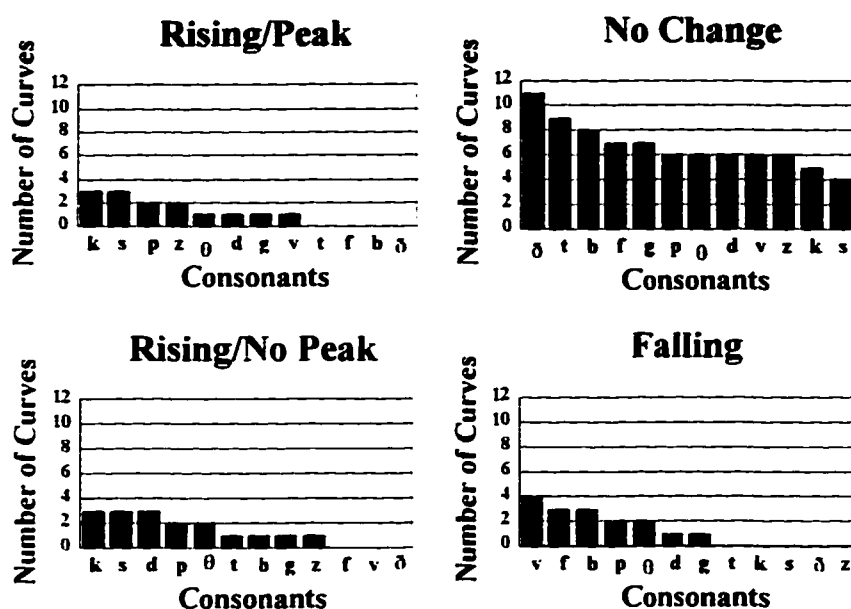
The orthogonal polynomial method of fitting curves to experimental data was used in order to determine, using an established statistical technique, whether there was any significant change in test score with level of enhancement and if so, the nature of this change. For example, if there was no significant change in test score with level of enhancement the result would be a straight line. The simplest orthogonal polynomial curve showing a change in test score with level of enhancement is a sloping straight line, that is, the coefficient of the linear term in the orthogonal polynomial expansion is statistically significant. If this coefficient is positive, the curve slopes upwards indicating an increase in test score with enhancement level. A negative coefficient for the linear term corresponds to a downward sloping straight line indicating a linear decrease in test score, with increasing level of enhancement. If the coefficient of the quadratic, cubic or any higher level term in the orthogonal polynomial expansion is significant, the fitted curve will show some curvature, possibly reaching a significant peak or valley within the range of enhancement levels used.

The CE functions for each subject and each consonant are shown in Appendix E.

These CE functions were classified into four groups:

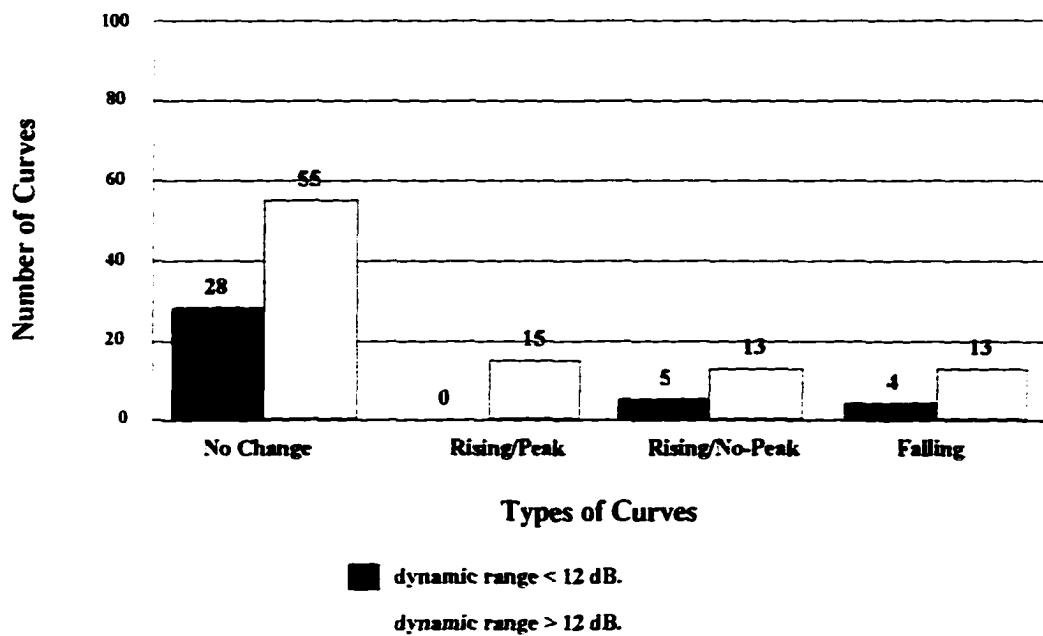
- No Change: These CE functions showed no statistically significant change in test score with level of enhancement. These CE functions are represented by horizontal straight lines.
- Rising/Peak: These CE functions showed a statistically significant increase in test score with level of enhancement reaching a distinct peak followed by a subsequent decline.
- Rising/No Peak: The test score for these curves increased monotonically with enhancement level with no evidence of a peak until the highest allowable level of enhancement was reached.
- Falling: These CE functions showed a statistically significant decline in test score with increasing level of enhancement.

The number of CE functions falling within each classification category was determined for each subject for each of the twelve consonants. The No Change classification represents the largest number of curves. The voiced fricative /ð/ showed the highest number of No Change CE functions. Enhancement of the voiceless alveolar stop /t/ and the voiced labial stop /b/ also yielded large numbers of No Change CE functions.



**Figure 5. Classification of Consonant Enhancement Functions**

The Rising/Peak and the Rising/No Peak CE functions were obtained most frequently with the voiceless glottal stop /k/ and the voiceless fricative /s/. The voiced alveolar stop /d/ also had a relatively large number of Rising/No Peak CE functions. The last category was comprised of Falling configurations. The voiced fricative /v/, the voiceless labial dental fricative /f/, and the voiced labial stop /b/ had the largest number of Falling CE functions.



**Figure 6. Number of Curves by Classification**

Figure 6 shows the number of CE functions in each category. The number of curves has been further divided into two groups within each category. The darker shaded bars represent the plots generated from responses of subjects with limited dynamic ranges, who could not tolerate five levels of consonant enhancement using 3 dB. increments. That is, the maximum allowable consonant enhancement for these subjects was 9 dB. or less. These subjects were mostly from the younger group. The lighter shaded bars represent subjects with a larger dynamic range who could tolerate consonant enhancements greater than 9 dB. Tables 4-7 show the maximum allowable consonant enhancement for each child for each consonant. Note that the maximum allowable enhancement for a given consonant was 3 dB less than UCL for that consonant.

**Table 4. Maximum Increase in Consonant Enhancement  
(dBMax)**

**Each VC in the Voiced Set**

**Subjects 5 - 6 years**

<u>SUBJECT</u>	<u>dBMax</u>	<u>VC</u>
AJ	15 dB 12 dB	/ad/ /ag/ /av/ /az/ /aθ/ /ab/
BD	6 dB 0 dB	/ab/ /ad/ /ag/ /av/ /az/ /aθ/
CD	24 dB 21 dB 18 dB	/av/ /ag/ /ab/ /ag/ /az/ /aθ/
EM	9 dB 6 dB	/ab/ /ag/ /az/ /aθ/ /av/ /ad/
KG	24 dB	/ab/ /ad/ /ag/ /av/ /az/ /aθ/
VL	9 dB 6 dB 3 dB 0 dB	/ad /ab/ /ag/ /aθ/ /av/ /az/

**Table 5. Maximum Increase in Consonant Enhancement  
(dBMax)**

**Each VC in the Voiced Set**

**Subjects 8 - 9 years**

<u>SUBJECT</u>	<u>dBMax</u>	<u>VC</u>
AM	24 dB	/ab/ /ad/ /ag/ /av/ /az/ /aθ/
AP	24 dB	/ab/ /ad/ /ag/ /av/ /az/ /aθ/
DD	24 dB	/ab/ /ad/ /ag/ /av/ /az/ /aθ/
LC	24 dB	/ab/ /ad/ /ag/ /av/ /az/ /aθ/
MK	24 dB 21 dB 0 dB	/ab/ /ag/ /av/ /aθ/ /az/ /ad/
VP	18 dB 15 dB 6 dB 3 dB	/az/ /ab/ /av/ /ag/ /aθ/ /ad/

**Table 6. Maximum Increase in Consonant Enhancement  
(dBMax)**

**Each VC in the Voiceless Set**

**Subjects 5 - 6 years**

<u>SUBJECT</u>	<u>dBMax</u>	<u>VC</u>
AJ	15 dB	/ɑ/ /ɑk/ /ɑf/
	12 dB	/ɑp/ /ɑs/ /ɑθ/
BD	15 dB	/ɑp/
	12 dB	/ɑs/
	6 dB	/ɑk/
	3 dB	/ɑθ/
	0 dB	/ɑ/ /ɑf/
CD	18 dB	/ɑp/ /ɑ/ /ɑk/ /ɑf/ /ɑs/ /ɑθ/
EM	9 dB	/ɑp/ /ɑ/ /ɑf/ /ɑs/ /ɑθ/
	6 dB	/ɑk/
KG	24 dB	/ɑp/ /ɑ/ /ɑk/ /ɑs/ /ɑf/ /ɑθ/
VL	9 dB	/ɑk/
	6 dB	/ɑ/ /ɑθ/
	3 dB	/ɑ/
	0 dB	/ɑk/

**Table 7. Maximum Increase in Consonant Enhancement  
(dBMax)**

**Each VC in the Voiceless Set**

**Subjects 8 - 9 years**

<u>SUBJECT</u>	<u>dBMax</u>	<u>VC</u>
AM	24 dB	/ɑp/ /ɑ/ /ɑk/ /ɑf/ /ɑs/ /ɑθ/
AP	24 dB	/ɑp/ /ɑ/ /ɑk/ /ɑf/ /ɑs/ /ɑθ/
DD	24 dB	/ɑp/ /ɑ/ /ɑk/ /ɑf/ /ɑs/ /ɑθ/
LC	24 dB	/ɑp/ /ɑ/ /ɑk/ /ɑf/ /ɑs/ /ɑθ/
MK	24 dB	/ɑp/ /ɑ/ /ɑk/ /ɑs/ /ɑf/ /ɑθ/
	21 dB	/ɑf/ /ɑs/
	0 dB	/ɑk/
VP	21 dB	/ɑp/
	18 dB	/ɑf/
	15 dB	/ɑs/ /ɑθ/
	3 dB	/ɑ/
	0 dB	/ɑk/

Twelve CE functions, one for each consonant, could be generated for each child for a total of  $12 \times 12 = 144$  curves. However, 133 CE functions are represented in Fig. 6. Eleven of these curves could not be categorized for the the following reasons:

1. The plots only contained one data point. That is, the subject could only tolerate the unenhanced level of VC presentation, as in the case of subject BD for VC's /at/ /af/ /að/ and /az/ and in the case of subject VL for VC's /af/ and /az/ and subject MK for VC's /ak/ and /ad/. In subsequent ANOVA's this curve was treated as No Change.
2. The CE functions fell initially and then rose again reaching a value not significantly different from the unenhanced condition (see subject AP for /aθ/ and subject LC for /ag/).
3. The CE functions fell then rose then fell again, as in the case of subject LC for /ak/ and subject AP for /aθ/.

The highest percentage of CE functions (62%) fell into the No Change category. A CE function of this type was represented by a straight line. The value of CEmax for this case was defined as 0 dB enhancement. In principal, any point on this curve corresponds to Pmax. A small percentage (6.7%) of the CE functions in this category represented scores of 100% at every level of enhancement; that is, subjects scored 100% at the unenhanced level and also at every level of increased consonant amplitude. In the No Change category 54.3% of the CE functions represented voiced consonants, while 45.7% of these configurations represented voiceless consonants. In terms of manner of articulation, 50.6% of the CE functions represented stop consonants and 49.4% represented fricative consonants.

The Rising/No Peak category of curves constituted 13% of the total number of CE functions. In this category 64.7% of the curves represented voiceless consonants and 35.3% of the curves represented voiced consonants. In terms of manner of articulation, 64.7% of the curves represented stop consonants, while 35.3% represented fricative consonants.

The Rising/Peak category of curves constituted 11% of the total number of CE functions. In this category, voiceless consonants were represented by 64.3% of the curves and voiced consonants were represented by 35.7% of the curves. Stop consonants constituted 57.2% of the curves while 42.8% of the curves represented fricative consonants.

The Falling category of curves constituted 12% of the total number of the CE functions. In this category 56.3% of the curves constituted voiced consonants and 43.7% of the curves constituted voiceless consonants. Fricative consonants were represented by 56.3% of the curves. Stop consonants were represented by 43.7% of the curves.

The effect of dynamic range on classification of the CE curves is also evident from Figure 6. In the No Change category 66.3% of the curves represent subjects with larger dynamic ranges (i.e., maximum allowable consonant enhancement of 12 dB or greater) and 33.7% of the curves represent subjects with smaller dynamic ranges. All of the curves in the Rising/Peak category represented responses from subjects with larger dynamic ranges. In the Rising/No Peak category 72.2% of the CE functions represent subjects with larger dynamic ranges, and 27.7% represent subjects with narrow dynamic ranges. In the Falling category 76.4% of the curves represent subjects with wide dynamic ranges, while 23.5% represent subjects with narrow dynamic ranges.

### ***Analysis of Consonant Recognition***

The following analyses were performed:

1. an analysis of consonant recognition with no enhancement
2. an analysis of consonant recognition for maximum score
3. an analysis of the improvement in consonant recognition in going from no enhancement (CE = 0dB) to CEmax
4. an analysis of the consonant enhancement necessary to maximize consonant recognition

#### **Analysis of Consonant Recognition with No Enhancement**

The first analysis was performed on data for the unenhanced condition (CE = dB). Note that the measures were repeated for each subject in each of the two age groups. For obvious reasons, different subjects were used for the younger and older groups. A repeated measures analysis of variance was performed for the following 3 factors:

1. Cognate Pairs: /b-p/ /d-t/ /g-k/ /v-f/ /ð-θ/ /z-s/
2. Voicing: voiced /b, d, g, v, ð, z/ or voiceless /p, t, k, f, θ, s/
3. Age: young subjects (5-6 years) or older subjects (8-9 years)

Note that factors 1 and 2 were repeated over both groups of subjects. All scores were subjected to the arc sine transformation to stabilize the error variance (Bennet and Franklin, 1954).

The results of this analysis are shown in Table 8. The factor of Cognate Pairs was significant at the .001 level. A post-hoc analysis was performed to test comparisons among Cognate Pairs for significance. Using the Tukey's Honest Significant Differences (HSD) method at .05 level of significance the Cognate Pairs could be divided into three groups.

The horizontal lines labeled Group A, Group B and Group C on the histogram identify these groupings. All Cognate Pairs lying below a given horizontal line do not differ significantly from each other (at the 0.05 significance level).

**Table 8. Analysis of Variance**

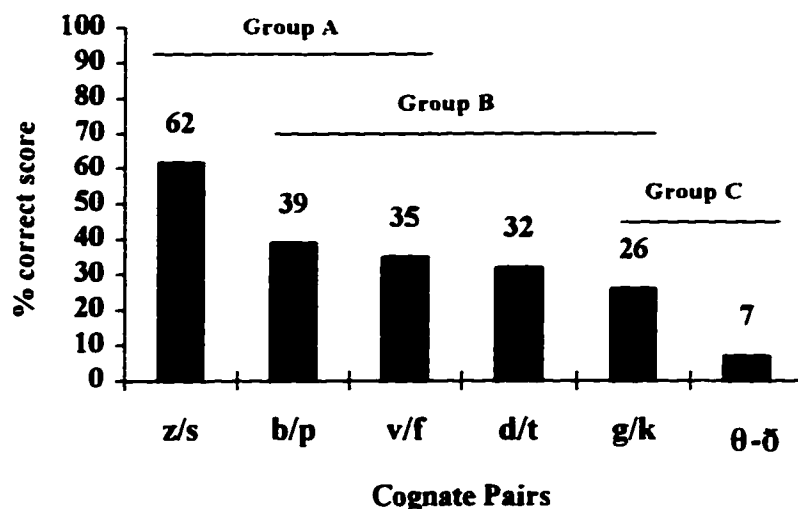
**Scores Obtained at the Unenhanced Level of Presentation  
of Vowel Consonant Syllables**

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	Significance Level
Cognate Pairs (P)	19.83	5	3.96	8.99	0.001*
Voicing (V)	0.18	1	0.18	1.9	0.22
P x V	0.18	5	0.03	0.27	0.91
Age (A)	0.14	1	0.14	0.2	0.67
P x A	1.09	5	0.21	0.48	0.78
V x A	0.42	1	0.42	3.65	0.11
P x V x A	0.74	5	0.14	1.58	0.2

\* Statistically Significant: Note that significant levels of 0.001 or lower are represented by 0.001.

The mean scores for the statistically significant interaction of Cognate Pairs with Voicing are shown below.

Cognate Pairs	b-p	d-t	g-k	v-f	θ-θ	z-s
Means	0.39	0.32	0.26	0.35	0.07	0.62

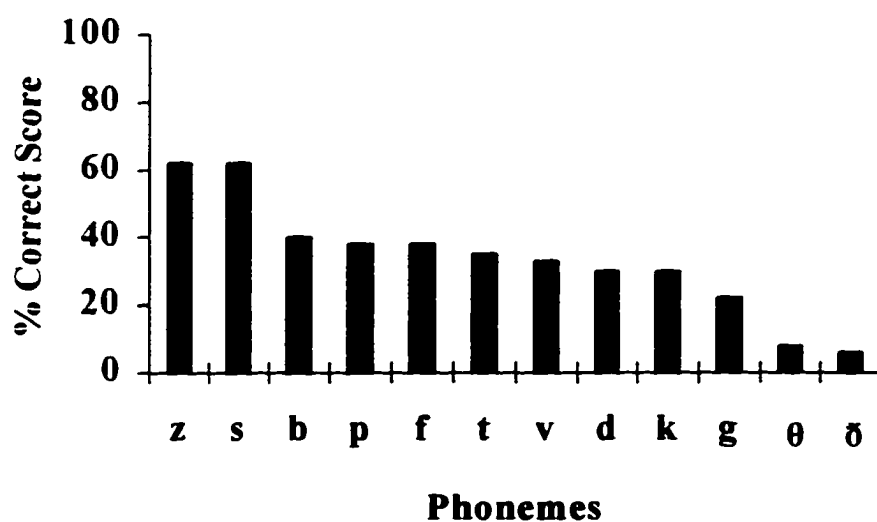


**Figure 7. Unenhanced Level; Cognate Pairs**

Figure 7 illustrates the mean Cognate Pairs at the unenhanced level.

The post-hoc analysis reveals that for the unenhanced condition, the test scores for the Cognate Pairs /z-s/, /b-p/, and /v-f/ do not differ significantly from each other. This group of Cognate Pairs showed the highest scores for the unenhanced condition and is identified by the horizontal line labeled Group A in figure 7.. The next highest set of scores correspond to Group B consisting of the Cognate Pairs /b-p/, /v-f/, /d-t/, and /g-k/. Note that the Cognate Pairs /b-p/ and /v-f/ belong to both Group A and Group B, meaning that scores for /b-p/ and /v-f/ do not differ from each other, nor do their scores differ from those for /z-s/ or /d-t/, although the scores for /z-s/ and /d-t/ differ significantly from each other. The lowest set of test scores were obtained for the Cognate Pairs /g-k/ and /ð-θ/ (Group C).

The interaction matrix, Cognate Pair vs. Voicing, identifies the test scores for individual consonants. Figure 8 shows the percent correct score for individual consonants at the unenhanced level in decreasing order. Since the interaction between Cognate Pair and Voicing was not statistically significant, it is to be expected that the test scores for individual consonants would be ordered in much the same way as their Cognate Pairs; i.e., the Cognate Pair showing the highest score was /z-s/ and the highest scoring individual consonants were /z/ and /s/ respectively. Similarly, the lowest scoring consonants were /θ/ and /ð/, which also formed a Cognate Pair.



**Figure 8. Unenhanced Level: Individual Consonants**

### Analysis of Consonant Recognition for Maximum Score (Ymax)

A second analysis of variance was performed on Ymax, the maximum test scores after transforming to arc sine units. Note, however, that after the statistical analysis the test scores have been converted back to percentages. The same set of factors were used as in the first analysis of variance.

The results of this analysis of variance are shown in Table 9. The factor of Cognate Pairs was significant at the .001 level. The Cognate Pair x Voicing interaction was also significant at the .01 level.

**Table 9. Analysis of Variance**

#### Maximum Scores

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	Significance Level
Cognate Pairs (P)	42.8	5	8.56	15.81	0.001*
Voicing (V)	0.33	1	0.33	1.58	0.26
P x V	4.3	5	0.86	3.67	0.01*
Age (A)	0.17	1	0.17	0.26	0.63
P x A	1.26	5	0.25	0.49	0.77
V x A	0.23	1	0.23	2.13	0.2
P x V x A	0.32	5	0.06	0.6	0.7

\* Statistically Significant: Note that significance levels of 0.001 or lower are represented by 0.001.

The mean scores for the statistically significant effect of Cognate Pairs are shown below.

Cognate Pairs	b-p	d-t	g-k	v-f	θ-θ	z-s
Means	0.52	0.52	0.4	0.54	0.08	0.88

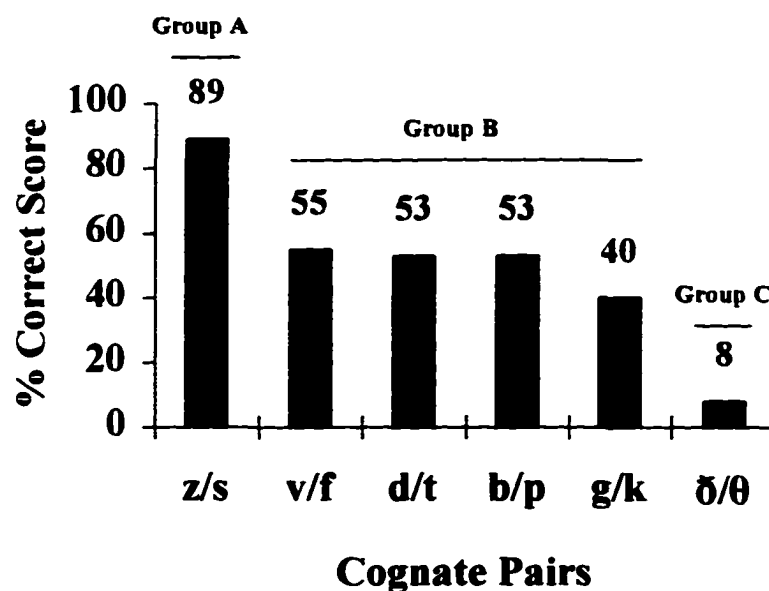
The mean scores for the statistically significant interaction of Cognate Pair by Voicing are shown below.

	<b>b</b>	<b>d</b>	<b>g</b>	<b>v</b>	<b>ð</b>	<b>z</b>
<b>voiced</b>	0.52	0.51	0.3	0.66	0.02	0.89

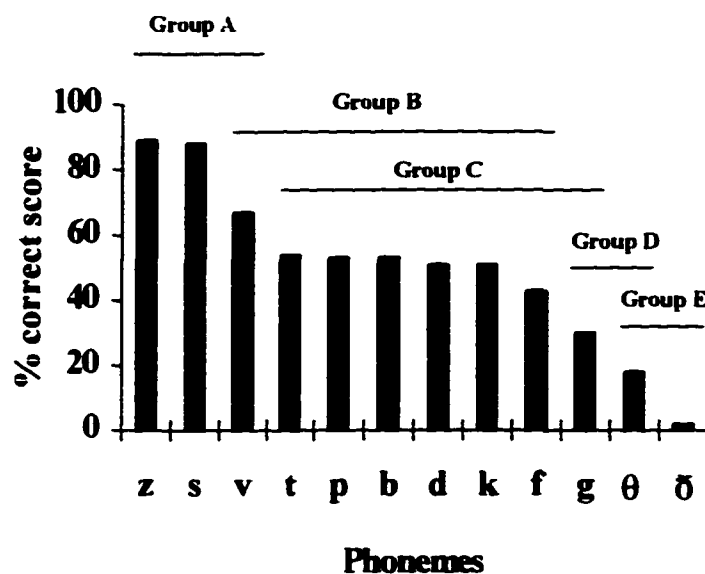
  

	<b>p</b>	<b>t</b>	<b>k</b>	<b>f</b>	<b>θ</b>	<b>s</b>
<b>voiceless</b>	0.52	0.54	0.5	0.43	0.18	0.88

A post-hoc analysis using the Tukey HSD method at the .05 level of significance found the factor of Cognate Pairs to have three significant subgroups. Figure 9 shows the percent correct scores for Cognate Pairs at CEmax in decreasing order. Group A consists of /z-s/, the cognate pair with the highest score. Group B consists of Cognate Pairs, /g-k/, /b-p/, /d-t/, and /v-f/. Test scores for these four Cognate Pairs do not differ significantly from each other. Group C consists of the Cognate Pair /ð-θ/, which had the lowest test score.



