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CONSONANT/VOWEL INTENSITY RATIO NECESSARY FOR MAXIMIZING CONSONANT RECOGNITION FOR LISTENERS WITH HEARING IMPAIRMENT

by

ELIZABETH ANN SHEPHERD KENNEDY

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

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ABSTRACT

CONSONANT/VOWEL INTENSITY RATIO NECESSARY FOR MAXIMIZING CONSONANT RECOGNITION FOR LISTENERS WITH HEARING IMPAIRMENT

by

Elizabeth Ann Shepherd Kennedy

Adviser: Professor Harry Levitt

The effect of adjusting the consonant-vowel (C-V) ratio on consonant recognition was investigated with 18 subjects with moderate to moderately-severe sensorineural hearing impairment. Forty-eight nonsense syllables consisting of 16 consonants and 3 vowels were used as stimuli. The C-V ratio of each nonsense syllable was adjusted in 3 or 6 dB steps to a maximum of 24 dB or 3 dB below the listeners level of discomfort. The level of consonant enhancement (CE_{max}) required for highest consonant recognition scores (CR_{max}) was obtained for each subject and each nonsense syllable. Consonant type and vowel environment showed significant effects on CE_{max} and CR_{max}. Audiometric configuration also had a significant effect but only at CR_{max}. A consonant by vowel environment interaction and a consonant by audiometric configuration interaction were observed. Results of this investigations showed that individualized adjustment of the C-V ratio can produce substantial increases in consonant recognition in nonsense syllables. These data can be used to estimate the upper bounds of performance that, in principle, can be obtained by appropriate adjustment of the C-V ratio.

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Chapter I

STATEMENT OF THE PROBLEM

Sensorineural hearing loss reduces the audibility and intelligibility of normal conversational speech. Traditionally, linear hearing aids have been the primary means of alleviating this problem by providing varying amounts of gain at different frequencies. The goal of prescriptive procedures for linear hearing aids is to increase the audibility of speech across the frequencies important for speech perception. To the degree that speech recognition abilities of listeners with hearing impairment increase when using traditional hearing aids, this technique can be viewed as successful. However, traditional linear instruments provide the same amount of gain to all signals with the same frequency, independent of the specific input levels of that signal. Individual frequencies may require differing amounts of gain in order to obtain best performance.

In normal conversational speech, the intensity of individual acoustic segments representing different phonemes are highly variable. Some phonemes, such as /a/, are quite intense relative to the overall intensity of speech. Others, such as /f/, are much less intense. Generally, the consonants (C) are much weaker than the vowels (V) although there is considerable variability within and across speakers and phonemes. A convenient way to report the relationship between relative intensities of consonants and vowels is the consonant vowel intensity ratio (C-V ratio).

Traditional linear hearing aids with appropriate frequency gain characteristics typically provide high frequency amplification. Such amplification causes the C-V ratio to be made more favorable for listeners with hearing impairment, primarily by increasing the audibility of the high frequencies that are important for consonant recognition.

Compression has been developed as a method of controlling output levels. Additionally, compression can improve speech intelligibility, primarily by improving the C-V ratio. The high intensity vowels are compressed while the low intensity consonants are amplified. As with frequency shaping, syllabic compression provides more gain to weak high frequency sounds.

Other evidence that boosting the C-V ratio will increase intelligibility comes from studies comparing "clear speech" with "conversational speech" (House, 1984; Picheny et al. 1985;1986). Speech judged intelligible has a better C-V ratio than speech judged less intelligible. Also, increasing the C-V ratio of the less intelligible speech to that of the intelligible speech resulted in greater intelligibility.

An alternate approach is phonemically based enhancement of the C-V ratio. Digital processing offers the potential of altering gain selectively for different phonemes. Theoretically, with appropriate automatic speech recognition algorithms, a digital hearing aid may be programmed to detect specific phonemes or groups of phonemes and provide gain only to the desired consonant portion. This gain could be variable such that an optimal C-V ratio may be achieved in each speech signal. Studies of digital manipulation of the C-V ratio reveal that such modifications increase speech recognition with nonsense syllables and with words (Gordon-Salant, 1986, 1987; Montgomery and Edge, 1988).

Of the traditional approaches which indirectly alter the C-V ratio, linear amplification with frequency shaping has been shown to be unable to handle changes in input level and compression provided ambiguous results (Braida et al. 1979; Nabelek, 1983). Phonemically based modifications to the C-V ratio offer the potential to increase speech perception for listeners with hearing impairment. Performance may be enhanced even more if the C-V ratio is individualized for the subject. Although a hearing aid incorporating C-V ratio modifications is not currently available, its development is technically feasible (Preves et al. 1991). Recent research has shown improved speech recognition performance with fixed increases to the C-V ratio (Gordon-Salant, 1986,1987; Montgomery and Edge, 1988; Freyman and Nerbonne, 1989; Preves et. al 1991). If the C-V ratio is optimized for different phonemes, there may be an even greater improvement in speech perception.

The proposed study is designed to determine how much improvement is possible by adjusting the C-V ratio to maximize consonant recognition for listeners with hearing impairment. The C-V ratios necessary for maximum intelligibility for each phoneme and each phoneme class (e.g. fricatives, stops, etc.) will be obtained. From this vantage point, comparison of improvement in intelligibility obtained by maximizing C-V ratio can be compared to those improvements obtained with existing technology. If maximizing C-V ratio yields substantially better intelligibility, then application(s) of this technique can be developed. If not, then application would not be worthwhile and further research would more productively be focused on an alternate problem.

CHAPTER II

REVIEW OF THE LITERATURE

The focus of this review is the extent to which various methods of signal processing affect intelligibility of speech for listeners with hearing impairment. The effects of the signal processing on other aspects of speech, such as quality, are not reviewed here. Several methods of processing speech for people with hearing impairment have been tried over the years. These include: (a) frequency shaping, (b) compression, including syllabic and multiband compression, and (c) modification of the C-V ratio. This chapter reviews each of these approaches briefly from the perspective of speech intelligibility.

FREQUENCY SHAPING

Frequency shaping of the acoustic signal is the most common method of signal processing used in hearing aids today. The gain is usually determined by means of a prescriptive formula which assumes the input signal will be speech at a conversational level. Prescriptive hearing aid fitting protocols most often require that adjustment of the frequency response of the instrument be based on the audiometric configuration of the hearing loss. Many different prescriptive methods exist which purport to determine an appropriate frequency response of a hearing aid for a given hearing loss (e.g.

McCandless and Lyregaard, 1983; Byrne and Dillon, 1986; Berger et al. 1989).

A common goal for prescriptive formulae is that weak sounds in speech should be made audible without rendering more intense sounds uncomfortable. In order to do this, many threshold based formulae provide gain targets where the insertion gain of the hearing aid is proportional to the hearing loss. The first of these prescriptive rules, known as the half-gain rule was developed by Lybarger (1955). For example, if the hearing loss at a given frequency is 60 dB, the target gain for that frequency would be 30 dB. The half-gain rule has been modified and several prescriptive formulae have been developed based on this approach. These rules typically differ in terms of the proportion of the hearing loss used to determine the gain as a function of frequency.

A widely used prescriptive procedure is that developed by the National Acoustics Laboratory of Australia. Their revised (NAL-R) procedure has been developed empirically from a substantial body of data and is perhaps the most widely used formula (Byrne and Dillon, 1986). It is a threshold based procedure which provides target frequency-gain characteristics for a hearing aid, based on audiometric configurations. A half-gain rule is combined with a one-third slope rule in the formula. The efficacy of the formula was evaluated by Byrne and Dillon (1986) with forty-four subjects with mild to moderate sensorineural hearing loss. The frequency response was determined for each listeners' hearing loss. Real-ear measures were used to match gain to prescription targets. Overall, agreement with prescribed gain and realized gain was good, except in the very high frequencies (4000-6000 Hz). Using a paired comparison task, listeners judged speech intelligibility in five different filtered conditions. Ideal gain, as predicted by the NAL formula, was very close on the average to gain levels chosen by the user for maximum intelligibility.

POGO (Prescription Of Gain/Output) is another commonly used prescriptive formula (McCandless and Lyregaard, 1983). The frequency response characteristics, gain and maximum output are all derived from audiometric measures. The half-gain rule holds for the mid and high frequencies but is modified at 250 and 500 Hz to provide less than half gain. Maximum output is equal to the average UCL (Uncomfortable Loudness Level) obtained at 500, 1000 and 2000 Hz.

Berger, Hagberg and Rane (1989) also developed a prescriptive procedure which dealt with gain, frequency response and maximum output of the hearing aid. They use a half-gain rule to prescribe gain targets for some frequencies; however, the frequencies between 1000-3000 Hz have targets that exceed half-gain. Corrections are provided for listeners with mixed or conductive hearing loss as well as for sensorineural hearing loss which exceeds 50 dB. Output levels are set at 3 dB below loudness discomfort level (LDL) for frequencies above 1000 Hz, at the lesser of either 97 dB HL or LDL-3 dB at 500 Hz and at 20 dB below the 500 Hz level for 250 Hz.

The above three prescriptive methods, which are widely used, are all based on threshold measurements. Non-threshold based methods have been suggested by Watson and Knudsen, 1940; Skinner, Pascoe, Miller, and Popelka, 1982, and others who proposed that the frequency-gain characteristics be such that the speech spectrum be at a comfortably loud level for all frequencies.

Comparison of methods of frequency shaping with uniform amplification show improved consonant recognition in the former. Watson and Knudsen (1940) determined the frequency response to mirror the listener's most comfortable equal loudness curve. Maximum gain was set to reach as high as the subject's threshold of feeling. Their results showed syllable recognition for seven listeners with hearing impairment was 65.5% on average (range of 48-91%) with uniform amplification and 75.5% on average (range of 58-97%) with frequency shaping which emphasized high frequencies.

Skinner (1980) contrasted the impact of five different frequency responses on the speech recognition scores of six listeners with noise induced hearing loss. Best performance was associated with the frequency response which provided greatest gain in the region of the listeners hearing loss. Her results indicate that altering the speech signal to compensate for specific hearing loss, rather than simply using a wide-band amplifier with flat frequency response (or a 6 dB per octave slope) as recommended by the classic study by Davis et al. (1947), enhances speech perception abilities. The increased audibility of the acoustic cues within the speech signal contributed to the increased word recognition. Her data also show that different frequency responses were better with different signal input levels. For example, when the input signal was at 30 dB SPL, mean word recognition scores were 37% with a flat frequency response and 47% with high frequency emphasis. At 55 dB SPL, mean word recognition was 63% with the flat frequency response and 72% with the high frequency emphasis. When the speech was at 85 dB SPL, word recognition was 71% and 79% for the flat frequency response and high frequency response conditions respectively.

Improvements of similar magnitude were observed by Gatehouse (1992). He evaluated four listeners with moderate sensorineural hearing impairment using monaural hearing aids with a high frequency emphasis. Although initial comparisons of word recognition scores with the aided ear using a flat frequency response and a shaped high frequency response showed no significant difference, a significant improvement (roughly 10%) in word recognition was observed with the shaped frequency response over the flat frequency response after the listener had acclimated to the hearing aid.

While appropriate frequency shaping has been shown to yield better speech recognition performance than an amplifier with a flat frequency response, differences in performance for different frequency responses are more difficult to demonstrate. For example, Sullivan, Levitt, Hwang and Hennessey (1988) found no significant difference in speech intelligibility when speech was at MCL (Most Comfortable Level). They compared four formulae with 14 subjects with moderate hearing impairment. Two paired-comparison measures, one for intelligibility and one for speech quality, as well as speech recognition scores were used as measurement tools. Results did not show any one prescriptive method to be consistently better than another. Moreover, they noted that performance associated with each formula varied with signal output level. In addition, significant variability existed across listeners.

A similar finding has been reported by Humes and Hackett (1990). They compared the speech recognition scores of three groups of listeners (total n=12) with sensorineural hearing loss. They used a commercial hearing aid which was adjusted to three prescriptive procedures: NAL-R, Cox and POGO. Speech recognition was obtained in quiet with speech at 70 dB SPL and in cafeteria noise, with a signal-to-noise ratio of 5 dB. Results were essentially the same, regardless of prescriptive method used. In the quiet condition, speech recognition was approximately 15% better than in the unaided condition. In the presence of the cafeteria noise, speech recognition was only slightly better (< 5%) than in the unaided condition.

In summary, there are many different approaches to frequency shaping and no clear consensus as to which is the best approach. Although there are large differences among the frequency-gain characteristics prescribed by the various approaches, the effects of these differences on speech intelligibility can be reduced considerably if the output of the hearing aid is adjusted to MCL. Additionally, there is a commonality among different approaches that have proven to be reasonably successful. For a typical high-frequency hearing loss, all of these approaches prescribe more gain in the high frequencies than in the low frequencies. Regardless of specific prescription used, frequency shaping is effective in altering the C-V ratio. Since weaker speech sounds typically have important high frequency acoustic cues and intense low frequency sounds contain formant information, amplification that selectively increases the intensity of the high frequencies will increase the C-V ratio. However, speech intelligibility is not the only important consideration in deriving the frequency-gain characteristics. There is also the danger of excessive amplification which can result in discomfort or possible damage to the ear. Thus in addition to frequency shaping, consideration must also be given to controlling output of hearing aids.

COMPRESSION

A central problem in sensorineural hearing loss is that the dynamic range of hearing is reduced significantly. Frequency shaping is helpful to some extent in that the weaker high frequency sounds are amplified more than the intense low frequency sounds thereby reducing the dynamic range of the speech signal. This reduction in the dynamic range achieved by this means, however, is limited. It is also insufficient to protect the ear from excessive amplification.

Many conventional hearing aids use peak-clipping to prevent the speech signal from exceeding the listeners UCL. This technique, however, introduces significant harmonic distortion. Compression amplification can be used both as a means for matching the dynamic range of the speech signal to that of the impaired ear as well as protecting the ear from excessively intense signals without creating significant non-linear distortion.

Many different types of compression exist. The following discussion is based on the description of compression by

Dillon (1988). Compression offers the ability to modify the gain requirements in a manner dependent upon the level of the input signal. That is, as the intensity of the input signal increases, the gain decreases. The key variables of a compression amplifier are compression threshold, compression ratio and the attack and release times.

The compression threshold refers to the input level at which the compressor becomes active. At less intense levels, the gain of the amplifier is unaffected by the signal level. At levels above the compression threshold the gain of the amplifier is a function of the input signal level.

The compression ratio is the change in input required to achieve a 1 dB change in the output. Higher ratios are indicative of greater compression.

Attack and release times describe the time taken for the compressor to change output level with a change in input level. Different combinations of these variables result in very different compression systems (Dillon, 1988).

A compression amplifier with high compression threshold and high compression ratios with short attack/release times is known as a compression limiter. It is used primarily to ensure that the maximum output does not exceed the listener's tolerance levels. As noted above, peak-clipping introduces harmonic distortion which reduces speech intelligibility. With a compression limiter and speech at a high intensity, word recognition does not decline (Davis et al., 1947: Hudgins et al., 1948).

A compressor with low compression threshold, moderate compression ratios and long time constants is referred to as a slow-acting automatic volume control (AVC) amplifier. This form of compression is designed to maintain the average speech signal, over time, within the listeners' dynamic range. The longer release times with short attack times have been shown to decrease speech intelligibility (Johansson, 1973). Lynn and Carhart (1963) also obtained reduced intelligibility but they did not control for output level which may have contributed to the reduction in intelligibility. More recent studies have shown that both intelligibility (Peterson et al., 1990) and quality (Neuman et al.,1994) of amplified speech can be improved for hearing-impaired listeners with small dynamic ranges.

A third type of compression is characterized by low compression thresholds, low compression ratios and attack/release times of less than 200 msec. This type of compression is known as syllabic compression. Systems with brief rise and fall times respond more closely to the rapid changes in the speech signal than do those with longer time constants. In this respect, the term syllabic compression may be a misnomer since with very short time constants significant changes in output level will occur within rather than between syllables.

Syllabic compression was initially designed to operate over the entire frequency range of the amplified speech signal. Several studies exist which describe the effect of different time constants on speech intelligibility (eg. Lynn and Carhart, 1963; Johansson, 1973; Ruhberg and Esser, 1973; Schweitzer and Causey, 1977).

Lynn and Carhart (1963) evaluated three groups of moderately hearing-impaired listeners using a single-channel compressor. They modified rise and fall times to determine the impact on speech intelligibility. Best performance was obtained using compression with short rise (6 msec) and release (30 msec) times. Attack times of 5, 6, 20, 70 and 85 msec and release times of 30, 80, 150, 400 and 1200 msec were assessed. Maximum speech intelligibility using compression was, on average, 93% for the otosclerotic group, 82% for the presbycusic group and 80% for the endolymphatic hydrop groups. Increases in speech intelligibility over that obtained with uniform amplification was 2%, 9% and 8% for the otosclerotic, presbycusic and hydrop group respectively. As the time constants lengthened speech intelligibility worsened, due to the consonants being presented while compressed.

Yanick (1973) also found a significant improvement in speech recognition using a compression hearing aid. Twelve listeners with mild to moderate sensorineural hearing loss were evaluated with their own linear hearing aids and a compression hearing aid. Results showed a dramatic improvement in word recognition scores when speech was presented at 70 dB SPL. With the linear aid, average scores were 39% while with the compressed aid, average scores were 91%. These results may be compromised by the lack of control over the linear hearing aid. Listeners using their personal instruments may have not been provided with optimal amplification.

Similarly, Verschurre, Prinsen and Dreschler (1994) found improvement in speech intelligibility with syllabic compression, but of a much more modest degree.

They compared consonant recognition scores of six listeners with mild to moderately-severe sensorineural hearing loss. Speech stimuli were CVC words presented at 3 or 5 levels bracketing MCL, depending on the listeners dynamic range. Three conditions were evaluated: linear amplification, syllabic compression and syllabic compression coupled with frequency shaping. Average speech recognition scores were 86% with linear amplification and 90% with syllabic compression. There was no difference in the scores with the addition of frequency shaping.

In contrast, Plomp (1994) reports negative rather than positive effects of syllabic compression. He cites van Dijkhuizen (unpublished data, 1993). She compared speech intelligibility scores of sentences in noise obtained from 2 groups of subjects: 16 listeners with normal hearing and 16 listeners with hearing-impairment.Six conditions were evaluated: linear amplification, single channel syllabic compression and four multiband syllabic compression systems (2, 4, 8 and 16 channel). Four compression ratios were used, while attack and release times were instantaneous and 20 msec respectively. In all conditions, speech intelligibility using compression was poorer than that obtained with linear amplification.

Other equivocal findings on the benefit of syllabic compression have been reported by Bernath et al. (1977). They compared the speech intelligibility scores of two groups of listeners: one using a linear hearing aid and one using a syllabic compressor. Speech was presented in quiet and in noise. Best performance in quiet and with a signal to noise ratio of 20 dB was obtained with the linear hearing aid. In the signal to noise ratio of 10 dB, scores obtained with the syllabic compressor were higher but only marginally (Walker and Dillon, 1982).

Experimental evaluations of single band syllabic compression have yielded mixed results. Whereas some studies have shown improved speech intelligibility and /or quality, others have not shown improved performance resulting from the use of short time constants that provide different amounts of amplification for different speech sounds. Syllabic compression has also been evaluated in two-channel, and multi-channel systems (Bustamante and Braida, 1987; Moore, 1987; Nabelek, 1983; Moore and Glasberg, 1988; Moore, Lynch and Stone, 1992). Use of multiple channels provides the potential to compress high intensity components of speech within a given frequency band using one set of compression characteristics while simultaneously compressing components in alternate bands with a different set of characteristics.

Villchur (1973) has pointed out the limitations of single band compression. For example, a single-channel compressor will reduce overall gain for a strongly voiced /z/ sound, thereby rendering inaudible the low-level high-frequency components which are also important. In his initial study, Villchur assessed the benefit of two-channel compression with six moderate to severely hearing-impaired listeners compared to results obtained using an uncompressed system with frequency shaping only below 750 Hz. The crossover frequency for the bands was individually set for each subject and varied from 1.3 to 2.5 kHz. The signal was also shaped to provide equalized gain midway within the subject's dynamic range. Compression ratio's were 2.1:1 for the low channel and 2.8:1 for the high channel. Attack time was less than one msec and release time was 20 msec. Significant improvement in consonant recognition

(recognition of final consonants rose from 40% to 62% in quiet and from 34% to 49% in speech-shaped noise in the control condition and in the processed condition respectively) was reported. However, it should be noted that observed improvement may not be due solely to the compression, as the control condition had a flat response above 750 Hz.

The above study has been criticized in that the control condition underestimates the performance that could be obtained with a linear amplifier with appropriate frequency shaping. In a more recent study using a three-channel compression system, Villchur (1987) evaluated the efficacy of compression on speech perception over a linear system with frequency shaping derived from the listeners equal loudness contours. Speech was presented at three different input levels with four profoundly hearing-impaired listeners. Compression ratios varied across subjects and channels. The ratios were 1.6 - 2.0 for the low channel, 1.9 - 2.6 for the mid channel and 2.1 - 5.0 for the high channel. As in the two-channel system, frequency-gain characteristics and crossover frequencies were set individually for each subject. Improvement with compression was statistically significant in all conditions and greatest with the softest speech. With speech presented at the listeners preferred level, word recognition was on average 33% with uncompressed speech and 41% with compressed speech. When speech was 15 dB below preferred level, word recognition was 12% and 37% with uncompressed and compressed speech respectively.

Moore (1987) describes the design and evaluation of a two-channel compression system originally built by Laurence. The hearing aid used compression in two stages. The signal was first compressed by a slow acting automatic gain control, then split into two channels with a cross-over frequency of 1500 Hz. Syllabic compression was then used in each channel. Attack and release times were 2 and 50 msec for the low frequency channel and 2 and 10 msec for the high frequency channel, respectively. The system was evaluated on eight subjects with bilateral moderate sensorineural hearing loss. Moore compared speech intelligibility in noise with the two-channel system, a linear hearing aid and a single-channel slow acting AVC amplifier. Results indicated that best performance was obtained most often with most subjects using the two-channel system. On average, speech reception thresholds (SRT) in noise were 2.4 dB better with the compressed speech than with the linear hearing aid. A change of 1 dB in SRT is equivalent to approximately an 11% change in intelligibility. It should be noted that in these investigations, the two-channel system used both a single-channel slow acting AVC in addition to two-channel syllabic compression. It could be argued that most of the improvement was due to the AVC rather than the syllabic compression.

In a follow-up study, Moore and Glasberg (1988) found that a two-channel compression system without additional long term AVC amplification yielded better speech recognition than a single-channel compressor, or a linear amplifier with frequency shaping. Six moderately hearing-impaired subjects with reduced dynamic range showed best performance with compression in the high frequency channel and no compression in the low frequency channel. On average, speech reception thresholds (SRT) were 5.5 dB in quiet and 4 dB in speech shaped noise better with the compressed speech than with the linear hearing aid. As in the previous study, a change of 1 dB in SRT is equivalent to approximately an 11% change in intelligibility. Moore and Glasberg concluded that since most of the subjects had a large dynamic range in the low frequencies and narrow dynamic range in the high frequencies, compression of the latter allowed for optimal audibility of acoustic cues while protecting the listener from excessive intensity of high frequency consonants. Use of compression in the high frequency channel allowed for compression of the intense consonants but appropriate amplification of the weak consonants.

Moore, Johnson, Clark and Pluvinage (1992) evaluated a two-channel syllabic compression system used in a commercial hearing aid. Eighteen subjects with moderate to moderately-severe sensorineural hearing loss were assessed with their own hearing aids, a linear aid and the two-channel syllabic compressor. Comparisons were also made of monaural vs binaural hearing aid use and performance on sentence tests in quiet and in noise. Results indicated a significant improvement in speech intelligibility with the two-channel syllabic compressor. This improvement was observed at several signal levels and was evident in both the quiet and noise conditions. For example, average word recognition scores with speech in quiet presented at 50 dB SPL were 18% in the unaided condition, 75% using linear amplification and 93% using the two channel syllabic compressor. When speech was at 65 dB SPL, the scores were approximately 55%, 90% and 94% respectively .

It should be noted that with the Villchur and Moore studies, the large improvements obtained in initial experiments were partly a result of using a control condition that did not use the best linear amplification.

In contrast to the above, several other studies of multiband compression have yielded either ambiguous results or poorer performance in comparison with single-channel compression with appropriate frequency shaping (Nabelek, 1983; Walker, Byrne and Dillon, 1984; Yund, Simon and Efron, 1987; Bustamante and Braida, 1987). Nabelek (1983) compared speech recognition using three different types of amplification: wide-band syllabic compression, three-channel syllabic compression and linear amplification with frequency shaping. Thirteen listeners with moderate sensorineural hearing loss and narrow dynamic ranges were tested. Speech recognition was determined in each condition with nonsense syllables and words in both quiet and in noise and under different reverberant conditions. Best performance was obtained using the wideband compressor in quiet or with a large signal to noise ratio. When the signal to noise ratio was less favorable, or when the reverberation was present, benefit from compression was not observed.

Walker, Byrne and Dillon (1984) evaluated a six-channel syllabic compression system on four subjects with moderate sensorineural hearing loss. Attack and release times varied for each of the six channels. The former was either 3 or 5 msec while the latter was 30, 50 or 100 msec. The higher frequency channels had the shorter time constants. Speech intelligibility was determined using nonsense syllables presented at MCL, 10 dB below MCL and 10 dB above MCL. Results failed to show a consistent difference between the compression system and a linear system with frequency shaping, although considerable subject variability was noted. One subject showed similar performance in all conditions while another showed best performance in the linear condition with soft speech but better performance with the compression with loud speech. Walker et. al (1984) noted that, although the multiband compression system failed to improve speech intelligibility for all subjects, it was helpful in some conditions for some listeners.

Yund, Simon and Efron (1987) obtained an ambiguous result. They evaluated speech processed through a conventional hearing aid, speech processed through an eight-channel aid and natural speech. It should be noted that of the 20 subjects, seven were evaluated using their own personal hearing aids. The remaining 13 subjects were evaluated using the experimental system adjusted to provide the frequency-gain characteristics of a hearing aid recommended by an independent audiologist using the Carhart procedure. Five signal to noise (S/N) ratios were used. Significant improvements in speech recognition were obtained using the multi-band system at all S/N ratios. These improvements were made in comparison with the subjects own personal hearing aid and not always with a single channel amplifier of a quality comparable to that of the experimental system (e.g. with respect to bandwidth, internal noise, non-linear distortion).

Bustamante and Braida (1987) evaluated a sixteen-channel compression system. They measured speech recognition of two subjects with moderate hearing impairment using CVC nonsense syllables. Four different configurations of the compressor were used along with two linear amplifiers.

One linear amplifier mirrored the audiogram while the second linear amplifier provided as much of the speech signal into the residual hearing as was allowed by the listeners' tolerance levels. The frequency shaping used in the two linear systems were incorporated into the compressors with either moderate limiting or severe limiting. For one subject, moderate limiting was 10 dB below discomfort levels while for the second subject the limiter was set at 20 dB below discomfort levels. With the severe limiter, these levels were set at 20 dB and 30 dB for subjects one and two, respectively. The CVC's consisted of 1600 combinations of 6 vowels and 17 consonants and were presented at four input levels. Best performance was obtained with the compressor set to severe limiting and the speech at low input levels. However, performance at high input levels with the compression system was worse than with the linear amplifiers. Bustamante and Braida concluded that the use of multiple bands of compression caused spectral distortions at high input levels, reducing speech intelligibility. They suggested that either a single-channel wide-band compression limiter or a wideband AVC followed by a wideband limiter may provide benefit equivalent to the multi-band compressor at low input levels without reduced performance at high input levels.

In an attempt to reduce the spectral distortions, Bustamante and Braida developed an advanced form of multi-band compression in which gain in each frequency band was dependent not only on signal level within that band but also on the gain in adjacent frequency bands. This technique, known as principle component compression, also did not show significant improvement in speech intelligibility relative to single-channel compression with appropriate frequency shaping. Levitt and Neuman (1991) used a form of compression similar to the above known as orthogonal-polynomial compression. In this form of compression the short-term spectrum is adjusted dynamically so as to lie at a comfortable level at all frequencies over time. They compared speech recognition scores of eight listeners with sensorineural hearing impairment using conventional uniform linear amplification and orthogonal-polynomial compression. When speech was presented at 55 dB, word recognition with the linear system was approximately 43% on average. With the compressed speech, word recognition was 70%. However, when speech was at 70 or 90 dB SPL, word recognition scores were equivalent with both systems. A second study with four of the previous eight listeners compared the same systems which had been further modified by frequency shaping. As before, the linear system gave lower score (on average 79%) than the compressed speech (on average 89%) when speech was at 55 dB. Note that the frequency shaping improved the overall word recognition scores in both conditions. However, the orthogonal-polynomial compressor with a uniform frequency response did not show significant improvements in average intelligibility when compared with single-channel compression with appropriate frequency shaping. There were, however, large individual differences among subjects and two of the eight subjects showed some evidence of improved performance with orthogonal-polynomial compression.

Plomp (1988) cites three reasons for the reduced performance of multi-band compression systems: (1) the use of several bands causes spectral distortions, (2) the dynamic relationships within the speech signal are altered and (3) individual bands can be activated by fluctuating interfering sounds which influence the primary speech input. The lack of success with multi-band compression in noise and reverberation reflects these problems.

In summary, compression amplification appears to be useful in improving the intelligibility of amplified speech but only to a limited extent. Compression limiting is superior to peak clipping as a means of protection from excessively intense levels. Slow acting single-channel compression (AVC) with appropriate frequency shaping is a particularly promising approach compared to conventional amplification without compression, i.e. the dynamic range over which speech is intelligible is greater using AVC. Studies of single and multi-band syllabic compression have provided equivocal results. There is some evidence that two-channel syllabic compression provides increased speech intelligibility over single-channel AVC. In general, experimental evaluation of multi-band compression having more than two channels have not shown significant improvement relative to single channel compression.

MODIFICATION OF THE C-V RATIO

It has been argued by House (1993) that a characteristic of intelligible speech is a high C-V ratio. Evidence in support of this view is provided by Picheny, Durlach and Braida (1985; 1986). In a series of studies they explored the differences between normal conversational speech and "clear speech." The latter was obtained by instructing the talker "to speak as clearly as possible, as if he were trying to communicate in a noisy environment or with an impaired listener." Clear speech was found to be more intelligible than conversational speech to hearing impaired listeners. Acoustic analysis of the speech samples indicated that clear speech is characterized by consonants which were more intense relative to the vowels, by longer durations and by less syllabic reduction than in conversational speech. Although an increase in C-V ratio was not the only way in which clear speech differed from conversational speech, these experiments indicate the importance of the C-V ratio as a variable linked to improved intelligibility.

The potential benefit of adjusting the C-V ratio by modifying acoustic speech signal was examined by Gordon-Salant (1986) on normal hearing listeners listening in a 12-talker background babble with a signal to noise ratio of +6 dB. In this study, the effect of increasing the C-V ratio was evaluated as well as increasing the duration of the consonant and combining the C-V ratio and consonant duration modifications. Consonant recognition in CV nonsense syllables was evaluated with young and elderly listeners. Three enhancement conditions were used: (1) consonant duration increased by 100%, (2) the C-V intensity ratio improved by 10 dB and (3) consonant duration and C-V ratio enhancement combined. Significant increases (p. of at least 0.01) in consonant recognition were observed in the second and third conditions but were not observed in the first condition. Gordon-Salant suggests the improvement in the third condition is due to the change in C-V ratio rather than the increase in duration. Improvement in consonant recognition was approximately 12 percentage points with changes in the C-V ratio. The magnitude of the increase in consonant recognition varied with the type of modification, vowel environment and presentation levels. For all listeners, the largest improvement was observed when the C-V ratio was increased. Elderly listeners made more errors than did the younger listeners but the pattern of the errors was essentially the same for both groups. Results suggest that although acoustic feature enhancement offers considerable promise for increased consonant recognition, enhancement is a complex and unpredictable process. That is, the effect of enhancement of one cue may be impacted by the enhancement of a different cue. Gains made by enhancing specific features may not be additive.

In a follow-up study using the same stimuli (Gordon-Salant, 1987), the effect of enhancement of acoustic cues with moderately hearing-impaired subjects was studied. Three groups of listeners were assessed: (1) elderly listeners with gradually sloping sensorineural hearing impairment, (2) elderly listeners with sharply sloping losses and (3) elderly listeners with hearing considered to be normal for their age. Two presentation levels (75 and 90 dB SPL) were used. At 75 dB SPL consonant recognition in the baseline condition, averaged across vowel environment, was approximately 53% for the listeners with gradually sloping hearing loss and 49% for those with sharply sloping hearing loss. Results for the same listeners with modification of the C-V ratio were, on average, 69% and 66% respectively. At 90 dB SPL consonant recognition rose from approximately 57% in the baseline condition to 67% with the C-V modification for listeners with gradually sloping hearing loss. Listeners with sharply sloping hearing loss had consonant recognition scores of approximately

49% in the baseline condition and 62% with changes in the C-V ratio. Combining the increase in C-V ratio with an increase in consonant duration did not further affect performance at either presentation level. However, increasing presentation level improved performance for the gradually sloping hearing-impaired group.

The relationship between loudness perception and increased C-V ratio was explored using speech and nonspeech material with both normal hearing and moderately hearing-impaired listeners. (Montgomery, Prosek, Walden and Cord, 1987) Results indicated that perception of loudness remained constant regardless of C-V ratio (over the range considered) or its equivalent in the nonspeech material. The same results for speech and nonspeech material suggested that loudness judgments may have been based on the most intense portion of the signal. Typically, the vowels are the most intense sounds in the speech signal. The possibility thus exists that larger increases in the C-V ratio can be introduced relative to those used previously without causing loudness discomfort.

Montgomery and Edge (1988) also explored the relative effects of increasing the C-V ratio and consonant duration with monosyllabic words with young moderately hearing-impaired listeners. Consonant intensity was increased such that the C-V ratio was near-zero and the consonant durations were lengthened by a total of 30 ms. Consonant recognition was obtained at 2 intensity levels (65 and 95 dB SPL) in four conditions: (1) unenhanced, (2) increased C-V ratio, (3) increased consonant duration and (4) combined C-V ratio and duration enhancements. Twenty subjects were evaluated with speech at 65 dB SPL. Mean scores were 43% for the unprocessed speech and 53% for the increased C-V ratio. Ten listeners were evaluated with speech at 95 dB SPL. Mean scores for the unprocessed speech and C-V ratio modification were 70% and 72% respectively. Gains made by enhancing the C-V ratio were not constant across different listening levels. At the lower intensity level, acoustic cues to consonants in the unenhanced speech may have been inaudible and, consequently, an increase in C-V ratio would have raised many of these consonantal cues above the threshold of hearing. At 95 dB SPL, however, many of these cues may already be audible in the unenhanced speech and a further increase in consonant level is not of much benefit in improving intelligibility.

Montgomery and Edge (1988) noted that some subjects reported informally that processed speech was not perceived as louder than unenhanced speech, even at 95 dB SPL. The perception of loudness may have been determined primarily by the more intense vowel sounds and not affected by altering consonant intensity. As noted earlier, it may thus be possible to use even larger C-V ratio's in order to improve consonant recognition without causing loudness discomfort.

The effect of manipulation of the C-V ratio, by means of waveform editing, on speech perception of eight CV syllables was assessed by Freyman and Nerbonne (1989). They evaluated a large number (50) of normal hearing listeners using eight CV syllables presented at 65 dB SPL in white noise with a zero signal to noise ratio. The intelligibility of ten talkers was compared in three conditions: (1) the C-V ratio was left in a natural condition and adjusted such that the vowel energy for all ten talkers was equal, (2) the C-V ratio was adjusted such that all consonants for a given talker were at the highest level for that talker and (3) the C-V ratio was unmodified but the consonants were equated to the highest consonant level for each talker. Average consonant recognition scores were approximately 52% for condition one, 64% for condition two and 70% for condition three. Best performance was obtained with the third condition. The average increase in consonant recognition varied significantly with consonant and with talker.

As previously discussed, an indirect method of increasing the C-V ratio is to provide a high-frequency boost to the signal since most of the consonantal sounds contain significant high frequency components and the vowels consist mostly of powerful low-frequency components. A frequency response that amplifies high frequencies more than low frequencies will effectively increase the C-V ratio. Similarly, adaptive forms of amplification, such as compression amplification, will provide more gain to the weaker high frequency consonants than to the more powerful low frequency vowels, thereby increasing the C-V ratio. Although the magnitude of the increase in C-V ratio obtained by these means is limited, they are nevertheless attractive in that these methods can be readily implemented using existing technology.

PRACTICAL METHODS FOR IMPLEMENTING C-V RATIO ADJUSTMENTS

As discussed in the preceding three sections, an appropriate frequency-gain characteristic as well as appropriate compression characteristics can improve intelligibility. Whether this improvement is due to an increase in the C-V ratio is an interesting question with important practical implications. Preves et al. (1991) evaluated four algorithms designed to enhance C-V ratio using combinations of frequency shaping and adaptive amplification. These were: (1) an adaptive high-pass filter, (2) a more rapid high-pass filter, (3) a high pass filter with expansion (i.e. compression ratio less than one) and (4) an infinite amplitude clipper. A 4-6 dB increase in C-V ratio was realized by each algorithm compared to unprocessed speech. All the systems were constructed using current in-the-ear hearing aid technology.

Two groups of listeners with sensorineural hearing loss were tested: four listeners with moderately sloping and four with sharply sloping losses. Stimuli were nonsense syllables. Listeners with moderately sloping hearing loss scored, on average, 68% in quiet and 62% in an eight talker babble noise (10 dB S/N) with the unprocessed speech. These scores were approximately 78% and 64% following modification of the C-V ratio. Listeners with sharply sloping hearing losses had average consonant recognition scores in quiet of 47% and 66% with unprocessed speech and modified C-V ratio, respectively. In noise, scores were essentially the same: 64% with unprocessed speech and 62% with processed speech. These results indicate that existing hearing aid technology can be used to increase the C-V ratio in a practical instrument and obtain a corresponding increase in speech intelligibility. A limitation of the above experiment, however, was that the experimental systems were not compared to a conventional frequency selective amplifier. It remains unclear whether or not the same improvement could have been obtained using conventional hearing aids with appropriate frequency shaping.

The effect of differences among vowels in deriving an appropriate C-V ratio must also be considered. The relative intensity of the consonant will vary with different vowels and these differences may impact on speech recognition in a hearing aid designed to adjust the C-V ratio for improved speech intelligibility. A complex interaction appears to occur between the configuration of the hearing loss, the vowel environment and the acoustic cues made available to the hearing-impaired listener. (Dubno, Dirks and Schaefer, 1987; Gordan-Salant,1987;). Performance is not equivalent with all vowels nor is it the same across studies. Dubno, Dirks and Schafer (1987) found performance with /i/ generally to be poorer than with /a/ or /u/ while Gordon-Salant (1987) found performance varied with sensation level and with enhancement conditions. Although the talkers in the two studies were different, as were the speech stimuli, further study is needed to understand the impact of vowel environment on C-V ratio and the nature of this relationship at C-V ratios designed to maximize speech intelligibility.

CONCLUSIONS

Modification of the C-V ratio appears to be a promising approach to improving speech intelligibility for hearing impaired listeners. Traditional methods of signal processing which have been shown to increase speech intelligibility, such as frequency shaping with high frequency emphasis and various forms of compression amplification also effectively improve the C-V ratio, but only by a small amount. Similarly, acoustic studies of clear speech show that one of the characteristics of intelligible speech is a higher C-V ratio. Further, experiments in which C-V ratio has been adjusted by manipulation of the acoustic speech signal have also shown improved intelligibility, although the magnitude of these improvements has been small. In these studies, however, fixed increases in consonant intensity were applied equally to all subjects for all conditions. Given the variability of intensity among consonants, the effect of the vowel environment on consonant intensity and the large individual differences among hearing-impaired subjects, it is likely that much larger improvements in consonant recognition could be obtained if increases in C-V ratio were adjusted individually for each consonant and vowel environment for each subject.

It would be very useful towards furthering our understanding of speech perception in hearing impaired listeners as well as providing useful practical information that could lead to the development of better hearing aids, to determine the conditions under which consonant recognition is maximized by adjustment of the C-V ratio. The purpose of this study was to determine the C-V ratio that maximizes consonant recognition as a function of consonant type, vowel environment and audiometric configuration.

CHAPTER III

EXPERIMENTAL METHOD

This chapter will describe the subjects, the stimuli, the equipment and the procedures used to obtain data.

SUBJECTS

Eighteen subjects were recruited for this study. Listeners were grouped according to their audiometric configurations and were classified as flat, sloping or precipitous. Flat audiograms were defined as those with pure tone thresholds within a 20 dB HL range for frequencies 500-4000 Hz. Six subjects, two males and four females, ranging in age from 16 to 80 years met this criterion. Sloping audiograms were those with pure tone thresholds falling at the rate of 20 to 40 dB HL in at least one octave across 500-4000 Hz. Six subjects, three males and three females, ranging in age from 31 to 78 years, met this criterion. Precipitous audiograms were those with pure tone thresholds that declined at minimum of 40 dB in at least one octave for frequencies 500-4000 Hz. This group was comprised of four males and two females, ranging in age from 38 to 72 years.

The wide range in age between 16 to 80 years reflected the difficulty in the availability of subjects. The influence of age on the auditory system was not considered a factor since the task involved single responses in a closed set of nonsense syllables. Older normal hearing listeners make the same type of speech recognition errors as do younger listeners, although the quantity of these errors may be higher (Gelfand and Silman, 1985). Similar findings were observed by Gordon-Salant with listeners with hearing impairment (Gordon-Salant, 1986).

Although every attempt was made to select equal numbers of male and female subjects for each group, this was not always possible given the available subject pool. Of the eighteen subjects, nine were male and nine female; all were native speakers of English. All listeners had sensorineural hearing loss with three-frequency pure tone averages between 40-70 dB HL in the ear used for this study. Although the three frequency average overestimates precipitous hearing loss when compared to flat hearing loss, it was used to limit subjects to those with mild to moderately severe hearing loss. Thirteen of the subjects had symmetrical hearing loss and used binaural amplification. One subject in the precipitous group had a symmetrical hearing loss but used a monaural hearing aid. A second subject in that group had an asymmetrical loss and used a CROS hearing aid. Both subjects used their aided ear for this study. Three subjects in the flat group had mild hearing loss in the non-test ear and used monaural amplification. Again, the aided ear was used for this research. Moderate to moderately-severe hearing-impaired listeners were chosen since they represented a large percentage of the hearing-impaired population and thus far have demonstrated benefit in studies involving modifications in the C-V ratio. (Gordon-Salant, 1987; Montgomery and Edge, 1988). Tables 1, 2 and 3 show the gender, age, pure tone thresholds and word recognition scores (Auditec recording NU-6 word list) for the test ear for each subject in the flat, sloping and precipitous groups respectively. Figures 1, 2 and 3 present composite audiograms of the mean threshold levels for each experimental group.

Subjects were assumed to have cochlear pathology in that audiograms, tone decay at 2000 Hz using the Olsen-Noffsinger (1974) technique, acoustic immittance procedures and reflex decay failed to reveal signs of conductive or retrocochlear pathology. All subjects were free of active otologic disease, as determined by subject report. Subjects were experienced hearing aid users, having worn amplification for at least one year in the test ear.

Normal-hearing subjects were recruited from a pool of office support staff, graduate students and faculty at a University Speech-Language-Hearing Center. The population of this pool was predominately female, and all males willing to participate failed to meet audiologic criteria. Six normal hearing, English speaking females between the ages of 23 and 44 served as controls. Each had pure tone thresholds better than 15 dB HL at all frequencies between 250 and 8000 Hz, normal acoustic immittance measures, no clinically significant tone decay or reflex decay and a negative history of otologic disease.

TABLE 1. Subject characteristics and audiometric data for the test ear in the flat audiometric configuration.

			Pure Tone Thresholds (db HL)										Word Recog.Score (% Correct)	
S.	Gender	Age (Yr.)	.25	.5	.75	1	1.5	2	3	4	6	8kHz.	%	@ MCL(dB HL)
F1	F	80	37	39	40	35	41	41	48	58	63	76	60	75
F2	M	72	51	41	40	44	41	35	42	53	54	77	38	90
F3	F	21	29	36	36	47	48	49	52	57	44	48	34	60
F4	M	16	14	31	42	48	57	68	62	58	56	62	66	80
F5	F	45	49	61	58	62	61	62	56	54	49	65	14	80
F6	F	40	52	61	68	65	63	60	51	53	48	48	24	80
	mean	45	38	44	47	50	51	52	51	55	52	62	39	77

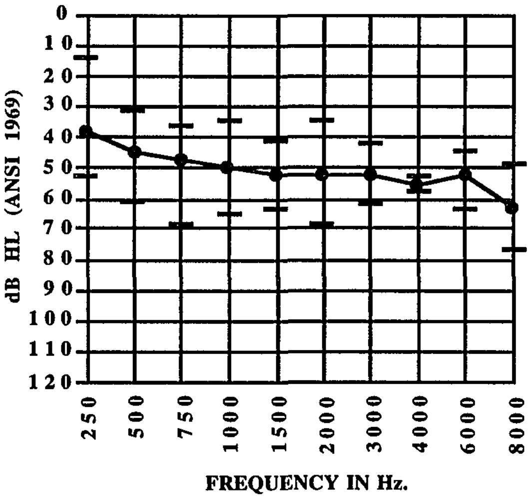

Figure 1. Mean thresholds and ranges for test ears in the flat audiometric configuration.

TABLE 2. Subject characteristics and audiometric data for the test ear in the sloping audiometric configuration.

			Pure Tone Thresholds (db HL)										Word Recog.Score (% Correct)	
S.	Gender	Age (Yr.)	.25	.5	.75	1	1.5	2	3	4	6	8kHz.	% @	MCL(dB HL)
S1	M	54	15	19	32	42	46	49	67	58	67	58	52	75
S2	M	78	12	25	32	44	63	57	63	67	64	69	56	70
S3	M	35	10	18	33	54	64	60	56	52	32	13	66	75
S4	F	39	13	22	40	60	63	52	55	48	60	76	74	75
S5	F	44	36	49	70	72	79	80	69	75	84	79	42	90
S6	F	31	31	34	38	51	65	59	50	51	52	55	46	75
	mean	46	19	27	40	53	63	59	60	58	59	58	56	77

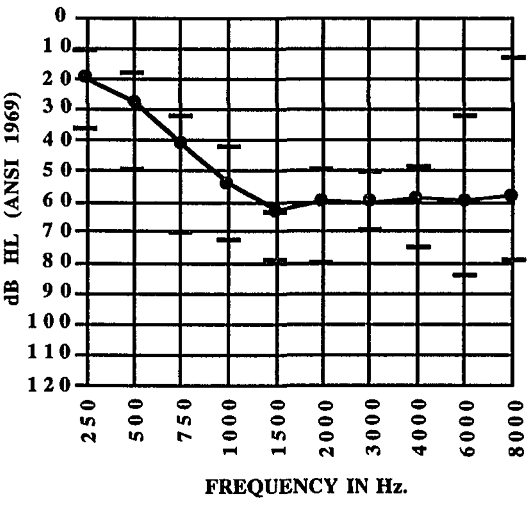

Figure 2. Mean thresholds and ranges for test ears in the sloping audiometric configuration.

TABLE 3. Subject characteristics and audiometric data for the test ear in the precipitous audiometric configuration.

			Pure Tone Thresholds (db HL)										Word Recog.Score (% Correct)	
S.	Gender	Age (Yr.)	.25	.5	.75	1	1.5	2	3	4	6	8kHz.	%	@ MCL(dB HL)
P1	F	38	22	23	30	28	35	55	79	81	81	77	66	65
P2	M	54	6	20	29	31	35	57	79	76	84	73	66	80
P3	M	72	37	39	25	23	58	65	96	83	110+	95+	46	85
P4	M	72	20	24	39	67	72	66	63	66	60	62	28	80
P5	M	53	23	62	73	82	81	91	104	104	91	84	12	90
P6	F	45	34	54	65	74	103	114	97	88	110+	95+	24	85
	mean	55	23	37	43	50	64	74	86	83	90	81	40	80

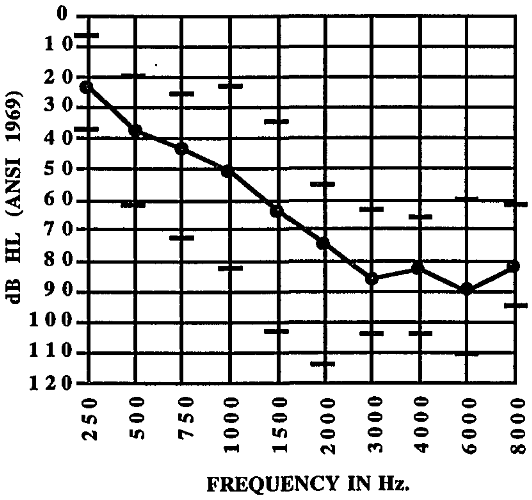

Figure 3. Mean thresholds and ranges for test ears in the precipitous audiometric configuration.

STIMULI

The stimuli were derived from selected subtests of the Nonsense Syllable Test (NST) (Resnick, Dubno, Hoffnung and Levitt, 1975). Although the NST has both vowel-consonant (VC) and consonant-vowel (CV) syllable subsets, only the VC syllables were used. Final consonants present the greatest difficulty in speech recognition tasks due to reduced overall intensity when compared to initial consonants and temporal masking of the preceding vowel (Picheny, Durlach and Braida, 1985; 1986) and because final consonants present the greatest difficulty to hearing-impaired listeners (Boothroyd, 1984). The NST tape was digitized using a 12 bit analog to digital converter (Data Translation 2801 Board) at a sampling rate of 20 kHz. The same board was used for digital to analog conversion after processing. Both input and output signals were low-pass filtered at 9.5 kHz to eliminate aliasing errors and imaging distortions.

Using the waveform editing techniques and procedures described in Dubno and Levitt (1981), the individual consonant and vowel portions of each VC in the digitized speech signal were isolated. This was accomplished by viewing the digitized waveform of each VC and partitioning the vowel and consonant portions. Differentiation of each segment was done at the point of abrupt change in the waveform. Sectioning of the vowel from the consonant was done at the zero crossing of the waveform. An acoustic analysis of each segment, performed by listening to both segments, verified the segmentation. That is, when the vowel was segmented visually from the VC, the resulting vowel in isolation was evaluated acoustically to insure the vowel remained complete and free from components of the consonant. In cases using stop consonants and fricatives, such differentiation was relatively easily determined. However, with the nasal consonants, due to coarticulatory effects, there was a lack of a clear visual point of segmentation. In such cases, the auditory analysis served to provide the best point of segmentation.

Several issues needed to be considered in specifying the C-V ratio. Both the level of the consonant and the level of the vowel varied from one nonsense syllable to the next. For convenience in specifying the changes in the C-V ratio that were investigated in this study, the unenhanced condition was defined to have a consonant enhancement level (CE level) of 0 dB. The CE level was incremented in steps of 3 or 6 dB steps to a maximum CE level of +24 dB. A Glossary of symbols used to represent each consonant and vowel precedes the appendices. Tables 4 and 5 show the C-V ratio (consonant intensity in dB less by vowel intensity in dB) for each nonsense syllable in the unenhanced condition. Note that for each subject the carrier phrase was presented at the listeners MCL. Hence, the consonant intensity shown in tables 4 and 5 are specified in dB relative to the subjects MCL.

Vowel environments /a/, /i/ and /u/ were used. Two sets of consonants were used: Set 1 consisted of the voiceless consonants /s,sh,t,p,k,th,f/ and Set 2 consisted of the voiced consonants /n, m, ng, z, d, b, v, g, vth,/. (Note that, as is shown in the Glossary, /vth/ is used throughout this paper to represent voiced

TABLE 4. C-V ratio of each consonant paired with each vowel for the voiced consonants.

Nonsense Syllable	C-V in dB
ang	- 8.1
an	- 6.6
am	- 4.3
az	-11.0
ag	-15.1
ad	-15.1
avth	-27.0
ab	-16.5
av	-15.5
ing	- 6.1
in	- 8.9
im	- 5.7
iz	- 8.8
ig	-11.6
id	- 9.6
ivth	-12.6
ib	-14.4
iv	-12.4
ung	- 4.3
un	- 2.7
um	- 5.6
uz	- 9.1
ug	-15.8
ud	-15.6
uvth	-15.0
ub	-17.4
uv	-16.6

TABLE 5. C-V ratio of each consonant paired with each vowel for the voiceless consonants.

Nonsense Syllable	C-V in dB
as	-12.8
ash	-11.5
at	-25.9
ak	-25.6
ath	-27.0
ap	-26.2
af	-28.7
is	- 1.9
ish	- 9.5
it	-15.1
ik	-19.5
ith	-20.0
ip	-23.6
if	-24.1
us	- 7.4
ush	-12.3
ut	-22.2
uk	-27.1
uth	-23.8
up	-28.0
uf	-24.6

interdental while /th/ is used to represent voiceless interdental.) A total of 168 tokens for Set 1 and 216 tokens for Set 2 were generated. The new C-V syllables were connected to the CUNY NST carrier phrase "You will mark ..." The final word "please" used in the original test was not attached to the new VC's. Appendix A shows waveforms of selected stimuli.

INSTRUMENTATION

Audiologic testing was done using a Madsen OB 802* clinical audiometer. Speech signals were played on a Technics cassette player routed though the audiometer. Bone conduction testing was done using a Radioear B-71 vibrator. All air conduction listening was performed under TDH 39 earphones with standard MX-41/AR cushions. Acoustic immittance measures were made using an Amplaid 702 clinical acoustic immittance meter.

The experimental stimuli were stored digitally (20 kHz sampling rate, 16 bit resolution) on the hard disk of a 386-based personal computer. Stimuli were selected randomly, converted to analog form using a Data Translation 2801-A data acquisition board and low pass filtered with a cut-off frequency of 9500 Hz to remove any aliasing or imaging errors. Signals were passed though a step attenuator and two variable amplifiers (Realistic) to the same TDH 39 earphones used during the audiometric testing. Voltage measurements were made with a voltmeter placed after the final amplifier. Subjects responses were made on an extended keyboard placed in the IAC booth with the subject. Figure 4 shows a block diagram of instrumentation.

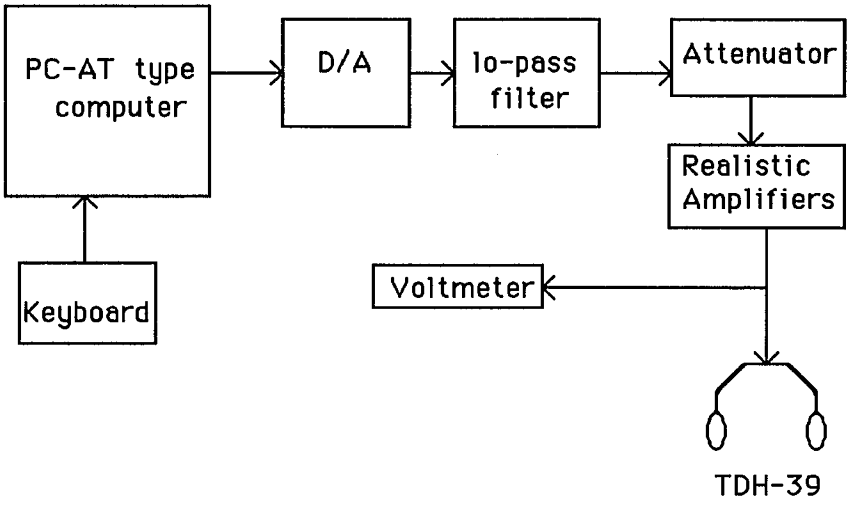

FIGURE 4: Block diagram of instrumentation used for data collection.

PROCEDURE

All testing was done in a sound treated environment (single wall IAC booth) in a quiet office. Sound field measurements confirmed ambient noise to be within the ANSI standards for audiologic testing. Prior to testing, subjects completed a history form (see Appendix B for form).

Pure tone air and bone conduction thresholds were obtained for test frequencies 250 through 8000 Hz using ASHA Guidelines for Manual Pure Tone Threshold

Audiometry (ASHA, 1977). All subjects had sensorineural hearing loss with air-bone gaps no greater than 10 dB and normal tympanograms. Tone decay at 2000 Hz using the Olsen - Noffsinger technique and reflex decay at 500 and 1000 Hz were performed to rule out retrocochlear pathology. All subjects had less than 20 dB tone decay in 60 seconds and no significant reflex decay within a 10 second period.

The test ear was chosen. Monaurally aided subjects listened with their aided ear; other subjects used their preferred ear. Pure tone thresholds were obtained a second time in the test ear using an adaptive up-down procedure with a final step size of one dB (Levitt 1978) to allow for precise audibility measures. All listening was completed in the same ear. Word recognition scores were obtained in the test ear using an Auditec recording of the NU-6 word list presented at MCL. All hearing-impaired subjects scored below 80% and all controls scored above 80% on this test using a fifty item list.

Most Comfortable Level (MCL) was obtained using the method outlined by Dirks and Kamm (1976). (Appendix C) Subjects established MCL using the carrier phrase " You will mark..." from the CUNY NST as stimulus. Once MCL was established, a voltage reading was taken of a 500 Hz calibration tone which served as the reference level for all subsequent presentations. This insured that all listening was done at the same signal level. All subsequent listening was done in the same ear with the vowel of the test item at MCL. MCL was chosen as presentation level for testing since most hearing-impaired listeners set hearing aids at this level.

Uncomfortable Listening Levels (UCL) measurements were obtained for each vowel and consonant combination to insure that stimuli remained safely within the subject's dynamic range. UCL measures were obtained using a modification of the Cox (1983) procedure. (Appendix D) Subjects were presented with each VC with the consonant intensity level increasing in 3 dB steps to a maximum of +24 dB. If a subject reported UCL at levels below 24 dB, the reported level was used to set the uppermost level for the enhanced VC for that specific subject. Maximum enhancement of each consonant was limited to a level 3 dB below the UCL for the specific consonant as measured by each subject. If subjects did not indicate speech tolerance at a level less than or equal to 24 dB, the tolerance was assumed to be in excess of 24 dB and the uppermost limit for the enhanced speech was set at 24 dB. Thus each consonant within a given test may have had a different range of enhancement across subjects. Each enhancement level had 20 presentations per consonant.

Consonant Enhancement (CE) functions were generated for each subject for each consonant in each vowel environment. Given that UCL varied across subjects for a given consonant and within subjects across consonants, the number of levels per CE function also varied. If the dynamic range was between 15 and 24 dB, each CE function was made up of 5 data points representing zero enhancement (natural speech) and 4 enhancement levels of the consonant. If the dynamic range was less than 15 dB, fewer points on the CE function were obtained. In order to be consistent across listeners' CE functions, the following guidelines were used:

UCL	POINTS ON CE FUNCTION
6 dB enhancement	0 and 3 dB enhancement
9 dB enhancement	0, 3 and 6 dB enhancement
12 dB enhancement	0, 3, 6 and 9 dB enhancement
15 dB enhancement	0, 3, 6, 9 and 12 dB enhancement
18 dB enhancement	0,6, 9, 12 and 15 dB enhancement
21 dB enhancement	0, 6, 12, 15 and 18 dB enhancement
24 dB enhancement	0, 6, 12, 18 and 21 dB enhancement
24+ dB enhancement	0, 6, 12, 18 and 24 dB enhancement

Tokens for each consonant were generated and randomized individually for each subject in each of the two sets. Twenty repetitions of each relevant VC were randomized and stored. The stimuli were presented to the subjects who were required to indicate which final consonant they heard. Subjects responded using a keyboard coded with the appropriate orthographic symbols. The keyboard was modified to render keys inoperable save those associated with the consonant set. The next stimulus was not presented until 1 second after the subject responded on the keyboard. This allowed subjects to progress at a reasonable rate but did not force subjects to respond in a fixed time. Responses, which were stored in computer memory, were scored by computer to obtain percentage correct scores at each presentation level. After the completion of the test, these data were plotted as CE functions.

Subjects were unable to complete the entire procedure in a single sitting. They were encouraged to take a break whenever the need arose. Subjects took from four to eleven visits to complete the experiment.

CHAPTER IV

RESULTS

Subject responses were organized and analyzed as follows. Percent correct scores and error patterns were determined for each VC at each level of enhancement. Confusion matrices of voiced and voiceless consonants were generated for each audiometric configuration in each vowel environment for unenhanced speech and maximum score conditions.

Consonant Enhancement (CE) functions were also generated for each VC for each subject (see Appendix E for CE functions). Two scores were obtained from each CE function: the percent correct using natural speech (0 dB enhancement on the CE function), and the percent correct at maximum score. The difference between these measures was determined in arc sine units to stabilize error variance. Additionally, the level of enhancement required to obtain maximum score (CE_{max}) was determined.

The following analyses were performed:

1). an analysis of consonant recognition

2). an analysis of improvement in consonant recognition

3). an analysis of CE_{max} (the enhancement level at which the at maximum score was obtained)

4). an analysis of consonant confusions

These analyses were performed using the following techniques:

i) Analysis of variance was performed on the test scores for the unenhanced (natural) speech. Separate ANOVA's were done for the voiced and voiceless conditions.

ii) The maximum score for each CE function was identified and ANOVA's were performed on maximum scores. Separate ANOVA's were done for the voiced and voiceless conditions.

iii) An ANOVA was performed on the difference between the maximum score condition and the unenhanced condition. In this Anova, the voiced and voiceless conditions were analysed together.

iv) Separate ANOVA's were performed on the CV ratio at which maximum score was obtained (CE_{max}). Separate ANOVA's were done for the voiced and voiceless conditions.

v) Consonant confusions were analysed by means of a Chi square performed on contingency tables for each audiometric group. Separate statistics were obtained for voiced and voiceless conditions.

ANALYSIS OF CONSONANT RECOGNITION

The first three ANOVA's provide information regarding the intelligibility of the signal. A four-way analysis of variance was performed on results obtained with the natural speech and with maximum performance (CR_{max}) in the enhanced condition for each of the voiced and voiceless sets. The data were subjected to an arc-sine transformation in order to stabilize the error variance. Factors used in each analysis were: Consonant (C) (either the voiced set of /b/d/g/v/vth/z/m/n/ng/ or the voiceless set of /p/t/k/f/th/s/sh/), Vowel Environment (V) (/a/u/i/), Audiometric Configuration (A) (flat, sloping, precipitous) and subject. A repeated measures ANOVA, with Subjects (S) nested within groups, was used.

The results of the ANOVA's for the unenhanced CV's are shown in Tables 6 and 7. The factors of Consonant (C), Vowel Environment (V) and CxV interaction were found to be significant at the .01 level or greater. Tables 8 and 9 show the results for the CR_{max}. Three factors, Consonant (C), Vowel Environment (V) and Audiometric Configuration, and the CxV interaction were found to be significant at the .01 level or greater in this analysis also.

Additional factors were significant in some analyses. Significant Consonant type by Audiometric Configuration (CxA) interactions were found for CR_{max} for both the voiced and the voiceless sets (Tables 8 and 9).

The magnitude of the Consonant effect is shown in Figures 5 and 6 for both the unenhanced condition and for CR_{max}. These data have been averaged across Vowel Environment and Audiometric Configuration. The light bars show the scores for the unenhanced conditions while the dark bars show CR_{max}. Averages were obtained for scores in arc sine units and were transformed back to proportions for ease in interpretation. Each diagram shows the consonants in order of relative intensity in the natural (unenhanced) speech condition. Intensity was used to establish consonant order since speech passed

TABLE 6: Analysis of Variance of Consonant Recognition Scores obtained with Natural Speech for Voiced Consonants. The asterisk (*) refers to the variance among Subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config (A)	07.68	02	03.84	00.73	
Consonant (C)	60.71	08	07.59	09.52	.001
Vowel (V)	16.71	02	08.35	23.15	.001
Variance(S)*	78.82	15	05.25		
A x C	15.61	16	00.98	01.22	
A x V	03.27	04	00.82	02.27	
C x V	44.88	16	02.80	06.70	.001
Variance(SC)*	95.61	120	00.36		
Variance(SV)*	10.83	30	00.43		
A x C x V	14.33	32	00.44	01.07	
Variance(SCV)*	100.54	240	00.38		
TOTAL	449.03	485			

TABLE 7: Analysis of Variance of Consonant Recognition Scores obtained with Natural Speech for Voiceless Consonants. The asterisk (*) refers to the variance among Subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config (A)	11.60	02	5.80	1.16	
Consonant (C)	51.60	06	8.60	8.78	.001
Vowel (V)	04.39	02	2.19	5.53	.01
Variance(S)*	75.32	15	5.02		
A x C	20.33	12	1.69	1.73	
A x V	02.19	04	0.54	1.38	
C x V	23.73	12	1.98	5.66	.001
Variance(SC)*	88.20	90	0.98		
Variance(SV)*	11.93	30	0.39		
A x C x V	05.54	24	0.23	0.66	
Variance(SCV)*	62.91	180	0.34		
TOTAL	357.80	377			

TABLE 8: Analysis of Variance of Maximum Consonant Recognition Scores obtained with Enhanced Speech for Voiced Consonants. The asterisk (*) refers to the variance among Subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config (A)	24.64	02	12.31	02.54	.001
Consonant (C)	129.37	08	16.17	12.69	.001
Vowel (V)	05.45	02	00.52	12.69	.001
Variance(S)*	72.81	15	04.85		
A x C	21.58	16	01.34	01.92	.05
A x V	02.49	04	00.62	02.91	.05
C x V	44.17	16	02.76	06.90	.001
Variance(SC)*	84.23	120	00.70		
Variance(SV)*	06.45	30	00.22		
A x C x V	15.23	32	00.47	01.19	
Variance(SCV)*	96.02	240	00.40		
TOTAL	502.44	485			

TABLE 9: Analysis of Variance of Maximum Consonant Recognition Scores obtained with Enhanced Speech for Voiceless Consonants. The asterisk (*) refers to the variance among Subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config (A)	25.12	02	12.56	03.81	.05
Consonant (C)	98.94	06	16.49	31.21	.001
Vowel (V)	03.08	02	01.54	07.53	.01
Variance(S)*	37.81	15	02.52		
A x C	21.41	12	01.78	03.38	.001
A x V	01.12	04	00.28	01.37	
C x V	18.34	12	01.53	06.32	.001
Variance(SC)*	47.55	90	00.53		
Variance(SV)*	06.13	30	00.20		
A x C x V	07.79	24	00.32	01.34	
Variance(SCV)*	43.56	180	00.24		
TOTAL	322.56	377			

through a conventional compressor would have the greatest impact on most intense consonants. Using intensity to set the order allows for comparison of current results with those anticipated using conventional compression.

The voiced consonants were grouped into four sets based on consonant intensity: /n,m,ng/, /z/ and /d,b,g/ /v,vth/. The intense fricative /z/, showed the greatest improvement in consonant recognition (26%) at CR_{max} over the unenhanced condition. The stops, which are less intense, showed an average improvement of 19%. The nasals formed the third group and are the most intense consonants. They showed least improvement (9%) in performance (Fig.5). The weak fricatives showed very different scores for each fricative. The /v/ showed improvement averaging 23% while the /vth/ showed nearly identical scores in both conditions (an average difference of .008%). Averaged across all voiced consonants, improvement was 15%.

The voiceless consonants were grouped into three sets based on consonant intensity: /s,sh/, /t,p,k/ and /th,f/ (Fig. 6). The more intense fricatives showed uniform and greatest improvement averaging 32.5%. The stops, which were less intense, show improvement (19%) within the group but did not yield gains consistently equal to those of the first group. The lingual-dental and the labial-dental fricatives were the least intense and formed the third group. The /f/ showed improvement averaging 37% while the /th/ had little difference (5%) between the two conditions. The lingual-dental fricative showed similar results in both the voiced and voiceless conditions. Averaged across all voiceless consonants, improvement was 24%.

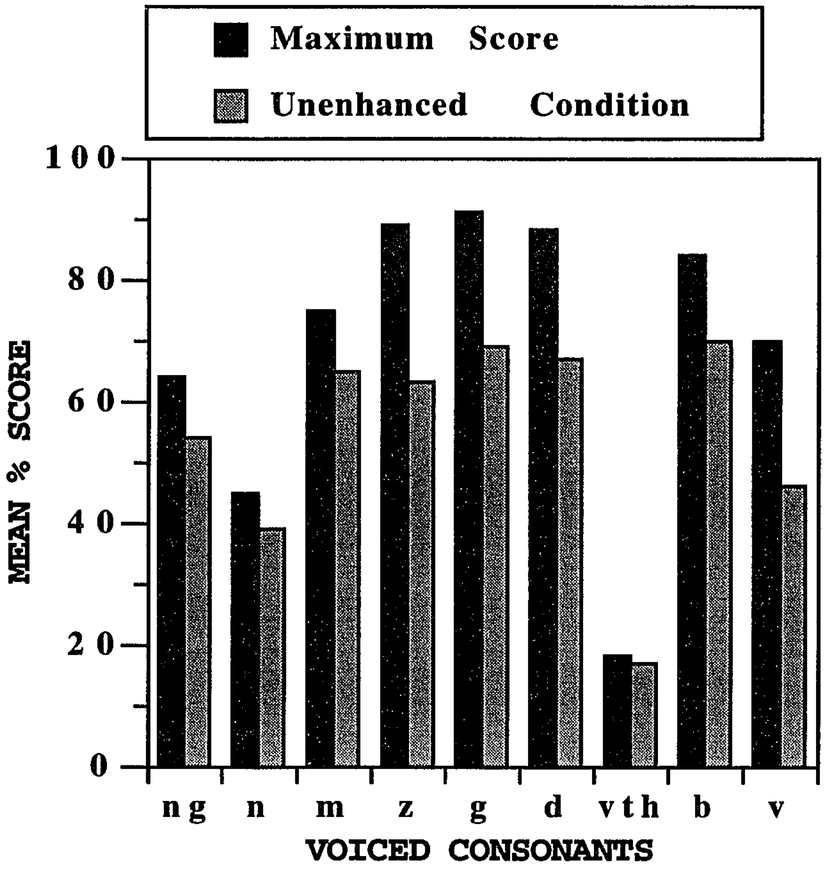

Figure 5. Histograms of mean scores for the voiced consonants obtained at CR_{max} for enhanced speech and for natural speech averaged over Subjects. These data have been averaged across Audiometric Configuration and Vowel Environment.

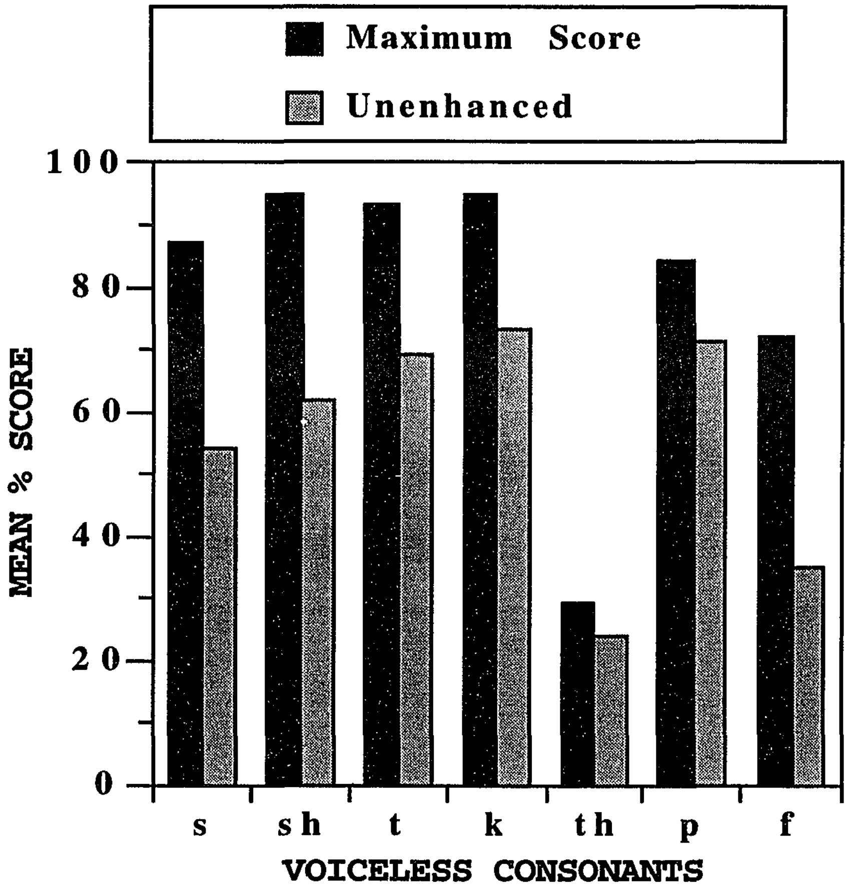

Figure 6. Histograms of mean scores for the voiceless consonants obtained at CR_{max} for enhanced speech and for natural speech averaged over Subjects. These data have been averaged across Vowel Environment and Audiometric Configuration.

The magnitude of the Vowel Environment effect is shown in Figure 7 for both the unenhanced condition and the CR_{max}. These data have been averaged across Consonant and Audiometric Configuration. As before, the light bars represent natural speech and the dark bars represent CR_{max}. For ease in interpretation, each figure shows the vowels in the same order.

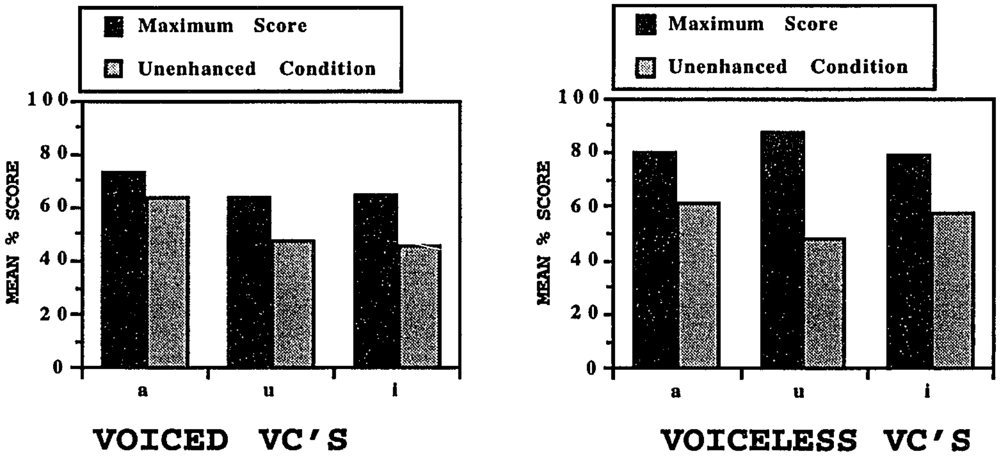

Figure 7. Histograms of means scores obtained at CR_{max} and for natural speech in different Vowel Environments. These data have been averaged across Consonants and Audiometric Configuration. The histograms on the left represent data with voiced VC's while those on the right represent voiceless VC's.

In the voiced consonants, highest average performance (77%) was obtained in the CR_{max} with the vowel /a/. Similar average performance, 69% and 67%, was obtained with /u/ and /i/ respectively. However, with the voiceless consonants, maximum score (87%) was obtained with the /u/ vowel, followed by /a/ at 80% on average and /i/ at 79% on average.

Several significant interactions were evident in the ANOVA's. There are significant Consonant and Vowel Environment (CxV) interactions in both consonant sets in the unenhanced condition and at CR_{max} (Tables 6-9). A significant Consonant by Audiometric Configuration (CxG) interaction is evident at CR_{max} with both the voiced and voiceless consonant sets.

Figure 8 shows the relationship between Consonant and Vowel Environments for the voiced set with unenhanced speech. As was the case with the main effect histograms, the consonants are presented in order of relative intensity in the natural speech condition. Dark bars show scores for consonants in the /a/ vowel environment, light bars show scores for the /u/ environment and crosshatched bars are associated with scores with the /i/ vowel. Consonant recognition varies significantly with Vowel Environment. For example, with /g/, performance in the unenhanced condition is 82%, 69% and 53% in the /a/, /u/ and /i/ environments. At CR_{max}, these scores were more uniform: 92% with /a/, 94% with /u/ and 86% with /i/. Note that the stop consonants and the fricatives show a similar pattern across vowel environment but the nasals, especially /n/, shows a much higher score (88%) with the /a/ vowel environment than for /u/ at 17% or /i/ at 13% in the unenhanced condition. For the /i/ environment, /m,n,ng/ show very different scores of 50%, 13% and 66% respectively.

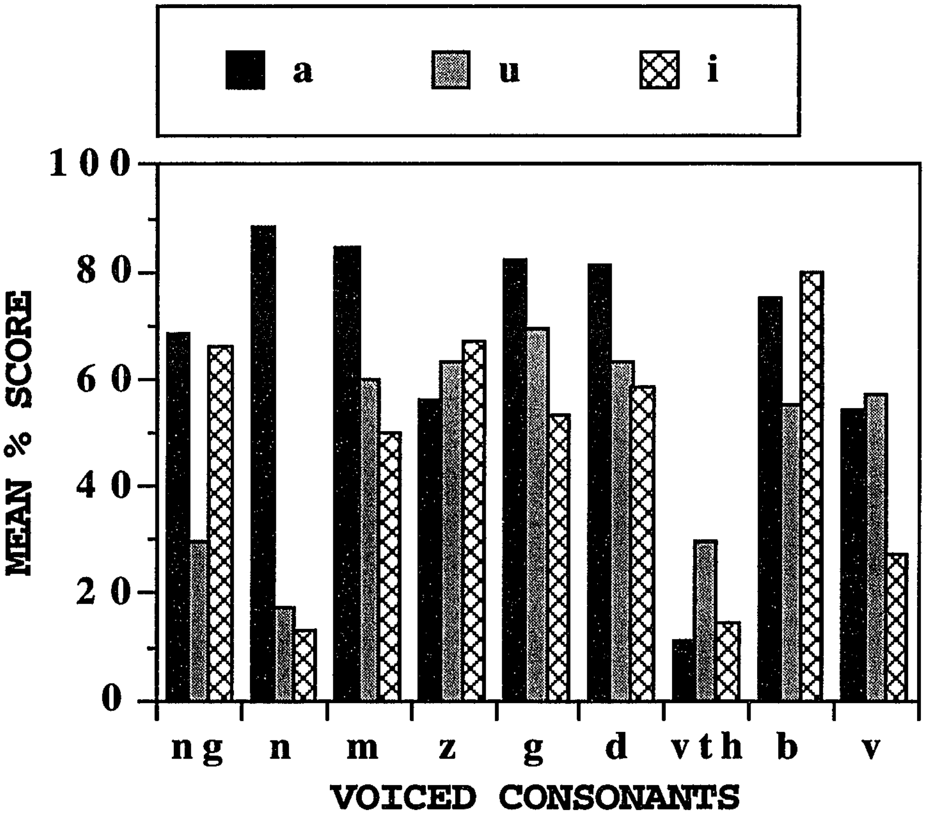

Figure 8. Histograms of mean consonant recognition scores for unenhanced speech showing the relationship between voiced Consonants and Vowel Environment averaged across Subjects. Data in this graph have been averaged across Audiometric Configuration.

