Effects of Amplitude Envelope Cues as an Aid to Enhanced Speechreading

by

Sharieff Ali Mansour

Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

This thesis developed methods of presenting two speech envelope cues in the small bandwidth likely to be available to people with severe hearing impairments. Identifying such methods could facilitate face-to-face communication substantially.

Seven presentation conditions were evaluated. Two of the conditions, the One-Envelope Monaural and the Two-Envelope Monaural, were developed by Grant, Braida and Renn (1991), and were used as a basis of comparison to the new conditions developed. The One-Envelope "Rough" Monaural, Two-Envelope "Rough" Monaural, Simple Binaural, Combination Binaural, and Low Binaural are the five presentation conditions developed in this project. Initial tests used normal hearing subjects to evaluate each proposed scheme. This avoided compounding perceptual interference factors with hearing loss. To ensure that these tests were indicative of the full potential of each method, subjects were familiarized with the envelope cues prior to testing.

Results of testing suggest that two of the new presentation conditions may prove beneficial to the hearing impaired. Both the Two-Envelope "Rough" Monaural and the Combination Binaural conditions were particularly successful in conveying speech (average scores using Harvard sentences were 74.1% and 72.1%, respectively).

Thesis Supervisor: Louis D. Braida
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Chapter 1

Introduction

1.1 Background

Many individuals with severe-to-profound hearing loss are only able to hear a limited range of low frequency sounds. Most of these individuals rely heavily on speechreading while conversing with others in their daily activities. Given the importance of speechreading to this population, it is important to identify ways to enhance these individual's ability to speechread. Though most of these listeners use contemporary hearing aids, many derive only small benefits to speechreading while using them.

Much effort has been made to identify methods for enhancing speechreading performance beyond the level obtained with amplified speech (as would be produced by a conventional hearing aid). Amplitude envelope cues derived from various parts from the speech spectrum seem particularly promising to aid listeners speechread. Several studies have shown that if the amplitude envelopes of appropriate bands of speech are presented in the form of modulated tones or broad-band noise, substantial benefits to speechreading can be achieved [1,2,3,4]. Such benefits improve speechreading of normal hearing individuals from 40% (speechreading alone) to approximately 80% (speechreading with single envelope cues)[4].

Several studies have examined the benefits that result from providing speechreaders with two envelope cues, derived from different spectral regions. In this approach, one envelope is usually derived from the lower portion of the speech spectrum (e.g., 500 Hz), while the other is derived from the higher frequency portion (e.g., 3300 Hz). If each of these cues is presented at the frequency from which it is derived (i.e. modulating the 500 Hz and 3300 Hz envelope cues to 500 Hz and 3300 Hz, respectively), substantial benefit is provided to speechreaders: scores of 87% can be obtained by listeners with normal hearing (speech material included meaningful Dutch sentences typical of everyday conversation) [1,2]. The envelope cue derived from the 3300Hz band enables the listener to perceive fricative and affricate sounds (e.g., /sh/, /s/, /th/).

Given the benefits of providing two envelope cues to speechreaders with normal hearing, the next step is to determine how to adapt this approach to benefit members of the deaf community. Since the deaf typically have a narrow range of residual hearing at low frequencies, it makes little sense to present the two envelopes at the frequencies from which they were derived; the deaf will not benefit from the high frequency cues. Rather, one or both envelope cues need to be transposed in frequency so that they can be heard. The amplitude envelope cues extracted from high frequency regions, which many severely hearing impaired individuals would not be able to perceive, would be presented at lower frequencies where they have some residual hearing. For example, if an amplitude envelope of a frequency band centered at 3300 Hz is used to modulate a carrier tone at 500 Hz, the amplitude envelope cues in the 3300 Hz band would be audible to a listener with hearing at 500 Hz. Such envelopes are especially useful for detecting the presence of fricatives and other sounds of speech that have most of their energy above 1000 Hz. Thus, these envelope cues enable the hearing impaired to make distinctions between speech sounds that they were unable to with amplified speech. Though the exact the placement of the two envelopes will vary among individuals (based on their audiograms), typical placements might be 200 Hz and 500 Hz for the low and high envelope cues respectively.

The promise associated with transposing the envelope cues to lower frequencies has not been realized: the results of doing so have proved disappointing. Past research has shown that when two envelope cues are transposed to low frequencies, the benefits to speechreading are no better than the most effective single envelope cue (e.g. 500 Hz modulated to 200 Hz) or low-pass filtered speech, each having the same bandwidth as the two envelope cues [5]. Philip Nadeau explored the notion that subjects' performance would improve with increased exposure to the envelope cues, but was unable to provide subjects with dependable, wearable aids [6]. The reasons for the failure of effectively transposing the envelope cues to low frequencies are unclear, and it is uncertain whether the benefits of such cues can be provided at low frequencies. Further research is needed to uncover a strategy that might provide for the desired benefits.