**Figure 9. Maximum Score Level; Cognate Pairs**



**Figure 10. Maximum Score Level; Individual Consonants**

Figure 10 shows the test scores, in decreasing order, for individual consonants at CEmax. In this case, the interaction between Cognate Pair and Voicing was statistically significant indicating that the ordering of test scores for individual consonants is not quite the same as that for Cognate Pairs. For example, the Cognate Pair /v-f/ has a relatively low score (40% correct). Although one member has a relatively high score (67% for /v/), the other member of the pair has a relatively low score.

The highest percent correct scores were obtained for phonemes /z/, /s/, and /v/ found in Group A. The next highest percent correct scores were achieved for phonemes /t, p, b, d, k, and f/ in Group B. The phonemes /v/ shares commonality in both Groups A and B. All the phonemes below the horizontal line labeled Group B do not differ from each other in significance. Many of the phonemes from Group B overlap into Group C which consists of phonemes /t, p, b, d, k, f,

and *g/*. The phonemes that fall below the horizontal line labeled Group C do not differ from each other in statistical significance. At the lower end of the scale is Group D comprised of the phonemes */g/* and */θ/*. They do not differ in statistical significance. The phonemes that yielded the lowest scores were */θ/* and */ð/* found in Group E in the histogram.

### Analysis of the Improvement from No Enhancement to CEmax

The third analysis of variance was based on the difference between the unenhanced score and the score at CEmax. The same factors as in previous analyses of variance were used. The results are shown in Table 10. As before, the factor of Cognate Pairs was found to be statistically significant at the .01 level.

**Table 10. Analysis of Variance**

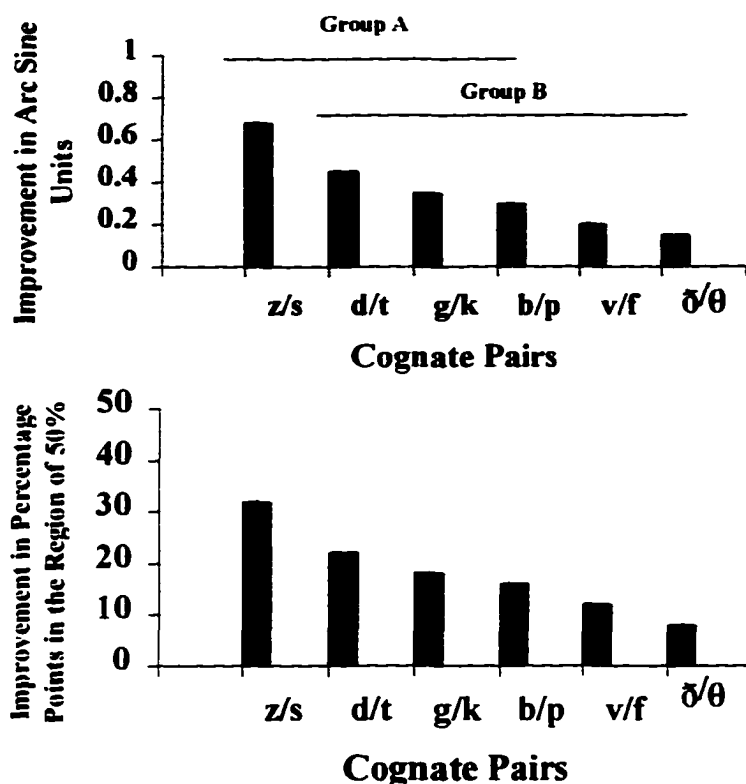
#### Difference Between Scores Obtained at the Unenhanced Level and Maximum Scores

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	Significance Level
Cognate Pairs (P)	4.78	5	0.95	3.43	0.01*
Voicing (V)	0.07	1	0.07	0.15	0.71
P x V	1.46	5	0.29	1.05	0.41
Age (A)	0.03	1	0.03	0.1	0.75
P x A	0.46	5	0.09	0.37	0.86
V x A	0.12	1	0.12	0.59	0.52
P x V x A	0.48	5	0.09	1.07	0.4

\* Statistically Significant: Note that significance levels of 0.001 or lower are represented by 0.001.

The mean scores for the statistically significant effect of Cognate Pairs are shown below.

<b>b-p</b>	<b>d-t</b>	<b>g-k</b>	<b>v-f</b>	<b>θ-θ</b>	<b>z-s</b>
0.31	0.48	0.35	0.22	0.18	0.73

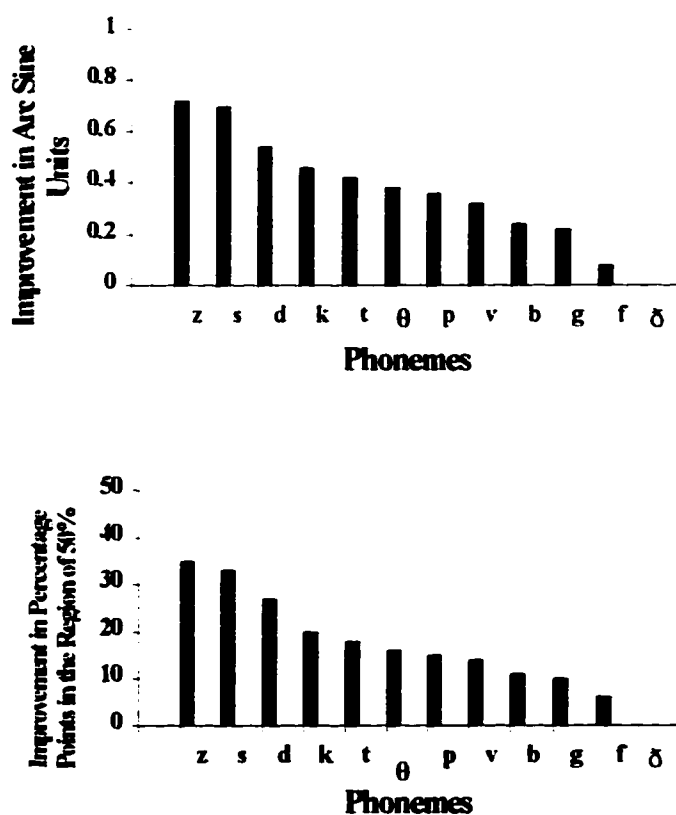


**Figure 11. Improvement from Unenhanced to Maximum Score**

In Figure 11, the top histogram illustrates, in decreasing order, the improvement in test scores going from the unenhanced level to CEmax expressed in arc sine units. The horizontal line labeled Group A delineates the Cognate Pairs /z-s/, /d-t/, /g-k/, and /b-p/. Post Hoc analysis using the Tukey HSD method found these Cognate Pairs do not differ from each other. Group B consists of /d-t/, /g-k/, /b-p/, /v-f/, and /ð-θ/. The bottom histogram shows the improvement in test score expressed in percentage points. Since the conversion from arc sine units to percentages differs depending on the region where measurements are obtained, the lower histogram has been normalized to show the improvement in percentage points in a specific region, i.e., in the region of 50% correct. For example, in the above diagram an

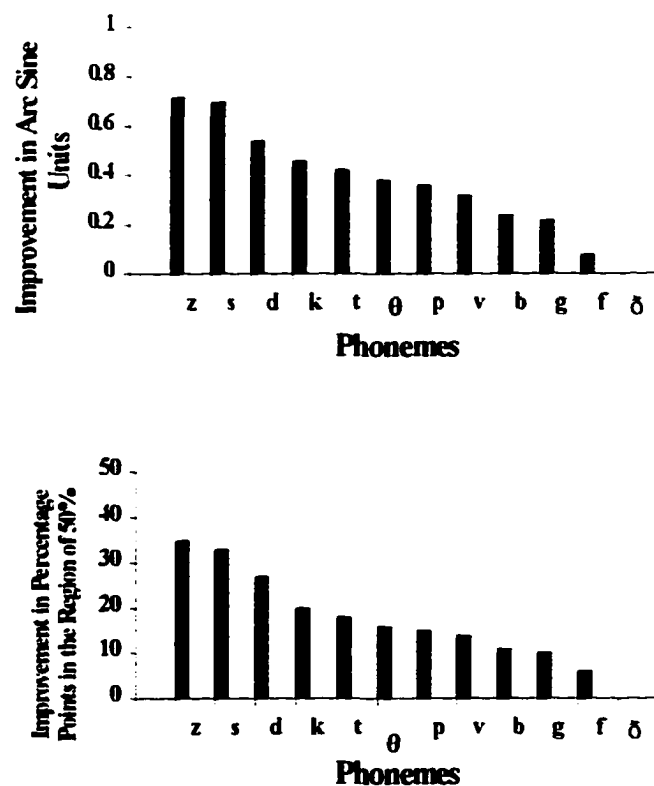
score of 68% correct. If the two scores, 32% and 68%, are converted to arc sine units, the improvement is 0.73 arc sine units as shown in the upper histogram for z/s.

Recognition of the Cognate Pair /z-s/ improved the most, followed by /d-t/. The Cognate Pair with the least improvement was /ð-θ/. Note that the order of the Cognate Pairs is the same regardless of how the data is expressed in either of the histograms.



**Figure 12. Improvement from Unenhanced to Maximum Score**

Figure 12 illustrates the improvement from unenhanced to maximum score for individual consonants. The top histogram shows the improvement in arc sine units. The bottom histogram shows the equivalent improvement in percentage points in the region of 50% correct. The most intense fricatives, /z/ and /s/, show the most improvement. The least improvement is shown by the weak fricative, /f/. The voiced weak fricative, /ð/, showed no improvement. It is of interest to note that, although the Cognate Pair /ð-θ/ yielded the least improvement, as illustrated in Figure 11, when the consonant was analyzed individually the voiceless component of the pair, /θ/, showed 16 percentage points of improvement in the region of 50%. The voiced component of the pair, /ð/, yielded no improvement and brought down the average improvement for the pair.



**Figure 12. Improvement from Unenhanced to Maximum Score**

### Analysis of Consonant Enhancement Level for Maximum Score (dB)

The fourth analysis of variance was performed on the enhancement levels for maximum score (CE<sub>max</sub>). The same factors as in the previous analyses of variance were used. The results are summarized in Table 11. The factor of age was significant at the .04 level.

**Table 11. Analysis of Variance**

#### Consonant Enhancement Required to Achieve Maximum Scores

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	Significance Level
Cognate Pairs (P)	669.27	5	133.85	2.35	0.06*
Voicing (V)	294.12	1	294.12	3.03	0.14
P x V	392.78	5	78.55	2.18	0.08*
Age (A)	81.9	1	81.9	6.72	0.04*
P x A	87.2	5	17.44	0.39	0.84
V x A	0.64	1	0.64	0.06	0.8
P x V x A	22.2	5	4.44	0.14	0.97

\* Statistically Significant: Note that significance levels of 0.001 or lower are represented by 0.001.

The mean scores in decibels for the statistically significant effect of Cognate Pairs are shown below.

b-p	d-t	g-k	v-f	θ-θ	z-s
6.6	7.9	6.2	6.4	4.4	11.4

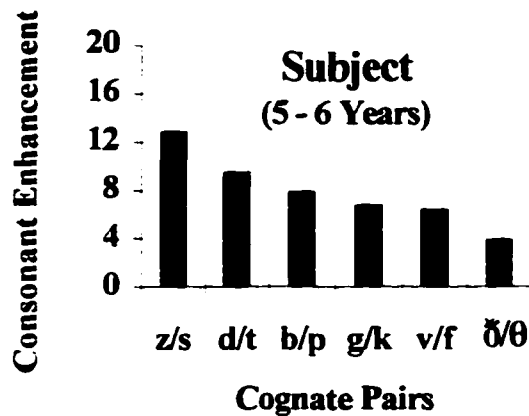
The mean scores in decibels for the statistically significant interaction of Cognate Pair by Voicing are shown below.

<b>b</b>	<b>d</b>	<b>g</b>	<b>v</b>	<b>θ</b>	<b>z</b>
4.7	7.8	4.6	7.3	0	10
<b>p</b>	<b>t</b>	<b>k</b>	<b>f</b>	<b>θ</b>	<b>s</b>
8.5	8	7.9	5.5	8.8	12.8

The mean scores in decibels for the statistically significant effect of Age are shown below.

<b>young</b>	7.9
<b>old</b>	6.4

Consonant enhancement required for maximum scores for Cognate Pairs for young subjects aged 5 - 6 years can be seen in Figure 13. The Cognate Pair /z-s/ required the greatest consonant enhancement (12.9 dB) to achieve maximum score. The Cognate Pair /d-t/ required the next highest amount of consonant enhancement (9.5 dB) for maximum score. The Cognate Pair /ð-θ/ required the least amount of consonant enhancement (3.9 dB) to achieve maximum score.



**Figure 13. Consonant Enhancement Needed for Maximum Score; Cognate Pairs**

Figure 14 shows the consonant enhancement required for maximum scores for the older group of children aged 8 - 9 years. The Cognate Pair /z-s/ required the greatest consonant enhancement (9.8 dB) to achieve maximum score. The Cognate Pair /ð-θ/ required the least amount of consonant enhancement (4.8 dB) to achieve maximum score. Although the order of the Cognate Pairs for maximum enhancement differs between the two age groups, these differences are not statistically significant since the Cognate Pair by Age interaction is not significant.

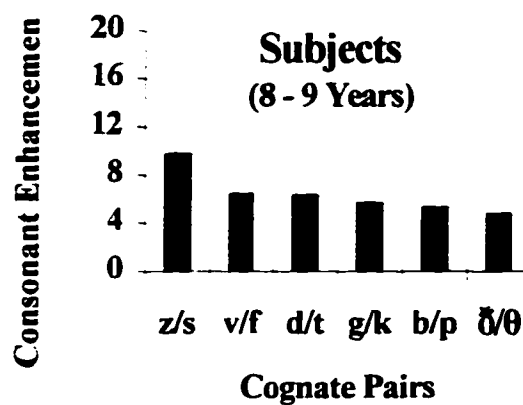
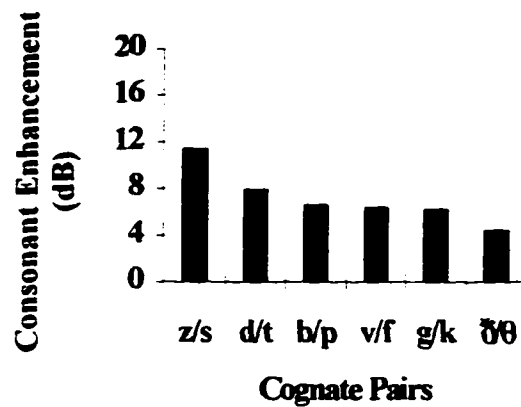


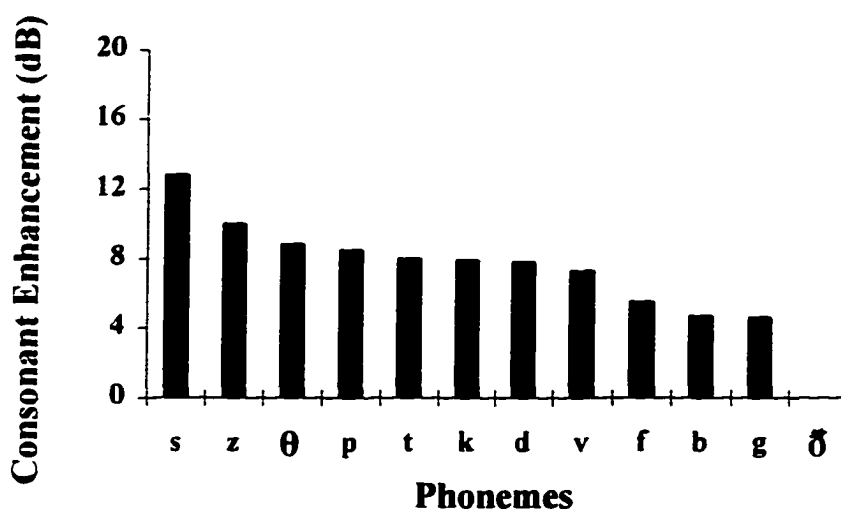
Figure 14. Consonant Enhancement Needed for Maximum Score

The consonant enhancement needed for maximum scores across all subjects is illustrated in Figure 15. The factor of Cognate Pairs was significant at the .04 level. The Cognate Pair /z-s/ required the greatest consonant enhancement (11.4 dB) to achieve maximum score. The Cognate Pair /ð-θ/ required the least amount of consonant enhancement (4.4 dB) to achieve maximum score.



**Figure 15. Consonant Enhancement Needed for Maximum Score; All Subjects Cognate Pairs**

The interaction between Cognate Pairs and Voicing was significant at the .08 level. This interaction term represents the consonant enhancement needed for maximum score for individual phonemes, as shown in Figure 16. The phoneme /s/ required the greatest amount of consonant enhancement (12.8 dB averaged across subjects) for the maximum score. The next highest amount of consonant enhancement (10 dB) was required for the phoneme /z/. The third highest amount of consonant enhancement (8.8 dB) was required for /θ/, while its voiced counterpart, /ð/, showed no enhancement and the average CE value for this consonant was 0 dB.



**Figure 16. Consonant Enhancement Needed for Maximum Score**

## Analysis of Patterns of Confusion that Emerge as a Function of Consonant Enhancement

### Confusion Matrices

The confusion matrix for voiced consonants at the unenhanced level (CE = 0 dB) for subjects 5-6 years of age:

		Response						
		<b>b</b>	<b>d</b>	<b>g</b>	<b>v</b>	<b>ð</b>	<b>z</b>	<b>NR</b>
Target	<b>b</b>	14	37	4	7	3	7	0
	<b>d</b>	28	9	7	11	6	11	0
	<b>g</b>	7	20	23	11	3	8	0
	<b>v</b>	14	10	5	28	12	3	0
	<b>ð</b>	9	18	4	17	1	23	0
	<b>z</b>	6	3	4	5	0	54	0

NR = No Response

The confusion matrix for voiced consonants at CEmax for subjects 5-6 years of age:

		Response						
		<b>b</b>	<b>d</b>	<b>g</b>	<b>v</b>	<b>ð</b>	<b>z</b>	<b>NR</b>
Target	<b>b</b>	16	36	5	2	4	9	0
	<b>d</b>	17	22	3	1	2	3	24
	<b>g</b>	5	11	30	12	6	8	0
	<b>v</b>	7	2	1	36	1	13	12
	<b>ð</b>	11	8	5	12	9	15	12
	<b>z</b>	6	3	4	5	0	54	0

NR = No Response

The confusion matrix for voiceless consonants at the unenhanced level (CE = 0 dB) for subjects 5-6 years of age:

		<b>Response</b>						
		<b>p</b>	<b>t</b>	<b>k</b>	<b>f</b>	<b>θ</b>	<b>s</b>	<b>NR</b>
<b>Target</b>	<b>p</b>	22	7	7	11	11	14	0
	<b>t</b>	6	38	5	10	5	8	0
	<b>k</b>	11	5	33	11	8	4	0
	<b>f</b>	13	5	10	33	5	6	0
	<b>θ</b>	2	4	8	36	7	15	0
	<b>s</b>	18	0	4	2	5	43	0

NR = No Response

The confusion matrix for voiceless consonants at CEmax for subjects 5-6 years of age:

		<b>Response</b>						
		<b>p</b>	<b>t</b>	<b>k</b>	<b>f</b>	<b>θ</b>	<b>s</b>	<b>NR</b>
<b>Target</b>	<b>p</b>	22	7	7	11	11	14	0
	<b>t</b>	6	38	5	10	5	8	0
	<b>k</b>	10	9	35	9	2	7	0
	<b>f</b>	13	5	10	33	5	6	0
	<b>θ</b>	8	5	6	24	13	16	0
	<b>s</b>	18	0	4	2	5	43	0

NR = No Response

Note that the younger group of children did not benefit from enhancement of the voiceless consonants and, hence, the numbers in the cells of both the unenhanced and CEmax confusion matrices are almost identical. This is a result of CEmax having been achieved at the unenhanced level.

The confusion matrix for voiced consonants at the unenhanced level (CE = 0 dB) for subjects 8-9 years of age:

		Response						
		<b>b</b>	<b>d</b>	<b>g</b>	<b>v</b>	<b>ð</b>	<b>z</b>	<b>NR</b>
Target	<b>b</b>	25	11	5	16	1	14	0
	<b>d</b>	30	13	7	14	3	5	0
	<b>g</b>	13	16	11	19	3	10	0
	<b>v</b>	15	10	7	18	8	8	6
	<b>ð</b>	20	12	2	20	10	8	0
	<b>z</b>	10	7	7	15	3	30	0

NR = No Response

The confusion matrix for voiced consonants at CEmax for subjects 8-9 years of age:

		Response						
		<b>b</b>	<b>d</b>	<b>g</b>	<b>v</b>	<b>ð</b>	<b>z</b>	<b>NR</b>
Target	<b>b</b>	25	11	5	16	1	14	0
	<b>d</b>	28	21	5	9	3	6	0
	<b>g</b>	8	13	12	12	7	7	13
	<b>v</b>	7	7	5	24	10	7	12
	<b>ð</b>	12	8	1	18	11	10	12
	<b>z</b>	3	3	2	3	6	55	0

NR = No Response

The confusion matrix for voiceless consonants at the unenhanced level (CE = 0 dB) for subjects 8-9 years of age:

		Response						
		p	t	k	f	θ	s	NR
Target	p	22	9	7	16	8	10	0
	t	17	16	5	16	13	5	0
	k	18	7	13	15	9	10	0
	f	12	10	5	24	13	8	0
	θ	16	5	6	21	9	14	1
	s	4	5	4	18	5	36	0

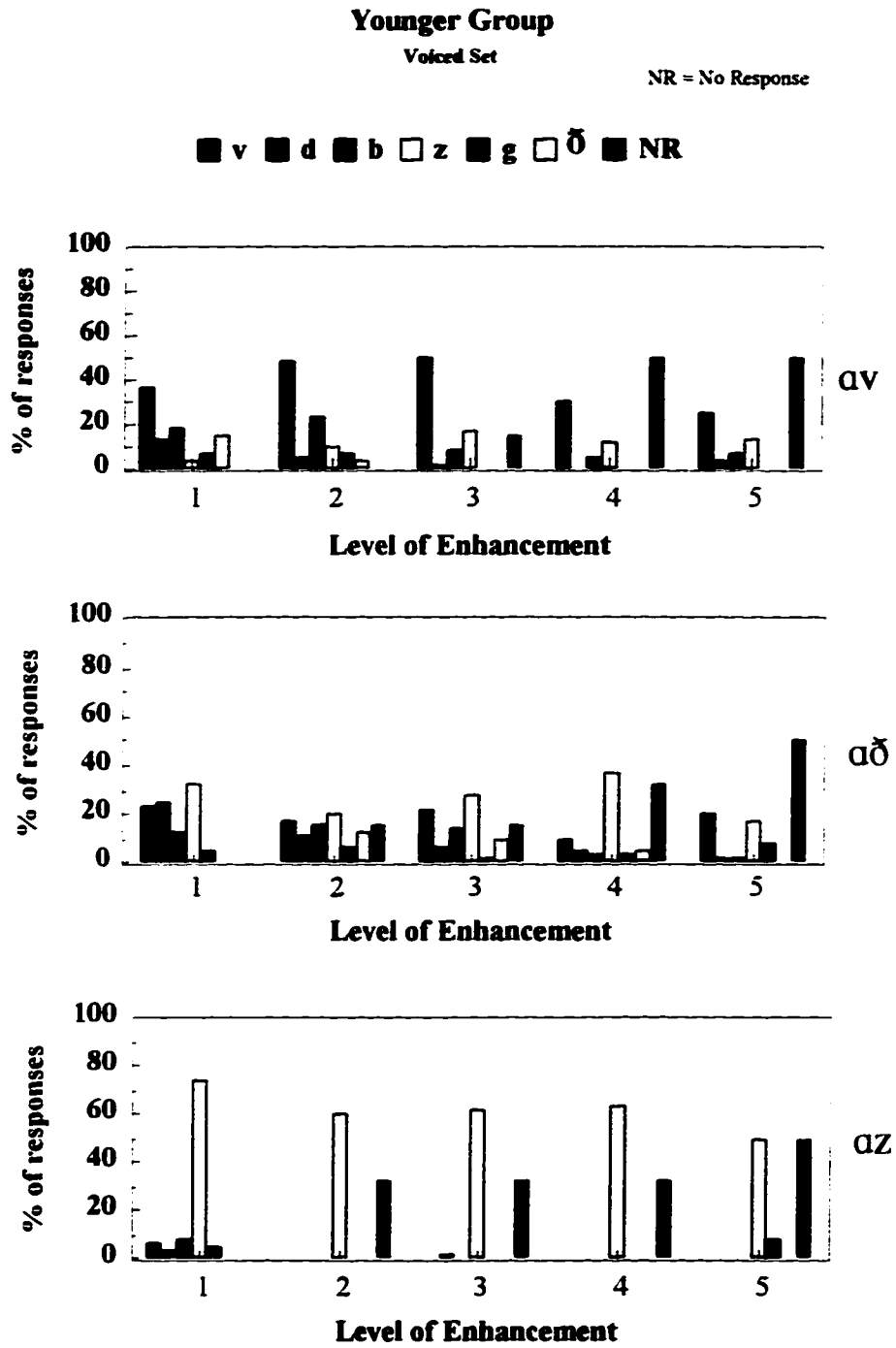
NR = No Response

The confusion matrix for voiceless consonants at CEmax for subjects 8-9 years of age:

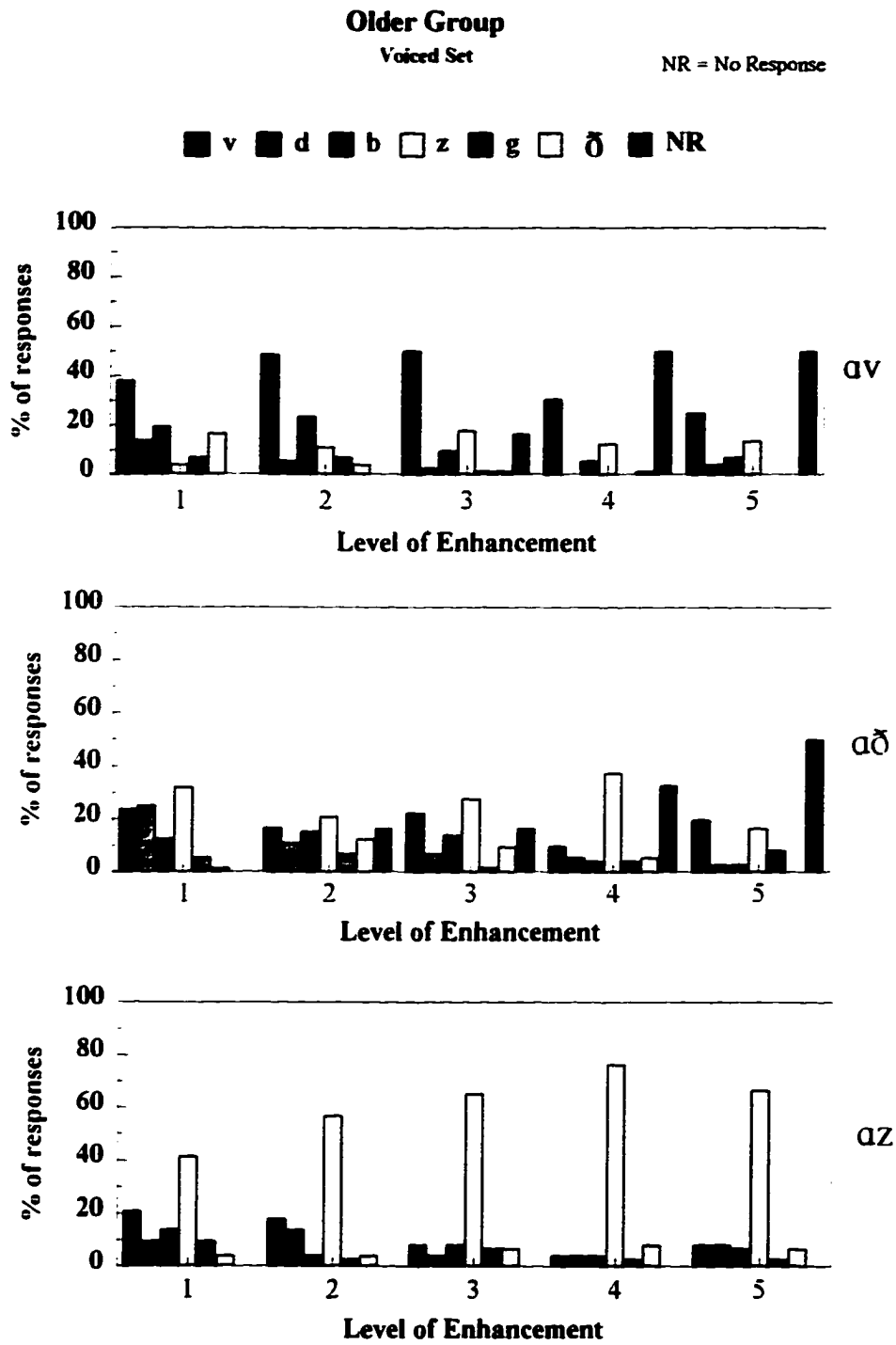
		Response						
		p	t	k	f	θ	s	NR
Target	p	30	18	6	7	7	4	0
	t	12	28	3	5	4	8	12
	k	14	2	25	4	1	2	24
	f	6	7	4	30	5	20	0
	θ	5	2	7	22	16	20	0
	s	0	2	2	1	2	65	0

NR = No Response

Consonant confusions of the voiced fricative consonants /v/, /ð/ and /z/ can be seen in Figure 17 for the younger children and in Figure 18 for the older children. For the voiced fricatives, /v/, /ð/, and /z/, both the younger and older groups of children showed similar consonant confusion patterns in that the consonant /ð/ was frequently confused with /v/ and /z/ for both age groups, although there were significant differences in the percent correct score between the two age groups. Presentations of /ð/ produced the fewest correct responses at any level of enhancement. The most common confusion for /v/ at 0dB enhancement was /b/; at CEmax it was /z/. For /ð/ essentially the same set of confusions, either /v/, /d/, /b/, or /z/ for /ð/ was observed at both 0dB enhancement and CEmax. The younger group, however, showed a higher rate of confusing /z/ for /ð/. The percentage correct score for /z/ was high for both groups of children resulting in relatively few confusions for this consonant. The few consonant confusions that were obtained appear to be randomly distributed occurring primarily at 0dB enhancement. The older group of children also showed more confusions for /z/ than the younger group.

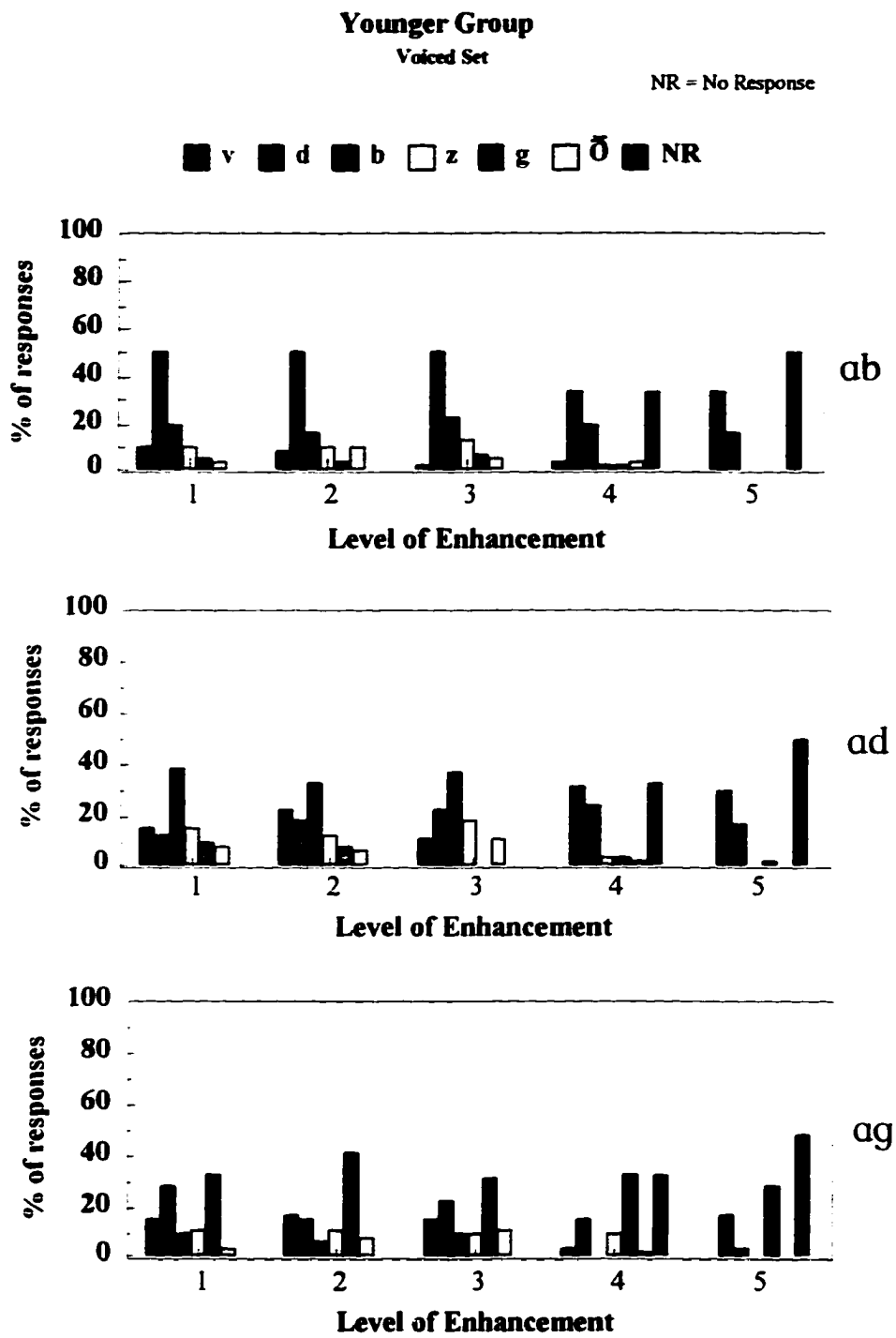


**Figure 17. Younger Group - Voiced Fricatives**

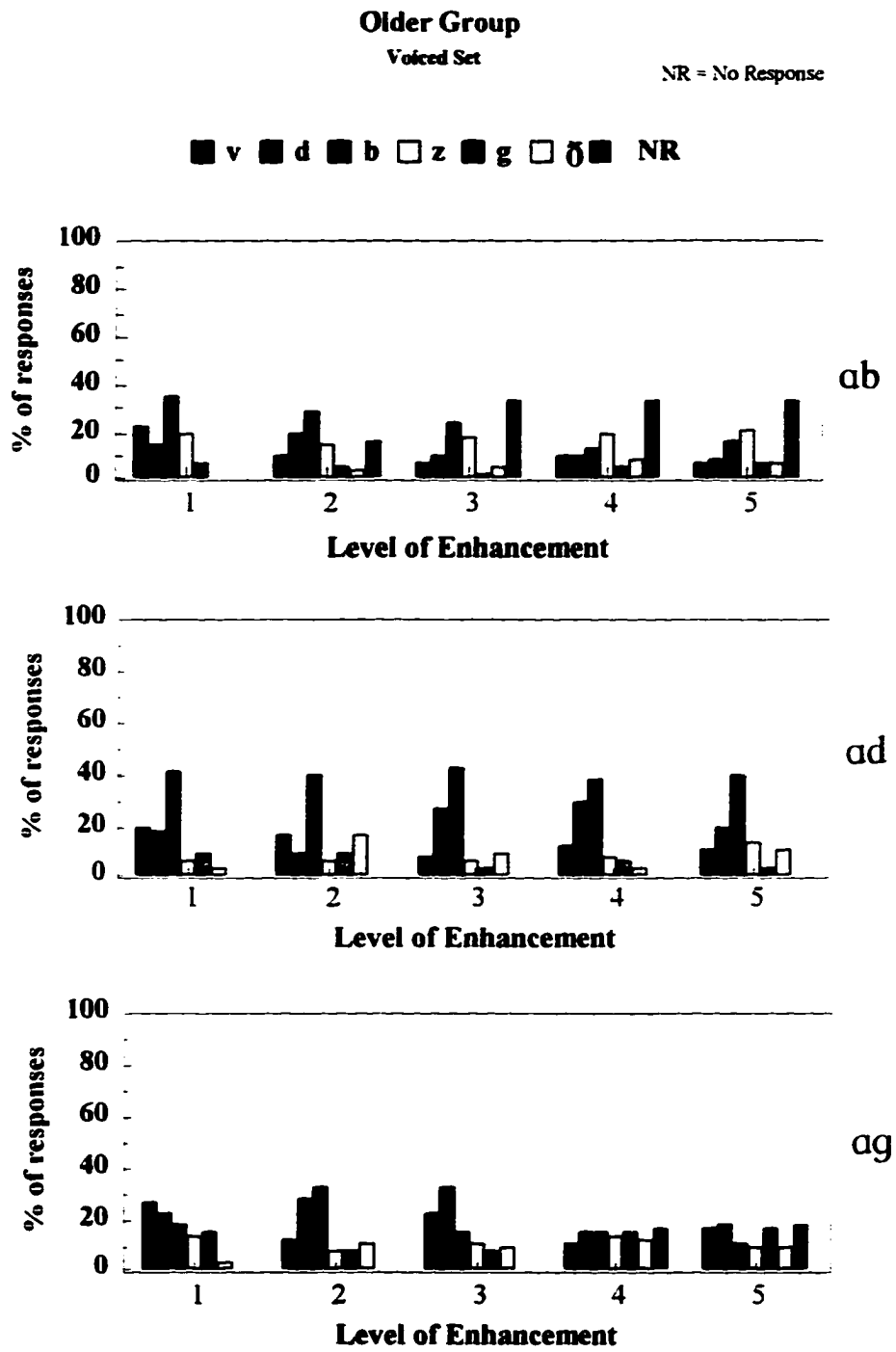


**Figure 18. Older Group - Voiced Fricatives**

Consonant confusions of the voiced stop consonants /b/, /d/, and /g/ can be seen in Figure 19 for the younger children and Figure 20 for the older children. The two groups of children showed different consonant confusion patterns. The younger children consistently made the error of responding with /d/ for /b/. The older children correctly responded to /b/ most of the time except at the higher levels of consonant enhancement when the children incorrectly responded with /z/. Similarly, the younger group more often responded with /b/ for /d/ except at the higher levels of consonant enhancement when they increased their percent correct recognition for /d/. In contrast, the older children most often responded with /b/ for presentations of /d/ at all levels of consonant enhancement. For both groups of children, /g/ was most often confused with /d/. Correct responses increased at higher levels of consonant enhancement.



**Figure 19. Younger Group - Voiced Stops**

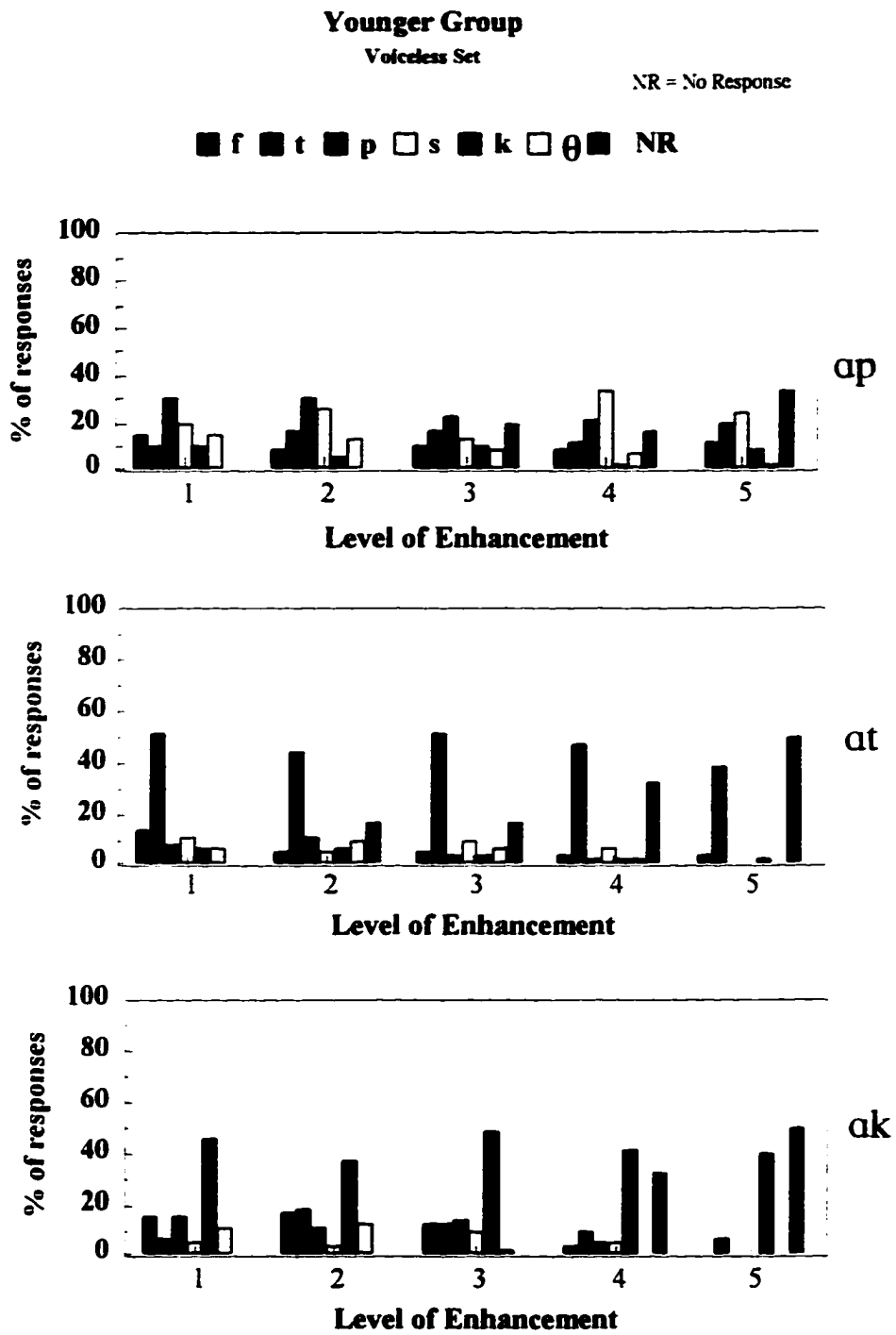


**Figure 20. Older Group - Voiced Stops**

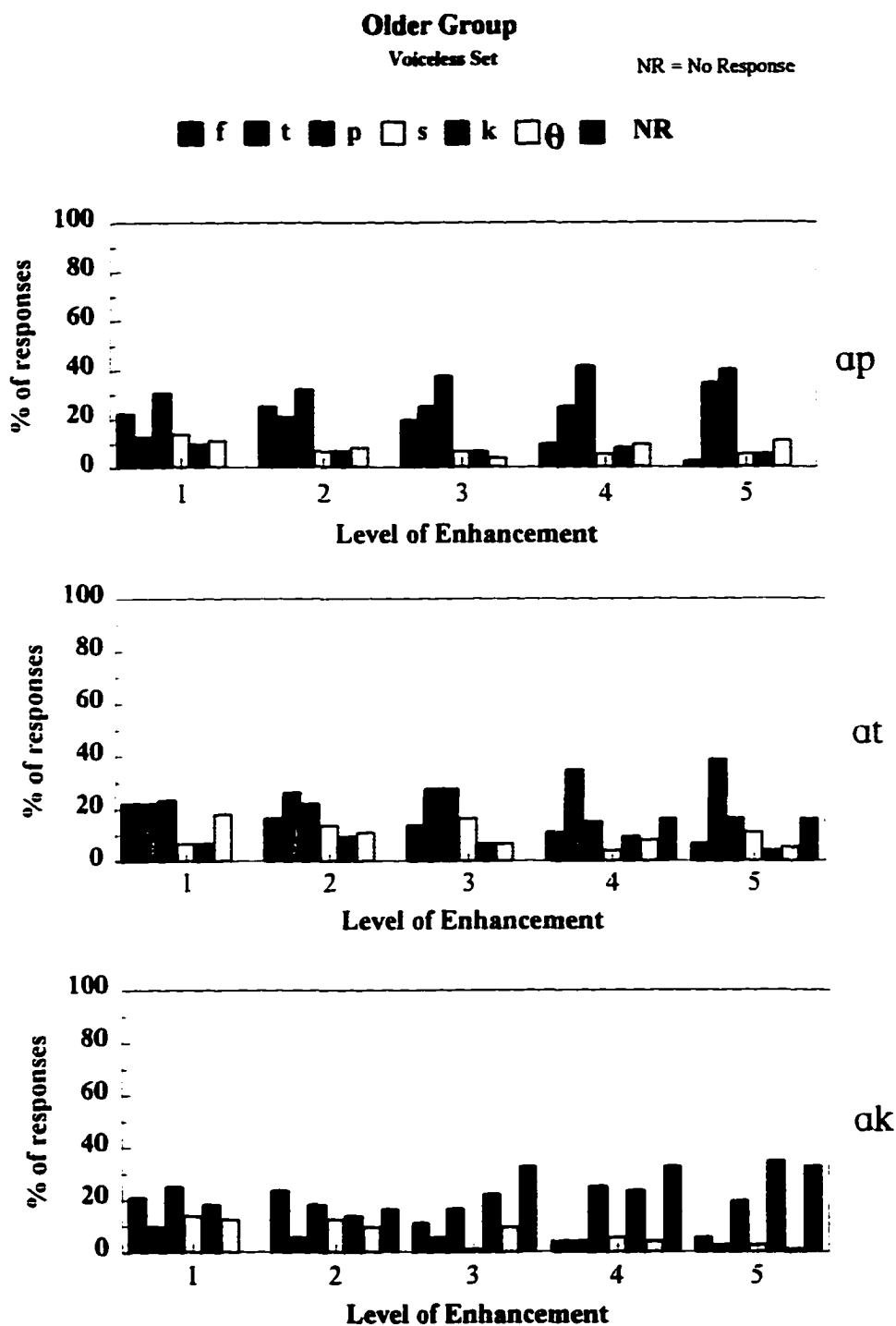
Consonant confusions of the voiceless stop consonants /p/, /t/, and /k/ can be seen in Figure 21 for the younger children and in Figure 22 for the older children. The pattern of consonant confusions differed between the two age groups in several respects. One striking difference was that the younger children correctly chose /t/ with high frequency. In contrast, the older group of children showed substantially more confusions when /t/ was presented. For these children, the most frequent confusion for /t/ was /p/ and it was only at the two highest levels of consonant enhancement that the percent correct score for //t/ exceeded the frequency of /p/ confusions.

Both groups of children showed high error rates for /p/. For the younger children, /s/ was the most common confusion. For the older children, /t/ was the most common confusion.

Another marked difference in the consonant confusion pattern was that the younger children showed relatively few consonant confusions for /k/. Further, the frequency of these consonant confusions decrease with an increasing consonant enhancement except for the /t/ confusion which showed a small but almost constant error frequency with consonant enhancement. In contrast, the older children showed a relatively high rate of consonant confusions for /k/. The frequency of these confusions was particularly high at low enhancement levels, but even at CEmax there was a high rate (19%) of /p/ confusions for /k/.