Figure 9 shows the same Consonant and Vowel Environment relationship in speech enhanced for CR_{max} in the voiced consonant set. Performance is better in all conditions. However, as with the unenhanced speech, there is significant variability in consonant recognition across the three vowel environments. With the vowel /a/ and the nasal /n/, performance of 90% continues to be dramatically better than in the /u/ or /i/ environment (20.5% on average). Performance with the stops consonants and the fricatives is much more uniform across Vowel Environments with the enhanced speech than with natural speech. Poorest performance was observed with the voiced lingual-dental fricative in all Vowel Environments.

In the voiceless set, a significant interaction was evident between Consonant and Vowel Environment (CxV) for both the unenhanced and maximum performance conditions. Figure 10 shows histograms of this interaction with unenhanced speech. As was evident with the voiced consonants, there is considerable variability in scores across Consonant and Vowel Environment. For example, with the consonant /k/, mean scores averaged across all subjects were 85% with /i/, 83% with /a/ and 47% with /u/. In contrast, with the consonant /th/ best performance of 37% was obtained with /u/ while scores of 28% and 10% were recorded with /i/ and /a/ respectively.

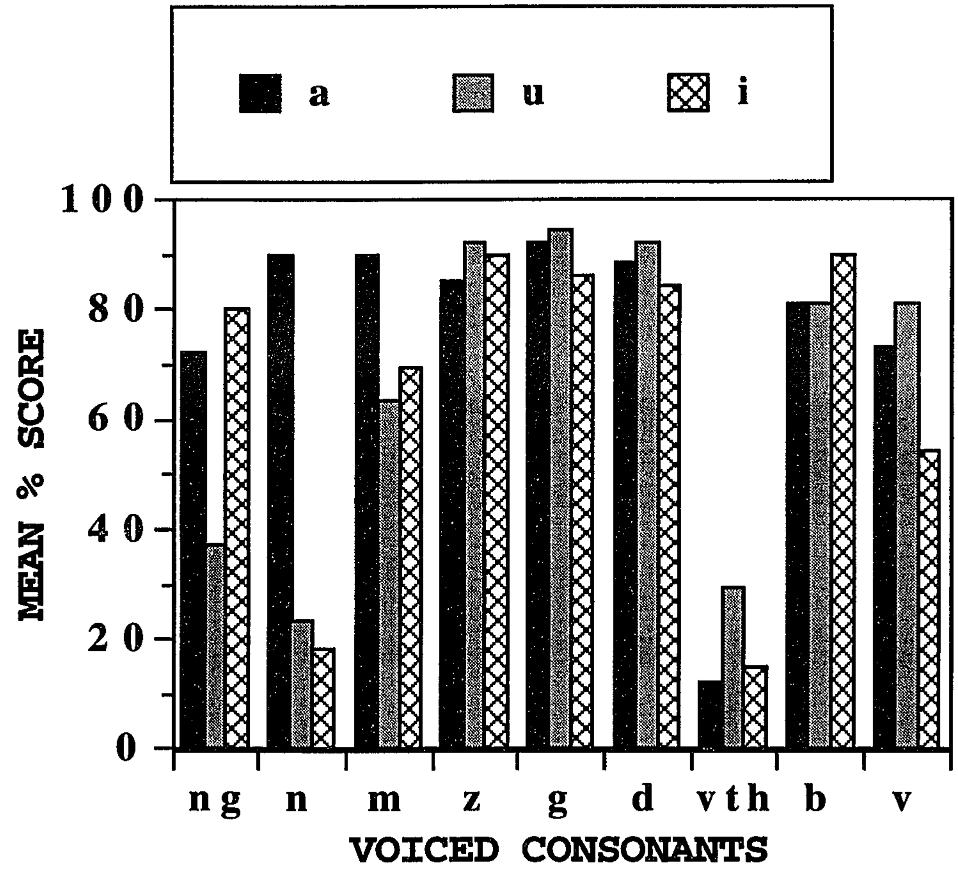

Figure 9. Histograms of mean consonant recognition scores at CR_{max} showing the interaction between voiced consonants and Vowel Environment averaged across Subjects. Data in this graph have been averaged across Audiometric Configuration.

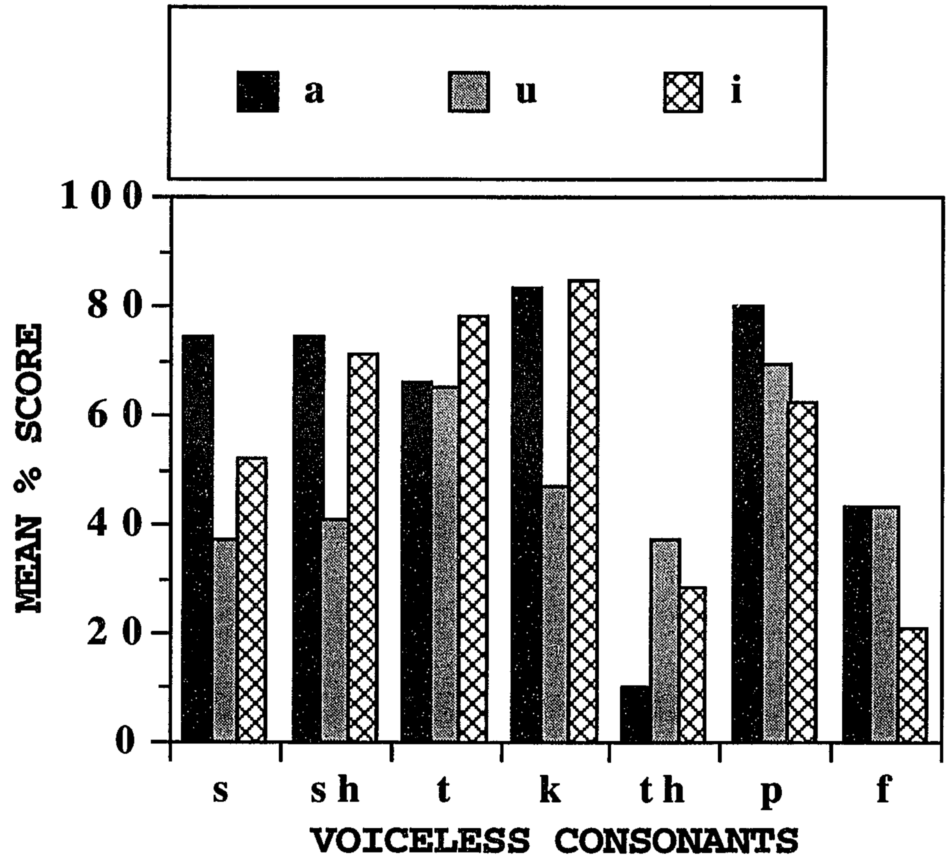

Figure 10. Histograms of mean scores for unenhanced speech showing the interaction between voiceless consonants and Vowel Environment averaged across Subjects. Data in this graph have been averaged across Audiometric Configuration.

Figure 11 shows the interaction between Consonant and Vowel Environment with speech at CR_{max} in the voiceless set. As with the voiced set, scores are greater at maximum performance with all consonants in all Vowel Environments. Note that the variability across Vowel Environments is less pronounced with the enhanced speech than with the natural speech. For example, with the /k/

mean scores averaged across subject groups were 95% with /u/, 95% with /i/ and 93% with /a/. The consonant /s/ showed best performance with /a/ (97%), and similar performance with /u/ (81%) and /i/ (79%). In contrast, the lingual-dental results were the poorest performance with 54% with /u/, 31% with /i/ and 8% with /a/. Note that scores for /th/ and /vth/ are lower than would be expected by random guessing. It is assumed that subjects had a response bias toward /f/ and /v/, respectively.

In the Consonant by Vowel Environment interactions, a consistent pattern of increased performance was not observed in either the voiced or voiceless sets. That is, in each condition, ranking the consonants from best to poorest performance failed to produce a ranking that was consistent across Vowel Environments. However, in all conditions the lingual-dental fricative showed the poorest score.

A significant interaction was also evident between Consonant and Audiometric Configuration (CxA) in the voiced and voiceless set at CR_{max}. Figure 12 presents the histograms of mean scores at CR_{max} showing the interaction between voiced consonants and Audiometric Configurations averaged across Vowel Environment. As was evident in the Consonant and Vowel Environment interactions, considerable variability exists across Audiometric Configurations. Averaged across Vowel Environment, mean scores were 81%, 73% and 57% for the flat, sloping and precipitous groups respectively. Best performance (99%) was observed with /z/ in the flat and sloping groups while poorest results (16%) was obtained with the lingual-dental in precipitous group.

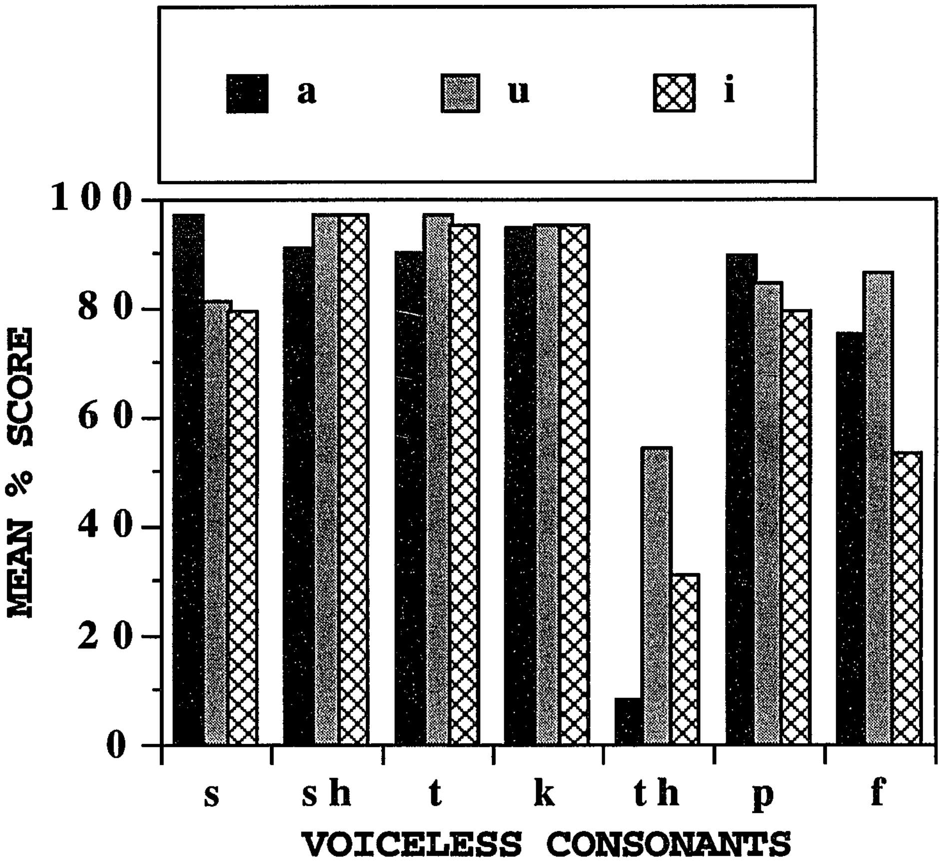

Figure 11. Histograms of mean scores at CR_{max} showing the interaction between voiceless consonants and Vowel Environment averaged across Subjects. Data in this graph have been averaged across Audiometric Configuration.

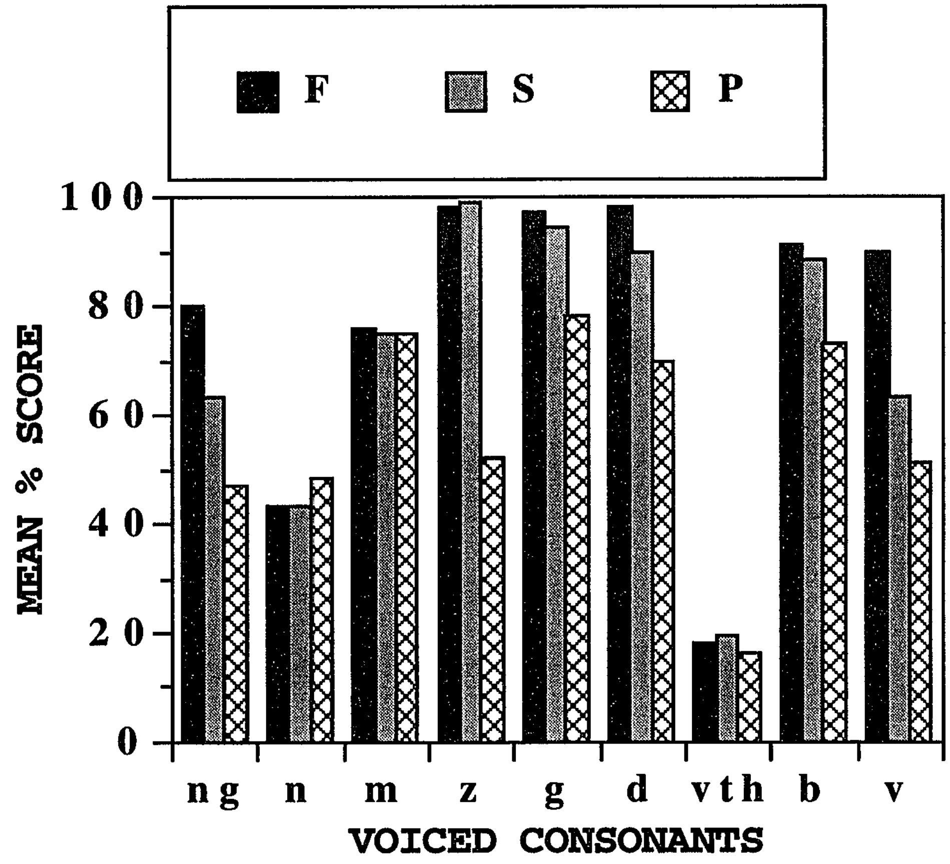

Figure 12. Histograms of mean scores at CR_{max} showing the interaction between voiced consonants and Audiometric Configuration averaged across Subjects. Data in this graph have been averaged across Vowel Environments. F, S and P represent the flat, the sloping and the precipitous groups respectively.

Figure 13 shows the same interaction with mean scores at CR_{max} for the voiceless group. On average, the sloping group scored 90%, the flat group scored 86% and the precipitous group 67%. Best performance (99%) was observed with /k/ and /sh/ in the sloping group while poorest performance (15%) was with /th/ in the flat group. Several consonants in all three Audiometric Configurations showed scores in excess of 90%.

As was the case in the Consonant by Vowel Environment interaction, in the Consonant by Audiometric Configuration interaction there is no consistent pattern of increased performance across consonants. In the voiced consonant set, the nasals and the interdental fricative show less improvement than do the remaining consonants. However, with the voiceless set, the least intense fricatives /th,f/ show poorer performance than the stops and more intense fricatives. Note that overall, the flat and sloping groups show similar benefit while the precipitous group shows much more variability and less benefit.

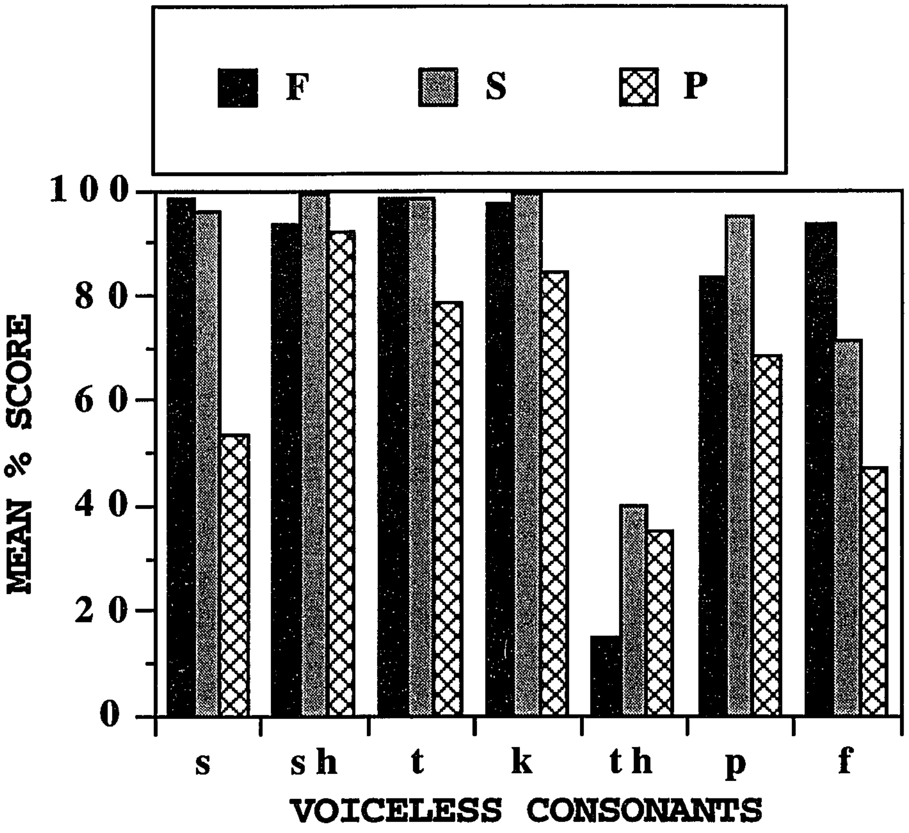

Figure 13. Histogram of mean scores at CR_{max} showing the interaction between voiceless consonants and Audiometric Configuration averaged across Vowel Environments. F, S and P represent the flat, the sloping and the precipitous groups respectively.

IMPROVEMENT IN CONSONANT RECOGNITION

The difference in performance between CR_{max} and consonant recognition in the unenhanced condition was analyzed using an ANOVA. In order to perform this analysis, proportional scores were transformed into arc-sine units for both conditions and the difference was calculated. The same factors were used in this analysis as in the previous ANOVA.

The results of the ANOVA are shown in Table 10. As was the case in the first two ANOVA's, the factors of Consonant (C) and Vowel Environment (V) were found to be significant. Two interactions were found to be significant: a Consonant by Vowel Environment (CxV) interaction and a Consonant by Audiometric Configuration (CxA) interaction.

The magnitude of improvement due to the Consonant effect is shown in Figures 14 and 15. To facilitate ease in interpretation, data are shown separately in voiced and voiceless groups although the analysis was performed on all sixteen consonants. Each histogram shows the percentage improvement in test scores for the consonants in order of their relative intensity. Data were analysed in arc-sine units. For ease in interpretation, the test score improvement is shown in arc-sine units on the left vertical axis and in equivalent improvement in percent correct in the vicinity of 50% level on the right vertical axis. With the voiced consonants, the greatest improvement is shown in the stops and the two most intense fricatives /z ,v/. The nasals and the lingua-dental fricative show much less of an improvement.

Improvement is more variable with the voiceless consonants. The more intense consonants /s / and /sh/ show greatest improvement as does the least intense fricative /f/. With the exception of the lingual-dental fricative, the voiceless consonants show greater change than the voiced consonants.

TABLE 10: Analysis of Variance of Improvement in Consonant Recognition obtained with Voiced and Voiceless Consonants. The asterisk (*) refers to the variance among subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config. (A)	09.98	02	4.99	01.61	
Consonant (C)	74.98	15	4.99	06.85	.001
Vowel (V)	14.98	02	7.49	15.37	.001
Variance(S)*	46.62	15	3.11		
A x C	46.00	30	1.53	02.10	.01
A x V	03.33	04	0.83	01.71	
C x V	23.61	30	0.78	02.96	.001
Variance(SC)*	164.15	225	0.73		
Variance(SV)*	14.62	30	0.49		
A x C x V	16.62	60	0.27	01.04	
Variance(SCV)*	119.53	450	0.26		
TOTAL	534.46	863			

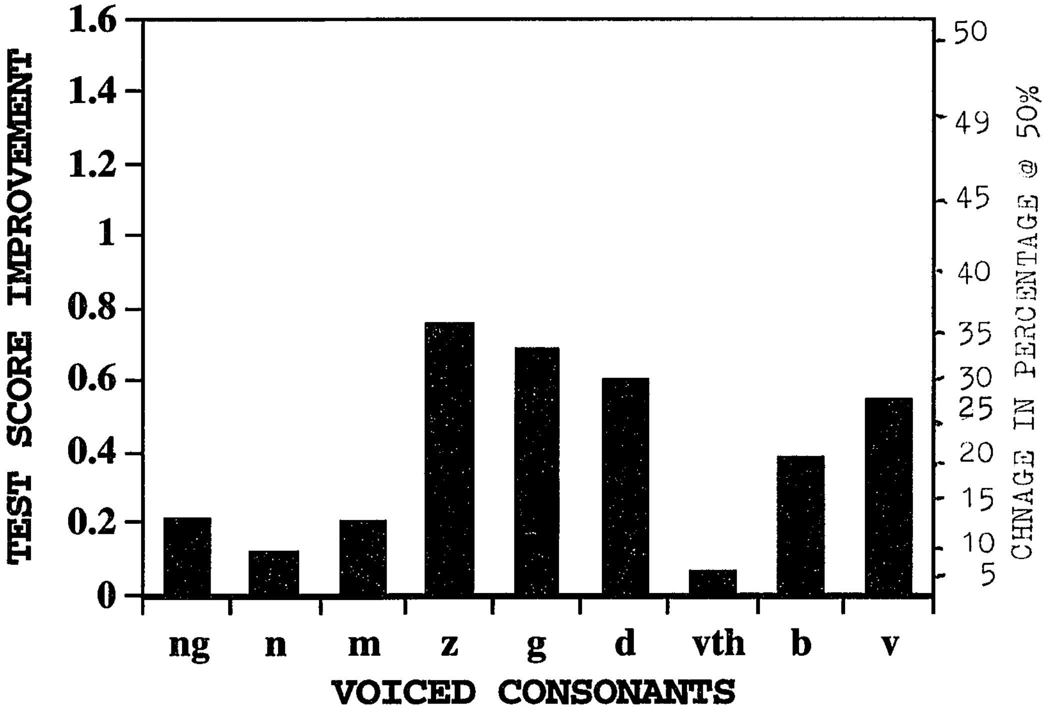

Figure 14. Histograms of test score improvement in consonant recognition between CR_{max} and natural speech condition for the voiced consonants averaged over Vowel Environment and Audiometric Configuration. The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at vicinity of the 50% region.

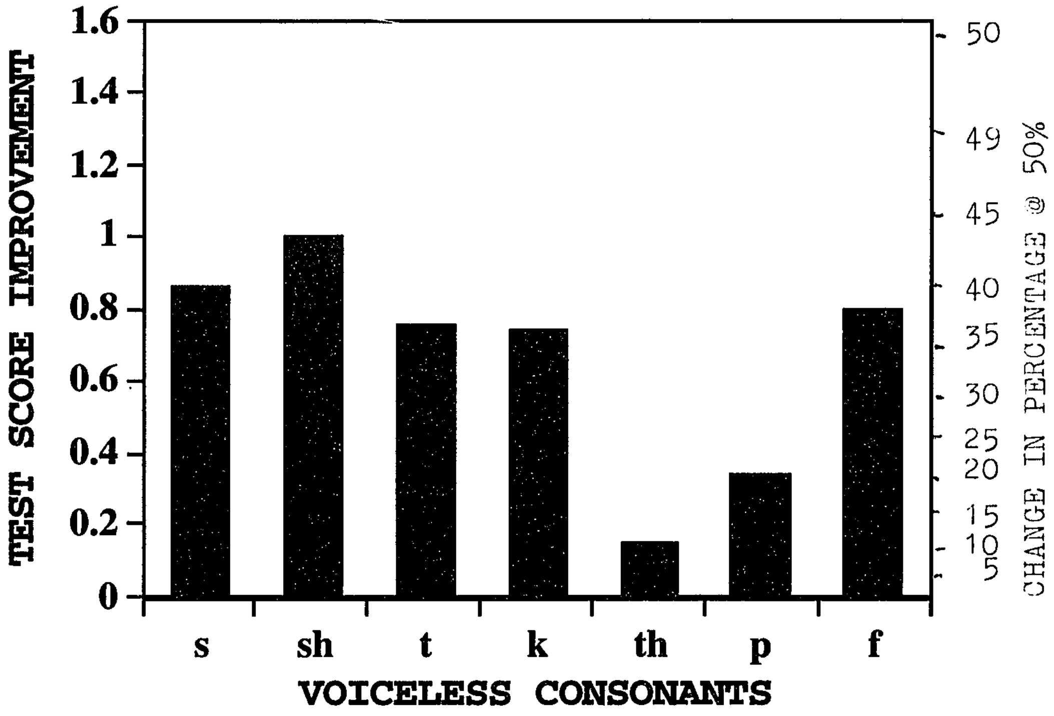

Figure 15. Histograms of test score improvement in consonant recognition between CR_{max} and natural speech condition for the voiceless consonants averaged over Vowel Environment and Audiometric Configuration. The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at the vicinity of the 50% region.

Figure 16 shows the magnitude of the Vowel effect. These data have been averaged across Consonant and Audiometric Configuration. The greatest difference between the natural speech and CR_{max} was observed with the vowel /u/. Significant benefit was also seen with /i/ and /a/.

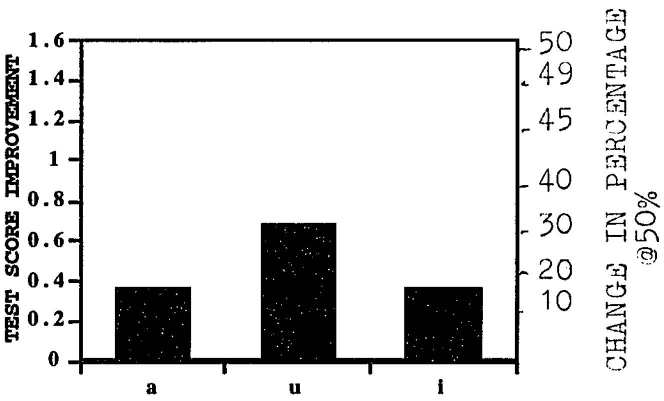

Figure 16: Histograms of test score improvement in consonant recognition between CR_{max} and natural speech condition in the three Vowel Environments averaged over Consonants and Audiometric Configuration.The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at the vicinity of the 50% region.

The CxV interaction is shown in Figures 17 and 18. Dark bars show data associated with /a/, light bars with /u/ and crosshatched bars with /i/. Although all the consonants were analysed as a single set, they are presented in two graphs. Figure 17 shows histograms of the voiced consonants while Figure 18 provides histograms of the voiceless ones.

Each histogram shows the consonants in order of relative intensity in natural speech. Data are averaged across Audiometric Configuration. Results show a marked difference between the voiced and voiceless consonants which is most pronounced in the /u/ environment. Note that the improvement in consonant recognition for the consonants /s, sh,k,f/ are much greater with /u/ than with /i/ or /a/. With the voiced consonants, improvement in consonant recognition are more uniform except for the nasals which show greater improvement with /i/ than with the other vowels.

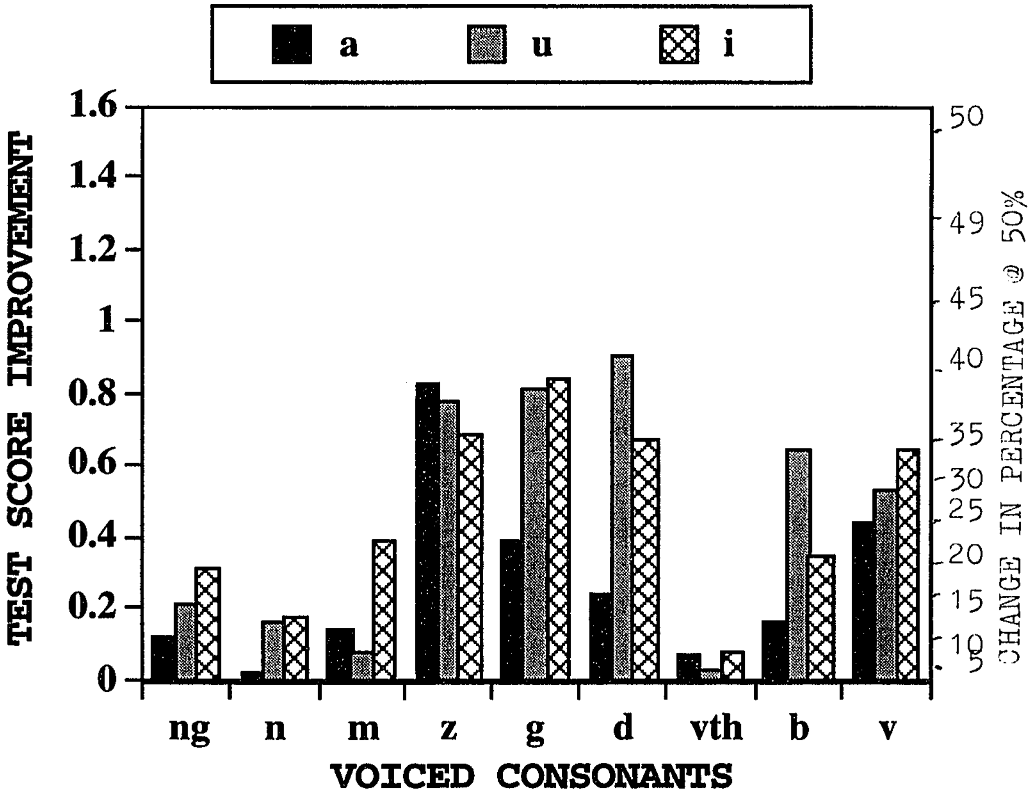

Figure 17. Histograms of test score improvement in consonant recognition of voiced consonants showing the interaction between Consonants and Vowel Environment averaged over Audiometric Configuration. Dark bars show data associated with /a/, light bars with /u/ and cross-hatched bars with /a/. The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at the vicinity of the 50% region.

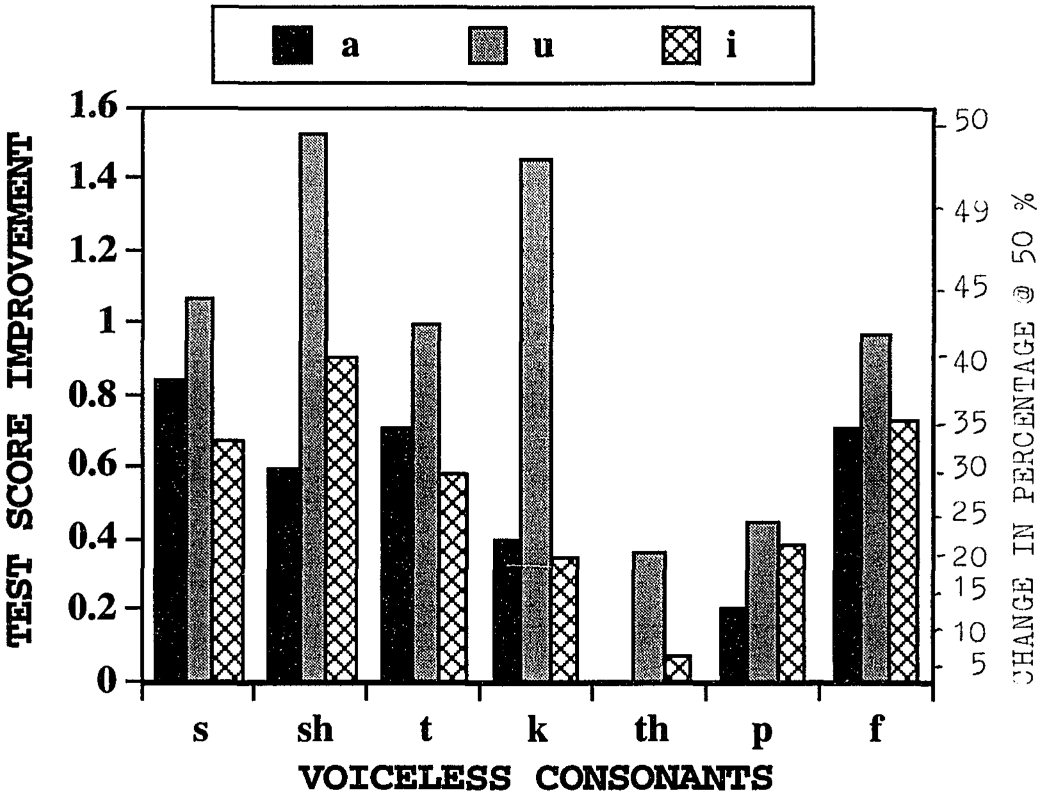

Figure 18. Histograms of test score improvement in consonant recognition of voiceless consonants showing the interaction between Consonants and Vowel Environment averaged over Audiometric Configuration. Dark bars show data associated with /a/, light bars with /u/ and cross-hatched bars with /i/. The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at the vicinity of the 50% region.

The CxA interaction is shown in Figures 19 and 20. Dark bars represent the flat group, light bars the sloping group and crosshatched bars the precipitous group. As with the CxV interaction, the data are presented in two graphs. Figure 19 and 20 show histograms of the voiced and voiceless consonants respectively. Each histogram shows the improvement in test score for the consonants in order of their relative intensity. Data are averaged across Vowel Environment. Results show very different patterns for the voiced and voiceless sets. Note that with the voiced consonants, the flat group achieves greatest benefit in the stops and /v/. The remaining consonants show more even performance for all groups except for /z/ which is unique. The sloping group shows significantly better improvement in consonant recognition with /z/ than either the flat or precipitous groups.

The voiceless consonants show more variability in improvement in consonant recognition across Audiometric Configuration than do the voiced consonants. The sloping group achieves highest scores with /s/, /sh/, and /t/ which are the most intense consonants in this group. Overall benefit is closer to uniform with the flat group while the precipitous group shows significant improvement in consonant recognition with the two intense fricatives and the stops.

As previously noted in the discussion of the main effect, the weak consonants showed greater improvement than did the intense consonants. However, in the analysis of the CxV or CxA interactions, a common pattern in improvement for both voiced and voiceless consonants failed to emerge.

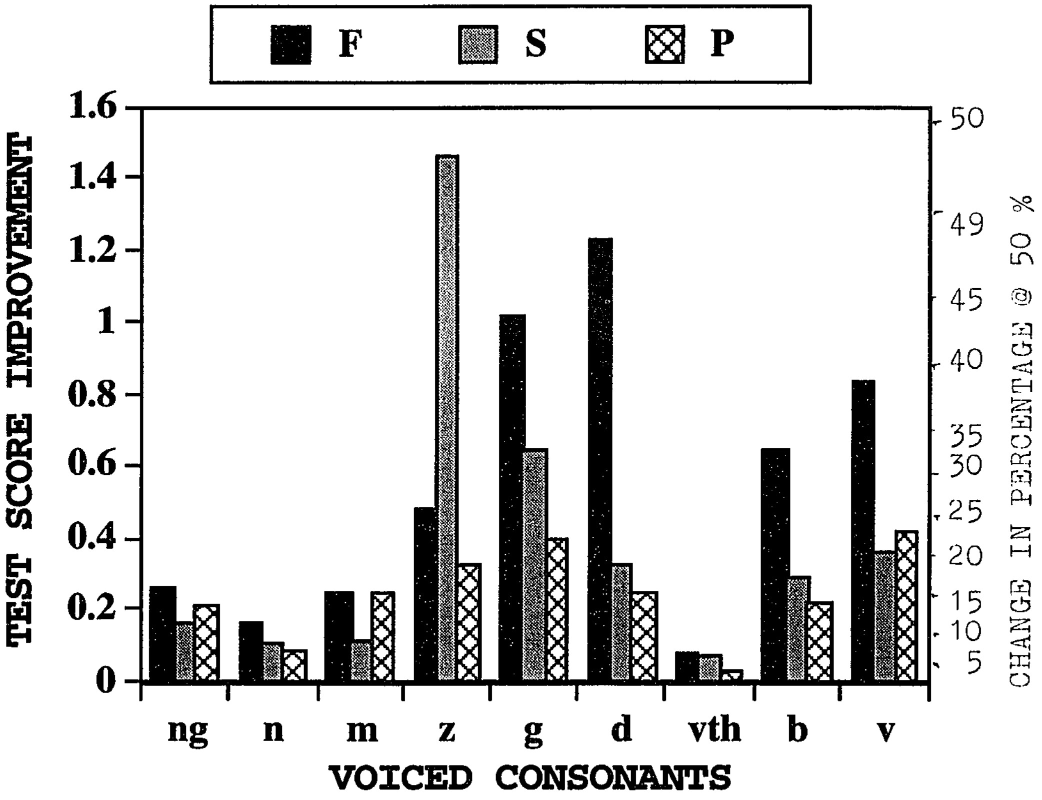

Figure 19. Histograms of test score improvement in consonant recognition with the voiced consonants showing the interaction between Consonants and Audiometric Configuration averaged over Vowel Environment. Dark bars show data associated with the flat group, light bars with the sloping and cross-hatched bars the precipitous group. The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at the vicinity of the 50% region.

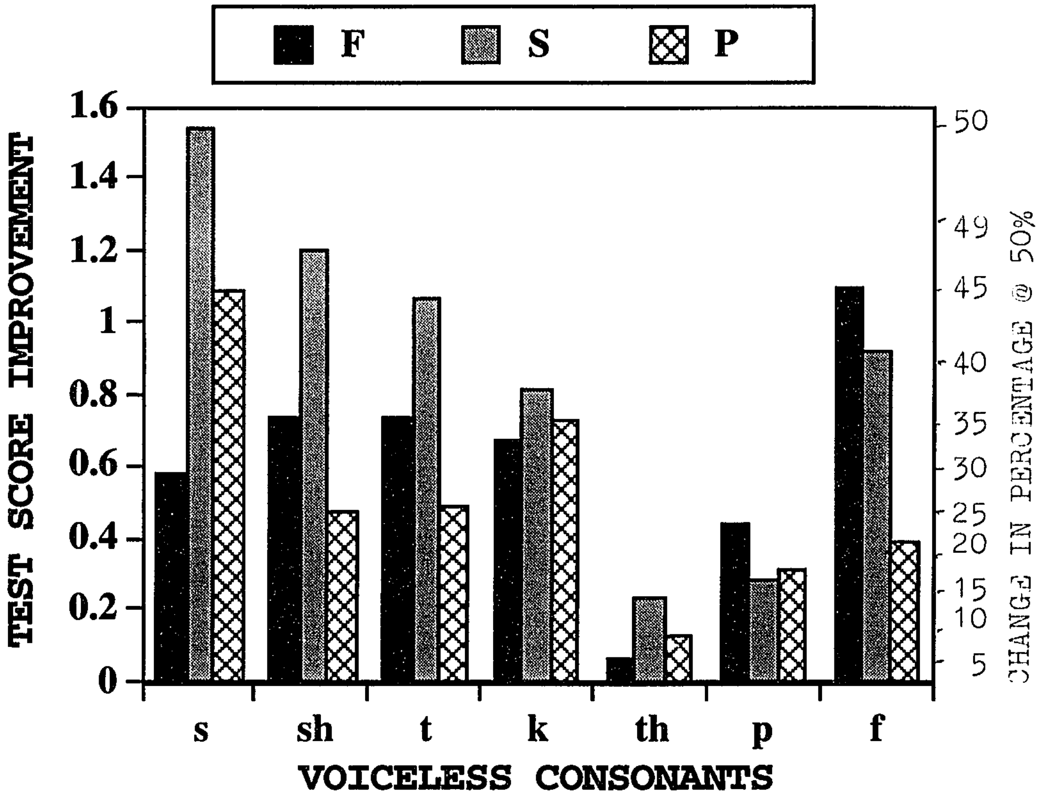

Figure 20. Histograms of test score improvement in consonant recognition with the voiceless consonants showing the interaction between Consonants and Audiometric Configuration averaged over Vowel Environment. Dark bars show data associated with the flat group, light bars with the sloping and cross-hatched bars the precipitous group. The left vertical axis is in arc-sine units. The right vertical axis is in equivalent percentage change at the vicinity of the 50% region.

ANALYSIS OF CE_{max}

An ANOVA was performed on the values of CE_{max}. Factors used were: Consonant (C), Vowel Environment (V), Audiometric Configuration (A) and Subjects (S). A repeated measures ANOVA, with subjects nested within Audiometric Configuration, was used. Results of the ANOVA for the voiced and voiceless sets are shown in Tables 11 and 12.

In order to perform this ANOVA, the CE_{max} was determined for each nonsense syllable for each subject. As discussed in the Experimental Procedures, consonant enhancement (CE) functions for the majority of the VC's assessed included five levels: 0, 6, 12, 18 and 24 dB enhancement. However, some subjects showed reduced dynamic ranges with some stimuli and the CE functions in these cases were narrower. Appendix E provides CE functions and Appendix F shows CE_{max} for each nonsense syllable and each subject.

Results of this ANOVA showed Consonant and Vowel Environment variables to be significant main effects. Figures 21 and 22 show the CE level (CE_{max}) necessary to obtain CR_{max} for voiced and voiceless consonants averaged across Vowel Environments and Audiometric Configurations. Note this change in the CE level is reported in dB. In both consonant sets, a larger CE_{max} level was evident in the stops than in the fricatives.

TABLE 11: Analysis of Variance of CE_{max} for voiced consonants. The asterisk (*) refers to the variance among Subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config (A)	15.52	02	7.76	00.09	
Consonant (C)	2473.51	08	309.19	05.68	0.001
Vowel (V)	316.60	02	158.30	04.07	0.05
Variance(S)*	1267.65	15	84.51		
A x C	1537.60	16	96.10	01.77	0.05
A x V	58.00	04	14.50	03.73	0.05
C x V	972.62	16	60.79	02.23	0.01
Variance(SC)*	6528.09	120	54.40		
Variance(SV)*	1166.72	30	38.89		
A x C x V	1046.09	32	32.69	27.16	
Variance(SCV)*	6520.01	240	33.84		
TOTAL	21902.41	485			

TABLE 12: Analysis of Variance of CE_{max} for voiceless consonants. The asterisk (*) refers to the variance among Subjects nested within groups.

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	SIGNIFICANCE LEVEL
Audiometric config (A)	452.26	02	226.13	2.05	
Consonant (C)	1725.20	06	287.53	4.44	0.001
Vowel (V)	162.13	02	81.06	1.88	
Variance(S)	1657.20	15	110.48		
A x C	464.67	12	38.72	0.60	
A x V	29.88	04	07.47	0.27	
C x V	761.91	12	63.49	2.37	0.01
Variance(SC)	5825.28	90	64.73		
Variance(SV)	1291.62	30	43.05		
A x C x V	755.11	24	31.46	1.18	
Variance(SCV)	4635.86	180	25.75		
TOTAL	17761.12	377			

For the voiced consonants, the CE_{max} averaged between 7 and 14 dB above the CE level for natural speech. A CE_{max} of 7 dB was observed with /n/ while a CE_{max} of 14 dB was observed with /z/. Within consonant classes, average CE_{max} was 12 dB for the stops, 12 dB for the fricatives and 8 dB for the nasals.

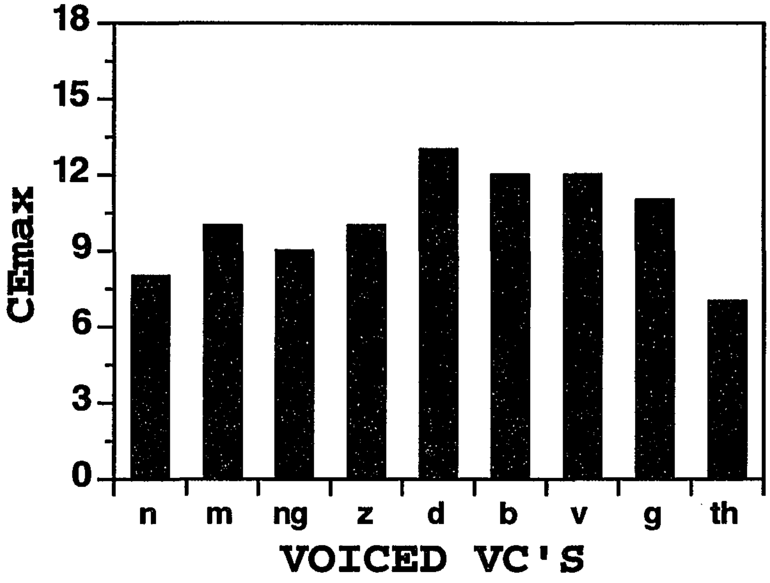

Figure 21. CE_{max} averaged across Audiometric Configurations and Vowel Environments for voiced consonants.

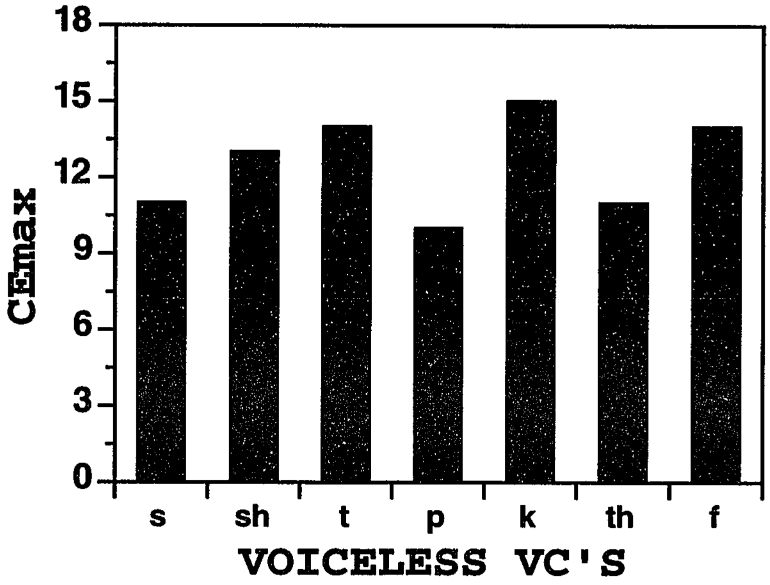

Figure 22. CE_{max} averaged across Audiometric Configuration and Vowel Environments for the voiceless consonants.

With the voiceless consonants, CE_{max} averaged between 9 and 16 dB above the C-V ratio in natural speech. The smallest CE_{max} (9 dB) was evident with /th/ while the largest CE_{max} (16 dB) was observed with /k/. Within consonant classes, CE_{max} was 12 dB for both the stops and for the fricatives.

CE_{max} also shows a significant Vowel Environment effect. Greatest CE_{max} (14 dB) was associated with the vowel /u/ and the voiceless consonants while least CE_{max} (9 dB) was observed with /a/ and the voiced set. Figure 23 shows histograms of CE_{max} for each Vowel Environment, averaged across Consonant and Audiometric Configurations.

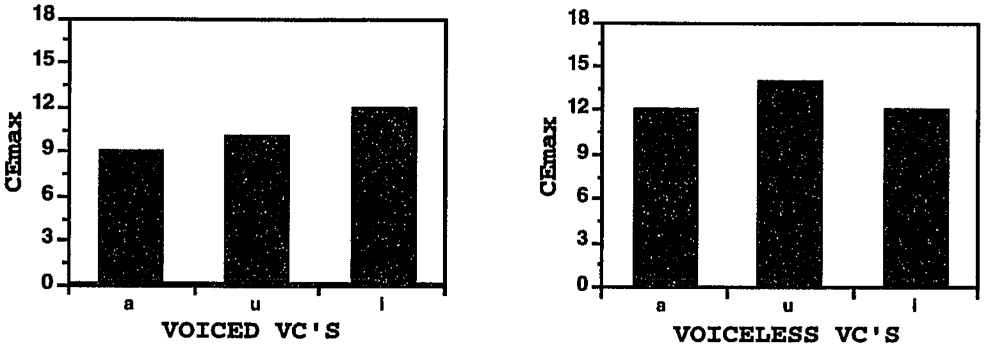

Figure 23. CE_{max} for each Vowel Environment, averaged across Consonant and Audiometric Configurations for voiced and voiceless consonant sets.

For each subject for each Vowel Environment and each Consonant, a CE function was obtained. A smooth curve was fitted to each CE function using the method of orthogonal polynomial (Bennett and Franklin, 1954; Levitt and Rabiner, 1971). Programs for fitting the curves were developed by Levitt and Oden. The highest point on the fitted curve determined the maximum score (CR_{max}). The corresponding enhancement level was CE_{max}. Five types of curves were observed: 1). decreasing, 2). flat 3). increasing with saturation, 4). increasing peaked and 5). increasing with no saturation. Decreasing curves show a reduction in consonant recognition at all levels of consonant enhancement. With the voiced consonants, 9.9% of the CE functions were of this type while only 5.3% were observed with the voiceless consonants. Note that the greatest percentage of decreasing functions (21%) occurred with the nasal consonants. There are two types of flat CE functions: those with scores at 100% and those with scores <100%. With the voiceless consonants, a total of 40% of the functions were flat, 18.8% at 100% and 21.2% with scores below 100%. Nearly half of the the voiced consonants showed flat CE functions. An average of 15.7% had scores at 100% while 33.6% had scores below 100%. There were three types of rising CE functions: those with saturation, those with rollover and those without saturation. With the voiced consonants, 40.8% of the CE functions were rising while with the voiceless consonants 54.7% were of this type. Increasing curves with saturation (i.e., scores that plateau at 100% below the highest CE level used) were observed with 8.1% and 11.7% with the voiced and voiceless consonants respectively. Functions which showed rollover (i.e. increasing scores to a maximum followed by decreasing scores) were observed on average 21.6% with the voiced consonant and 26.8% with the voiceless consonants. With the voiced consonants, 11.1% of the CE functions had increasing scores with no saturation while 16.2% of the voiceless CE functions were of this type.

Table 13 shows the types of CE-Functions and the relative frequency of each curve type in percentage.

Table 13: Frequency of Occurrence of CE-Function Types by Consonant Groups. Each entry in the table is the frequency of occurrence (in percent) for each type of CE-function within each Consonant Group. D, F1, F2, I1, I2 and I3 represent decreasing, flat with values at <100%, flat with values of 100%, increasing with saturation, increasing with a peak and increasing with no saturation CE-Functions respectively.

Consonant Group	Type of CE-Function						
	D	F1	F2	I1	I2	I3	Sum
VOICED							
Nasals	21.0	39.5	7.4	2.5	17.9	11.7	100
Strong Fricatives	3.7	18.5	35.2	11.1	24.1	7.4	100
Stops	5.5	26.5	16.7	13.0	24.1	14.2	100
Weak Fricatives	9.2	50.0	3.7	5.6	20.4	11.1	100
Mean	9.9	33.6	15.7	8.1	21.6	11.1	100
VOICELESS							
Strong Fricatives	2.8	14.8	25.9	20.4	25.9	10.2	100
Stops	5.6	13.6	29.6	7.4	28.4	15.4	100
Weak Fricatives	7.4	35.2	1.0	7.4	25.9	23.1	100
Mean	5.3	21.2	18.8	11.7	26.8	16.2	100

ANALYSIS OF CONSONANT CONFUSIONS

Eight confusion matrices were generated, showing error patterns with unenhanced speech for voiced and voiceless consonants for the three audiometric configurations and the normal hearing controls. Six additional matrices were derived for voiced and voiceless sets in the maximum score condition with the three audiometric configurations. Appendix G shows these 14 confusion matrices for each vowel environment.

The voiceless consonants showed a greater number of confusions than did the voiced consonants for all vowel environments and audiometric configurations. Fewest confusions were observed with the control group while the greatest number of confusions was observed in the precipitous group. Performance varied with Vowel Environment. Tables 14 and 15 show the most frequent substitutions for each consonant set in the unenhanced condition for the control group. Tables 16 to 21 show the most frequent substitutions for each voiced and voiceless consonant for each audiometric configuration in both the unenhanced and maximum score conditions.

In the unenhanced voiced condition, the highest frequency of errors occurred with the nasals, /z/ and /vth/ after /a/, the nasals after /u/ and /n/, /vth/ and /d/ after /i/. Note that Audiometric Configurations showed different error patterns. For example, with /vth/, most frequent substitutions were /v/, /b/, /b/ and /z/ for the control, flat, sloping and precipitous groups respectively. If the nasals are excluded as a group, a greater number of substitutions occurred with the less intense consonants than with the more intense consonants.

With the unenhanced voiceless set, the most frequent substitution was /f/ for the target /th/ with all three vowel environments, although in the control and sloping groups the most frequent substitution was /p/ after /i/. With the voiceless consonants, error patterns were less variable than in the voiced set.

Substitutions were much less frequent at CR_{max} than with the unenhanced speech for all three audiometric configurations. In the voiced set, frequency of errors remains highest in the nasals and /vth/, regardless of vowel environment. Error patterns do not remain consistent across Audiometric Configuration. For example, with /vth/, most frequent errors were /n/, /g/ and /g/ after /a/ and /v/, /b/, /v/ after /i/ for the flat, sloping and precipitous groups respectively.

In the voiceless set, substitutions were more frequent in the flat and precipitous groups than in the sloping group. For most target consonants, substitutions remained the same across all Vowel Environments. The notable exception was /f/ which was perceived as /p/ in the flat group, /th/ in the sloping group and /s/ in the precipitous group after /a/. As in the unenhanced condition, the weaker fricatives presented with the most frequent errors.

Best performance varied with Vowel Environment. With the flat group, poorest performance was observed in the /a/ environment for both the voiced and voiceless sets while best performance occurred in the /i/ environment. However, for the sloping group, poorest performance was observed for the vowel /i/ and best performance was observed in the /a/ environment. The precipitous group showed worst performance with the vowel /u/ and best performance with the vowel /i/.

TABLE 14: Most frequent substitutions in the control group for each Vowel Environment for the voiced consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)		
	UNENHANCED SPEECH		
	/a/	/u/	/i/
n			m(9) ng(9)
m			
ng		**n**(18)	
z			
d			
b		**g**(5)	
v	**b**(12)		**th**(10)
g			
th	**v**(7)		**v**(22)

TABLE 15: Most frequent substitutions in the control group for each Vowel Environment for the voiceless consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)		
	UNENHANCED SPEECH		
	/a/	/u/	/i/
s			
sh			
t			
p			
k			
th	**f**(45)	**f**(5.8)	**p**(31)
f		**th**(5)	

TABLE 16: Most frequent substitutions in the flat Audiometric Configuration for each Vowel Environment for the voiced consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)					
	UNENHANCED SPEECH			MAXIMUM SCORE CONDITION		
	/a/	/u/	/i/	/a/	/u/	/i/
n	**ng**(15.8)	d(33.3)	**ng**(20)	**ng**(14.2)	d(44.1)	**m**(34.1)
m	**n**(40.8)	**th**(14.1)	b(15)	**n** (33.3)	**th**(14.1%)	
ng	**n**(10)	**m**(40)	**m**(5)	g(8.3)	**m**(28.3)	
z	g(11.6)	**th**(10)	**v**(10)			
d	**g**(12)	**th**(21.6)	**b**(39.1)			
b	**d**(15.8)	**v**(26.6)	**v**(7.5)	**d**(22.5)	**d**(5.8)	
v	**d**(10)	**th**(13.3)	**th**(13.3)		**n**(34.1)	**ng**(10)
g	**d**(14.1)	**b**(15)	**v**(15.8)		**d**(6.6)	**ng**(5)
th	**d**(30.8)	**v**(9.1)	**b**(41.6)	**n**(34.1)	**v**(48.3)	**v**(30)

TABLE 17: Most frequent substitutions in the flat Audiometric Configuration for each Vowel Environment for the voiceless consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)					
	UNENHANCED SPEECH			MAXIMUM SCORE CONDITION		
	/a/	/u/	/i/	/a/	/u/	/i/
s		**sh**(12.5)	**th**(8.3)			
sh	**f**(21.6)	**f**(33.3)	**f**(23.3)	**f**(13.3)	**f**(7.5)	**f**(10.8)
t	**p**(11.6)	**th**(19.1)	**th**(7.5)	**p**(6.6)		
p	**t**(28.3)	**f**(16.6)	**t**(16.6)	**t**(25.8)	**f**(11.6)	**t**(20)
k	**p**(22.5)	**p**(33.3)		**t**(12.5)		
th	**f**(65)	**f**(55)	**f**(60.8)	**f**(74.1)	**f**(50)	**f**(68.3)
f	**p**(28.5)	**p**(28.3)	**th**(29.1)	**p**(7.5)		**th**(11.6)

TABLE 18: Most frequent substitutions in the sloping Audiometric Configuration for each Vowel Environment for the voiced consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)					
	UNENHANCED SPEECH			MAXIMUM SCORE CONDITION		
	/a/	/u/	/i/	/a/	/u/	/i/
n		d(40.8)	**m**(27.5)		d(53.3)	**ng**(36.6)
m		**n**(10.8)	**ng**(20)	**n** (5.8)	**n**(8.3)	**ng**(17.5)
ng	**n**(21.6)	**n**(24.1)	**n**(10.8)	**n**(28.3)	**th**(28.3)	**n**(6.6%)
z	g(19.1)	**v**(14.1)	**v**(14.1)			
d		**b**(15)	**b**(33.3)		**g**(8.3)	**b**(18.3)
b	**g**(10)	**g**(16.6)	**d**(12.5)	**g**(6.6)	**g**(14.1)	
v	**th**(18.3)	**g**(10.8)	**th**(32.5)	**th**(15.8)	**g**(7.5)	**ng**(20)
g	**d**(7.5)	**v**(17.5)	**b**(21.6)	**d**(6.6)		**d**(6.6)
th	**g**(30)	**v**(29.1)	**b**(47.5)	**g**(18.3)	**v**(33.3)	**b**(30.8)

TABLE 19: Most frequent substitutions in the sloping Audiometric Configuration for each Vowel Environment for the voiceless consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)					
	UNENHANCED SPEECH			MAXIMUM SCORE CONDITION		
	/a/	/u/	/i/	/a/	/u/	/i/
s	**th**(12.5)		**th**(33.3)	**th**(29.1)	**sh**(5)	**t**(6.6)
sh	**f**(11.6)	**th**(29.1)	**f**(13.3)			
t	**k**(15.8)	**p**(13.3)	**p**(15.8)			
p	**k**(5)	**th**(6.6)	**t**(15)		**k**(5.8)	**t**(11.6)
k	**p**(6.6)	**p**(31.6)	**p**(10)			
th	**f**(50)	**f**(30)	**p**(18.6)	**f**(57.5)	**f**(34.1)	**f**(23.3)
f	**p**(40)	**p**(32.5)	**p**(18.6)	**th**(15.8)	**th**(7.5)	**th**(45)

TABLE 20: Most frequent substitutions in the precipitous Audiometric Configuration for each Vowel Environment for the voiced consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)					
	UNENHANCED SPEECH			MAXIMUM SCORE CONDITION		
	/a/	/u/	/i/	/a/	/u/	/i/
n	**m**(9.1)	d(38.3)	**m**(20.8)	**m**(5.8)	d(35)	**m**(14.1)
m		**n**(17.5)	**n**(21.6)		**th**(20)	**n**(16.6)
ng	**n**(19.1)	**n**(36.6)	**m**(21.6)	**n**(33.3)	**n**(25.8)	**m**(20)
z	**n**(39.1)	**n**(15.8)	**n**(15.8)	**n**(30)	**th**(19.1)	**n**(15.8)
d	**b**(10)	**th**(19.1)	**b**(21.6)	**g**(12.5)	**v**(8.3)	**b**(16.6)
b	**v**(10.8)	**th**(17.5)	**d**(20)	m(10.8)	**d**(11.6)	**d**(16.6)
v	**b**(12.5)	**z**(16.6)	**g**(15.8)	**n**(10.8)	**th**(12.5)	**n**(14.1)
g	**ng**(22.5)	**th**(15) **b**(15)	**d**(19.1)	**v**(34.1)	**b**(7.5)	ng(7.5)
th	**g**(35.8)	**v**(26.6)	**z**(15)	**g**(28.3)	**v**(20.8)	**v**(22.5)

TABLE 21: Most frequent substitutions in the precipitous Audiometric Configuration for each Vowel Environment for the voiceless consonants. Bold type shows those substitutions due to place errors, underlined type shows those due to manner errors and underlined bold type shows combined place and manner errors. Substitutions with less than 5% occurrence are not indicated.

TARGET	SUBSTITUTION (FREQUENCY IN %)					
	UNENHANCED SPEECH			MAXIMUM SCORE CONDITION		
	/a/	/u/	/i/	/a/	/u/	/i/
s	**f**(20.9)	**th**(41.6)	**th**(35)		**th**(34.1)	**sh**(19.1)
sh	**s**(20)	**th**(35.8)	**p**(15)		**s**(10.8)	
t	**f**(23.3)	**th**(33.3)	**th**(15)	**k**(15.8)	**th**(15.8)	**p**(10)
p	**f**(26.6)	**th**(18.3)	**t**(30)	**f**(13.2)	**th**(10.8)	**t**(19.1)
k	**f**(20.8)	**p**(24.1)	**t**(20.8)	**f**(14.1)	**th**(11.6)	**t**(13.3)
th	**f**(45)	**f**(17.5)	**f**(31.6)	**s**(45)	**f**(27.5)	**f**(27.5)
f	**s**(30)	**th**(20.8)	**th**(37.5)	**s**(30)	**sh**(15)	**th**(25.8)

As is evident from the confusion matrices, errors were not evenly distributed across consonants. Rather, some consonants were more easily recognized, especially in the maximum score condition. In several confusion matrices there are a number of correct scores approaching 100%, resulting in several cells totaling less than 5. The large number of cells with values less than 5 prohibited use of the Chi square on the full confusion matrices. The confusion matrices were collapsed into three categories based on error type: place errors, manner errors and combined place and manner errors. Appendix H shows the collapsed matrices.

Totals of each confusion matrix collapsed across Audiometric Configuration were analyzed by comparing error types with the unenhanced speech and at CR_{max}. Table 22 shows the percentage of type of error in unenhanced speech and maximum score condition averaged across Vowel Environment and Audiometric Configuration. For example, with unenhanced speech, there were 1070 place errors which is 21.2 % of the total 9720 stimulus tokens.

TABLE 22: Percentage of type of error in unenhanced speech and maximum score condition averaged across Vowel Environment and Audiometric Configuration. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	21.2	5.1	19.8	27.4	1.1	17.2
MAXIMUM SCORE	15.2	3.9	13.4	17.6	0.5	4.7

Contingency tables were then generated and Chi-square significance test was performed for each contingency table for each Vowel Environment and each Audiometric Configuration. Appendix I shows the contingency tables and the Chi-square values.

Results of the Chi square tests indicate that the modification of the CE_{max} shifts the error patterns of hearing-impaired listeners to a closer approximation of those obtained with normal listeners. Note that in the Chi-square test, the error patterns are significantly different in the maximum score condition than with the unenhanced speech for all the voiceless consonants in all Vowel Environments for each Audiometric Configuration. They are also significant for the voiced consonants in the /u/ environment for the flat group and the /i/ environment with the sloping group. For these conditions, place error patterns are more common in the maximum score condition than either manner or place and manner combined. In the control group, place errors are the most common.

SUMMARY

Results of this investigation show that a substantial increase in consonant recognition can be achieved with adjustment of the C-V ratio. The largest improvements were observed with the strong voiceless fricatives /s,sh/ followed by the weak voiceless fricative /f/. The next largest improvements were observed in the voiceless stops and the strong voiced fricative /z/. The smallest improvements were observed with the nasals. Vowel Environment was a significant main effect. Greatest improvements were in the /u/ Vowel Environment with the voiceless consonants. Slightly less improvement was observed in the /a/ Vowel Environment. Least improvement was observed with /i/. With the voiced consonants, improvement in consonant recognition was more uniform across all three Vowel Environments. Audiometric Configuration was not a significant main effect but was significant as an interaction at CE_{max}. This interaction was stronger with the sloping audiometric configuration more than with the flat or precipitous audiometric configuration.

Analysis of errors patterns indicated that both the number and the type of errors are different in the maximum score condition than with the unenhanced speech. Contingency table analyses were performed on error types for each audiometric configuration. Separate statistics were obtained for voiced and voiceless conditions. Results indicate that the modification of the C-V ratio so as to maximize consonant recognition shifts the error patterns of hearing-impaired listeners to a closer approximation of those obtained with normal listeners.

Chapter V

DISCUSSION

The purpose of this investigation was to determine if modification of the C-V ratio improved consonant recognition of final consonants in VC syllables and, if so, whether there are differences in the amount of enhancement needed for different consonants and whether the consonant enhancement is affected by the vowel environment and the listeners audiometric configuration.

The main findings were that: 1). substantial improvements in consonant recognition can be obtained provided the C-V ratio is adjusted so as to maximize consonant recognition and 2). both the magnitude of the increase in consonant recognition and the adjustment to the C-V ratio needed for maximum recognition (i.e. CE_{max}) depend critically on Consonant type and to a lesser extent on Vowel Environment. Audiometric Configuration was found to have a relatively small effect.

In the discussion that follows the three variables considered, Consonant, Vowel Environment and Audiometric Configuration, are discussed in order of their relative effect on consonant recognition.

CONSONANT EFFECT

The consonants considered in this study were /s,sh,t,p, k,th,f,n,m,ng,z,d,b,v,g,vth,/. These consonants can be classified in various ways. A classification based on how the sounds are produced is perhaps the most common approach, e.g. voicing, manner and place of articulation. This classification is used here but in addition, a secondary classification based on relative intensity is used within a group when appropriate.

The voiceless consonants, which as a group are less intense than the voiced consonants, showed the largest improvement in consonant recognition scores, on the average (see Figures 5 and 6). Within this group the greatest improvement was shown by the two strongest fricatives /s/ and /sh/. The next highest improvement was shown by the stops followed by a relatively small improvement for the weaker fricatives (/f/ and /th/). Essentially the same pattern of results was observed for the voiced consonants, i.e. the largest improvement was shown by the strong fricative /z/, the next largest improvement by the stops and a relatively small improvement by the weak fricatives /v/ and /vth/. The nasal consonants showed very small improvements, if any. The amount of enhancement required for maximum consonant recognition also varied significantly as a function of consonant type. The voiceless consonants on the average needed more enhancement than the voiced consonants. Within each of these groups, the larger improvements in consonant recognition frequently required larger increases in the C-V ratio.

The weak fricative pairs, (/v/ and /vth/ for the voiced fricatives and /f/ and /th/ for the voiceless fricatives) represent a special case in that the sounds within each pair are frequently confused with each other. That is, the weak fricatives in both the voiced and voiceless sets showed high rates of within group substitutions. Further, even at CR_{max}, the rate of substitution was essentially the same for the unenhanced and enhanced conditions. For example, in the unenhanced condition /th/ substitutions for /f/ was 41% while at CR_{max} the average frequency of these substitutions was 46%. In contrast, the next highest rate of consonant substitution (/b/ substituted for /g/) was 24% for the unenhanced condition and only 14% for CR_{max}. With the voiceless consonants, the next highest rate of substitution was 21% in the unenhanced condition and <5% CR_{max} for the consonant pair /p/-/k/. The high frequency of substitutions within the two pairs of weak fricatives is presumably a result of the similar acoustic structure of these two pairs since the normal hearing control groups also showed a high rate of substitution for these consonants. The normal controls do not show a comparably high rate of substitutions involving stop consonants.

A comparison of the consonant confusions between the unenhanced speech and CR_{max} revealed that modification of the C-V ratio alters error patterns as well as reducing the overall error rate. For the unenhanced condition, the error pattern showed a very high rate of place-of-articulation substitution (24.3 %) followed by a moderately high rate of combined place-manner substitutions (18.5 %). There were relatively few errors involving manner of articulation only (3.1 %). At CR_{max}, place-of-articulation errors were reduced by about one-third (from 24.3 % to 16.4 %) whereas combined place-manner errors were reduced by half (from 18.5 % to 9.1 %). The frequency of manner only substitutions was reduced by only a small amount (from 3.1 % to 2.2 %). The relatively large reduction in combined place-manner errors was greater for the voiceless consonants than the voiced consonants.

These changes in the pattern of errors resulting from adjustment of the C-V ratio are of particular importance in lipreading. The visual cues in lipreading provide substantial information on place of articulation but relatively little information on manner of articulation. In contrast, for moderate to severe hearing impairments, the auditory signal conveys significant information on manner of articulation but relatively little information on place of articulation. The two sets of cues thus complement each other rather well.

One area in which visual cues are of limited benefit involves combined place-manner errors. Visual cues may be helpful in modifying place-manner errors to manner only errors, but not in eliminating these errors. As shown in this study, place-manner errors can be reduced substantially by modification of the C-V ratio. As a consequence, modification of the C-V ratio should be particularly effective in improving face-to-face speech communication since the technique reduces those errors that are not readily eliminated by the normal combination of auditory and visual cues.

EFFECT OF VOWEL ENVIRONMENT

Vowel environment was found to have a significant effect on improvement in consonant recognition and on CR_{max}. With unenhanced speech, the highest consonant recognition scores were obtained for the /a/ vowel environment. Scores for the /u/ and /i/ vowel environments were similar but lower. In contrast, in the maximum score condition the voiceless consonants showed highest scores in the /u/ environment with consonant recognition scores for /a/ and /i/ being roughly equal (see Figure 7).

A possible explanation for the relatively large gain in consonant recognition in the /u/ environment is that in the unenhanced condition consonant intensity is relatively low. For example, with the consonant /k/ C/V in dB is -27.1 dB in /uk/, -25.6 dB in /ak/ and -19.5 in /ik/ (Table 4). As a consequence, the /k/ in /uk/ is less likely to be audible to a hearing impaired listener than in /ik/. If poor audibility is the primary cause of low consonant recognition, then increasing the C-V ratio should provide a greater relative improvement in the /u/ environment.

The amount of consonant enhancement required for maximizing consonant recognition did not show a significant Vowel Environment effect but there was a significant Consonant by Vowel Environment (CxV) interaction. Specifically, the values of CE_{max} for voiceless consonants in the /u/ environment were greater, on average, than for the other vowels.

EFFECT OF AUDIOMETRIC CONFIGURATION

The data did not show a significant main effect on Audiometric Configuration. At CR_{max}, however, a significant Consonant by Audiometric Configuration interaction was observed for both the voiced and voiceless consonants. This was the weakest of the significant effects. The flat and sloping audiometric groups performed similarly while the precipitous group performed poorly on high frequency consonants as shown in Figures 12 and 13.

The above interaction can be explained in terms of relative audibility in terms of low and high frequency cues for the different subjects groups. Listeners with flat losses have access to more of the acoustic cues than do listeners with sloping losses. Those with precipitous losses have substantially less access to higher frequency cues. Additionally, as the slope of the hearing loss steepens, distortion of the signal further reduces access to the available cues. As a consequence, it was anticipated that an interaction with audiometric configuration would occur because of different high frequency content in the individual consonants. For example, with /p/ and /b/, important cues lie in the low frequencies while with /k/ and /g/, important cues lie in the high frequencies (Halle, Hughes and Radley, 1957). Results support this interpretation. The flat group, on average, showed greatest improvement with C-V ratio modification followed by the sloping group. As the slope of the hearing loss fell from 20 to 40 db per octave, consonants became less intense. The precipitous group, with a drop of >40 dB per octave showed the least change in consonant recognition in the maximum score condition over unenhanced speech. The slope of the hearing loss in this group was sufficiently sharp to render the consonants inaccessible even at maximum enhancement of +24 dB.

COMPARISONS WITH THE LITERATURE

The results of this investigation can be compared with two other types of studies; 1.) investigations of consonantal confusions in hearing impaired listeners with no signal processing other than uniform amplification, and 2) previous investigations on adjustment of the C-V ratio. The three most relevant studies in the first category are those of Dubno and Levitt (1981), Margulies (1980) and Dunn (1993). These three studies all used the same set of nonsense syllables, with the same speaker, as were used in the present investigation. The relevant studies in the second category are those of Gordon-Salant (1986; 1987), and Montgomery and Edge (1988).

The data reported by Dubno and Levitt were for normal-hearing listeners. Two speakers were used: one male and one female. The error patterns for their subjects in quiet were essentially the same as the data collected for the control group in the present study, indicating that the two studies were mutually consistent.

The most extensive comparisons can be made with the Margulies study. Using stimuli obtained from four talkers, she compared three groups of subjects with audiometric configurations similar to those used in this study. The consonant confusions obtained in her study were similar, but not identical to those obtained in the present study for the unenhanced condition. In both studies the strong fricatives showed the lowest error rates followed by the stops and the weak fricatives. Similar results were also obtained for audiometric configuration with the flat and sloping groups showing higher scores, on average, than the precipitous group. There were, however, some differences with respect to vowel environment. In the Margulies study, for example best performance for /s/ was obtained with the vowel /i/ followed by equal scores with /u/ and /a/. In the present study, best performance for /s/ was obtained with the vowel /a/ followed by /i/ and /u/ with unenhanced speech. Apart from differences, the two studies yielded essentially the same results for those experimental conditions that were directly comparable.

The subjects in the Dunn study differed from those of the present study in that his subjects demonstrated rollover in their PI functions, an effect which is not very common in purely cochlear impairments. Nevertheless the pattern of consonantal confusion was very similar in the two studies. (As before, the strong fricatives showed the lowest error rates, followed by the stops and the weak fricatives.) As with the Margulies study, however, there were differences in the effect of vowel environment. With the voiced consonants, best performance at the peak of the PI function was obtained with /a/ while with the voiceless consonants best performance was obtained with /i/. In the current study, best performance at maximum score condition was observed in the /a/ environment for the voiced consonants and the /u/ environment for the voiceless consonants (see Figure 7).

Comparisons with previous investigations on adjustment of C-V ratio showed similar patterns of improvement, but the magnitude of improvement was much greater in the current study. Montgomery and Edge (1988) report improvements in consonant recognition of 10.5% with speech at 65 dB SPL but no significant improvement with speech at 90 dB SPL following adjustment of the C-V ratio. Gordon-Salant (1987) showed improvements of 5-15% in consonant recognition following modification of the C-V ratio. Additionally, changes in error patterns similar to those in the present study following modification of the C-V ratio were noted. Place and manner errors were reduced in the modified condition when compared to baseline. Both increased consonant recognition scores and changes in error patterns varied significantly with presentation level, vowel environment and audiometric configuration.

Individual adjustment of the C-V ratio is obviously important in order to benefit substantially from this form of processing. It also helps to explain the differences between the Montgomery and Edge and Gordon-Salant studies. These investigations used fixed presentation levels with the same increase in C-V ratio for all subjects whereas the current study allowed for individualized adjustment of the C-V ratio for each consonant and each vowel environment, presented at MCL.

Montgomery and Edge (1988) adjusted C-V ratios in words and used two presentation levels: 65 or 95 dB SPL. When the speech was presented at 65 dB SPL, consonant recognition increased. However, the increase was not evident at the higher presentation level. They suggested that the increased consonant intensity in the modified C-V ratio condition with speech at 65 dB SPL was required for recognition while at 90 dB SPL, sufficient intensity was present for recognition in both the natural and altered C-V ratio. The data in the present study support this conclusion. For some subjects and some consonants, dramatic improvement in consonant recognition was observed with minimal enhancement. Other consonants required greater enhancement for equivalent performance while others worsened with enhancement.

Gordon-Salant (1987) also showed improvement varied with presentation level. Hearing-impaired listeners with gradually sloping hearing loss showed better performance at a presentation level of 75 dB SPL than at 90 dB SPL. However, those with sharply sloping hearing losses scored comparably with the signal at either 75 or 90 dB SPL. The former group included those whose audiometric configurations decreased from 5-15 dB HL per octave between 250 and 8000 Hz and were similar to the subjects in the Montgomery and Edge study. The latter group consisted of subjects with audiograms <20 dB from 250 to 1000 Hz and >40 dB HL for 4000 to 8000 Hz. These groups are similar to the flat group and sloping group, respectively, used in the present study.

Gordon-Salant (1986; 1987) also reported a vowel environment effect with both normal-hearing and hearing-impaired listeners in noise. Changes in consonant recognition improved significantly more with C-V ratio changes in consonants paired with /i/ and /u/ than with /a/ for the normal-hearing listeners. In contrast, moderately hearing-impaired listeners showed greater improvement in consonant recognition when the consonant was paired with /u/ than with either /i/ or /a/ and are consistent with the present study. Although failing to support the same order of improvement relative to vowel environment, both studies show a significant vowel environment effect.

The lack of a significant main effect for audiometric configuration is consistent with Noble's (1978) observation that there is a poor correlation between tonal thresholds and speech discrimination. Noble, however, also noted that although discrimination scores cannot be predicted reliably from tonal thresholds, it is possible to predict to some extent a pattern of errors from the audiogram (i.e. high frequency hearing impairment effects high frequency consonants more than low frequency consonants). These observations help explain why the main effect of audiometric configuration was not significant although there was a significant interaction between audiometric configuration and consonant type.

The C-V ratio for maximum consonant recognition (CE_{max}) varied significantly across consonant type and vowel environment. Although audiometric configuration did not show a significant main effect on CE_{max}, there were substantial individual differences within groups. For example, with the /uk/ syllable, subject F4 achieved the maximum score condition with 6 dB enhancement whereas subject F6 required 18 dB for maximum performance (Appendix G). Over-enhancement of the consonant portion of the nonsense syllable often resulted in a flattening or rollover of the CE function. Increased consonant intensity did not ensure increased intelligibility. For some subjects and with some consonants, increasing consonant intensity beyond a critical level resulted in a reduction of consonant recognition.