An attempt to improve the efficacy of the two envelope cues using the strategy described above was made during the summer of 1996. The focus of that project was a continuation of Philip Nadeau's work with the SIVO hearing aids [6]. Specifically, an attempted was made to optimize the existing code in order to incorporate more substantial filters that would produce "cleaner" envelope cues. Such an optimization was hoped to enhance performance of the two envelope scheme, beyond the level of the single envelope cue. However, meaningful progress was not possible, due to several fundamental problems with the hardware and software tools. Details of this project are provided in Appendix A.

1.2 Objective

The goal of this thesis is the search for a method of presenting two envelope cues to speechreaders that would enhance speechreading beyond the degree achieved with single envelope cues. Identifying such a method could allow deaf individuals to derive more information from speech, which would facilitate them in their daily activities. Although similar research has already been conducted without success, only a few approaches have been studied and possible schemes that have yet to be examined.

Before discussing these possibilities, it is important to consider why the benefits of using two envelopes when speechreading are apparently "lost" when they are transposed to low frequencies. Reduced performance may be explained by masking effects or perceptual interference that may occur between the cues. That is, one envelope signal may obscure the cues provided by the other envelope signal. Thus, subjects will only be able to benefit from the prevailing cue. Also, presenting the higher frequency envelope cue at a significantly lower frequency may produce a sound that is unfamiliar to subjects. This sound could distract subjects to the point where the higher frequency cue would be perceived as "noise". Thus, individuals would have to exert much effort to obtain information from the low frequency envelope cue in the presence of this additive noise.

If the benefits of presenting a second envelope cue to the same ear are limited by simple masking effects, it should be possible to overcome them by presenting the second cue to the contralateral ear. Little contralateral masking is seen when sounds are separated in frequency. This dichotic presentation condition may not reduce other types of perceptual interference, however. Moreover, it would not be applicable to a listener with only one functional ear. Nevertheless, it is an important condition to test because it is free of one type of perceptual interference.

Moreover, there may be benefit from modulating nearby frequencies. In particular, summing two tones separated by approximately 40 Hz typically elicits a sensation of roughness that is independent of the loudness of the tone complex. If one envelope modulates the lower frequency tone, while the other modulates the higher (by 40 Hz) frequency tone, then variations in roughness can be used to convey information about high frequency energy in the uttered words (e.g. the occurrence of fricatives.)

The problem is simple to state: The optimal presentation of two envelope cues must be determined in order to provide aid to speechreading by members of the deaf community. This presentation will involve the right combination of the envelope cues (or portions of each) that will enable an individual to perceive more information than with the presentation of just one envelope cue.

In searching for the right combination of the envelope cues, initial tests would use normal hearing subjects to evaluate each proposed scheme. This avoids compounding perceptual interference factors with hearing loss. To ensure that these tests will be indicative of the full potential of each method, subjects will be provided with a training regime to familiarize them with the cues they hear when tested. Past research has shown that such training improves performance during testing. Thus, training subjects before testing is expected to produce results that are indicative of the ultimate potential of each proposed scheme.

Chapter 2

Method

2.1 Speech Materials

Three types of sentences were employed. CUNY sentences were used during the initial screening and training of subjects [7]. Harvard sentences were also used during the initial screening and were used during the testing portion of the project [8]. Finally, Clarke sentences were used during follow-up testing [9]. All sentences used were recorded by female speakers onto laser videodiscs. The following is a description of each type of sentence list used.

2.1.1 CUNY sentences

The CUNY sentences address conversational topics that subjects find fairly familiar. Examples include, "Have you eaten yet?", "My sister has a new boyfriend" and "I like playing tennis." There are 60 lists of CUNY sentences, each list containing twelve sentences. The length of these sentences range from three to fourteen words, for a total of 102 words per list. Performance scores were based on the total number of words correctly perceived.

These sentences were used during training so that subjects could use sentence context as they became comfortable with the presentation schemes and thus learn how to use the envelope cues to enhance lipreading. Forty two lists were used during training.

2.1.2 Harvard sentences

The Harvard sentences are substantially more difficult to understand because they incorporate fewer contextual cues. These sentences were designed so that subjects cannot easily deduce a word in a sentence simply by knowing the other words in the sentence. Examples include, "The birch canoe slid on the smooth planks", "A large size in stockings is hard to sell", and "Glue the sheet to the dark blue background." Using these lists of sentences during testing should reveal the ability of the presentation schemes to convey speech in the absence of contextual cues. There are 72 lists of these sentences, each containing 10 sentences. Each sentence contains five key words for a total of 50 key words per list. Subjects' performance scores were based on the number of correct key words. Seventy lists were used during testing, with 10 lists devoted to each of the seven presentation conditions.

2.1.3 Clarke sentences

Clarke sentences are easier to interpret than are Harvard sentences, but are more difficult than CUNY sentences. Examples include, "Seven boys made a long table at school", "The boys played in the basement after school", and "Most boys do not like to work on hot days." Clarke sentences were used during follow-up testing. Unlike Harvard and CUNY sentences, these sentences are not organized in formal lists. There are a limited number of Clarke sentences available. One hundred sentences were available and used during follow-up testing, with 25 sentences devoted to each of the 4 conditions tested. Like the CUNY lists, performance scores with the Clarke sentences were determined by the number of words correctly interpreted.