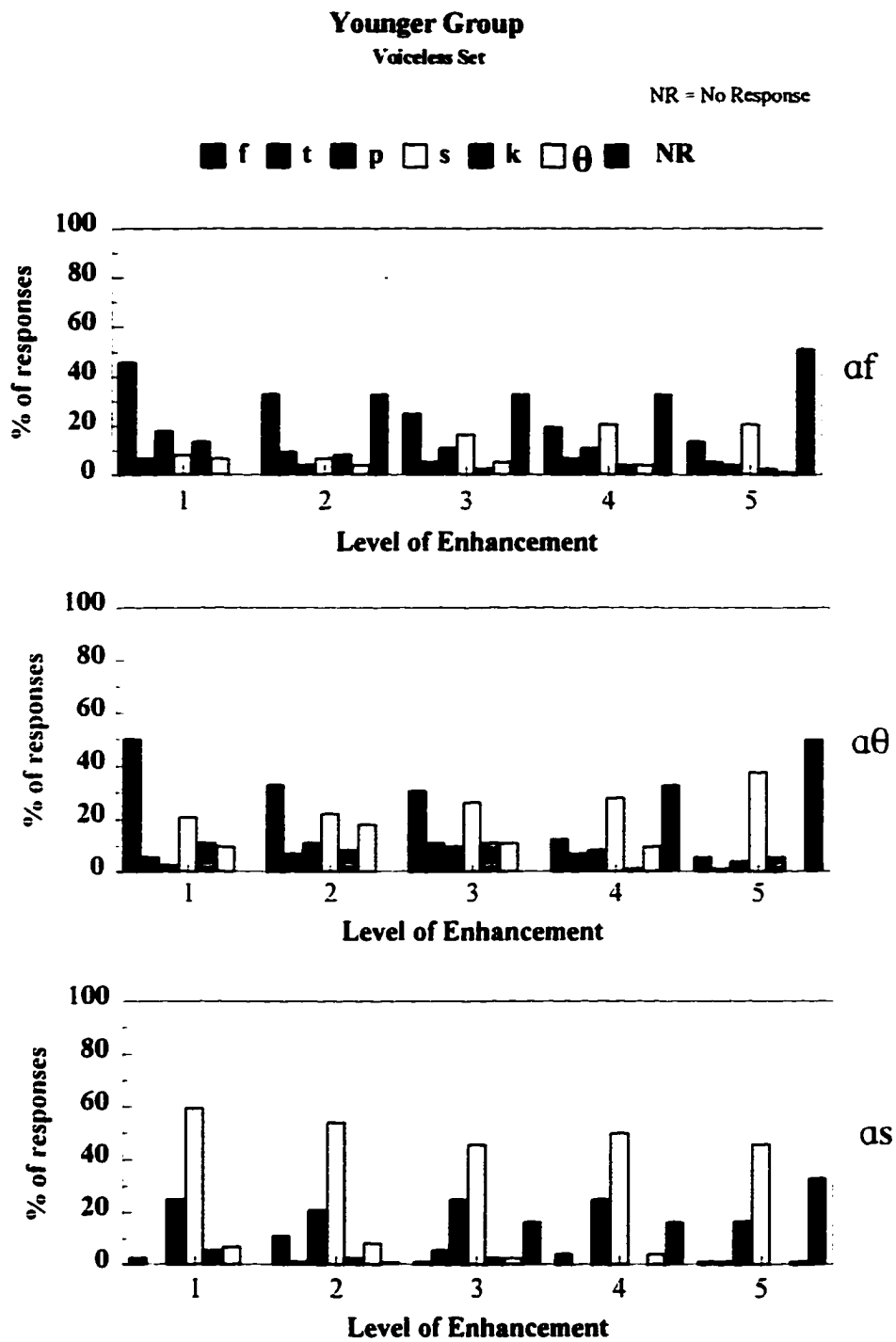


**Figure 21. Younger Group - Voiceless Stops**

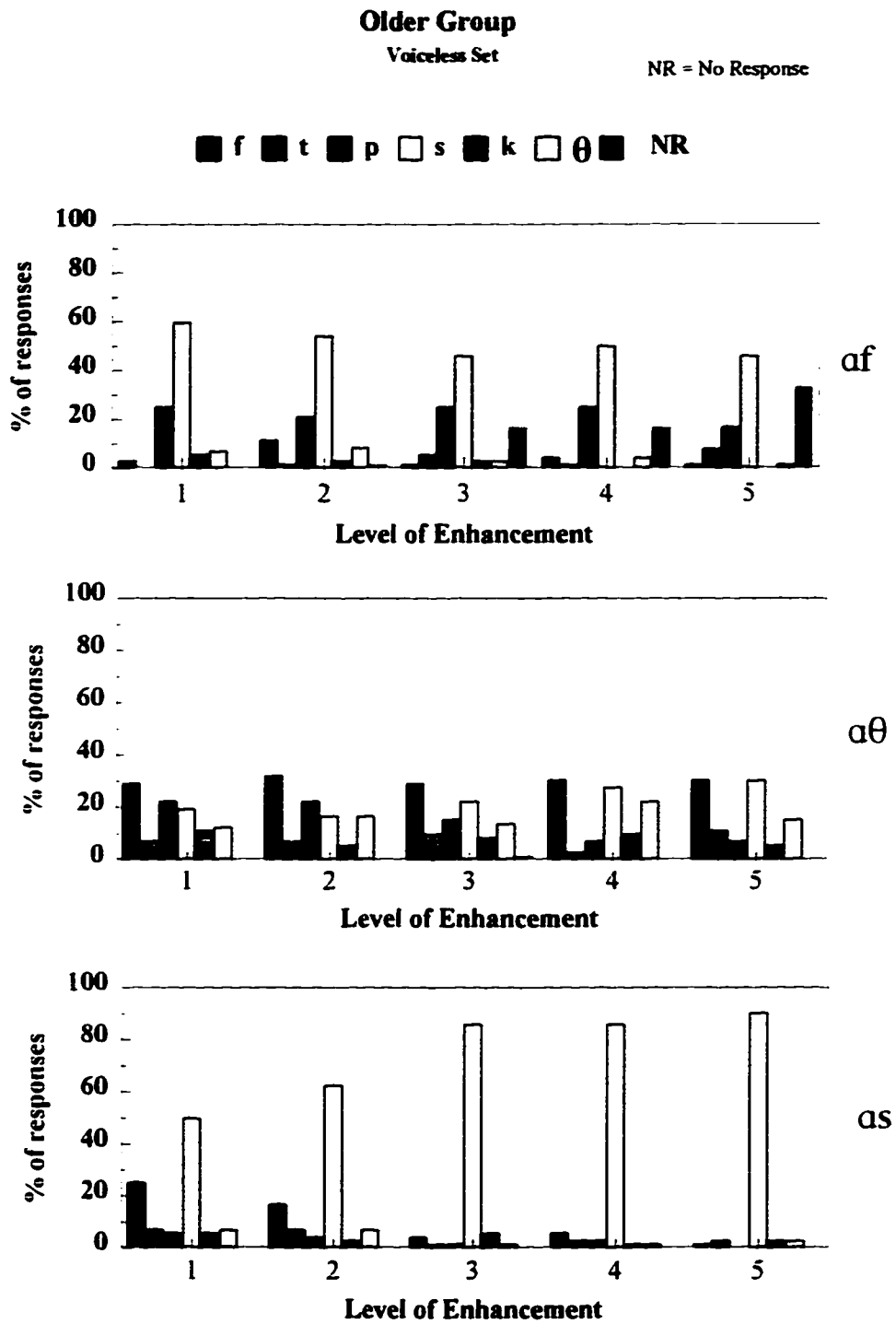


**Figure 22. Older Group - Voiceless Stops**

For the voiceless fricatives, the consonant confusion pattern was similar for the two groups of children. Consonant confusions of voiceless fricatives can be seen in Figure 23 for the younger children and in Figure 24 for the older children. The most frequent confusions were /s/ for /f/ and /s/ for /θ/ occurring at the higher levels of consonant enhancement. At the lower levels of enhancement, /f/ was frequently mistaken for /θ/. When /s/ was the target, both groups of children identified /s/ correctly most of the time at all levels of enhancement. The older children did better at the higher levels of enhancement showing a negligible frequency of confusion at CEmax. The younger children showed only a small reduction in consonant confusions for /s/ with consonant enhancement. These children often confused /p/ with /s/ and this frequency of confusion did not change significantly at different levels of enhancement.



**Figure 23. Younger Group - Voiceless Fricatives**



**Figure 24. Older Group - Voiceless Fricatives**

### **Comparison with Adult Data**

How do these results compare with adult norms found by Kennedy (1994)? In Kennedy's data, the greatest improvement for the voiced set was shown for /z/ followed by /v/. In this study, the children also showed the greatest improvement for /z/ in the voiced set, /d/ and /v/ showing the next largest improvement. Enhancement of the voiced fricative /ð/ yielded the smallest improvement for the adults and no improvement for the children.

For the voiceless set, the greatest improvement for Kennedy's adult subjects was found for /s/ and the next highest improvement was for /t/ and /f/. The children showed a similar result in that the voiceless fricative /s/ yielded the greatest improvement followed by /k/ and /t/. The adults exhibited no improvement in recognition of /θ/, but the children showed a 16% improvement of this consonant. On the other hand, the adults showed a large improvement in recognition of /f/ at CEmax while consonant enhancement of /f/ yielded the least improvement in the voiceless set for children.

## **CHAPTER V. DISCUSSION**

The purpose of this investigation was to determine the effect of increasing the consonant amplitude (i.e., consonant enhancement) on the recognition of these sounds by hearing impaired children. Should improved recognition be obtained it is of interest to determine the magnitude of this improvement, and whether there are measurable age effects for the age range studied. A secondary interest was the effect of consonant enhancement on the pattern of consonant confusions in hearing-impaired children.

The following were of interest: a) the shape of the consonant enhancement (CE) function, b) consonant recognition for the unenhanced condition c) consonant recognition at CEmax, the consonant enhancement needed for maximum score, d) the difference between the unenhanced condition and the CEmax, e) the enhancement levels (in dB) needed for maximum consonant recognition, and f) the way in which the pattern of consonant confusions changed with level of enhancement.

Almost all of the CE functions (133 out of 144) could be categorized into one of four groups: Rising/Peak, Rising/No Peak, No Change, and Falling. Both the Rising/Peak and Rising/No Peak configurations indicate that improved consonant recognition is possible with an appropriate amount of consonant enhancement. The Rising/No Peak category of CE functions indicate that even greater improvements in consonant recognition might be possible if greater levels of enhancement could be tolerated.

The Rising/Peak category of CE functions constituted 11% of the total number of such functions. All of the Rising/Peak CE functions were obtained with subjects having a relatively large (>12 dB) dynamic range. The Rising/No Peak category of shapes constituted 13 % of the total number of CE functions. In the Rising/No Peak category 72.2% of the CE functions represent subjects with relatively wide dynamic ranges and 27.7% represent subjects with narrow dynamic ranges. These data indicate that in about 1 in 4 cases (11% and 13%) it is possible to improve consonant recognition by this means of consonant enhancement. The magnitude of this improvement will be discussed shortly.

A CE function classified as No Change indicates no significant change from the unenhanced level to the maximum level of enhancement. The No Change classification of shapes represented the highest percentage of CE functions at 62% of all the CE functions. In the No Change category 66.3% of the curves represent subjects with dynamic ranges of 15 dB or larger while 33.7% of the curves were based on responses from subjects with narrower dynamic ranges.

A Falling CE function signifies a decrease in performance as a result of consonant enhancement. The Falling category of curves constituted 12% of the total of the CE functions. In this category, 76.5% of the curves represent subjects with wide dynamic ranges, while 23.5% represent subjects with narrow dynamic ranges. The older children had wider dynamic ranges than the younger children and as a consequence the older children showed more improvement in consonant recognition than the younger children.

The CE function showing an improvement in consonant recognition (i.e., the Rising/Peak and Rising/No Peak configurations) occurred most frequently with the

voiceless consonants except for /f/ and /t/ which showed small improvements. There were relatively few Rising/Peak or Rising/No Peak CE functions for the voiced consonants. The few rising CE functions that were observed for the voiced consonants occurred primarily with the consonants /z/ and /d/.

In order to discuss the effects of consonant enhancement on the different consonants it is necessary to review briefly the results obtained for the unenhanced condition which serves as the baseline for this investigation. The analysis of variance for the unenhanced condition showed a significant effect for the factor Cognate Pairs. Of the six cognate pairs considered in this study, the strong fricatives /z/ and /s/ showed the highest score and the weak fricatives /ð/ and /θ/ showed the lowest score. The use of Cognate Pairs as a factor allowed for a relatively sensitive test (i.e., in a balanced factorial design) for the effect of voicing which turned out to be not statistically significant, indicating that the scores for the members of each cognate pair did not differ significantly from each other. This is evident from a comparison of the ordering of correct scores in Figures 7 and 8.

The post-hoc analysis also showed that the cognate pairs could be divided into three groups:

1. the highest scoring group consisting primarily of the acoustically powerful fricatives /s/ and /z/; the fricatives /v/ and /f/ and the relatively strong stop consonants /b/ and /p/.
2. the lowest scoring group consisting primarily of the acoustically weak fricatives /ð/ and /θ/; the relatively weak stops /g/ and /k/ also fell in this group.
3. an intermediate scoring group consisting of all six stop consonants, as well as the moderately powerful fricatives /f/ and /v/.

Note that membership in a group does not preclude membership in any other group; i.e., the groups are not mutually exclusive.

The above results show a consistent pattern in which test scores and post-hoc groupings are related to the relative acoustic power of individual consonants.

A second analysis of variance was performed on the consonant recognition scores at CEmax, the condition yielding the highest test score. As in the analysis for the unenhanced condition, Cognate Pairs was a significant factor. In this case there was also a significant Cognate Pair by Voicing interaction. This implied that test scores for individual consonants differed from that for cognate pairs. This interaction, however, was relatively small and the consonants showing the highest score, /z/ and /s/, were also the highest scoring cognate pair. Similarly, the consonants showing the lowest score, /ð/ and /θ/ were also the lowest scoring cognate pair. One of the differences between the unenhanced condition and the CEmax condition is that the post-hoc analysis shows less overlap between the three groups (A, B and C) for the later condition compared to these groups for the unenhanced condition.

Note that statistical analyses used the transformed arc sine values ( $Y_0$  and  $Y_{max}$ ), the results have been transformed back to percent correct scores and are shown as such in the figures.

A third analysis of variance was performed based on the difference in test scores (in arc sine units) at CEmax and the unenhanced condition (i.e.,  $Y_{max} - Y_0$ ). It is important that the improvement in performance from the unenhanced level to the maximum score level is specified as  $Y_{max} - Y_0$  and not  $P_{max} - P_0$  which can be

easily misinterpreted. For example, if  $P_o = 5\%$  and  $P_{max} = 15\%$  then  $P_{max} - P_o = 10$  percentage points. However, if  $P_o$  is  $50\%$  and  $P_{max}$  is  $60\%$ ,  $P_{max} - P_o$  is also equal to 10 percentage points. In the first case,  $P_{max}$  is 3 times  $P_o$  but in the second case  $P_{max}$  is only 1.2 times greater than  $P_o$ , which in practical terms, is a relatively small improvement. Further, the error variance in estimating  $P_o$  and  $P_{max}$  in the first case is quite small, whereas it is relatively large when  $P_o$  and  $P_{max}$  are in the 50% to 60% region.

The arc sine transformation takes care of both of the above problems. For the case when  $P_o=5\%$  and  $P_{max}=15\%$ , the corresponding values of  $Y_o$  and  $Y_{max}$  are 0.45 and 0.80, respectively, yielding an improvement of 0.35 arc sine units. For the case of  $P_o=50\%$  and  $P_{max}=60\%$ , the corresponding values of  $Y_o$  and  $Y_{max}$  are 1.57 and 1.77, respectively, yielding an improvement of 0.20 arc sine units, which is a much smaller improvement. The error variance of the measured improvements is  $1/(2n)$  arc sine units in both cases, where  $n$  is the number of trials in estimating each percentage.

The results of this analysis of variance showed that the factor of Cognate Pairs was significant at the .01 level. The recognition of the cognate pair /z-s/ improved most from the unenhanced to the maximum score level of enhancement. The cognate pair /ð-θ/ showed the least improvement. When examining improvement of individual phonemes /z/ closely followed by /s/ showed the greatest improvement. The least amount of improvement in recognition occurred with /ð/. However, its voiceless cognate, /θ/, showed a significant improvement. As in the preceding analysis, there was evidence of a Cognate Pairs by Voicing interaction and, as a consequence, test scores for individual members of a cognate pair were

not always similar, as is evident from Figures 11 and 12. Further, the voiceless consonants showed larger improvements, on average, than their voiced cognates.

The fourth and final analysis of variance was performed on the consonant enhancement needed to achieve maximum score (i.e., CEmax). As before, Cognate Pairs was found to be a significant factor. This was the only analysis that found Age to be significant. The significant age effect appears to be a result of the difference between the dynamic ranges of the younger and older groups of children. The younger children in this investigation had narrower dynamic ranges than the older children and as a consequence CEmax was limited to a narrower range.

The greatest amount of enhancement for the younger group was approximately 13 dB, on average, for the Cognate Pair /z-s/. The older group needed approximately 10 dB gain, on average, to achieve the best score for the Cognate Pair /z-s/. Although the older group tolerated higher intensity levels they needed approximately 3 dB less gain to achieve maximum scores than the younger group. Similarly, the younger group's next highest amount of consonant enhancement to achieve the maximum score was approximately 10 dB, on average, for the Cognate Pair /d-t/. The older group needed approximately 6 dB, on average, to achieve maximum score for /d-t/.

The Cognate Pair /ð-θ/ required the least amount of consonant enhancement to achieve maximum scores in both groups of children. The younger group needed approximately 4 dB gain, on average, and the older group needed approximately 5 dB gain, on average, to obtain their best scores for /ð-θ/. However, enhancement of this cognate pair resulted in the smallest improvement in consonant recognition.

When analyzed individually, /ð/ showed little or no improvement, but the voiceless counterpart, /θ/ showed some improvement with consonant enhancement, requiring approximately 9 dB of gain on average. The voiced fricative /ð/ thus brought down the average improvement for this cognate pair. A comparison of Figures 15 and 16 shows that this was the only Cognate Pair for which the component consonants did not have essentially the same scores (in this case, consonant enhancement levels).

It is important to bear in mind that only 12 severely hearing impaired children participated in this study. Because of this small sample size any generalization of the results to all hearing-impaired children must be made with caution. For example, the data reported in this study are for severely hearing-impaired children receiving an aural/oral education. Children with moderate hearing impairment may show different results. Since the findings obtained with those severely hearing-impaired children are roughly similar to those obtained by Kennedy with moderately hearing impaired adults it is likely that moderately hearing impaired children will also show similar results.

A more subtle issue was the significant Age effect observed in this study. Although a repeated measures analysis of variance was used showing a significant Age effect, this result is believed to be a consequence of the difference in dynamic range between the younger and older children and may not reflect age per se. That is, the observed Age effect may be a result of the older children being more accustomed to the use of hearing aids. As a consequence, the older children may have shown a wider dynamic range because they were more accustomed to a the high speech levels and hence an Age effect.

## **Comparisons with Previous Research**

The data for the unenhanced condition in the present investigation represents a link with other published data as well as providing a baseline for evaluating improvements in consonant recognition. An analysis of the consonantal substitutions made by the children showed a high proportion of place substitutions, but relatively few manner errors. This finding is consistent with other studies on consonant perception by hearing impaired individuals.

Erber (1972) found that children with sensorineural hearing loss of 70 dB to 95 dB had difficulty with the auditory perception of place of articulation but not of manner or voicing. Boothroyd (1984) found that children with sensorineural hearing loss no greater than 75 dB are able to perceive consonant place, and initial consonant voicing and manner. Similar results have been obtained with hearing-impaired adults. Bilger and Wang (1976) examined the kinds of consonant confusions made by individuals with sensorineural hearing loss as it related to audiometric configuration. All of the consonant phonemes of English were studied using both CV and VC syllables in a 16 alternative forced-choice response task. The syllables were presented at approximately 40 dB above subject SRT. They found that intersubject similarities in patterns of perceptual confusion were systematically related to the subjects' audiometric configurations. For example, listeners with high frequency hearing loss had difficulty with sibilant consonants.

Sher and Owens (1974) examined consonant confusions associated with hearing loss above 2000 Hz. Thirty-five listeners with hearing loss greater than 2000 Hz and 28 hearing listeners tested under filtering to simulate high frequency hearing

loss showed similar consonant confusions. Overall scores indicated difficulty in phonemic identifications. Position in the syllable was significant. Phonemes substituted in the initial position were the same in manner of articulation as the stimuli. Pickett, Revoile, and Danaher (1983) found similar results, that is, consonants with the same manner of articulation are most easily confused.

The study by Kennedy (1994) is particularly relevant to the current study because the same set of stimuli and similar methodology were used. As in the current study, Kennedy also showed the factor of Cognate Pairs to be highly significant with the highest scores being obtained with the strong fricatives /s/ and /z/ and the lowest scores with the weak fricatives /θ/ and /ð/.

For the voiceless consonants, both adults and children showed the greatest improvement in recognition of the fricative /s/. The adults showed an average improvement of .85 arc sine units whereas the children showed a slightly smaller improvement of .72 arc sine units. The second highest improvement for the adults reported by Kennedy for a voiceless consonant was .7 arc sine units for the voiceless stop consonant /t/. The second highest average improvement for the children in this study, for a voiceless consonant was .46 arc sine units for /k/ followed closely by /t/ at .40 arc sine units. The adults showed a similar average improvement for /k/ at .40 arc sine units. The voiceless consonant showing the smallest improvement was /f/ for the children and /θ/ for the adults. These 2 consonants have a similar acoustic structure and are frequently confused with each other by both adults and children. The adults typically reported hearing /f/ for either /f/ or /θ/. Whereas the children typically reported hearing /θ/ for either /f/ or /θ/. For both adults and children the smallest improvements were obtained with the weak /ð/.

For voiced consonants, both the adults and the children showed the greatest improvement with amplitude enhancement of /z/ approximately .8 arc sine units. The adults showed more of an improvement with /v/ and /g/ than the children, while the children showed a greater improvement than the adults with /d/.

Another area of interest was the way in which the pattern of consonant confusions changed with level of enhancement. Both the children in the current study and the adults in Kennedy's study confused /θ/ with /f/ and /ð/ with /v/ at essentially the same rate for the unenhanced and enhanced conditions. Similarly, both adults and the older children confused /p/ with the other voiceless stops in the unenhanced condition. The older children frequently confused /p/ with /t/ and the adults often confused /p/ with /k/ in the unenhanced condition. The younger children confused /p/ for /s/ in the unenhanced condition and at low levels of enhancement. At the level of enhancement that yielded the highest percent correct responses, these confusions decreased.

The older children and the adults confused /f/ for the target /s/ at the unenhanced level and low levels of enhancement. This pattern did not occur with the younger group of children. They substituted /p/ for /s/. At higher levels of enhancement the confusion was not seen by the older children or adults.

The adults confused /s/ for the target /f/ in both unenhanced and enhanced conditions. At the unenhanced level and low to mid range enhancement levels the children often recognized /f/, however, as the amplitude enhancement increased the substitutions of /s/ for the target /f/ increased as well for both groups of children.

The difference between the Kennedy study with moderately hearing-impaired adults and the current study with severely hearing-impaired children can be summarized as follows. Both adults and children showed similar effects of consonant enhancement for the fricatives. The major difference between adults and children involved the stop consonants both in terms of the order and the manner of improvement. The pattern of confusions was also similar for both the adults and the children for fricatives but not for stop consonants. Differences in the patterns of confusions for the stop consonants were also observed between the 2 groups of children.

It is also of interest to compare the results of the present investigation with those of Neuman (1982). She investigated the effect of reverberation on the consonant discrimination of hearing children using similar test material (nonsense disyllables). The results showed that children made more errors than adults although children over 9 years made the same type of errors as the adults. Similarly, the older hearing-impaired children in the present investigation and the hearing-impaired adults in the Kennedy (1994) made similar errors. These similarities in consonant confusions suggest that the older children may perform more like adults.

Insight into the reason for improvement in recognition for /z-s/ with amplitude enhancement may be found in the early findings of Harris (1958). She found that adult listeners identified syllable-initial /z/ and /s/ based on the spectral characteristics of the friction or noise. Perhaps, the increased intensity level of the friction portion of /z/ and /s/ in the present investigation and in Kennedy's investigation (1994) investigation provided the hearing-impaired listeners a noise cue for identification of /z/ and /s/. Harris found identification of /v/ and /f/ less

dependent on a noise cue. Her hearing adult listeners based judgments for /v/ and /f/ largely on the vocalic portion of the stimuli. In the present study, the pattern of consonant confusion indicates that increased intensity of the frication portion of /af/ produced an increase in /as/ responses for children of both age groups.

This study as well as that of Kennedy (1994), differed from previous studies involving adjustment of consonant vowel ratio in that previous studies did not attempt to optimize the CVR individually for each subject. Montgomery and Edge (1988) and Gordon-Salant (1987) used the same adjustments in CVR for all subjects. As a consequence the improvement in consonant recognition obtained in this study and in Kennedy (1994) are greater than reported previously. Montgomery and Edge (1988) found improvements of approximately 10.5% in consonant recognition among their hearing-impaired listeners. Gordon-Salant (1987) reported 5 - 15% improvement in consonant recognition with consonant enhancement in the region of 75 dB SPL. The subjects in both of these investigations had generally mild/moderate sensorineural hearing loss. In this study the average improvement was approximately 15% for severely hearing impaired children, while that obtained by Kennedy was approximately 20%.

Revoile, et al. (1987) investigated consonant enhancement with severe to profoundly hearing-impaired individuals at the most comfortable listening level. By increasing the consonant amplitude approximately 21 dB above the neighboring vowel, they found improvement for the voicing distinction between the fricatives /v, f/ and /z, s/.

In summary, the results of the present investigation compare most closely with Kennedy (1994). The same methodology and stimuli were used. The children in

the present study showed patterns of improvement similar to Kennedy's adults, although the magnitude of the improvements were not as large as Kennedy's. Both adults and children in the present study showed the largest improvements for the strong fricatives /z/ and /s/, and the least improvements for the weak fricatives /ð/ and /θ/. The pattern of consonant confusions was similar for both the adults and the children for the fricatives with only gross similarities in the pattern of confusions for the stop consonants. A common consonant confusion made by both groups was the identification of /s/ for the target /f/ especially at high intensity levels of presentation. Another frequent confusion for both groups occurred with the identification of /f/ or /s/ as /θ/.

### **Implications for Acoustic Amplification**

Consonant enhancement can improve recognition of certain consonants for hearing-impaired children from 5 - 9 years of age. In order to implement consonant enhancement in the form of personal amplification, several factors must be considered.

First, individual differences must be considered because intersubject variability was significant throughout this investigation. Although there was no age effect on improvement of recognition of consonants, the decibel level needed to achieve maximum scores was significantly different between the younger children and the older children. The younger children, in general, had narrower dynamic ranges than the older children.

Second, recognition of enhanced consonants in this investigation is based on twelve consonants but only one vowel environment. Separate consonant

enhancement functions would be needed for every vowel environment for each hearing-impaired individual in order to know the conditions for maximizing consonant recognition.

Third, improvement in consonant recognition of enhanced consonants was selective in this investigation. Amplitude enhancement of voiceless consonants, in general, yielded greater improvement in recognition than voiced consonants. The strong fricatives, /z/ and /s/, were more likely to yield improvement in recognition than the weak fricatives, /v/ and /f/. Recognition of lingual-dental fricatives, /ð/ and /θ/, showed little improvement, if any, from consonant enhancement. Any attempt to implement these findings must take into consideration the large individual differences that were obtained in terms of the enhancement needed for each subject for the various consonants.

A signal processing strategy that provides a fixed consonant enhancement for a range of phonetic environments, rather than attempting to optimize consonant enhancement for each consonant in every phonetic environment may be a practical possibility. Those consonants that had CE functions of the form of Rise/No Peak are most likely to benefit from this type of processing since the amount of enhancement needed to provide improved recognition can be as large as possible without causing discomfort. High gain without discomfort can be implemented by means of compression limiting, i.e., weak sounds requiring substantial enhancement will receive high gain whereas strong sounds requiring less enhancement will receive less gain, both types of sounds receiving the maximum gain permissible.