IMPLICATIONS FOR ACOUSTIC AMPLIFICATION

A major finding of this investigation was that substantial improvement in consonant recognition can be obtained by adjusting the C-V ratio. A practical limitation of this techniques, however, is that the necessary adjustment to the C-V ratio for maximizing consonant recognition is a complex function of Consonant, Vowel Environment and, to a lesser extent, Audiometric Configuration. In addition, substantial individual differences were observed within Subject groups.

The above problems indicate that it may be extremely difficult, if not impossible, to develop a signal processing strategy for maximizing consonant recognition under all conditions for all hearing impaired listeners. A more realistic goal, however, would be to develop a signal processing strategy that improves consonant recognition substantially (although not maximally) for a wide range of conditions. Even if maximum consonant recognition cannot be achieved in practice, an average increase that is significantly greater than that obtained by conventional means (e.g. compression amplification with an appropriate frequency-gain characteristic) would still have great practical value. The results of the current investigation indicate that this second goal may be feasible.

A practical hearing aid embodying automatic adjustment of C-V ratio could be developed if a reasonable estimate to CE_{max} could be derived from the CE functions. For example, with CE functions showing an increasing curve with saturation at 100%, then the algorithm would require sufficient adjustment of the C-V ratio to enable all the consonants to reach saturation. That is, consonants which are amplified beyond the point of saturation would remain at 100%. This type of CE function is very attractive from a signal processing perspective. Note that an average of 11.1% of the voiced strong fricatives and 20.4% of the voiceless strong fricatives are this type of function. However, increasing CE functions with no saturation or those with rollover require substantially more precise modifications.

Recall that the CE functions for some of the consonants were a horizontal line: i.e. percent consonant recognition did not vary with C-V ratio. This situation usually occurred when the recognition score was either 0% or 100% and was independent of the C-V ratio. This situation was frequently the result of a floor or ceiling effect. For example, if the consonant recognition score is 100% in the unenhanced condition, there would be no room for improvement by adjusting the C-V ratio. Similarly, if a consonant is particularly difficult to recognize, then adjustment of the C-V ratio might not be sufficient to raise its recognition score above 0%.

As is shown in Table 13, there are five types of CE functions. Falling and flat CE functions suggest adjustment of the CE function will not increase consonant recognition, at least with speech presented at MCL. However, nearly half of the CE functions indicate substantial benefit from adjustment of the C-V ratio. It may be possible to develop appropriate signal processing algorithms that would automatically adjust gain to obtain a good approximation of the CE_{max} based on these CE functions.

In developing new methods of signal processing for automatic adjustment of the C-V ratio, it is necessary to compare the results with other possible techniques. Preves et al. (1991) for example, used four analog algorithms involving frequency shaping, amplitude compression or a combination of both to alter the C-V ratio. Results indicate that conventional amplitude compression combined with high-frequency emphasis can also effectively increase the C-V ratio. Since the latter technique can be implemented using existing technology, it could serve as a useful control condition in evaluating more advanced signal processing schemes.

Chapter VI

SUMMARY

This investigation was designed to determine the amount of improvement in consonant recognition that is possible through adjustment of the C-V ratio for listeners with sensorineural hearing impairment. Eighteen subjects participated: six with flat audiometric configurations, six with sloping audiometric configurations and six with precipitous audiometric configurations. Stimuli consisted of sixteen consonants and three vowels for a total of 48 nonsense syllables in a VC format. Adjustment of the C-V ratio was individualized for each subject and for each VC such that the maximum enhancement was the lesser of either 3 dB below UCL for that VC or 24 dB. The stimuli were divided into voiced and voiceless groups, randomized to accommodate 20 presentations of each VC and presented at each listeners MCL.

Subject responses were sorted to obtain percent correct scores for each VC at each enhancement level. Consonant enhancement (CE) functions were obtained for each subject and VC (Appendix E). Additionally, consonant confusion matrices were generated for each subject (Appendix G). Four analyses were performed: an analysis of consonant recognition, an analysis of improvement in consonant recognition, an analysis of C-V ratio at the maximum score condition and an analysis of consonant confusions.

In the first analysis, a four-way repeated measures ANOVA with subjects nested within groups was performed on results obtained with unenhanced speech and with speech in the maximum score condition. Each ANOVA was performed separately for the voiced and voiceless consonants. Results showed significant consonant type and vowel environment main effects in all four conditions. With both the voiced and voiceless stimuli, a significant consonant type by vowel interaction was also present with unenhanced speech and at the maximum score condition. A significant consonant type by audiometric configuration interaction was evident with the voiced and voiceless stimuli but only with speech presented at the maximum score condition.

The improvement in consonant recognition was determined by comparing the difference in scores obtained with unenhanced speech and with speech at the maximum score condition. A four-way repeated measures ANOVA with subjects nested within groups was performed on these values. As with the first analysis, significant consonant type and vowel environment main effects were found. Additionally, two interactions were found to be significant: a consonant type by vowel environment interaction and a consonant type by audiometric configuration interaction.

In the first two analyses, improvements in consonant recognition scores following modification of the C-V ratio were greater with the weaker consonants than with the intense consonants. Additionally, the observed improvements were more substantial with the voiceless stimuli than with the voiced consonants.

In order to perform an analysis of C-V ratio at the maximum score condition, the CE_{max} was determined for each VC for each subject. A four-way repeated measures ANOVA with subjects nested within groups was performed. As was observed in the previous ANOVA's, significant consonant type and vowel environment main effects were found. The CE_{max} for voiced consonant was, on average, less than the CE_{max} for voiceless consonants. Additionally, CE functions used to determine CE_{max} were assessed. Five patterns of CE functions were found: falling, flat with scores <100%, flat with scores at 100%, increasing with saturation, increasing with a peak and increasing with no saturation.

The final analysis involved a contingency table analysis of error patterns for both the unenhanced speech and the maximum score conditions. The results showed that the error patterns for the maximum score condition approximated that obtained with normal hearing listeners.

CONCLUSIONS

The results of this investigation have implications regarding the potential effects of adjusting the C-V ratio on consonant recognition for the hearing impaired population. Scores obtained in the unenhanced condition showed a high degree of consistency with data obtained by other researchers using the same stimuli with sensorineurally impaired listeners with similar audiometric configurations. The results may thus be regarded as reasonably representative of such listeners. However, considerable variability was observed within and across audiometric configuration which limits the predictability on an individual basis.

The results also indicate that consonant recognition can be improved substantially by appropriate adjustment of the C-V ratio. The amount of enhancement required for maximizing consonant recognition varies critically with the consonant type and, to a lesser extent, vowel environment. Audiometric configuration has a relatively small effect.

The improvement in consonant recognition score obtained with individual adjustment of the C-V ratio was substantially greater than that reported in previous studies on C-V ratio adjustment. However, in order to achieve these large improvements in consonant recognition, individualized adjustment of the C-V ratio for each subject for each consonant and vowel combination is needed. The data obtained in this way can nevertheless be used to estimate the improvements in consonant recognition that are possible if such careful adjustment can be implemented.

The value of CE_{max} also varied significantly with consonant type and vowel environment. Many of the CE functions showed rollover indicating that simply increasing the C-V ratio does not necessarily improve consonant recognition. The complexity of the relationship between CE_{max} and the variables considered in this study helps explain the divergent results reported by previous investigators. Further investigation of this relationship could lead to the development of new signal processing algorithms for improving consonant recognition by automatic adjustment of the C-V ratio based on CE functions.

SUGGESTIONS FOR FUTURE RESEARCH

Two broad areas are ripe for future research regarding the C-V ratio necessary for maximum consonant recognition: 1.) signal processing changes and 2.) signal differences.

The data in this investigation were obtained using VC nonsense syllables and may not necessarily be applicable for continuous speech. As continuous speech becomes lengthier, it becomes more redundant and dependence upon specific acoustic cues will be reduced. Effects of adjusting the C-V ratio in words, phrases and sentences needs to be evaluated. Factors such as speaker characteristics, linguistic effects and the relationship between speech intelligibility and quality potentially all contribute to consonant recognition. Further research is needed to determine the applicability of phonemic based modification of the C-V ratio for natural conversational speech.

The focus of this study was to determine the C-V ratios for maximizing consonant recognition. Other than changes in the consonant intensity, the signal was presented with a uniform frequency response at MCL. Typically, hearing aids use frequency shaping. Preves et al.(1991) have shown that changing the frequency response, in combination with amplitude compression, also modifies the C-V ratio. It is unclear how such frequency shaping will interact with modifications of the C-V ratio, however, Preves' data can serve as a useful control condition for comparison of more advanced algorithms used to adjust the C-V ratio.

Changing the parameters of the modification also needs to be explored to determine if a more beneficial algorithm is possible. Where in the temporal domain should increases in consonant intensity begin and at what rate should they occur? In this study the increase in consonant intensity occurred in the first 10 msec of the consonant. If the increase in consonant intensity began earlier in the VC's to include vowel transition cues, results may be different. Alternately, a more gradual onset in the increase in the consonant intensity may provide different results.

Alternative approaches to increasing the consonant intensity may influence consonant recognition and/or speech quality. The latter was not measured in this study. However, some subjects commented spontaneously on the unnatural quality of the processed speech signal. It would be helpful to explore speech quality measures as well. Signal processing which increases consonant recognition but changes perceived speech quality in a negative manner may not be embraced by many hearing impaired listeners.

Additional data are required to determine if the observed effects of increasing the C-V ratio are stable across speakers. For example, the higher fundamental frequency typical of most female speakers may interact differently with the configuration of the hearing loss than was observed with the male speaker in the present study. This should be most observable with listeners in the sloping or precipitous groups.

Speaker differences, especially articulatory precision, will affect the number of acoustic cues for consonant recognition in the speech signal. Less clear speakers will have fewer acoustic cues in the speech signal. Changing the C-V ratio for such speakers may not show equivalent improvement as in the present study. Recall that many of the CE functions obtained in the present study were flat with scores at or near 100%, even though subjects with word recognition scores greater than 80% were not represented. With a less articulate speaker, there may be more room for improvement in the unenhanced condition resulting in fewer flat curves at 100%. Additionally, it would be interesting to determine if with such speakers improved consonant recognition is possible when increasing the consonant intensity begins during the vowel transitions.

GLOSSARY

SYMBOLS USED
THROUGHOUT THE TEXT

For ease in reading, the following symbols were used throughout the text.

/a/ as in the first vowel in *father*
/u/ as in the vowel in *shoe*
/i/ as in the vowel in *see*
/s/ as in the consonant in *see*
/sh/ as in the consonant in *shoe*
/t/ as in the consonant in *toe*
/p/ as in the first consonant in *part*
/k/ as in the first consonant in *keep*
/th/ as in the first consonant in *thing*
/f/ as in the first consonant in *first*
/n/ as in the consonant in *no*
/m/ as in the consonant in *me*
/ng/ as in the final consonant in *sing*
/z/ as in the consonant in *zoo*
/d/ as in the consonant in *did*
/b/ as in the consonant in *bee*
/v/ as in the first consonant in *vote*
/g/ as in the consonant in *go*
/vth/ as in the consonant in *the*

APPENDIX A

WAVEFORMS OF
SELECTED STIMULI

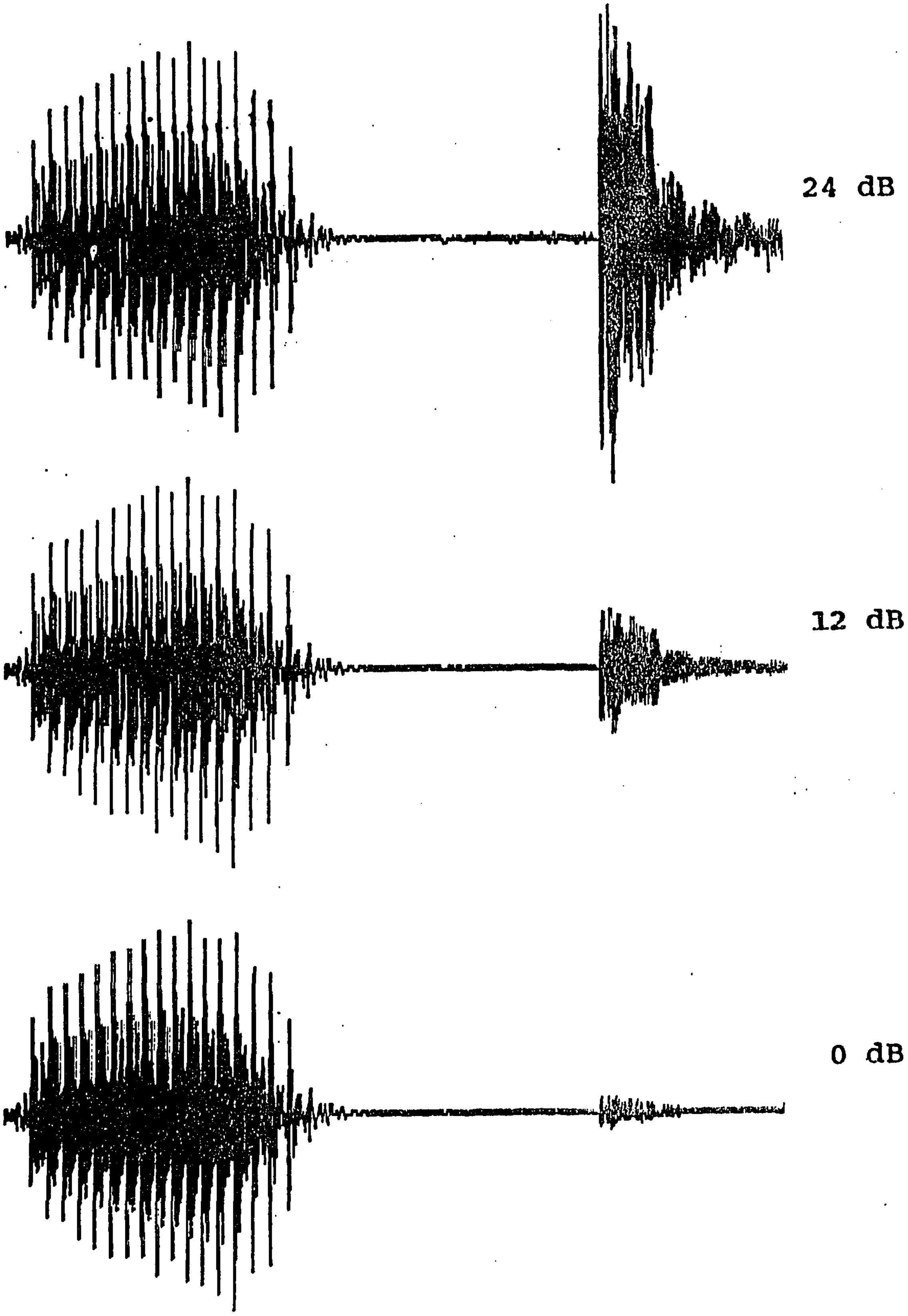

Figure 24. Waveform of /at/ showing adjustment of the C-V ratio.

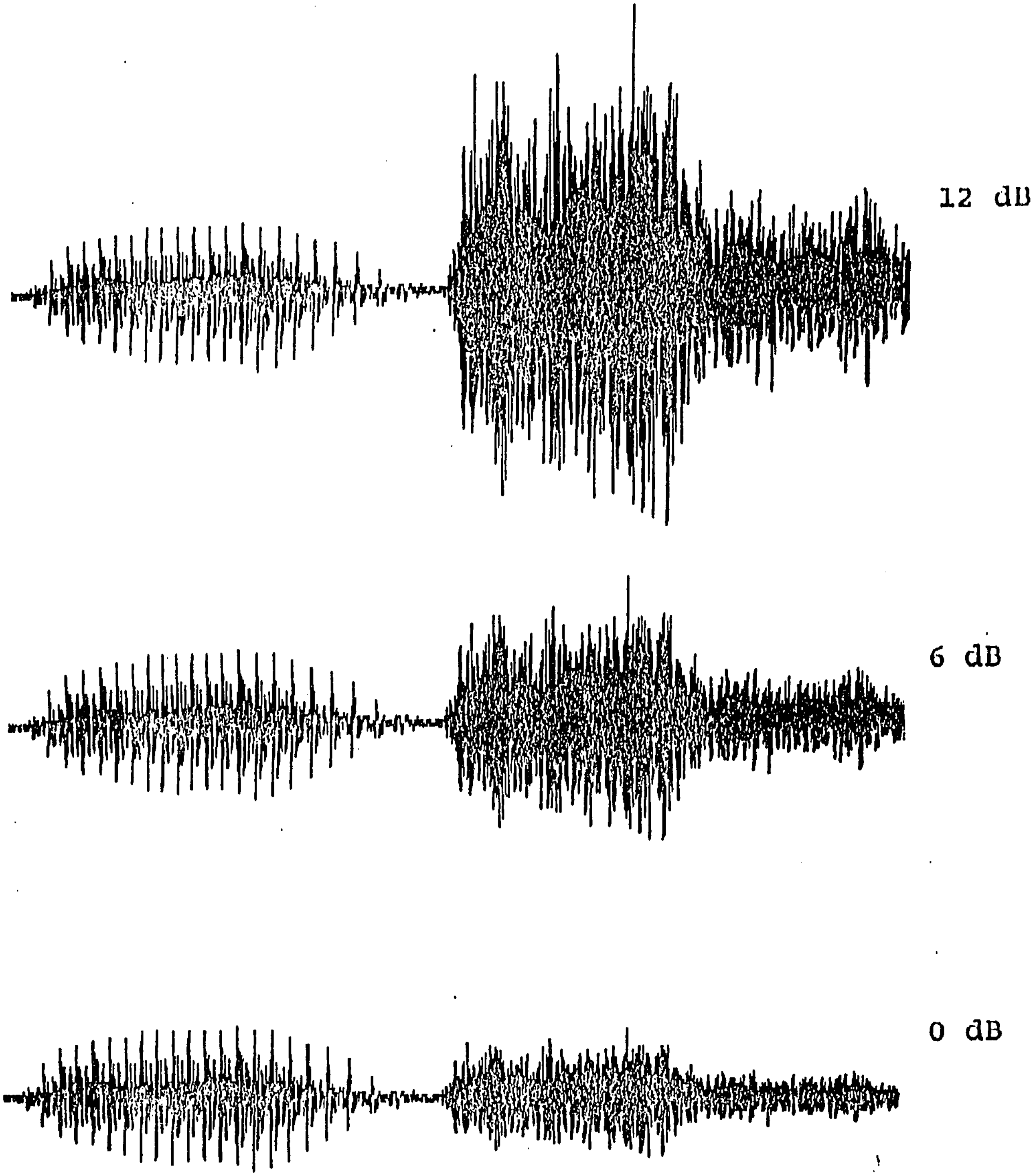

Figure 25. Waveform of /az/ showing adjustment of the C-V ratio.

APPENDIX B

SUBJECT HISTORY FORM

CASE HISTORY INFORMATION SHEET

Subject _________________________ Date______________

Date of Birth_______________________ Sex_____________

Cause of Hearing Loss _______________________________

____

Age at onset of Hearing Loss___________________________

Hearing Aid Use: years in right ear_________left ear_______
Type of hearing aid: right ear_________left ear___________

Medical History: indicate which conditions hve occurred

drainage/discharge from the ear_____________________
fullness/pressure in the ear________________________
constant ringing in the ear_________________________
vertigo/disabling dizziness_________________________
otologic surgery____________________________________
medications____
stroke, head trauma, concussion_____________________
neurologic disorders________________________________
noise exposure______________________________________
family history of hearing loss______________________

APPENDIX C

MCL PROCEDURE

Most comfortable level was obtained by averaging the lower and upper limits of the range of comfortability to arrive at a mid-point. Subjects were given written instructions which described the target speech level sought.

For the lower limit, the stimulus was presented at a sub-audible level and increased in 10 dB steps until the subject indicated the speech was at a comfortable level. The speech stimuli was increased by 10 dB and a descending run for the lower limit was performed. This bracketing procedure was repeated with 5 dB steps sizes and then with a final step size of 1 dB to determine the lower level of comfort. The subject removed the earphones and a voltage measurement was taken of the calibration tone. The stimulus level was increased by 10 dB, and using the same bracketing procedure, the subject repeated the judgement. This was repeated to obtain three voltage measurements which were averaged to provide a single voltage representing the lower limit.

The upper limit of comfortability was obtained using the same bracketing procedure with subjects directions modified to focus on the upper limit of the comfortable range. Determination of lower and upper limit levels was counterbalanced across subjects.

The final most comfortable level was determined by averaging the lower and upper levels. All further testing was done with speech at this level.

INSTRUCTIONS FOR MOST COMFORTABLE LEVEL TEST - LOWER LEVEL

The purpose of this test is to find and maintain a loudness at which speech is *most comfortable to listen.* We want you to decide when the speech is at a level which you feel is your most comfortable listening level.

Press the < ENTER > key to hear the speech.

Press the < ↓ > key when the speech is at your most comfortable listening level. Push the < ↑ > key when the speech is SOFTER than the most comfortable level. You must push < ↓ > or < ↑ > to continue the test.

REMEMBER: THE PURPOSE OF THE TEST IS TO FIND AND MAINTAIN A LOUDNESS LEVEL AT WHICH SPEECH IS MOST COMFORTABLE TO LISTEN.

PRESS < HOME > WHEN YOU ARE FINISHED.

INSTRUCTIONS FOR MOST COMFORTABLE LEVEL TEST - UPPER LEVEL

The purpose of this test is to find and maintain a loudness at which speech is *most comfortable to listen.* We want you to decide when the speech is at a level which you feel is your most comfortable listening level.

Press the < ENTER > key to hear the speech.

Press the < ↑ > key when the speech is at your most comfortable listening level. Push the < ↓ > key when the speech is LOUDER than the most comfortable level. You must push < ↑ > or < ↓ > to continue the test.

REMEMBER: THE PURPOSE OF THE TEST IS TO FIND AND MAINTAIN A LOUDNESS LEVEL AT WHICH SPEECH IS MOST COMFORTABLE TO LISTEN.

PRESS < HOME > WHEN YOU ARE FINISHED

APPENDIX D

UCL PROCEDURE

Loudness discomfort level was obtained by crossing the target level three times Subjects were given written instructions which described the target speech level sought.

The stimuli were presented at MCL and included each VC combination. Each VC began with the C/V ratio at 0 (natural speech). The consonant portion was increased in intensity in 3 dB steps to a maximum of 24 dB. If the speech crossed the subjects' tolerance level, the consonant was decreased by 6 dB and a new ascending run was performed. Discomfort level was judged to be that level which preceded a reversal three times.

Final UCL used in the experiment was the discomfort level minus 3 dB. This ensured that the speech stimuli remained within the subjects dynamic range.

INSTRUCTIONS FOR LOUDNESS DISCOMFORT LEVEL TEST

This is a test in which you will be hearing speech. We want you to decide when the speech is at a level that you think is uncomfortably loud or unpleasantly loud. By UNCOMFORTABLY OR UNPLEASANTLY LOUD we mean when the speech is so loud that you would choose not to listen to it for any period of time.

Push the < HOME> key to hear the speech.

Push the < ↓ > key when the speech is at a loudness to which you would not choose to listen. Push the < ↑ > key when the speech is below that level. You must push the < | > or < | > key to continue the test.
Press < HOME > key when you are ready to begin.

APPENDIX E

INDIVIDUAL CONSONANT ENHANCEMENT FUNCTIONS FOR EACH VC

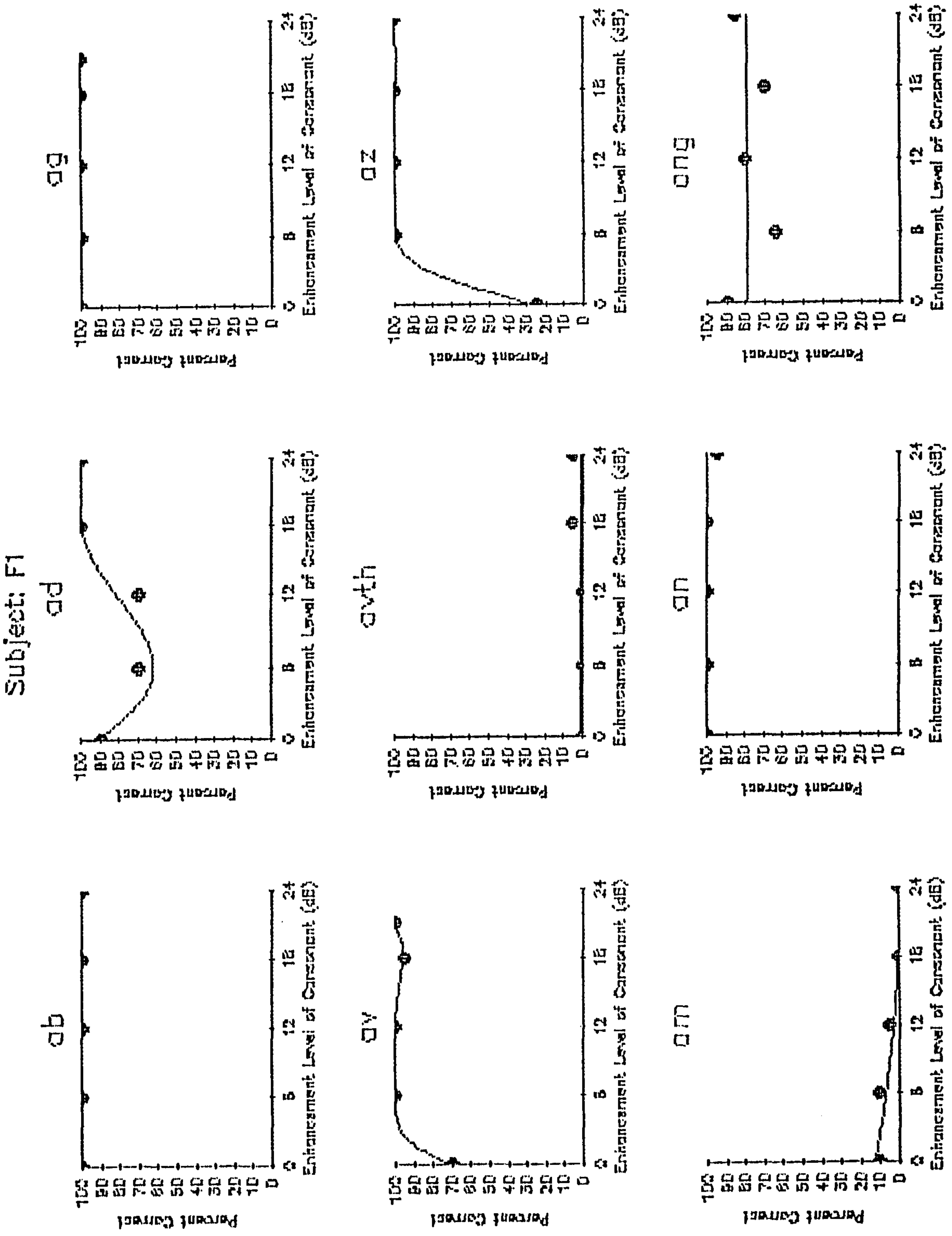

Figure 26. CE functions of the voiced consonants with /a/ for subject F1.

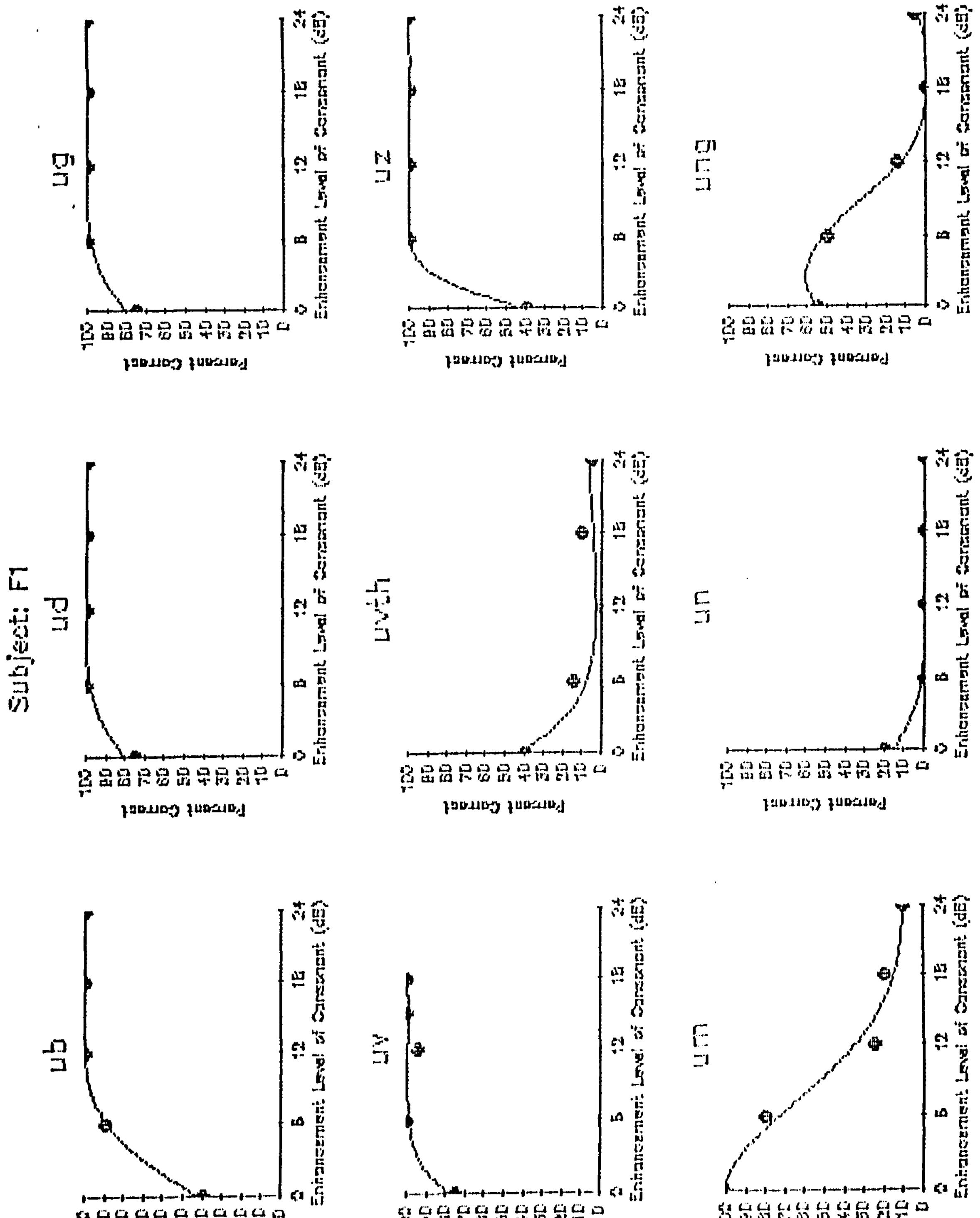

Figure 27. CE functions of the voiced consonants with /u/ for subject F1.

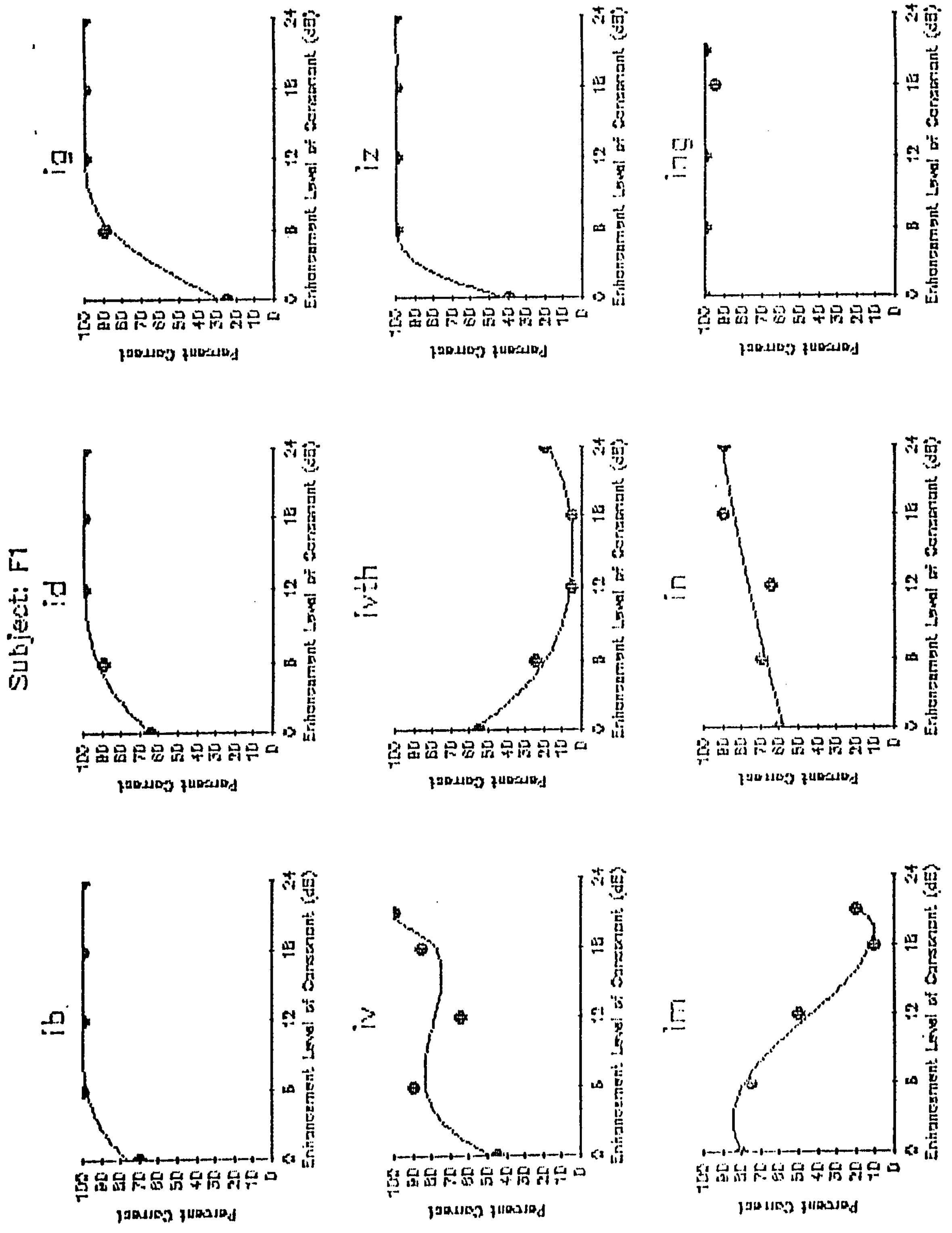

Figure 28. CE functions of the voiced consonants with /i/ for subject F1.

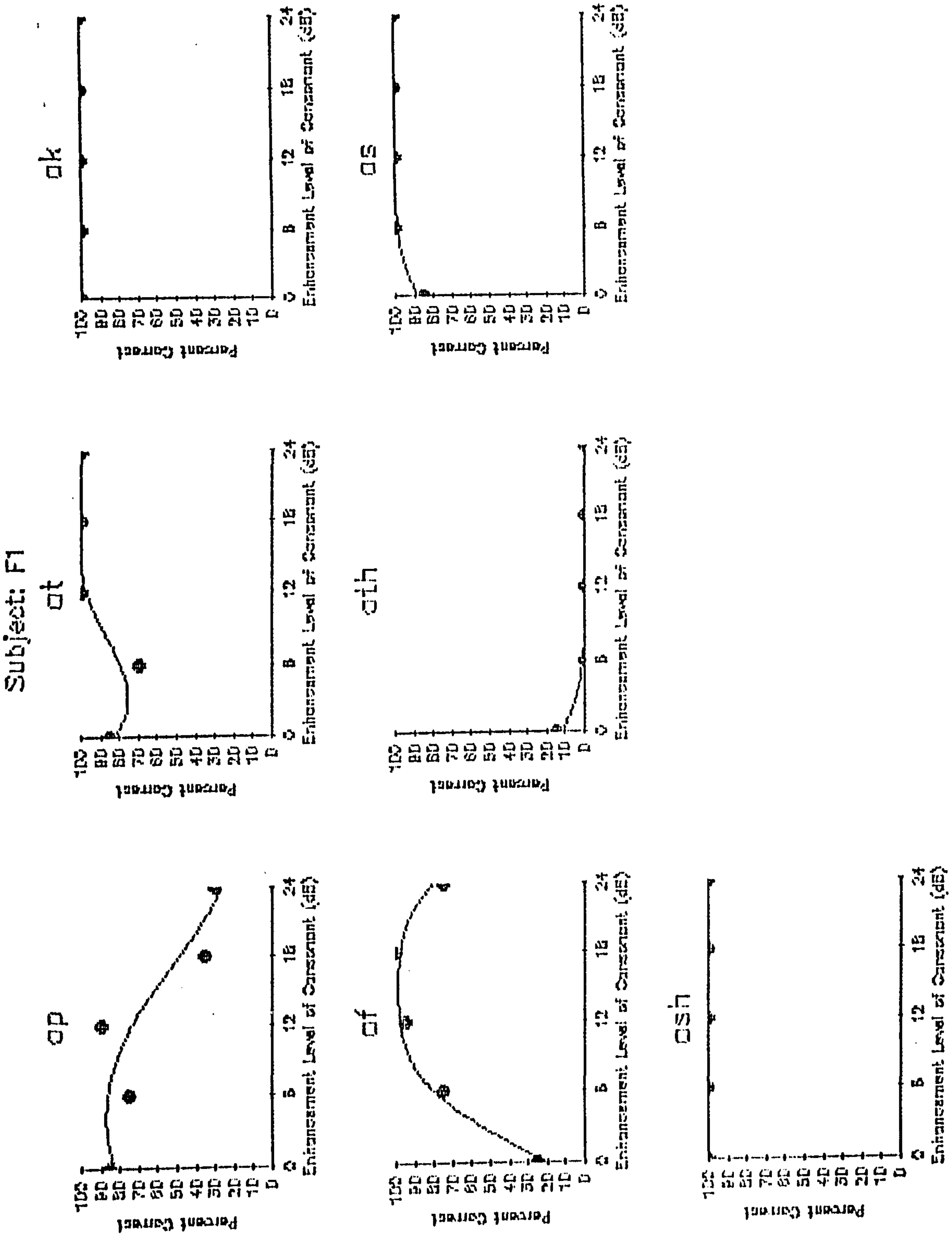

Figure 29. CE functions of the voiceless consonants with /a/ for subject F1.

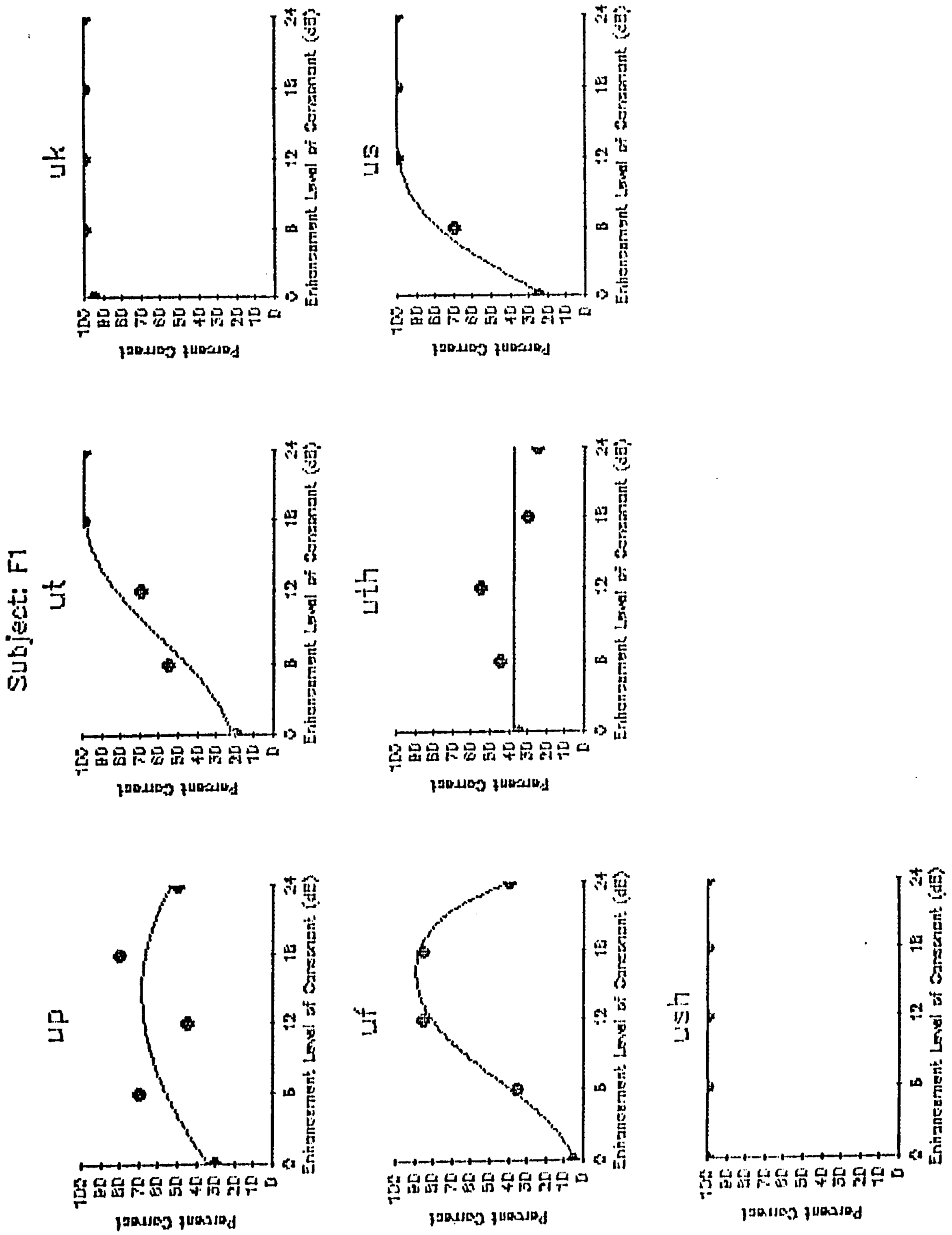

Figure 30. CE functions of the voiceless consonants with /u/ for subject F1.

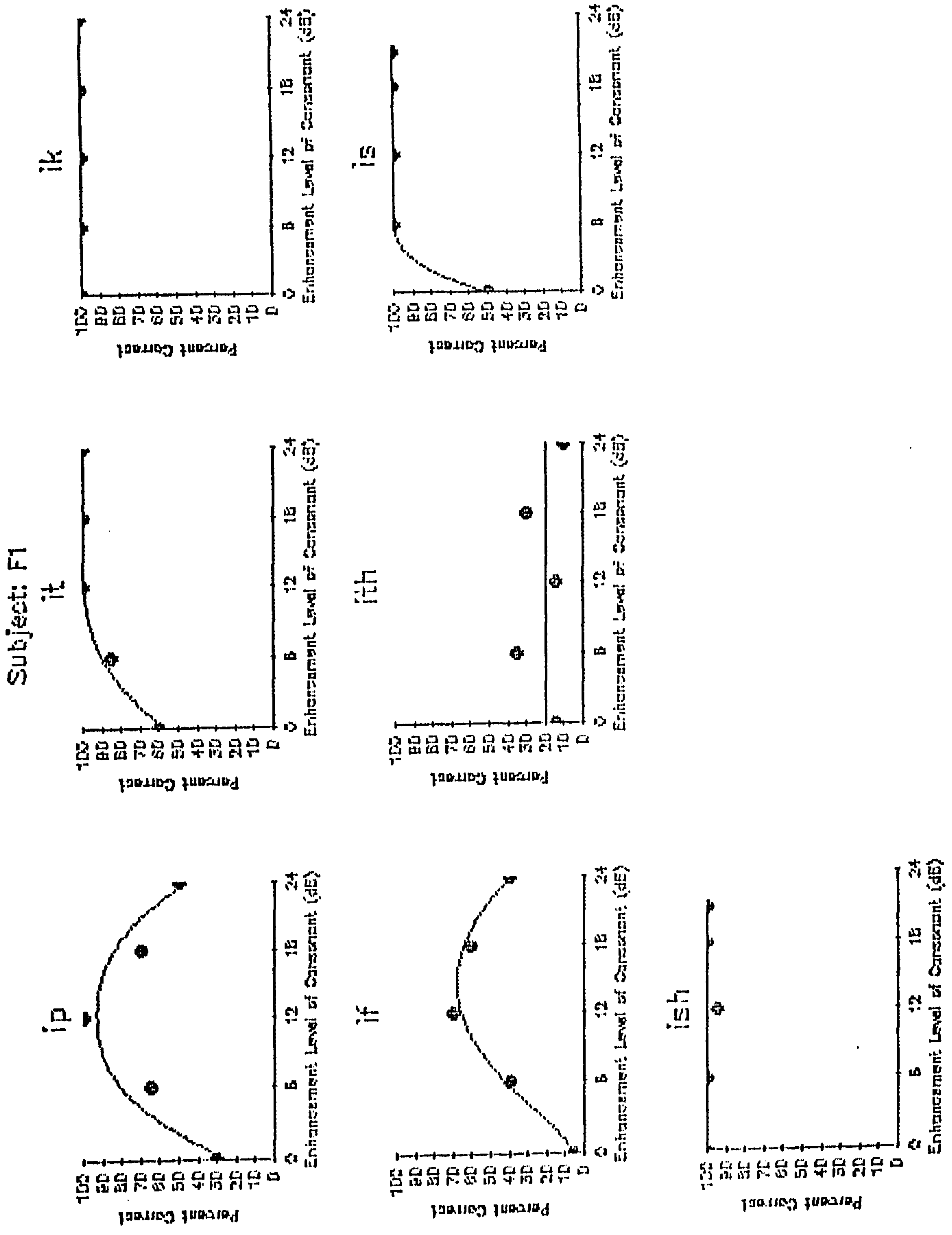

Figure 31. CE functions of the voiceless consonants with /i/ for subject F1.

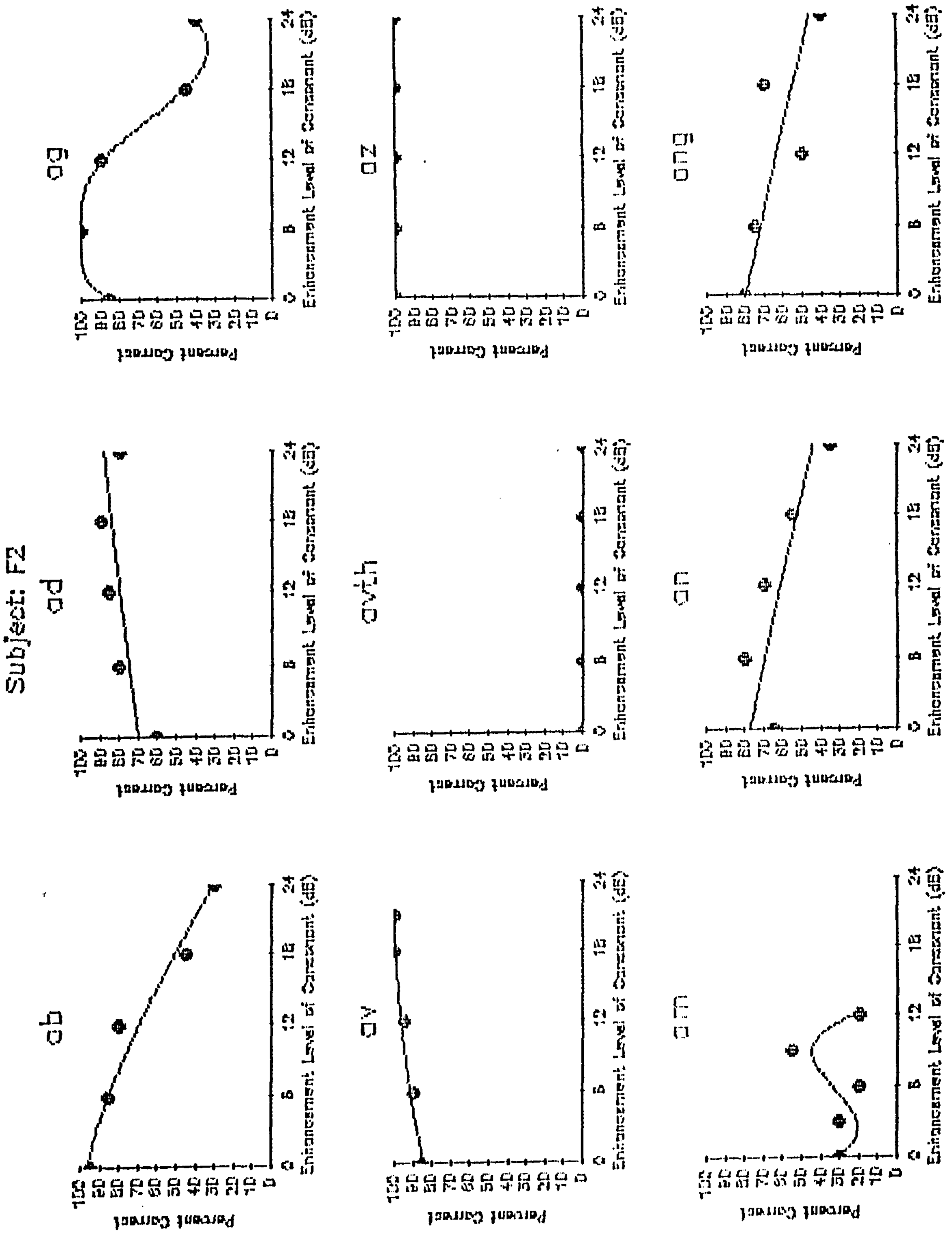

Figure 32. CE functions of the voiced consonants with /a/ for subject F2.

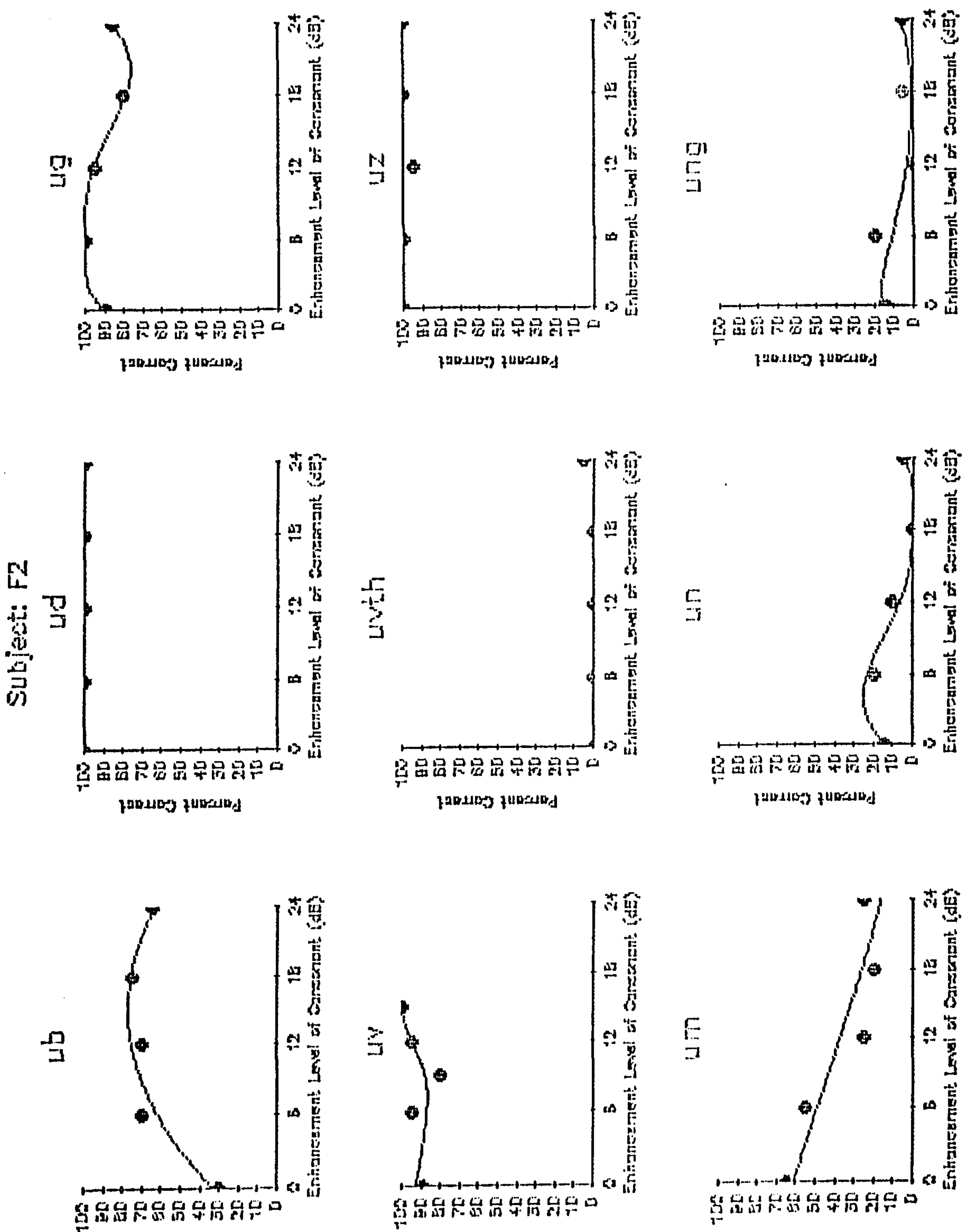

Figure 33. CE functions of the voiced consonants with /u/ for subject F2.

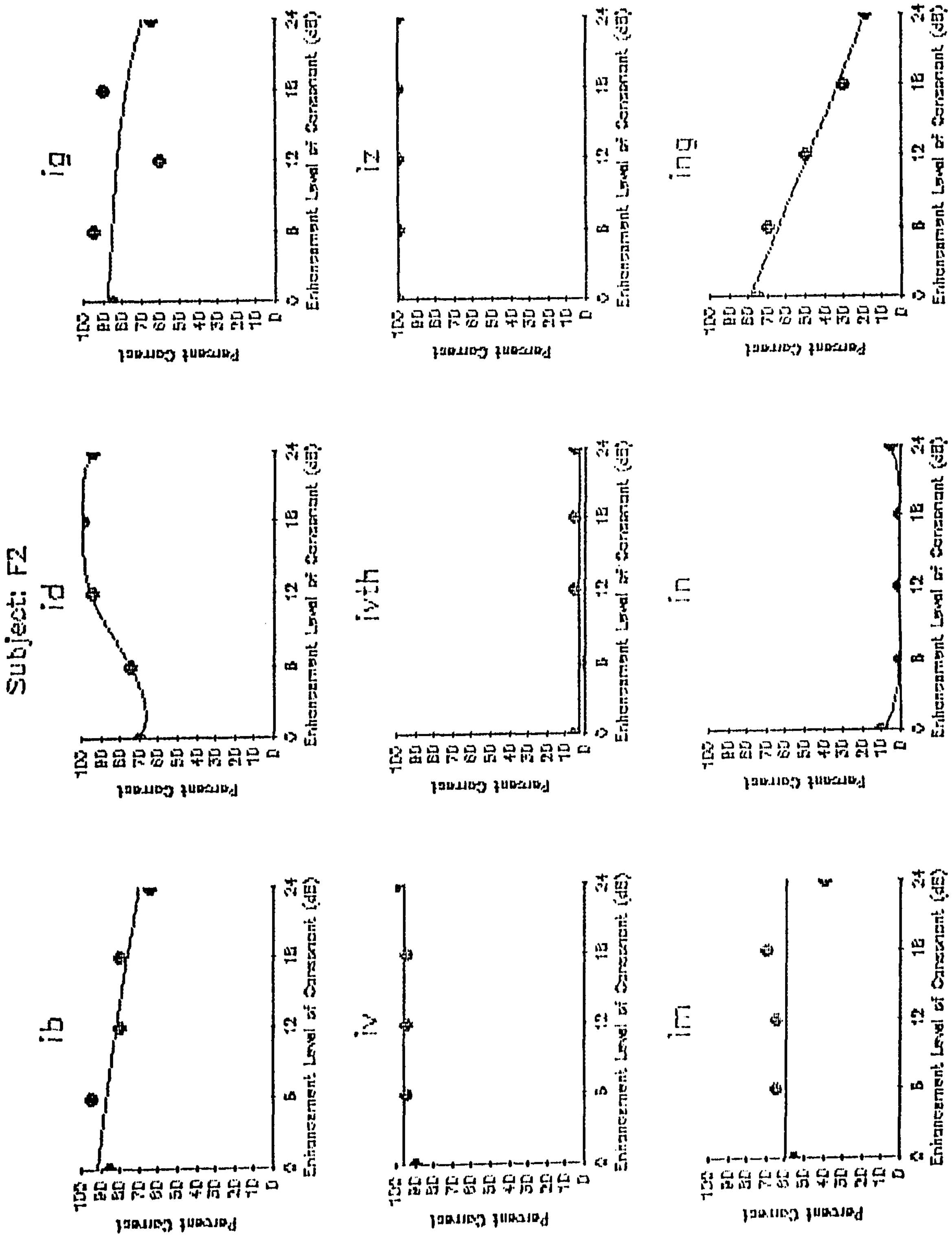

Figure 34. CE functions of the voiced consonants with /i/ for subject F3.

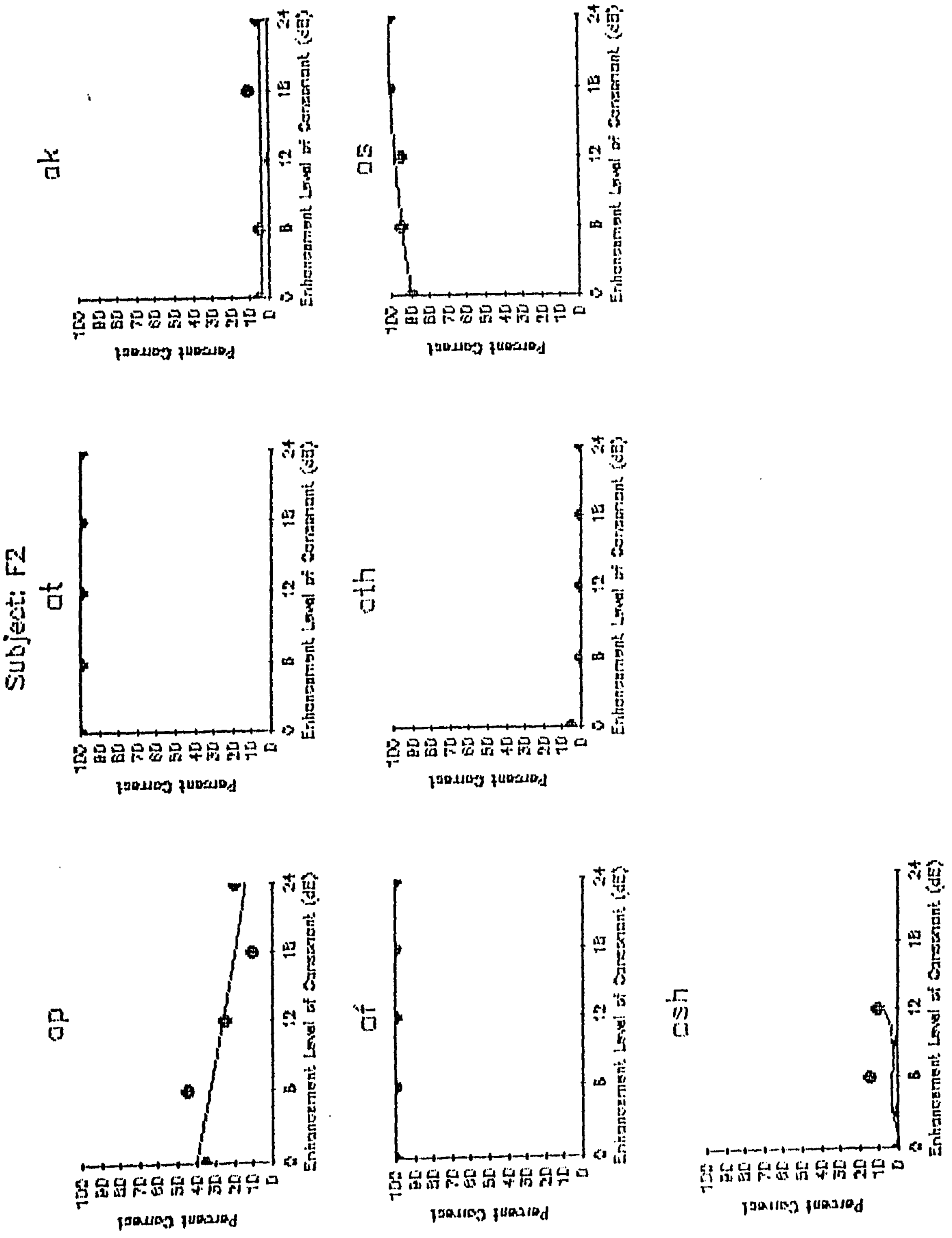

Figure 55. CE functions of the voiceless consonants with /a/ for subject F2.

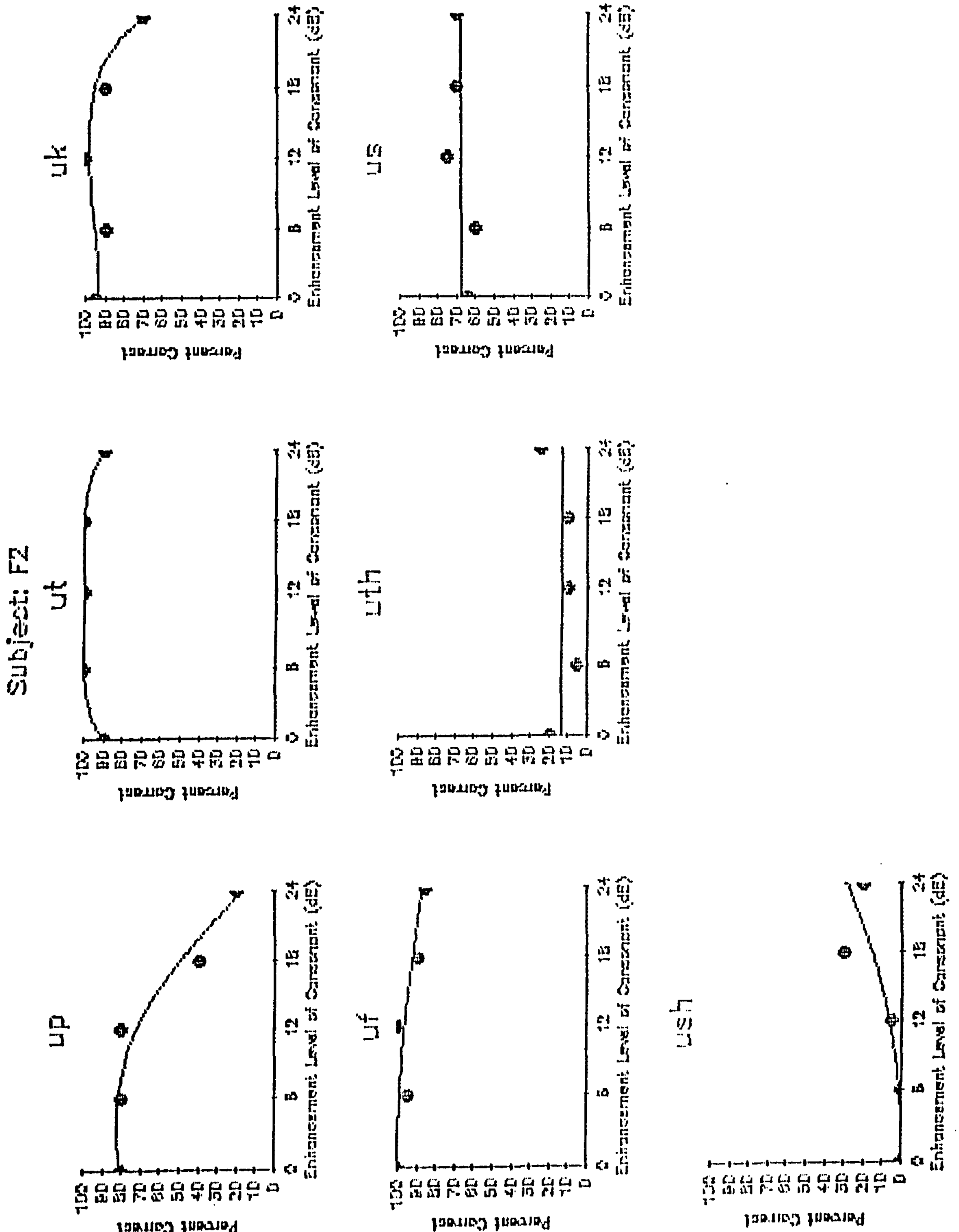

Figure 36. CE functions of the voiceless consonants with /u/ for subject F2.

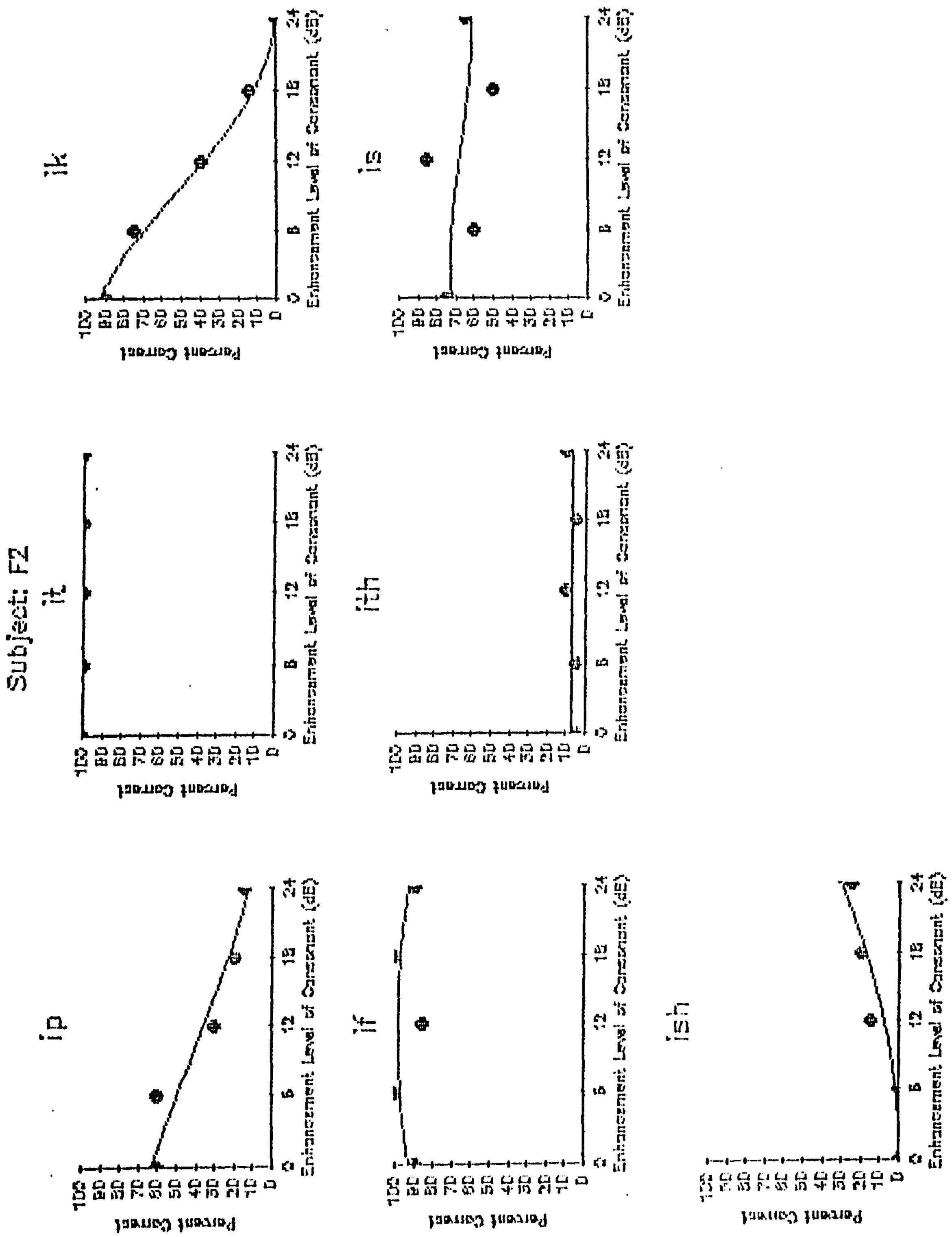

Figure 57. CE functions of the voiceless consonants with /i/ for subject F2

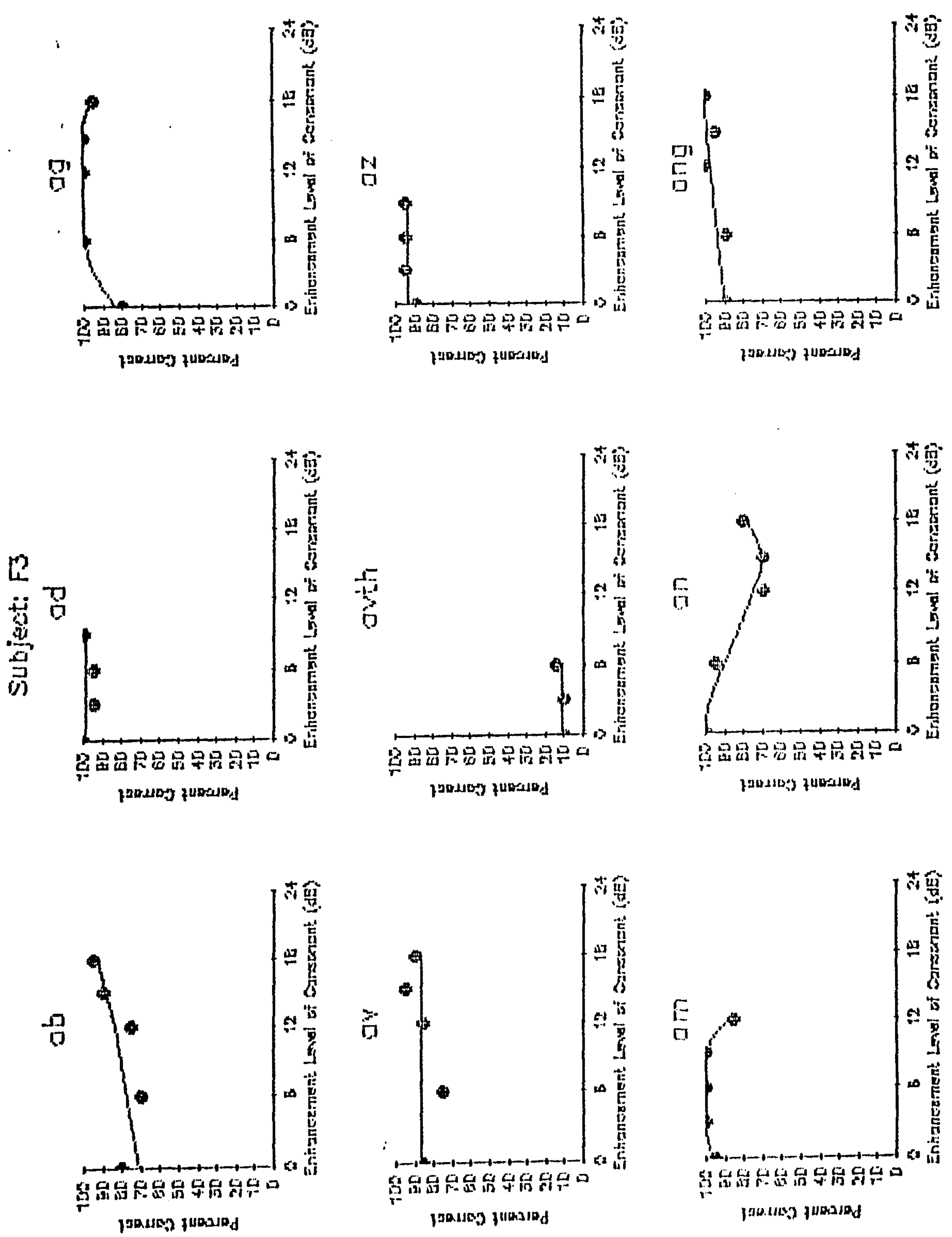

Figure 38. CE functions of the voiced consonants with /a/ for Subject F3

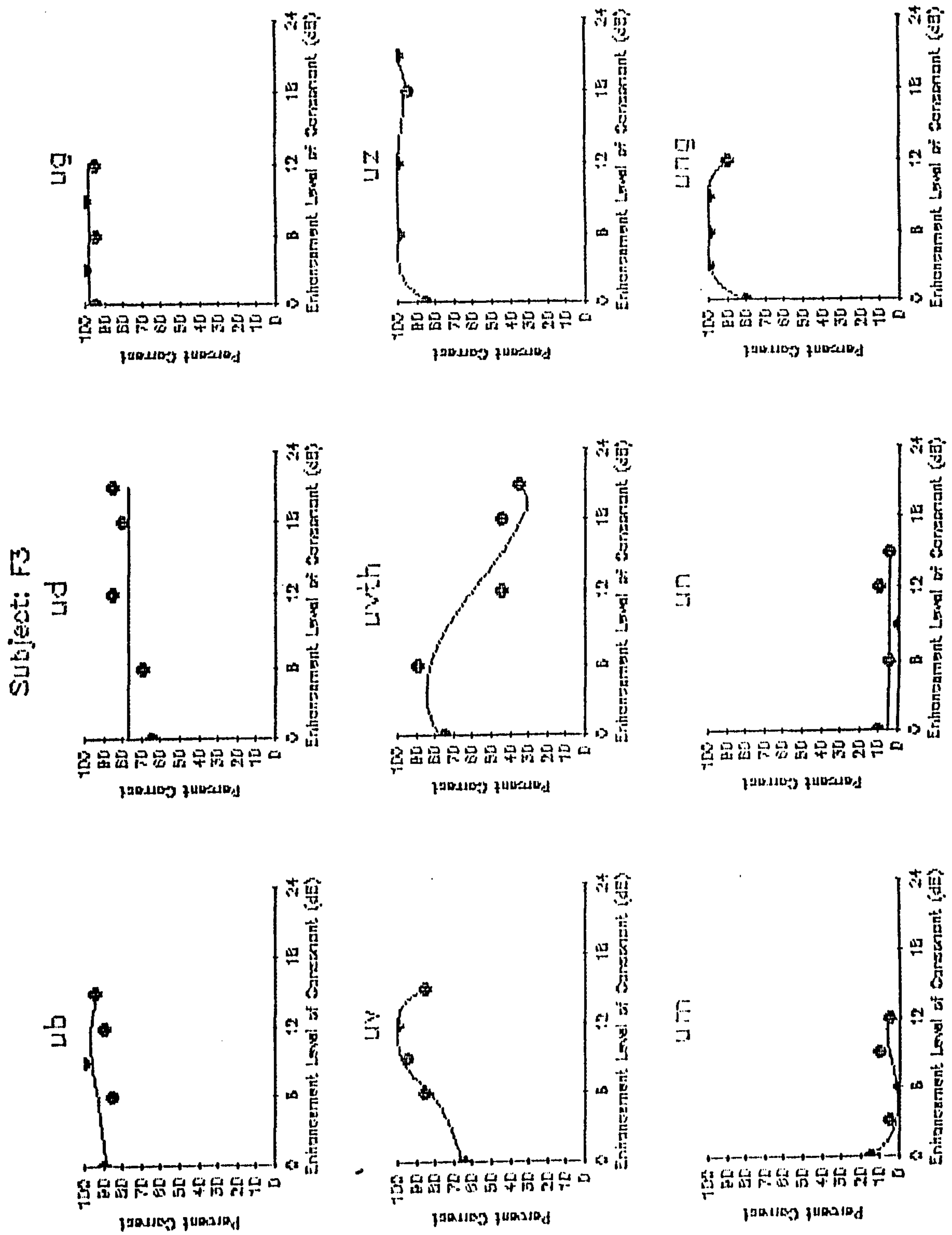

Figure 39. CE functions of the voiced consonants with /u/ for subject F3.

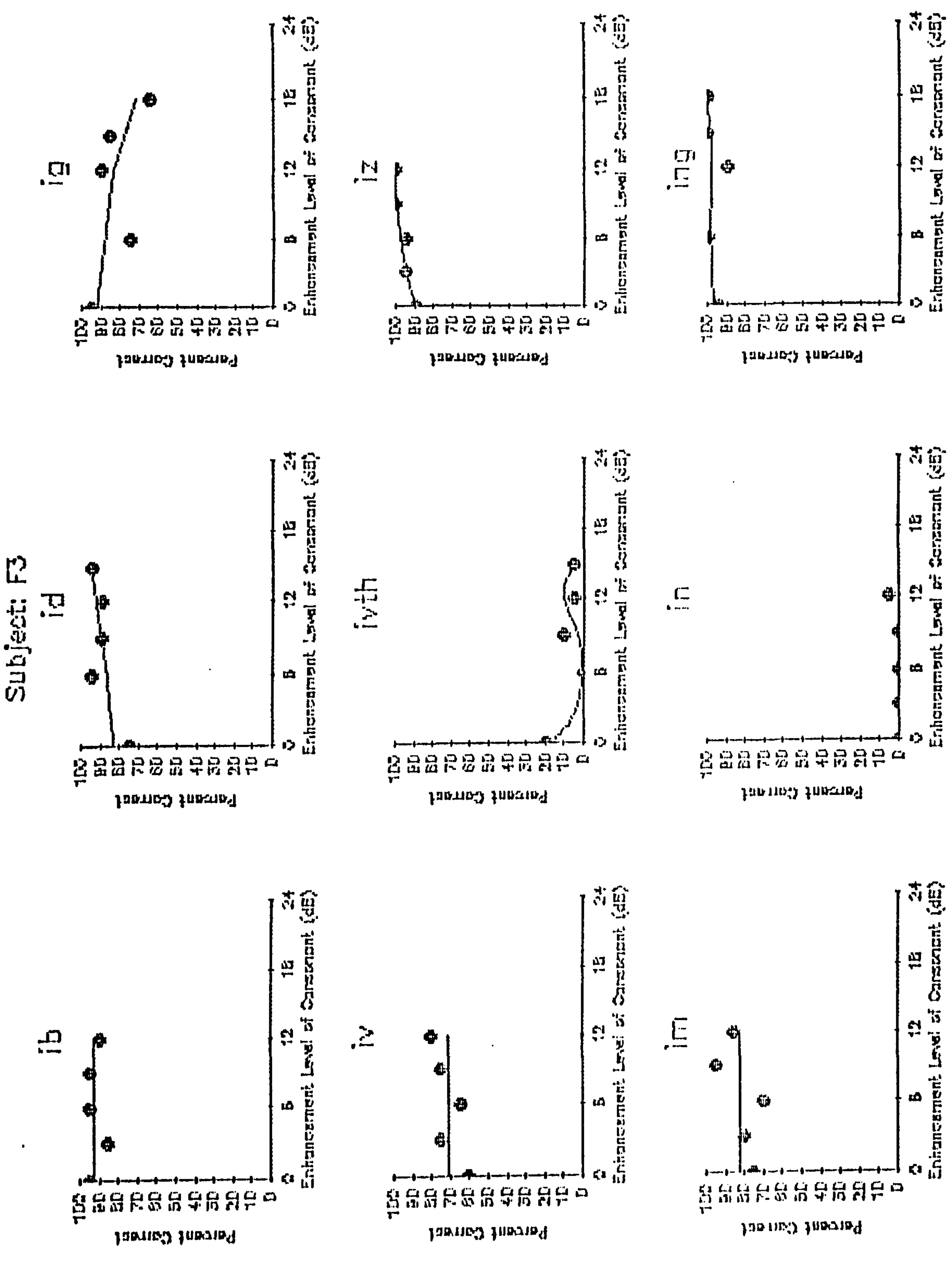

Figure 40. CE functions of the voiced consonants with /i/ for subject F3.