2.2 Subjects

2.2.1 Screening

Because the focus of the this study is to determine ways to enhance speechreading, it is important that the subject's ability to speechread does not change during training. If a subject is a poor speechreader, practice may improve speechreading skills, giving a false impression of the benefits provided by the auditory cues. Thus, the first session tested reception of CUNY and Harvard sentences that were presented to subjects through vision alone. According to past research, untrained normal hearing subjects should identify roughly 40% of the words in CUNY sentences correctly and 20% of the words in Harvard sentences [4]. Only subjects who met or surpassed these criteria during this initial screening participated in the study.

The screening session was composed of seven lists of sentences; four CUNY lists and three Harvard lists. The CUNY lists were presented to subjects before the Harvard lists. The first of the four CUNY lists was used to allow subjects to overcome the initial shock of having to interpret speech in the absence of sound. The remaining three CUNY lists and all the Harvard lists were graded for performance. Performance evaluation was based on the averages of subjects' performance with each type of sentence list.

Fifteen subjects were screened for the project. Of these, only four individuals met or surpassed the performance criteria, as shown in Table 2.1. NN, EL, AC, and RB were asked to participate in the project and thus were trained and tested with the envelope cues. Both NN and EL are 21 year old females, while RB is a 20 year old female. AC, 23 years old, was the only male subject in the project. No subject had prior experience with lipreading exercises before participating in this project.

2.3 Procedure

During training, testing, and follow-up testing, subjects were presented with sentences visually on a Panasonic AG-513A monitor while envelope cues were presented over

Subjects Who Did Not Meet Performance Criteria		
Subject Name	CUNY Ave.	Harvard Ave.
EC	16	7
MQ	21	6
RS	24	9
JR	25	7
DO	17	4
MS	13	7
NC	32	18
HT	25	11
AK	20	10
KH	35	15
JP	15	7
Avg.	22.1	9.2

Subjects Who Participated In Project		
Subject Name	CUNY Ave.	Harvard Ave.
EL	54	25
NN	43	20
AC	51	26
RB	49	26
Avg.	49.25	24.25

Table 2.1: Results of Initial Screening (Each score is the percentage of words identified correct)

a pair of Telephonics TDH-39P earphones. Subjects wrote down each sentence list on answer sheets, which were used to measure their ability to interpret the spoken words. The following is a detailed description of each phase of the project.

2.3.1 Training

The purpose of training is to familiarize subjects with the envelope cues that were used during testing. Since these individuals have not experienced such sounds while trying to interpret speech, they are expected to require time to learn how to use the auditory cues to improve speechreading. CUNY sentences were used since these sentences are significantly easier to interpret than are Harvard sentences.

The duration of the training period was six sessions. During each session, subjects were presented with seven lists of sentences. Each list was accompanied by a different audio presentation. The order of the audio presentations was kept constant during all training sessions. Subjects recorded the sentences on answer sheets, which were analyzed for performance. After each session, subjects were given the option to see the correct answers to each sentence list used, but were not required to do so. Nonetheless, subjects generally opted to see the answers, especially when they encountered sentences that piqued their interest.

Subjective impressions were solicited from subjects during training. In order to ensure their comfort with the audio tones, the sound intensity was adjusted to a comfortable level for each subject. Also, subjects were encouraged to ask any questions they had about the different presentations in order to familiarize themselves with the envelope cues. Subjects generally inquired about the source the envelope cues in an effort to understand them better.

2.3.2 Testing

Once subjects completed training, the next phase measured their ability to understand the words in Harvard sentences. Testing lasted for a period of ten sessions for each subject, which allows for accurate measurements of each presentation scheme's potential. The format of each testing session was identical to that of training sessions. Also, subjects were given the option to see the answer lists, but were not required to do so. Each condition was tested by a total of ten lists. Thus, subjects were presented with five hundred key words per condition during testing.

2.3.3 Feedback Form

Each subject was asked to complete a feedback form upon completion of training and again after testing. Subjects were asked to explain their experiences and taste for the tones themselves (e.g. high or low) and the various presentation schemes. To ensure that they were able to remember the presentation schemes, a sample of each scheme was presented to subjects before they completed the form. This information will be useful when analyzing their performance during testing, as the subject's like or dislike of a particular tone or presentation will invariably affect their performance. A copy of the feedback form given to subjects is included in Appendix B.

2.3.4 Follow-up Testing

Upon completion of testing subjects, it was realized that further testing was needed. Initial analysis of the data collected identified certain trends that needed to be verified. Since each subject was presented with the same sentences under the same conditions, there may be some correlation between performance and the sentences used (i.e. the sentences may have been particularly difficult or easy, irrespective of the presentation scheme used.) The Harvard sentence lists have not been equated for speechreading difficulties; there may be some variation in sentence difficulty from list to list. In order to isolate each condition's ability to convey speech, each subject should be tested under each condition with different lists of sentences than any other subject.

Since all Harvard sentences were used during testing and it is not desirable to present the same sentences to subjects more than once, Clarke sentences were used during follow-up testing. Because there was a limited number of sentences available, only four presentation conditions were evaluated. Hence, there were twenty five sentences available for each condition (there were only one hundred sentences available.) Each subject was presented with a different set of twenty five sentences for a given condition.