The children in this investigation demonstrated fewer Rise/No Peak CE functions than the adults in Kennedy (1994) indicating that this type of algorithm would probably be of less benefit to children than adults. The relatively high frequency of No Change or Falling CE functions in children compounds the difficulty in developing such an algorithm. The algorithm would need to bypass consonants that do not benefit from enhancement. Methods of implementing a practical algorithm that could improve CVRs in everyday speech are currently being investigated by Preves, Fortune, Woodruff, and Newton (1991).

### **Conclusions**

This investigation has shown that consonant enhancement, as implemented in this study, improves recognition for certain types of consonants. The consonants /z/ and /s/ benefited most from enhancement. The consonant showing the least improvement was /ð/. Large individual differences were observed making it difficult to implement these findings in a practical hearing aid. Care should be taken not to generalize these results in that twelve consonants in only one vowel environment were studied.

Age was not found to be a significant factor in terms of improvement in consonant recognition by means of consonant enhancement for the severely hearing-impaired children in this study although adults with less hearing impairment showed greater improvement with consonant enhancement as reported by Kennedy (1994). An age effect was observed with respect to the enhancement levels (in dB) needed to achieve maximum scores. This effect is believed to be due to smaller dynamic ranges observed for the younger children participating in this study.

### **Suggestions for Future Research**

Similar investigations should be done using a larger group of consonants in a wider range of vowel environments. This would provide more information regarding the benefits of consonant enhancement.

Further study is needed concerning comfortable listening and unacceptably loud levels in young children. Information of this nature could greatly improve hearing aid fittings in this population.

There is a need for more research regarding speech perception of hearing-impaired children in order to develop algorithms for the new age of digital signal processing hearing aids. Although evidence exists indicating auditory processing differences between children and adults, it remains unclear as to how children process speech. Age-related differences in auditory sensitivity do not entirely account for age-related differences in perceptual weighting strategies, according to Nittrouer (1996). Furthermore, most speech perception studies involve hearing children. There is a need to investigate speech processing differences between hearing and hearing-impaired children using speech stimuli.

This investigation used isolated speech stimuli by a single talker with portions of the signal enhanced. Studies are needed to determine if similar benefits of consonant enhancement can be obtained in everyday speech by different talkers. It is unclear as to whether or not similar benefits of consonant enhancement would be present in an ongoing stream of speech or with a different talker.

A need exists for research into the development of nonlinear amplification systems that provide optimum speech information in varying environmental conditions. Consonant enhancement is only one technique among many possibilities that may

be explored further. The selection of hearing aid circuitry is especially important for children who may not be able to provide adequate feedback regarding the acoustic signal. The optimal speech signal is necessary for young hearing-impaired children developing speech and language skills.

**APPENDIX A**  
**Letter of Consent**

Dear Parents.

I am a Ph.D. candidate in Speech and Hearing Science at the City University of New York. My field of interest, speech perception of hearing impaired children, grew from my eight years of teaching in schools and programs for the deaf as well as my most current work as a research associate in speech and hearing aid research at the Lexington Center, Inc., New York.

My dissertation is based on listening experiments with hearing impaired children. The task involves listening to computer generated syllables and repeating them. As the tester I will manipulate the amplitude of the consonant portion of the speech sample. The purpose of this experiment is to determine the optimal consonant amplitude in relation to the vowel. A long term goal of this research is the development of a digital hearing aid that can change the input of speech in such a way that recognition is improved. In other words, this research may be instrumental in the development of a new hearing aid that makes speech more understandable to hearing impaired children.

I need moderately and severely hearing-impaired children to act as subjects in this experiment. There is no danger involved. The task simply involves listening under headphones to syllables and repeating them. Please note that the Graduate School has a committee that safeguards your interests. While the results of this study will be reported at professional meetings and may be published, subject anonymity will be protected. Each child would be seen for approximately twelve 20 minute sessions over the course of the semester. Subjects will be compensated at the rate of \$5.00 an hour. Payment will be received through the mail after the final testing session.

If you have any questions regarding your child's participation as an experimental subject, please feel free to contact Harry Levitt, Ph.D. at the Graduate School (212) 642-2352 or myself, Lynn Z. Smith, at (908) 449-9784.

**I AGREE TO ALLOW MY CHILD TO PARTICIPATE IN THE EXPERIMENTAL INVESTIGATION DESCRIBED ABOVE. I UNDERSTAND THAT MY CHILD'S PARTICIPATION IS VOLUNTARY AND THAT I MAY WITHDRAW AT ANY TIME WITHOUT PENALTY.**

NAME: \_\_\_\_\_

SIGNATURE: \_\_\_\_\_

**APPENDIX B**

**Finding MCL**

## APPENDIX B

## MOST COMFORTABLE LOUDNESS PROCEDURE:

## 1. LOWER LIMIT

- a. Subjects will be trained in listening for the most comfortable level - lower limit.
- b. Subjects will listen to a tape loop of the carrier phrase, "You will mark" at a subthreshold level. The tester will manipulate the attenuator in increasing steps until the subject reports the speech is comfortable.
- c. Using a voltmeter, the tester will take a measurement of a calibration tone at the final step.
- d. MCL plus 10 dB will serve as the next starting level for the repetition of steps b and c.
- e. The "new" MCL minus 10 dB will serve as the next starting level for the repetition of steps b and c.
- f. An average of the three MCL's will be obtained. The 3 levels may not vary by more than 5 dB. If they do, the lowest MCL will be eliminated and only two MCL's will be averaged. Hit Home when MCL is found.

## 2. UPPER LIMIT

- a. Subjects will be trained in listening for the most comfortable level - upper limit.
- b. Subjects will listen to a tape loop of the carrier phrase, "You will mark", at subthreshold level. The tester will manipulate the attenuator in increasing steps until the subject reports the speech is louder than comfortable.
- c. Using a voltmeter the tester will take a measurement of a calibration tone at the final step increase.
- d. MCL plus 10 dB will serve as the next starting level for the repetition of steps b and c.
- e. The "new" MCL minus 10 dB will serve as the next starting level for the repetition of steps b and c.
- f. An average of the three MCL's will be obtained. The three levels may not vary by more than 5 dB. If they do, the highest level will be eliminated and only two MCL's will be averaged.

### 3. FINAL LEVEL

a. Steps 1 and 2 will be counterbalanced across subjects in each experiment.

b. The mean of the lower limit and the mean of the upper limit will be averaged to determine the final MCL across subjects in each experiment. This level will serve as MCL throughout all further testing. Hit Home when level is reached.

### INSTRUCTIONS FOR MOST COMFORTABLE LEVEL TEST

Look at the pictures of the boy. A little man is talking to him.

Sometimes the man is talking too softly and the boy can't hear him (1).

Sometimes the boy can hear the man a little bit (2). LOWER LEVEL MCL

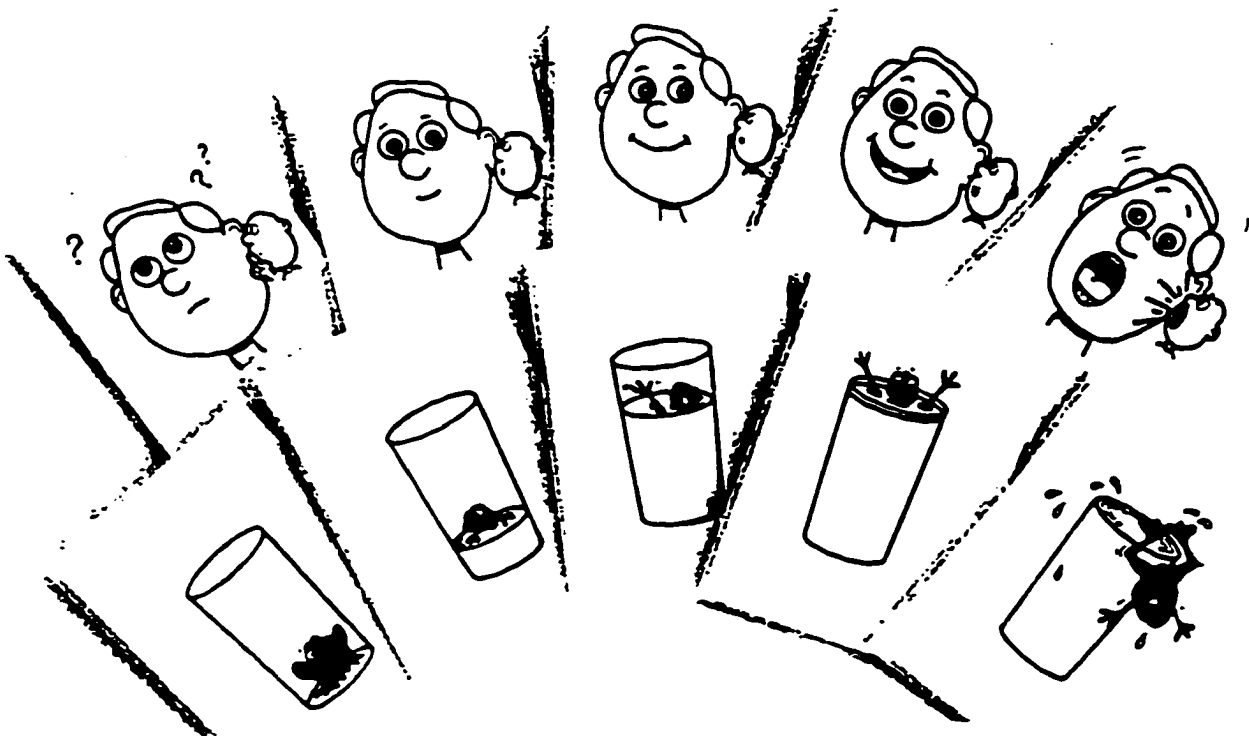
The boy smiles when he hears the man talking. He likes this best (3). MCL

Sometimes the man talks loud. (4). UPPER LEVEL MCL

When the man talks too loud the boy doesn't like it (5).

Listen to the man talking. How does he sound? Too quiet (1)? Too loud (5)? Show me the picture.

(The picture cards are programming materials developed by Cochlear Corporation to teach the concept of loudness and loudness scaling to young hearing impaired children)



**APPENDIX C**

**Finding UCL**

**INSTRUCTIONS FOR LOUDNESS DISCOMFORT LEVEL TEST**

Look at the pictures of the boy. Where is the picture that shows the little man talking too loud?

Now it's your turn to listen to the man talking. If the man is talking too loud push the DOWN arrow. If the man is talking O.K. push the UP arrow.

Are you ready? Push the <HOME> key to start.

(Picture cards are programming materials developed by Cochlear Corporation to teach the concepts of loudness and loudness scaling.)

## APPENDIX C

## UNCOMFORTABLE LOUDNESS PROCEDURE:

1. The instrumentation will be set for MCL.
2. The subject will be trained in loudness discomfort level using the same picture cards that were used for determining most comfortable listening level. During this procedure the subject will be trained to use the keyboard to respond. The <HOME>, <I> and <I> keys will be used to begin, increase and decrease loudness levels respectively.
3. Three tokens of a given VC will be presented at level 1, the unenhanced level or C/V at 0. Three more tokens of the VC will be presented now increased by 3 dB. The subject will respond via the keyboard to increase <I> or decrease <I> the loudness level. Given that the subject will choose to increase the loudness level the token will be increased once again by 3 dB. This procedure will continue until the subject indicates that the level is uncomfortable. The uppermost presentation will be 24 dB above MCL.
4. The enhancement level will be reduced by 6 dB (or 3 dB if UCL is 3 dB level of enhancement). Step 3 will be repeated.
5. Step 4 will be repeated until 3 UCL are chosen at the same level of enhancement.
6. Steps 3, 4 and 5 will be repeated with all consonants in sets 1 and 2 each paired with /a/.

**APPENDIX D****Table 3. Conversion of Raw Data to dB Level of Consonant Enhancement**

### **Table 3. Conversion of raw data to dB level of consonant enhancement**

**(/ap/ used as example)**

ap.0 = no enhancement

ap.1 = 3 dB

ap.2 = 6 dB

ap.3 = 9 dB

ap.4 = 12 dB

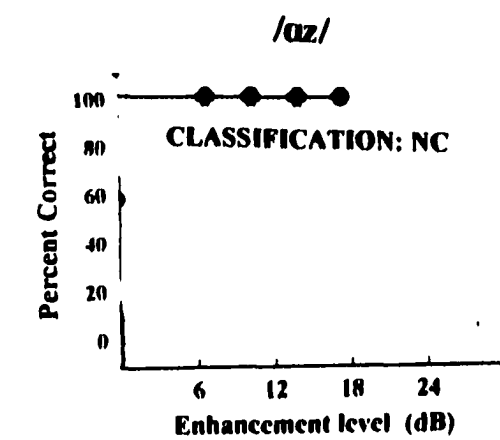
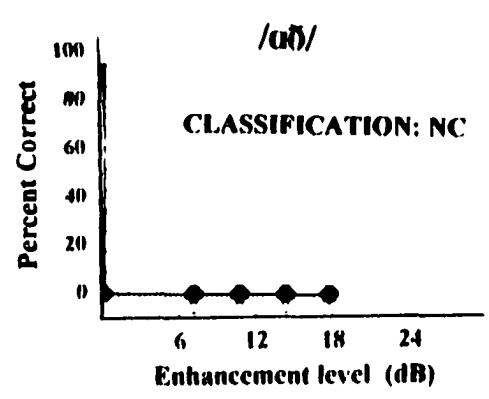
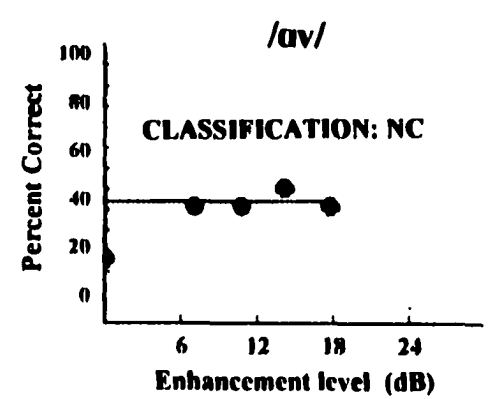
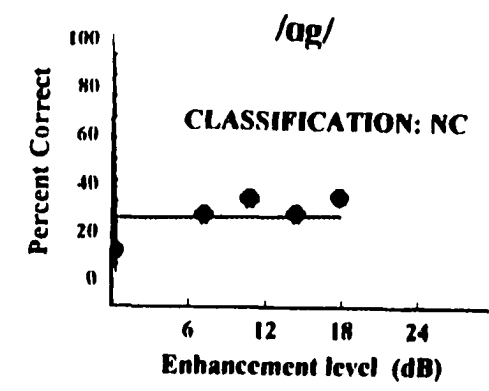
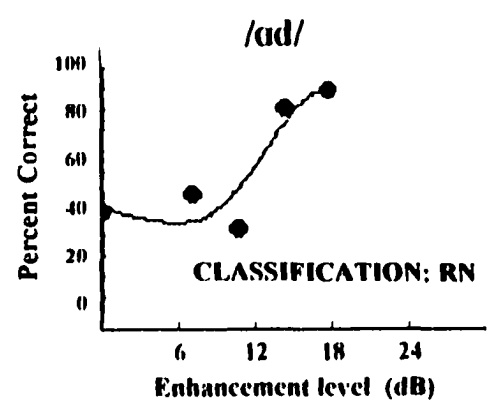
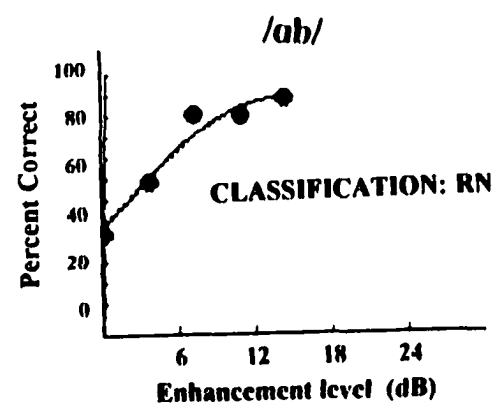
ap.5 = 15 dB

ap.6 = 18 dB

ap.7 = 21 dB

ap.8 = 24 dB

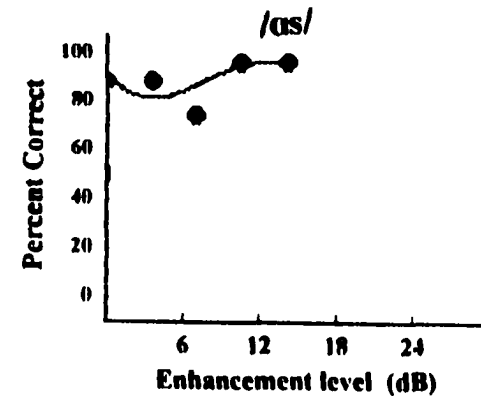
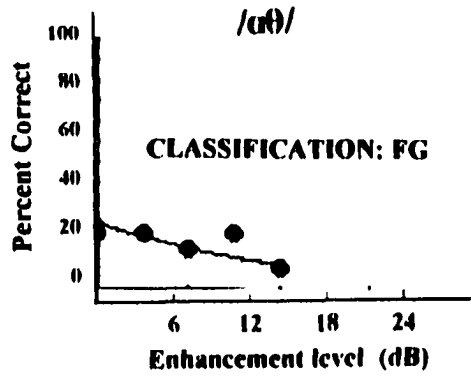
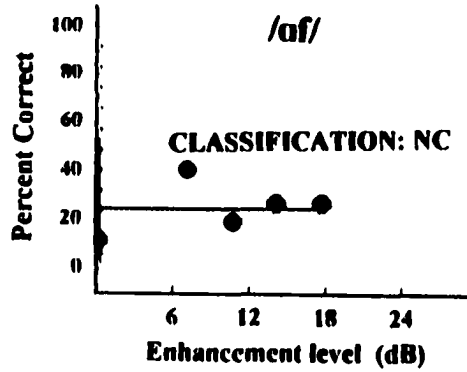
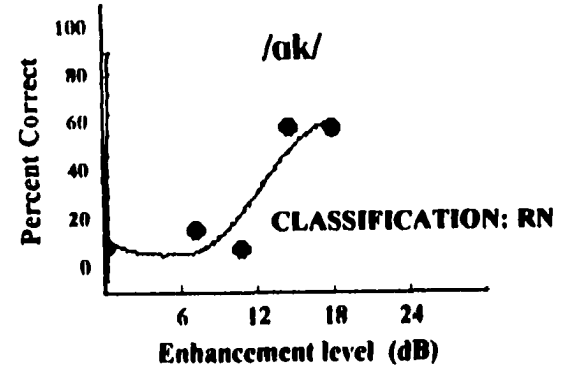
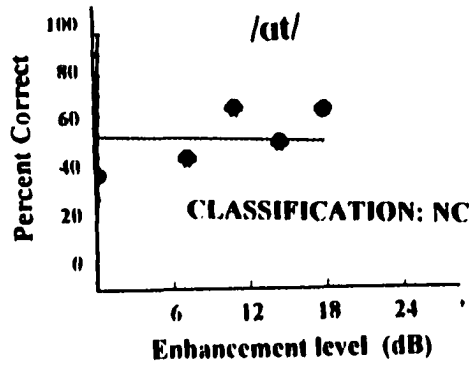
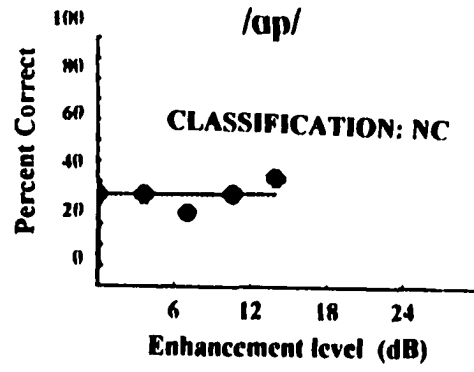
**APPENDIX E****Consonant Enhancement Functions for each subject**



# Subject: AJ

## Classification of CE Function Shape

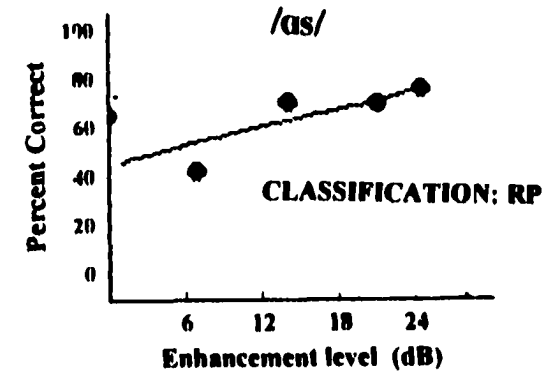
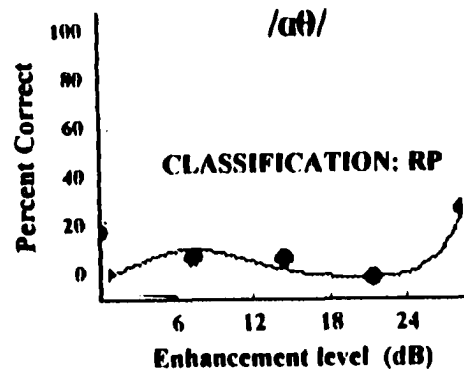
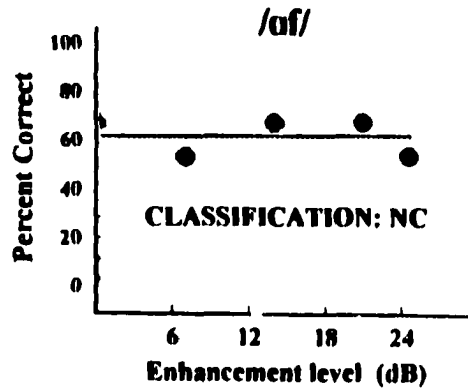
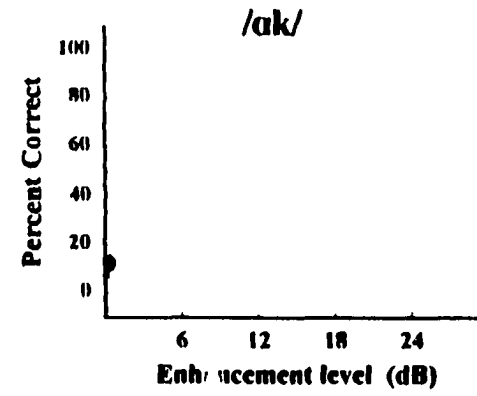
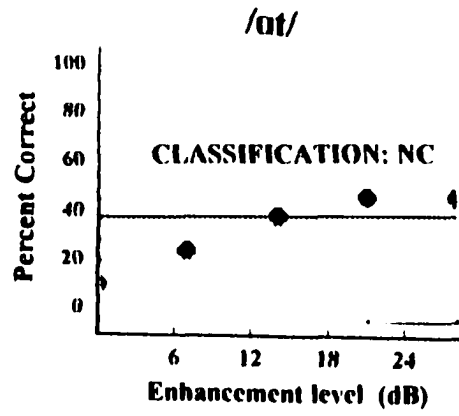
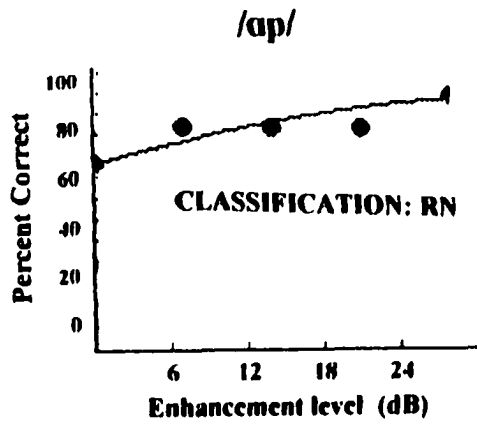
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: AJ