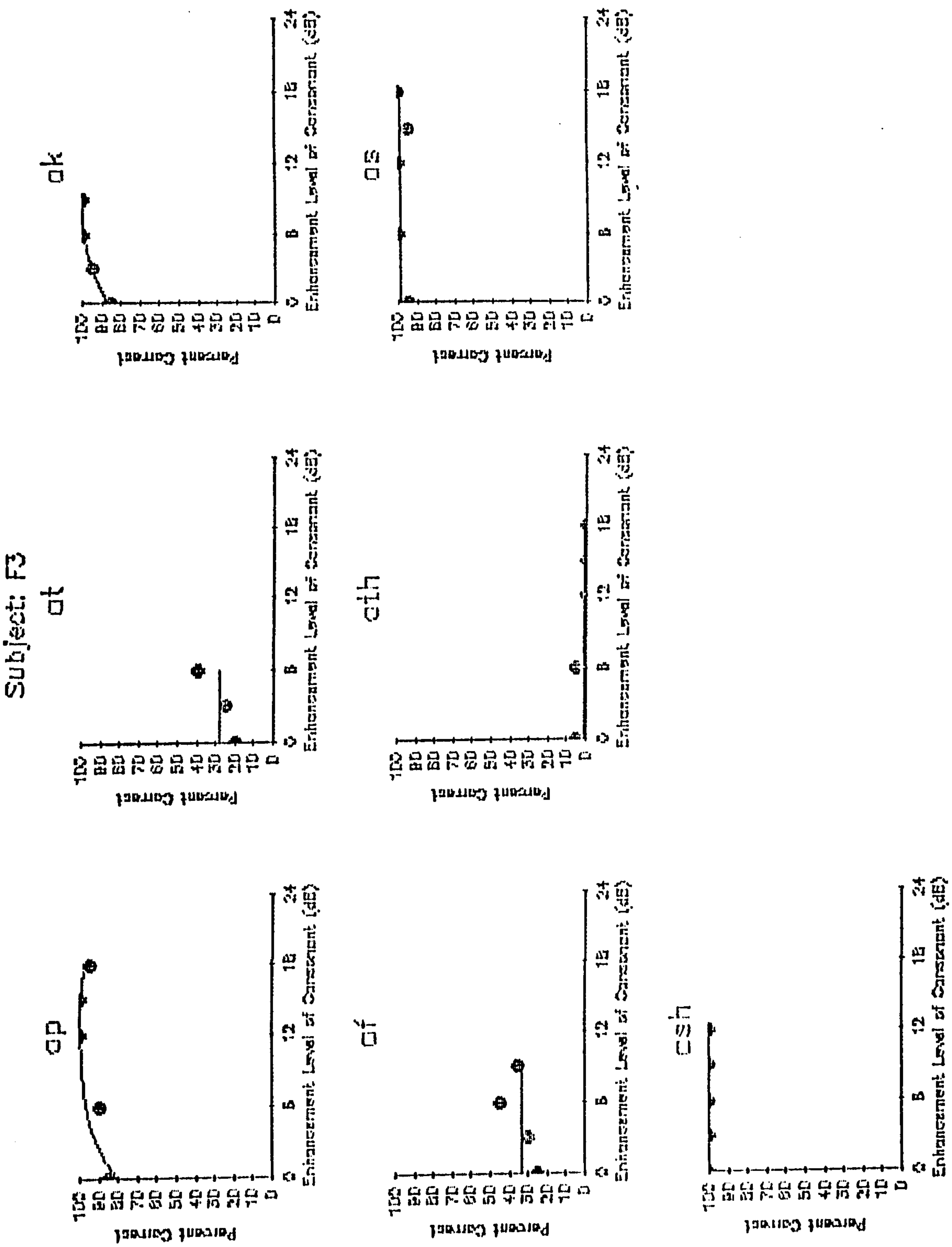

Figure 41. CE functions of the voiceless consonants with /a/ for subject F3.

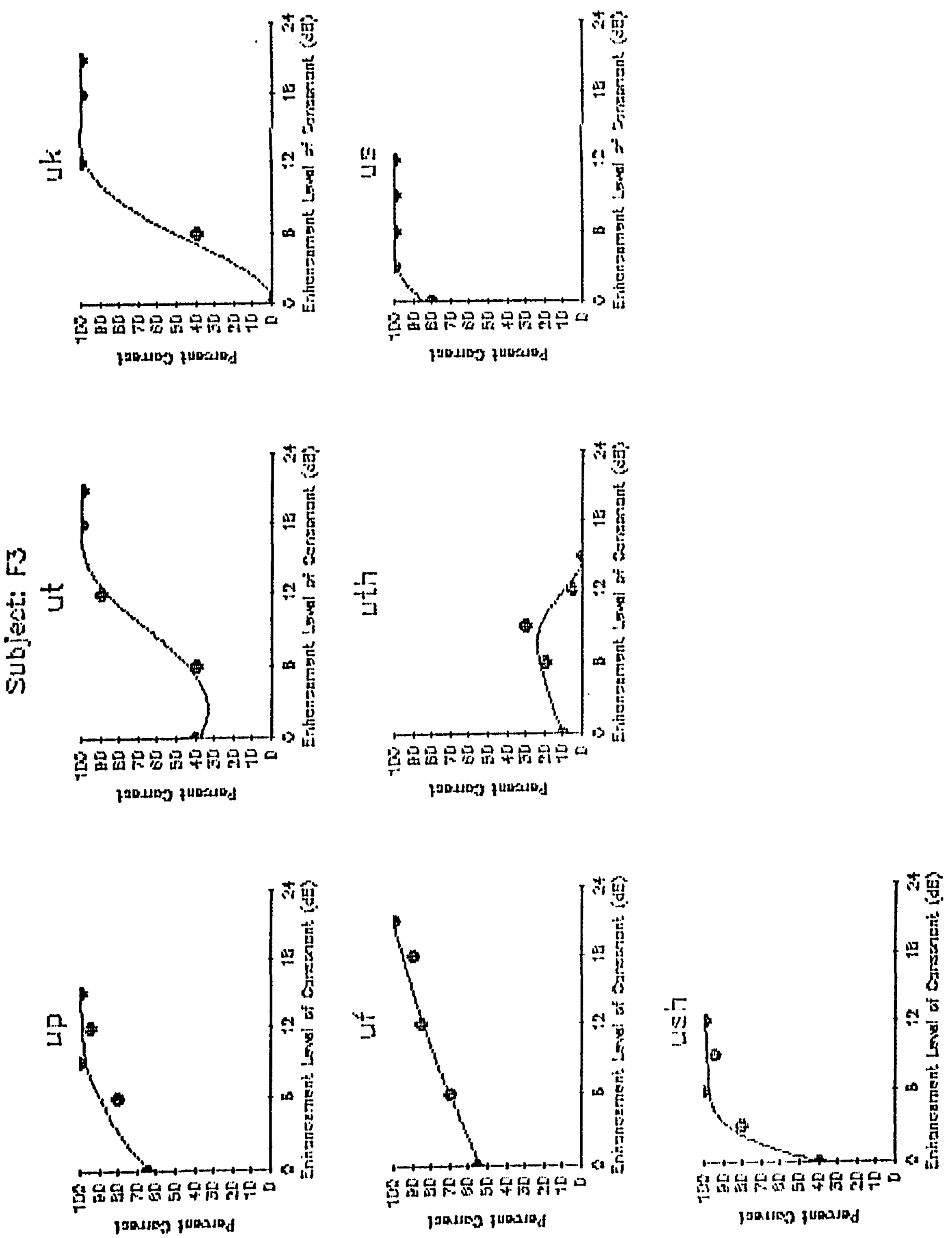

Figure 42. CE functions of the voiceless consonants with /u/ for subject F3.

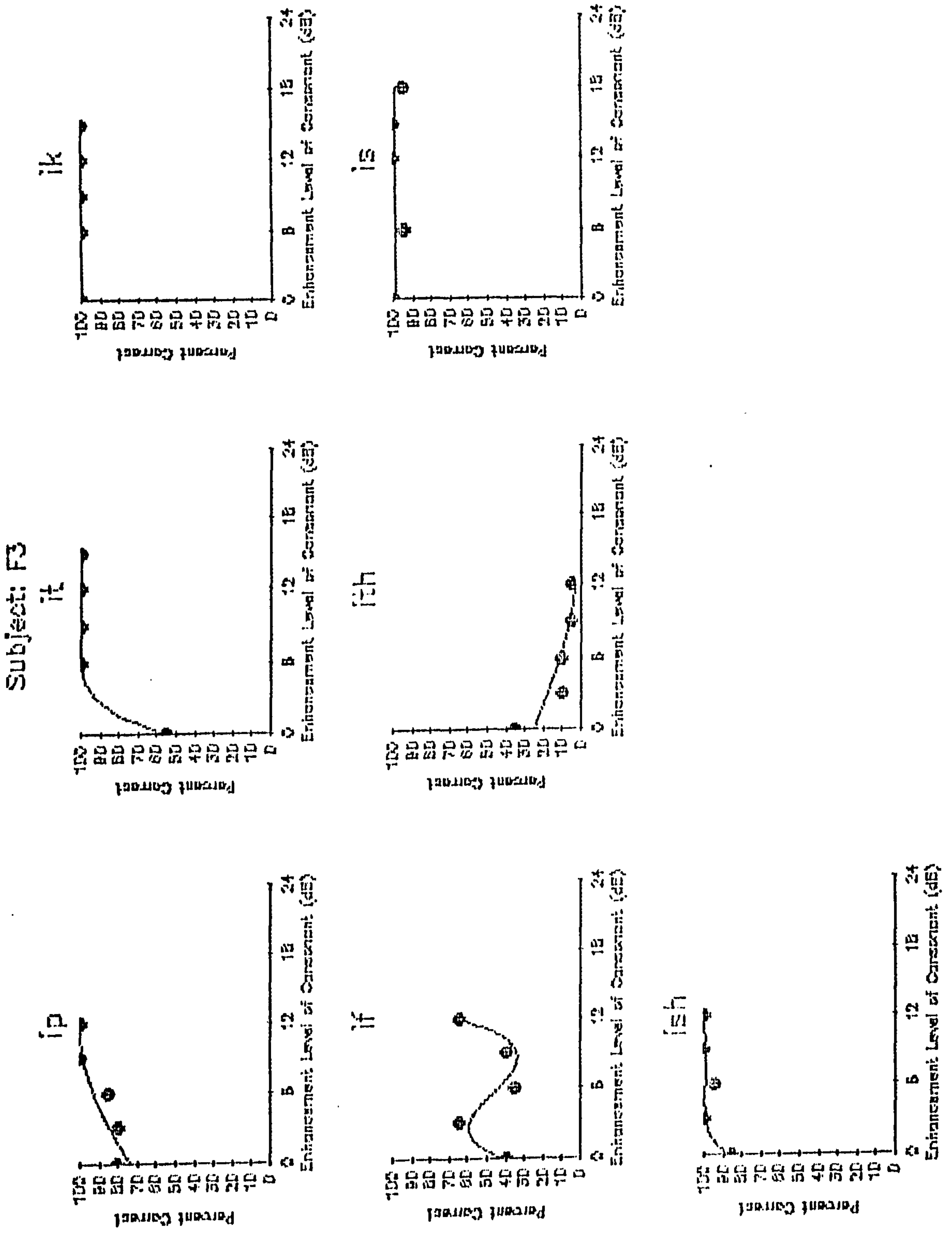

Figure 43. CE functions of the voiceless consonants with /i/ for subject F3.

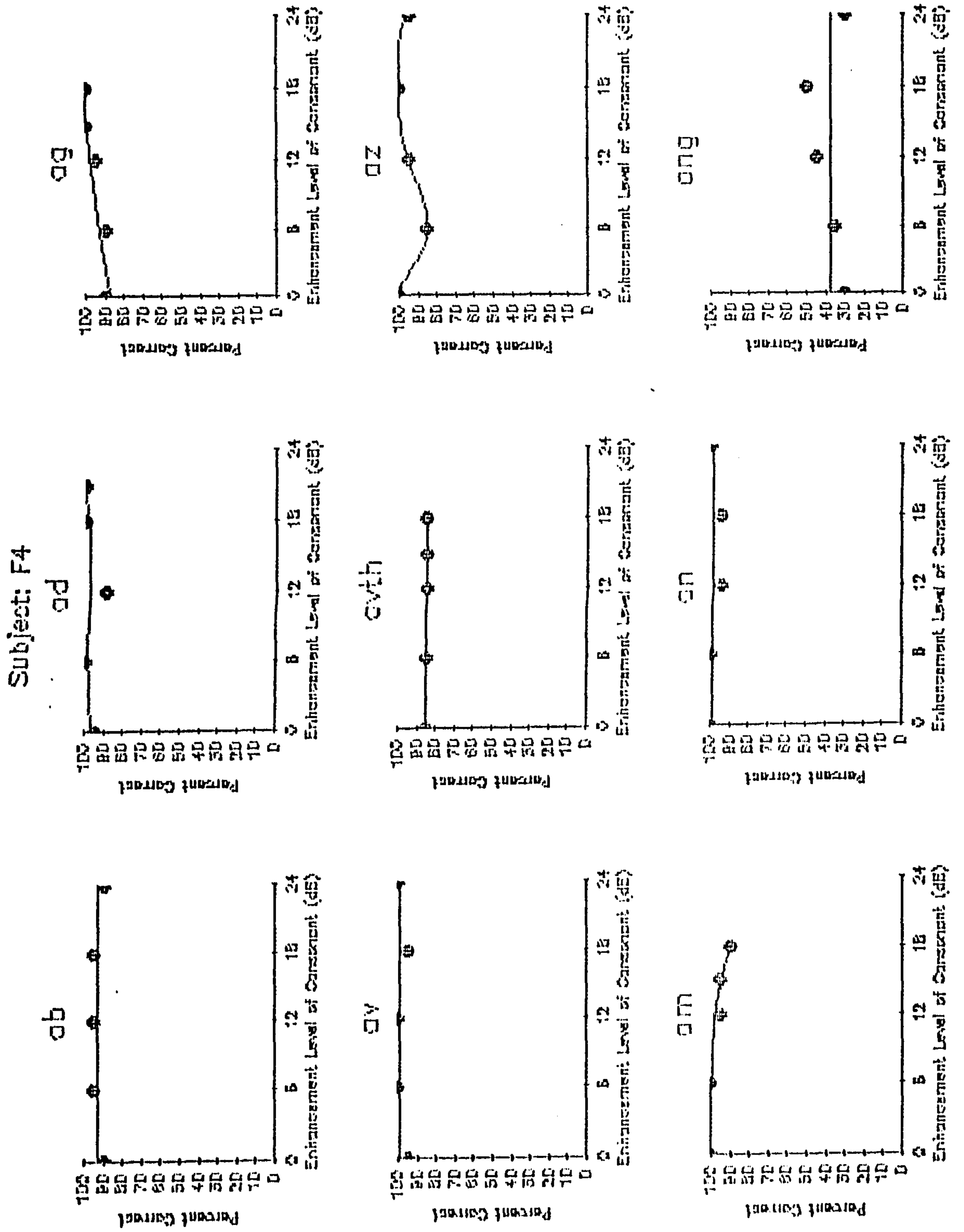

Figure 44. CE functions of the voiced consonants with /a/ for subject F4.

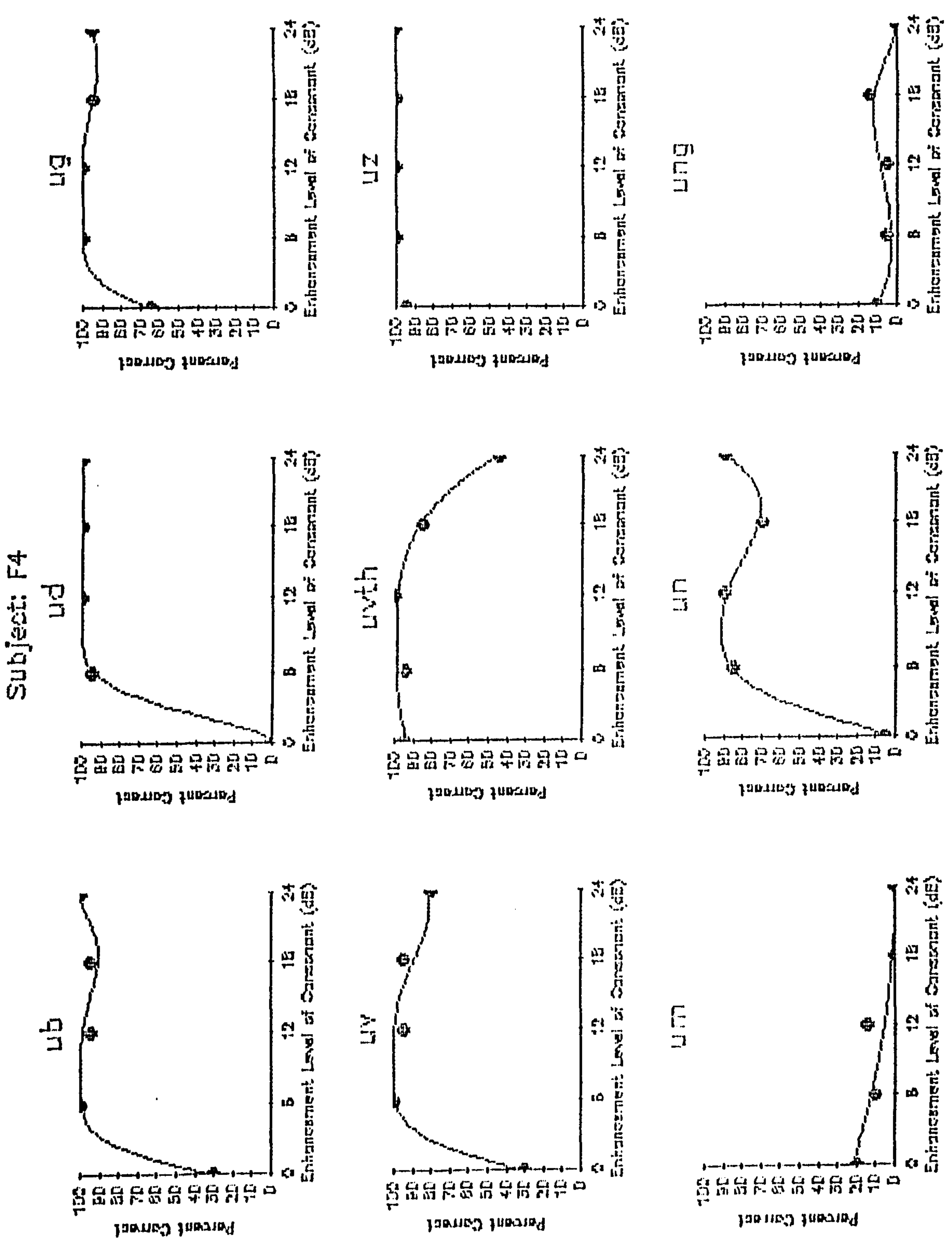

Figure 45. CE functions of the voiced consonants with /u/ for subject F4.

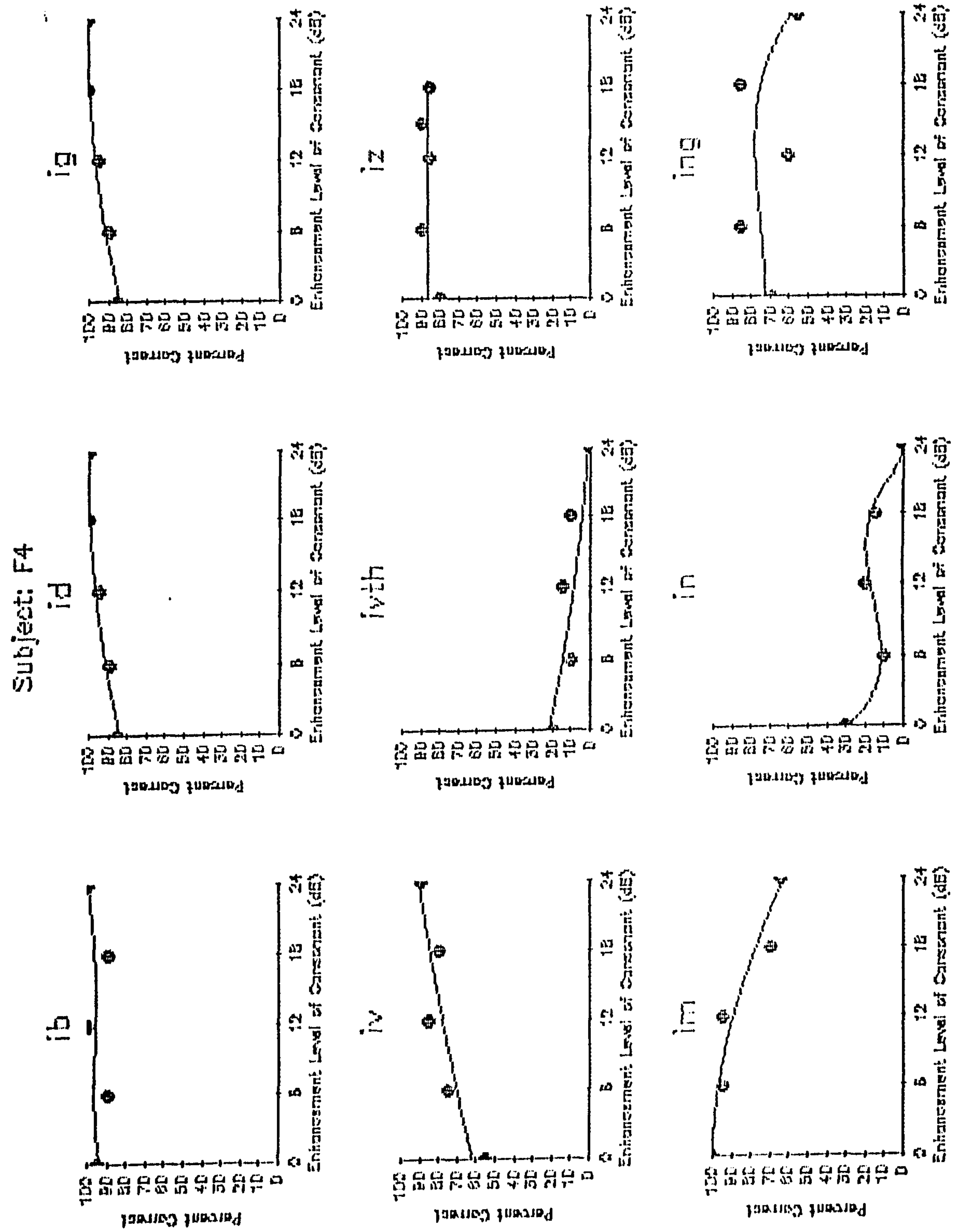

Figure 46. CE functions of the voiced consonants with /i/ for subject F4.

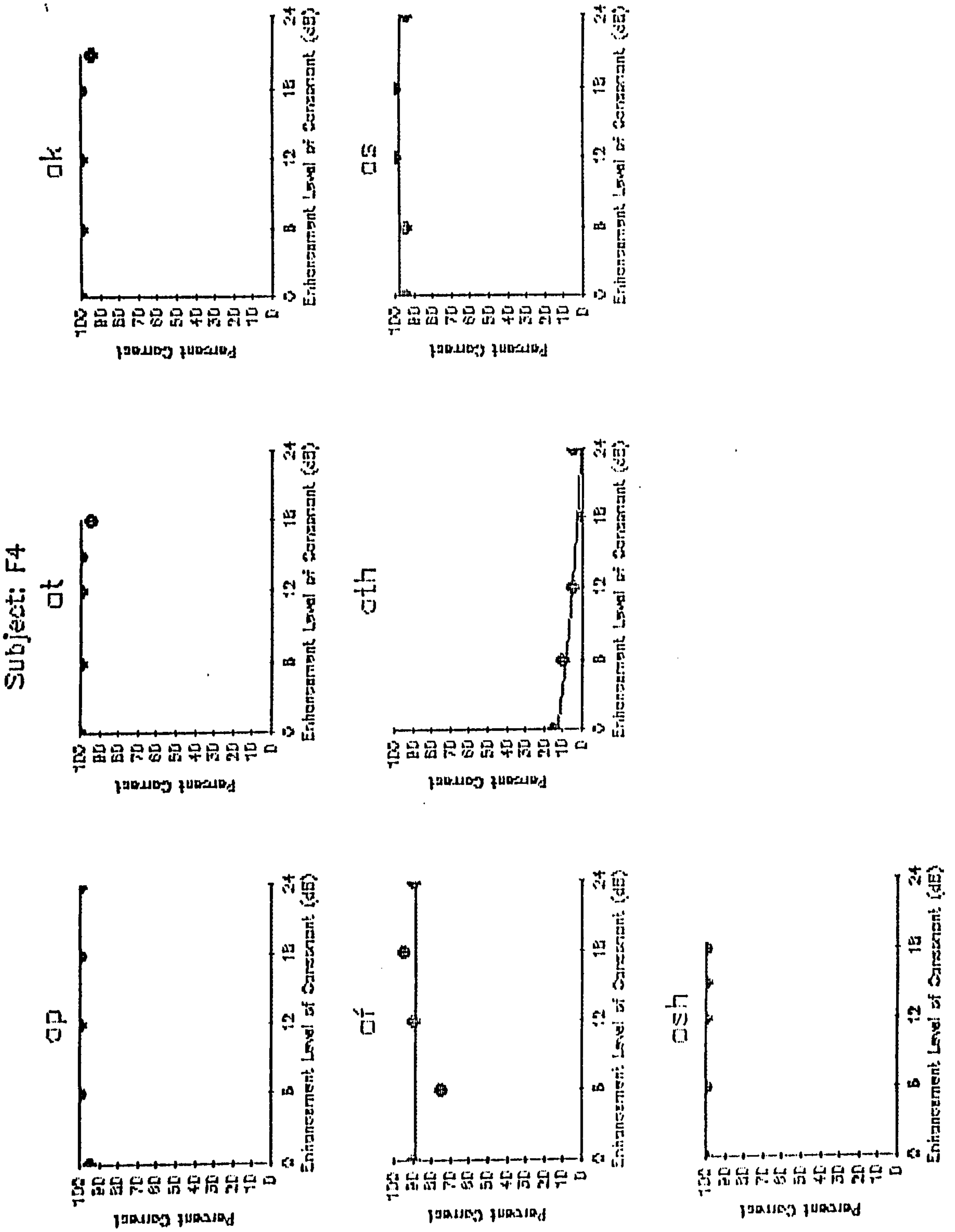

Figure 47. CE functions of the voiceless consonants with /a/ for subject F4.

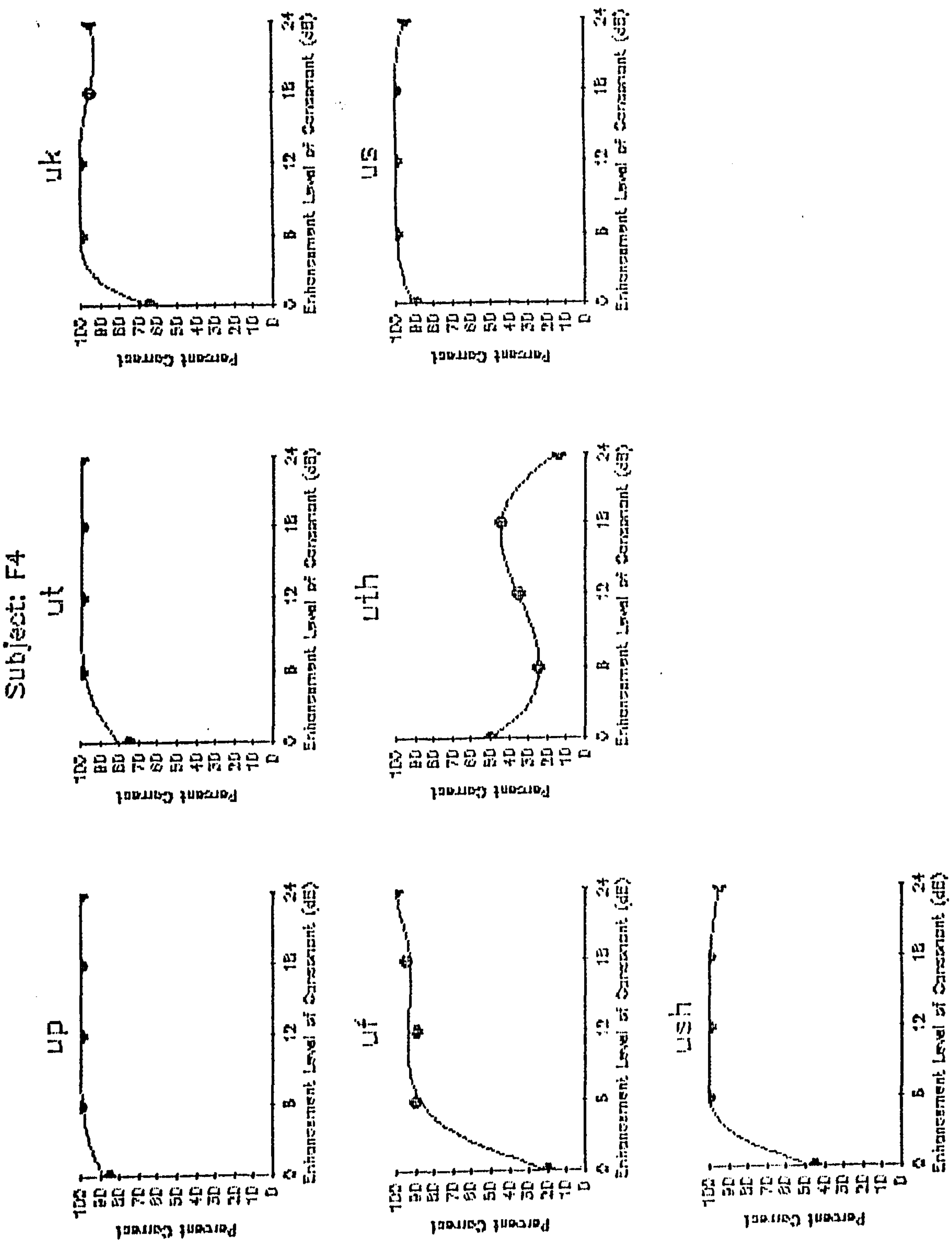

Figure 48. CE functions of the voiceless consonants with /u/ for subject F4.

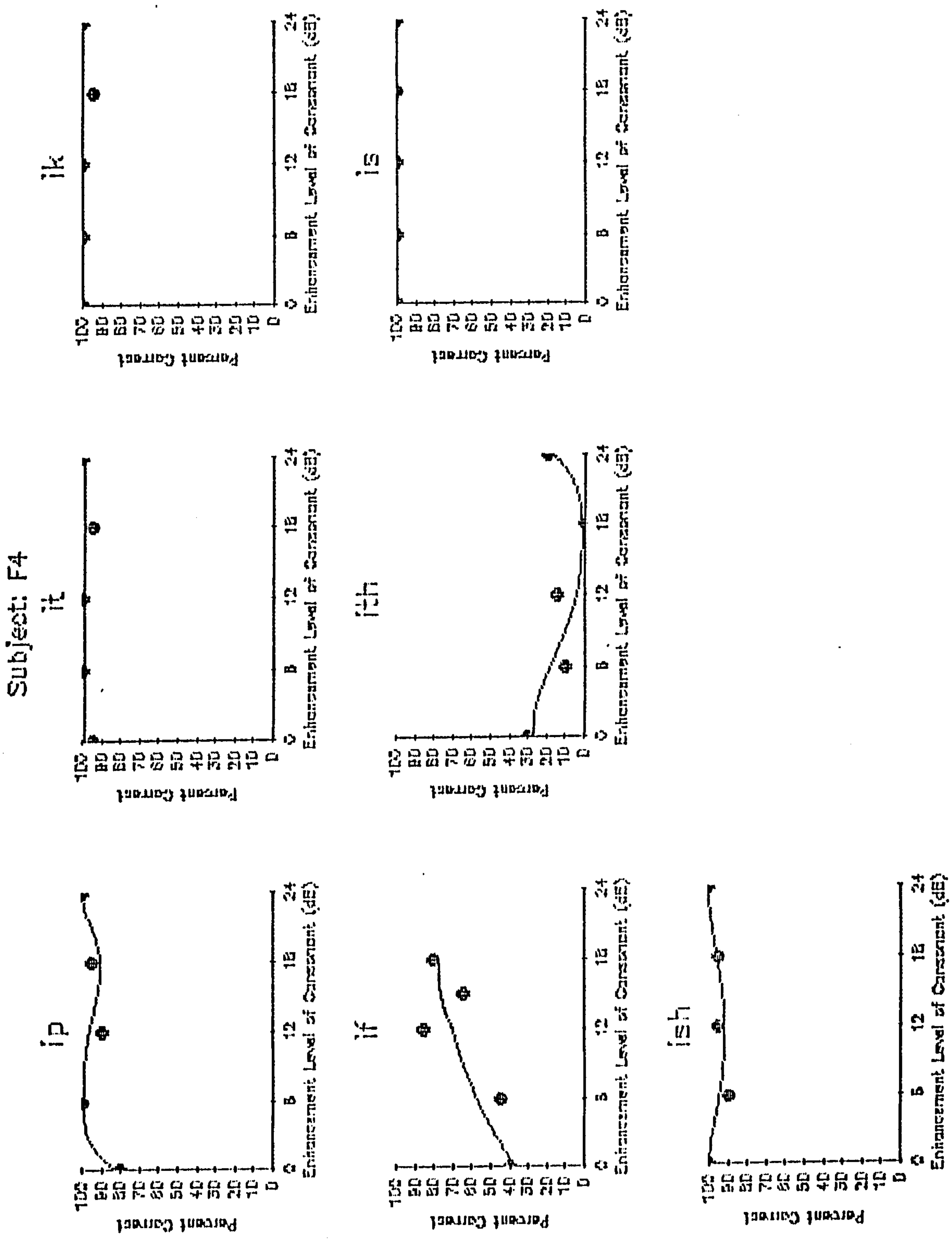

Figure 49. CE functions of the voiceless consonants with /i/ for subject F4.

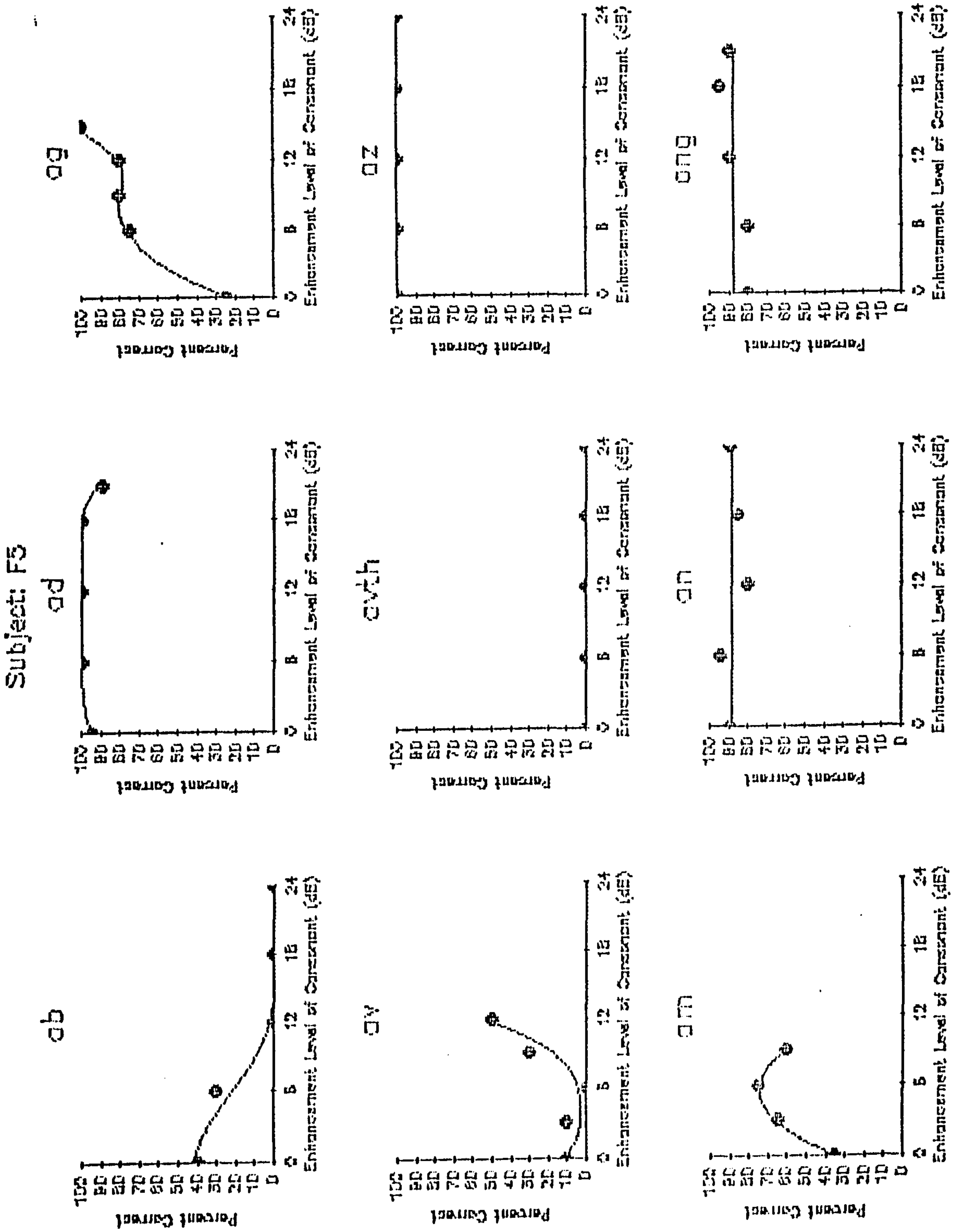

Figure 50. CE functions of the voiced consonants with /a/ for subject F5.

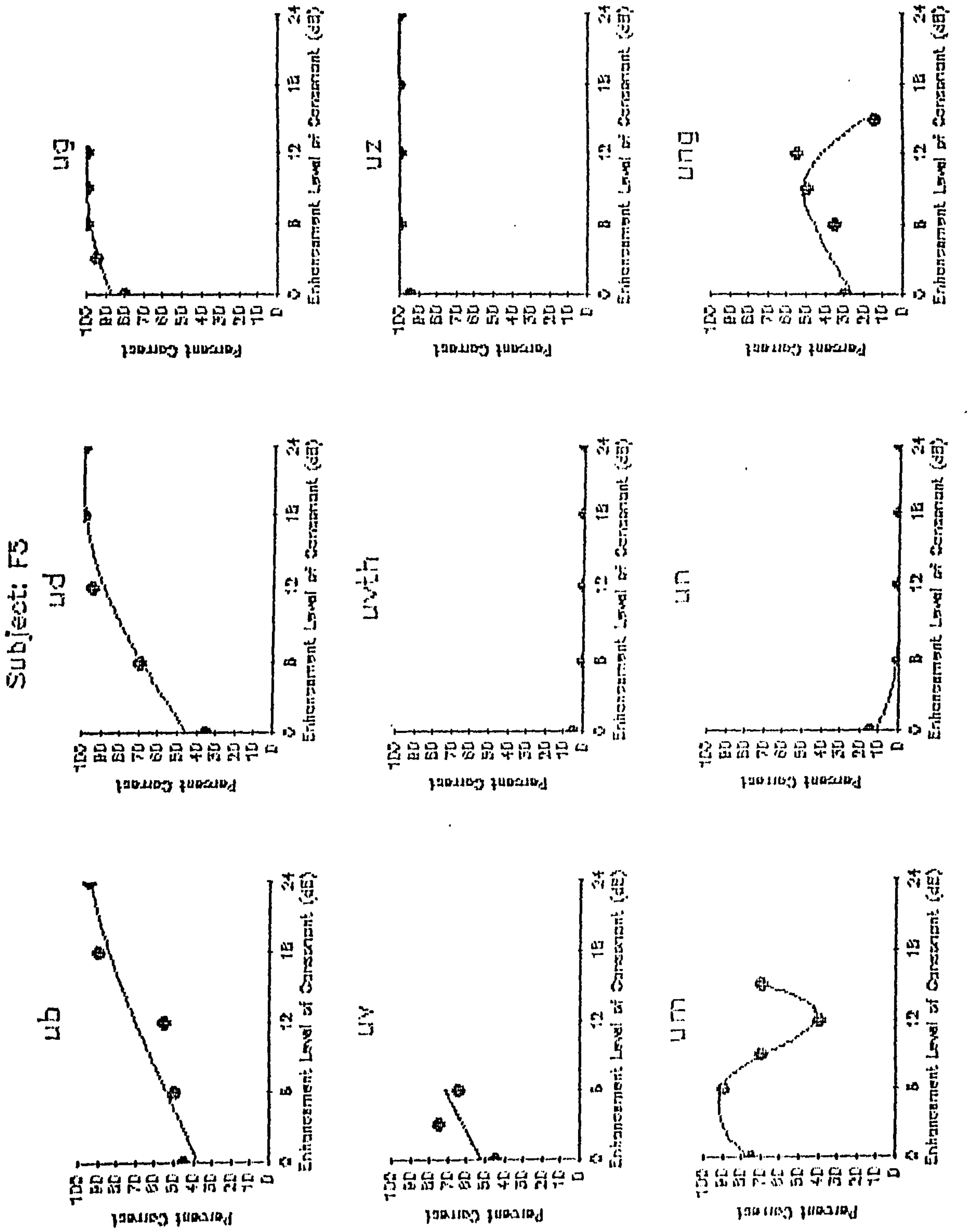

Figure 51. CE functions of the voiced consonants with /u/ for subject F5.

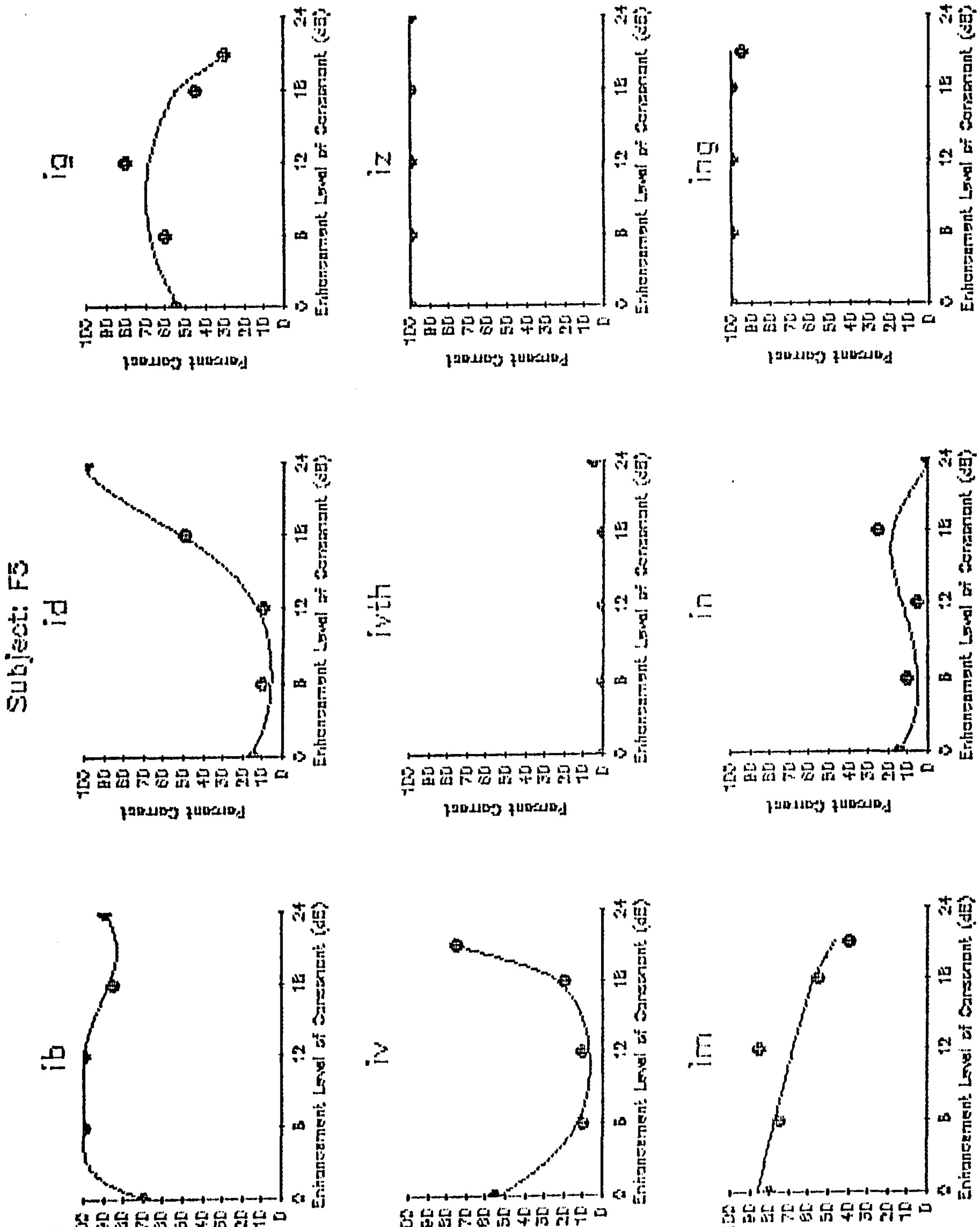

Figure 52. CE functions of the voiced consonants with /i/ for subject F5.

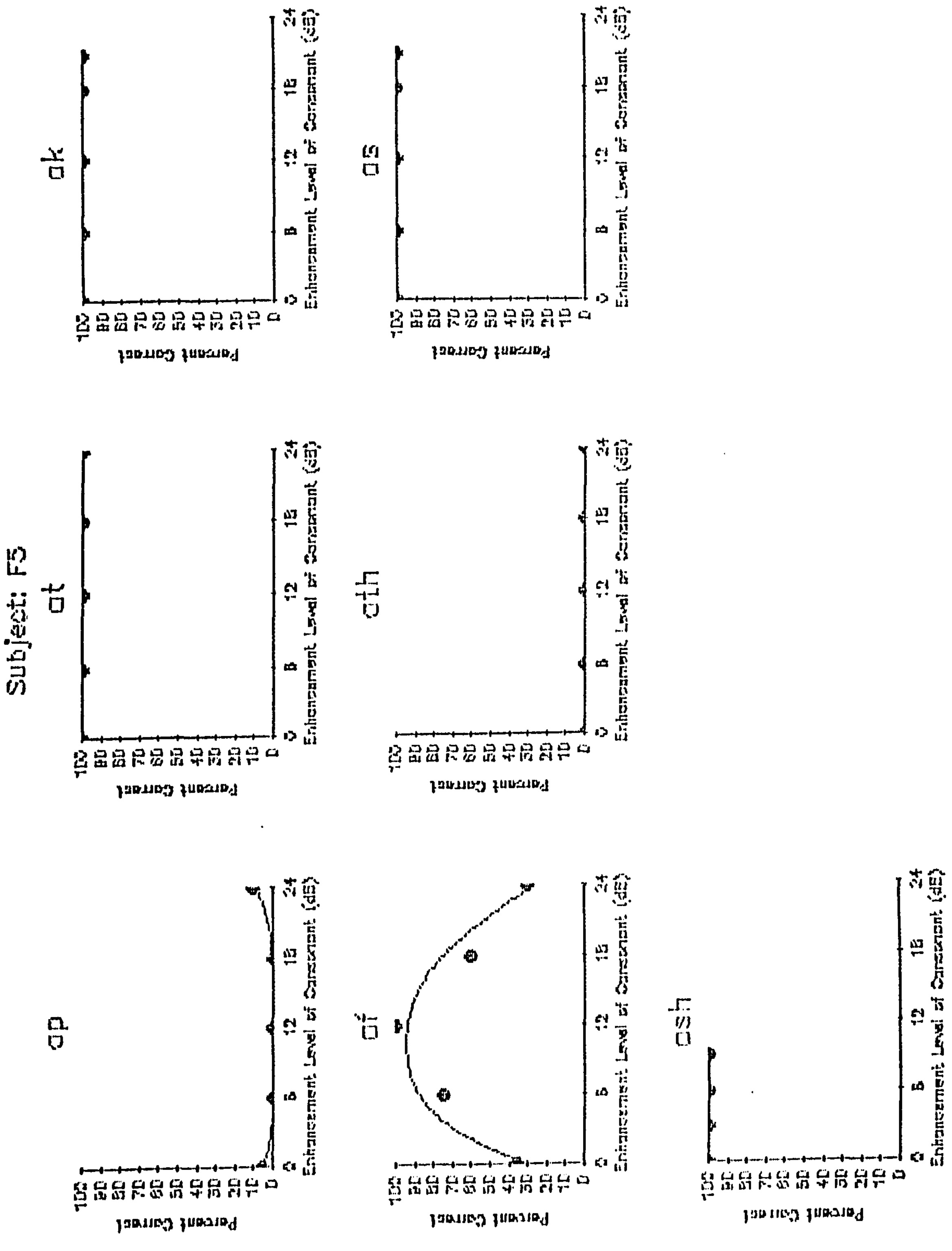

Figure 53. CE functions of the voiceless consonants with /a/ for subject F5.

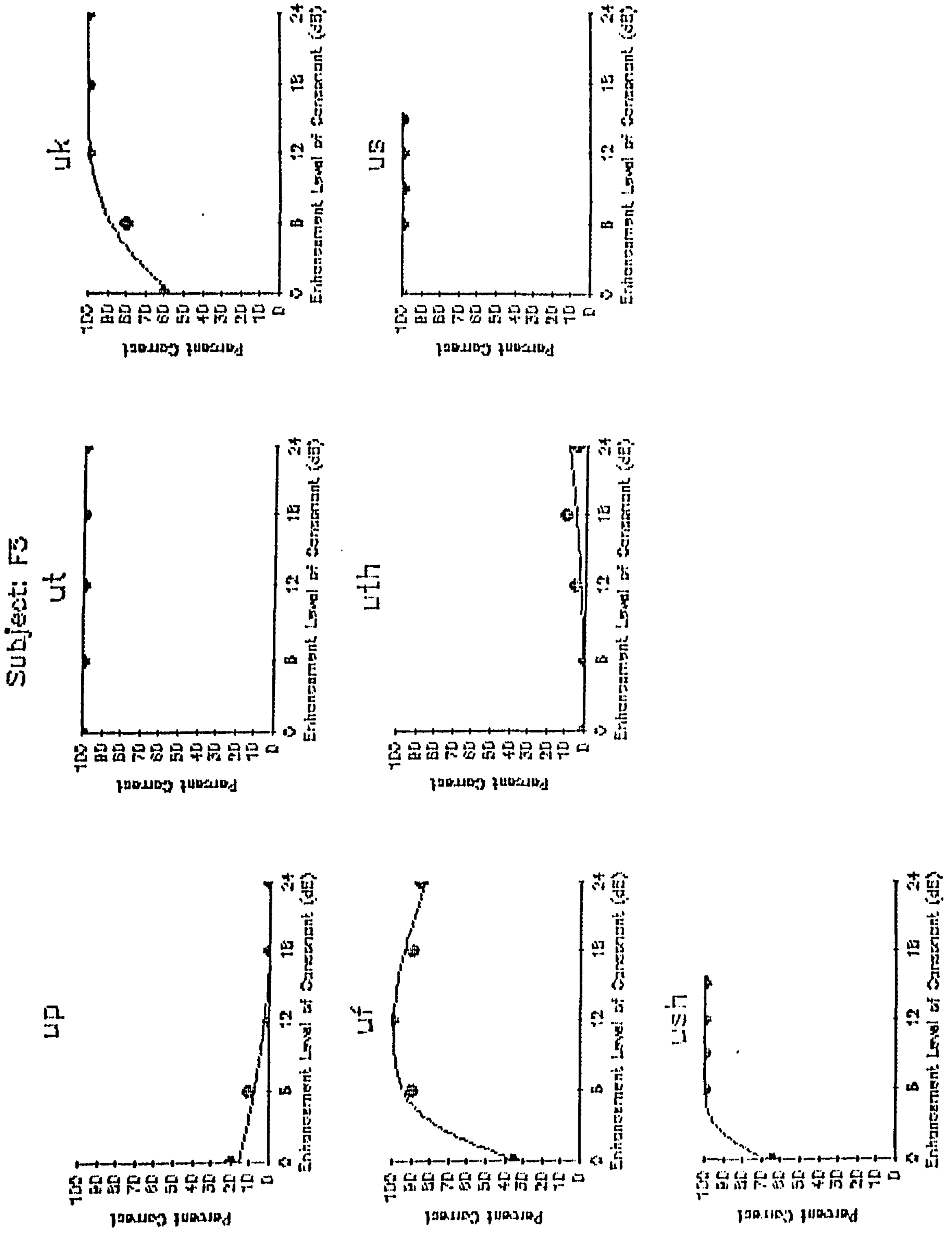

Figure 54. CE functions of the voiceless consonants with /u/ for subject F5.

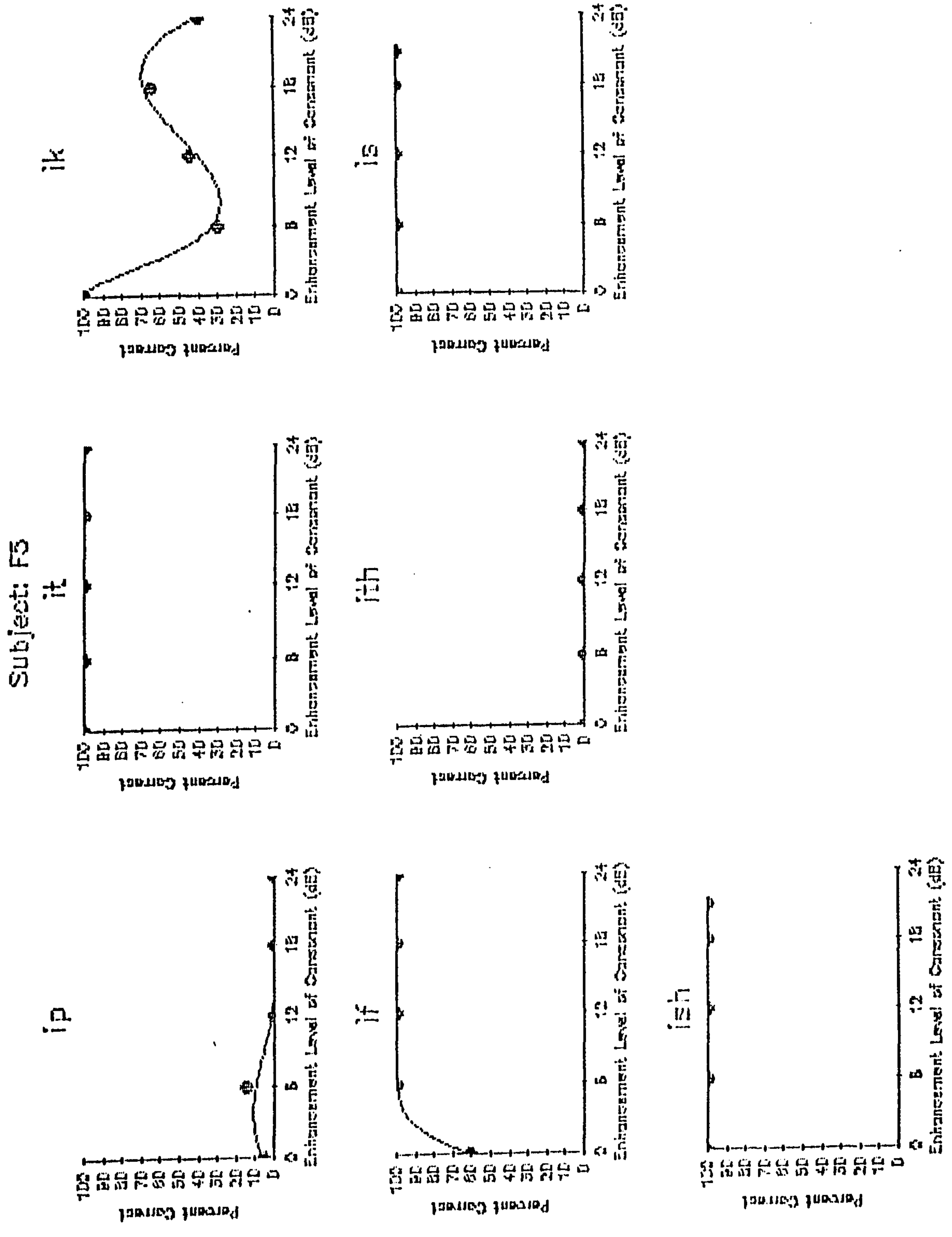

Figure 55. CE functions of the voiceless consonants with /i/ for subject F5.

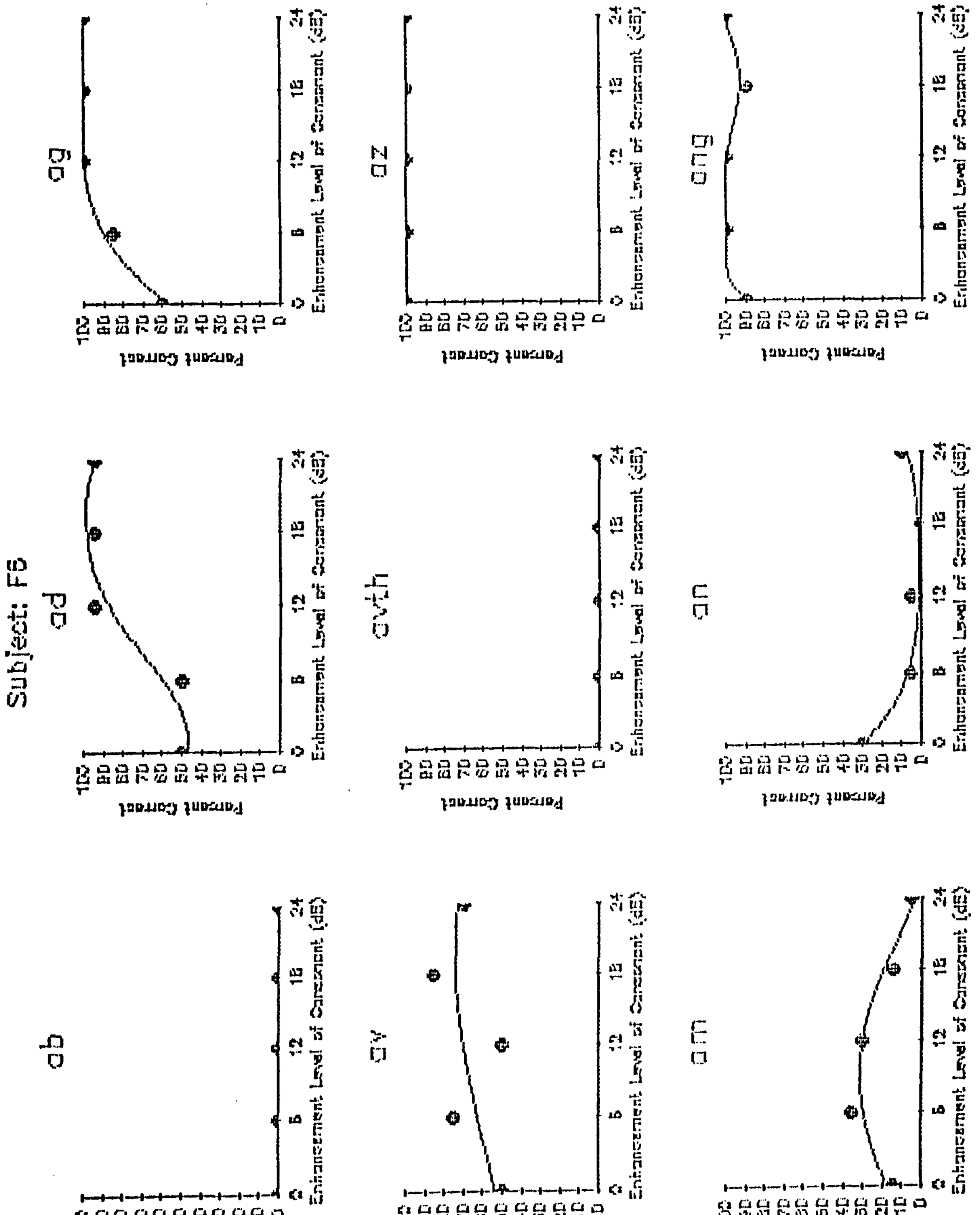

Figure 56. CE functions of the voiced consonants with /a/ for subject F6.

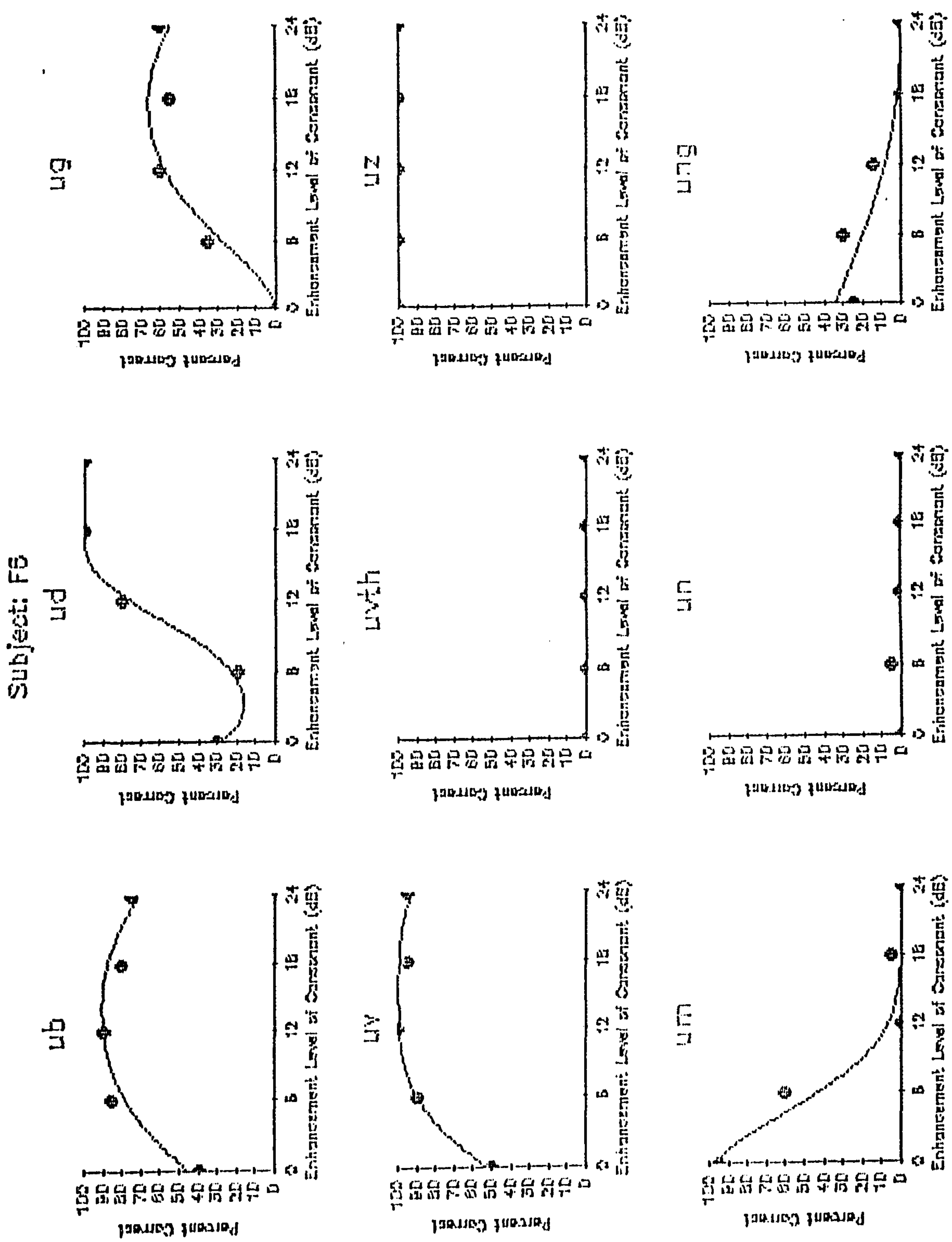

Figure 57. CE functions of the voiced consonants with /u/ for subject F6.

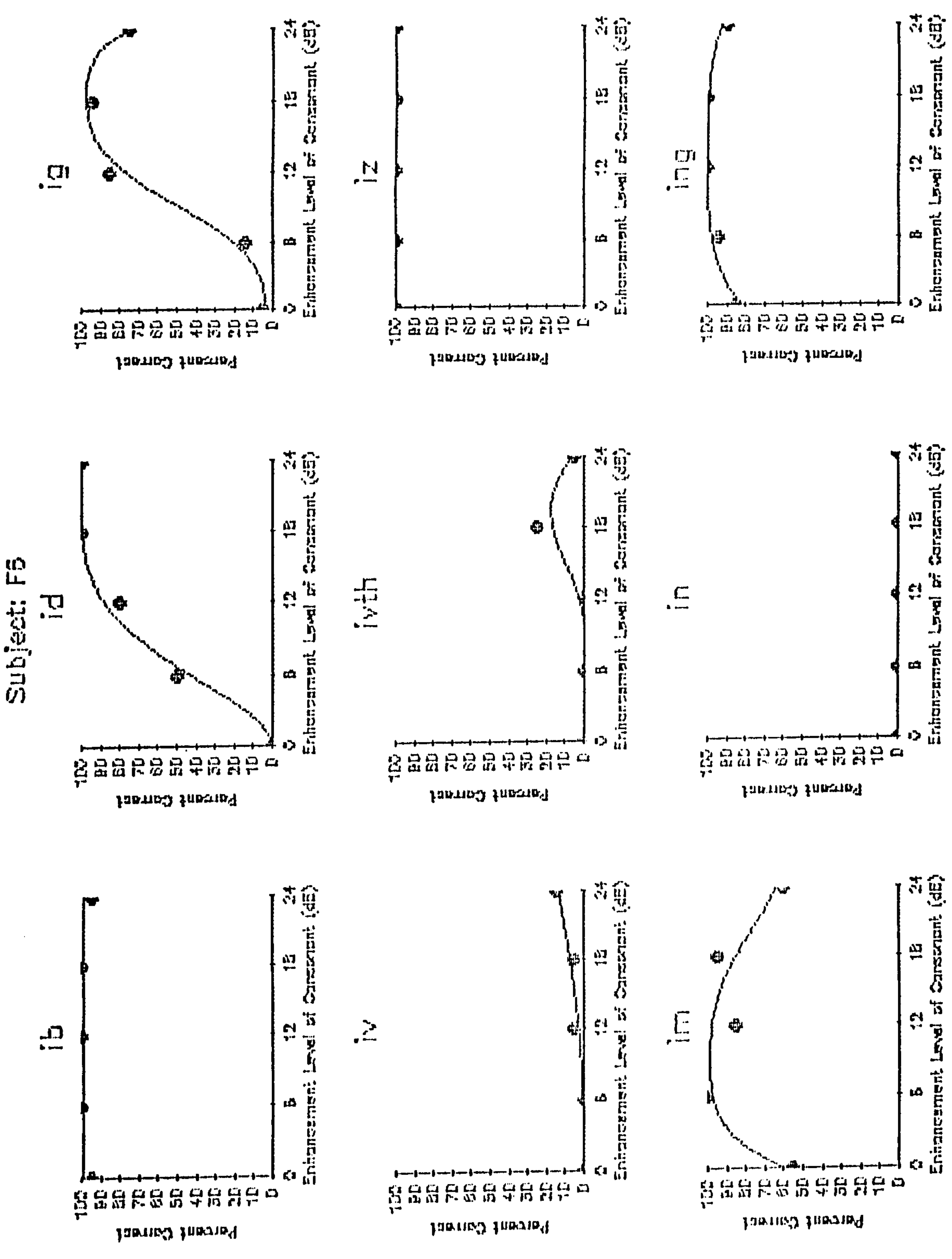

Figure 58. CE functions of the voiced consonants with /i/ for subject F6.

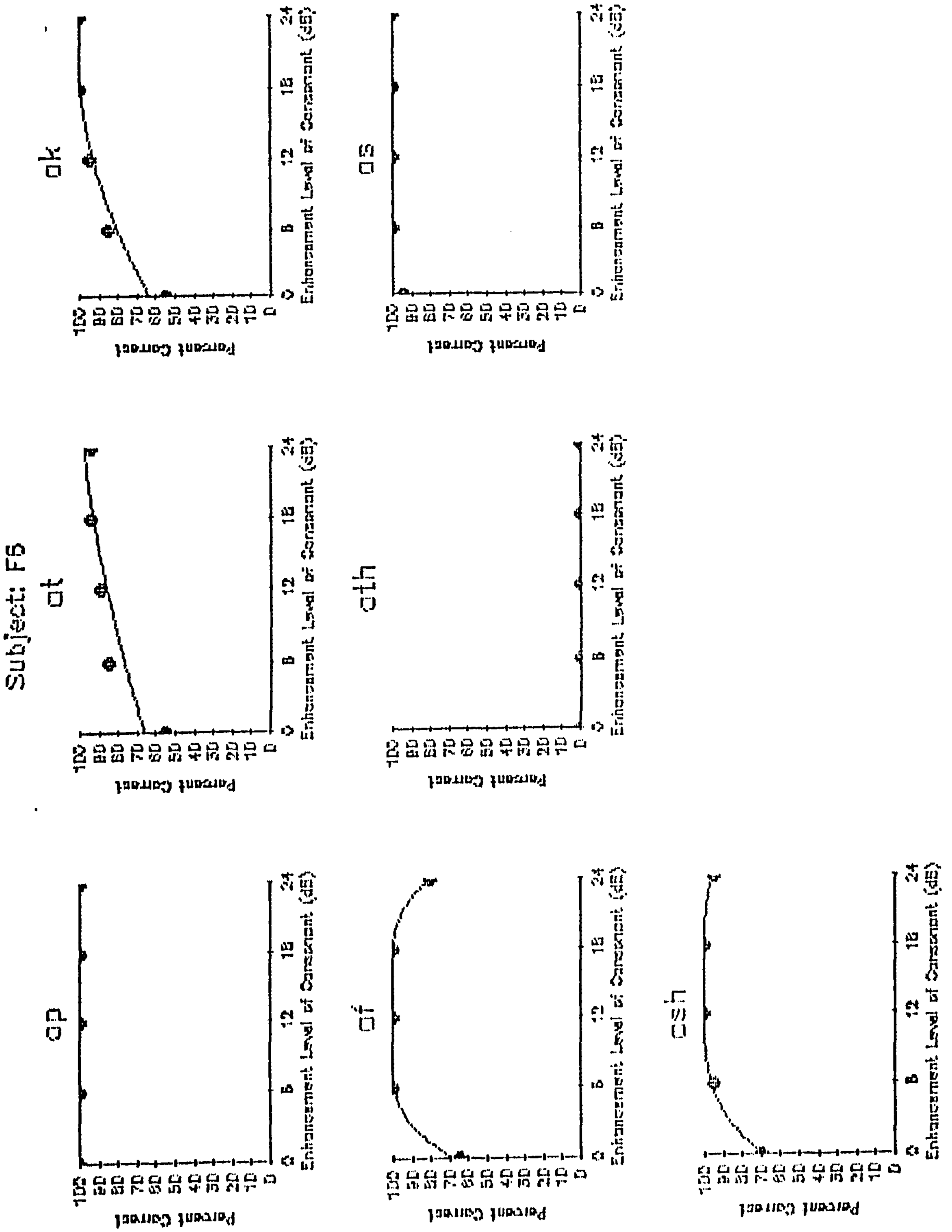

Figure 59. CE functions of the voiceless consonants with /a/ for subject F6.

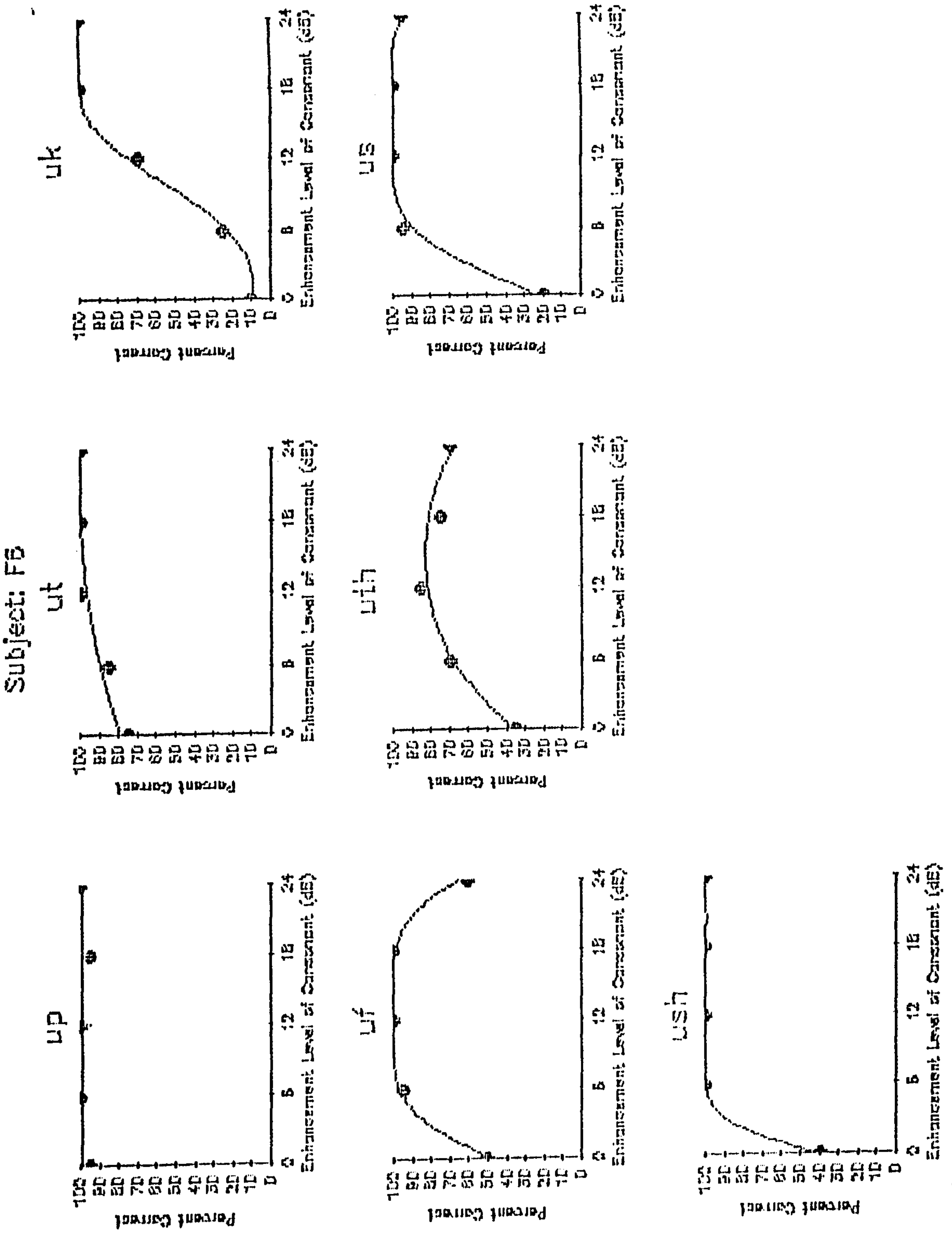

Figure 60. CE functions of the voiceless consonants with /u/ for subject F6.