There were two follow-up tests. Each group of twenty five sentences was broken into two lists; a ten sentence list and a fifteen sentence list. Each testing session consisted of two ten sentence lists and two fifteen sentence lists.

2.4 Presentation Schemes

The presentation schemes studied attempt to present one or two envelope cues. One cue derives from a 1000 Hz bandpass filter centered at 500 Hz, while the other derives from a 2000 Hz bandpass filter centered at 3300 Hz. In each presentation scheme evaluated, the input signal(s) passes through one or both of the prefilters described above. The filtered signal(s) is then full-wave rectified. Finally, the rectified signal(s) passes through a smoothing filter(s) before being modulated by a sinusoidal carrier. The smoothing filter(s) used is a butterworth low-pass filter with a cut-off frequency of 100 Hz.

The presentation schemes differ mainly with respect to which prefilter(s) are used, the carrier frequencies, and the combinations of the envelope cues taken before being presented to subjects. If a scheme presents two envelope cues, combinations of these cues may be taken after modulation occurs. The full-wave rectifiers and the smoothing filters are the same in each presentation scheme.

Below are descriptions of the presentation schemes evaluated in this project. The order in which these conditions are discussed coincides with the order in which they were presented to subjects during training and testing. Spectrum plots of these presentations is provided in Appendix C. The following presentations were evaluated.

2.4.1 One-Envelope Monaural

The first of the presentation schemes evaluated was the One-Envelope Monaural. This is similar to the most effective one-envelope presentation developed by Grant, Braida, and Renn [4]. The only difference is that the bandwidths of the prefilter and the smoothing filter are slightly larger. A 1000 Hz bandwidth prefilter was incorporated instead of an octave bandpass prefilter and the cutoff frequency of the smoothing filter is 100 Hz, instead of 50 Hz. Since much is known about this presentation, it is primarily used as a basis of comparison to the new presentations developed in this project. Figure 2-1 displays the set up used for this presentation scheme.

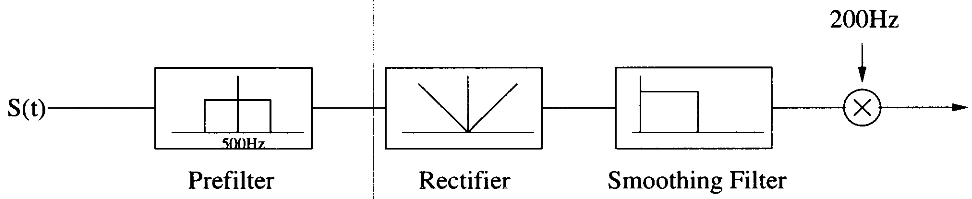

Figure 2-1: The One-Envelope Monaural Presentation

2.4.2 Two-Envelope Monaural

Another condition evaluated was the Two-Envelope Monaural. Like the One-Envelope Monaural, this presentation is very similar to the most effective two-envelope transposed condition developed by Grant, Braida, and Renn [4] and was used as a basis of comparison. Again, the only difference between this condition and the one developed by Grant et al. is that the bandwidths of the filters used are slightly larger (refer to Sec. 2.4.1 for details). Figure 2-2 displays the set up for this presentation scheme.

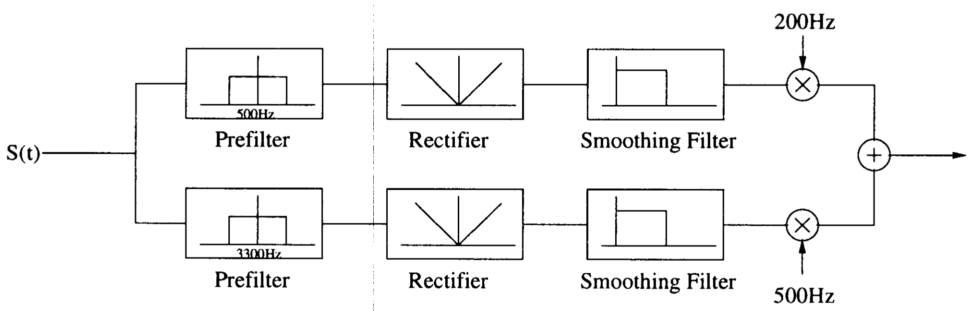

Figure 2-2: The Two-Envelope Monaural Presentation

The top branch of this block diagram performs the same signal processing as the One-Envelope Monaural presentation. The bottom branch produces a second envelope cue, derived from a bandpass filter centered at 3300 Hz, that modulates a 500 Hz carrier. The sum of the two envelope cues is presented to listeners.

2.4.3 One-Envelope "Rough" Monaural

The remaining presentation conditions are new and were developed and evaluated in this project.

The One-Envelope "Rough" Monaural presentation condition, Fig. 2-3, conveys the same envelope cue as the One-Envelope Monaural condition. The "roughness" character of this presentation is produced when the two carrier frequencies are within 40 Hz of one another.