### Classification of CE Function Shape

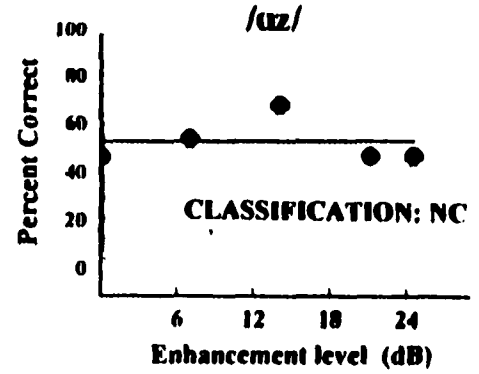
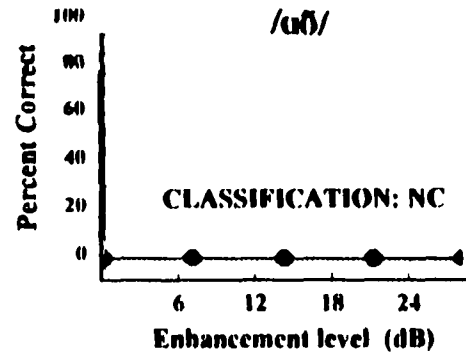
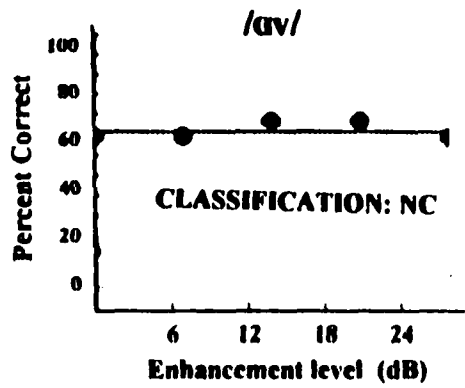
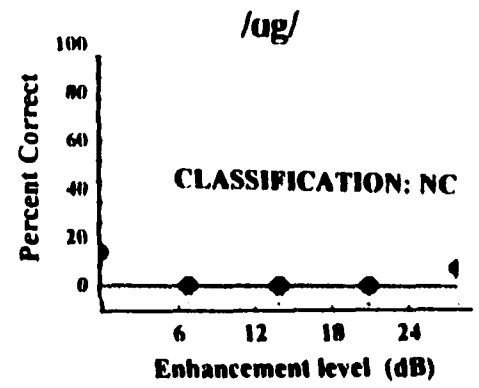
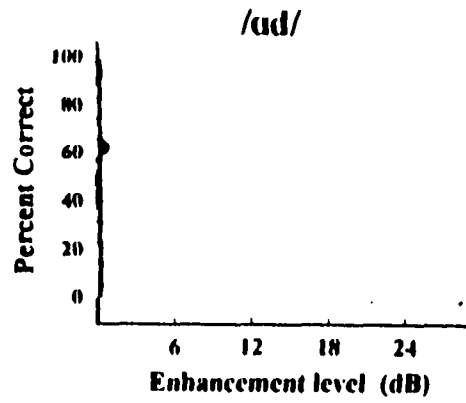
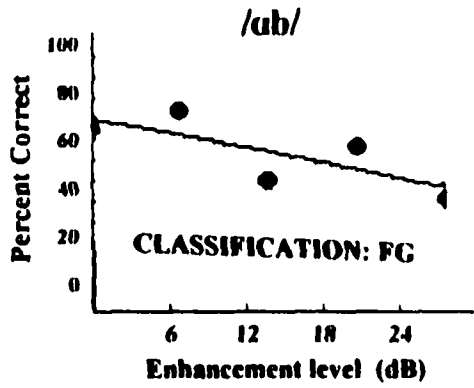
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: MK

### Classification of CE Function Shape

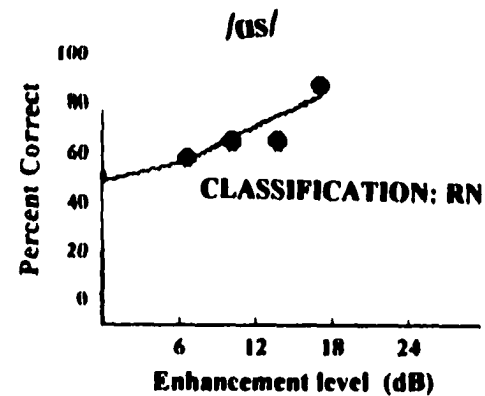
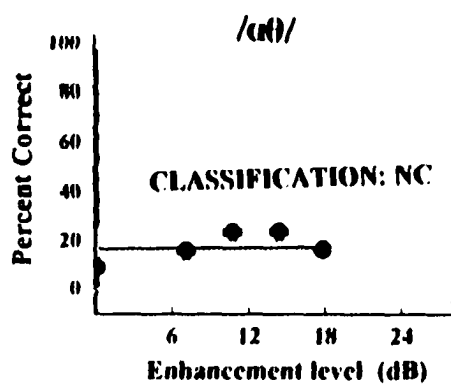
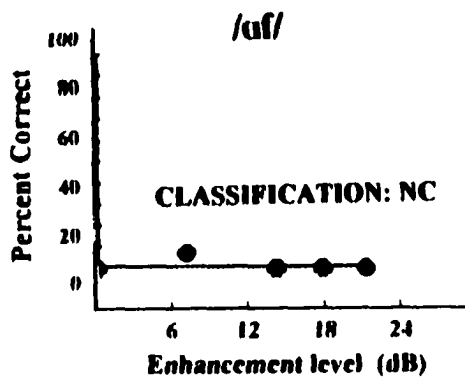
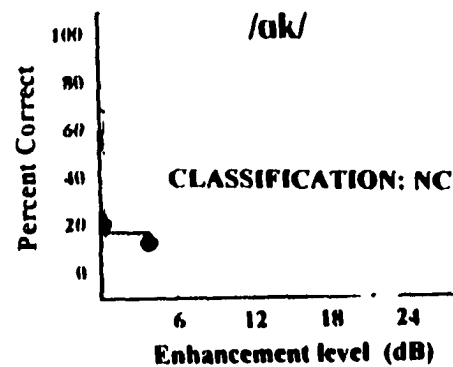
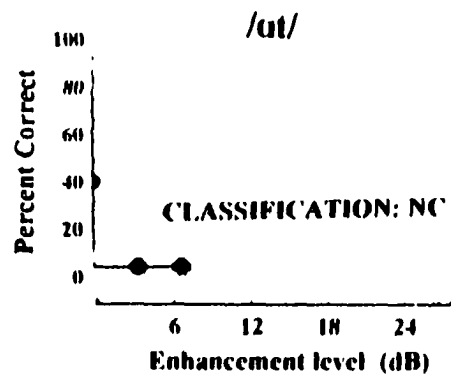
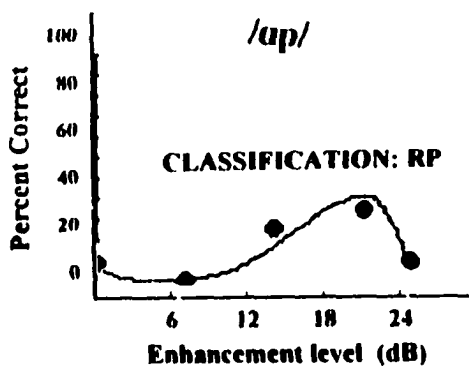
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: MK

### Classification of CE Function Shape

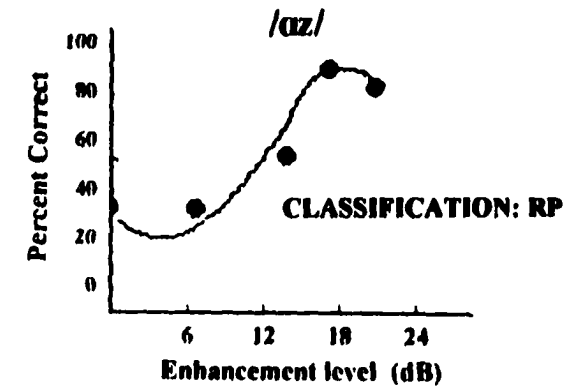
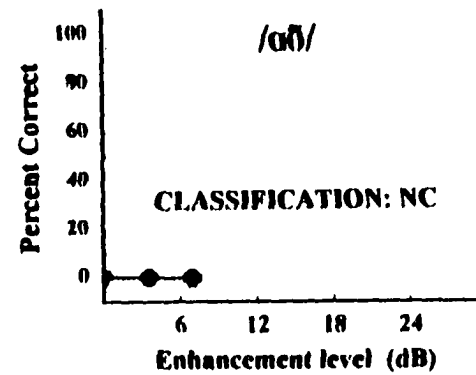
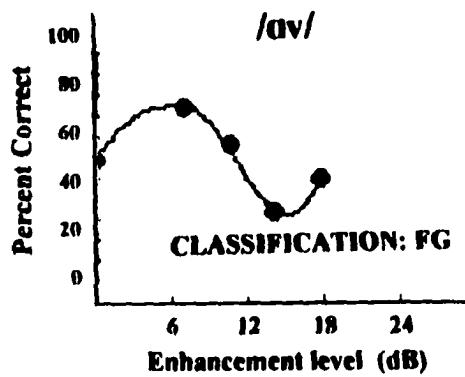
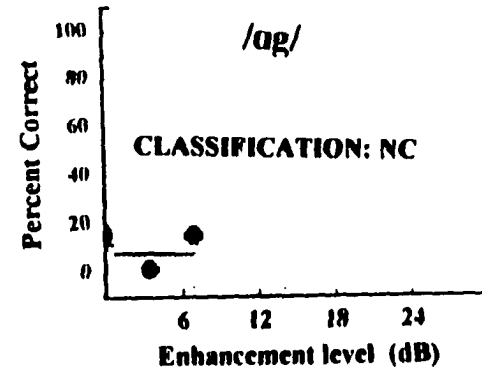
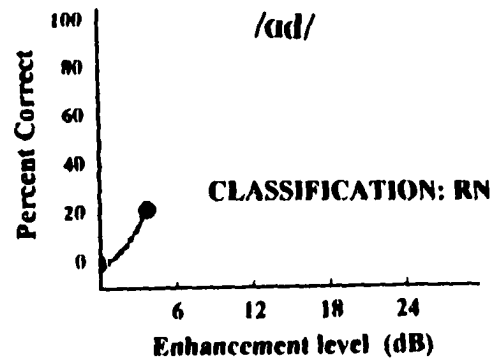
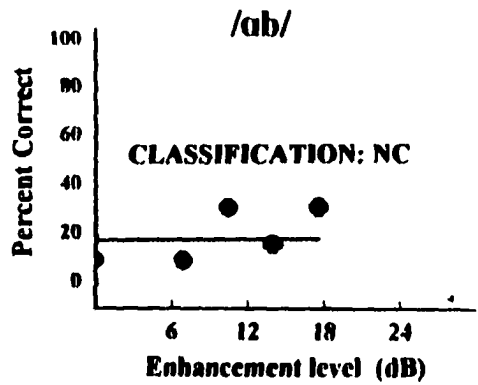
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: VP

### Classification of CE Function Shape

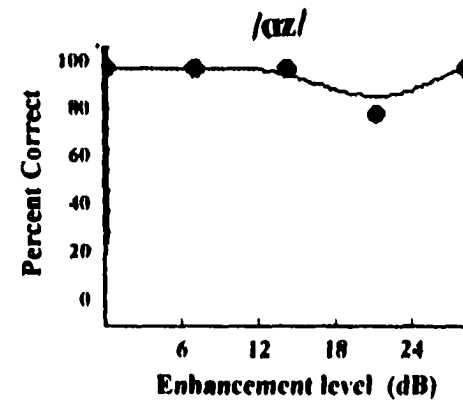
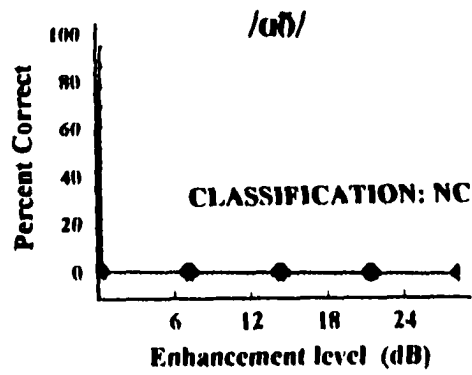
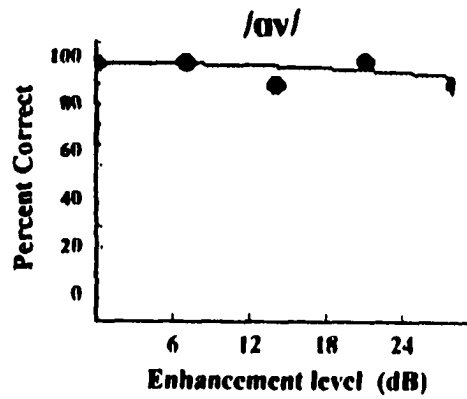
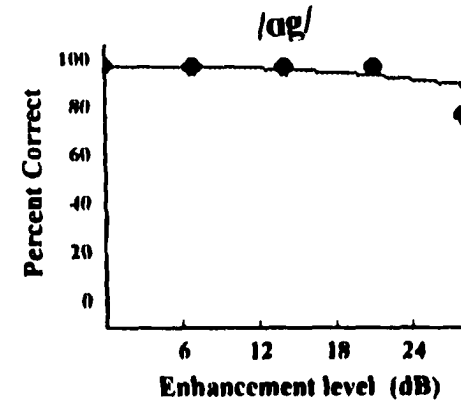
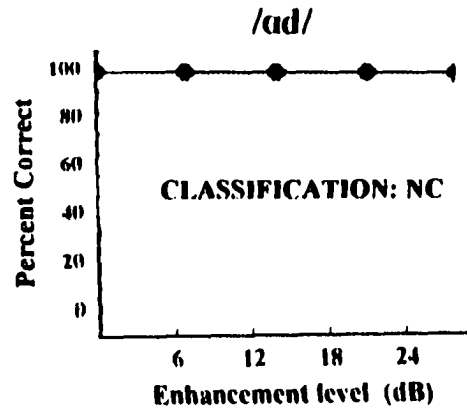
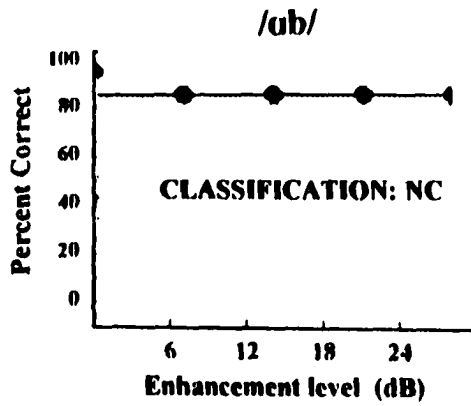
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: VP

### Classification of CE Function Shape

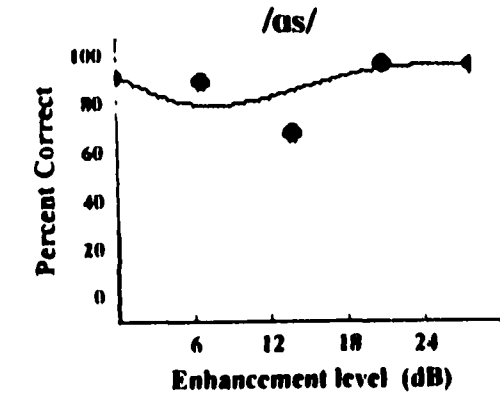
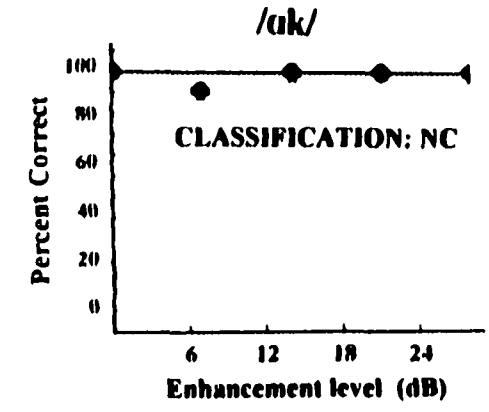
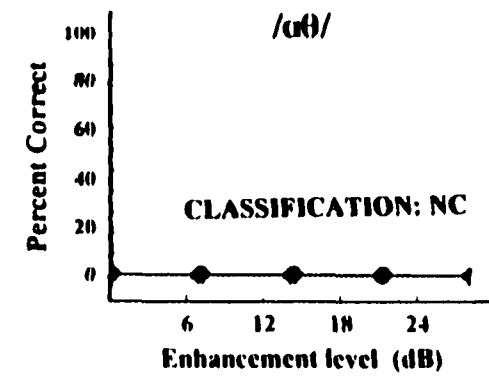
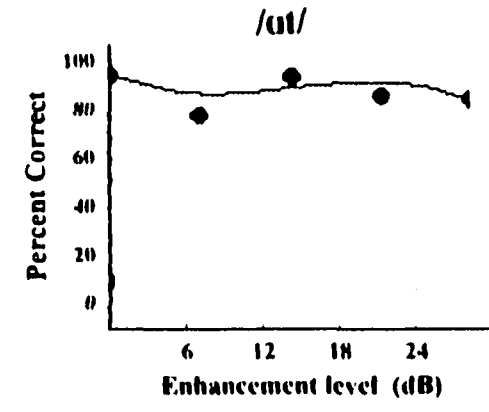
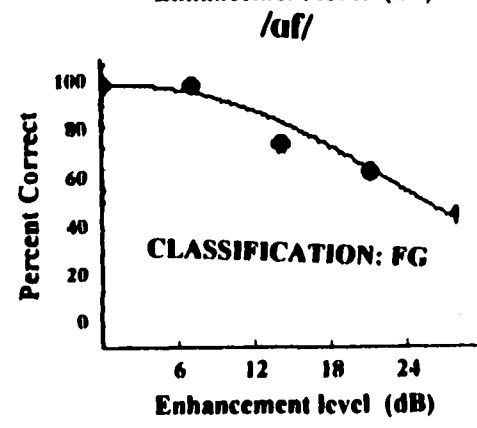
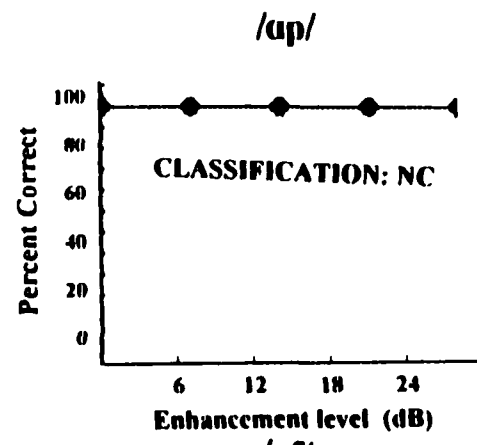
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- RN = Rising/No Peak
- FG = Falling



## Subject: KG

### Classification of CE Function Shape

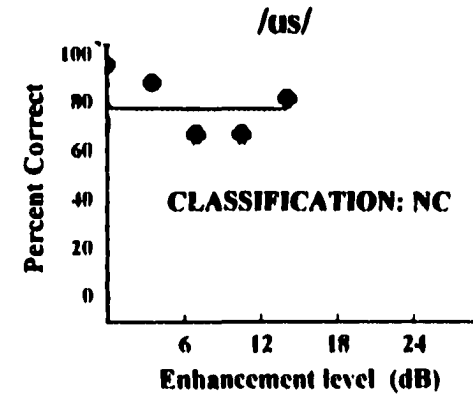
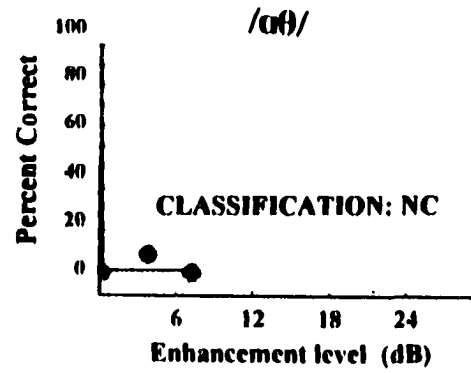
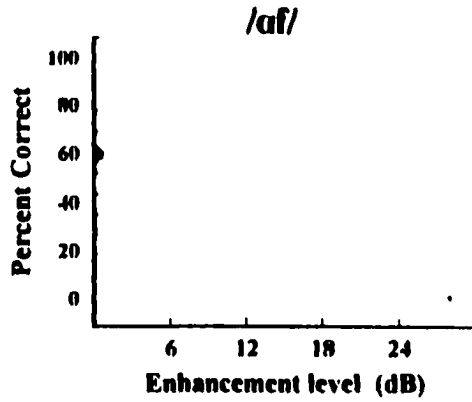
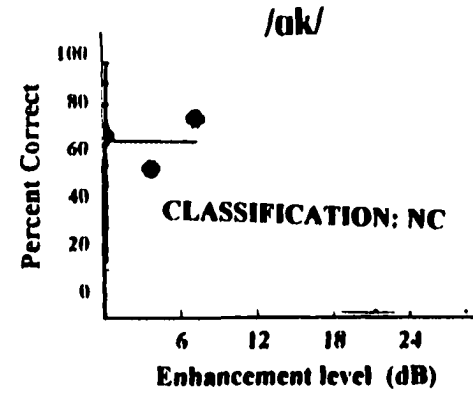
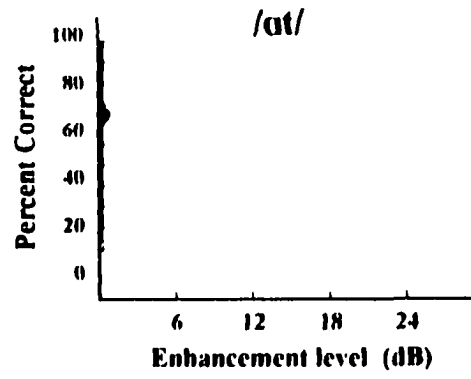
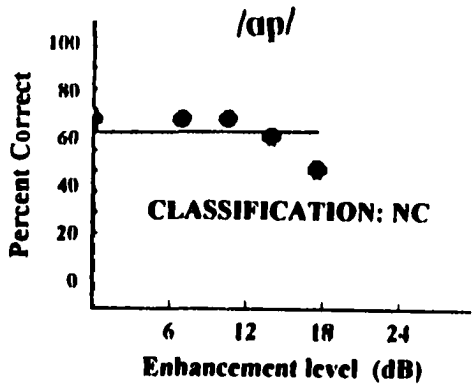
- NC = No Change
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- RN = Rising/No Peak
- FG = Falling



## Subject: KG

### Classification of CE Function Shape

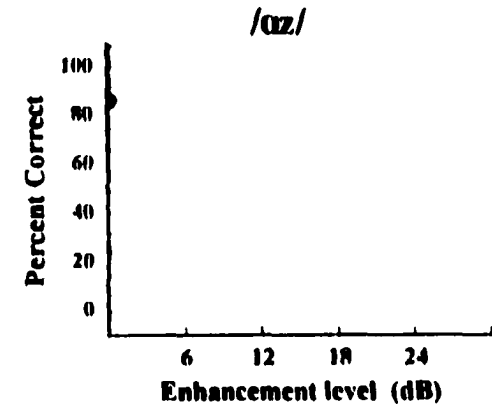
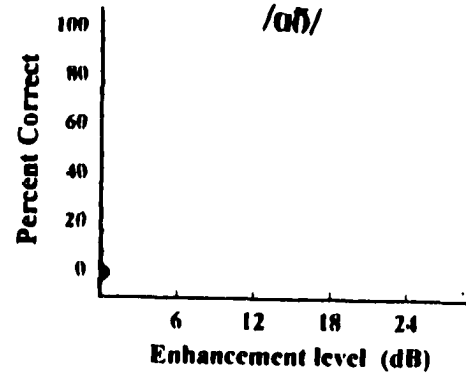
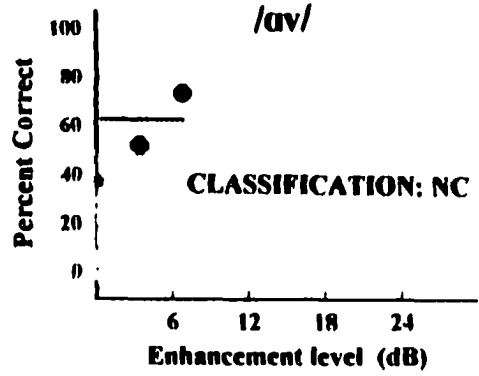
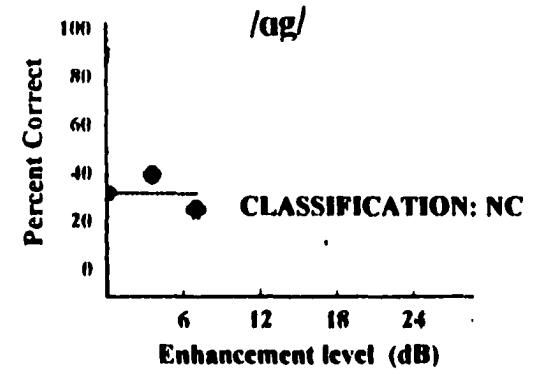
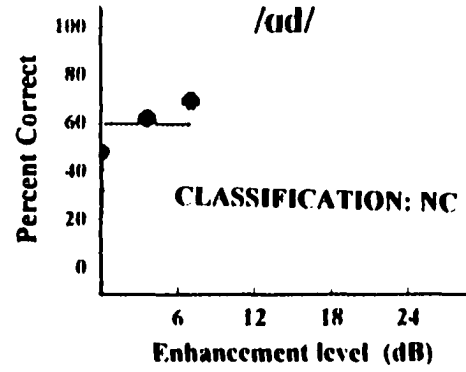
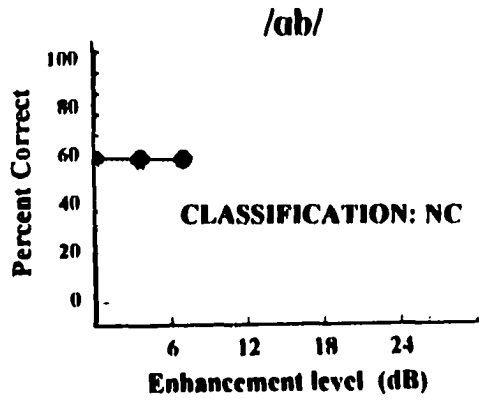
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: BD