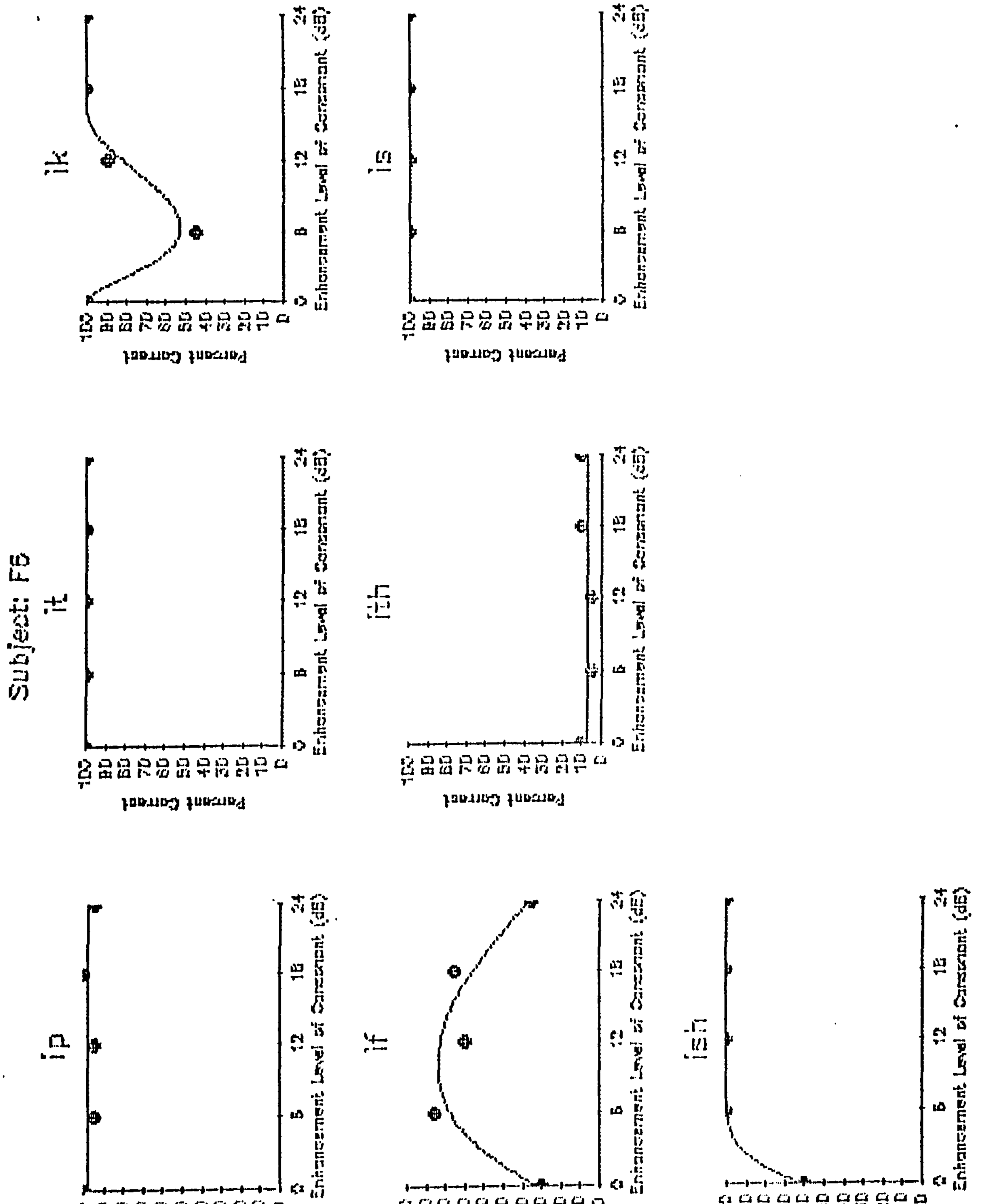

Figure 61. CE functions of the voiceless consonants with /i/ for subject F6.

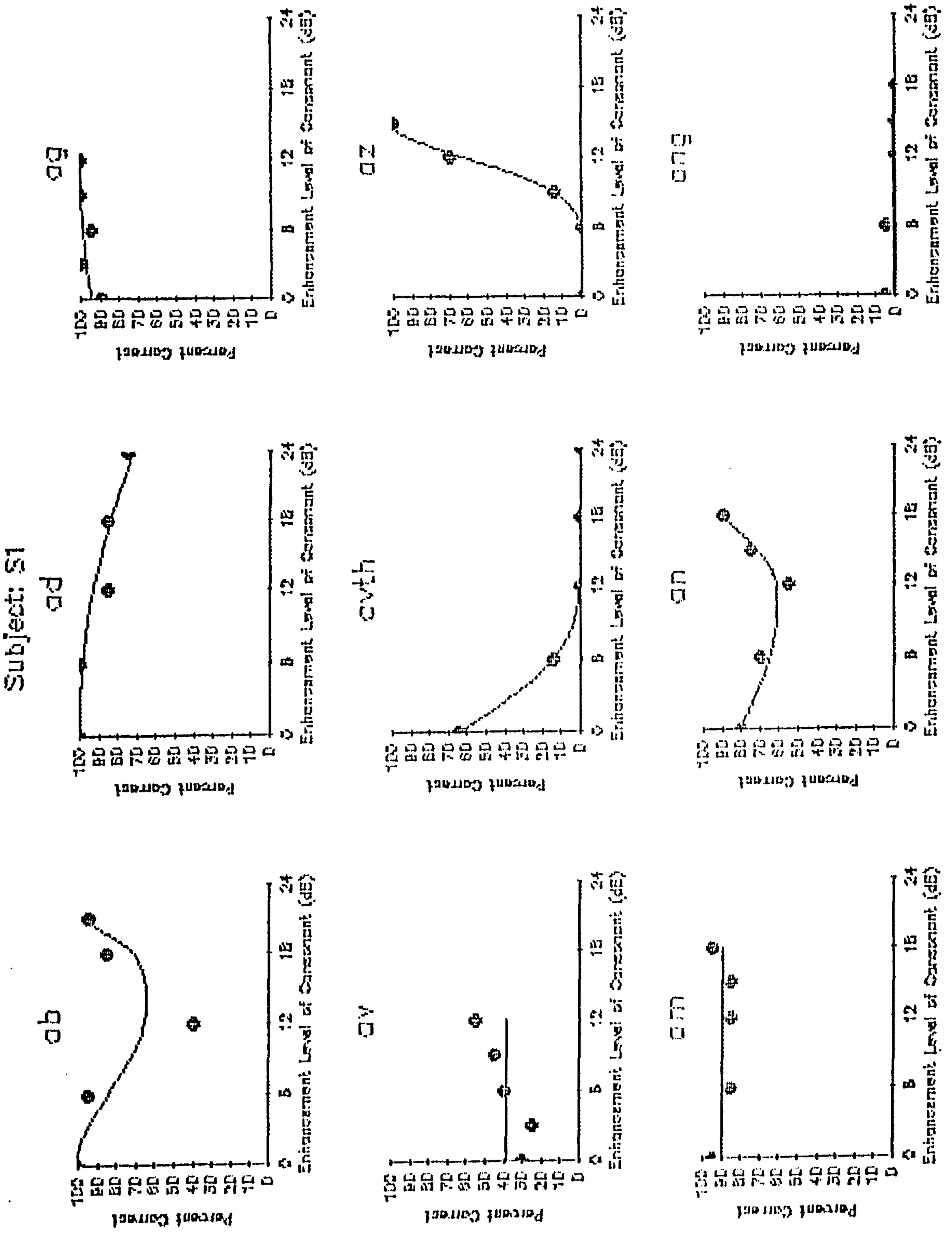

Figure 62. CE functions of the voiced consonants with /a/ for subject S1 .

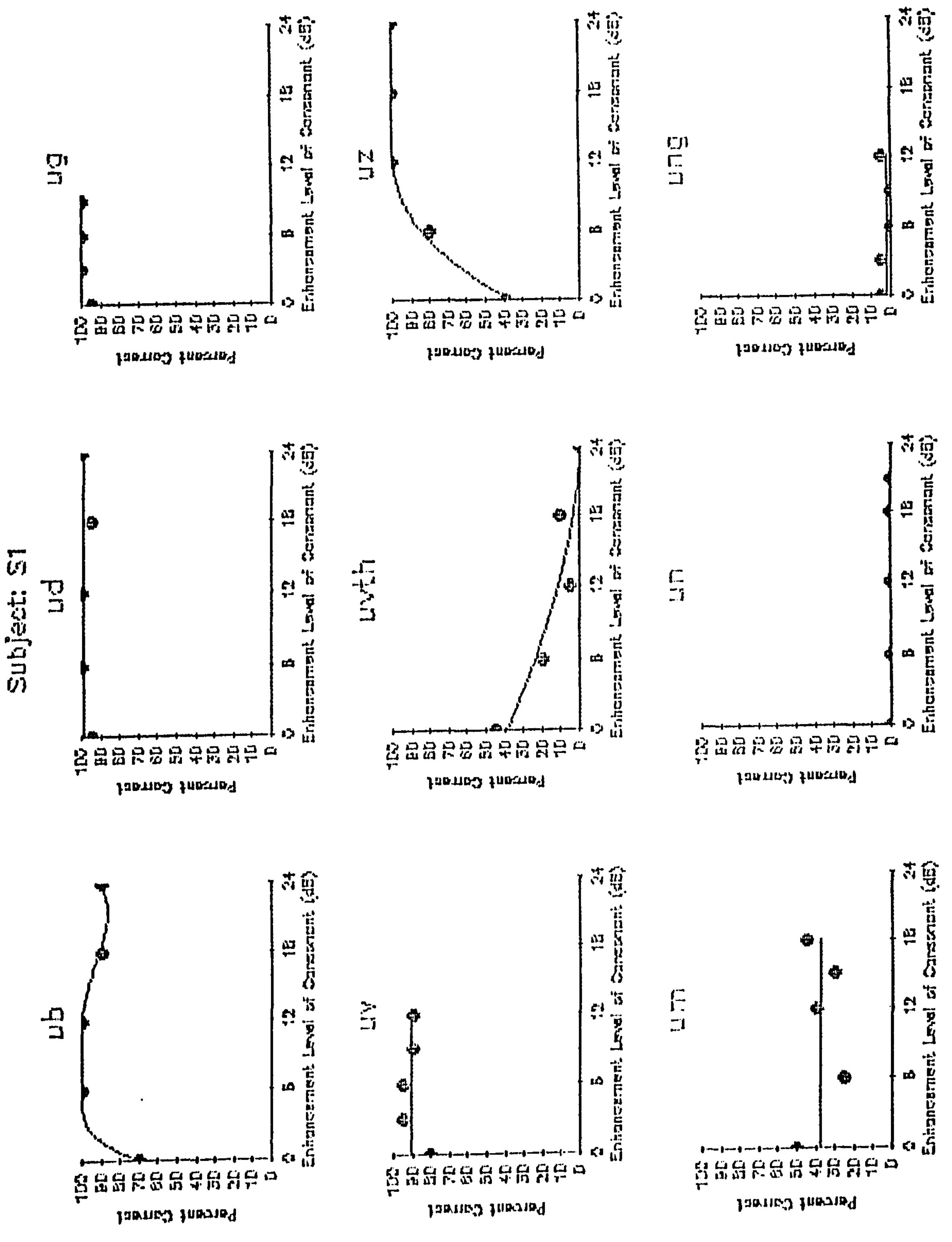

Figure 63. CE functions of the voiced consonants with /u/ for subject S1.

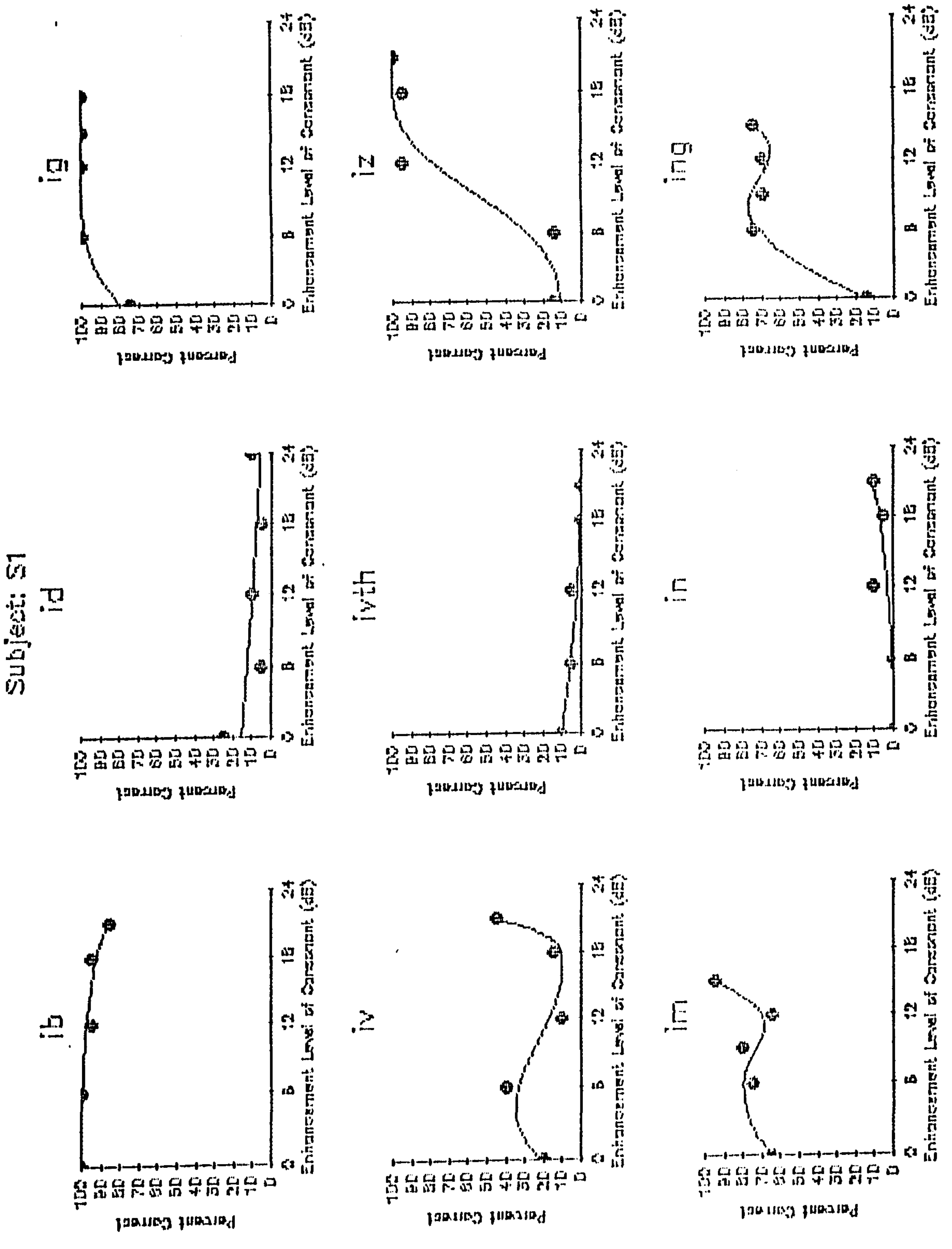

Figure 64. CE functions of the voiced consonants with /i/ for subject S1.

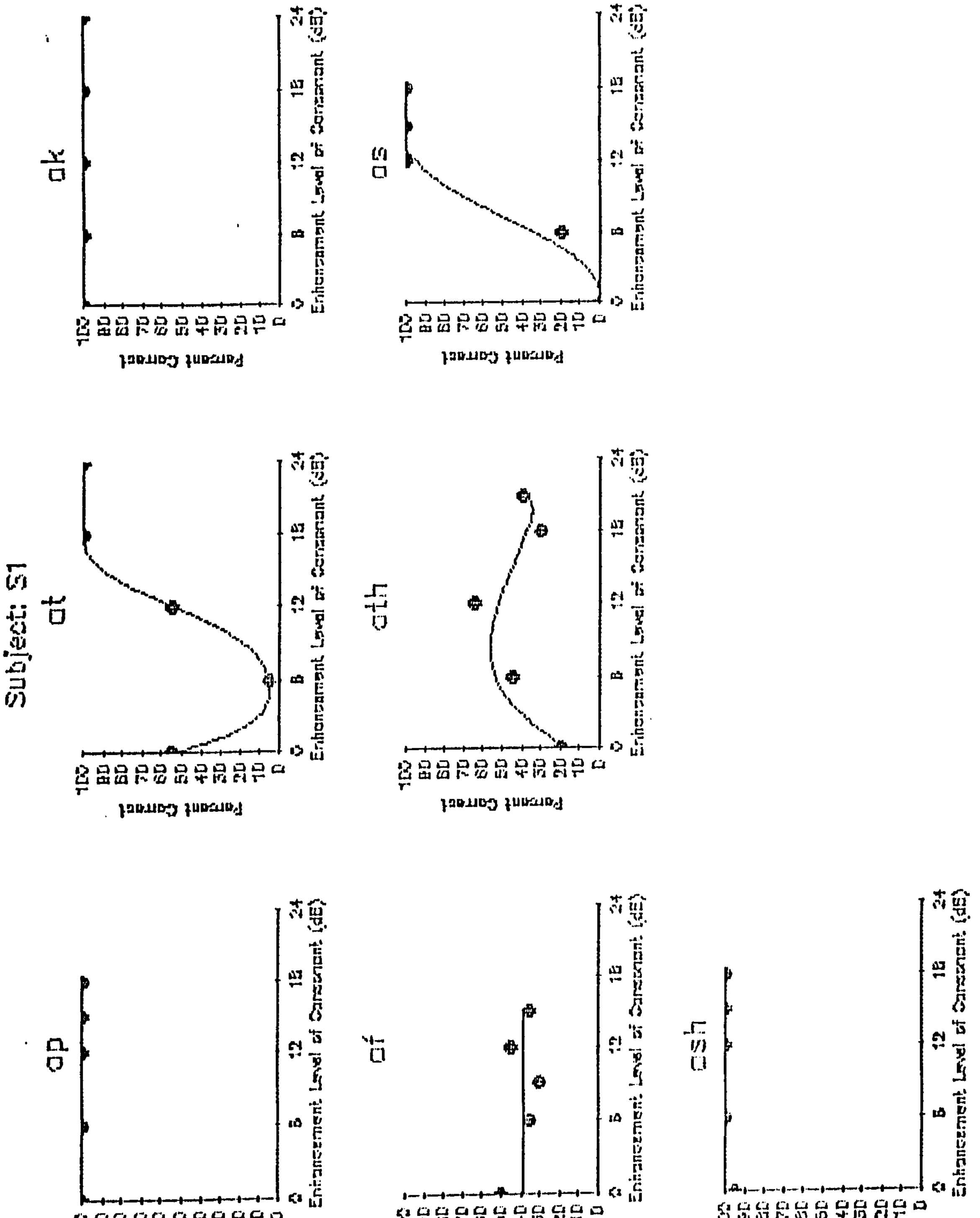

Figure 65. CE functions of the voiceless consonants with /a/ for subject S1.

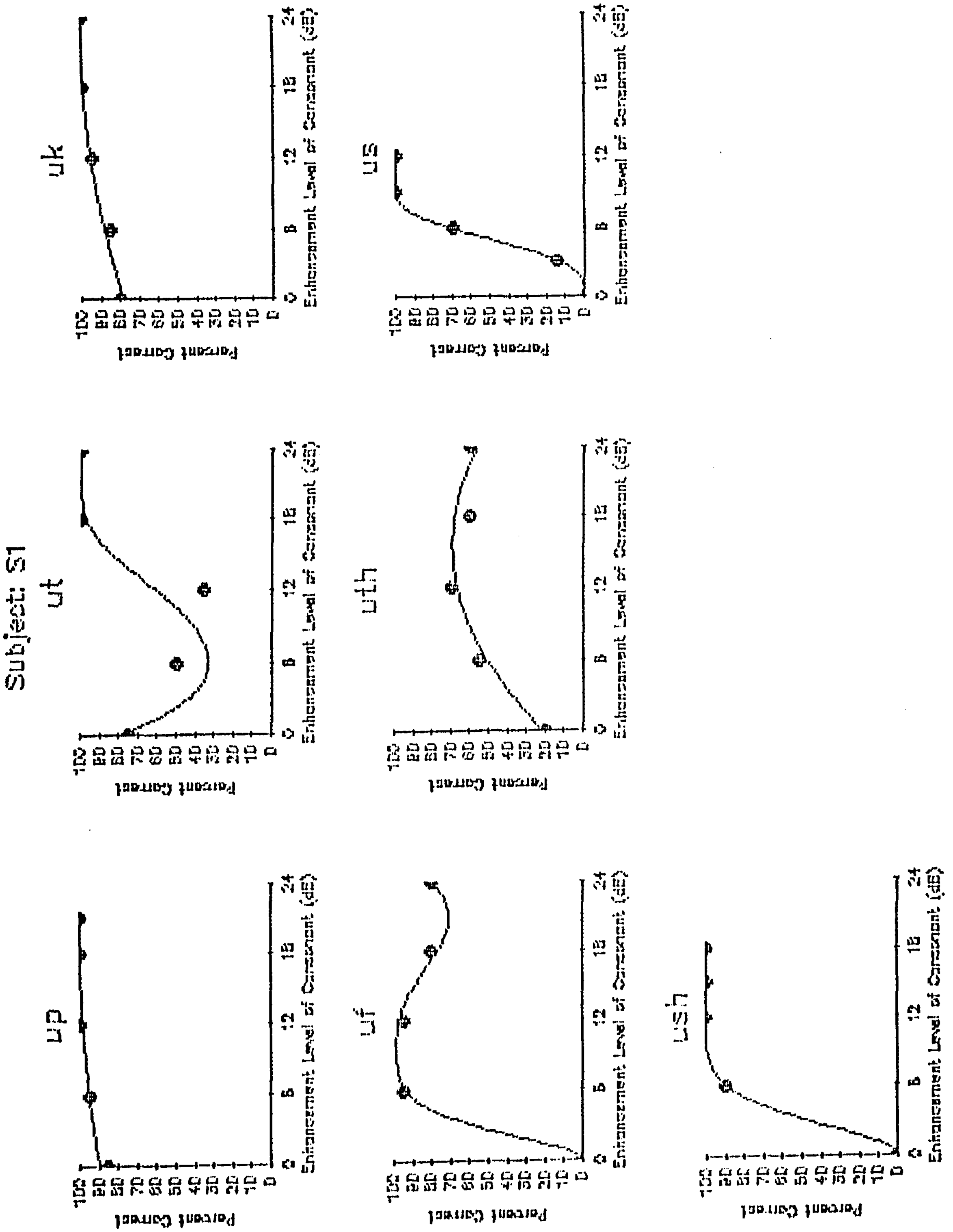

Figure 66. CE functions of the voiceless consonants with /u/ for subject S1.

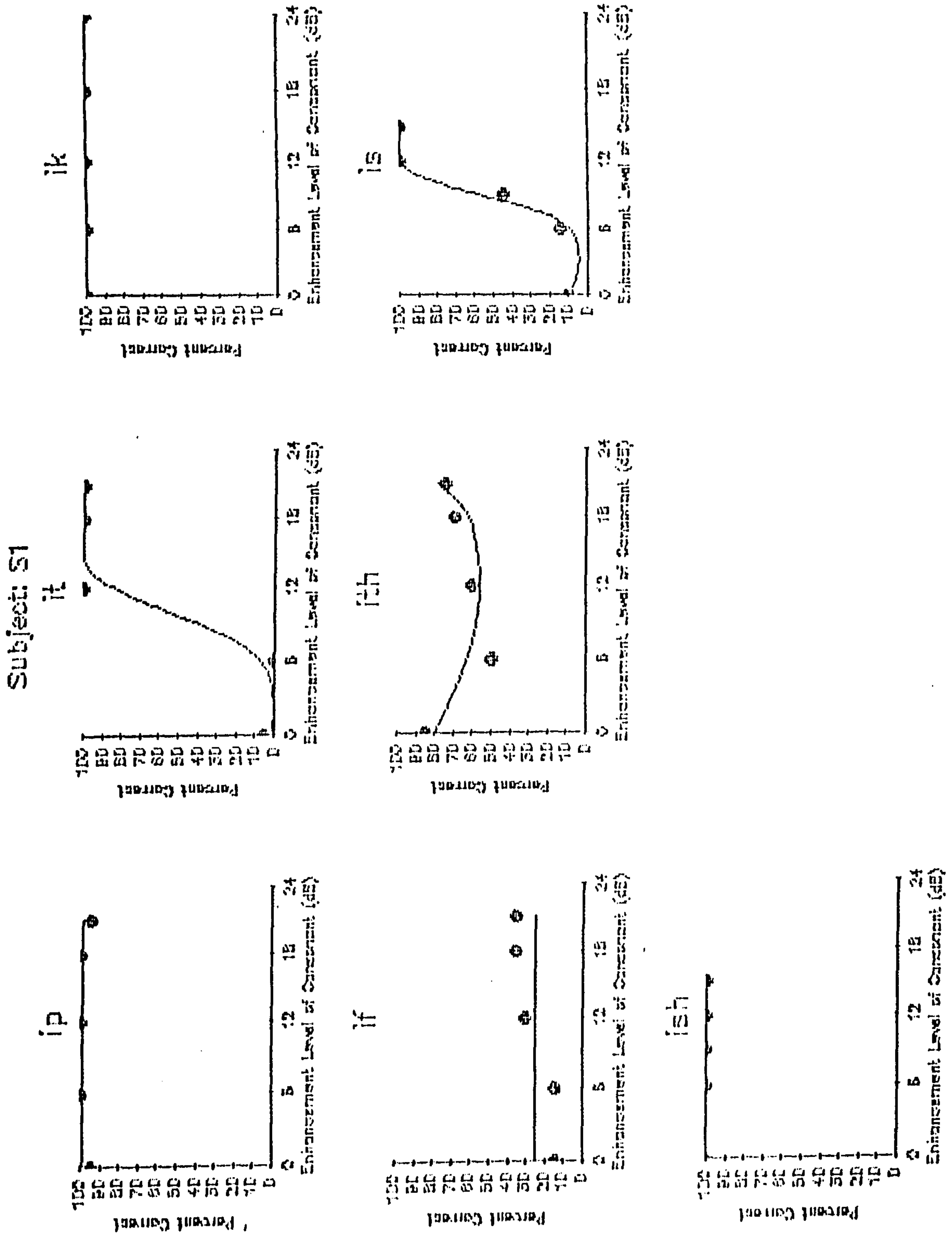

Figure 67. CE functions of the voiceless consonants with /i/ for subject S1.

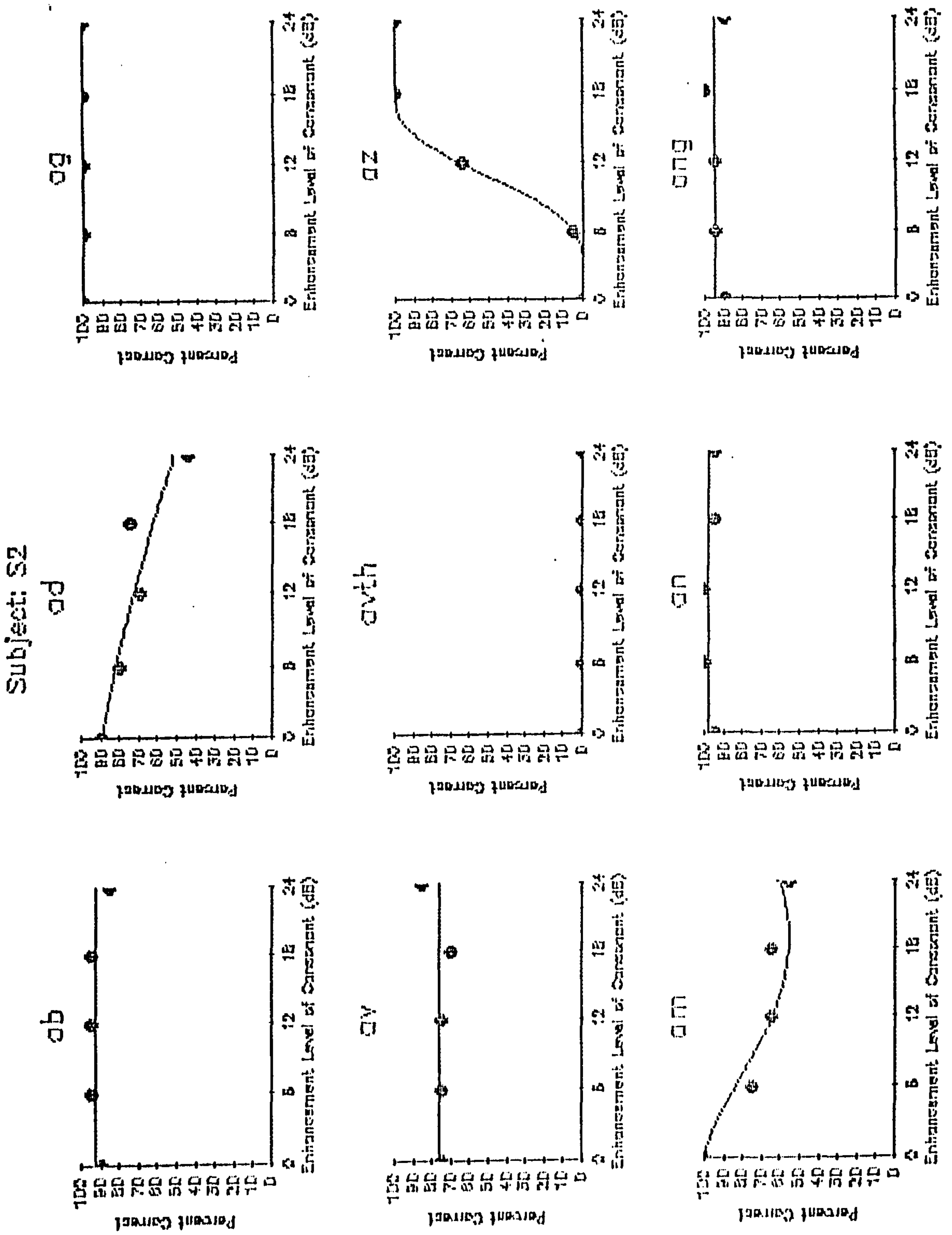

Figure 68. CE functions of the voiced consonants with /a/ for subject S2.

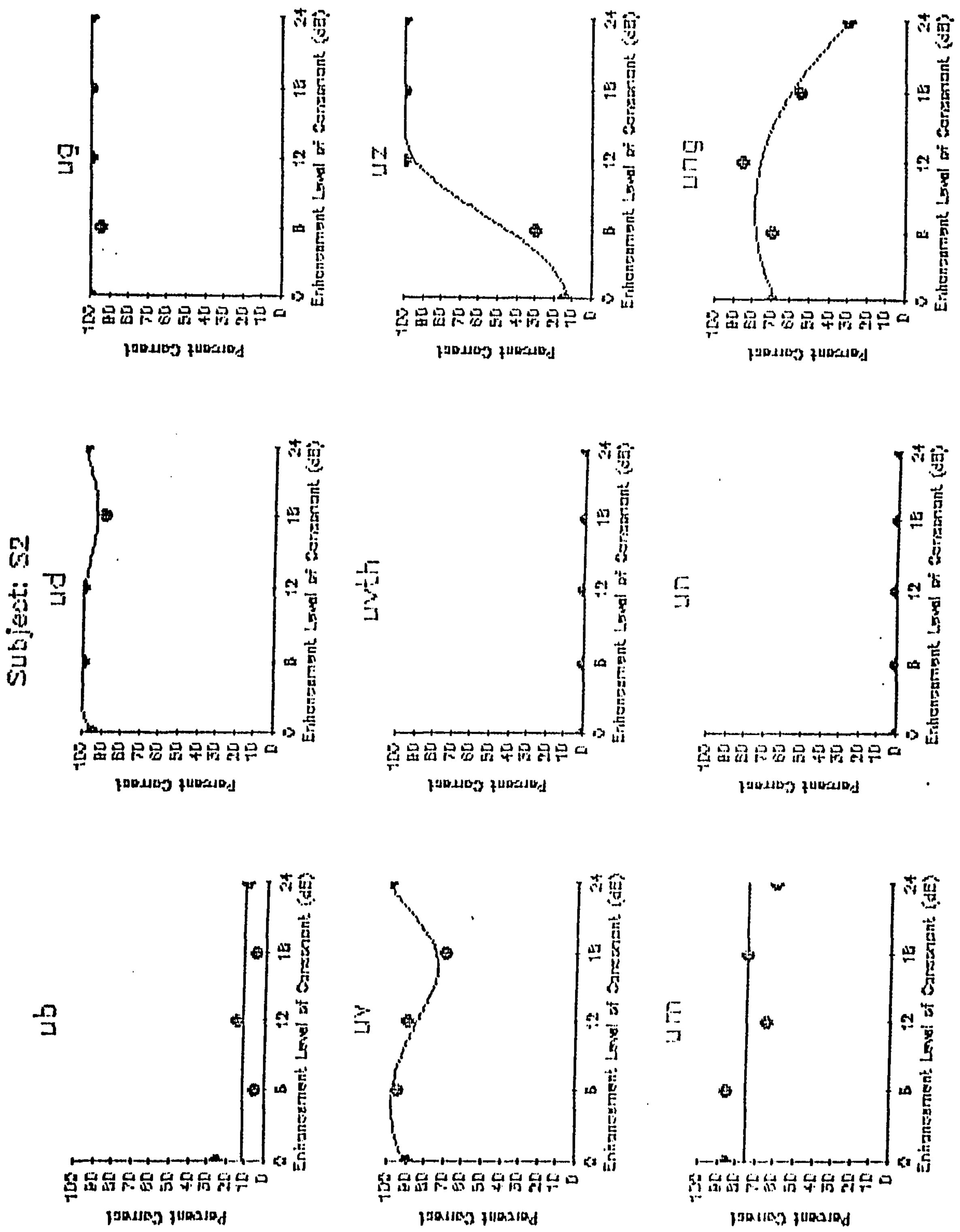

Figure 69. CE functions of the voiced consonants with /u/ for subject S2.

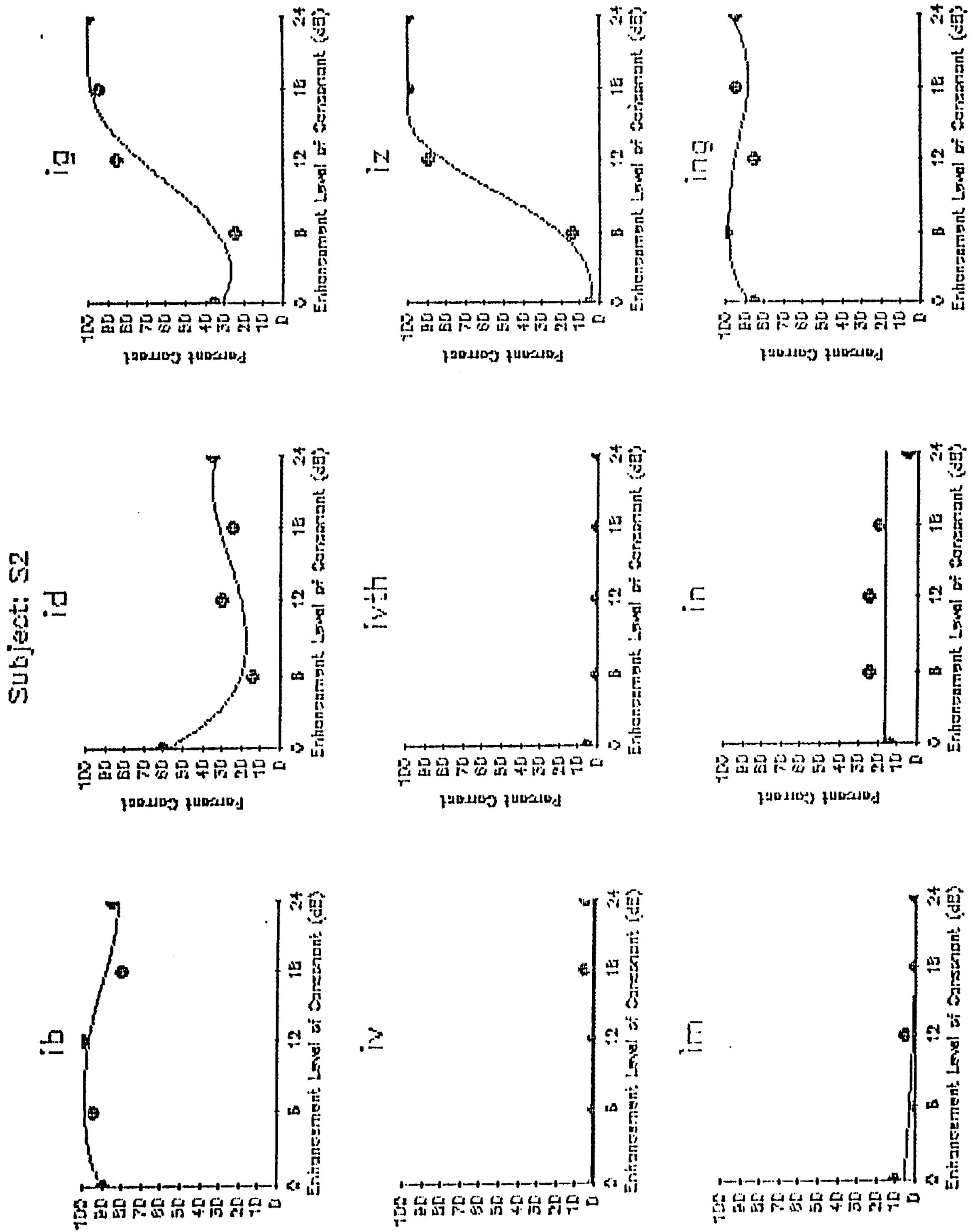

Figure 70. CE functions of the voiced consonants with /ɪ/ for subject S2.

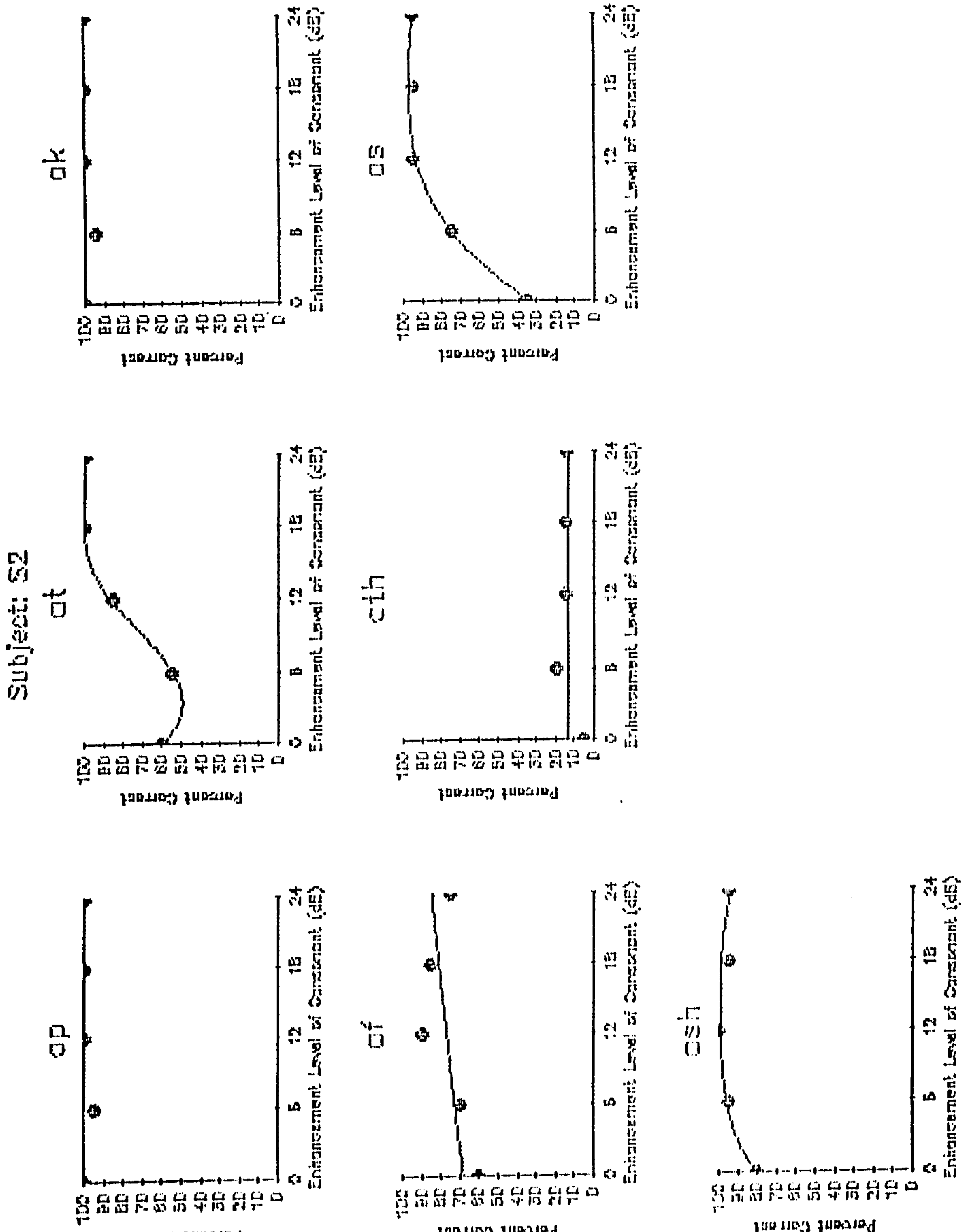

Figure 71. CE functions of the voiceless consonants with /a/ for subject S2.

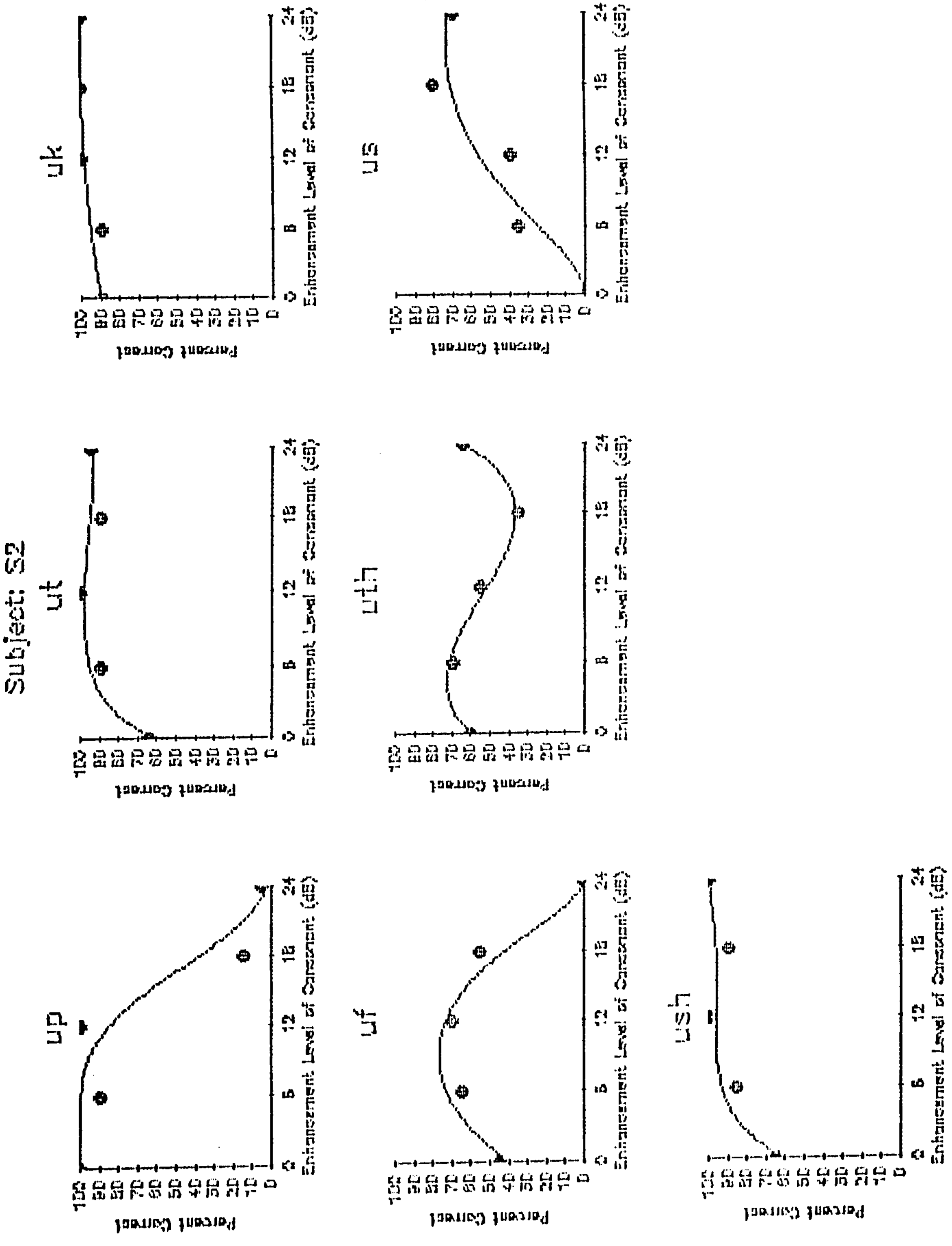

Figure 72. CE functions of the voiceless consonants with /u/ for subject S2.

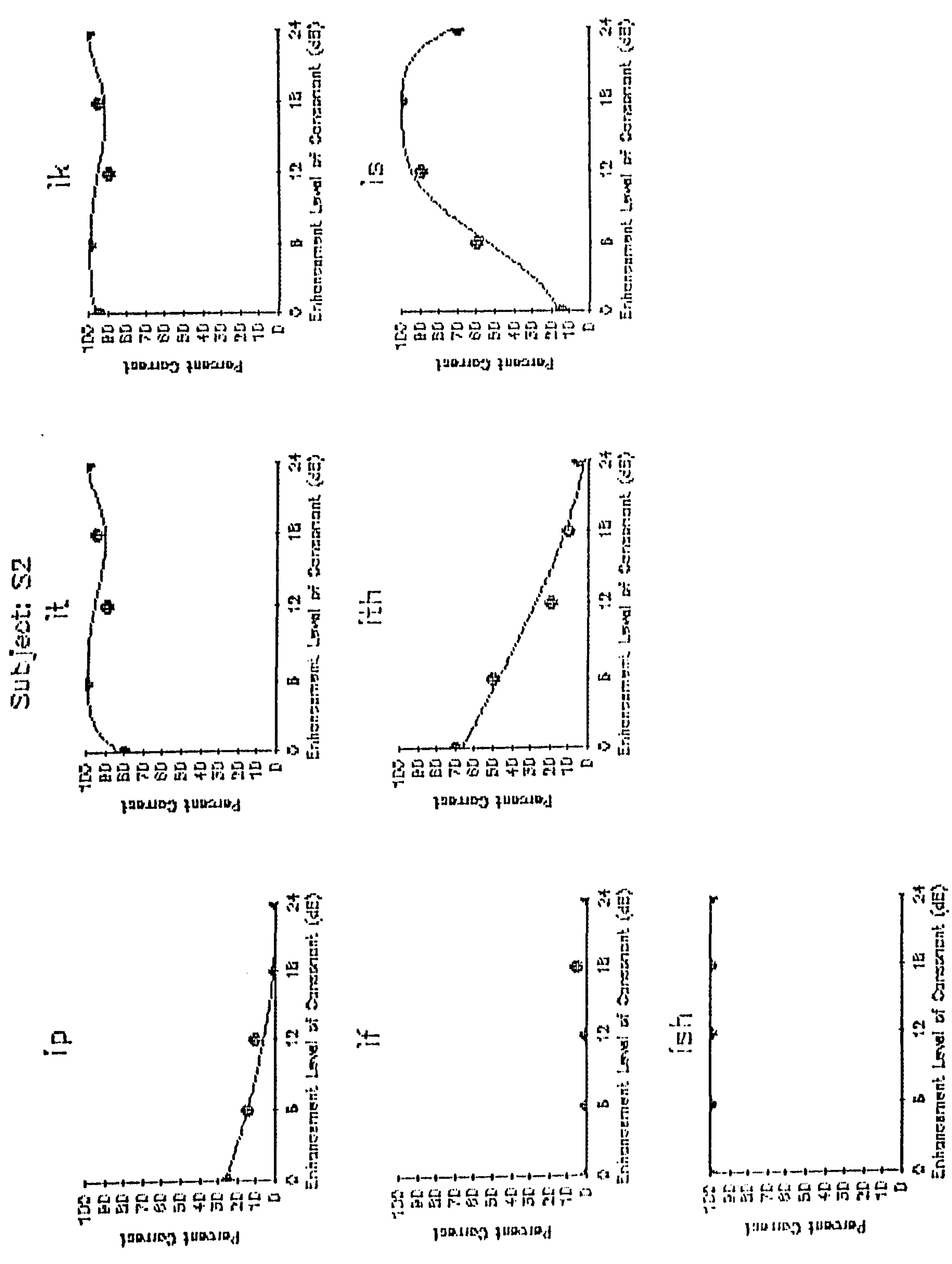

Figure 73. CE functions of the voiceless consonants with /i/ for subject S2.

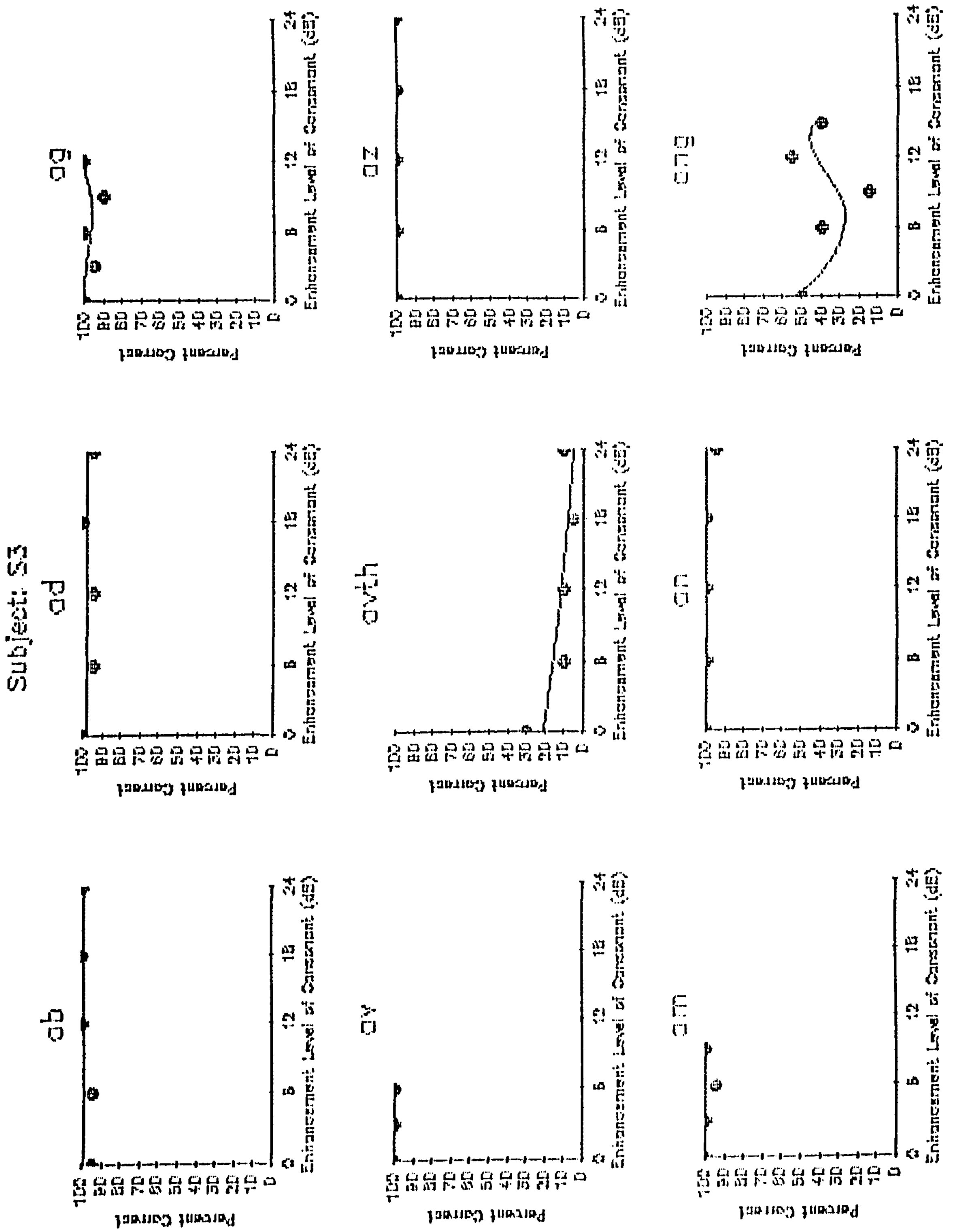

Figure 74. CE functions of the voiced consonants with /a/ for subject S3.

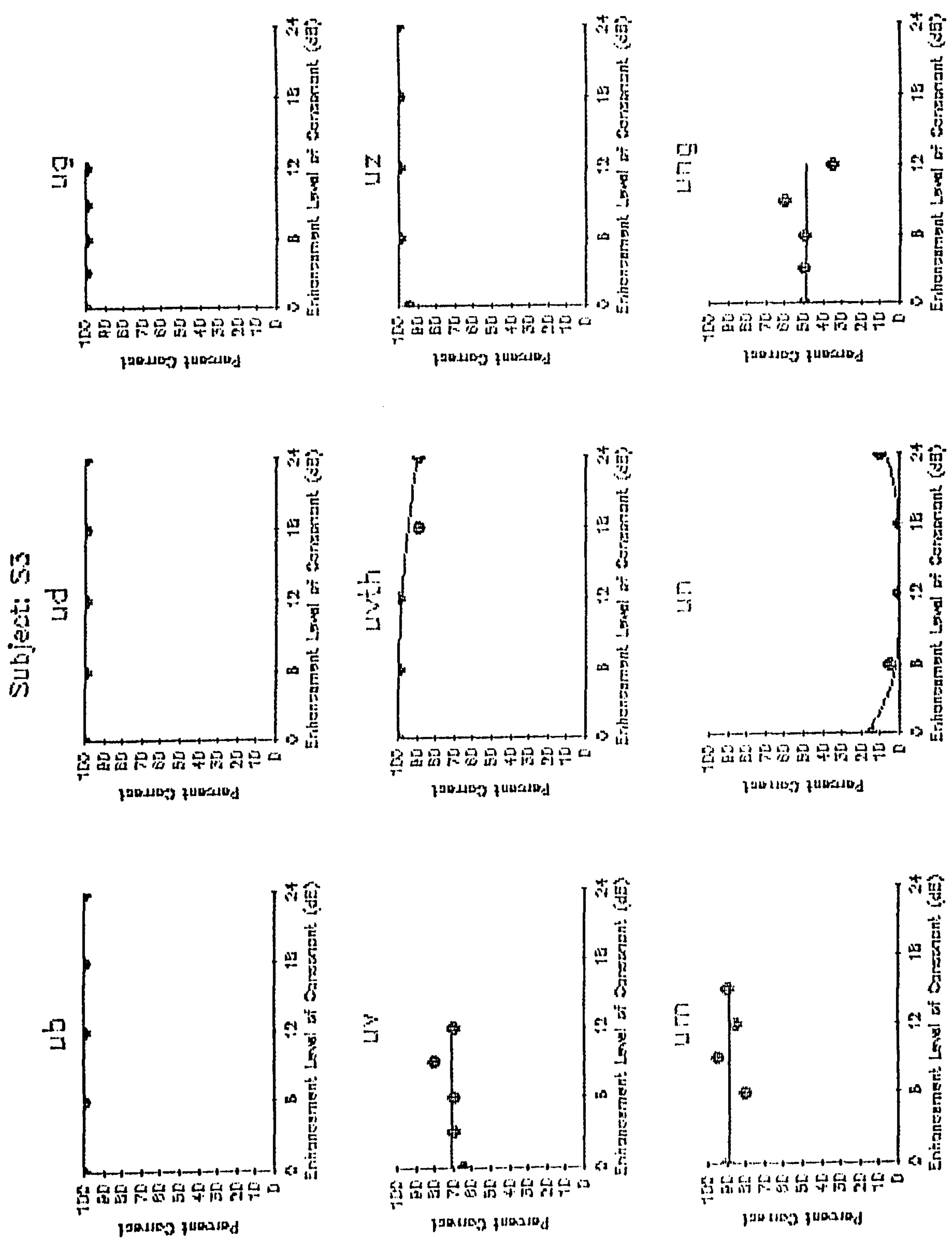

Figure 75. CE functions of the voiced consonants with /u/ for subject S3.

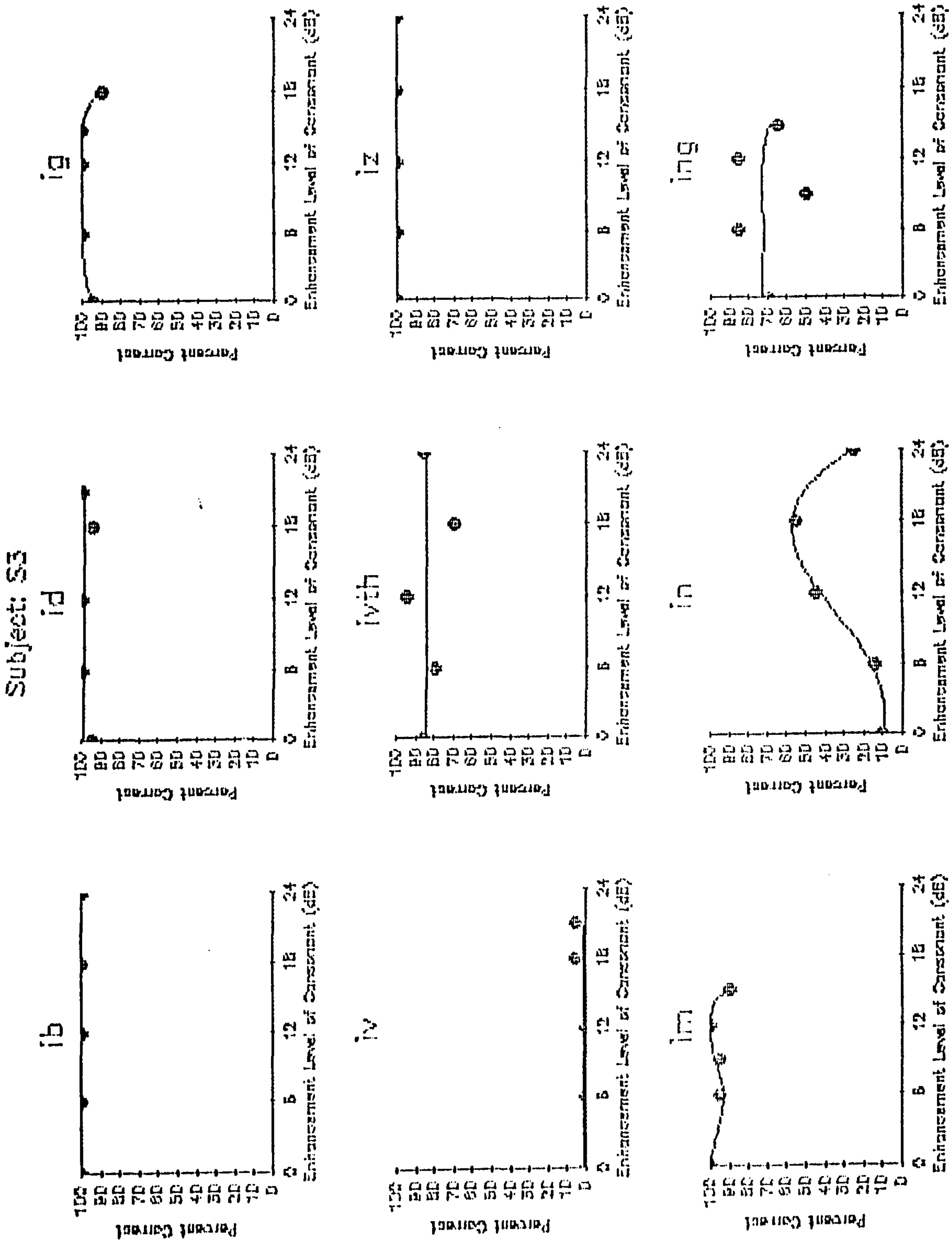

Figure 76. CE functions of the voiced consonants with /i/ for subject S3.

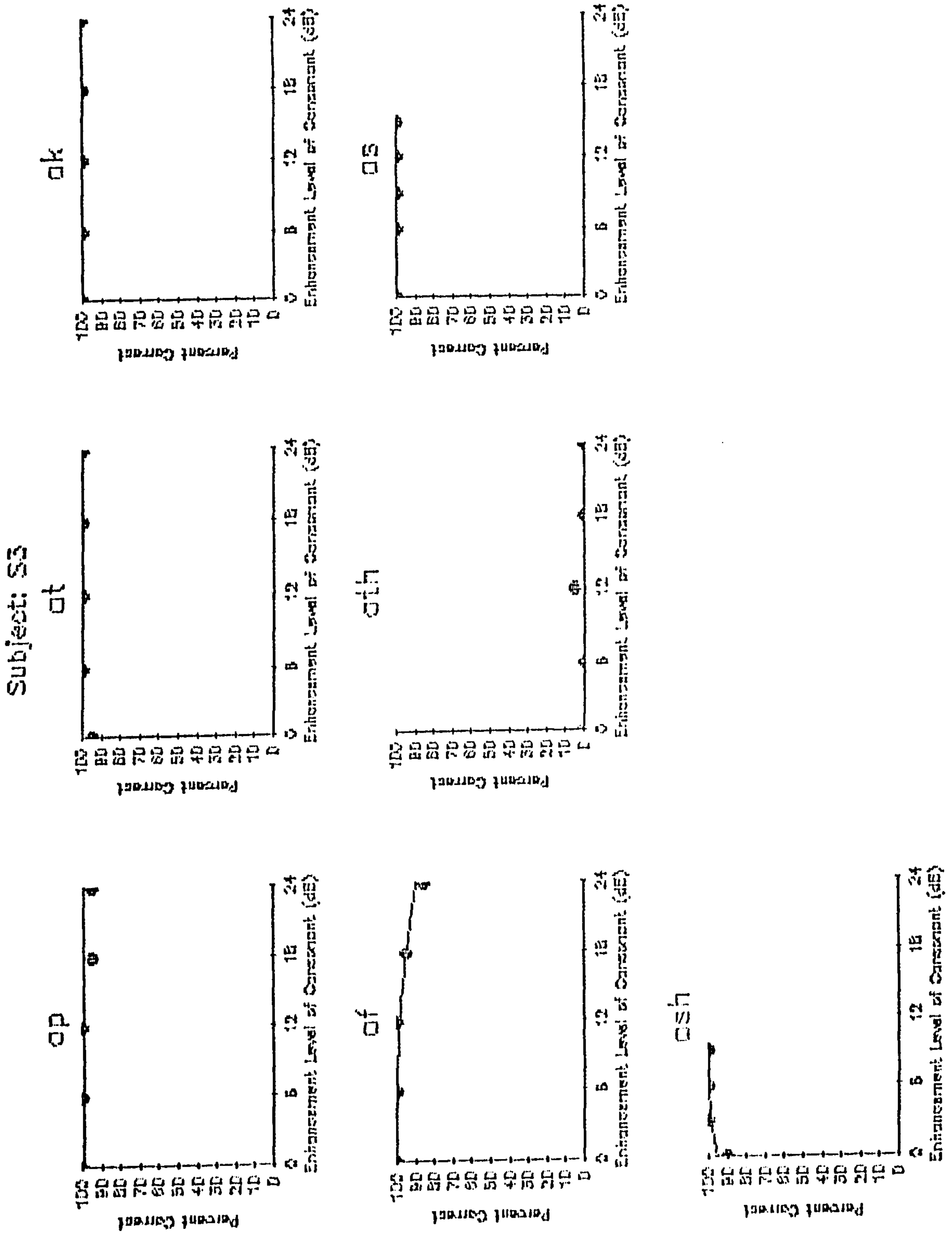

Figure 77. CE functions of the voiceless consonants with /a/ for subject S3.

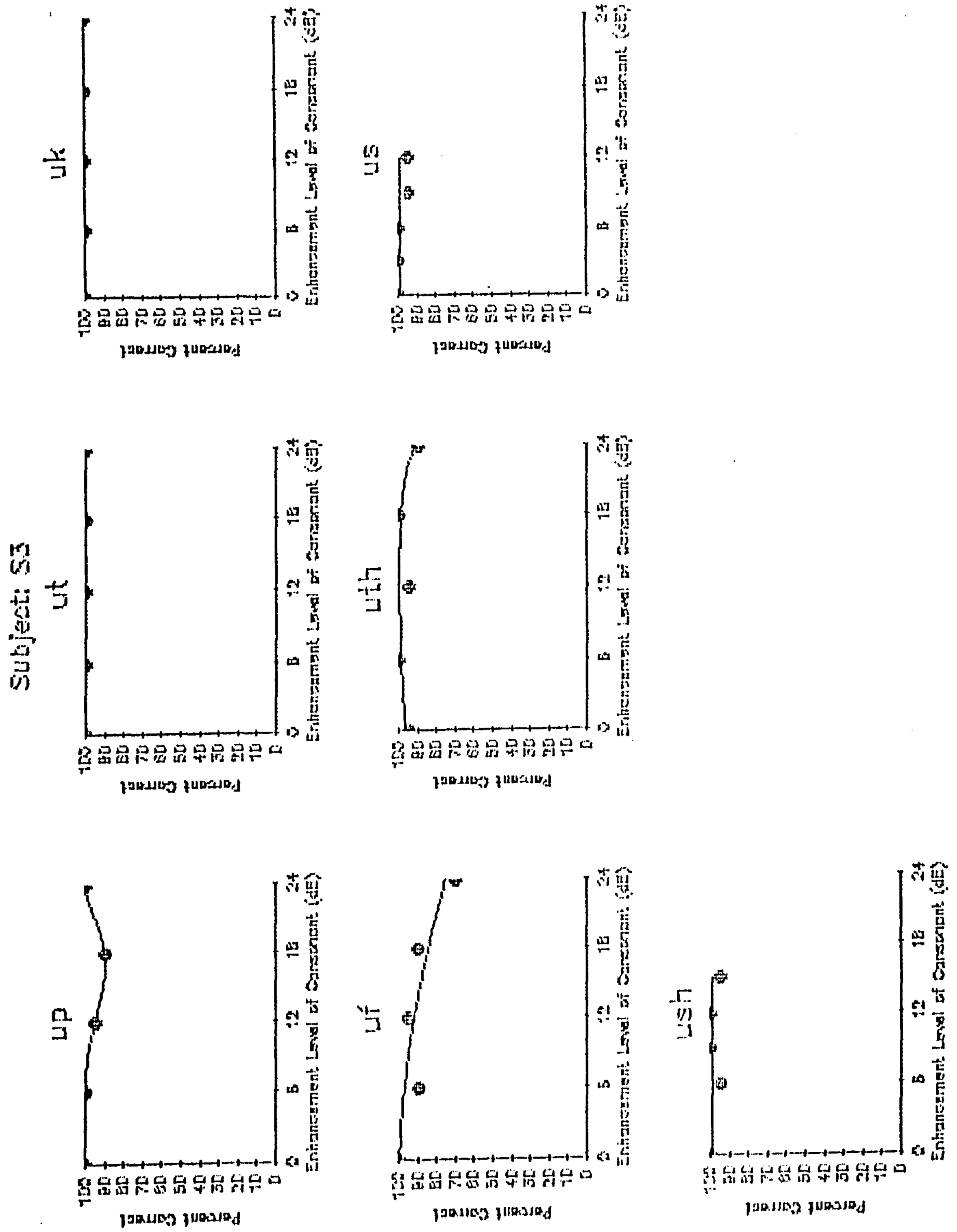

Figure 78. CE functions of the voiceless consonants with /u/ for subject S3.

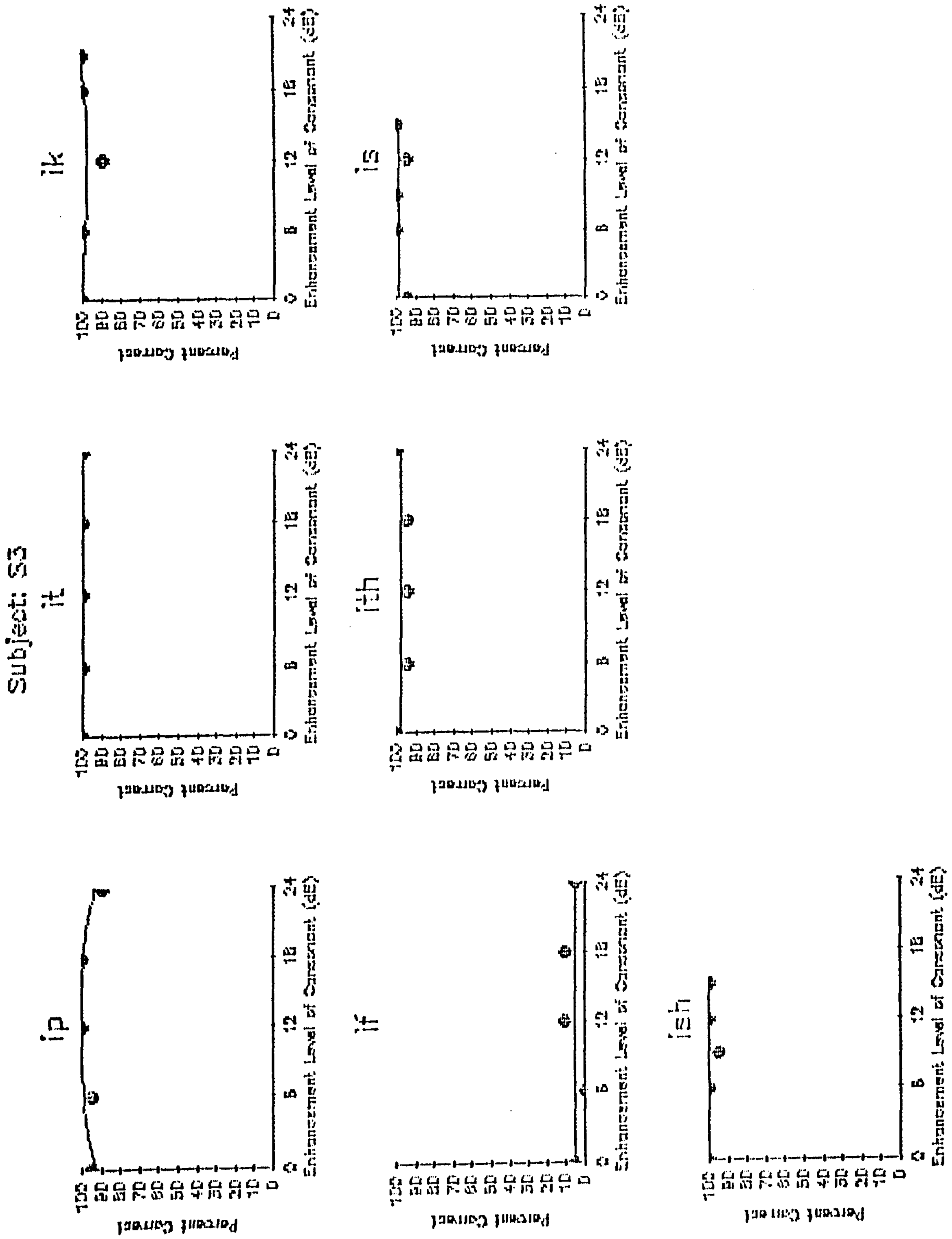

Figure 79. CE functions of the voiceless consonants with /i/ for subject S3.

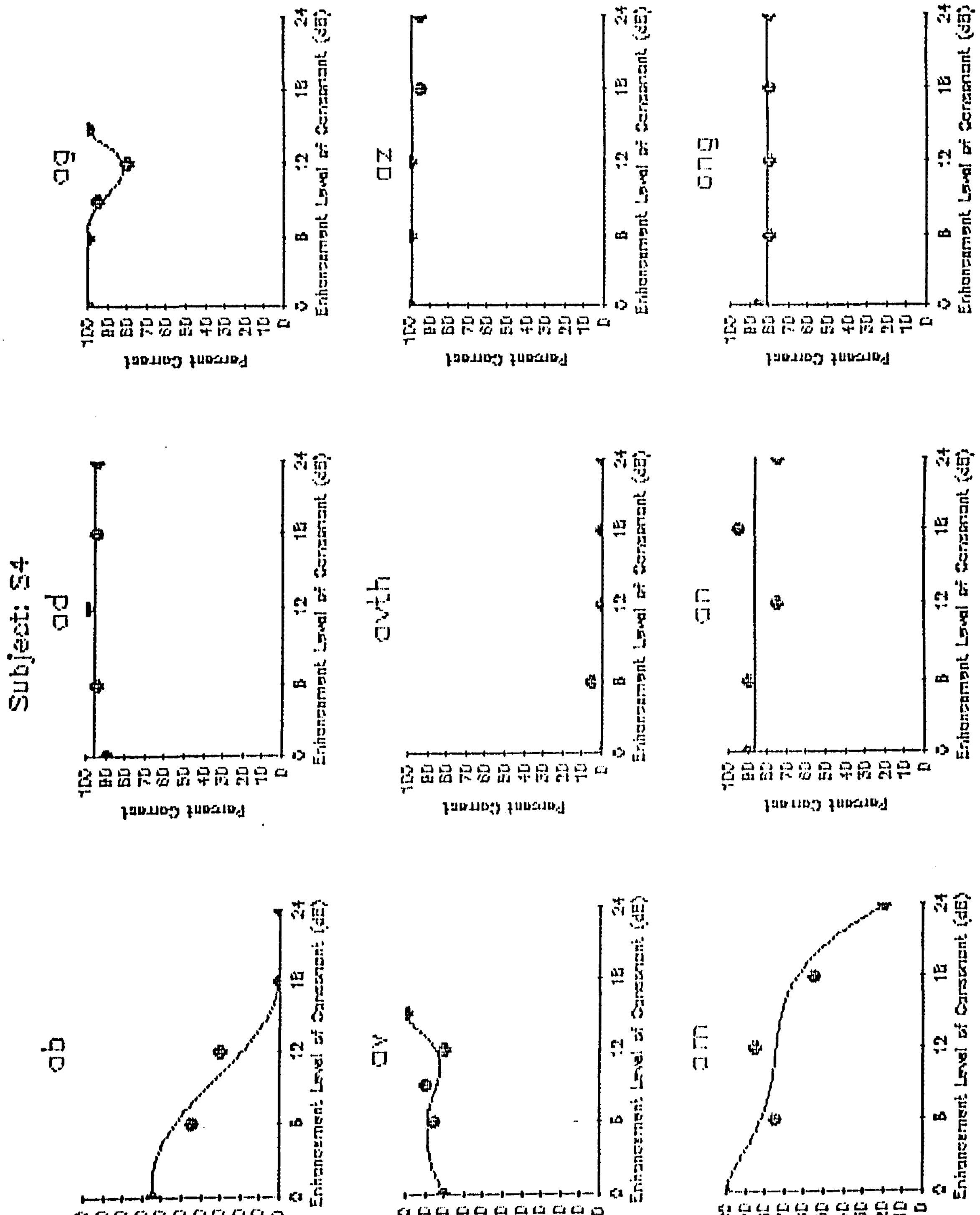

Figure 80. CE functions of the voiced consonants with /a/ for subject S4.

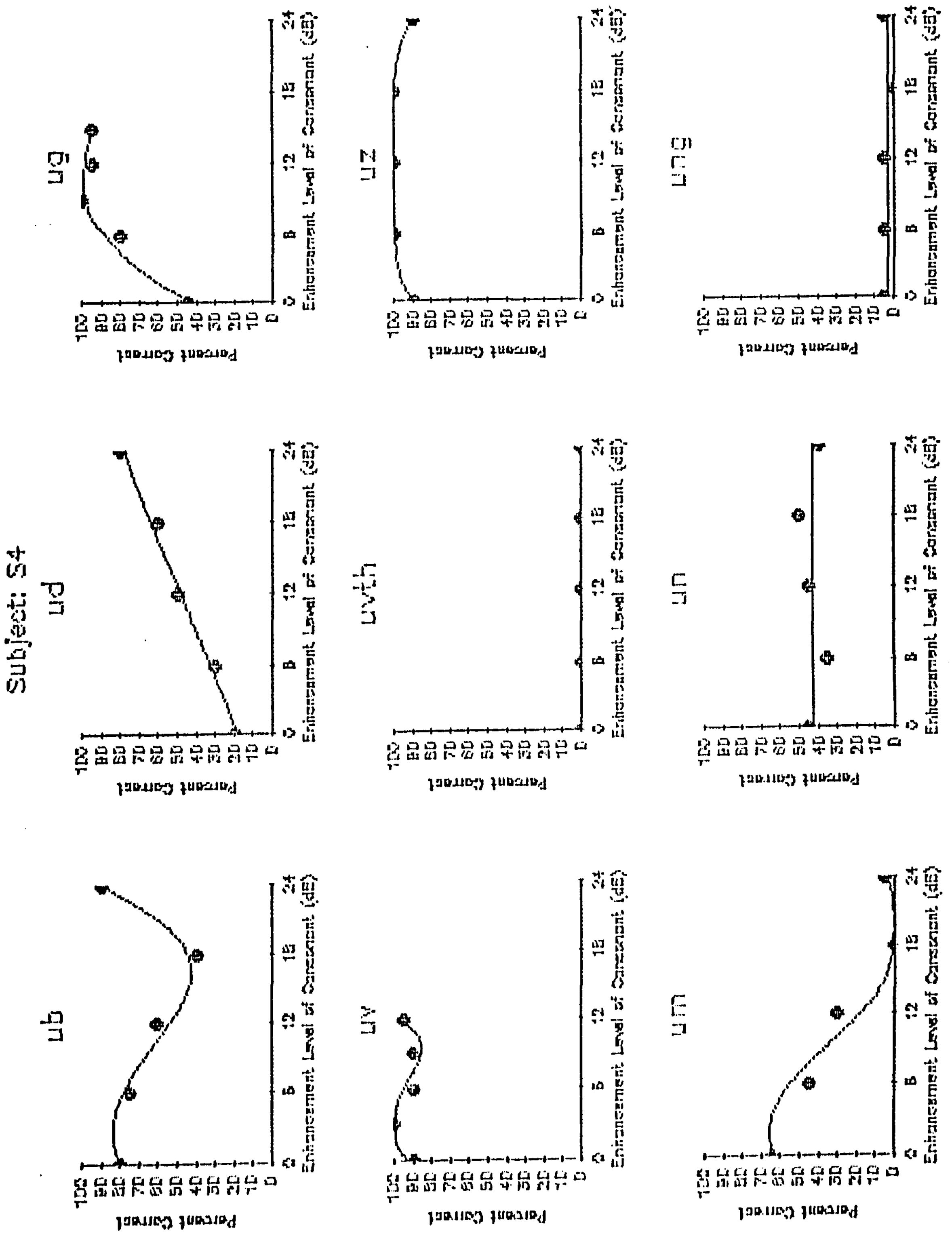

Figure 81. CE functions of the voiced consonants with /u/ for subject S4.