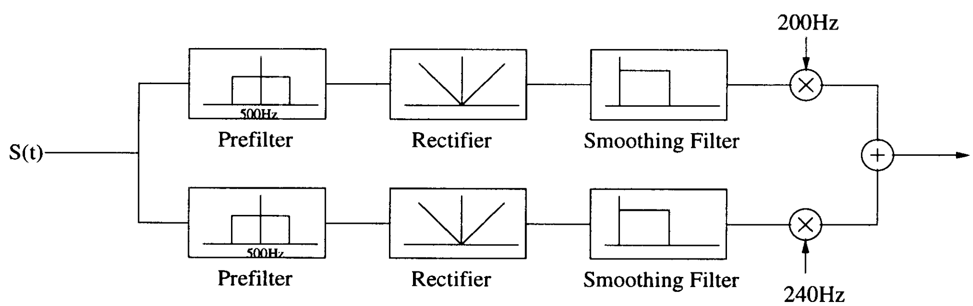

Figure 2-3: The One-Envelope "Rough" Monaural Presentation

The two envelopes derive from 1000 Hz bandpass filters, each with a center frequency of 500 Hz. Once the envelopes pass through the identical smoothing filters, one envelope is modulated to 200 Hz and the other at 240 Hz (thus producing the desired "rough" effect). The sum of the modulated envelope cues is then presented to listeners.

2.4.4 Two-Envelope "Rough" Monaural

The Two-Envelope "Rough" Monaural condition, Fig. 2-4, produces a "rough" sensation in the tones presented to listeners. However, the two envelopes in this presentation derive from *different* spectral regions, one centered at 500 Hz, the other at 3300 Hz. As Fig. 2-4 shows, the low frequency envelope cue modulates a 200 Hz carrier tone, while the high frequency envelope cue modulates a 240 Hz carrier tone. Once the envelope cues are transposed to their appropriate frequency, the result is summed together, using the TuckerDavis SM3 weighted summer, and then presented to listeners.

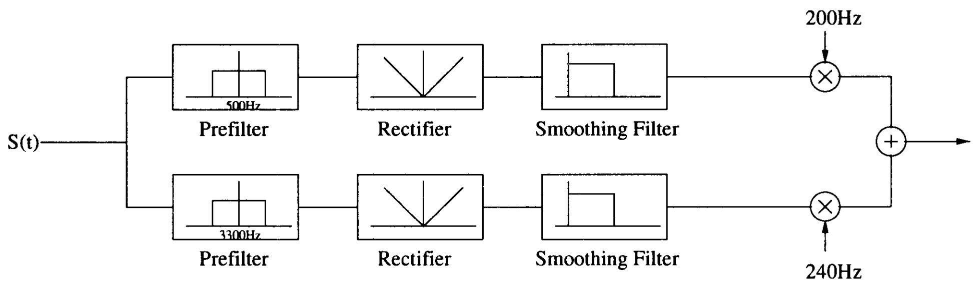

Figure 2-4: The Two-Envelope "Rough" Monaural Presentation

What is unique about this condition is that the roughness sensation is only apparent when the uttered words contain substantial energy in both the low and high frequency region.

2.4.5 Simple Binaural

In the Simple Binaural presentation, Fig. 2-5, one of the envelope cues is presented to each of the subject's ears: The lower frequency envelope cue is presented to one ear, while the higher frequency envelope cue is presented to the opposite ear. Presenting the envelope cues in this manner may eliminate any masking effects that may exist between the two cues when presented monaurally.

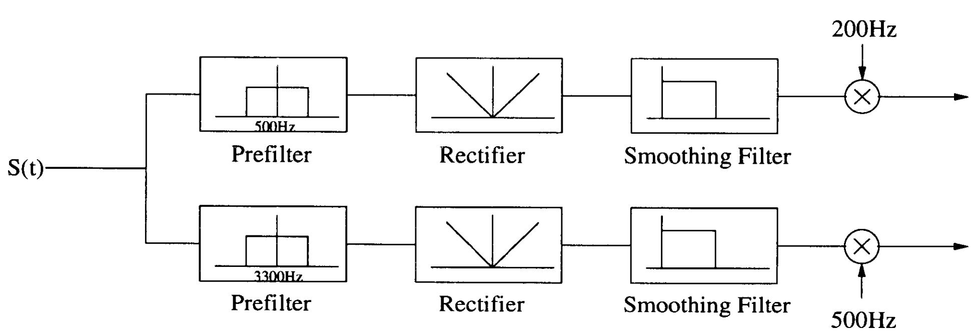

Figure 2-5: The Simple Binaural Presentation

2.4.6 Combination Binaural

In the Combination Binaural presentation, Fig. 2-6, the sum of the envelope cues is presented to one ear, while the difference of the envelopes is presented to the other. It is important to note that the combinations of the envelopes cues are taken after amplitude modulation occurs. Thus, the envelope cues are presented on separate channels and the Tucker-Davis SM3 weighted summer is used to produce the sum and difference of the modulated envelope cues.