### Classification of CE Function Shape

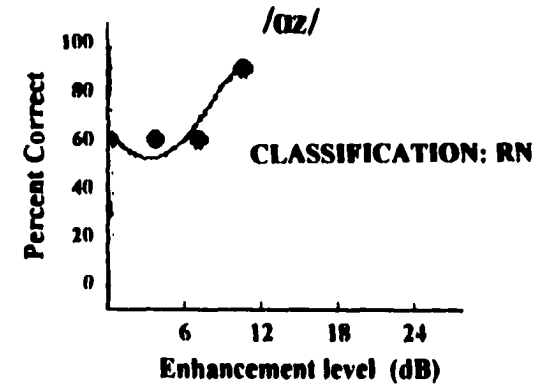
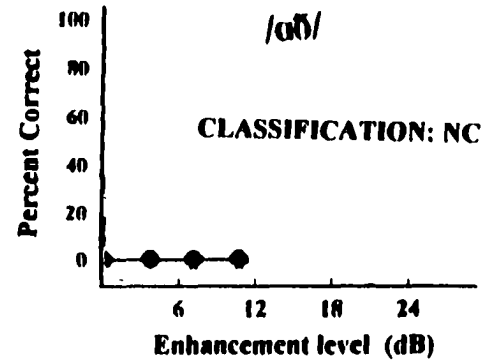
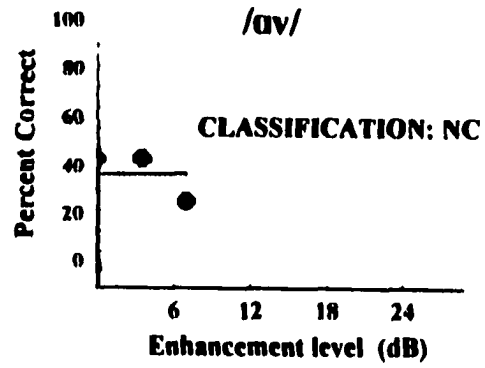
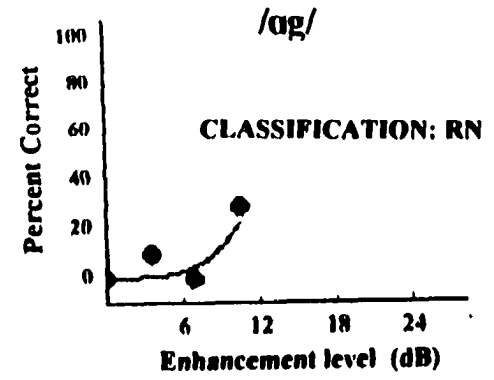
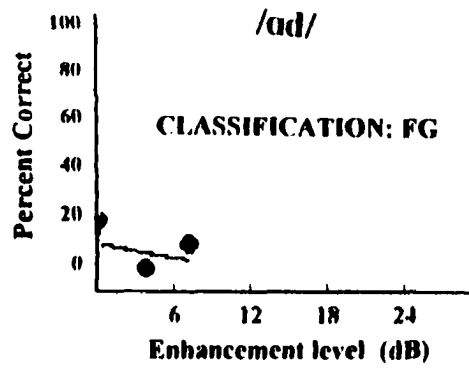
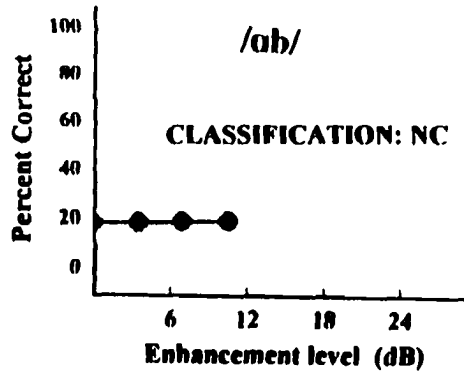
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: BD

### Classification of CE Function Shape

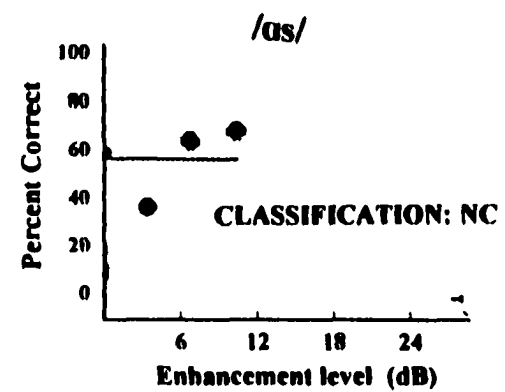
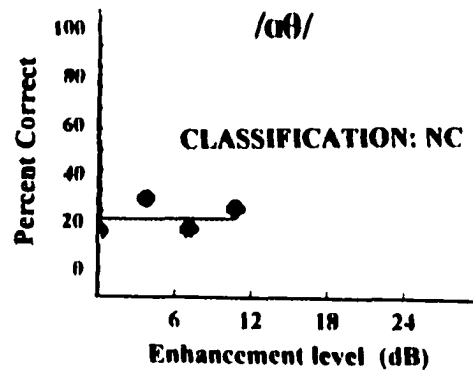
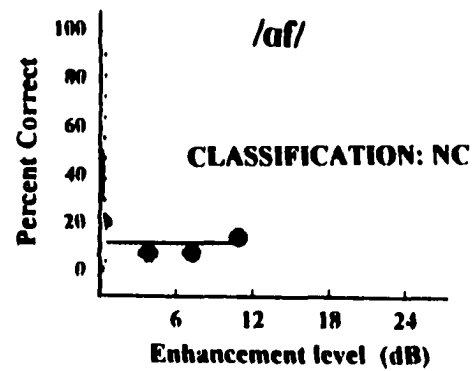
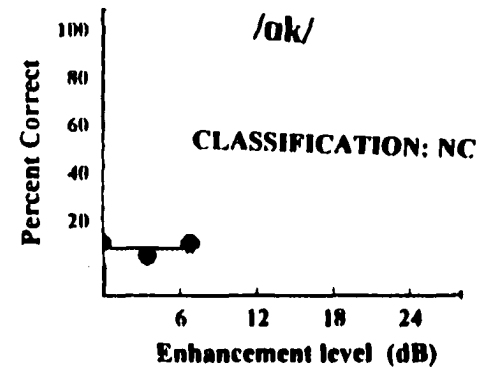
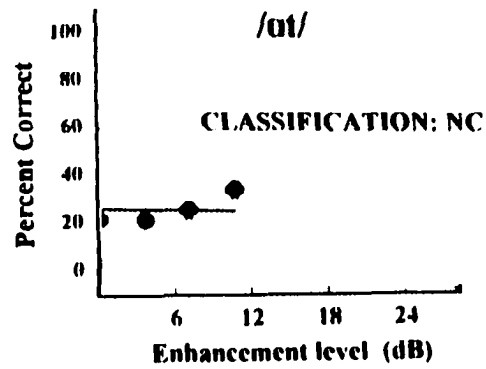
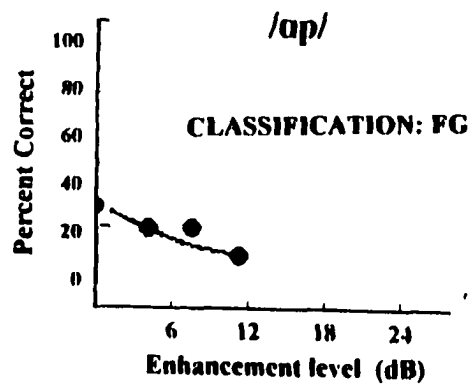
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: EM

### Classification of CE Function Shape

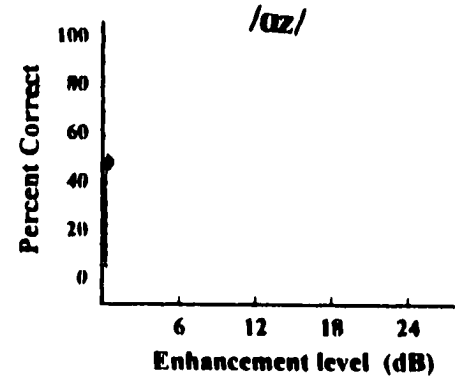
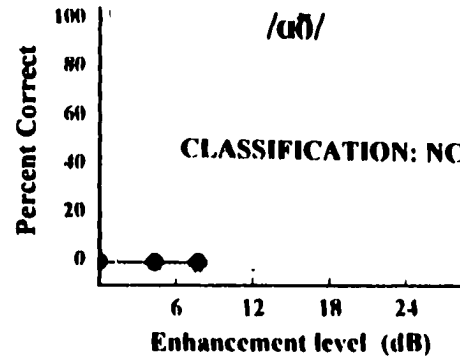
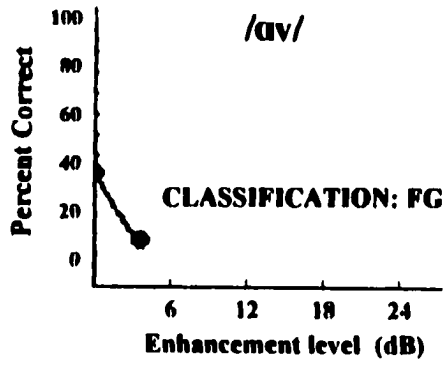
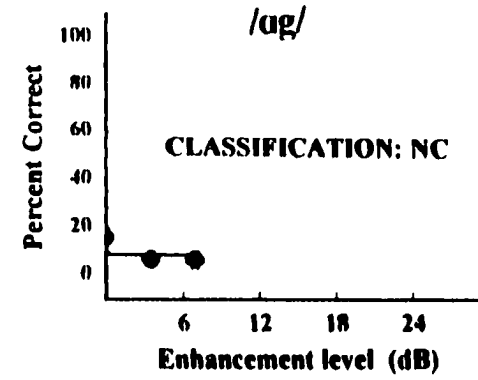
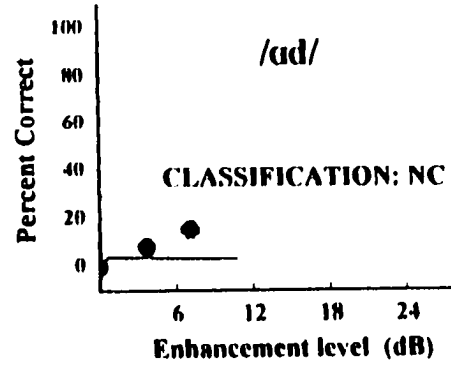
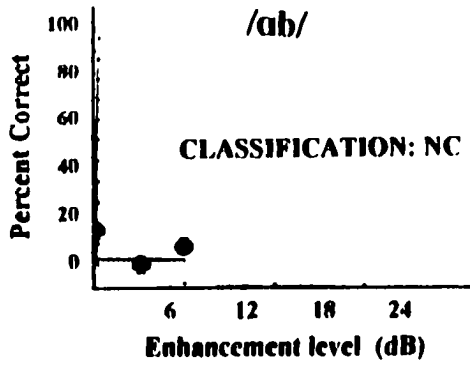
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: EM

### Classification of CE Function Shape

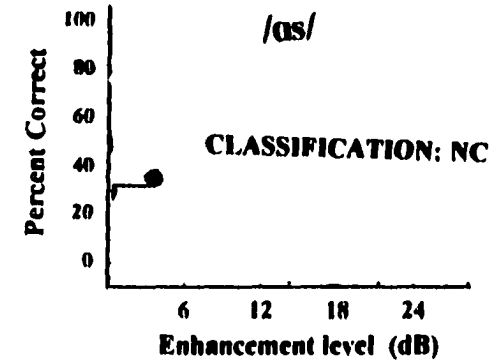
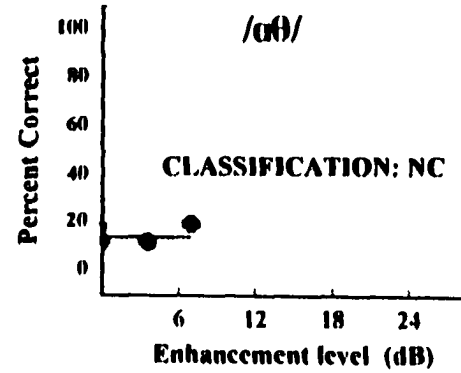
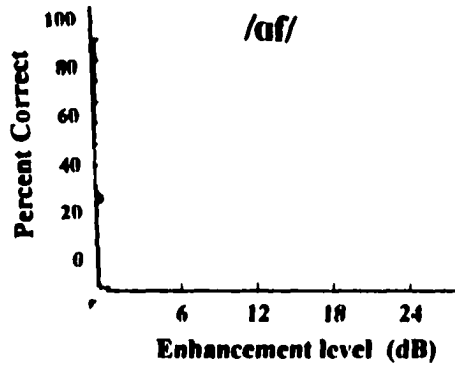
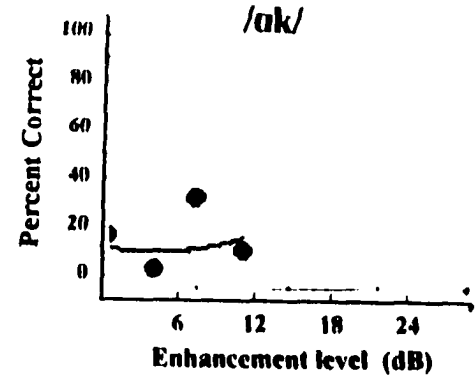
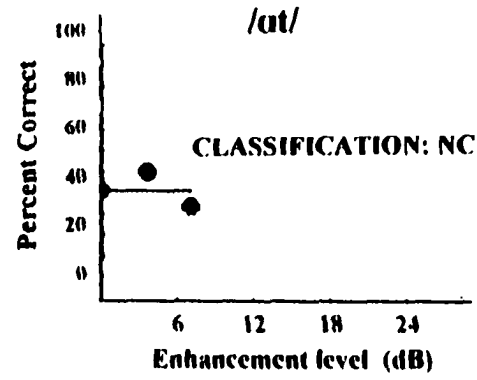
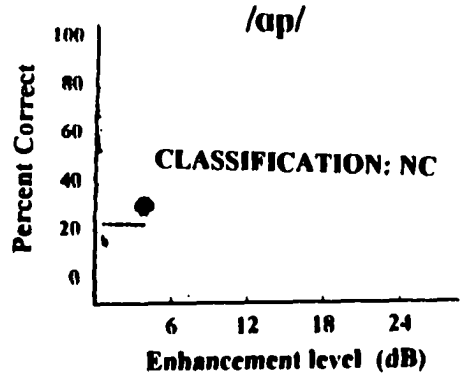
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: VL

### Classification of CE Function Shape

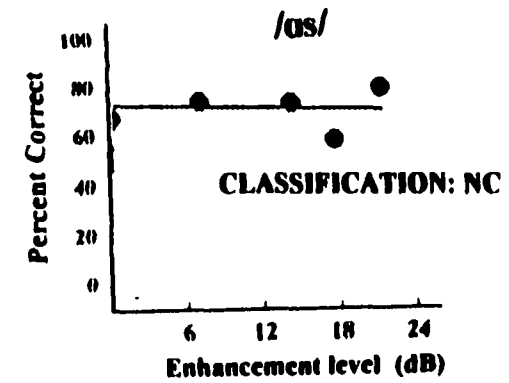
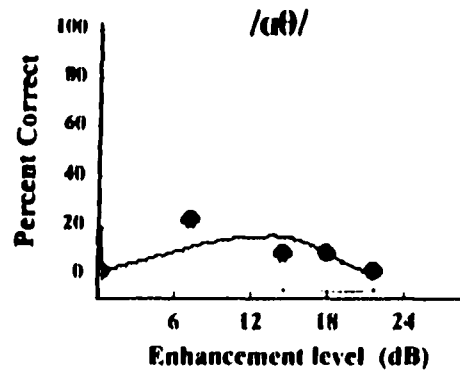
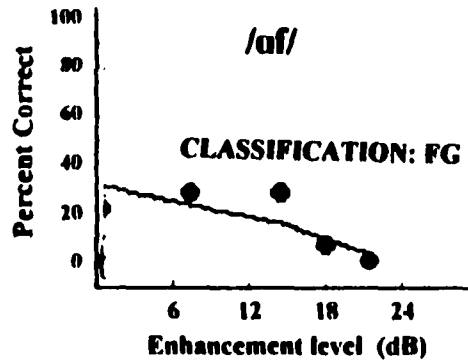
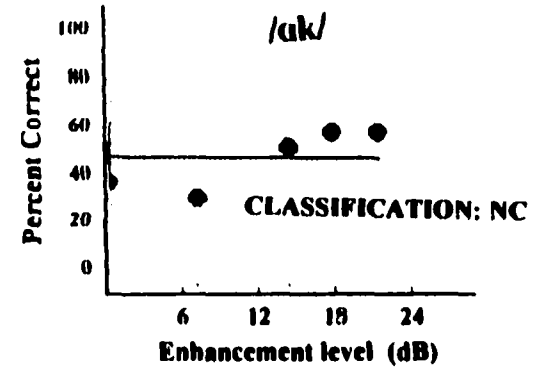
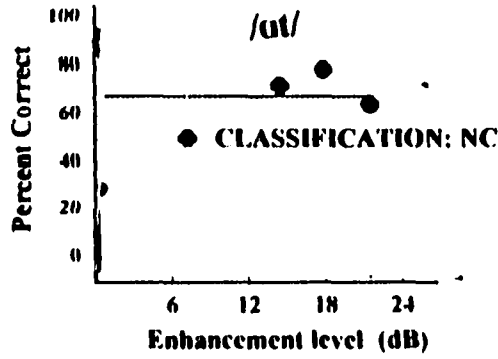
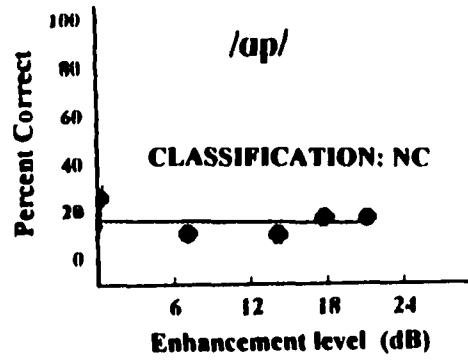
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- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: VL

### Classification of CE Function Shape

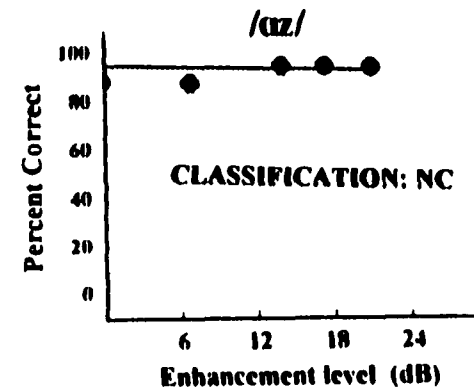
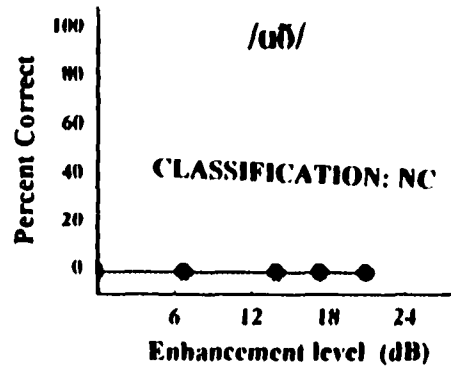
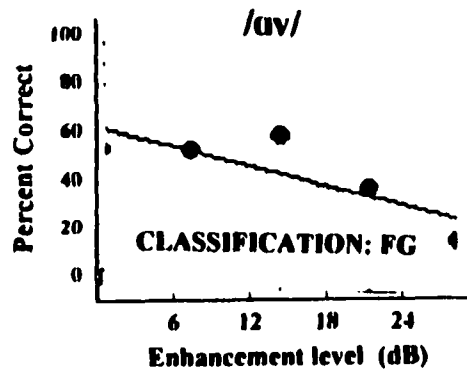
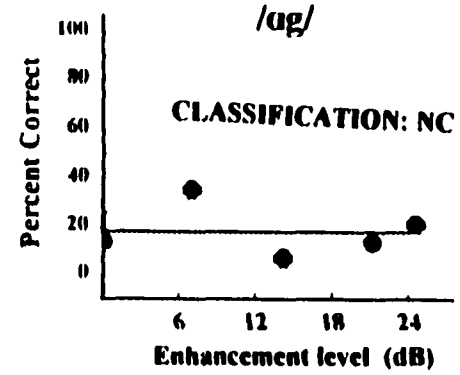
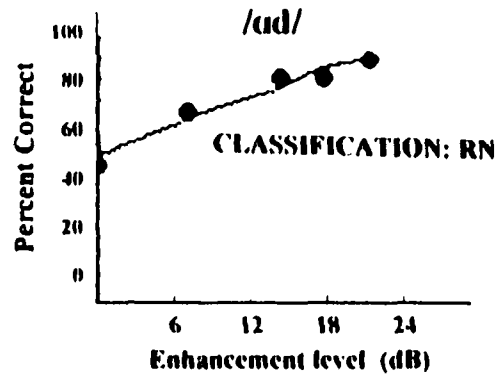
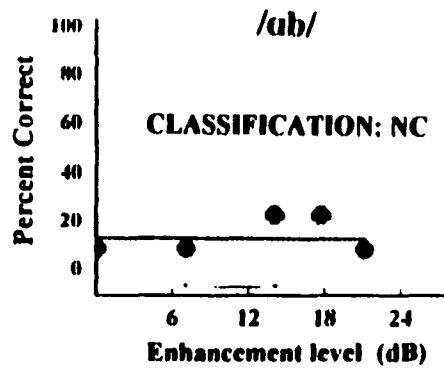
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: CD

### Classification of CE Function Shape

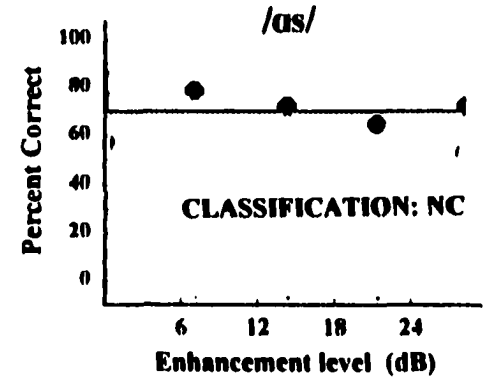
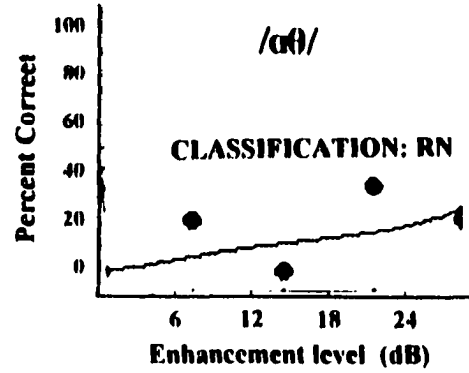
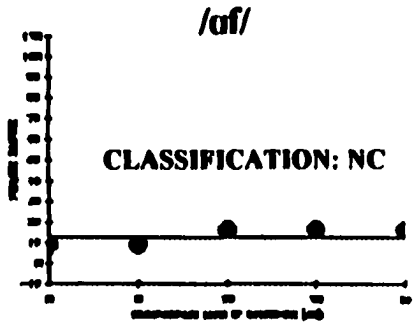
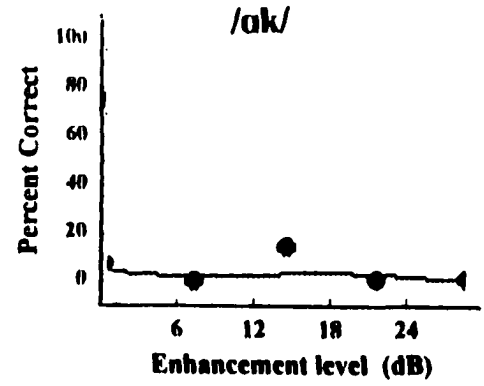
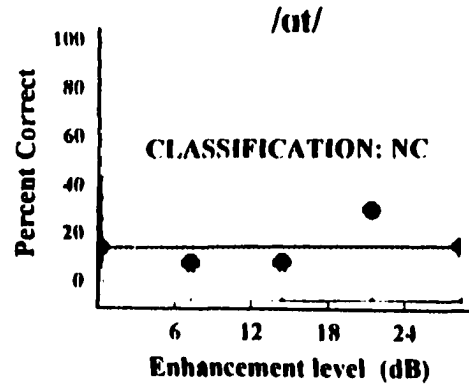
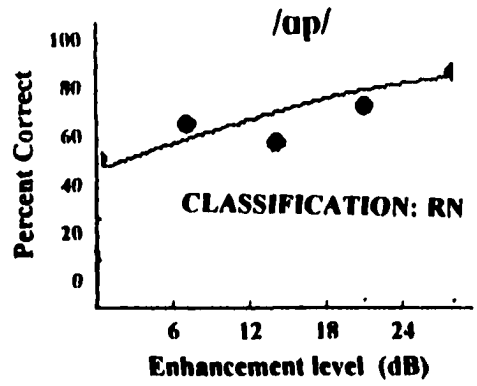
- NC = No Change
- RP = Rising Peak
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- FG = Falling