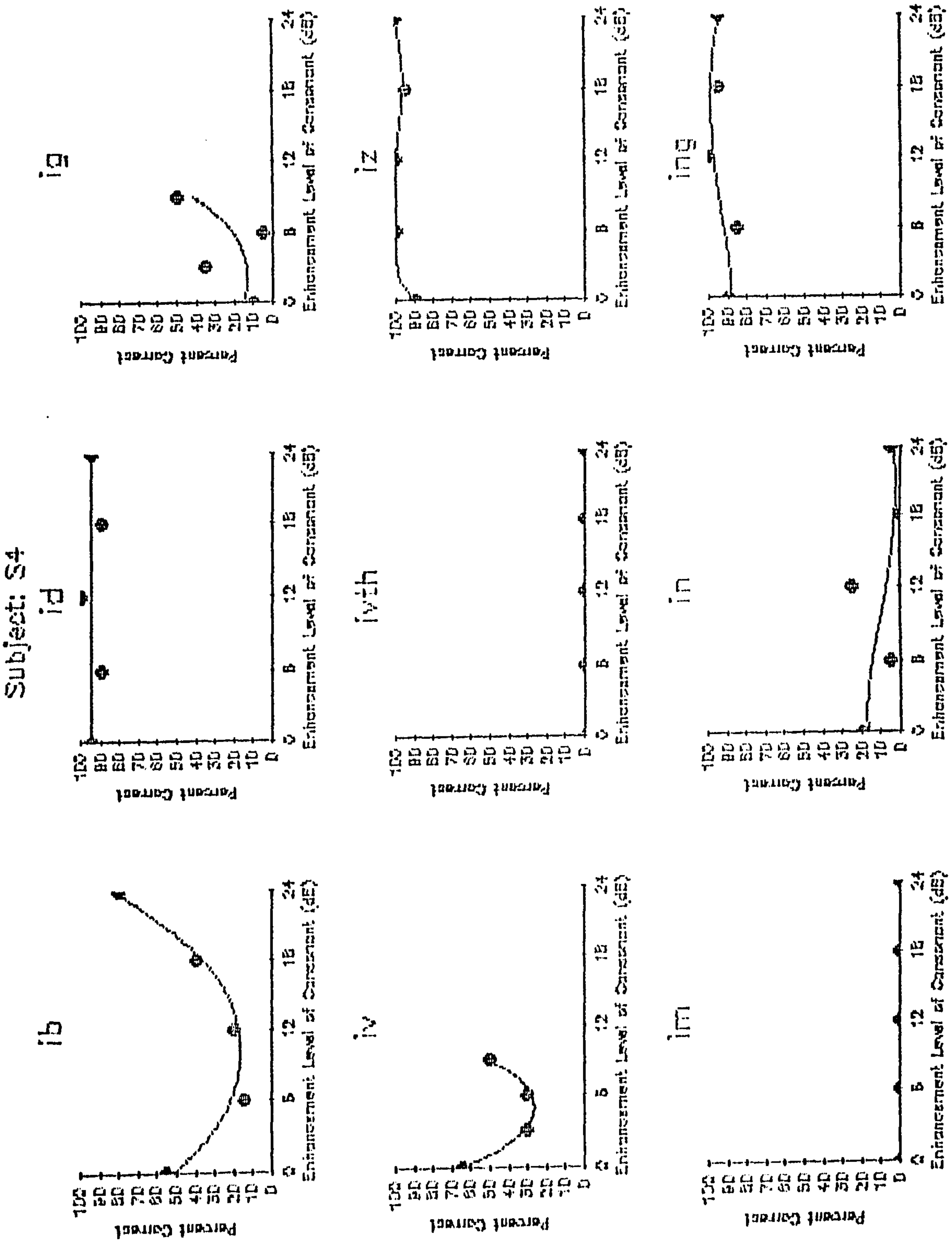

Figure 82. CE functions of the voiced consonants with /i/ for subject S4.

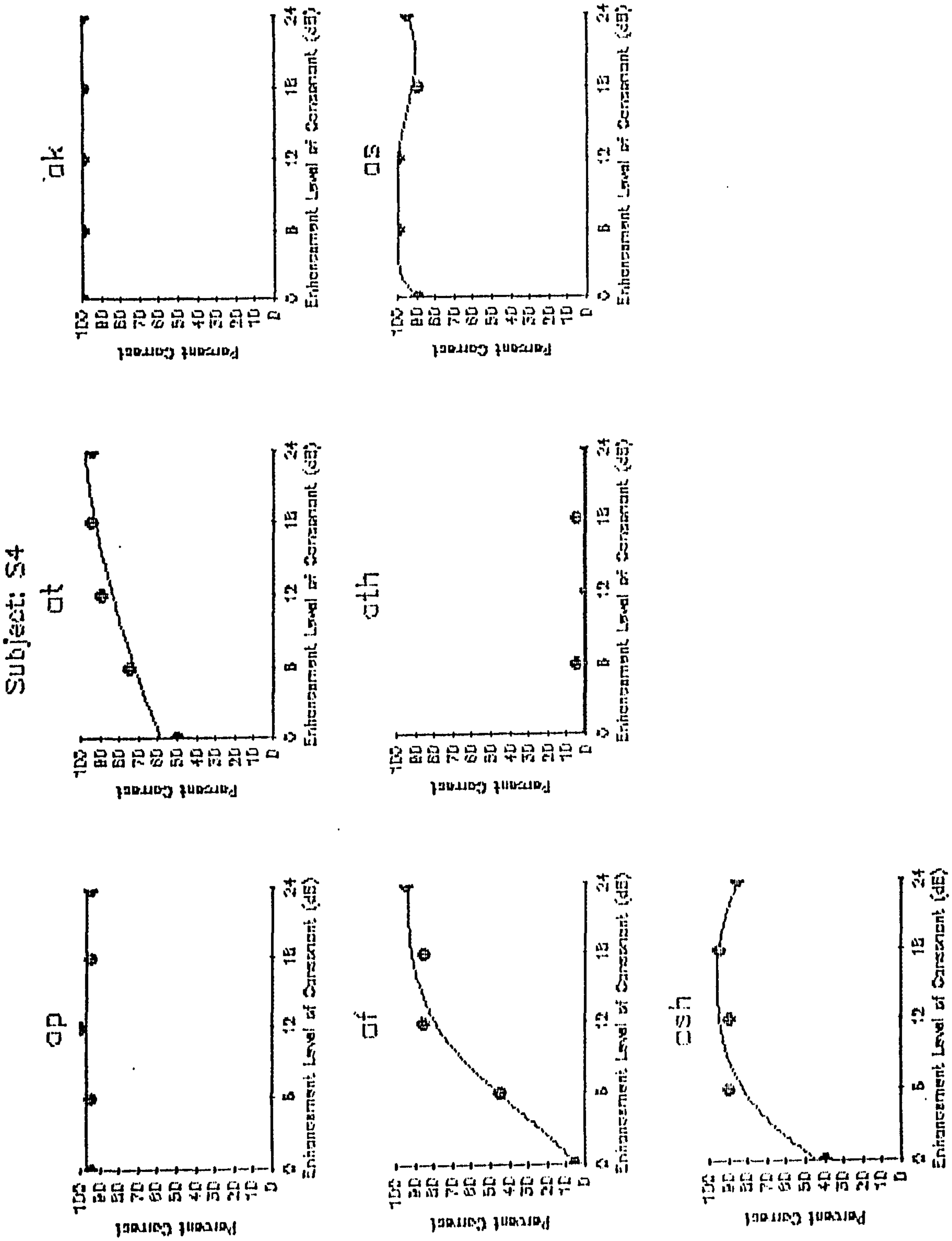

Figure 83. CE functions of the voiceless consonants with /a/ for subject S4.

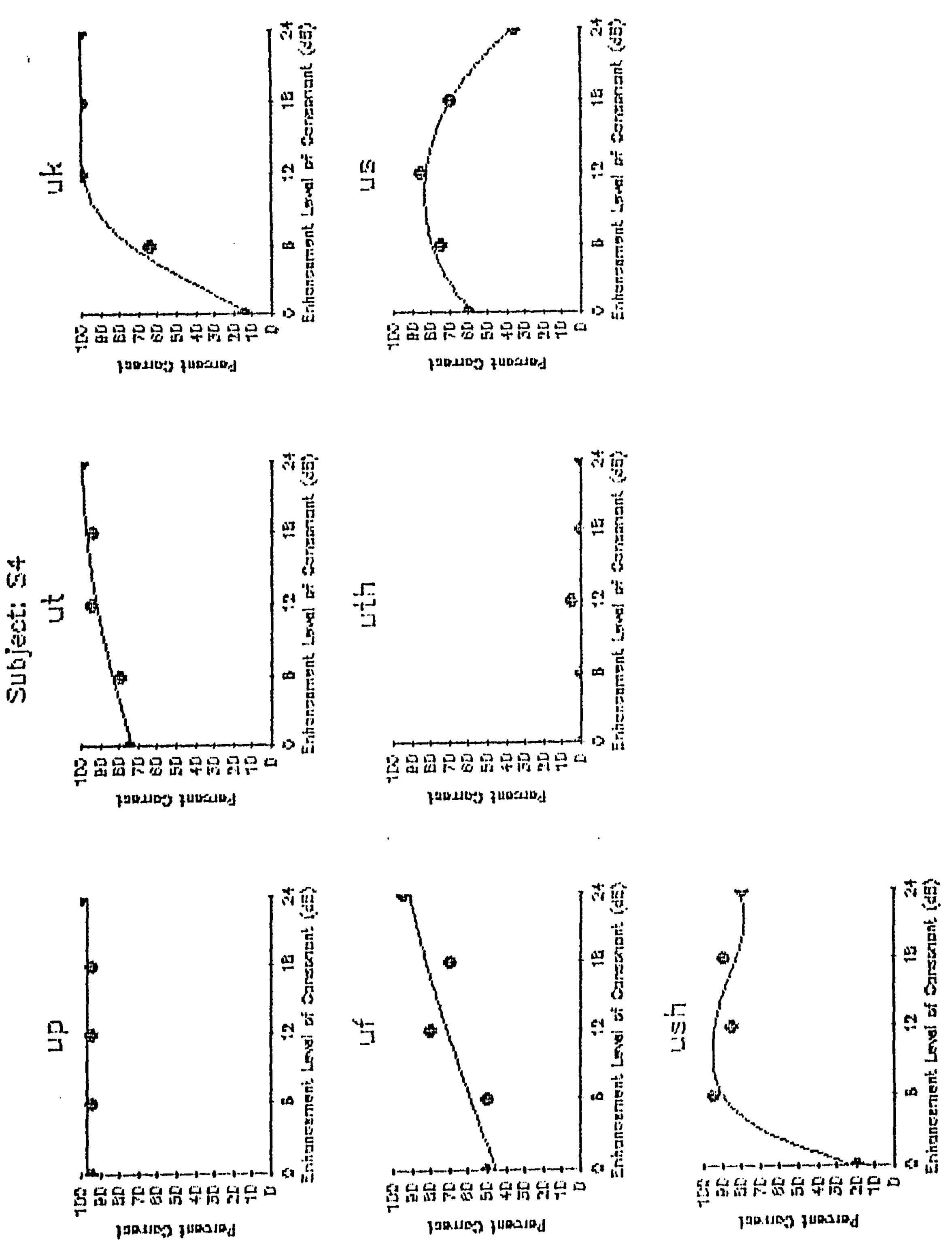

Figure 84. CE functions of the voiceless consonants with /u/ for subject S4.

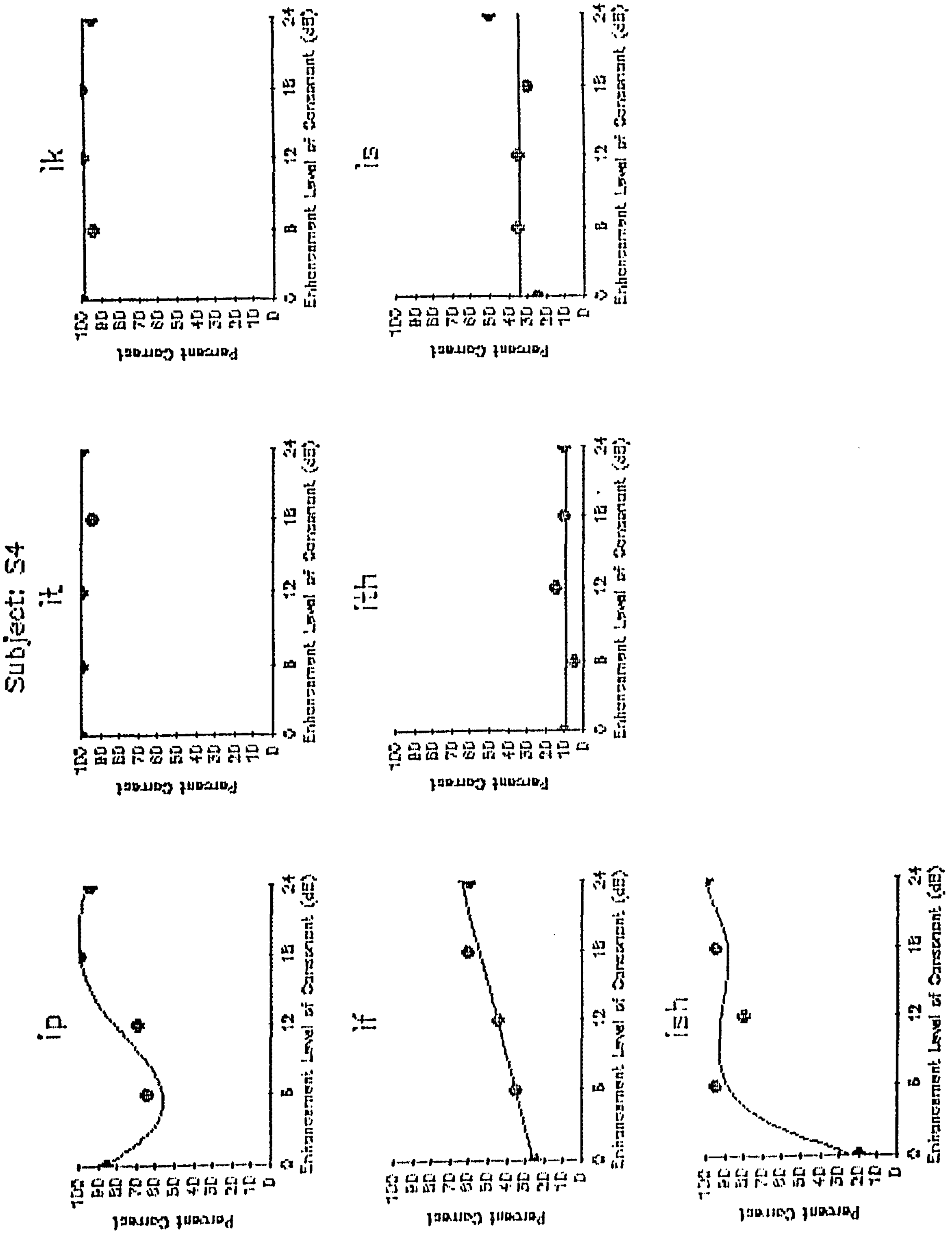

Figure 85. CE functions of the voiceless consonants with /i/ for subject S4.

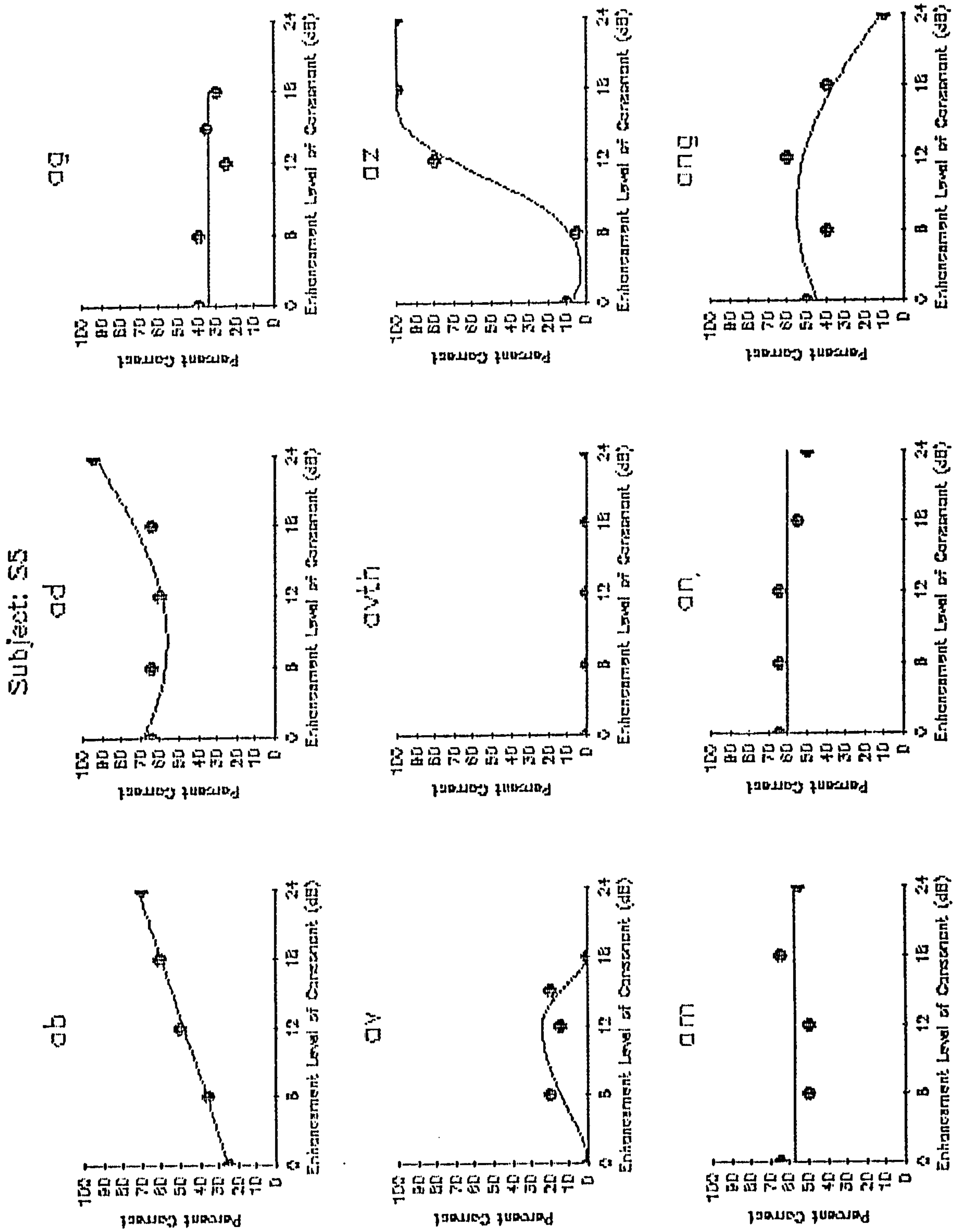

Figure 86. CE functions of the voiced consonants with /a/ for subject S5.

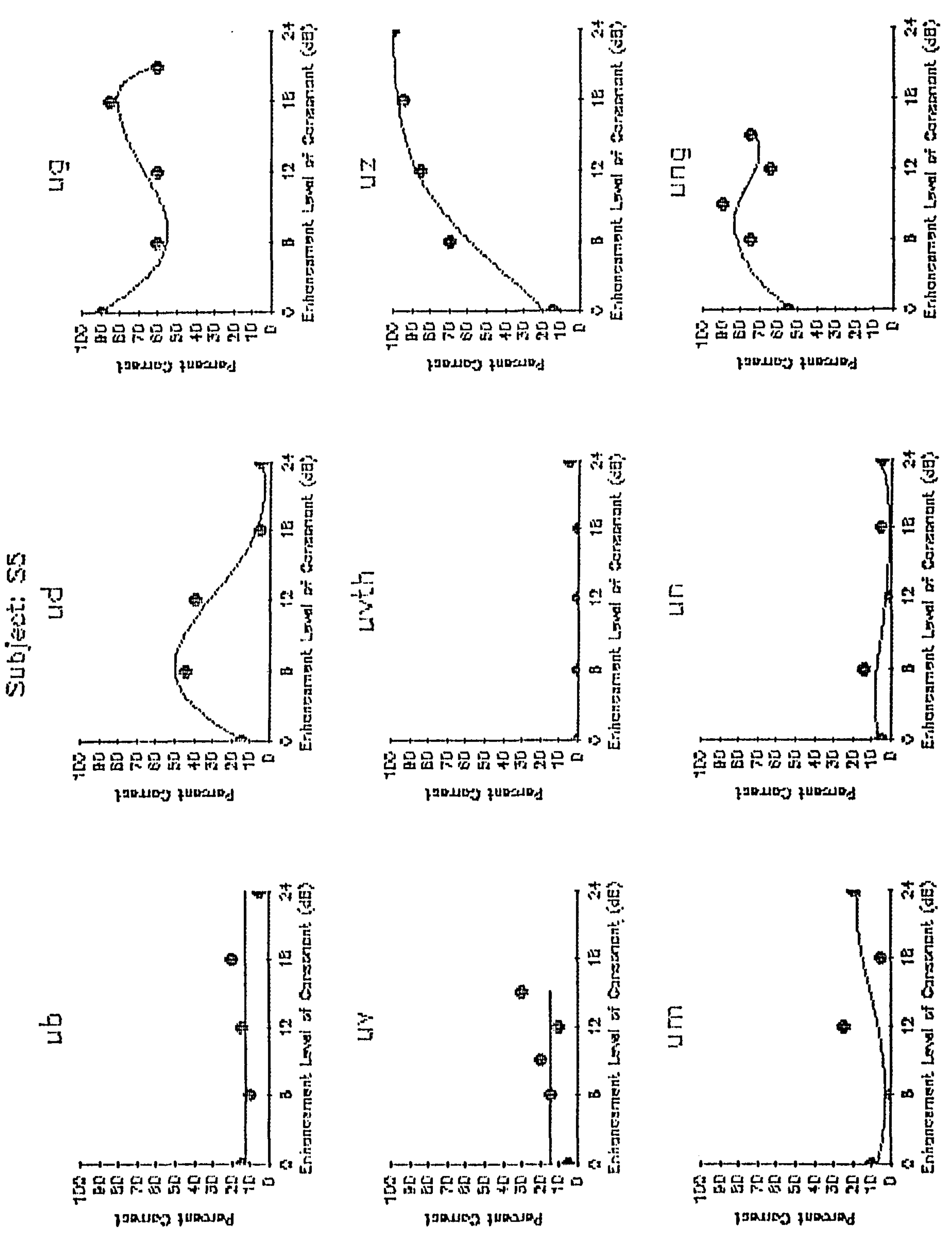

Figure 87. CE functions of the voiced consonants with /u/ for subject S5.

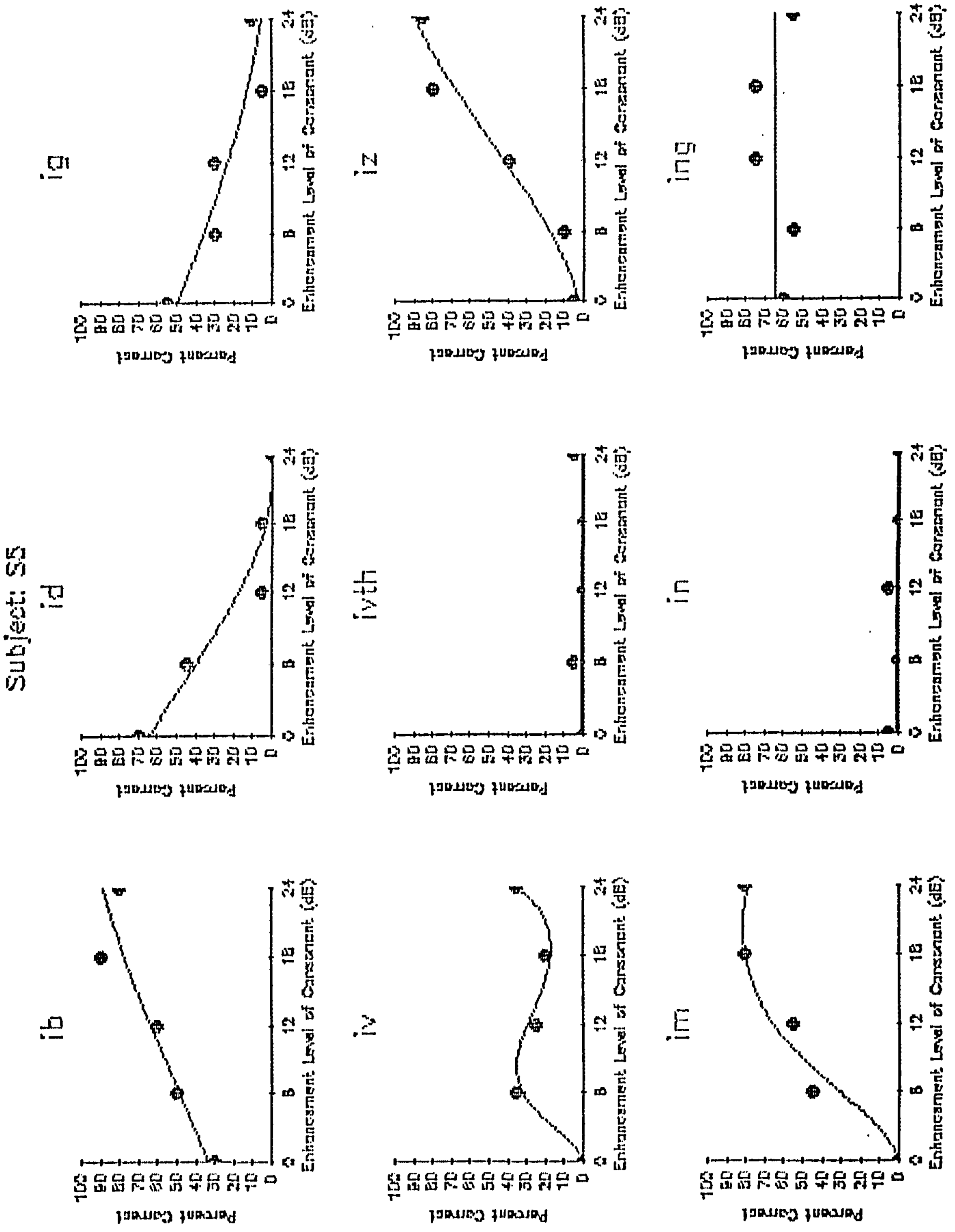

Figure 88. CE functions of the voiced consonants with /i/ for subject S5.

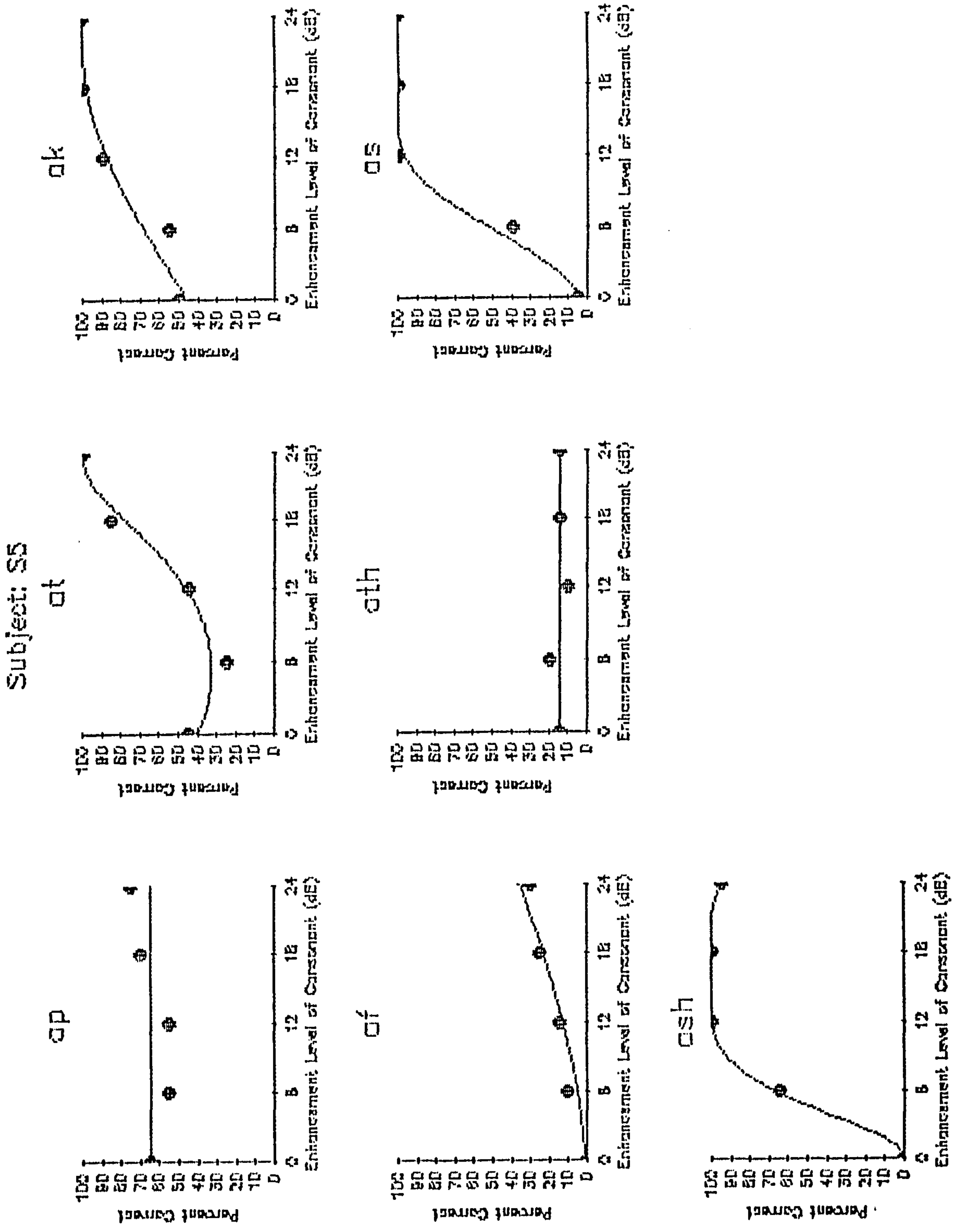

Figure 89. CE functions of the voiceless consonants with /a/ for subject S5.

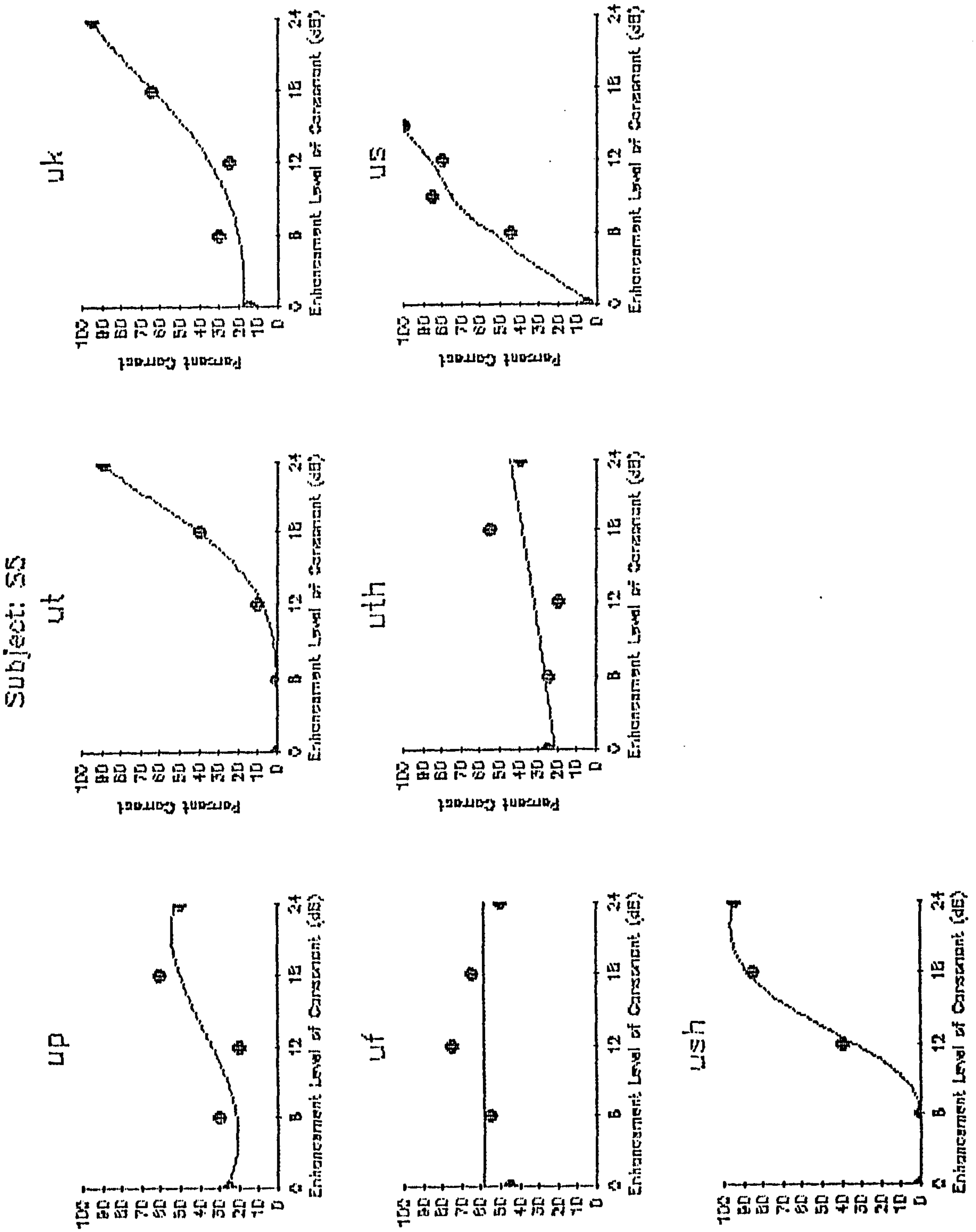

Figure 90. CE functions of the voiceless consonants with /u/ for subject S5.

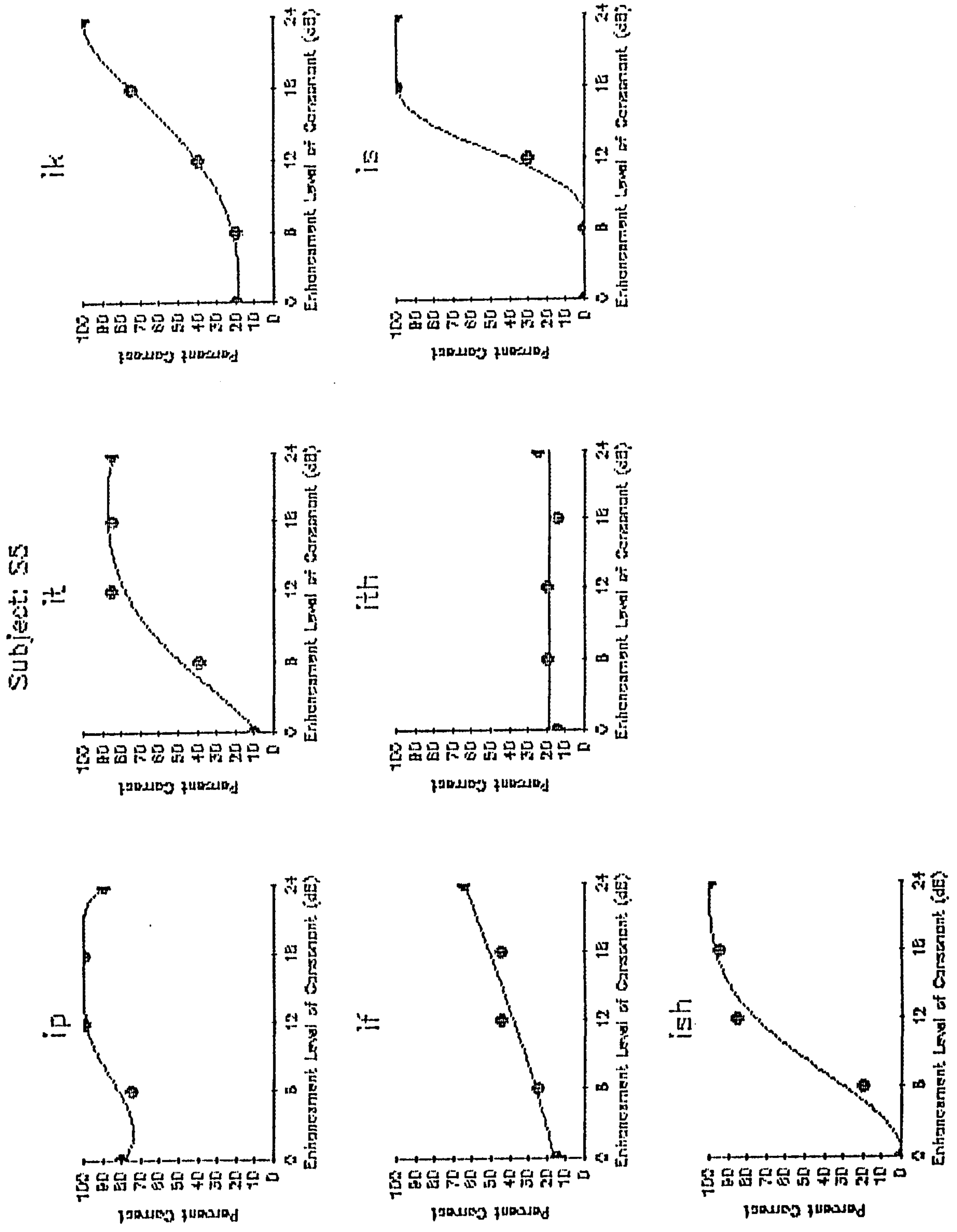

Figure 91. CE functions of the voiceless consonants with /i/ for subject S5.

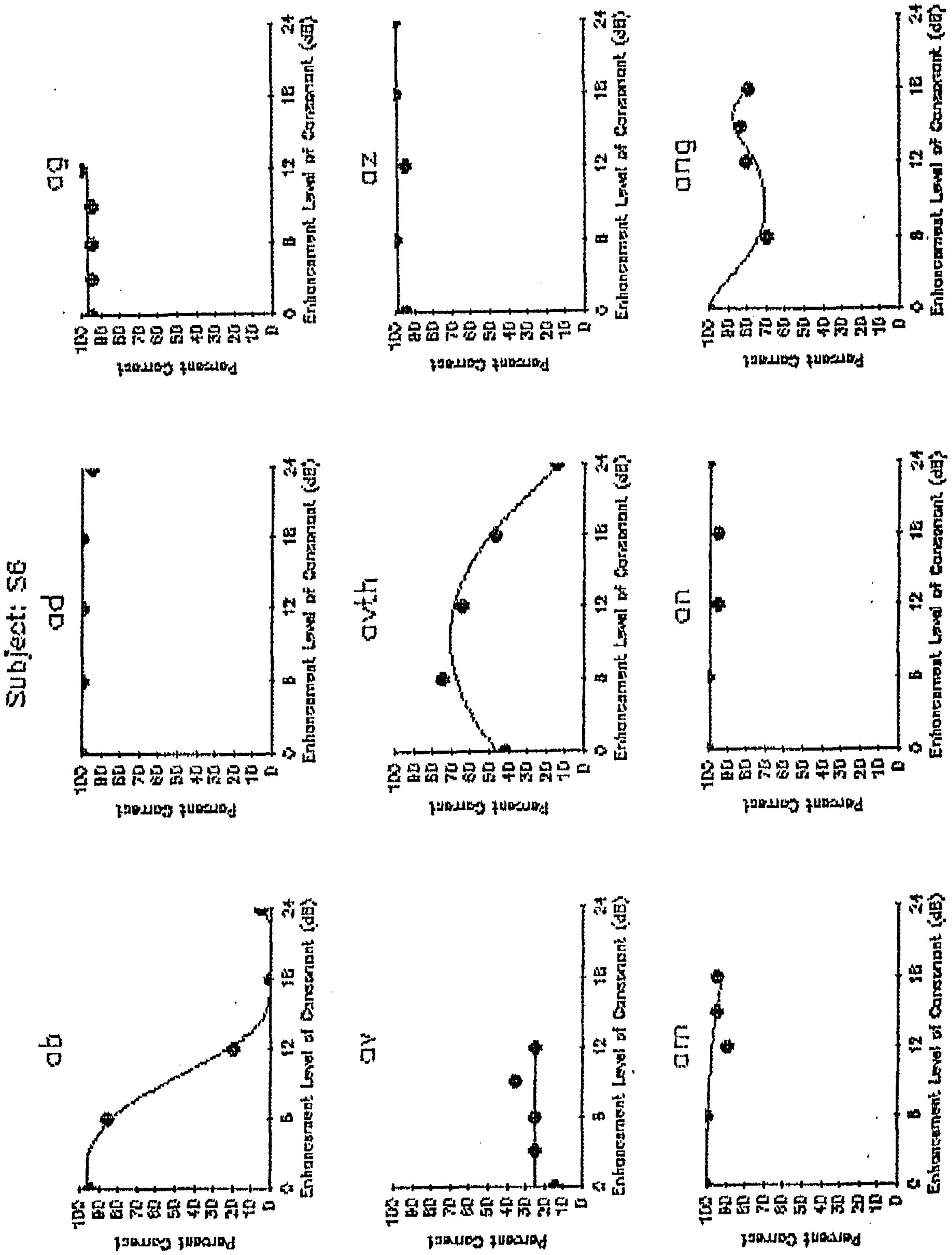

Figure 92. CE functions of the voiced consonants with /a/ for subject S6.

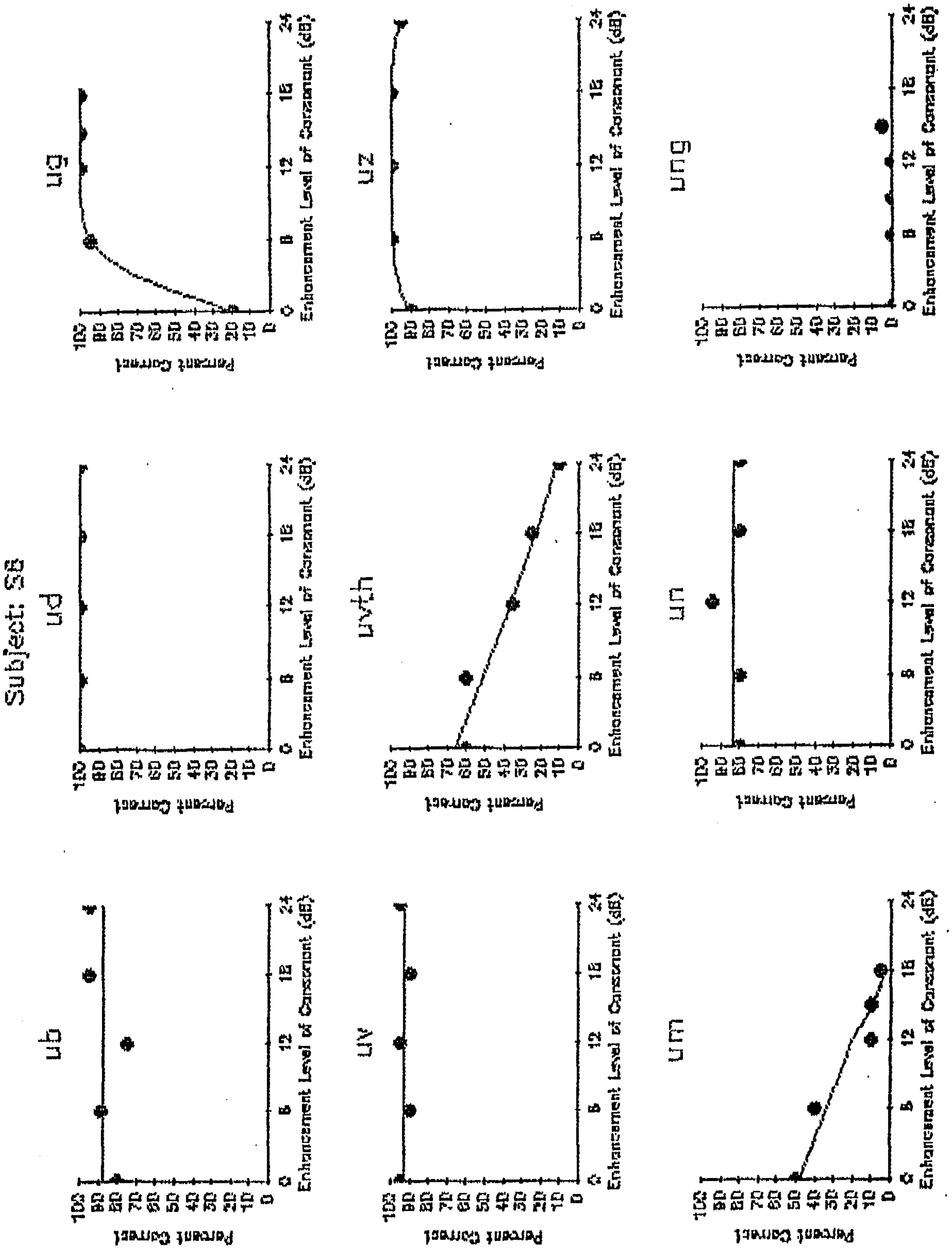

Figure 93. CE functions of the voiced consonants with /u/ for subject S6.

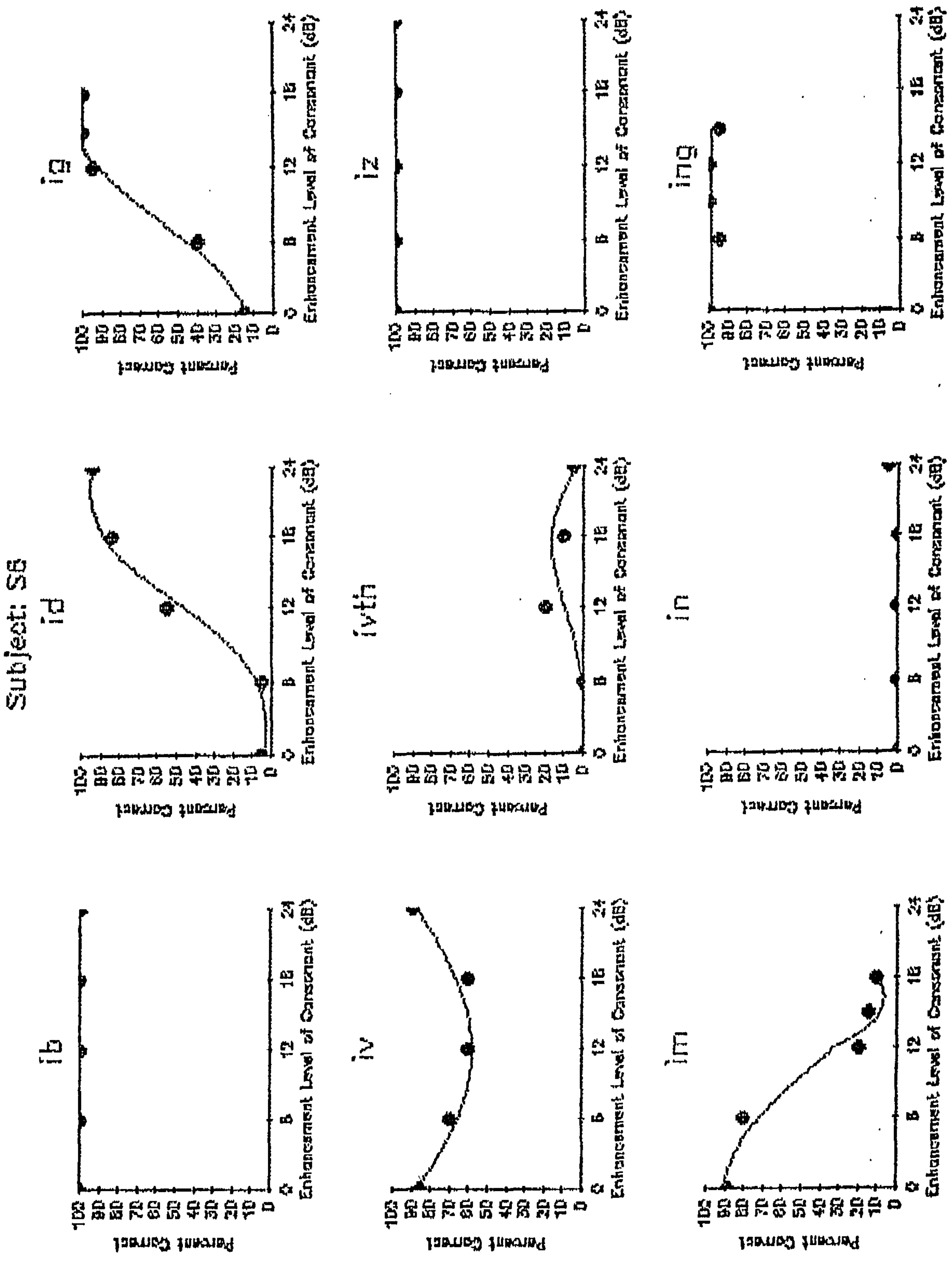

Figure 94. CE functions of the voiced consonants with /i/ for subject S6.

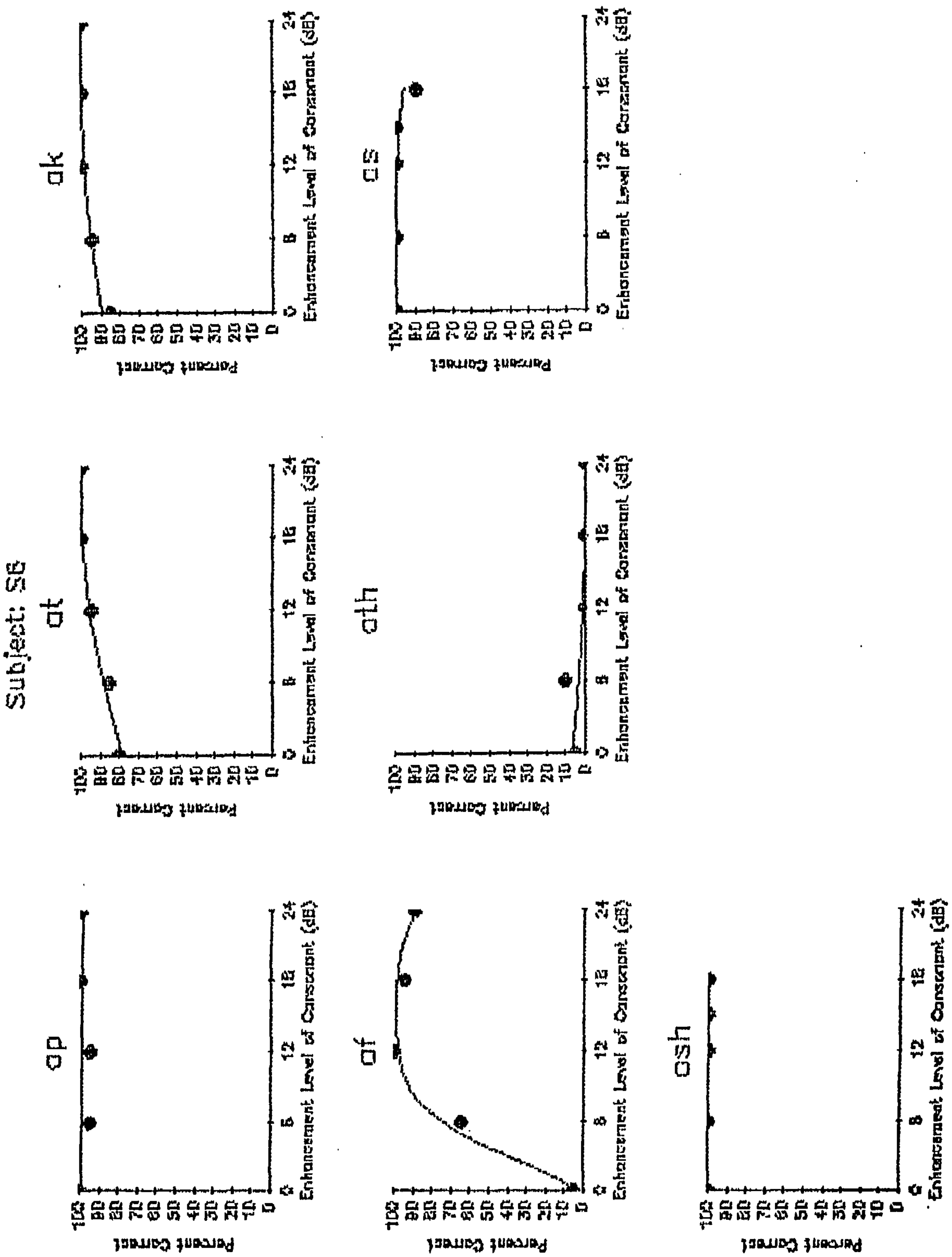

Figure 95. CE functions of the voiceless consonants with /a/ for subject S6.

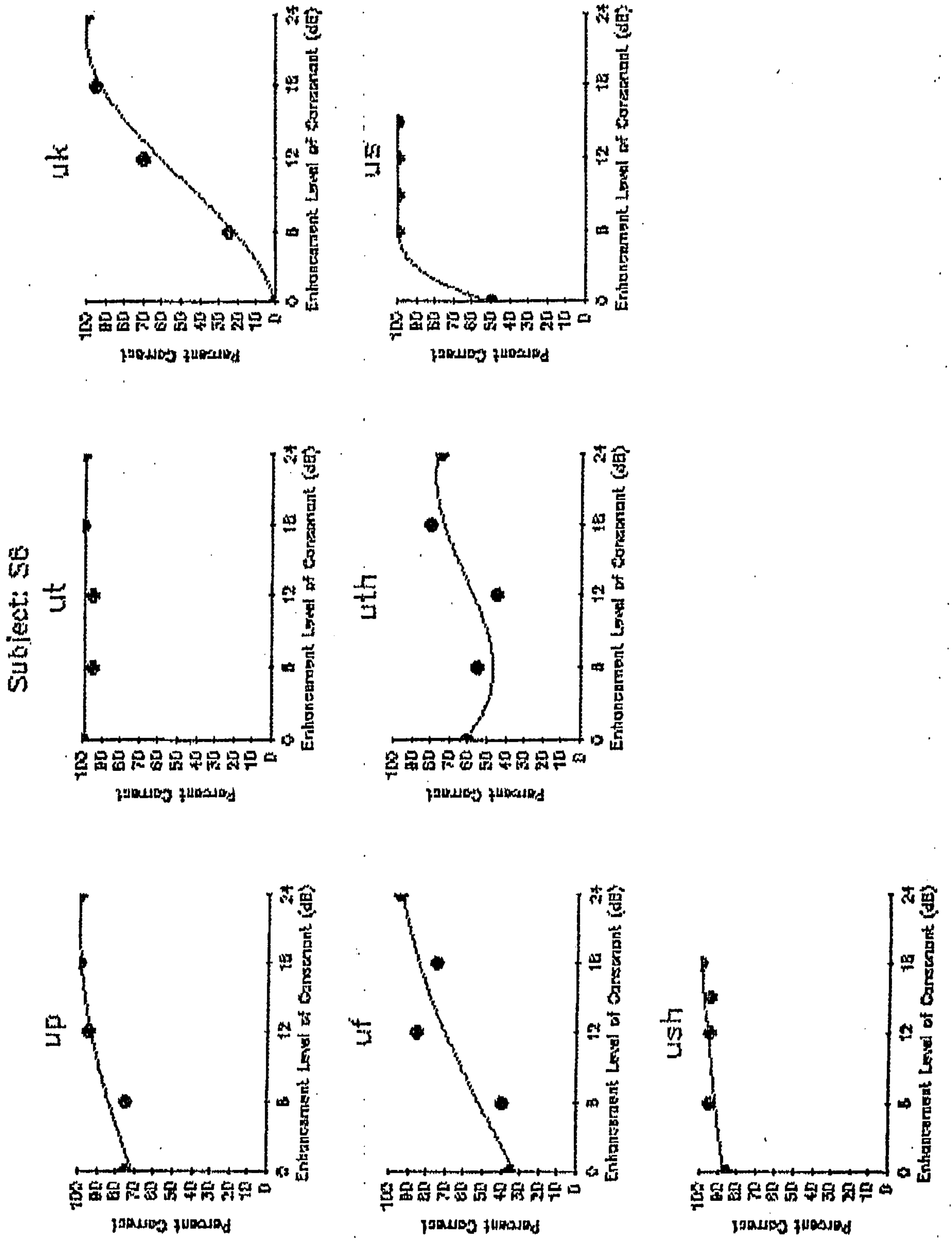

Figure 96. CE functions of the voiceless consonants with /u/ for subject S6.

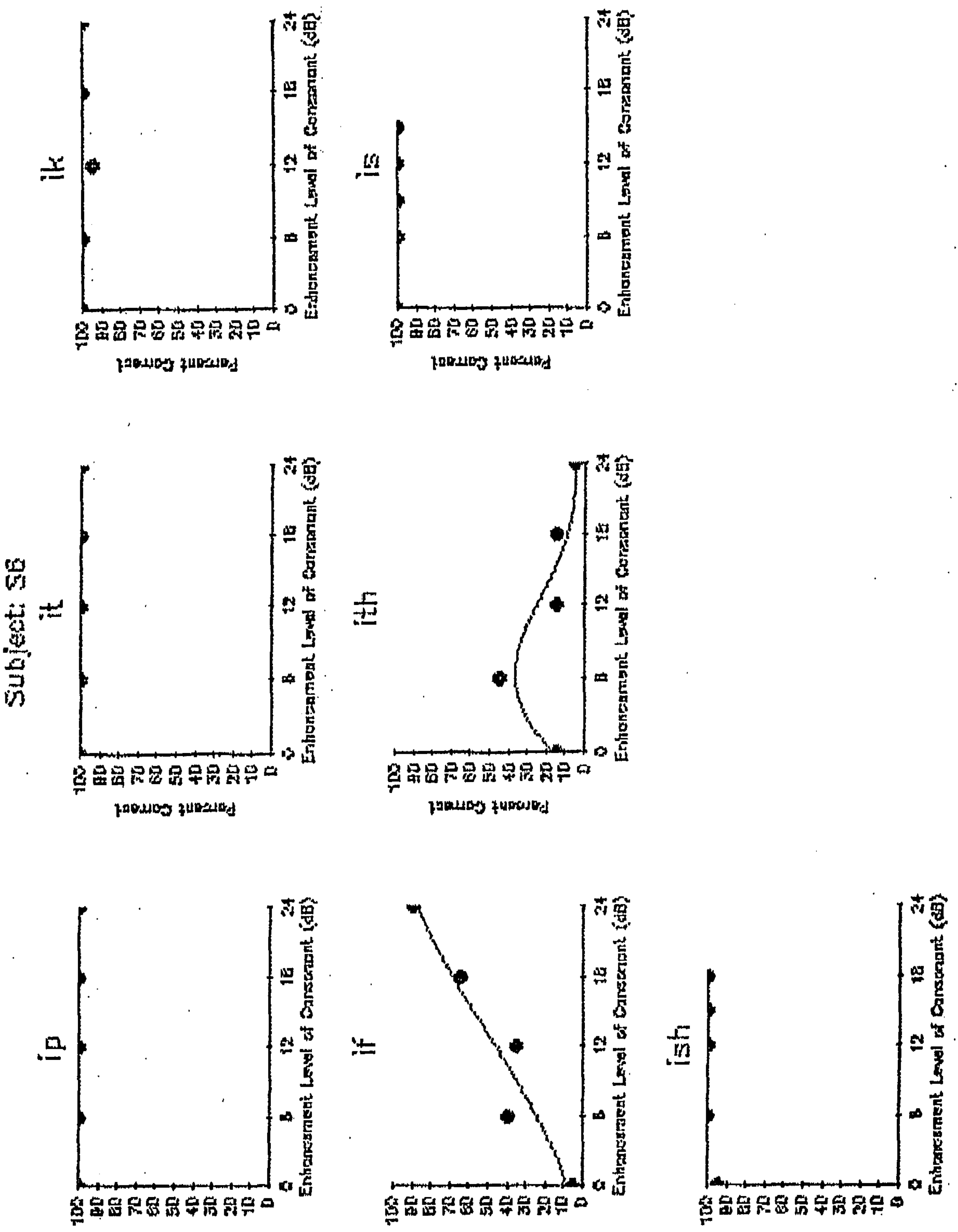

Figure 97. CE functions of the voiceless consonants with /i/ for subject S6.

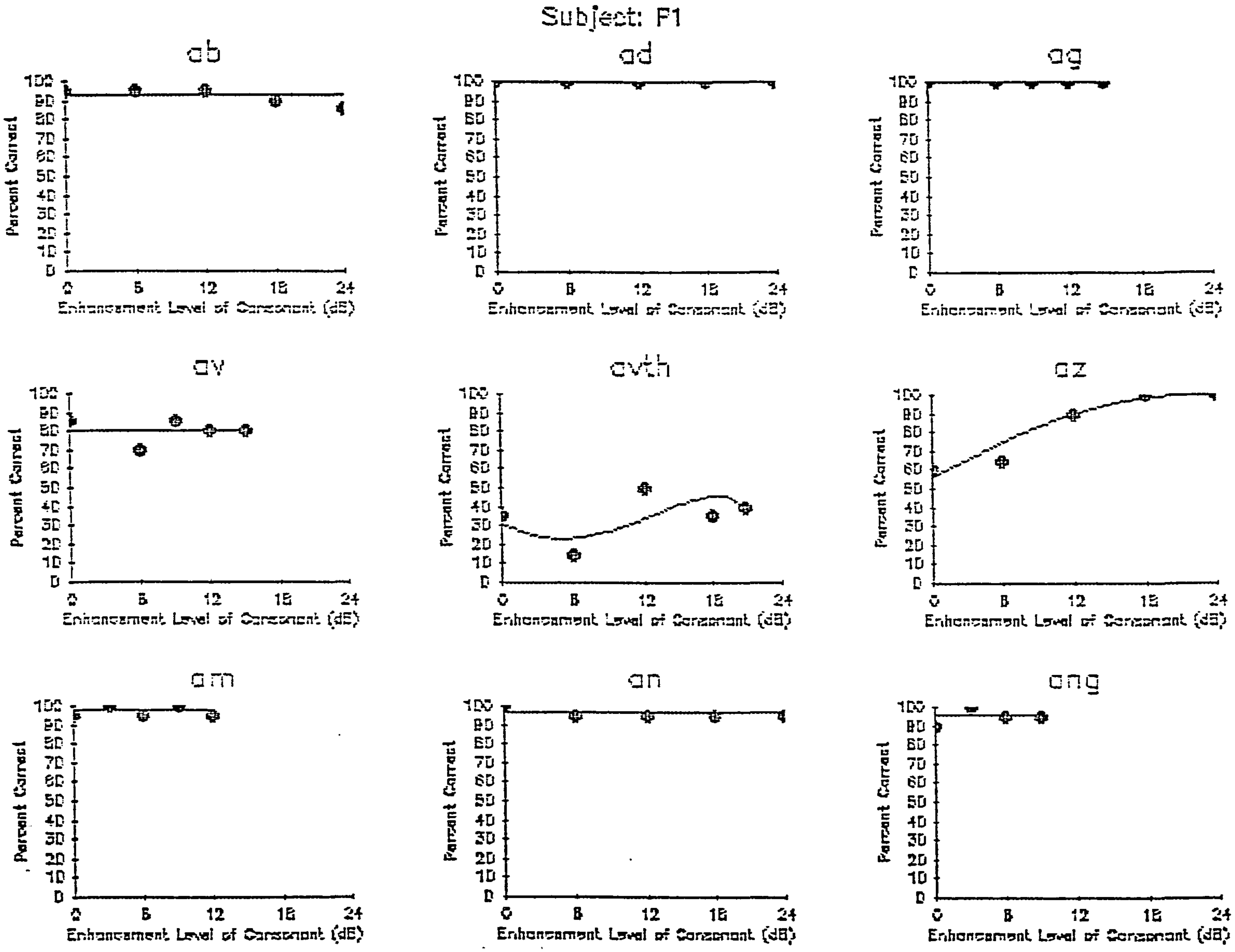

Figure 98. CE functions of the voiced consonants with /a/ for subject F1.

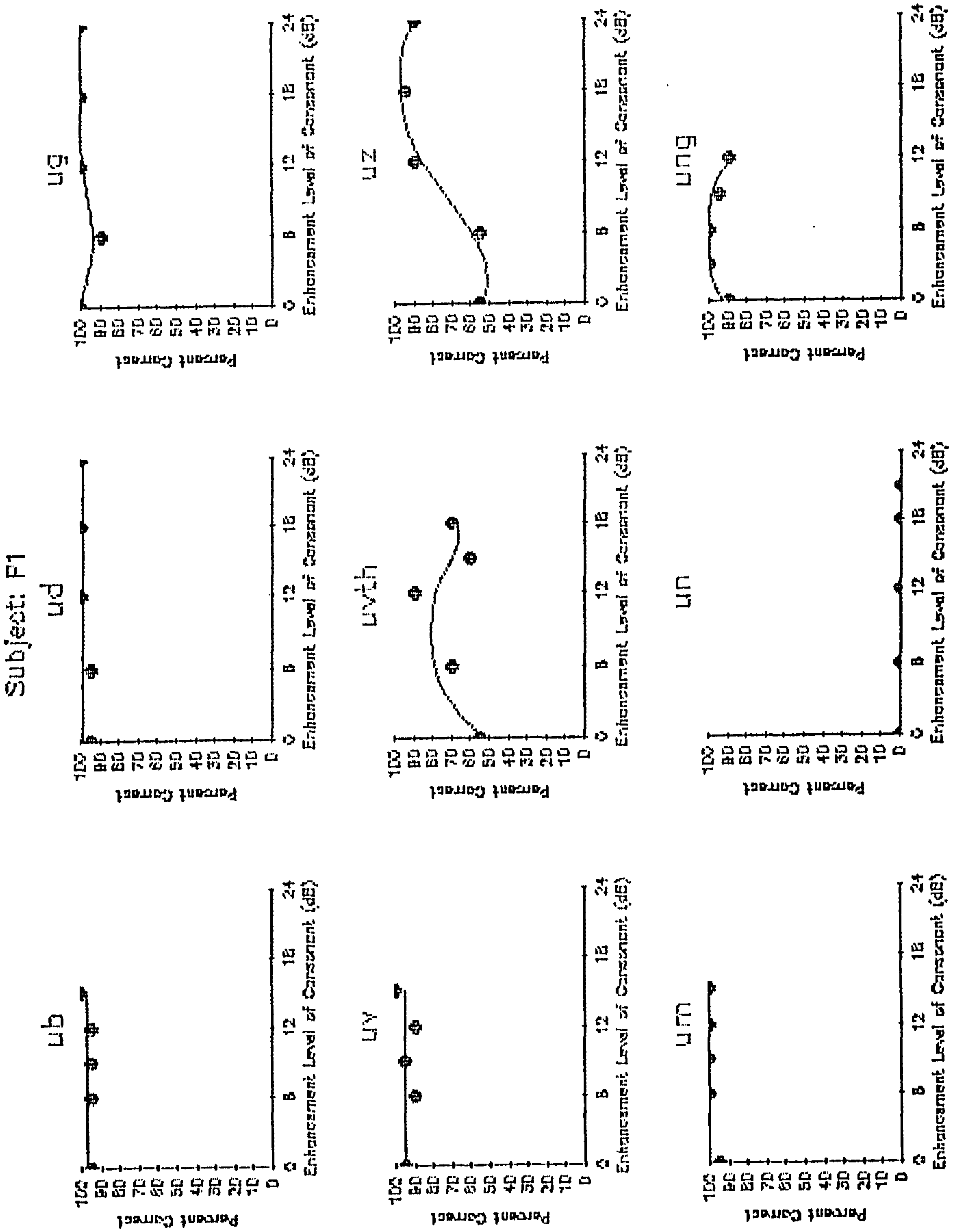

Figure 99. CE functions of the voiced consonants with /u/ for subject F1.

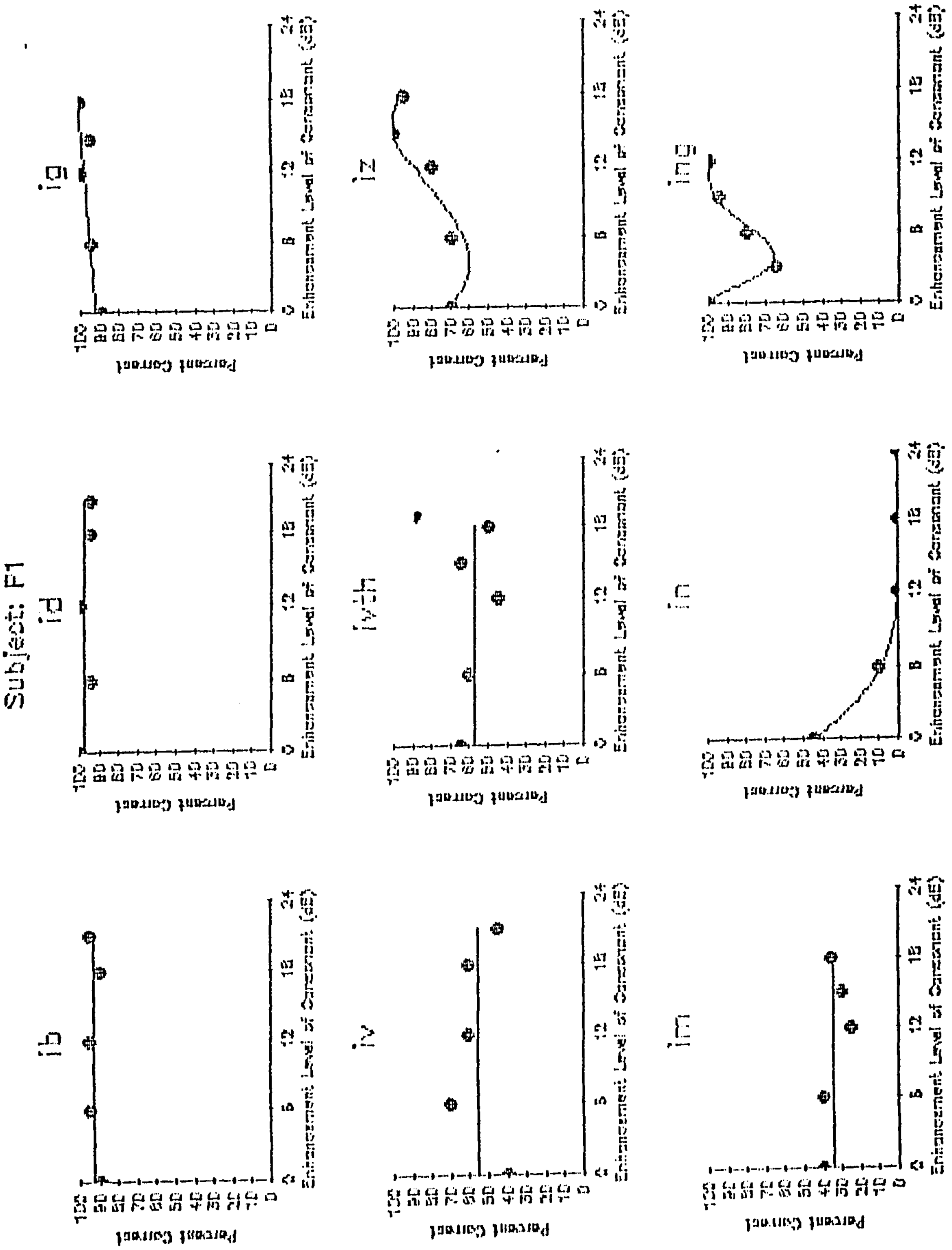

Figure 100. CE functions of the voiced consonants with /i/ for subject P1.

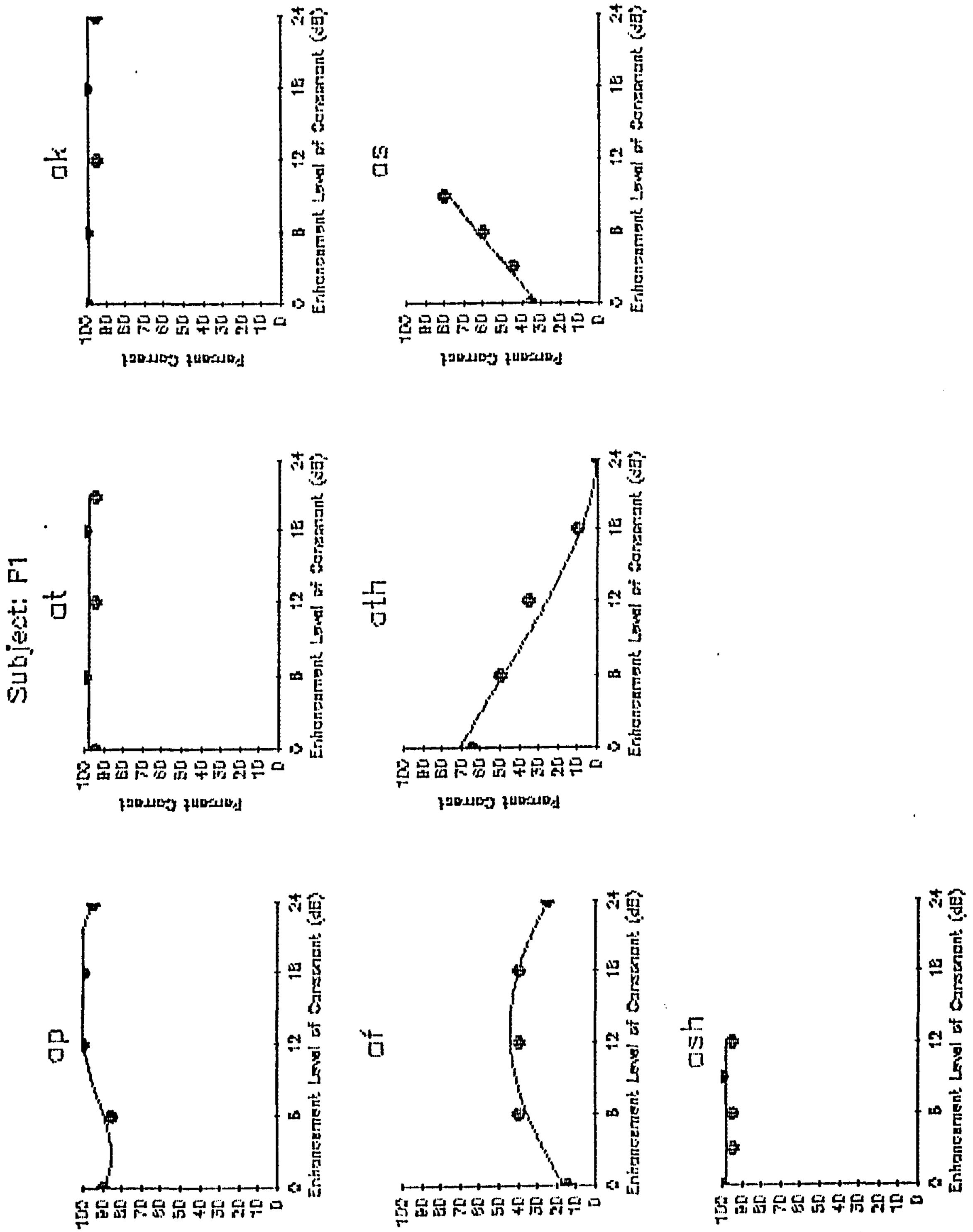

Figure 101. CE functions of the voiceless consonants with /a/ for subject P1.

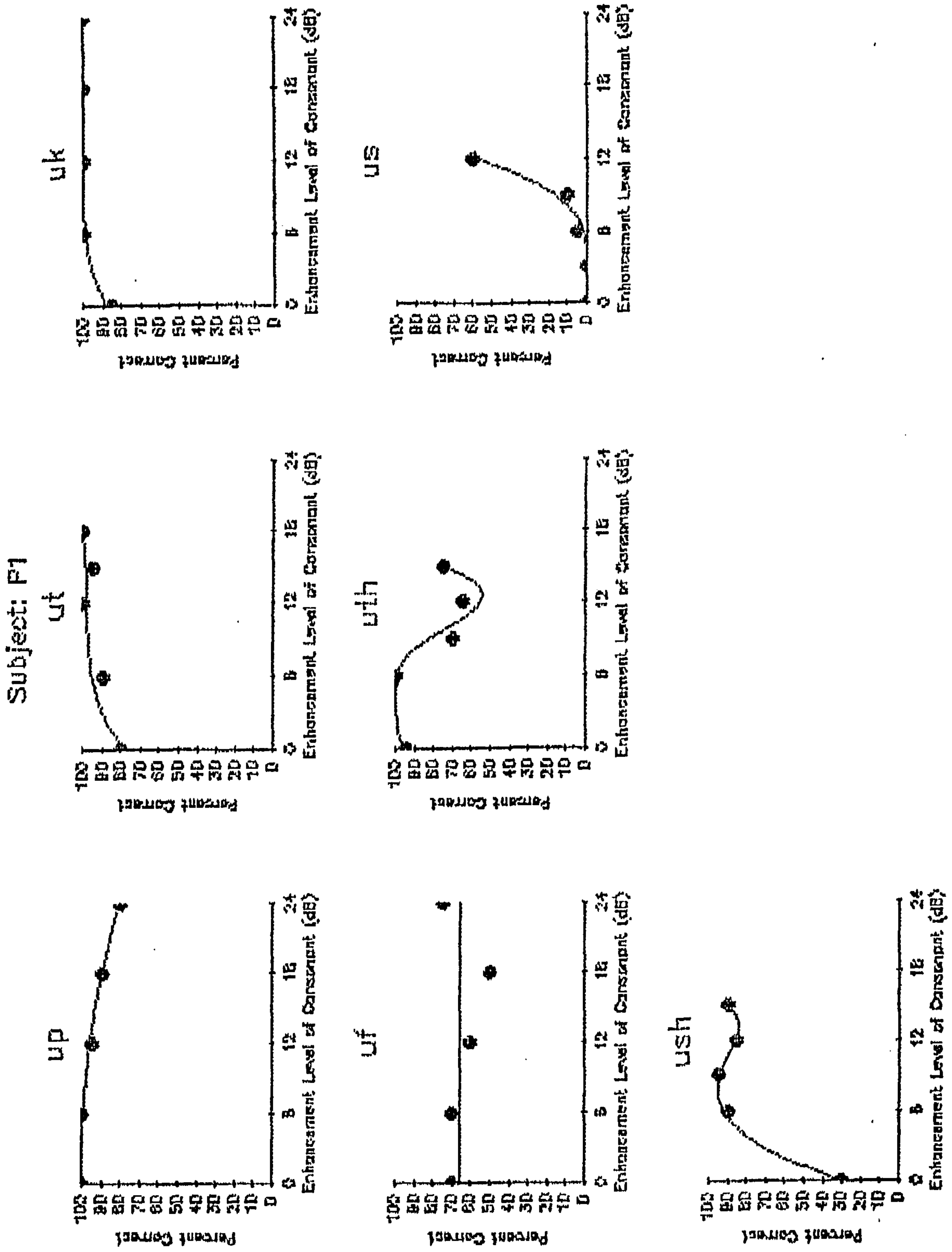

Figure 102. CE functions of the voiceless consonants with /u/ for subject P1.