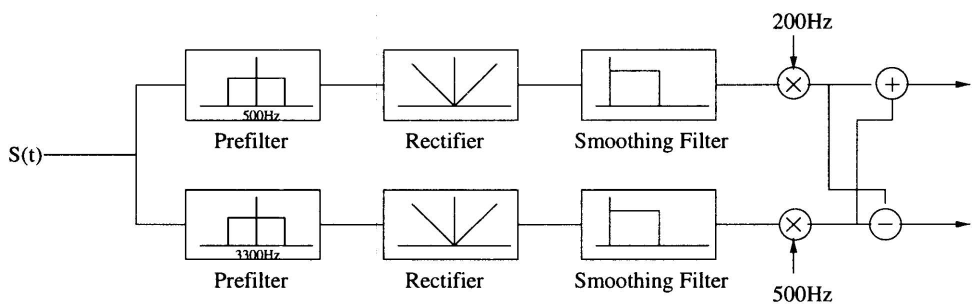

Figure 2-6: The Combination Binaural Presentation

2.4.7 200Hz Binaural

In the 200 Hz Binaural presentation, Fig. 2-7, both the envelope derived from the 500 Hz band and the envelope derived from the 3300 Hz band are presented at 200 Hz (one to each ear). This scheme is intended for individuals who have a very restricted range of hearing at low frequencies, but have hearing in both ears.

2.5 Signal Processing

The signal processing necessary to produce the envelope cues is performed on an Ariel DSP board, using a Motorola 96000 DSP chip. The following is a description of the software tools needed to produce the particular presentations schemes evaluated in this project.

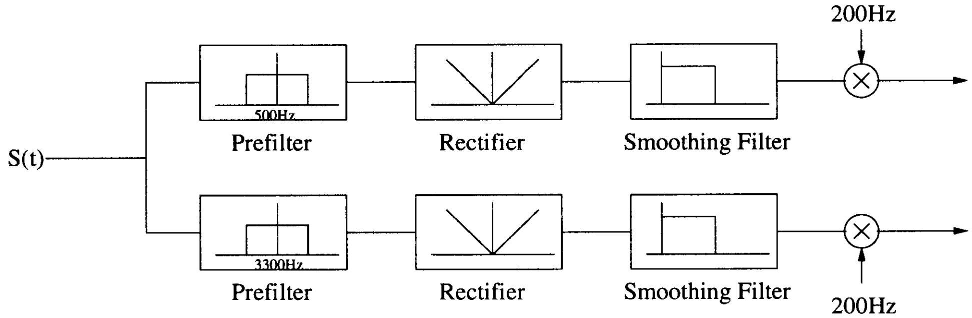

Figure 2-7: The Low Binaural Presentation

The code used to produce the envelope cues for each presentation scheme was based on the "Envs" program [10]. There are essentially two components of the "Envs" routine. One component runs on the PC's processor, while the other is executed on the Ariel board. The portion that runs on the PC's processor, which is written in C, acts primarily as the front-end of the routine. This code initializes the Ariel board, collects the user's parameters, and computes the signal processing parameters (i.e. filter coefficients, oscillator coefficients and state variables).

Once these tasks are performed, the second component, written in assembly language, executes on the Motorola DSP chip. Before computation begins, the code allocates space to store the state variables and the data values produced while processing speech. Once this is done, computation of the envelope cues commences, according to the parameters provided from the front-end. Most of the discussion that follows concentrates on this component of the "Envs" routine, as this component was modified to provide for some of the new conditions evaluated.

Consistent with the monaural approach, the "Envs" program was designed to produce and sum the envelope cues and present the result to one ear. The One-Envelope Monaural, Two-Envelope Monaural, and One-Envelope "Rough" Monaural presentations are produced by the "Envs" routine directly.

In order to explore the effects of the remainder of the presentation schemes, the "Envs" routine was modified. Modifications were made to "Envs.asm", while the front-end was left unchanged. The essential modifications involved presenting different envelope cues on separate output channels. The changes made includes allocating memory to store one modulated envelope cue, while the other is produced. Once the second envelope cue is modulated to the appropriate frequency, the two envelope cues are integerized and then presented on separate channels. The modified program, called "Binenvs.asm", provides substantial flexibility, because once the cues are produced, they can be easily combined in many ways. The Two-Envelope "Rough" Monaural, Simple Binaural, Combination Binaural and the Low Binaural presentations are produced using the "Binenvs" routine.

Copies of the "Envs.asm" and "Binenvs.asm"routines are included in Appendix D. The ammended code in "'Binenvs.asm", is highlighted.

When presenting the tones of each condition to subjects, it is important to verify the signal processing by monitoring the output signals. Hence, the correctness of each condition was evaluated, both by an oscilloscope and orally, using the Tucker-Davis HB6 Headphone Buffer and a pair of Telephonics TDH-39P earphones. Moreover, spectrum plots of each presentation were taken to verify that subjects only experienced the intended tones throughout the project.

Chapter 3

Results

3.1 Training

Subjects' training performance with the envelope cues are shown in Table 3.1. Each row of the table shows the subjects' average scores with each presentation scheme. The last row of the table displays the over-all average for each condition.