## Subject: CD

### Classification of CE Function Shape

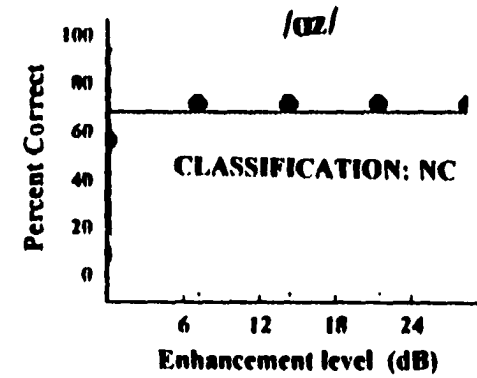
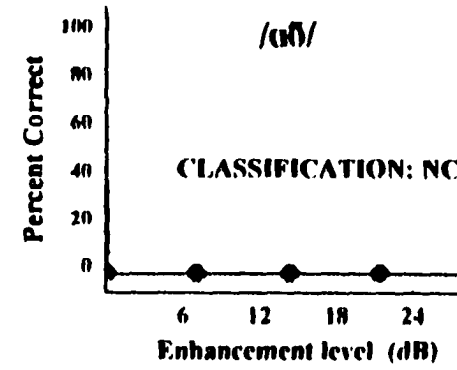
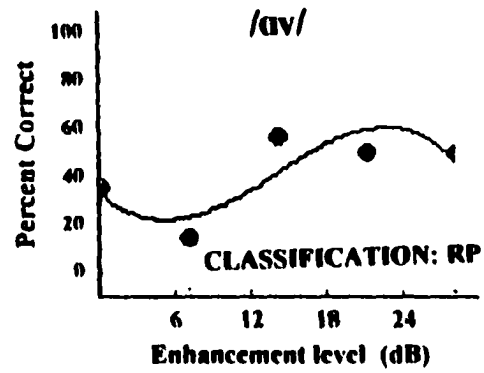
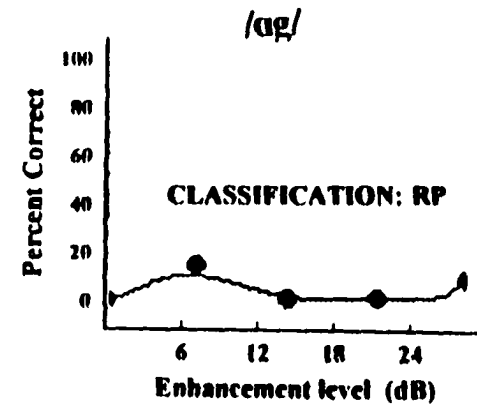
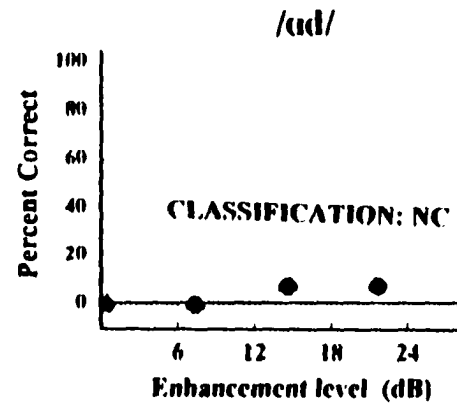
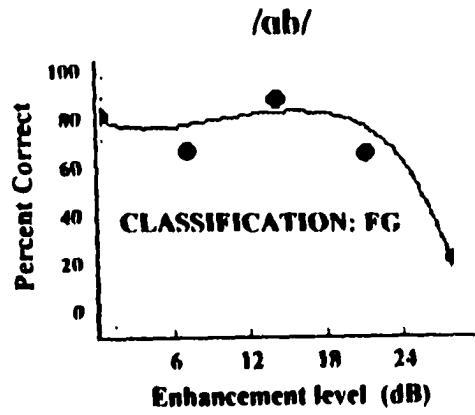
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: AM

### Classification of CE Function Shape

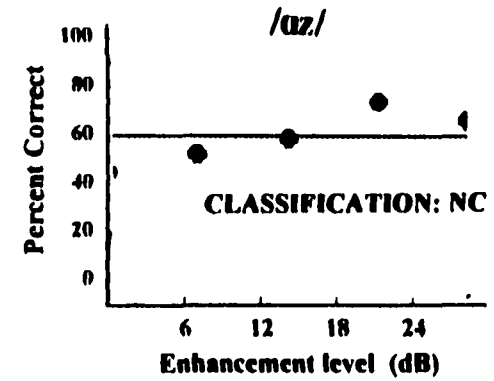
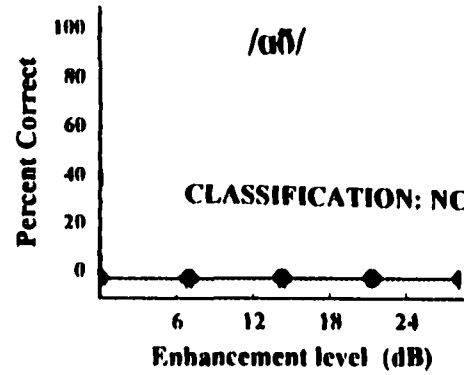
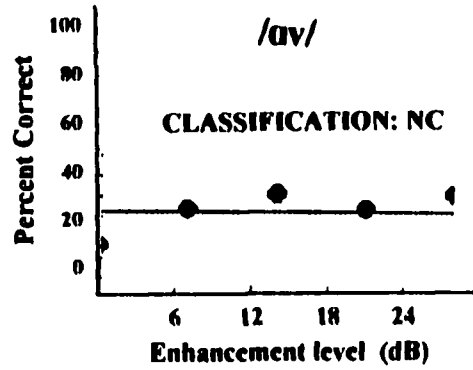
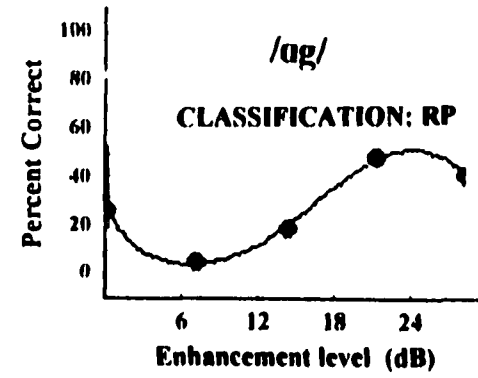
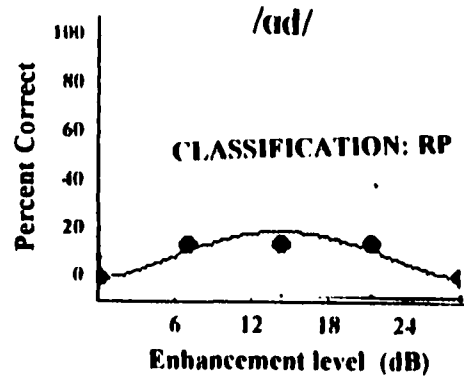
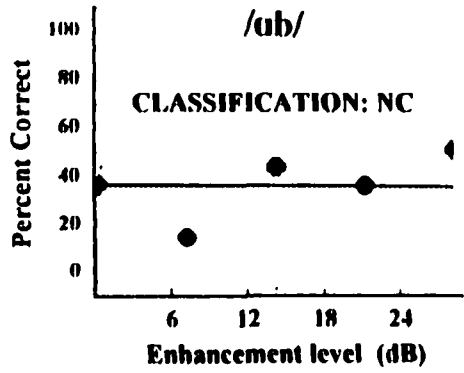
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: AM

### Classification of CE Function Shape

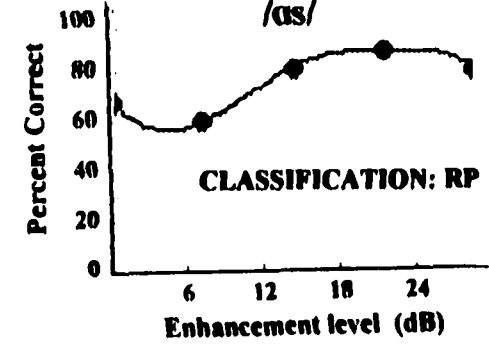
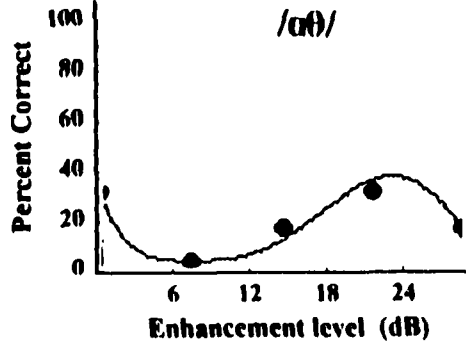
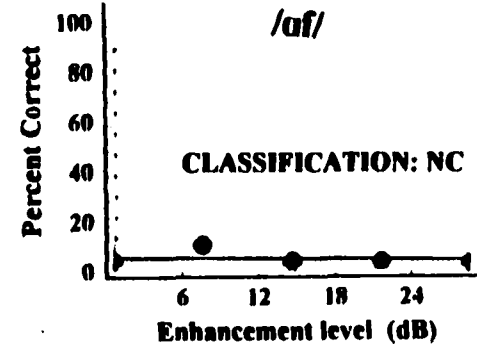
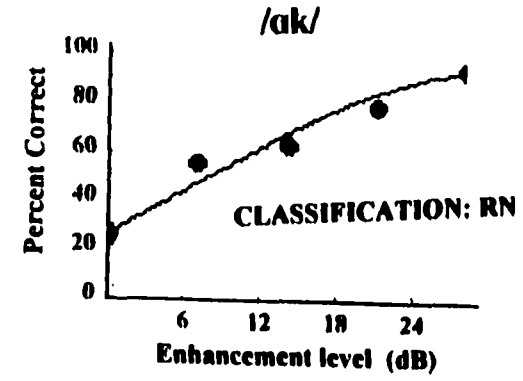
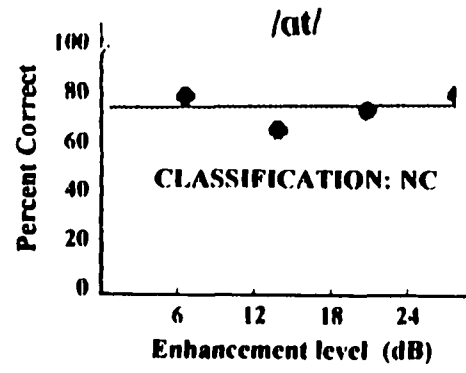
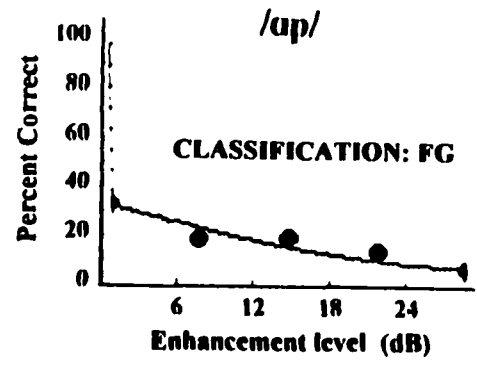
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- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: AP

### Classification of CE Function Shape

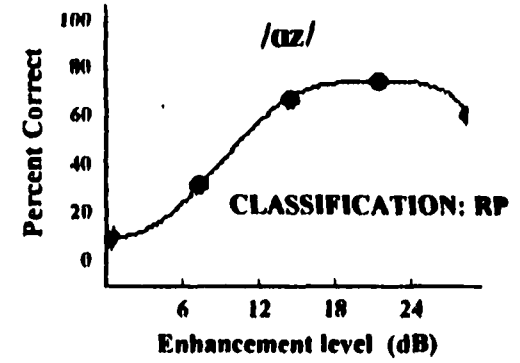
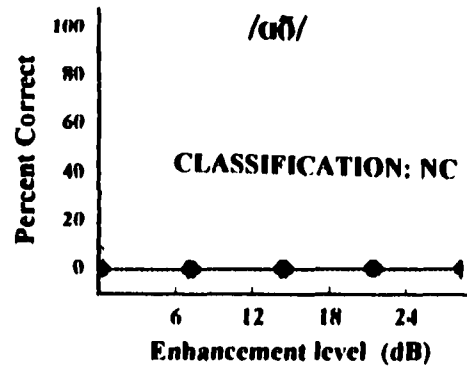
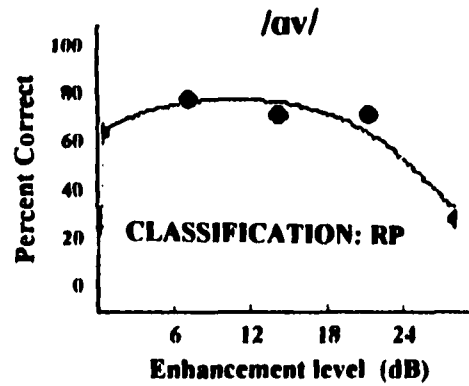
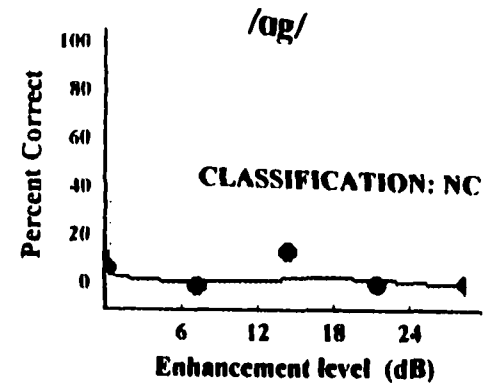
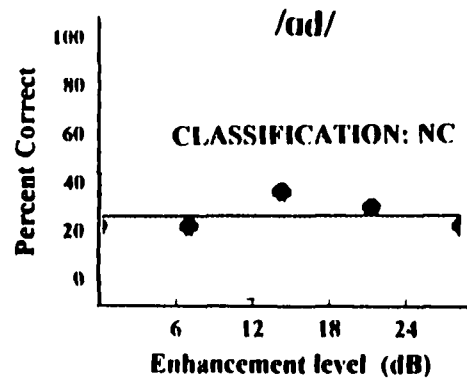
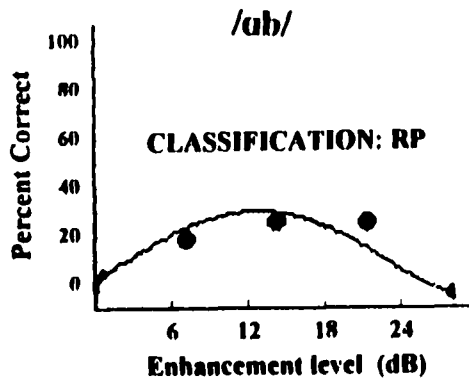
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: AP

### Classification of CE Function Shape

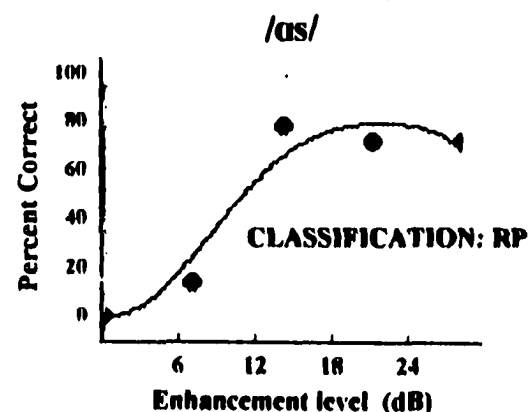
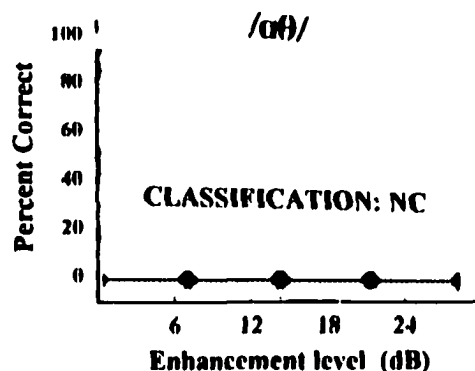
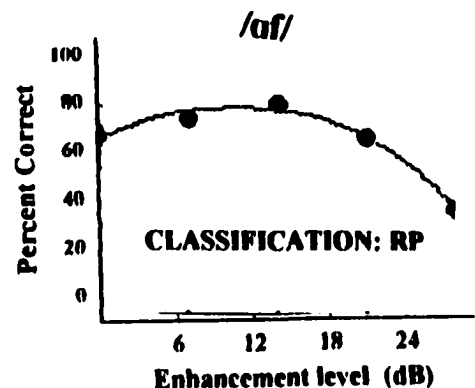
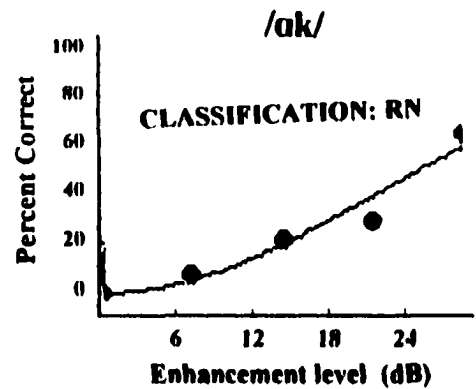
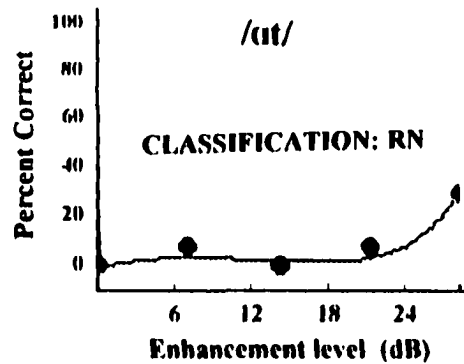
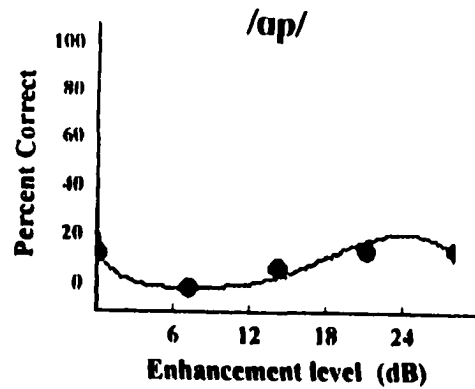
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: DD

### Classification of CE Function Shape

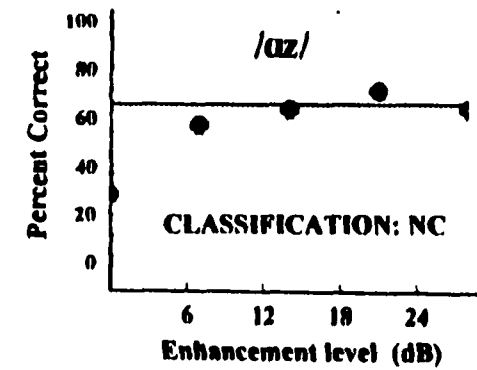
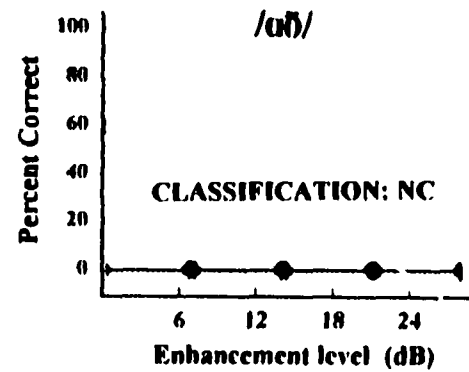
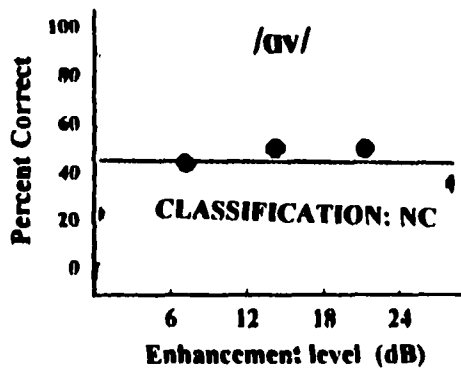
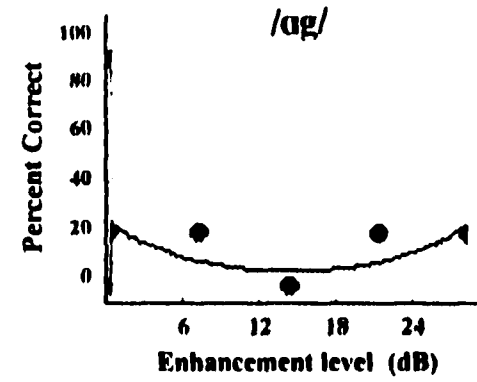
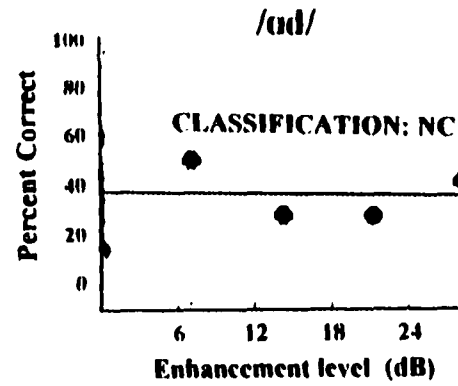
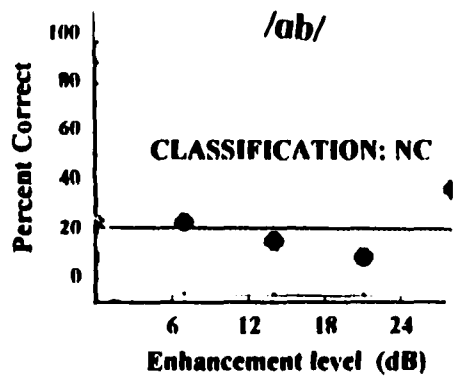
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: DD

### Classification of CE Function Shape

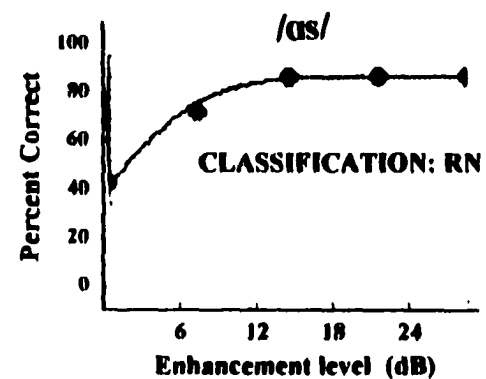
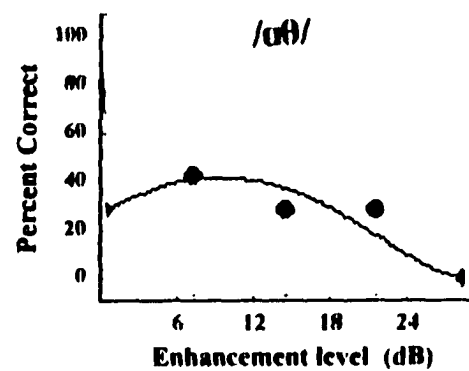
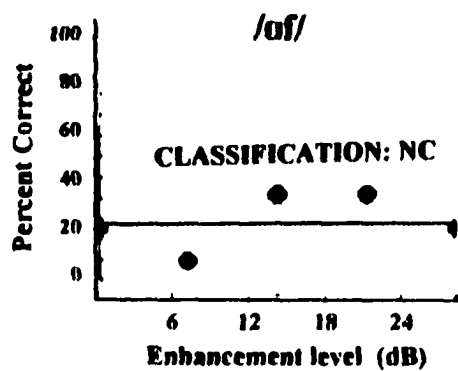
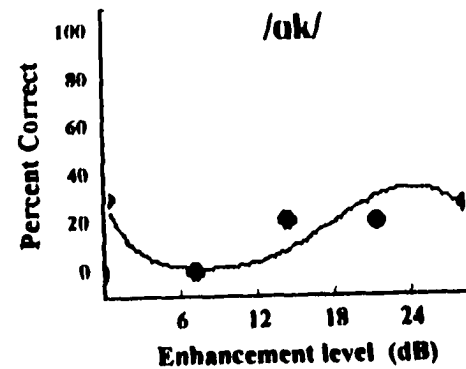
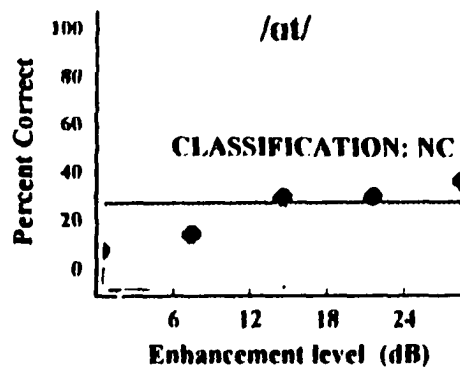
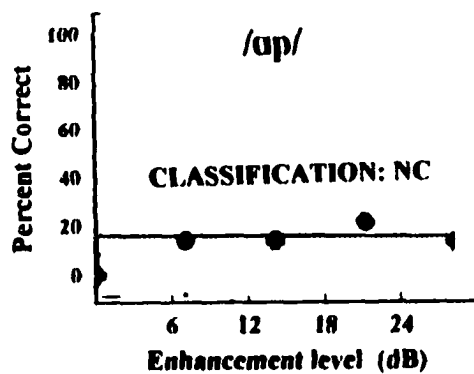
- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: LC

### Classification of CE Function Shape

- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling



## Subject: LC

### Classification of CE Function Shape

- NC = No Change
- RP = Rising Peak
- RN = Rising/No Peak
- FG = Falling

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