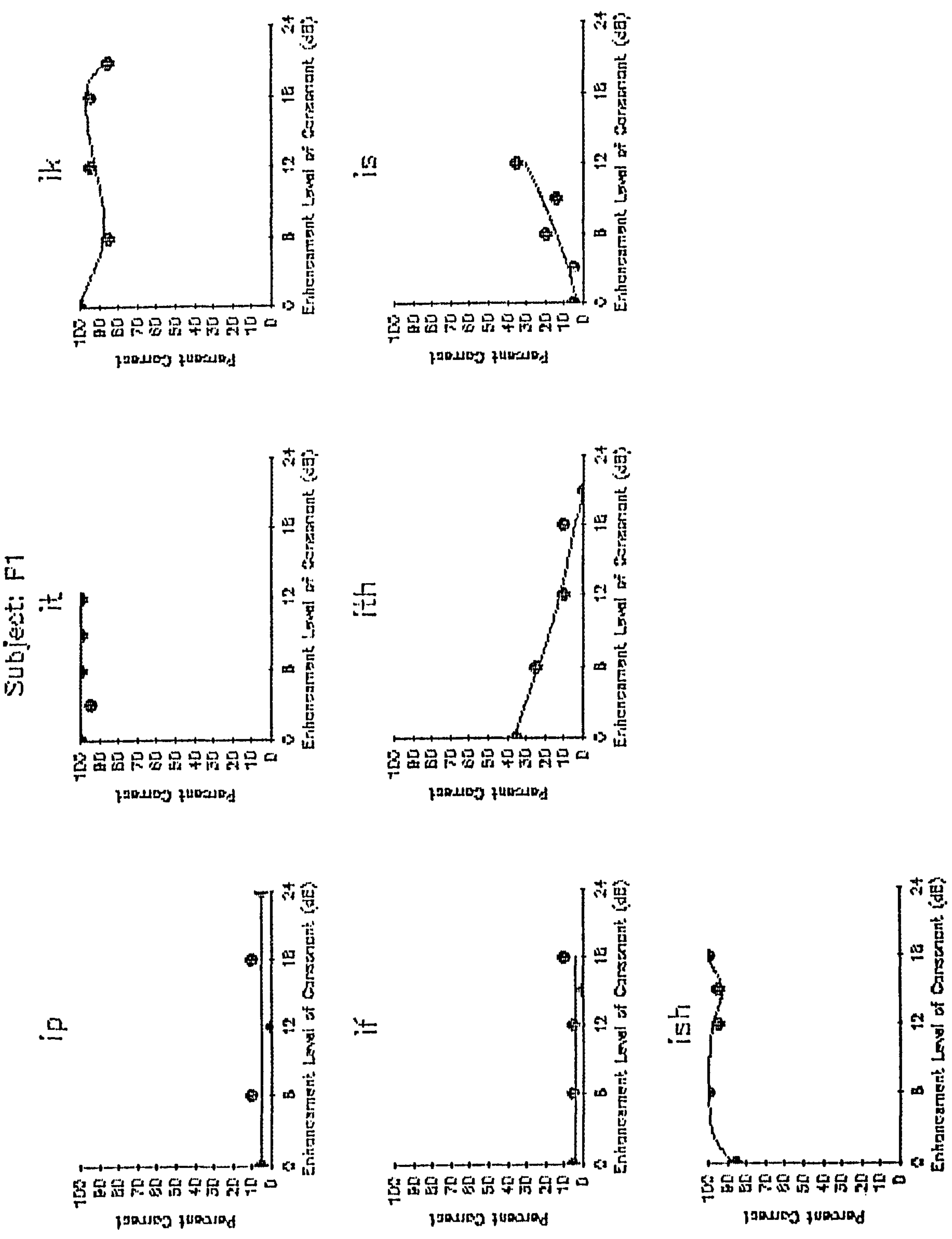

Figure 103. CE functions of the voiceless consonants with /i/ for subject P1.

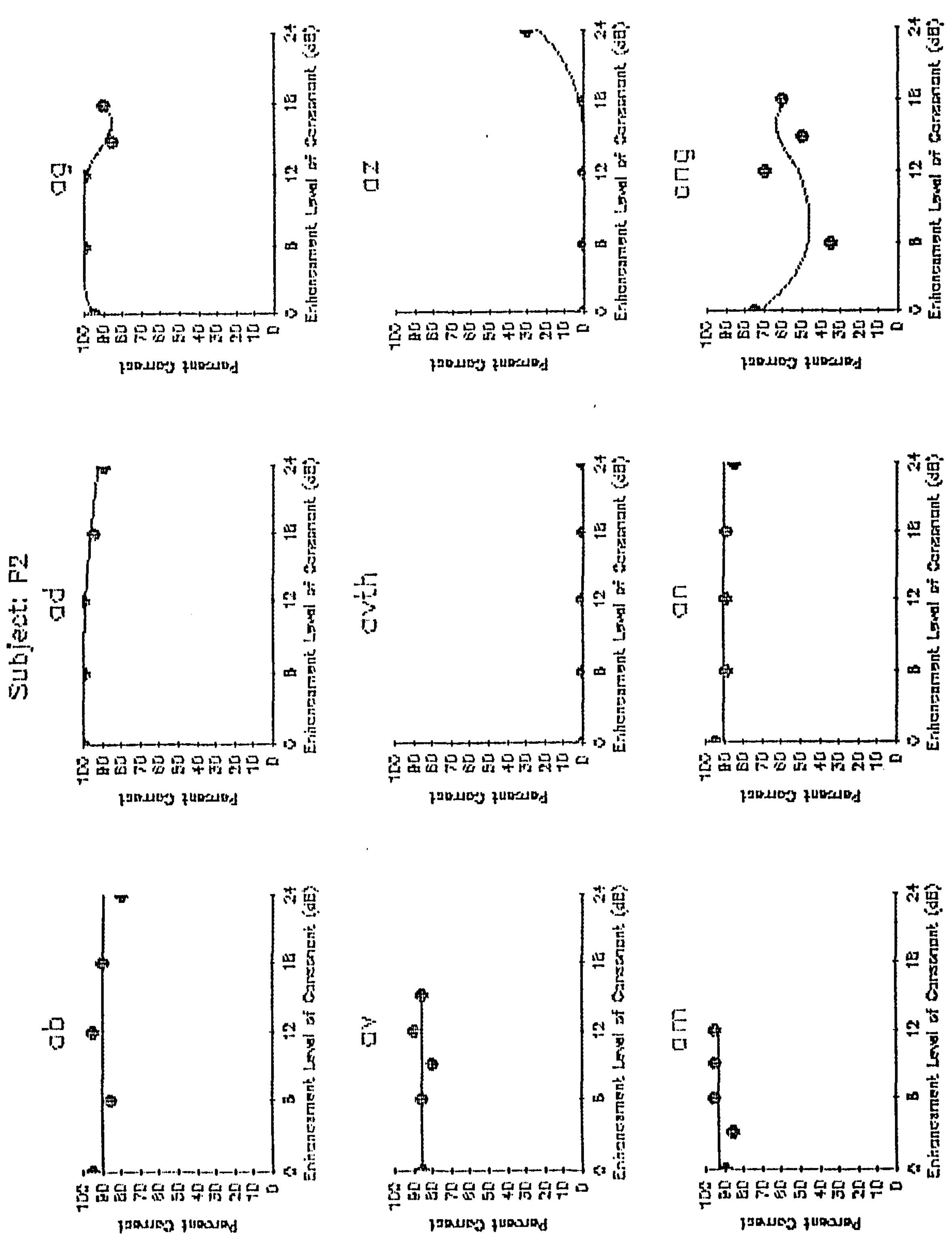

Figure 104. CE functions of the voiced consonants with /a/ for subject P2.

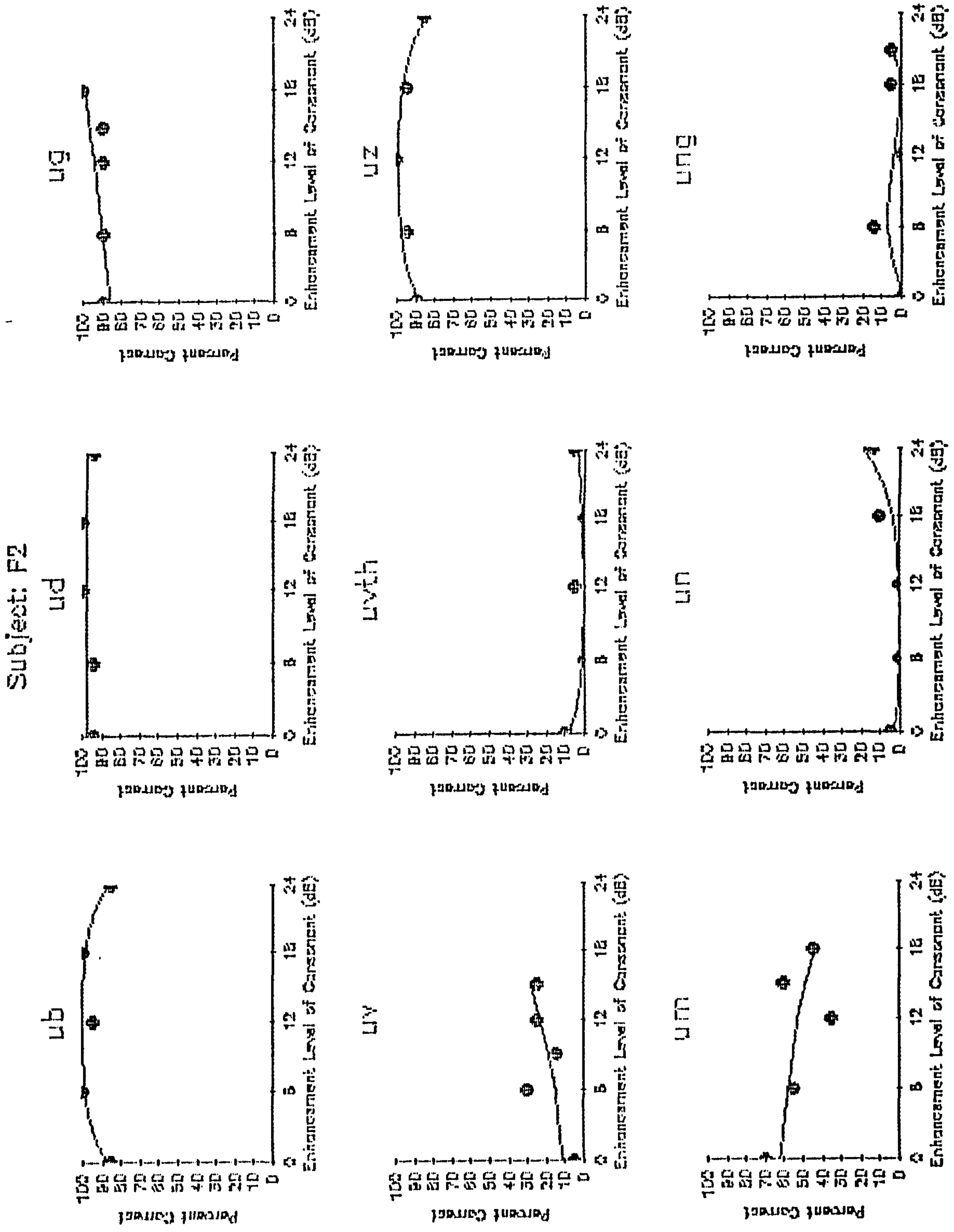

Figure 105. CE functions of the voiced consonants with /u/ for subject P2.

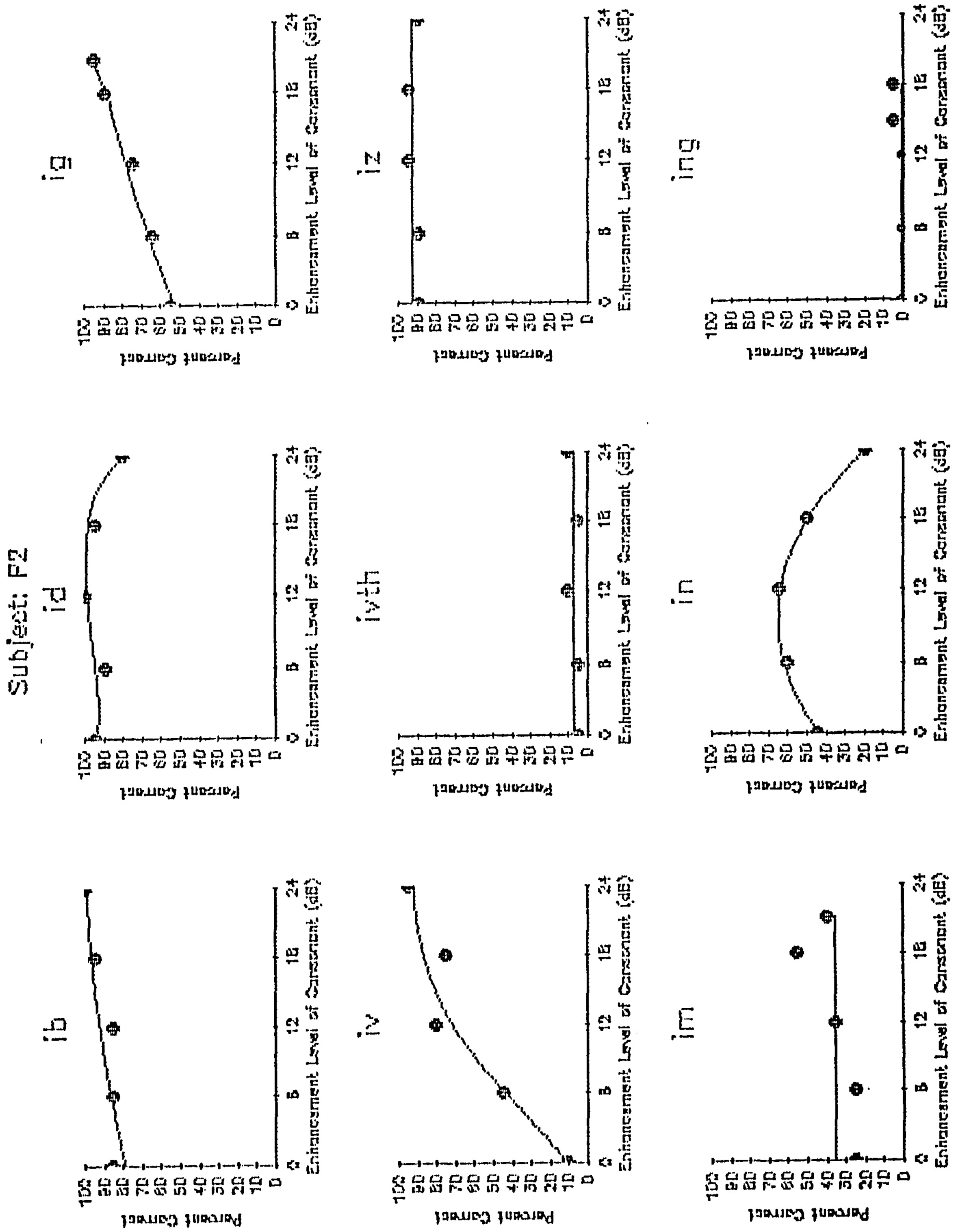

Figure 106. CE functions of the voiced consonants with /i/ for subject P2.

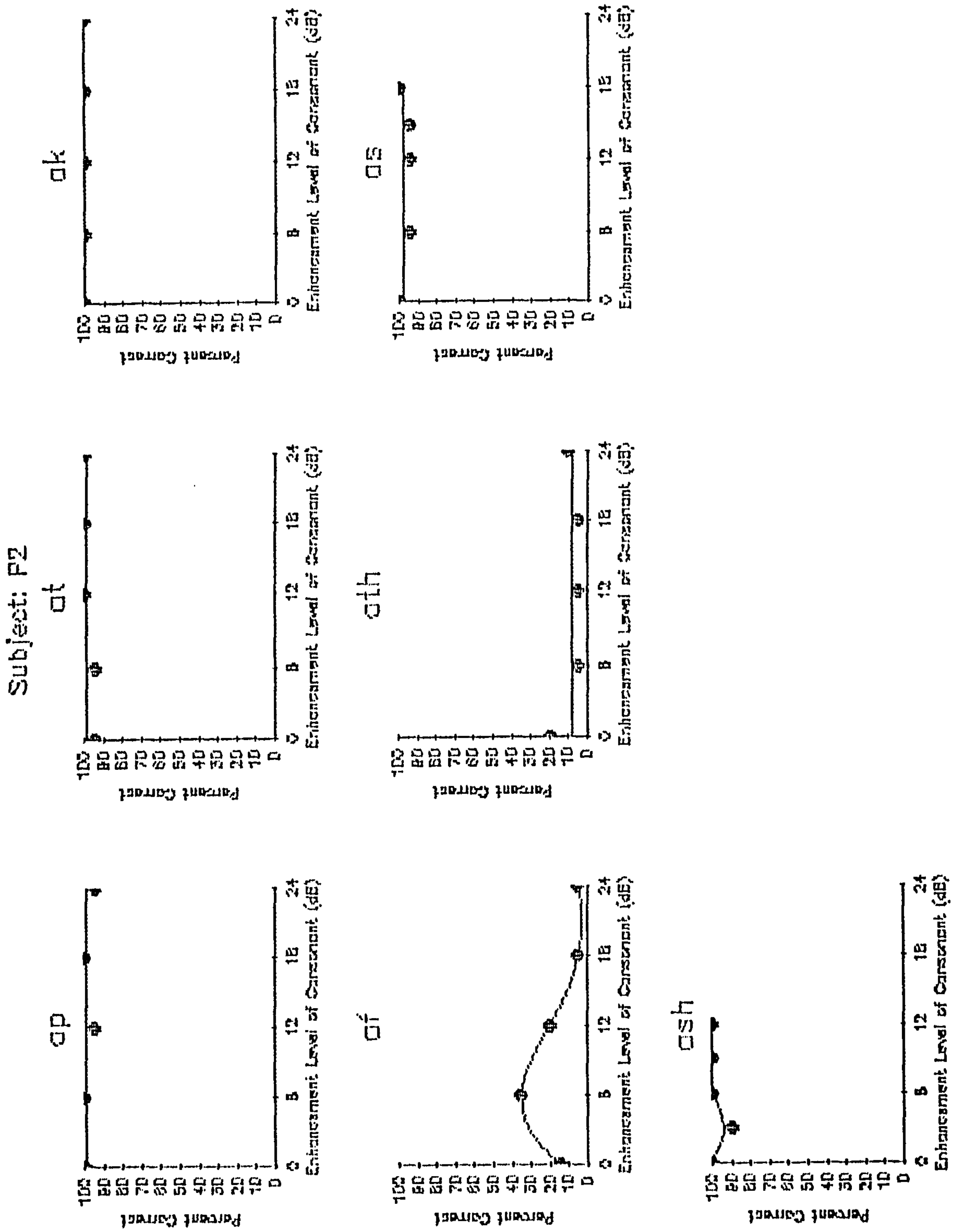

Figure 107. CE functions of the voiceless consonants with /a/ for subject P2.

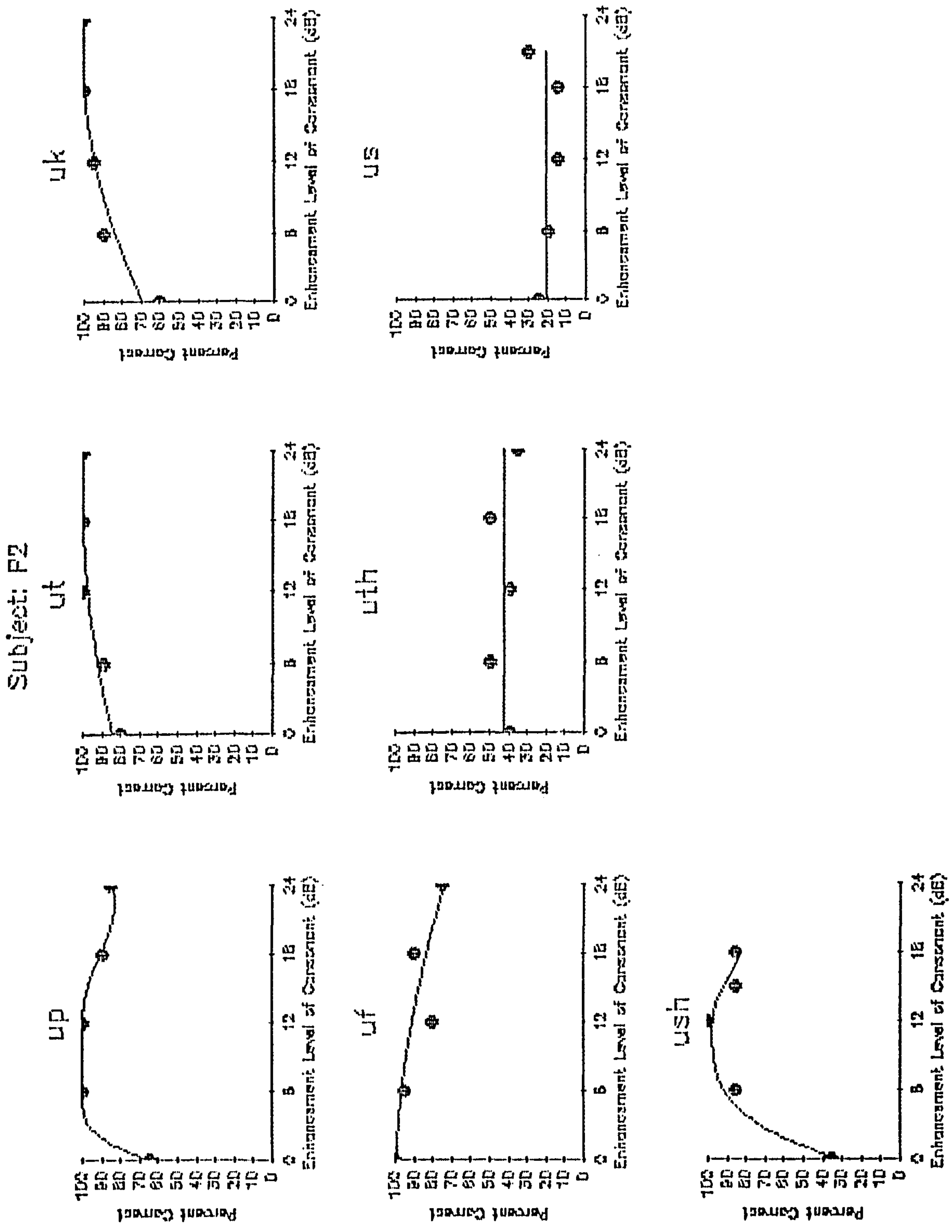

Figure 108. CE functions of the voiceless consonants with /u/ for subject P2.

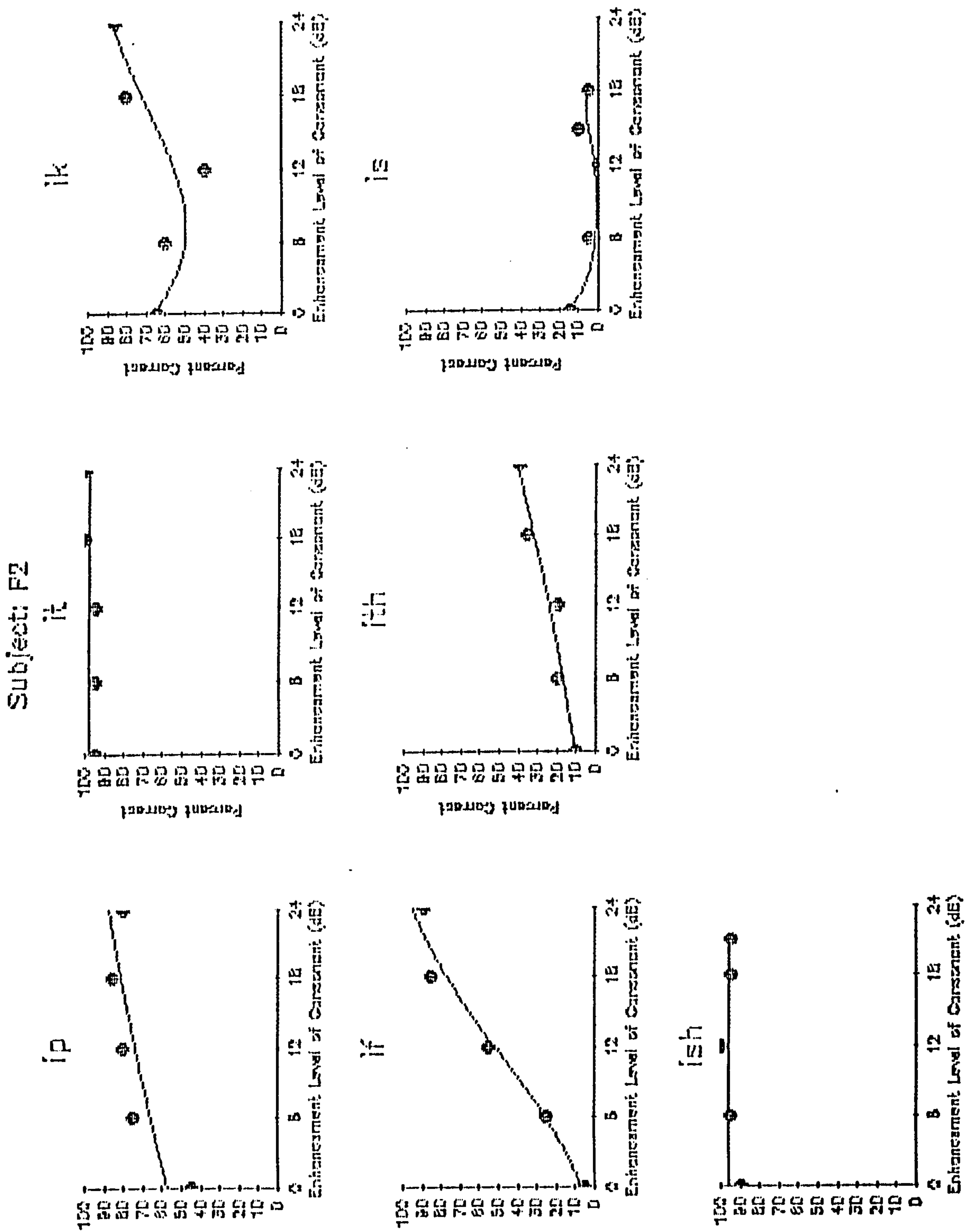

Figure 109. CE functions of the voiceless consonants with /i/ for subject P2.

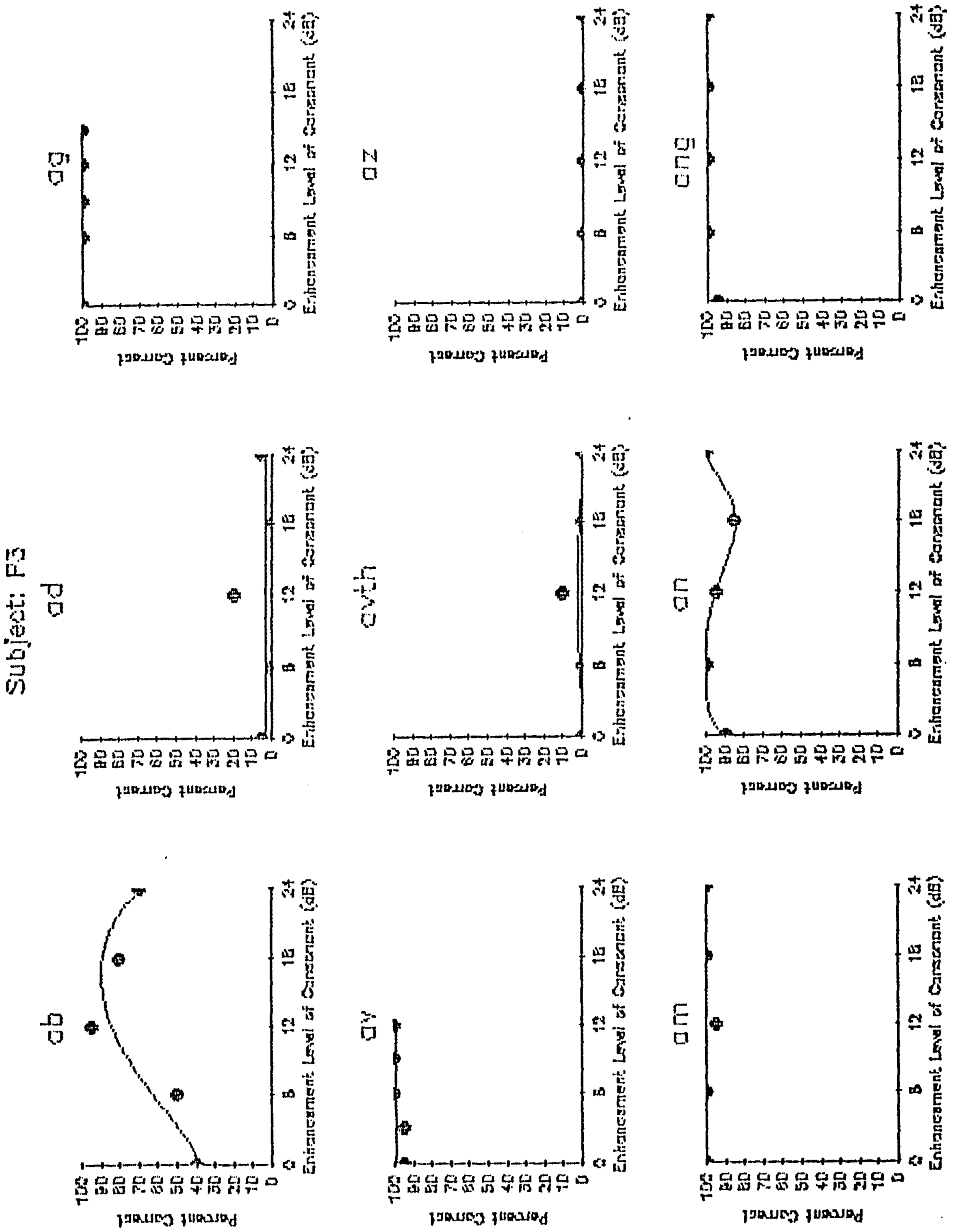

Figure 110. CE functions for the voiced consonants with /a/ for subject P3.

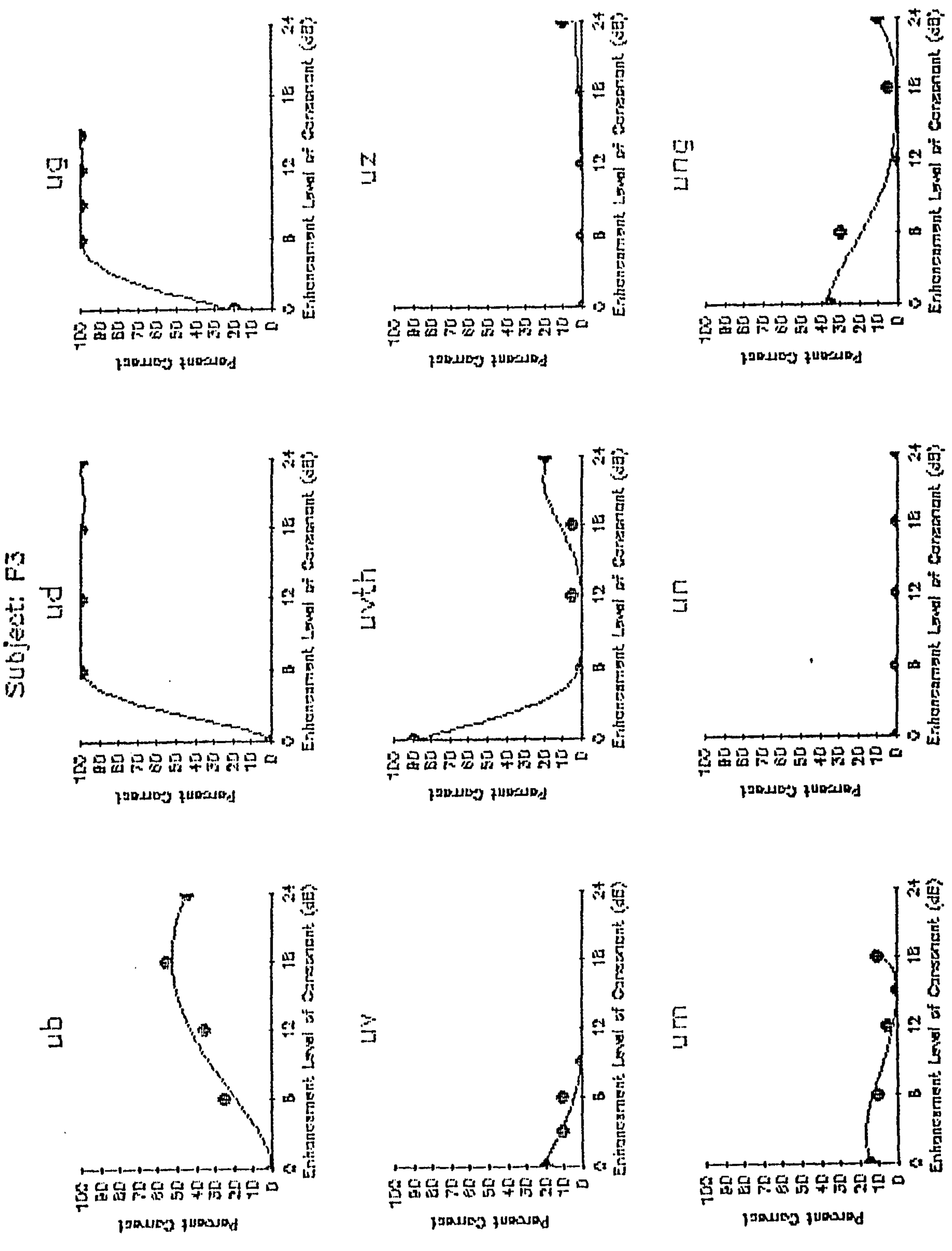

Figure 111. CE functions of the voiced consonants with /u/ for subject P3.

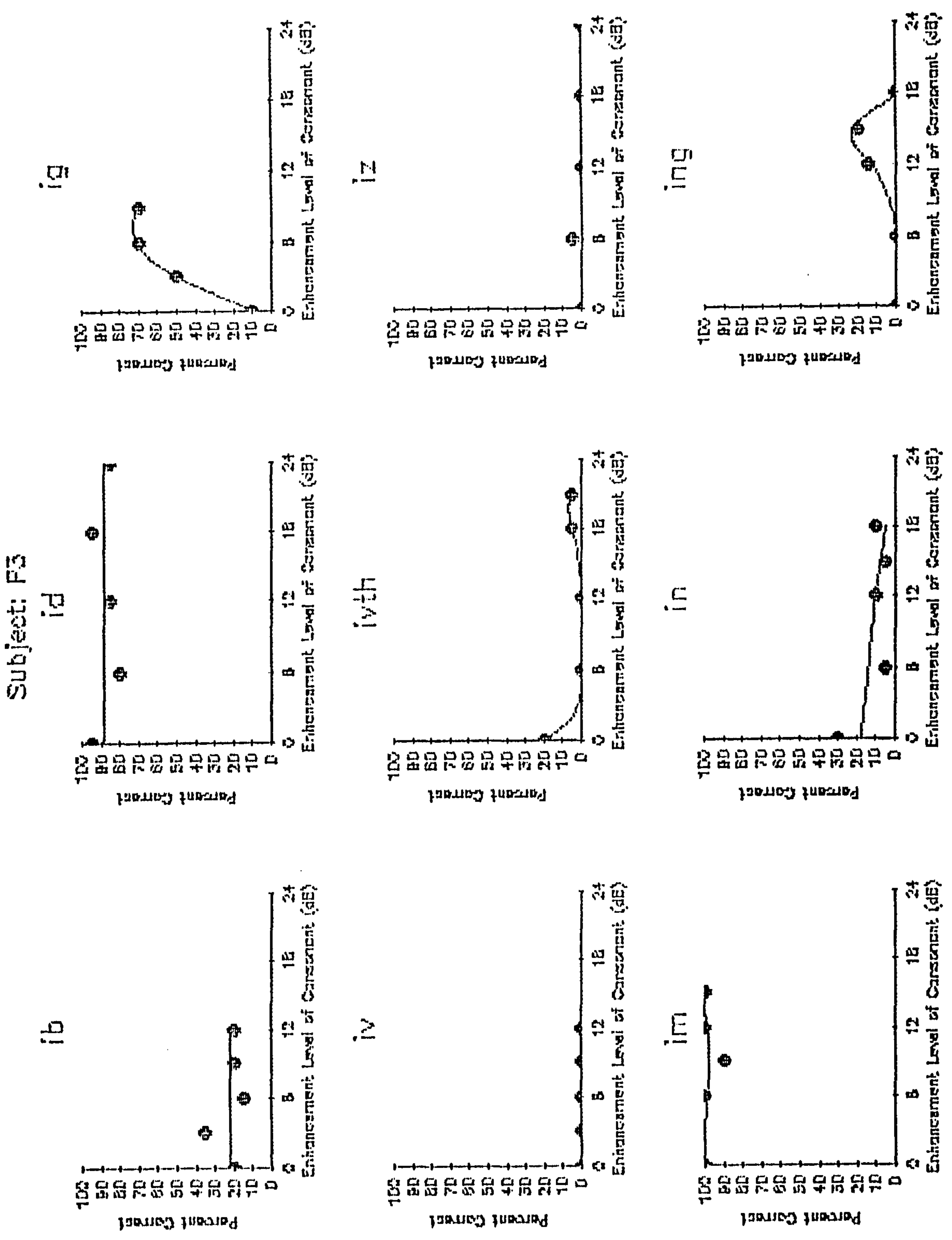

Figure 112. CE functions of the voiced consonants with /i/ for subject P3.

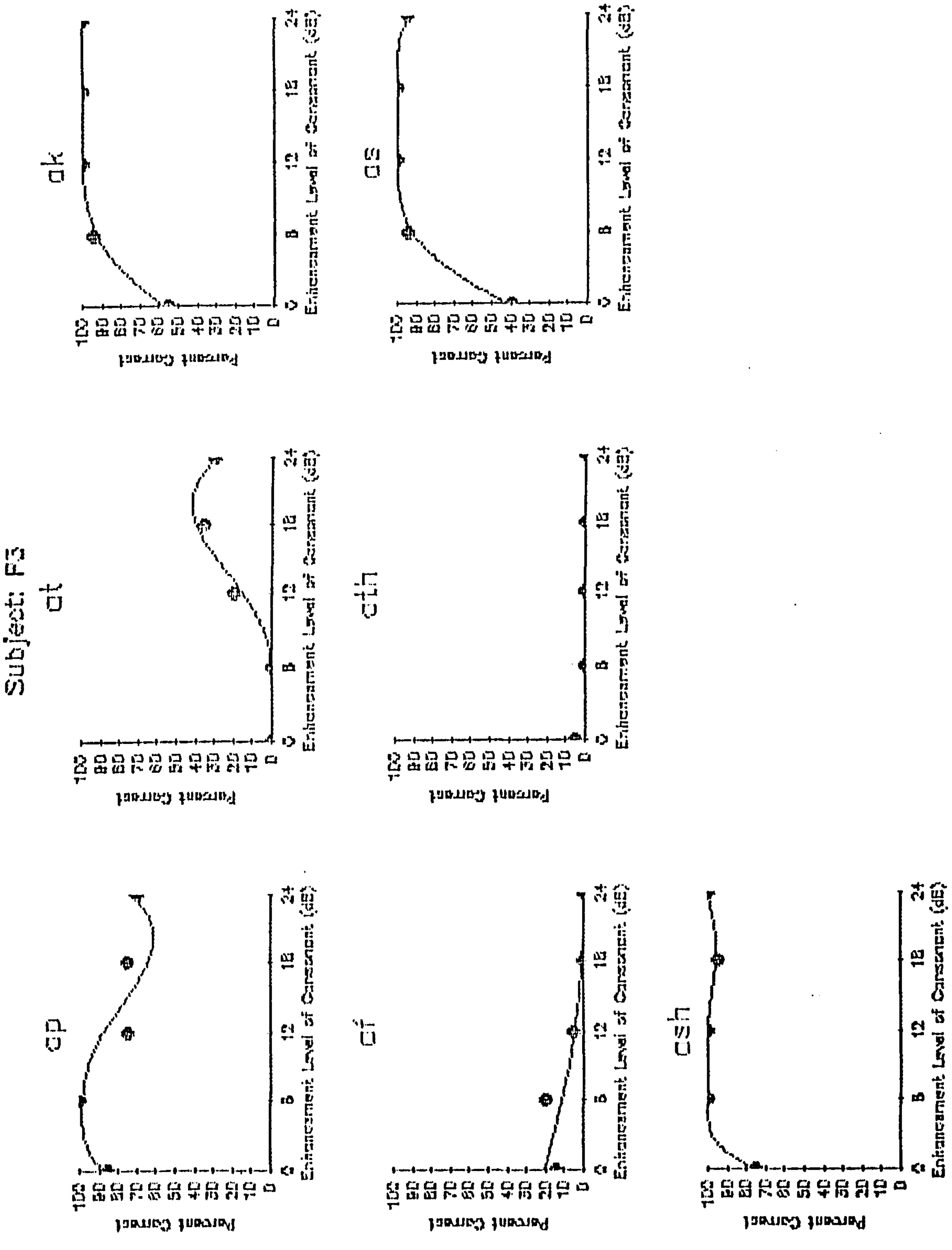

Figure 113. CE functions of the voiceless consonants with /a/ for subject P3.

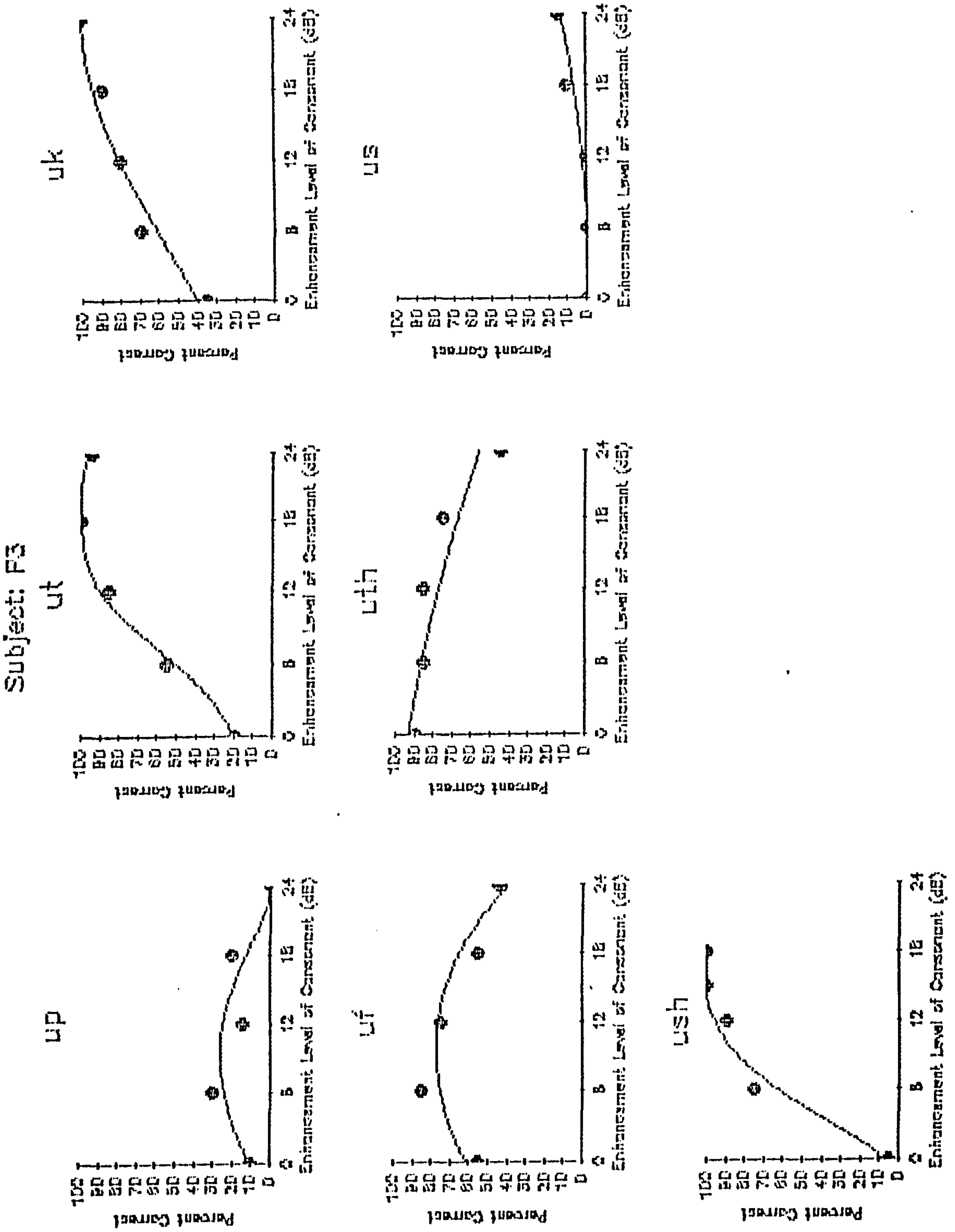

Figure 114. CE functions of the voiceless consonants with /u/ for subject P3.

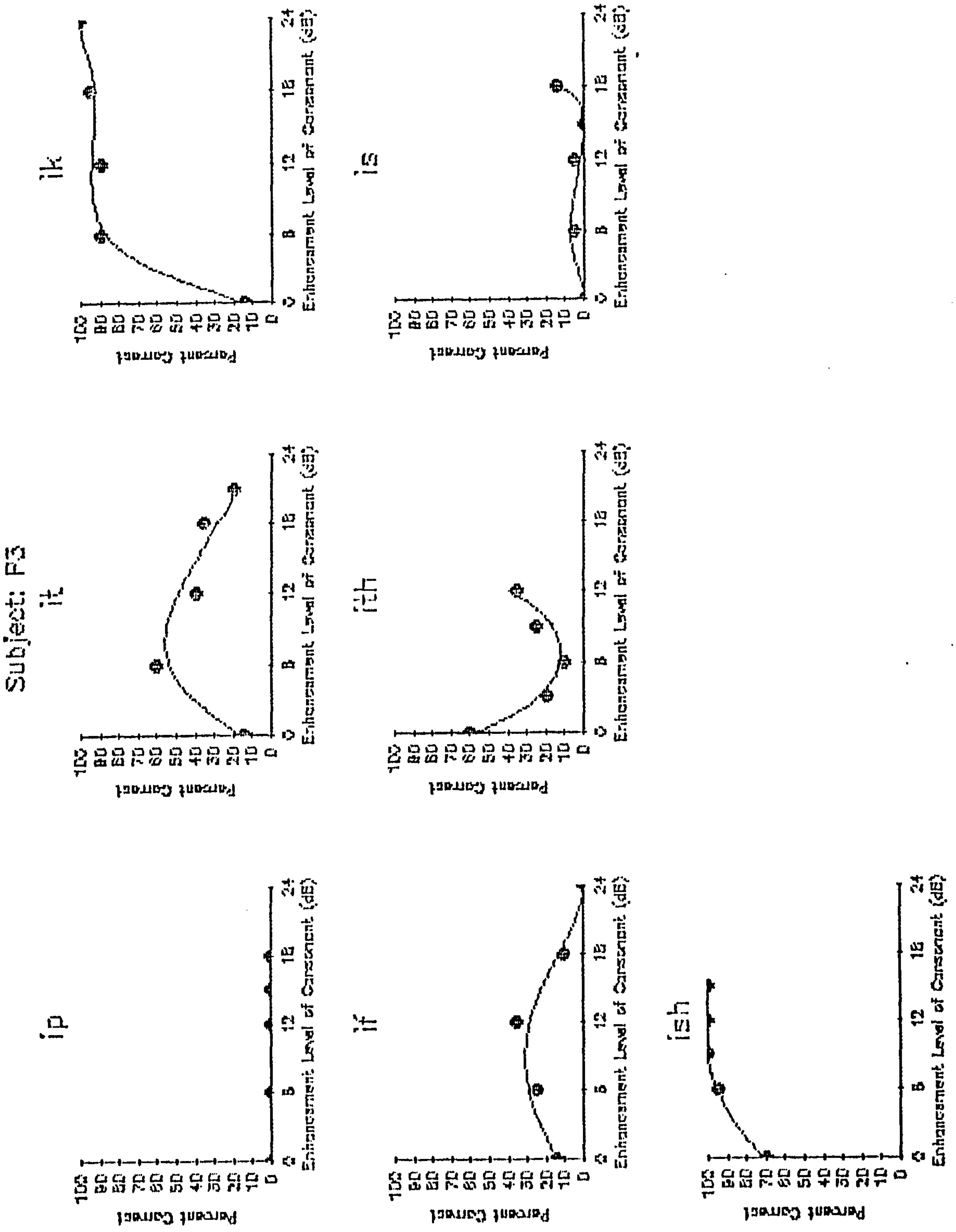

Figure 115. CE functions of the voiceless consonants with /i/ for subject P3.

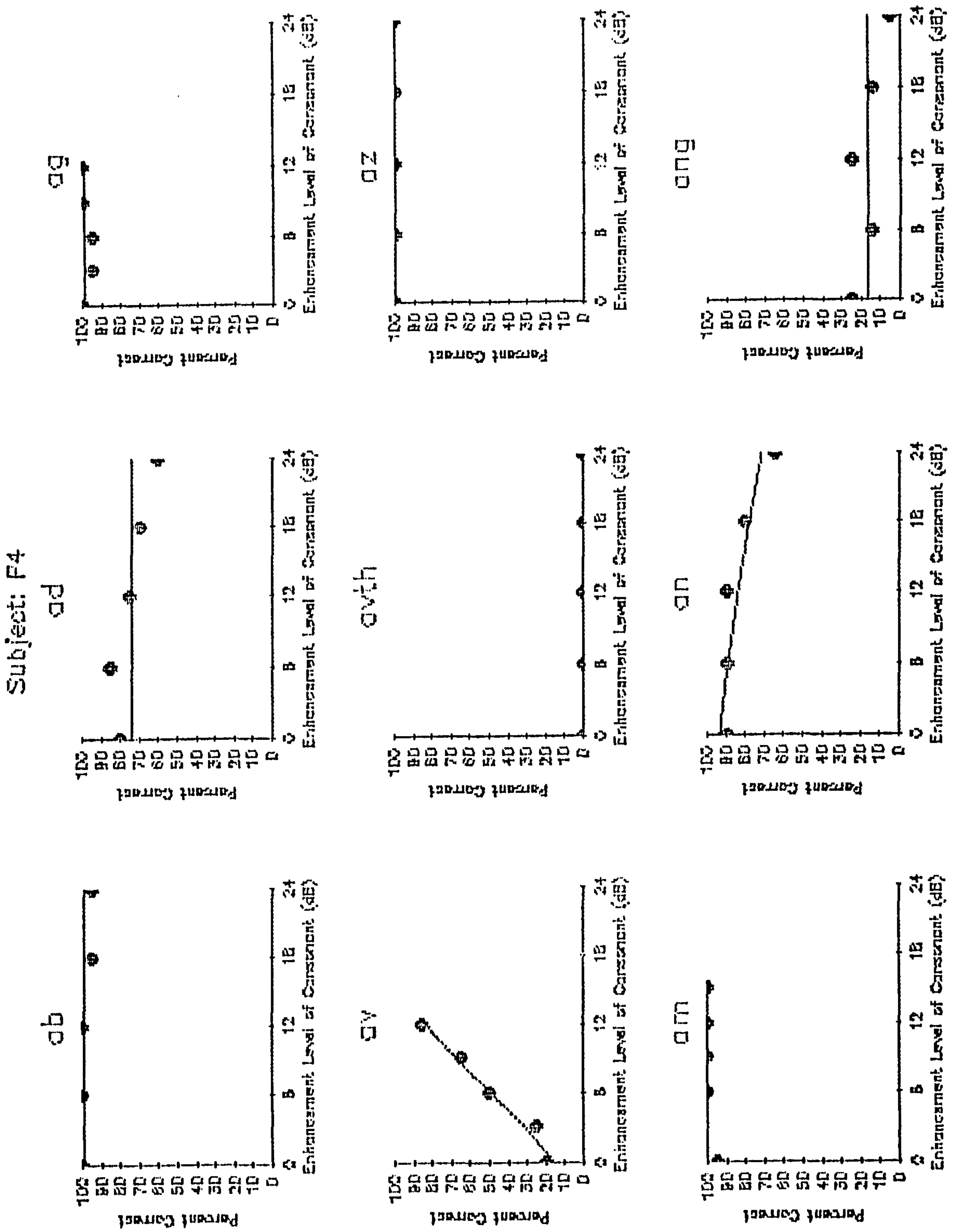

Figure 116. CE functions of the voiced consonants with /a/ for subject P3.

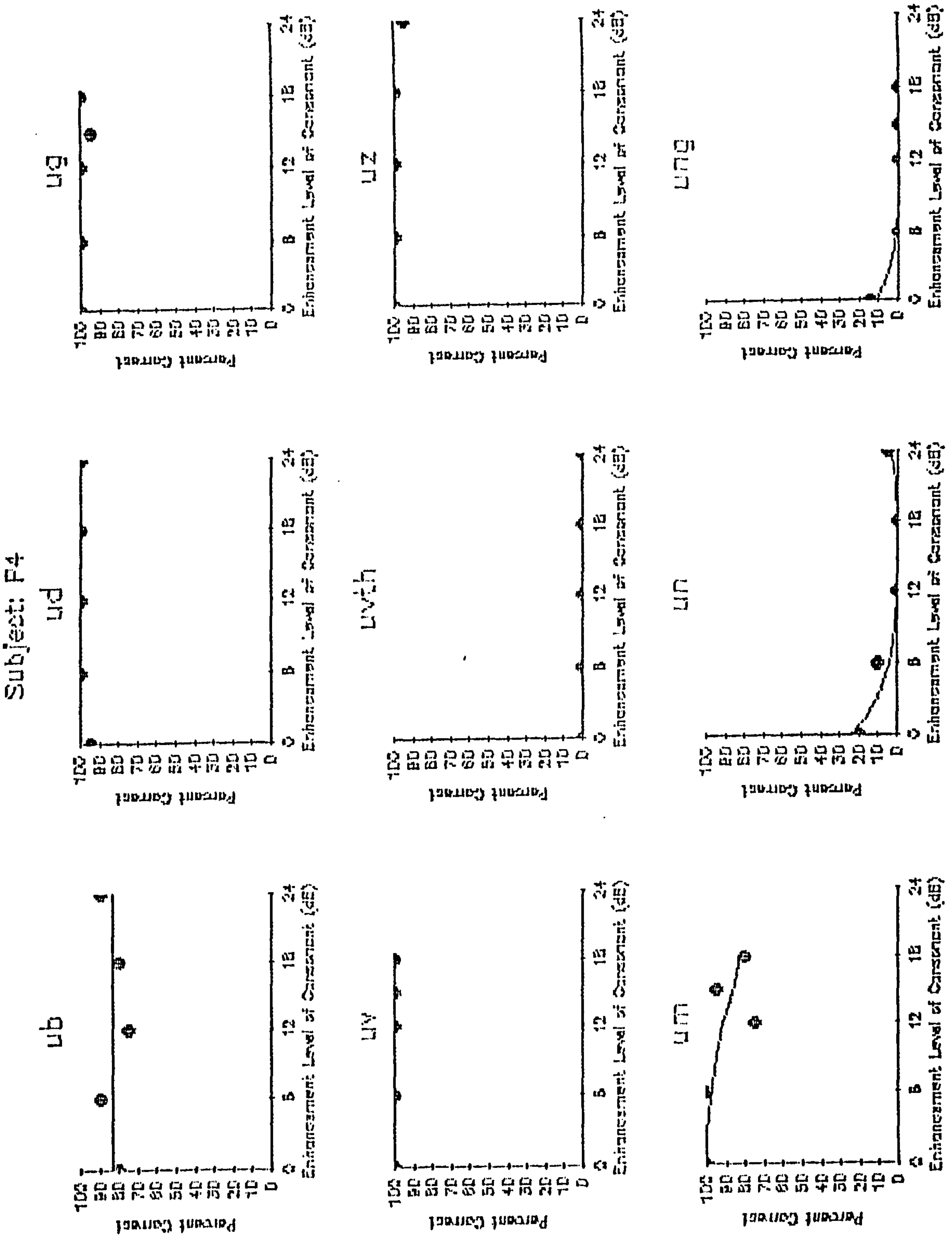

Figure 117. CE functions of the voiced consonants with /u/ for subject P4.

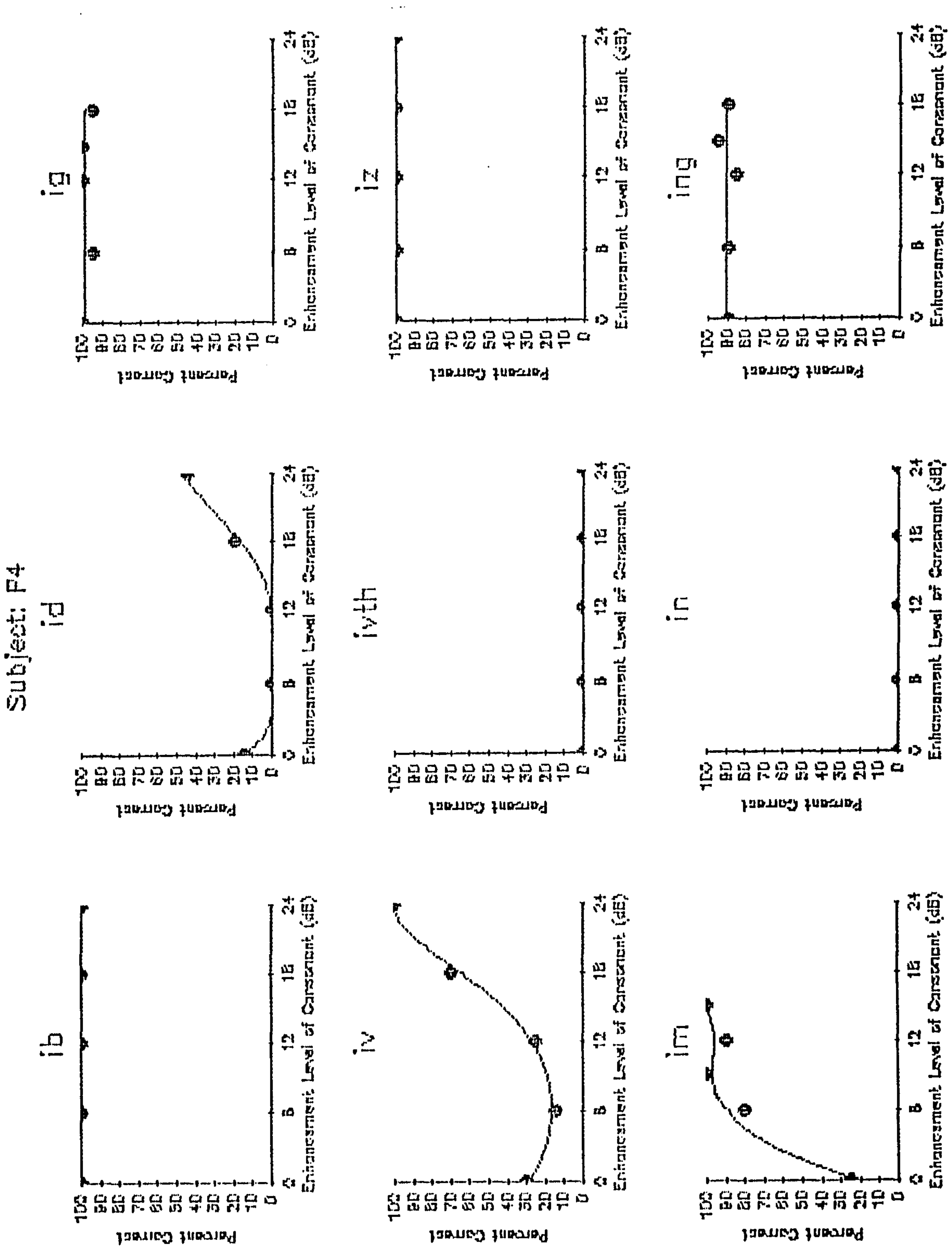

Figure 118. CE functions of the voiced consonants with /i/ for subject P4.

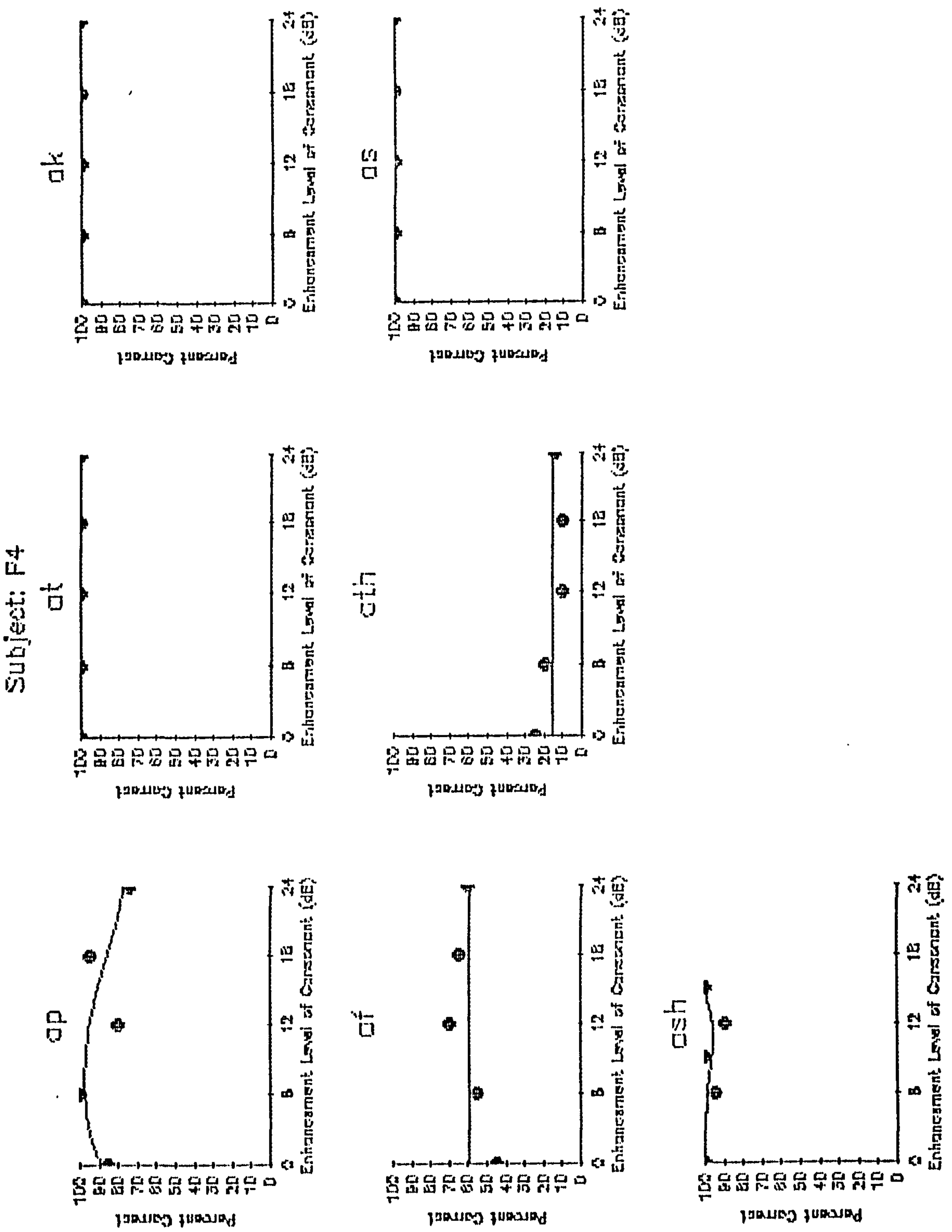

Figure 119. CE functions of the voiceless consonants with /a/ for subject P4.

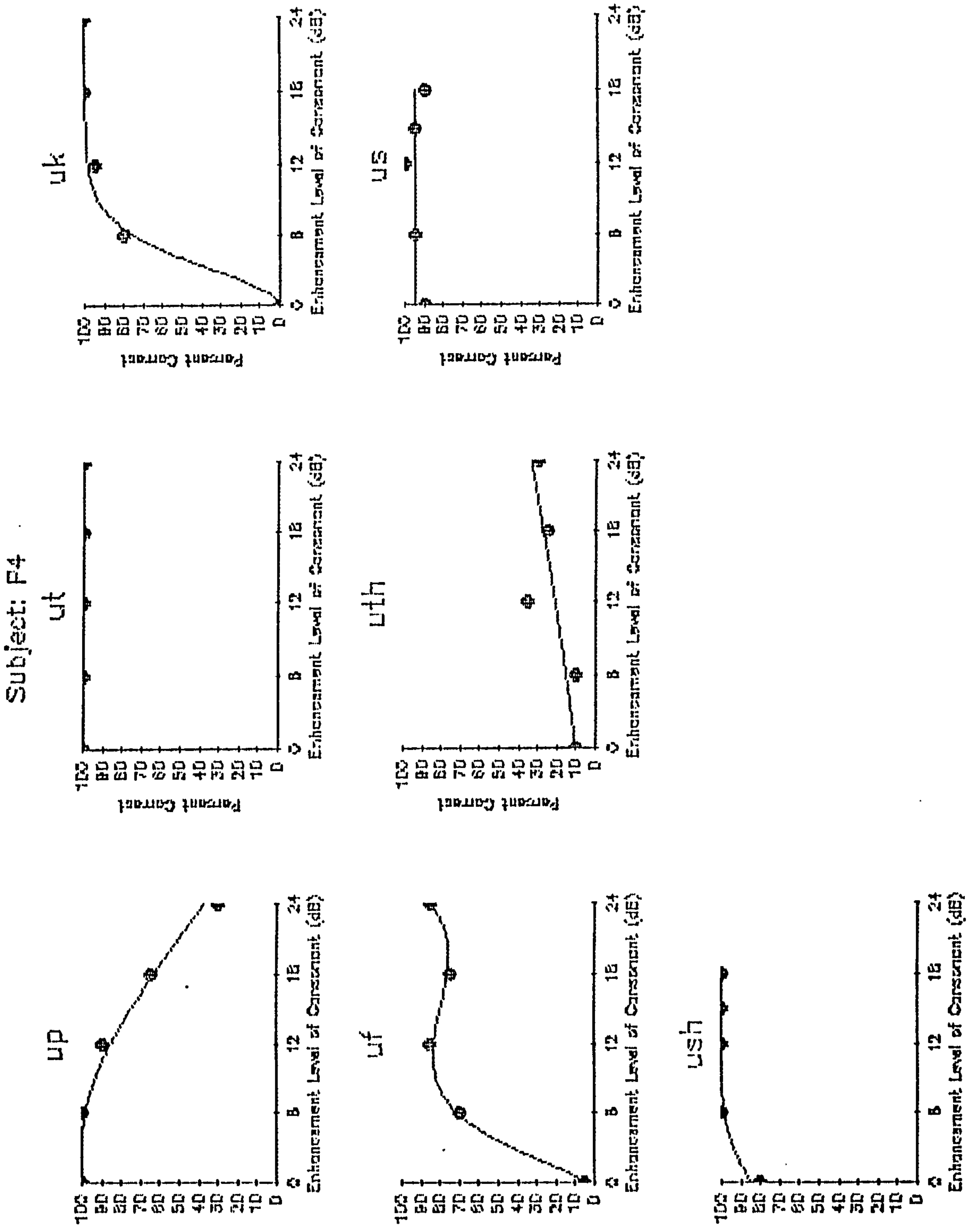

Figure 120. CE functions of the voiceless consonants with /u/ for subject P4.

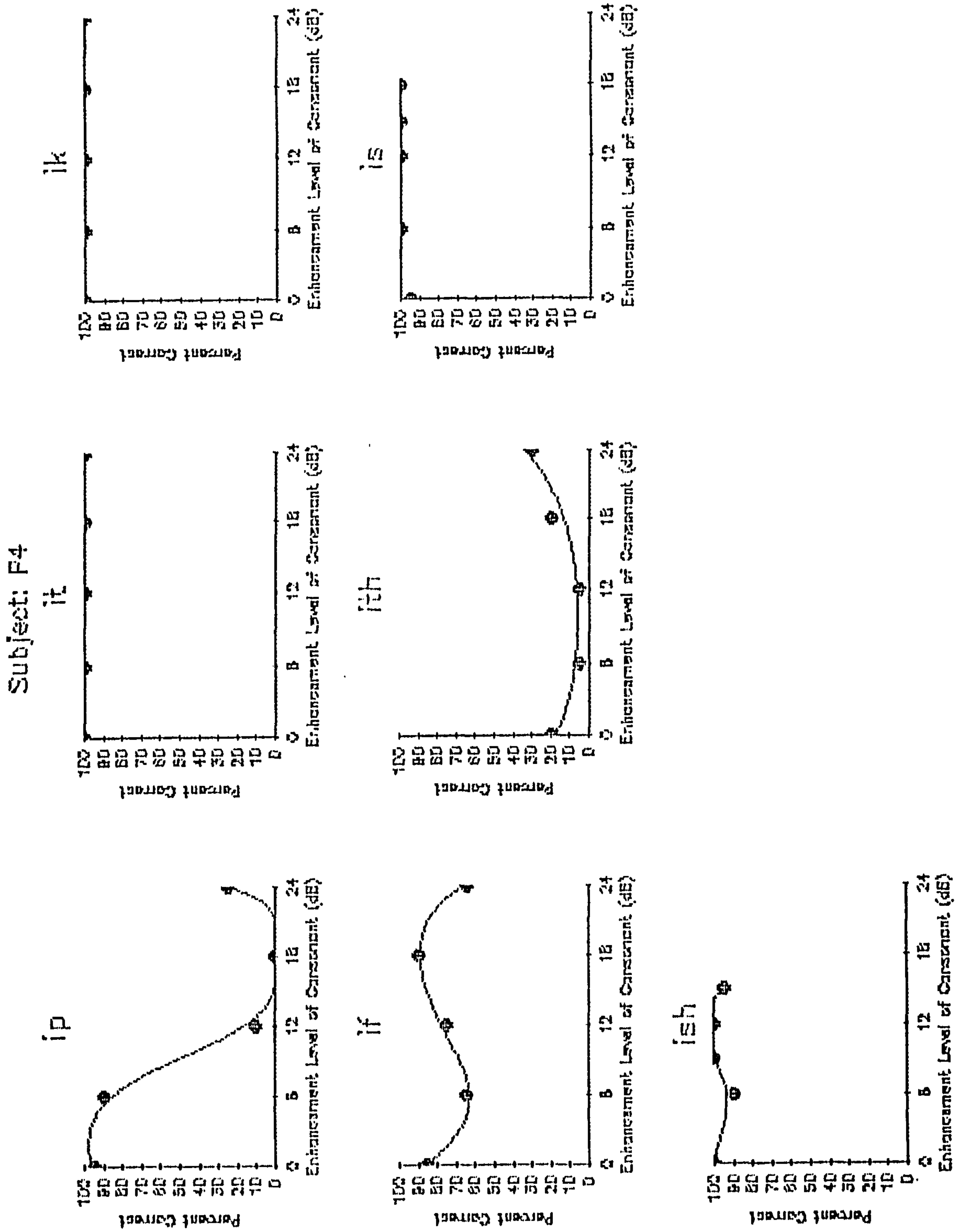

Figure 121. CE functions of the voiceless consonants with /i/ for subject P4.

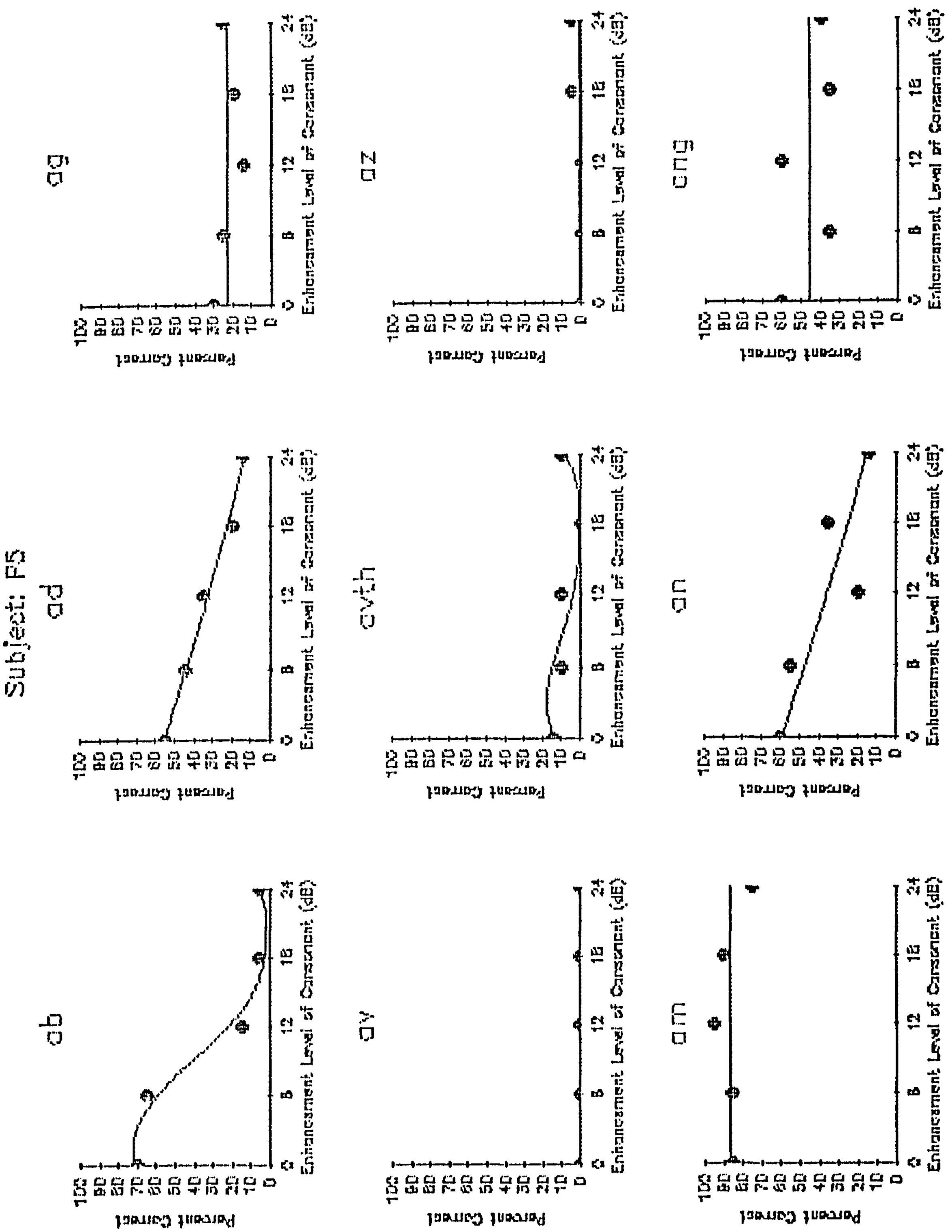

Figure 122. CE functions of the voiced consonants with /a/ for subject P5.