Subject	1-Env M.	2-Env M.	1-Env R.M.	2-Env R.M.	S.B.	C.B.	L.B.
NN	85.1	92.9	88.2	88.6	88.75	87.5	84.3
EL	85.9	87.2	91.7	87.4	88.9	93.3	87.3
AC	80.7	91.3	92.8	87.9	91.3	93.3	87.1
RB	89.7	87.9	92.1	87.3	82.4	89.2	82.4
Avg.	85.4	89.9	91.2	87.8	87.8	90.8	85.3

Table 3.1: Training Averages (scores represent percentage correct)

Detailed figures and tables of the training performance is provided in Appenix E. As shown in these figures and tables, NN participated in only five of the six training sessions due to scheduling complications. Nonetheless, her performance with each presentation scheme indicated that she was comfortable with the envelope cues and was thus ready to proceed to testing.

3.2 Training Feedback

Once subjects completed training, they were asked to complete a feedback form (see Appendix B for copy of feedback form). The following are excerpts of subjects' responses to the questions asked.

3.2.1 Question 1

When asked to compare the low tones to the high tones in their ability to convy information about speech, NN and AC found the high tones more helpful than the low tones. NN noted that low tones alone seemed "muddled and fuzzy." AC noted that the high tones were generally more helpful, though they were "static filled and fuzzy" at times.

EL is the only subject who preferred the low tones over the high tones. She felt that the low tones were very helpful with the syllables and "established rhythm." EL noted that the high tones were somewhat helpful as a secondary or background tone.

Finally, RB was indifferent between the low and high tones. Though she noted that the high tones were "quite a bit distracting" at first, after a short "adjustment period", both tones worked equally well. This was especially the case when the two tones were presented together (as opposed to presented to separate ears, as in the Simple Binaural presentation.)

3.2.2 Question 2

When asked about their preference between the monaural and binaural presentations, NN and EL were partial to monaural presentations. NN felt that tones presented to both ears were "confusing" and "distracting", especially when the tones delivered to each ear sounded different. Likewise, EL noted that binaural presentations were especially "disorienting" because the tones delivered to each ear were different.

AC found the monaural presentations more helpful at first. However, as training progressed, he found the binaural presentations "more helpful than just the one ear tones (i.e. monaural presentations)."

Finally, RB was indifferent between the monaural and binaural presentations. She noted that after an "adjustment period", she was equally "comfortable" with both types of presentations.

3.2.3 Question 3

When asked which conditions were comfortable and helpful, subjects' responses varied. NN noted that she liked the Two-Envelope Rough monaural; the tones were "comfortable" to listen to. However, the two presentations that were most comfortable for her were the Two-Envelope monaural and the Combination Binaural. She claimed that although the Combination Binaural involved both ears (a presentation she generally did not like), the tones delivered to each ear sounded very similar and thus was not distracting. Moreover, she noted that the Combination Binaural was "quite clear" and "helpful" when interpreting speech.

AC first noted that he was especially comfortable with the Simple Binaural and Low Binaural presentations. He felt that these two presentations were "probably the most helpful" conditions. Of the monaural presentations, AC mentioned that the One-Envelope and the Two-Envelope Rough monaural conditions "gave a consistent amount of information [about speech] without distracting from lipreading."

EL noted that she preferred the rough monaural presentation. She felt that it helped with the "rhythm" of the sentence. She also liked the two-envelope monaural presentation, after a small adjustment period.

Finally, RB was immediately comfortable with the simple and Combination Binaural conditions. However, as training progressed, she felt comfortable with all the presentation schemes, with the exception of the one-envelope and two-envelope monaural presentations.

3.2.4 Question 4

Finally, subjects were asked to discuss any condition that they particularly disliked. NN disliked both the One-Envelope Rough monaural and the Low Binaural presentations. The One-Envelope Rough monaural sounded too "robotlike" to her and was thus not comfortable. Moreover, NN felt that the Low Binaural tones were too "hollow."

AC disliked the One-Envelope Rough monaural and the Two-Envelope monaural conditions. AC felt that the One-Envelope Rough monaural sounded like "annoying mumble" that was difficult to "decipher." As for the Two-Envelope monaural condition, AC noted that presenting the high and low tones together was sometimes "distracting." Finally, AC mentioned that the high tone in the Combination Binaural condition was "unconfortable and distracting" at times.

Neither EL nor RB disliked any of the presentation schemes strongly. As noted before, RB mentioned that after an adjustment period, she felt that she was able to gather the same amount of information from each condition.

The following table summarizes subjects' preferences to the presentation schemes:

Subject	1-Env M.	2-Env M.	1-Env R.M.	2-Env R.M.	S.B.	C.B.	L.B.
NN	-	P	NP	P	-	P	NP
EL	-	P	P	-	-	-	-
AC	P	NP	NP	P	P	NP	P
RB	P	P	P	P	P	P	P

Table 3.2: Summary of subjects' preferences to the presentation schemes: P=preferred, NP=not preferred

3.3 Testing

Subjects' testing performance and standard deviation are shown in Tables 3.3 and 3.4, respectively. Each row of the tables shows the subjects' performance with each presentation scheme. The last row of each table displays the overall average for each condition.