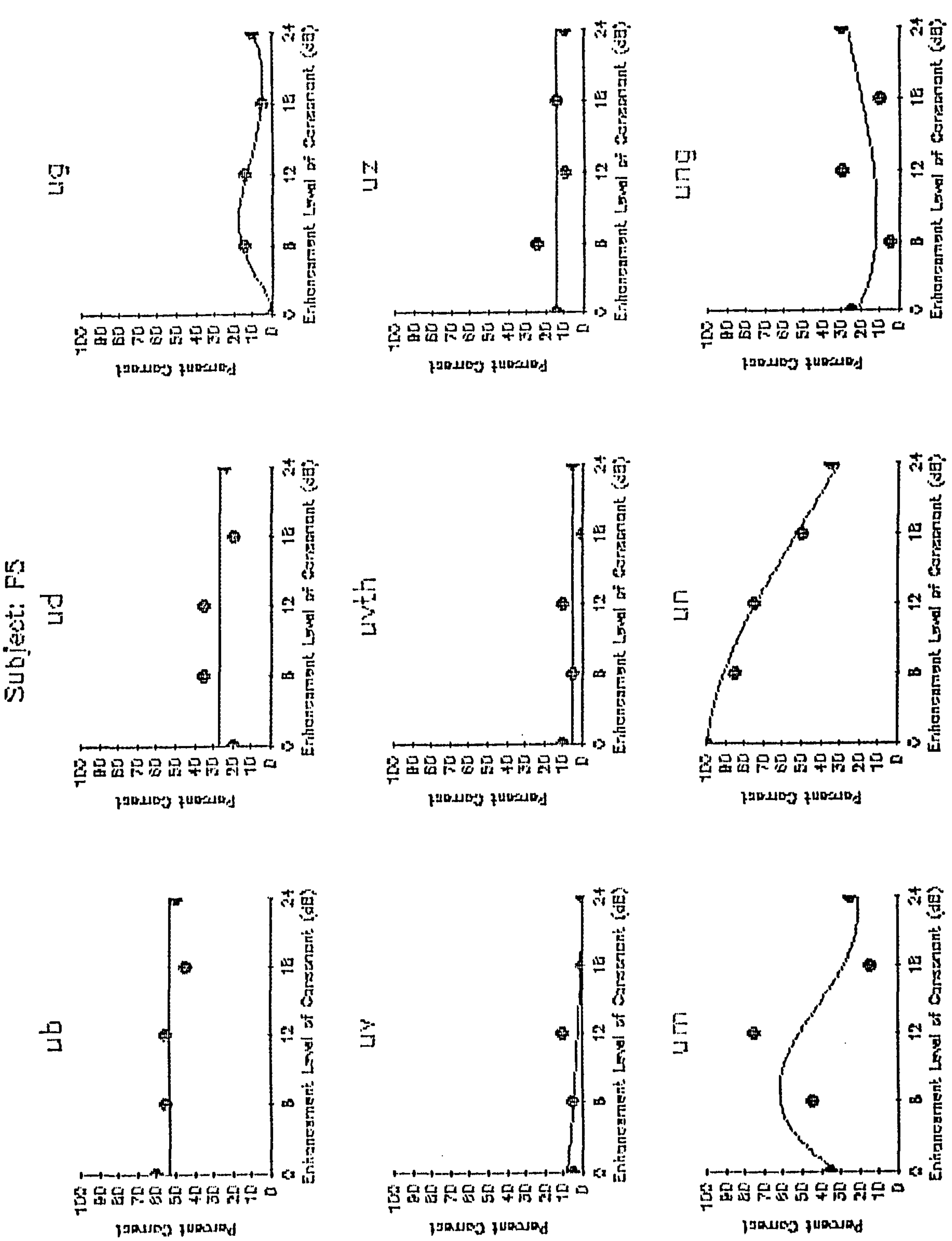

Figure 123. CE functions of the voiced consonants with /u/ for subject P5.

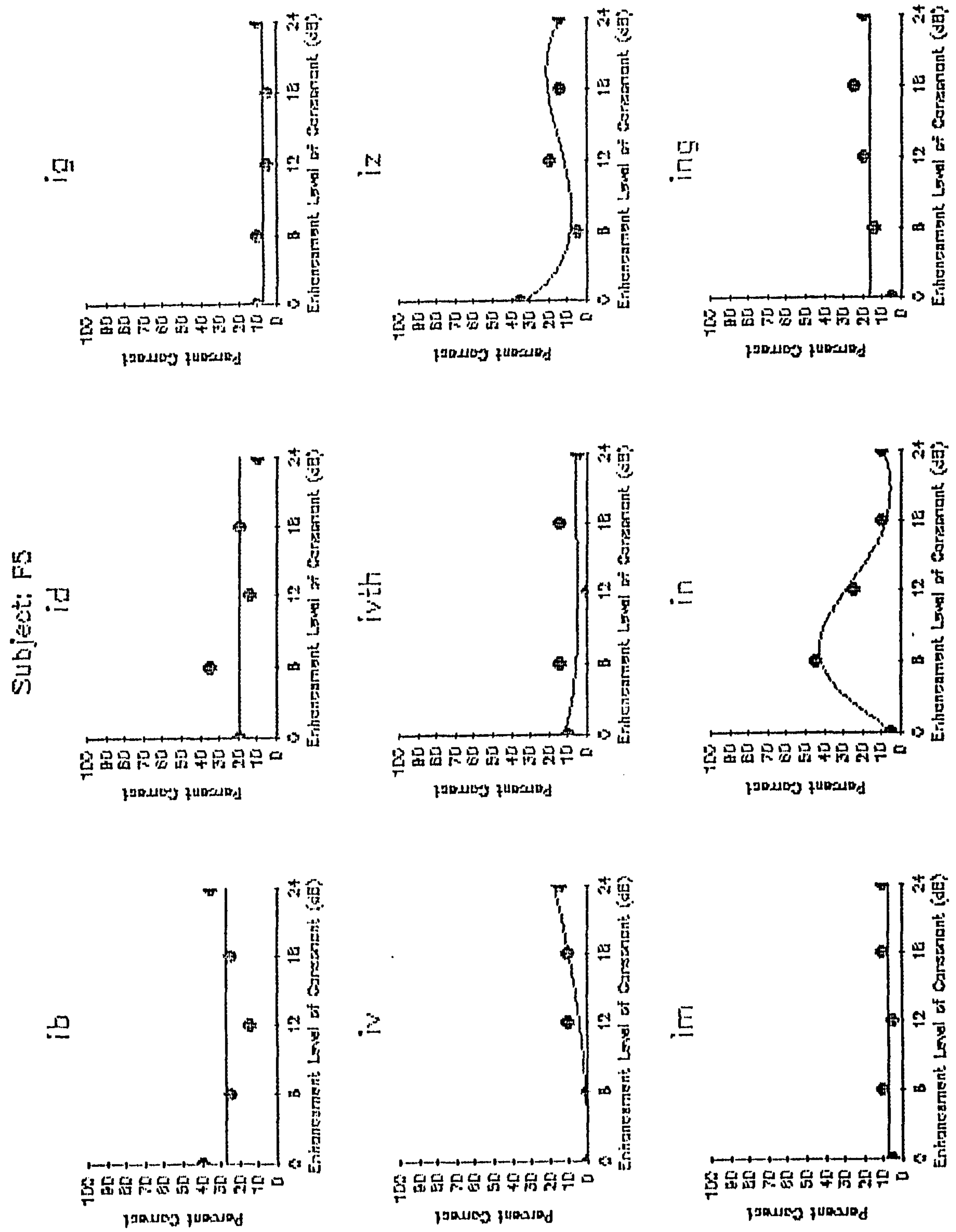

Figure 124. CE functions of the voiced consonants with /i/ for subject P5.

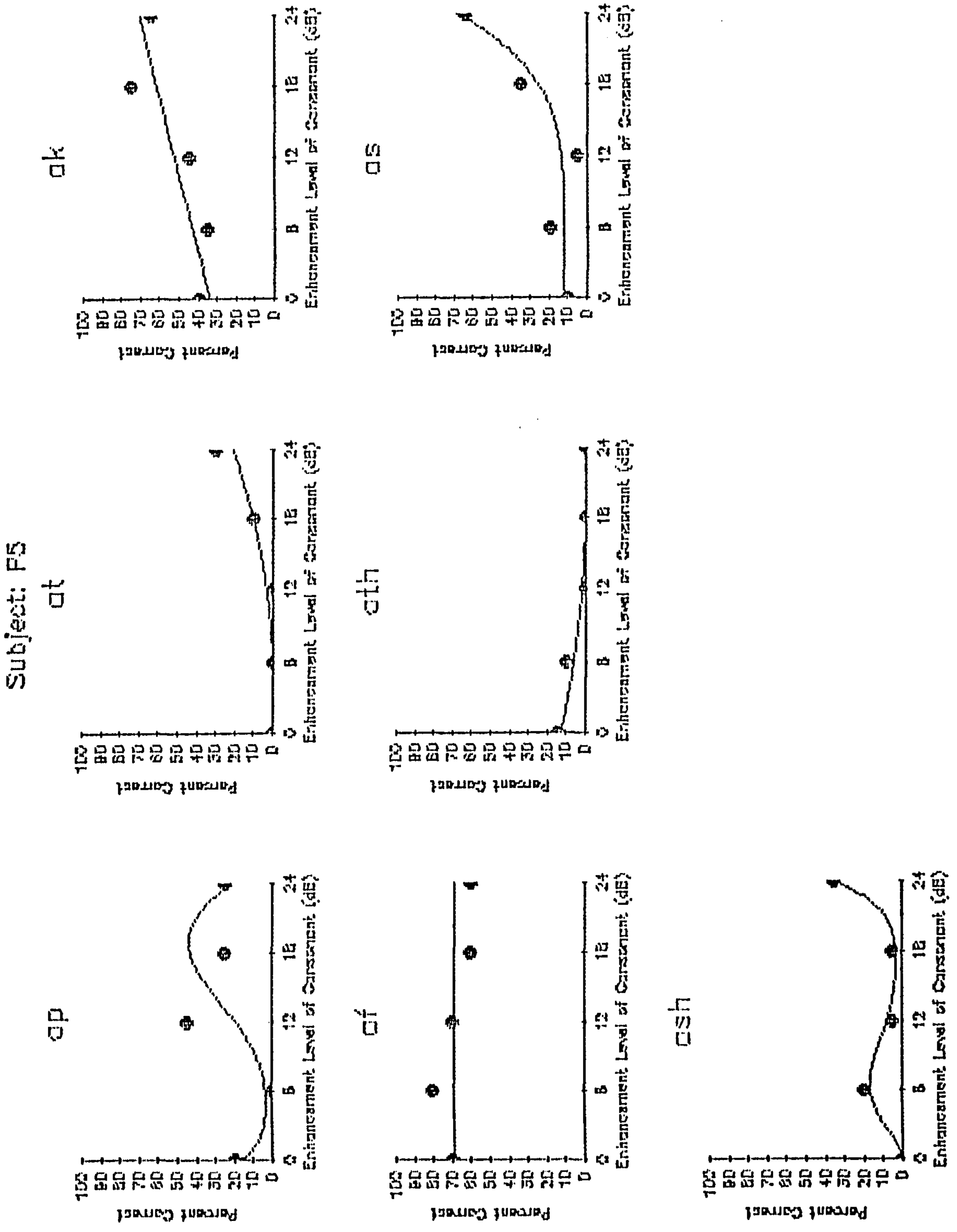

Figure 125. CE functions of the voiceless consonants with /a/ for subject P5.

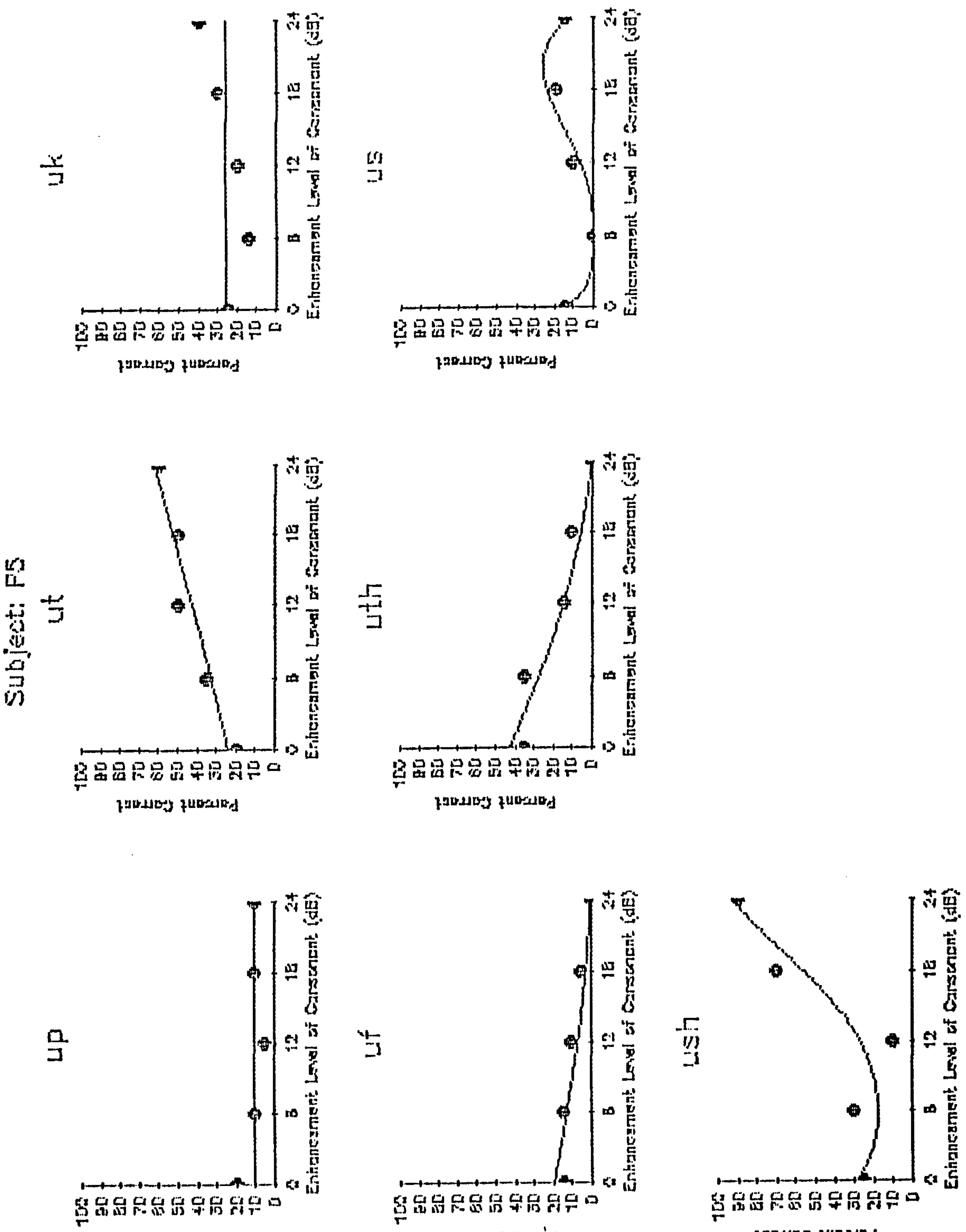

Figure 126. CE functions of the voiceless consonants with /u/ for subject P5.

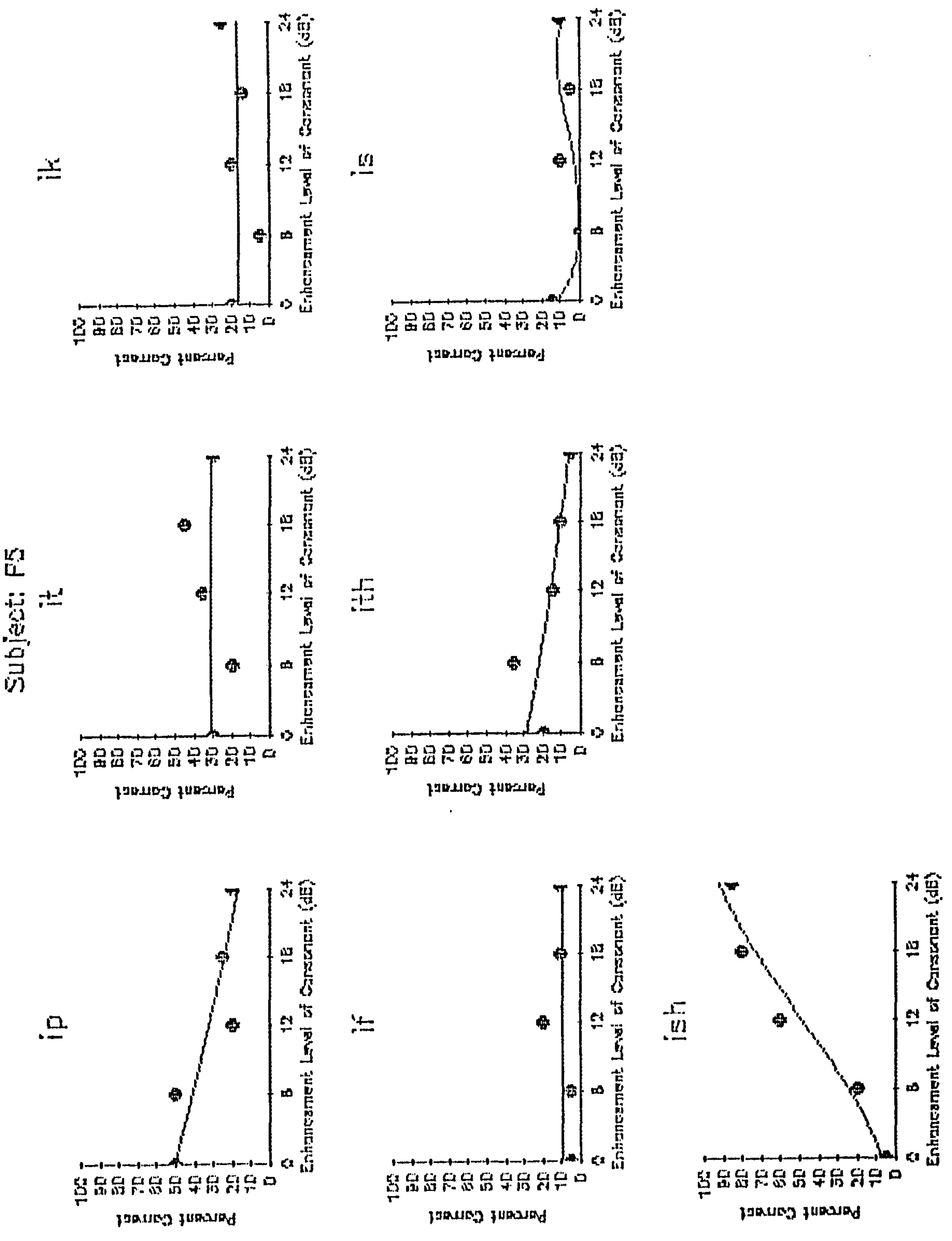

Figure 127. CE functions of the voiceless consonants with /i/ for subject P5.

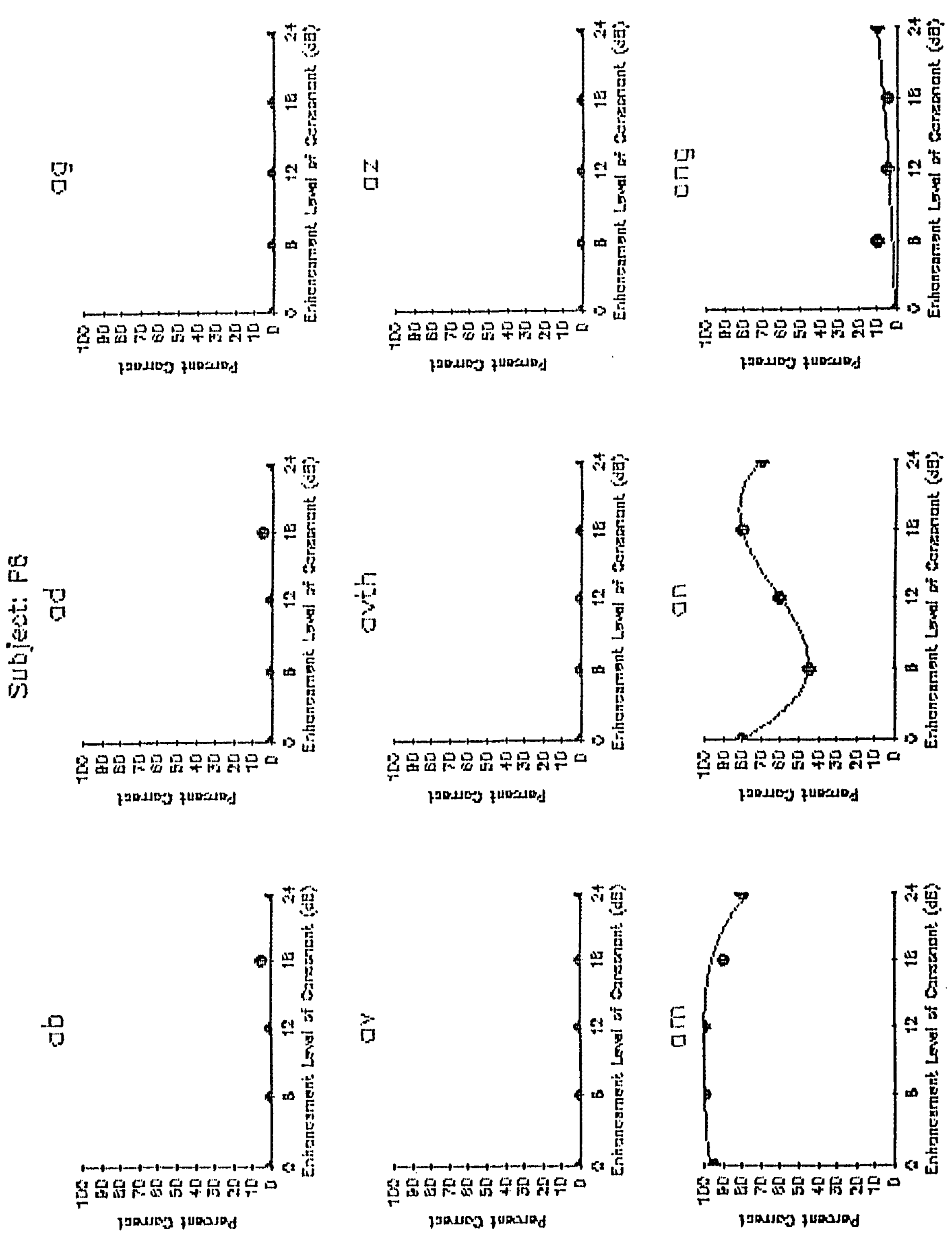

Figure 128. CE functions of the voiced consonants with /a/ for subject P6.

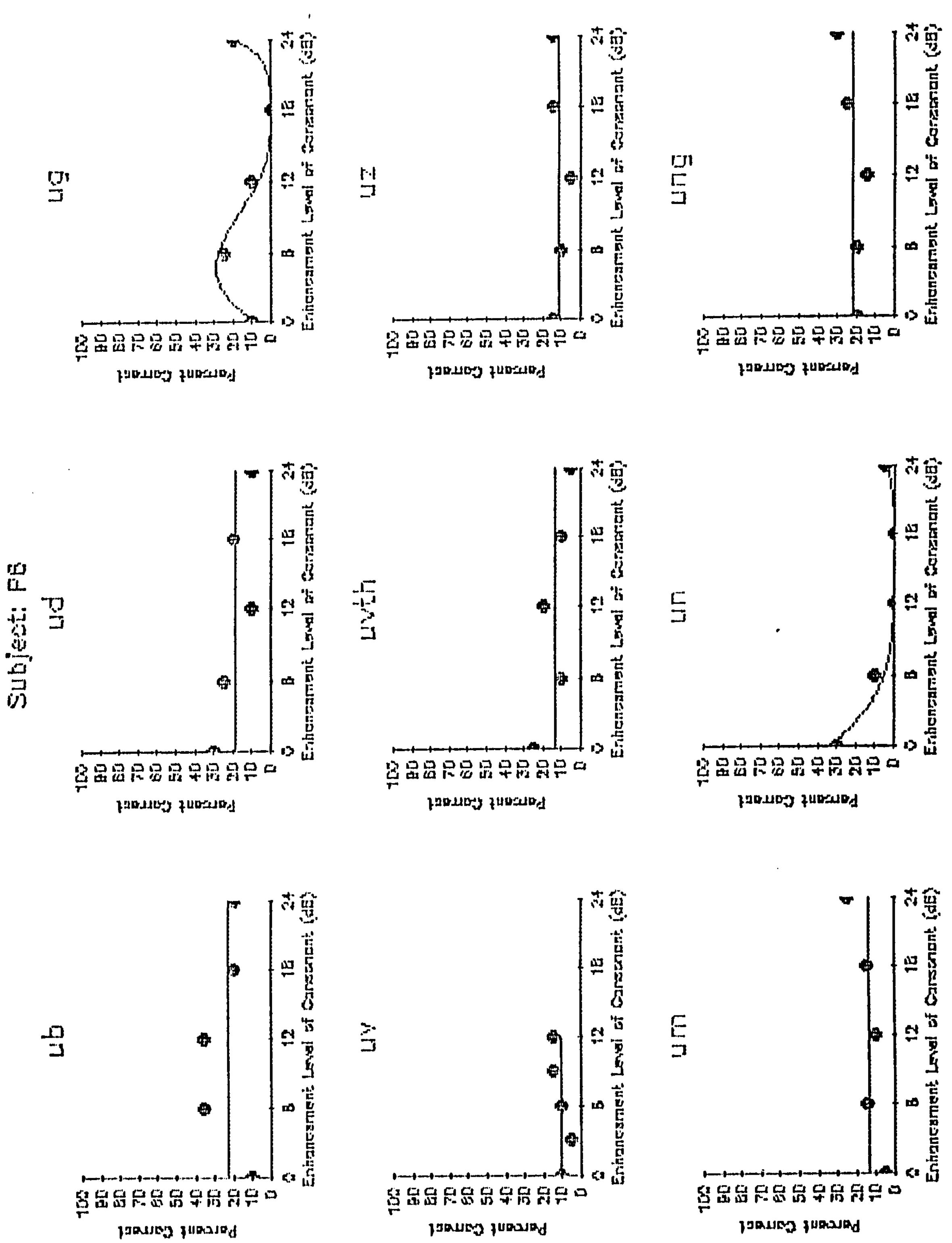

Figure 129. CE functions of the voiced consonants with /u/ for subject P6.

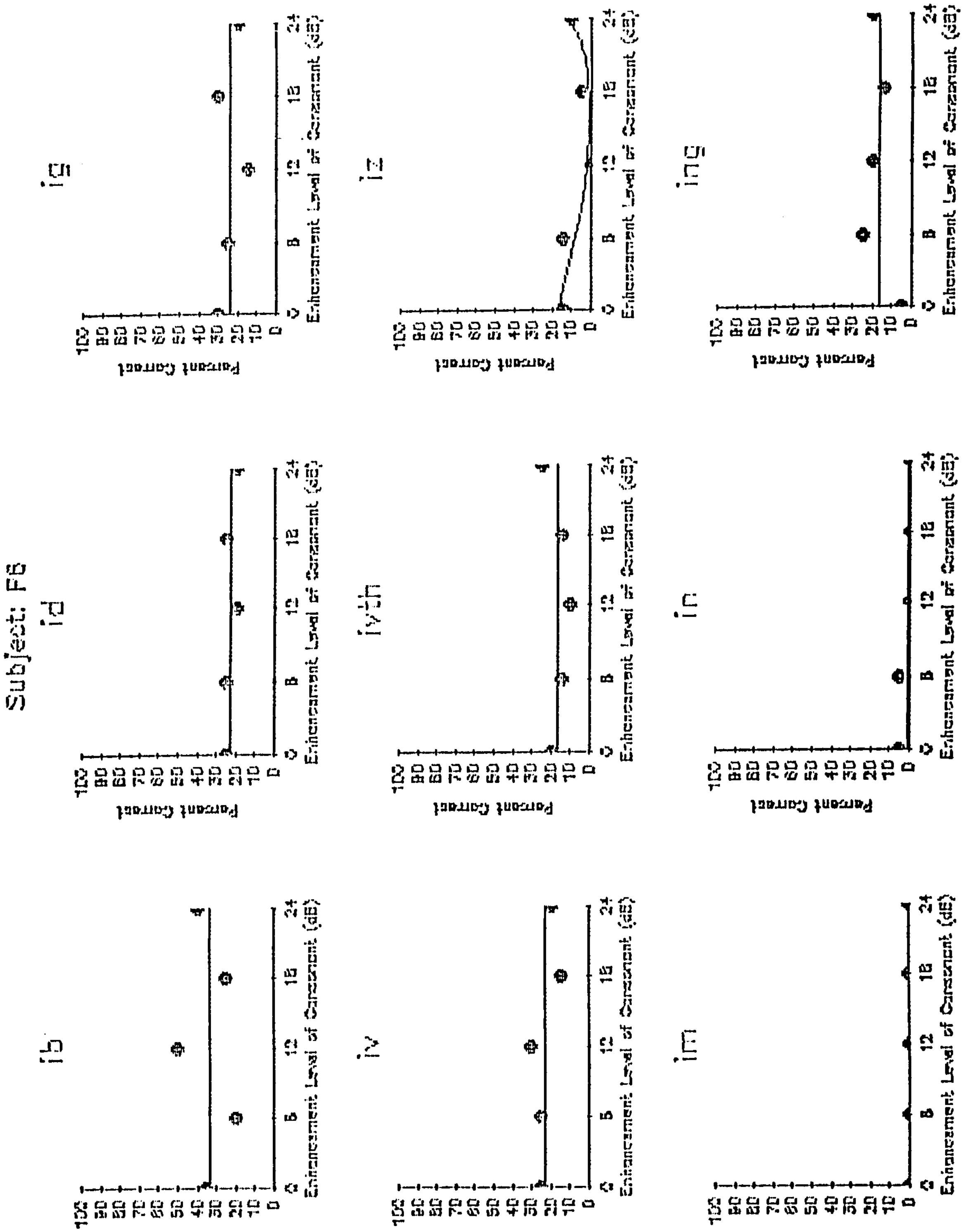

Figure 150. CE functions of the voiced consonants with /i/ for subject P6.

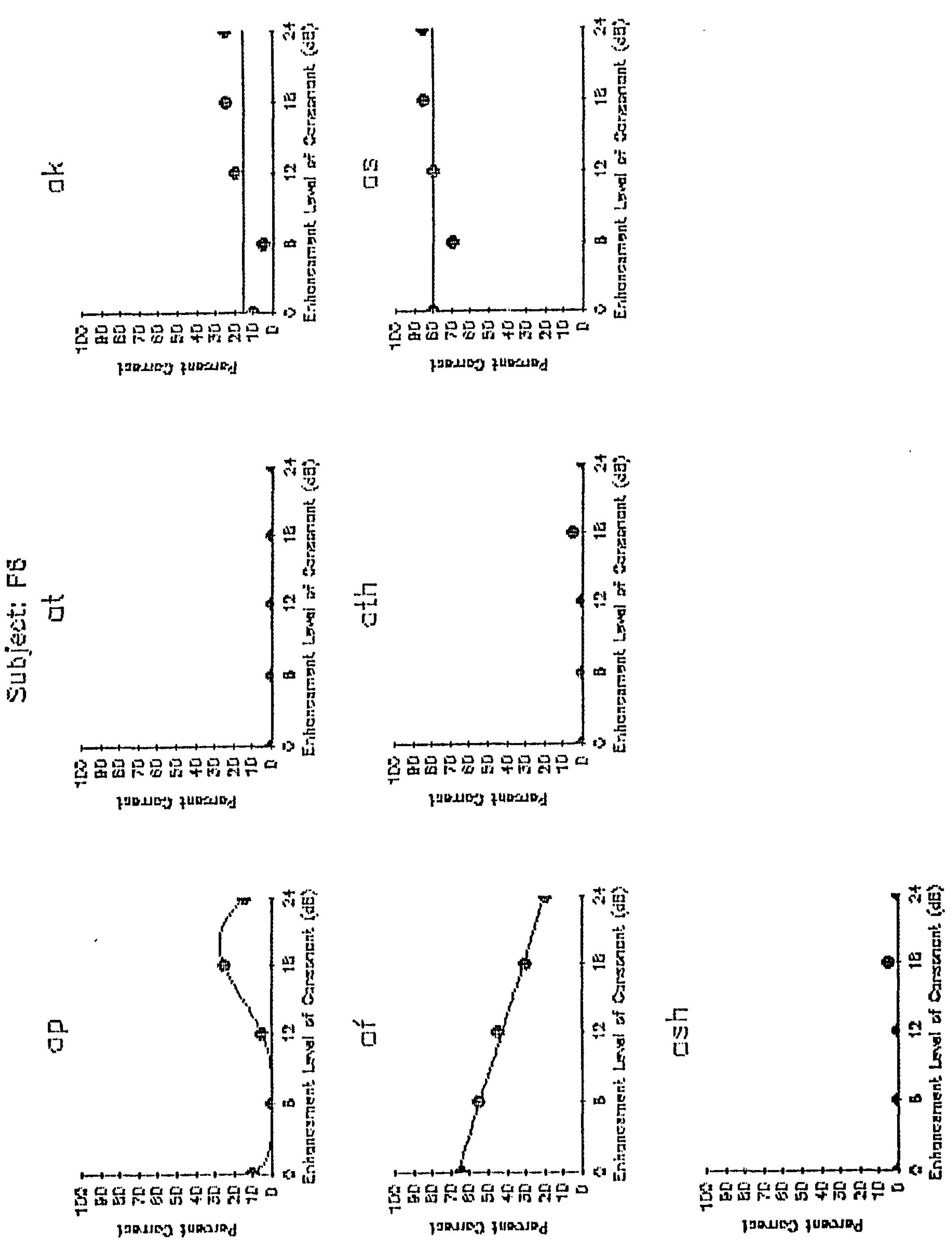

Figure 131. CE functions of the voiceless consonants with /a/ for subject P6.

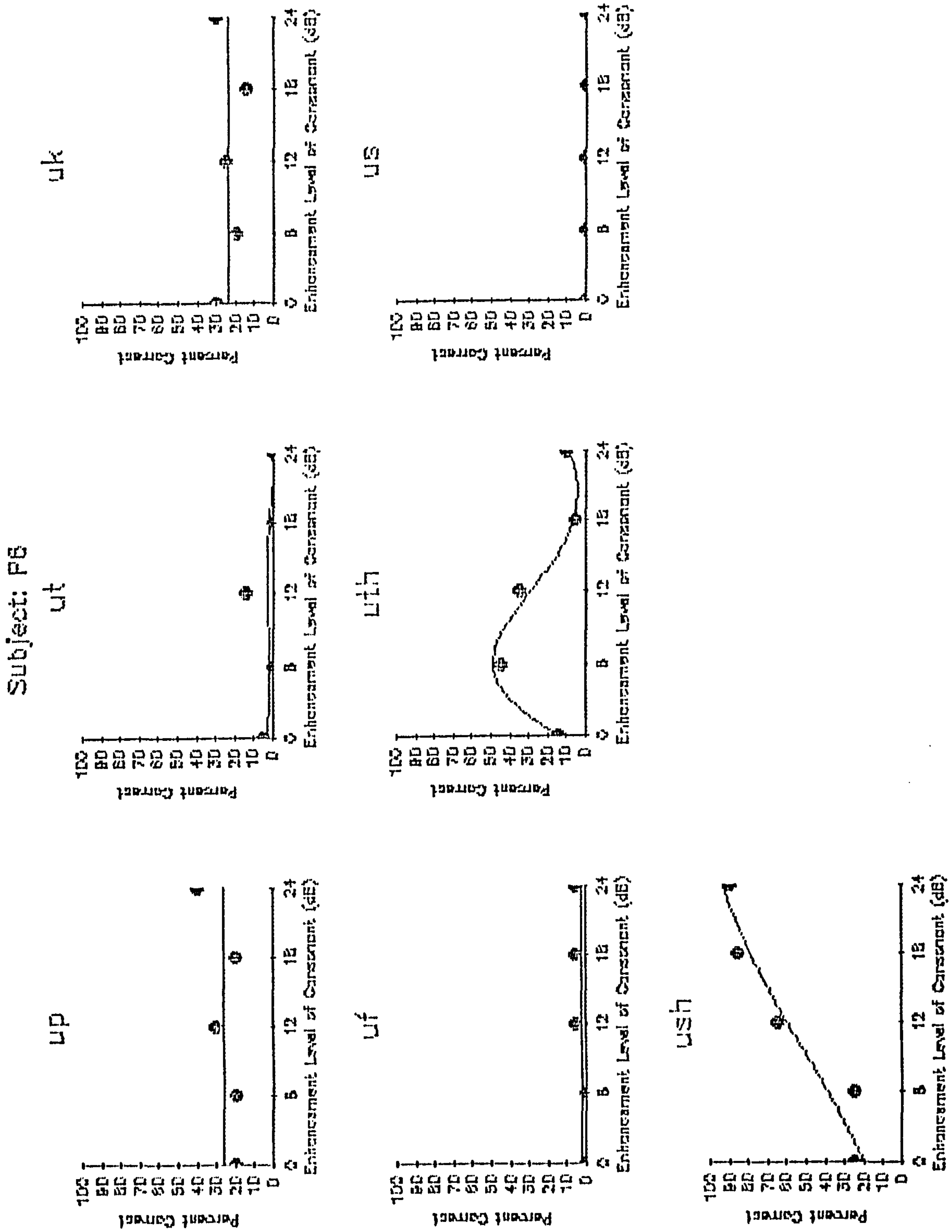

Figure 132. CE functions of the voiceless consonants with /u/ for subject P6.

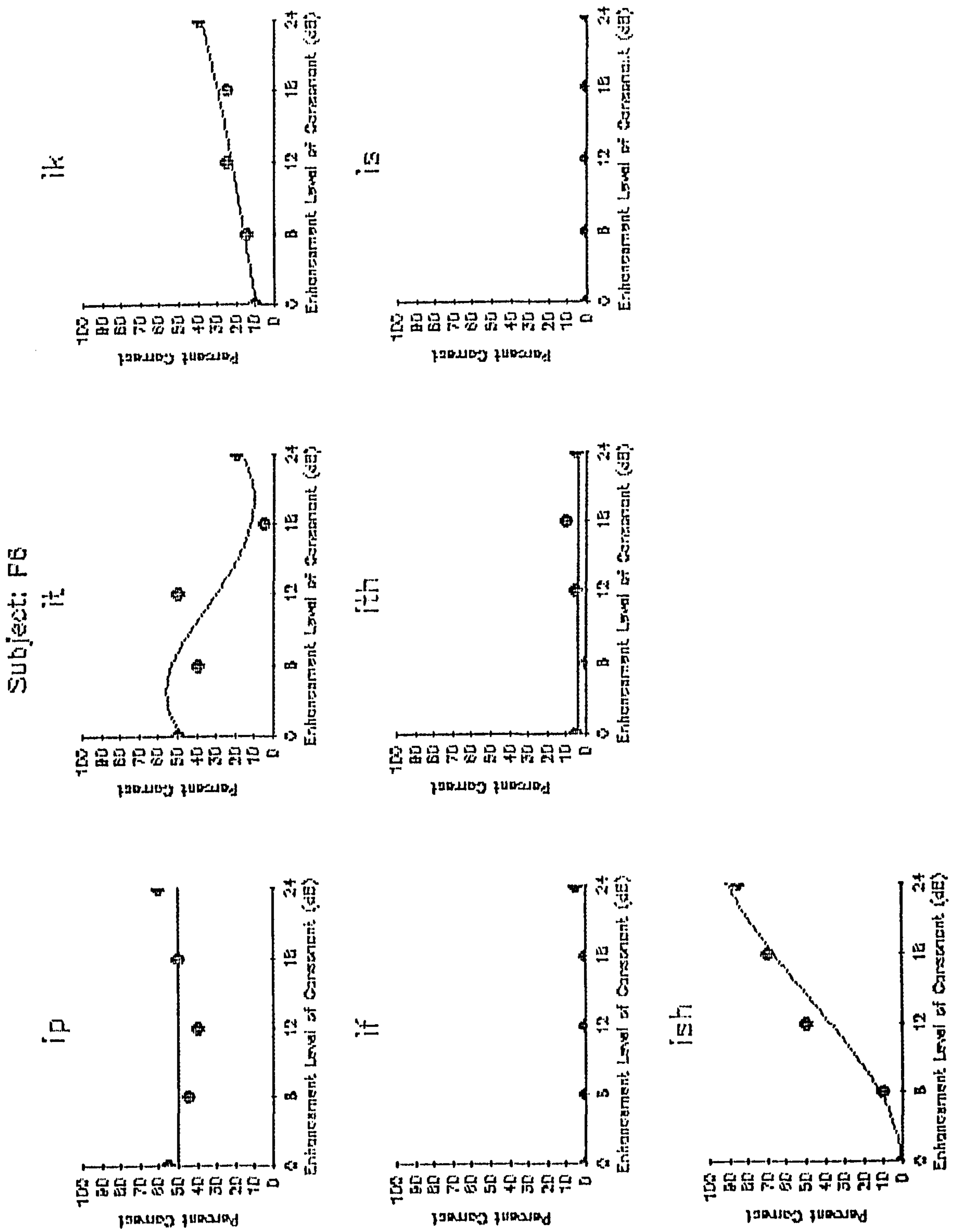

Figure 133. CE functions of the voiceless consonants with /i/ for subject P6.

APPENDIX F

CE_{MAX}
FOR EACH VC
FOR EACH SUBJECT

Table 23: Maximum increase in C-V ratio used for each VC in the voiced set with each subject in the flat audiometric configuration.

SUBJECT	MAXIMUM INCREASE IN C/V RATIO	VC
F1	24 dB	ab, ad, avth, az, am, an, ang, ib, id, ig, ivth, iz, in, ub, ud, ug, uvth, uz, um, un, ung
	21	ag, av, im, iv
	18	uv, ing
F2	24	ab, ad, ag, avth, az, am, an, ang, ib, id, ig,iv, ivth, iz, im, in, ing, ub, ud, ug, uvth, uz, un, ung
	21	av
	15	uv
	12	um
F3	21	uz, uvth, ud
	18	an, ang, ab, ag, av, ing, ig
	15	un, ub, uv, ivth, id
	12	am, ung, um, ug, iz, in, im, ib,iv
	9	az, ad
	6	avth
F4	24	ab, av, ang, az,an, ib, id, ig, iv, ivth, im, in, ing,ung, ub, ud, ug, uv, uvth, uz, um, un
	21	ad
	18	avth, am, ag, iz
F5	24	ab, az,an, avth,ib, id, iz, in, ivth, ub, ud, uz,un, uvth,
	21	ang, ad, ing, im, ig, iv
	15	ag, ung, um
	12	av, ug
	9	am
	6	uv
F6	24	ab, ad, ag, av, avth, az, am, an, ang, ib, id, ig, iv, ivth, iz, im, in, ing, ub, ud, ug, uv, uvth, uz, um, un, ung,

Table 24: Maximum increase in C-V ratio used for each VC in the voiceless set with each subject in the flat audiometric configuration.

SUBJECT	MAXIMUM INCREASE IN C/V RATIO	VC
F1	24 dB	ap, at, ak, af, ath, as, ash, up, ut, uk, uf, uth, us, ush, ip, it, ik, if, ith,
	21	is, ish
F2	24	ap, at, ak, af, ath, as, up, ut, uk, uf, uth, us, ush, ip, it, ik, if, ith, is, ish
	12	ash
F3	21	uf, ut
	18	ap, as, ath, uk, is
	15	up, uth, it, ik
	12	ash, us, ush, if, ip, ish, ith
	9	af, ak
	6	at
F4	24	ap, af, ath, as, up, ut, uk, uf,uth, us, ush, ip, ik, if, ith, is, ish,
	21	ak
	18	at, ash, it
F5	24	ap, at, ak, af, ath, up, ut, uk, uf, uth, ip, it, ik, if, ith,
	21	as, is, ish
	15	us, ush
	9	ash
F6	24	ap, at, ak, af, ath, as, ash ,up, ut, uk, uf, uth, us, ush, ip, it, ik, if, ith, is, ish

Table 25: Maximum increase in C-V ratio used for each VC in the voiced set with each subject in the sloping audiometric configuration.

SUBJECT	MAXIMUM INCREASE IN C/V RATIO	VC
S1	24	ad, avth, id, ub, ud, uz, uvth,
	21	ab,un,iz,in, ivth, ib, iv
	18	an, ang, am, um, ig
	15	az, ing, im
	12	ag, av, ung, uv
	9	ug
S2	24	ab, ad, ag, av, avth, az, am, an, ang, ib, id, ig, iv, ivth, iz, im, in, ing, ub, ud, ug, uv, uvth, uz, um, un, ung
S3	24	ab, ad, avth, az, an, ib, iz, in, ivth, ub, ud, ug, uz, un, uvth
	21	id, ig, iv
	15	ang, um, ing, im
	12	ag, ung, ug, uv
	9	am
	6	av
S4	24	ab, ad, avth, az, am, an, ang, ib, id, ivth, iz, im, in, ing, ub, ud, uvth, uz, um, un, ung,
	15	ag, av, ug
	12	uv
	9	ig, iv
S5	24	ab, ad, avth, az, an, ang, ib, id, iv, iz, in, ivth, ub, ud, uv, uz, un,
	18	am, um, ug, im, ig
	15	ung, ing
	12	ag, av
S6	24	ab, ad, avth, az,an, ib, id, iv, iz, in, ivth, ub, ud, uv, uvth, un, uz
	18	ang, am, um, ug, im, ig
	15	ung, ing
	12	ag, av

Table 26: Maximum increase in C-V ratio used for each VC in the voiceless set with each subject in the sloping audiometric configuration.

SUBJECT	MAXIMUM INCREASE IN C/V RATIO	VC
S1	24	ath, ak, ath, ut, uk, uf, uth, ik, ith,
	21	ash, up, if, ip, it, ish
	18	ap, as,
	15	af, is, ish
	12	us, ush
S2	24	ap, at, ak, af, ath, as, ash ,up, uk, uf, uth, us, ush,ut, ip, it, ik, if, ith, is, ish
S3	24	ap, at, ak, af, ath, up, ut, uk, uf, ush, ip, it, if, ith,
	21	ik
	15	as, ush, is, ish
	12	us
	9	ash
S4	24	ap, at, ak, af, ath, as, ash,up, ut,uk, uf, uth, us, ush, ip, it, ik, if, ith, is, ish
S5	24	ap, at, ak, af, ath, up, ut, uk, uf, uth, ip, it, ik, if, ith
	21	as
	18	ash, ush, ish
	15	us, is
S6	24	ap, at, ak, af, ath, as, ash,up, ut,uk, uf, uth, ush, ip, it, ik, if, ith, is, ish
	15	us

Table 27: Maximum increase in C-V ratio used for each VC in the voiced set with each subject in the precipitous audiometric configuration.

SUBJECT	MAXIMUM INCREASE IN C/V RATIO	VC
P1	24	ab, ad, az, an, in, ud, ug, uz
	21	avth, un, id, ib, iv
	18	uvth, iz, ivth, im, ig
	15	ag, av, um, ub, uv
	12	am, ung, ing
	9	ang
P2	24	ab, ad, avth, az, an, ang, ib, id, iv, ivth, iz, in, ub, ud, uz, un, ung
	21	uvth, im, ig
	18	ag, um, ug, ing
	15	av, uv
	12	am
P3	24	ad, av, avth, az, am, an, ang, id, iz, ub, ud, uvth, uz, un, ung,
	21	ivth
	18	in, um, ing
	15	ag, ug, im
	12	ab, ib, iv
	9	uv, ig
P4	24	ab, ad, avth, az, an, ang, ib, id, iv, ivth, iz, in, ub, ud, uvth, uz, un
	18	ung, um, ug, uv, ing, ig
	15	am, im
	12	ag, av
P5	24	ab, ad, ag, av, avth, az, am, an, ang, ib, id, ig, iv, ivth, iz, im, in, ing, ub, ud, ug, uv, uvth, uz, um, un, ung
P6	24	ab, ad, ag, av, avth, az, am, an, ang, ib, id, ig, iv, ivth,iz, im, in, ing, ub, ud, ug, uvth, uz, um, un, ung
	12	uv

Table 28: Maximum increase in C-V ratio used for each VC in the voiceless set with each subject in the precipitous audiometric configuration.

SUBJECT	MAXIMUM INCREASE IN C/V RATIO	VC
P1	24	ap, ak, af, ath, as, uk, uf, ip
	21	at, up, ut, ik, ith
	18	if, it, ish
	15	ush, uth
	12	ash, us, is
	9	as
P2	24	ap, at, ak, af, ath, up, ut, uk, uf, uth, ip, it, ik, if, ith
	21	ish
	18	as, us, is
	12	ash, ush
P3	24	ap, at, ak, af, ath, as, ash,up, uk, uf, uth, us, ik,if, ut,
	21	it
	18	ip, is, ush
	15	ish
	12	ith
P4	24	ap, at, ak, af, ath, as, up, ut, uk, uf, uth, ip, it, ik, if, is,
	18	us, ush, ith
	15	ash, ish
P5	24	ap, at, ak, af, ath, as, ash, up, uk, uf, uth, us, ush, ut, ip, it, ik, if, ith, is, ish
P6	24	ap, at, ak, af, ath, as, ash, up, uk, uf, uth, us, ush, ut, ip, it, ik, if, ith, is, ish

APPENDIX G

CONFUSION MATRICES

TABLE 29: Confusion matrix for control subjects with unenhanced voiced consonants in the /a/ vowel environment. Note that for this matrix, rows total to 100 representing 5 subjects.

	n	m	ng	z	d	b	v	g	vth
n	100	0	0	0	0	0	0	0	0
m	0	96	4	0	0	0	0	0	0
ng	0	0	99	0	0	0	0	1	0
z	0	0	0	99	0	0	1	0	0
d	0	0	0	0	100	0	0	0	0
b	0	0	0	0	0	99	0	1	0
v	0	0	0	1	0	12	86	1	0
g	0	0	0	0	0	0	0	100	0
vth	0	0	0	0	3	0	7	2	88

TABLE 30: Confusion matrix for control subjects with unenhanced voiced consonants in the /u/ vowel environment. Note that for this matrix, rows total to 100 representing 5 subjects.

	n	m	ng	z	d	b	v	g	vth
n	97	0	0	0	0	0	0	0	3
m	0	100	0	0	0	0	0	0	0
ng	18	11	70	0	0	0	0	1	0
z	0	0	0	100	0	0	0	0	0
d	0	0	0	0	98	0	1	0	1
b	0	2	0	0	0	86	4	5	3
v	0	2	0	0	0	1	95	0	2
g	0	1	0	0	0	2	2	94	1
vth	0	1	0	0	1	0	3	0	95

TABLE 31: Confusion matrix for control subjects with unenhanced voiced consonants in the /i/ vowel environment. Note that for this matrix, rows total to 100 representing 5 subjects.

	n	m	ng	z	d	b	v	g	vth
n	80	9	9	0	0	0	1	1	0
m	0	100	0	0	0	0	0	0	0
ng	3	1	96	0	0	0	0	0	0
z	0	0	0	100	0	0	0	0	0
d	0	0	0	0	94	4	1	0	1
b	0	1	0	0	2	96	0	1	0
v	0	0	0	0	1	2	87	0	10
g	0	0	0	0	5	4	5	78	8
vth	0	0	0	0	1	4	22	0	73

TABLE 32: Confusion matrix for control subjects with unenhanced voiceless consonants in the /a/ vowel environment. Rows total to 120, representing 6 subjects.

	s	sh	t	p	k	th	f
s	120	0	0	0	0	0	0
sh	1	119	0	0	0	0	0
t	0	0	120	0	0	0	0
p	0	0	0	120	0	0	0
k	0	0	0	0	120	0	0
th	0	0	0	0	0	66	54
f	0	0	0	7	0	7	106

TABLE 33: Confusion matrix for control subjects with unenhanced voiceless consonants in the /u/ vowel environment. Rows total to 120, representing 6 subjects.

	s	sh	t	p	k	th	f
s	119	1	0	0	0	0	0
sh	0	120	0	0	0	0	0
t	0	0	120	0	0	0	0
p	0	0	0	119	0	1	0
k	0	0	1	0	119	0	0
th	0	0	0	3	1	110	6
f	1	0	3	1	0	5	110

TABLE 34: Confusion matrix for control subjects with unenhanced voiceless consonants in the /i/ vowel environment. Rows total to 120, representing 6 subjects.

	s	sh	t	p	k	th	f
s	120	0	0	0	0	0	0
sh	1	118	0	0	0	1	0
t	0	0	120	0	0	0	0
p	0	0	0	120	0	0	0
k	0	0	0	0	120	0	0
th	0	0	1	12	1	100	6
f	0	0	0	4	1	69	46

TABLE 35: Confusion matrix for unenhanced voiced consonants in the /a/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	97	0	19	0	2	0	1	1	0
m	49	57	3	0	4	3	0	4	0
ng	12	0	92	0	0	0	0	16	0
z	0	0	0	103	3	0	0	14	0
d	0	0	0	0	98	7	2	12	1
b	0	1	0	1	19	81	10	8	0
v	0	0	0	1	12	9	79	17	2
g	1	1	0	0	17	4	8	88	1
vth	5	0	0	1	37	3	31	24	19

TABLE 36: Confusion matrix for unenhanced voiced consonants in the /u/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	13	22	8	0	40	6	5	4	22
m	2	74	9	0	1	0	5	12	17
ng	5	48	43	0	0	0	2	5	17
z	0	0	0	103	2	1	2	0	12
d	0	0	0	0	61	17	14	2	26
b	1	2	0	0	4	55	32	11	15
v	0	3	0	4	0	13	71	13	16
g	1	1	0	0	1	18	8	81	10
vth	0	4	0	1	11	5	55	1	43

TABLE 37: Confusion matrix for unenhanced voiced consonants in the /i/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	23	52	24	0	1	10	7	3	0
m	3	89	4	0	3	18	2	1	0
ng	2	6	106	0	0	0	1	5	0
z	0	0	1	102	1	1	12	1	2
d	0	2	1	0	62	47	5	3	0
b	0	2	0	0	2	102	9	4	1
v	0	4	4	2	8	13	61	12	16
g	0	1	1	0	11	14	19	70	4
vth	0	1	0	1	7	50	40	1	20

TABLE 38: Confusion matrix for unenhanced voiceless consonants in the /a/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	112	2	4	0	0	1	1
sh	0	94	0	0	0	0	26
t	2	1	92	14	8	2	1
p	0	0	34	81	0	4	1
k	0	0	3	27	89	0	1
th	1	1	7	21	4	8	78
f	1	0	7	31	4	9	68

TABLE 39: Confusion matrix for unenhanced voiceless consonants in the /u/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	76	15	7	0	0	11	11
sh	5	58	1	0	0	16	40
t	0	0	80	7	2	23	8
p	0	0	8	75	3	14	20
k	0	0	1	40	65	10	4
th	0	0	16	6	2	30	66
f	0	0	11	34	13	9	53

TABLE 40: Confusion matrix for unenhanced voiceless consonants in the /i/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	105	4	0	0	0	10	1
sh	2	89	0	0	0	1	28
t	1	0	102	4	1	9	3
p	0	0	20	71	3	18	8
k	0	0	1	0	118	1	0
th	2	0	4	18	4	19	73
f	2	0	17	12	1	35	53

TABLE 41: Confusion matrix for unenhanced voiced consonants in the /a/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	106	4	5	0	0	0	0	2	3
m	5	112	0	0	0	0	0	2	1
ng	26	0	76	0	0	0	1	6	11
z	4	7	2	61	1	3	1	23	18
d	1	0	0	0	109	5	0	5	0
b	1	0	0	1	10	94	2	12	0
v	0	0	0	2	8	9	60	19	22
g	0	0	0	0	9	3	1	105	2
vth	0	1	0	2	16	7	30	36	28

TABLE 42: Confusion matrix for unenhanced voiced consonants in the /u/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	29	5	9	10	49	3	1	8	6
m	13	70	11	1	2	3	7	7	6
ng	29	10	37	0	0	2	17	10	15
z	1	0	3	69	13	2	17	4	11
d	0	0	0	0	85	18	2	14	1
b	1	0	0	2	12	74	5	20	6
v	0	0	2	1	6	1	85	13	12
g	1	0	0	1	7	2	21	83	5
vth	0	0	0	12	17	5	35	10	41

TABLE 43: Confusion matrix for unenhanced voiced consonants in the /i/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	10	33	32	7	1	4	12	7	14
m	15	53	24	1	4	10	4	9	0
ng	13	2	84	0	1	0	2	7	11
z	4	0	0	63	5	13	17	3	15
d	0	0	0	0	70	40	0	9	1
b	0	0	1	0	15	95	1	7	1
v	0	0	5	3	10	14	34	15	39
g	0	2	6	0	24	26	2	58	2
vth	0	0	0	3	19	57	16	5	20

TABLE 44: Confusion matrix for unenhanced voiceless consonants in the /a/ vowel environment with the Sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	66	0	13	10	4	15	12
sh	9	82	2	6	1	6	14
t	1	1	77	17	19	3	2
p	0	0	2	112	6	0	0
k	0	0	5	8	107	0	0
th	1	0	10	20	20	9	60
f	1	0	9	48	5	13	44

TABLE 45: Confusion matrix for unenhanced voiceless consonants in the /u/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	43	11	1	0	0	40	25
sh	0	54	1	4	0	35	26
t	0	0	83	16	4	13	4
p	1	0	2	96	6	7	8
k	0	0	2	38	60	8	12
th	0	0	2	26	4	52	36
f	0	0	2	39	6	18	55

TABLE 46: Confusion matrix for unenhanced voiceless consonants in the /i/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	49	0	10	6	2	35	18
sh	0	83	1	12	1	7	16
t	0	0	79	19	10	7	5
p	0	0	18	96	1	4	1
k	0	0	2	12	103	2	1
th	3	2	12	22	4	59	18
f	1	1	19	22	2	62	13

TABLE 47: Confusion matrix for unenhanced voiced consonants in the /a/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	103	11	4	1	1	0	0	0	0
m	4	112	1	2	0	0	0	1	0
ng	23	2	87	0	2	1	0	4	1
z	47	6	10	32	2	0	16	3	4
d	9	4	9	1	68	12	5	8	4
b	4	10	7	0	4	80	13	1	1
v	8	8	9	0	5	15	57	11	7
g	1	0	27	0	2	1	1	85	3
vth	18	3	8	0	17	0	21	43	10

TABLE 48: Confusion matrix for unenhanced voiced consonants in the /u/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	31	8	3	2	46	4	4	1	21
m	21	64	6	1	1	1	6	1	19
ng	44	11	37	3	1	3	8	3	10
z	19	0	1	55	11	8	11	8	7
d	1	0	1	5	67	9	11	3	23
b	0	0	1	8	8	66	9	7	21
v	1	1	0	20	11	19	49	3	16
g	1	0	1	7	5	18	6	64	18
vth	1	0	2	21	8	16	32	2	38

TABLE 49: Confusion matrix for unenhanced voiced consonants in the /i/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	26	25	12	10	3	15	6	14	9
m	26	39	2	6	5	17	12	1	12
ng	24	26	40	7	6	4	6	6	1
z	19	2	2	62	5	10	9	4	7
d	0	0	2	7	70	26	4	5	6
b	0	0	2	4	24	74	7	6	3
v	16	5	3	17	12	11	20	19	17
g	5	0	3	6	23	11	7	59	6
vth	5	1	3	18	17	35	15	2	24

TABLE 50: Confusion matrix for unenhanced voiceless consonants in the /a/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	73	0	1	3	4	14	25
sh	24	75	2	1	1	0	17
t	19	0	58	4	4	7	28
p	2	0	4	78	2	2	32
k	6	0	1	1	81	6	25
th	21	1	1	1	0	42	54
f	36	1	2	14	4	18	45

TABLE 51: Confusion matrix for unenhanced voiceless consonants in the /u/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	26	5	12	9	5	50	13
sh	1	40	9	8	5	43	14
t	1	3	61	6	8	40	1
p	5	2	16	63	7	22	5
k	4	0	16	29	47	24	0
th	5	4	7	20	6	57	21
f	0	0	10	24	12	25	49

TABLE 52: Confusion matrix for unenhanced voiceless consonants in the /i/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	26	6	17	20	4	42	5
sh	4	70	11	18	3	11	3
t	1	5	78	14	4	18	0
p	3	0	36	50	9	21	1
k	0	1	25	13	62	19	0
th	4	18	10	18	2	30	38
f	2	5	22	22	1	45	23

TABLE 53: Confusion matrix for voiced consonants in the maximum score condition in the /a/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	101	0	17	0	0	0	1	1	0
m	40	75	3	0	0	0	1	1	0
ng	6	1	103	0	0	0	0	10	0
z	0	0	0	119	0	0	0	1	0
d	0	0	0	0	117	1	1	1	0
b	0	1	0	0	27	85	3	4	0
v	7	3	0	0	0	1	106	3	0
g	0	0	0	0	0	0	0	120	0
vth	41	0	0	0	27	0	27	4	21

TABLE 54: Confusion matrix for voiced consonants in the maximum score condition in the /u/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	32	9	13	0	53	5	2	4	2
m	2	77	4	0	1	1	5	13	17
ng	4	34	55	0	0	0	7	2	18
z	0	0	0	120	0	0	0	0	0
d	0	0	0	0	117	1	1	0	1
b	0	0	0	0	7	112	1	0	0
v	0	0	0	0	0	0	115	5	0
g	0	0	0	0	8	0	0	112	0
vth	0	1	0	2	10	2	58	0	47

TABLE 55: Confusion matrix for voiced consonants in the maximum score condition in the /i/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	32	41	21	0	2	9	11	4	0
m	4	106	3	0	0	5	2	0	0
ng	1	2	113	0	0	0	0	4	0
z	0	0	0	118	0	0	2	0	0
d	0	0	0	0	119	1	0	0	0
b	0	0	0	0	1	118	0	1	0
v	0	0	12	1	2	7	92	0	6
g	0	0	6	0	0	0	1	113	0
vth	1	10	1	1	13	32	36	1	25

TABLE 56: Confusion matrix for voiceless consonants in the maximum score condition in the /a/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	120	0	0	0	0	0	0
sh	0	103	0	0	0	1	16
t	1	0	107	8	2	1	1
p	0	0	31	89	0	0	0
k	0	0	15	3	102	0	0
th	8	1	6	6	2	8	89
f	2	0	0	9	1	0	108

TABLE 57: Confusion matrix for voiceless consonants in the maximum score condition in the /u/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	115	5	0	0	0	0	0
sh	2	106	0	0	0	3	9
t	0	0	120	0	0	0	0
p	0	0	6	96	3	1	14
k	0	0	0	0	120	0	0
th	5	0	3	1	0	51	60
f	0	0	0	0	0	3	117

TABLE 58: Confusion matrix for voiceless consonants in the maximum score condition in the /i/ vowel environment with the flat audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	117	2	0	0	0	0	1
sh	0	105	0	0	0	2	13
t	0	0	120	0	0	0	0
p	0	0	24	95	0	0	1
k	0	0	1	0	118	1	0
th	5	5	0	4	2	22	82
f	1	0	3	1	0	14	101

TABLE 59: Confusion matrix for voiced consonants in the maximum score condition in the /a/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	110	3	4	0	1	0	0	0	2
m	7	112	1	0	0	0	0	0	0
ng	34	0	81	0	0	0	0	4	1
z	0	0	0	120	0	0	0	0	0
d	1	0	0	0	117	1	0	1	0
b	0	0	1	1	3	105	2	8	0
v	3	2	2	0	4	7	79	4	19
g	0	0	0	0	8	3	1	108	0
vth	1	5	0	5	18	3	31	22	35

TABLE 60: Confusion matrix for voiced consonants in the maximum score condition in the /u/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	35	5	14	0	64	1	0	1	0
m	10	74	5	1	3	7	5	9	6
ng	16	14	50	0	0	2	17	0	21
z	0	0	0	120	0	0	0	0	0
d	0	0	0	0	105	5	0	10	0
b	0	0	1	1	8	86	7	17	0
v	0	1	3	1	1	0	100	9	5
g	0	0	0	0	2	0	0	118	0
vth	0	1	0	18	17	0	40	2	42

TABLE 61: Confusion matrix for voiced consonants in the maximum score condition in the /i/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	25	22	44	1	2	2	13	6	5
m	19	70	21	2	3	2	2	0	1
ng	8	0	107	1	0	0	1	3	0
z	0	0	0	117	0	0	3	0	0
d	0	1	0	0	90	22	0	7	0
b	0	0	0	0	3	114	2	1	0
v	3	3	24	2	3	6	49	9	21
g	1	0	2	0	8	5	3	101	0
vth	1	0	1	3	22	37	20	9	27

TABLE 62: Confusion matrix for voiceless consonants in the maximum score condition in the /a/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	119	1	0	0	0	0	0
sh	1	119	0	0	0	0	0
t	0	0	119	0	0	0	1
p	0	0	5	115	0	0	0
k	0	0	0	0	120	0	0
th	1	0	6	10	9	25	69
f	5	0	1	1	1	19	93

TABLE 63: Confusion matrix for voiceless consonants in the maximum score condition in the /u/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	113	6	1	0	0	0	0
sh	2	118	0	0	0	0	0
t	1	0	118	1	0	0	0
p	0	0	0	112	7	0	1
k	0	0	0	1	119	0	0
th	0	0	0	2	1	76	41
f	0	0	0	4	1	9	106

TABLE 64: Confusion matrix for voiceless consonants in the maximum score condition in the /i/ vowel environment with the sloping audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	110	2	8	0	0	0	0
sh	0	120	0	0	0	0	0
t	1	0	117	2	0	0	0
p	0	0	14	105	0	1	0
k	0	0	0	0	120	0	0
th	4	7	1	14	2	64	28
f	1	3	0	8	1	54	53

TABLE 65: Confusion matrix for voiced consonants in the maximum score condition in the /a/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	105	7	6	1	1	0	0	0	0
m	1	118	1	0	0	0	0	0	0
ng	40	1	74	0	0	1	0	3	1
z	36	4	8	47	3	0	13	1	8
d	9	2	9	1	73	9	1	15	1
b	0	13	8	0	4	92	1	1	1
v	13	7	6	0	4	9	72	3	6
g	1	0	27	0	1	1	41	46	3
vth	25	0	6	0	17	2	21	34	15

TABLE 66: Confusion matrix for voiced consonants in the maximum score condition in the /u/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	33	10	3	2	42	4	4	1	21
m	6	75	5	2	1	3	3	1	24
ng	31	24	39	2	1	5	3	3	12
z	7	1	1	66	4	4	8	6	23
d	0	0	1	1	93	8	10	5	2
b	0	0	1	4	14	88	6	4	3
v	6	8	6	9	6	11	55	4	15
g	0	0	3	4	6	9	6	88	4
vth	3	1	2	22	6	12	25	4	45

TABLE 67: Confusion matrix for voiced consonants in the maximum score condition in the /i/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	n	m	ng	z	d	b	v	g	vth
n	42	17	16	3	5	14	12	4	7
m	20	61	7	7	7	3	9	3	3
ng	14	24	54	7	5	4	3	6	3
z	19	2	1	70	5	6	6	6	5
d	0	0	2	4	80	20	4	5	5
b	0	0	1	2	20	84	5	5	3
v	17	4	3	5	6	9	62	3	11
g	8	0	9	3	5	2	5	81	7
vth	12	2	3	7	23	13	27	6	27

TABLE 68: Confusion matrix for voiceless consonants in the maximum score condition in the /a/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	106	5	0	1	1	2	5
sh	13	107	0	0	0	0	0
t	10	0	73	6	19	1	11
p	1	0	1	94	7	1	16
k	0	0	1	1	100	1	17
th	54	1	1	1	0	27	36
f	36	2	0	4	1	15	62

TABLE 69: Confusion matrix for voiceless consonants in the maximum score condition in the /u/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	34	25	8	4	5	41	3
sh	2	115	1	0	0	1	1
t	0	0	95	3	3	19	0
p	1	2	12	75	10	13	7
k	0	0	8	3	94	14	1
th	7	5	5	7	6	57	33
f	1	18	9	4	0	15	73

TABLE 70: Confusion matrix for voiceless consonants in the maximum score condition in the /i/ vowel environment with the precipitous audiometric configuration. Rows total to 120 representing 6 subjects.

	s	sh	t	p	k	th	f
s	52	23	12	13	3	15	2
sh	1	114	0	2	1	2	0
t	0	1	91	12	11	4	1
p	0	0	23	78	15	2	2
k	0	0	16	9	90	5	0
th	3	19	4	17	2	42	33
f	1	16	5	14	3	31	50

APPENDIX H

CONFUSION MATRICES
COLLAPSED
ACROSS ERROR TYPES

TABLE 71: Error patterns for the control group with unenhanced speech for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner. Note that for this table, the group consists of 5 subjects whereas all others consist of 6 subjects.

Target	PLACE Vowel			MANNER Vowel			PLACE/MANNER Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i
n	0	0	18	0	0	1	0	3	1
m	4	0	0	0	0	0	0	0	0
ng	0	29	4	1	1	0	0	0	0
z	1	0	0	0	0	0	0	0	0
d	0	0	4	0	0	0	0	2	2
b	1	5	3	0	2	1	0	7	0
v	1	2	10	0	0	0	13	3	3
g	0	2	9	0	0	0	0	4	13
vth	7	3	22	0	0	0	5	2	5
TOTAL	14	41	70	1	3	2	18	21	24

TABLE 72: Error patterns for the control group with unenhanced speech for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

Target	PLACE Vowel			MANNER Vowel			PLACE/MANNER Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	0	1	0	0	0	0	0	0	0
sh	1	0	2	0	0	0	0	0	0
t	0	0	0	0	0	0	0	0	0
p	0	0	0	0	0	0	0	1	0
k	0	1	0	0	0	0	0	0	0
th	54	6	6	0	0	0	0	4	14
f	7	6	69	0	0	0	7	4	5
TOTAL	62	14	77	0	0	0	7	9	19

TABLE 73: Error patterns for the flat audiometric configuration with unenhanced speech for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
n	19	30	76	2	40	1	2	37	20
m	52	11	7	3	0	18	8	35	6
ng	12	53	8	16	5	5	0	19	1
z	0	14	14	3	2	0	14	1	4
d	19	19	50	0	0	0	3	40	8
b	27	15	6	1	2	2	11	48	10
v	3	20	18	0	0	0	38	29	41
g	21	19	25	0	0	1	11	20	24
vth	32	56	41	0	0	0	69	21	59
TOTAL	185	237	245	25	49	27	156	250	173

TABLE 74: Error patterns for the flat audiometric configuration in the maximum score condition for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
n	17	22	62	0	53	2	2	13	24
m	43	6	7	0	1	5	2	36	2
ng	7	38	3	10	2	4	0	25	0
z	0	0	0	0	0	0	1	0	2
d	2	1	1	0	0	0	1	2	0
b	31	7	2	1	0	0	3	1	0
v	0	0	7	0	0	0	14	5	21
g	0	8	0	0	0	6	0	0	1
vth	27	60	37	0	0	0	72	13	58
TOTAL	127	142	119	11	56	17	95	95	108

TABLE 75: Error patterns for the flat audiometric configuration with unenhanced speech for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	4	37	15	4	7	0	0	0	0
sh	26	61	31	0	0	0	0	1	0
t	22	9	5	2	0	1	4	31	12
p	34	11	23	0	0	0	5	34	26
k	30	41	1	0	0	0	1	14	1
th	80	66	75	0	0	0	32	24	26
f	10	9	37	0	0	0	42	58	30
TOTAL	206	234	187	6	7	1	84	162	95

TABLE 76: Error patterns for the flat audiometric configuration in the maximum score condition for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	0	5	3	0	0	0	0	0	0
sh	17	14	15	0	0	0	0	0	0
t	10	0	0	1	0	0	2	0	0
p	31	9	24	0	0	0	0	15	1
k	18	0	1	0	0	0	0	0	1
th	98	65	92	0	0	0	14	4	6
f	2	3	15	0	0	0	10	0	4
TOTAL	176	96	150	1	0	0	26	19	12

TABLE 77: Error patterns for the sloping audiometric configuration with unenhanced speech for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
n	9	14	65	0	59	8	5	18	37
m	5	24	39	0	3	10	3	23	18
ng	26	39	15	6	10	7	12	34	14
z	19	28	32	8	14	9	32	9	16
d	10	32	49	1	0	0	0	3	1
b	22	32	22	0	0	0	4	14	3
v	24	13	42	0	0	0	36	22	44
g	12	9	50	0	0	6	3	28	6
vth	38	47	19	0	0	0	54	32	81
TOTAL	165	238	333	15	86	40	149	183	220

TABLE 78: Error patterns for the sloping audiometric configuration in the maximum score condition for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
n	7	19	66	1	64	3	2	2	26
m	8	15	40	0	7	2	0	24	8
ng	34	30	8	4	0	3	1	40	2
z	0	0	3	0	0	0	0	0	0
d	2	15	29	1	0	0	0	0	1
b	11	25	4	0	0	0	4	9	2
v	19	6	23	0	0	0	22	14	48
g	11	2	13	0	0	2	1	0	4
vth	36	58	23	0	0	0	49	20	70
TOTAL	128	170	209	6	71	10	79	109	161

TABLE 79: Error patterns for the sloping audiometric configuration with unenhanced speech for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	27	76	53	13	1	10	14	0	8
sh	29	61	23	0	0	0	9	5	14
t	36	20	29	1	0	0	6	17	12
p	8	8	19	0	0	0	0	16	5
k	13	40	14	0	0	0	0	20	3
th	61	36	23	0	0	0	50	32	38
f	14	18	64	0	0	0	62	47	43
TOTAL	188	259	225	14	1	10	141	137	123

TABLE 80: Error patterns for the sloping audiometric configuration in the maximum score condition for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	1	6	2	0	1	8	0	0	0
sh	1	2	0	0	0	0	0	0	0
t	0	1	2	0	1	1	1	0	0
p	5	7	14	0	0	0	0	1	1
k	0	1	0	0	0	0	0	0	0
th	70	41	39	0	0	0	25	3	17
f	24	9	58	0	0	0	3	5	9
TOTAL	101	67	115	0	2	9	29	9	27

TABLE 81: Error patterns for the precipitous audiometric configuration with unenhanced speech for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
n	15	11	37	2	48	13	0	30	44
m	5	27	28	0	1	17	3	28	36
ng	25	55	50	4	3	6	4	25	24
z	20	18	16	49	30	24	19	17	18
d	20	12	31	10	6	7	22	35	12
b	5	15	30	10	0	0	25	39	16
v	7	36	34	0	0	0	56	35	66
g	3	23	34	27	1	3	5	32	24
vth	21	53	33	0	0	0	89	29	63
TOTAL	121	250	293	102	89	70	223	270	303

TABLE 82: Error patterns for the precipitous audiometric configuration in the maximum score condition for the voiced consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
n	13	13	33	2	44	8	0	30	37
m	2	11	27	0	3	3	0	31	29
ng	41	55	38	3	3	6	2	23	21
z	21	31	11	39	11	24	13	12	15
d	24	13	25	10	1	4	13	13	11
b	5	18	25	13	0	0	10	14	11
v	6	24	16	0	0	0	42	41	42
g	2	15	7	27	3	9	45	14	23
vth	21	47	34	0	0	0	84	28	59
TOTAL	135	227	216	94	65	54	209	206	248

TABLE 83: Error patterns for the precipitous audiometric configuration with unenhanced speech for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	39	68	53	1	12	17	7	14	24
sh	41	58	18	0	0	0	4	22	32
t	8	14	18	19	1	1	35	44	23
p	6	23	45	0	0	0	36	34	25
k	2	45	38	0	0	0	37	28	20
th	76	30	60	0	0	0	2	33	30
f	55	25	52	0	0	0	20	46	45
TOTAL	227	263	284	20	13	18	141	221	199

TABLE 84: Error patterns for the precipitous audiometric configuration in the maximum score condition for the voiceless consonants. Errors have been collapsed into three types: place, manner and combined place and manner.

	PLACE			MANNER			PLACE/MANNER		
Target	Vowel			Vowel			Vowel		
	/a/	/u/	/i/	/a/	/u/	/i/	/a/	/u/	/i/
s	12	69	40	0	8	12	2	9	16
sh	13	4	3	0	0	0	0	1	3
t	25	6	23	10	0	0	12	19	6
p	8	22	38	0	0	0	18	23	4
k	2	11	25	0	0	0	18	15	5
th	91	45	55	0	0	0	2	18	23
f	53	34	48	0	0	0	5	13	22
TOTAL	204	191	232	10	8	12	57	98	79

APPENDIX I

CONTINGENCY TABLES AND CHI SQUARE VALUES

TABLE 85: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the flat audiometric configuration with the vowel /a/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	185	25	156	206	6	84
MAXIMUM SCORE	127	11	95	176	1	26
CHI-SQUARE	1.599 p=.4495			19.867 p=.0001**		

TABLE 86: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the flat audiometric configuration with the vowel /u/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	237	49	250	234	7	162
MAXIMUM SCORE	142	56	95	96	0	19
CHI-SQUARE	24.82 p=.0001**			25.422 p=.0001**		

TABLE 87: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the flat audiometric configuration with the vowel /i/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	245	27	173	187	1	95
MAXIMUM SCORE	119	17	108	150	0	12
CHI-SQUARE	2.499 p=.2866			39.462 p=.0001**		

TABLE 88: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the sloping audiometric configuration with the vowel /a/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	165	15	149	188	14	141
MAXIMUM SCORE	128	6	79	101	0	29
CHI-SQUARE	5.443 p=.0658			22.655 p=.0001**		

TABLE 89: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the sloping audiometric configuration with the vowel /u/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	238	86	183	259	1	137
MAXIMUM SCORE	170	71	109	67	2	9
CHI-SQUARE	2.854	p=.2401		20.763	p=.0001**	

TABLE 90: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the sloping audiometric configuration with the vowel /i/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	333	40	220	225	10	123
MAXIMUM SCORE	209	10	161	115	9	27
CHI-SQUARE	9.324	p=.0094*		15.454	p=.0004**	

TABLE 91: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the precipitous audiometric configuration with the vowel /a/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	121	102	223	227	20	141
MAXIMUM SCORE	135	94	209	204	10	57
CHI-SQUARE	1.474 p=.4786			20.57 p=.0001**		

TABLE 92: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the precipitous audiometric configuration with the vowel /u/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	250	89	270	263	13	221
MAXIMUM SCORE	227	65	206	191	8	98
CHI-SQUARE	2.348 p=.3092			21.079 p=.0001**		

TABLE 93: Chi-Square and contingency tables showing type of error in unenhanced speech and maximum score condition for the precipitous audiometric configuration with the vowel /i/. P, M and PM refer to place, manner and combined place and manner errors respectively.

	VOICED CONSONANTS			VOICELESS CONSONANTS		
ERROR TYPE	P	M	PM	P	M	PM
UNENHANCED	293	70	303	284	18	199
MAXIMUM SCORE	216	54	248	232	12	79
CHI-SQUARE	.714	p=.6998		20.756	p=.0001**	

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