Detailed figures and tables of testing performance is provided in Appendix E.

Subject	1-Env M.	2-Env M.	1-Env R.M.	2-Env R.M.	S.B.	C.B.	L.B.
NN	58	72	58.2	71.4	69.6	64.4	64
EL	62.8	73.8	61	71.6	69.4	70	67.6
AC	68.6	81.4	70.8	77.4	78.4	81.4	76.4
RB	61.87	75.6	68.6	75.9	69.2	72.6	65.4
Total Av.	62.8	75.7	64.7	74.1	71.7	72.1	68.4

Table 3.3: Testing Averages (scores represent percentage correct)

Subject	1-Env M.	2-Env M.	1-Env R.M.	2-Env R.M.	S.B.	C.B.	L.B.
NN	15.88	15.77	12.42	12.72	10.14	11.11	17.96
EL	17.65	11.64	15.06	10.49	9.04	10.54	15.05
AC	17.56	6.93	10.59	7.83	14.01	11.43	9.37
RB	14.72	10.49	11.28	6.08	11.89	6.74	11.08
Avg.	16.45	11.21	12.34	9.28	11.27	9.96	13.37

Table 3.4: Standard Deviation of Subjects' Test Scores

3.4 Testing Feedback

Upon completion of testing, subjects were asked to complete the same feedback form given to them after training. This was done to monitor subjects' opinion of the presentation schemes. The following is a brief description of subjects' responses.

3.4.1 Question 1

Subject's preference of the tones generally remained unchanged since training. The only difference from the earlier responses is that RB seemed to find the low tones "particularly helpful"; more so than the high tones.

3.4.2 Question 2

Both EL and RB did not change their preferences about the monaural and binaural presentations: EL still preferred monaural presentations, while RB was indifferent between the two types.

NN, who was uncomfortable with the binaural presentations after training, was "completely comfortable" with both presentation types. The binaural conditions were no longer "distracting", but rather helpful in "providing clues to the sentences."

AC felt much more comfortable with the binaural presentations after testing. He noted that the binaural conditions "became much more informative and comfortable" as testing progressed.

3.4.3 Question 3

After testing, it was clear that subjects had clearer preferences for the different presentations. NN felt most comfortable with the Two-Envelope monaural, the Two-Envelope Rough monaural, and the Combination Binaural presentations.

AC was most comfortable with Two-Envelope monaural and the Combination Binaural presentations. He felt that the tones in these presentations "complemented each other and gave a lot of valuable information."

RB preferred the One-Envelope monaural, Two-Envelope monaural, Simple Binaural, and the Combination Binaural presentations. RB also noted that the Two-Envelope Rough monaural and the Low Binaural were helpful, but not as much as the other conditions.

EL noted that she definitely liked the Two-Envelope monaural, Two-Envelope Rough monaural, the Simple Binaural, and the Combination Binaural presentations. EL thought these conditions to be most helpful while trying to understand the Harvard sentences.

3.4.4 Question 4

NN firmly disliked the one-envelope monaural and the rough monaural conditions after testing. Since the speaker of the Harvard sentences had a lower voice than the speaker of the CUNY sentences, NN felt that the low tones were less useful.

AC did not like the rough monaural condition. Also, he felt much less comfortable with the monaural presentations overall. He noted that the monaural presentations "began to leave [him] unbalanced trying to to concentrate on the tones from just one ear."

RB was not comfortable with the rough monaural presentation. She noted that the "mush" that she heard with this presentation was not useful when trying to decipher words.

Finally, EL intensely disliked the Low Binaural presentation. It was "extremely uncomfortable."

The following table summarizes subjects' preferences to the presentation schemes:

Subject	1-Env M.	2-Env M.	1-Env R.M.	2-Env R.M.	S.B.	C.B.	L.B.
NN	NP	P	NP	P	-	P	-
EL	-	P	-	P	P	P	NP
AC	NP	P	NP	NP	-	P	-
RB	P	P	NP	P	P	P	P

Table 3.5: Summary of subjects' preferences to the presentation schemes:P=preferred, NP=not preferred

3.5 Follow-up Testing

Results of the follow-up testing is diplayed in Table 3.6. Each row of the table shows the subjects' average scores with each presentation scheme tested. The last row of the table display the over-all average for each condition.

Subject	1-Env M.	2-Env M.	2-Env R.M.	C.B.
NN	89.6	94.1	95.9	95
EL	88.8	97.9	91.2	92.6
AC	97.6	97.7	96.6	94.2
RB	96.1	98.8	95.8	95
Total Av.	93	97	94.9	94.2

Table 3.6: Follow-up Averages (scores represent percentage correct)

Chapter 4

Discussion

4.1 Presentation Schemes Reviewed

The purpose of testing subjects was to determine the ability of the presentation schemes to convey speech. To verify the correctness of each presentation, the spectra of the envelope signals were measured using an HP 35660A Dynamic Signal Analyzer. As shown in Appendix C, each condition delivered envelope cues at the proper modulated frequencies, which means that subjects were presented with only the intended tones. The data collected from these subjects suggests that a few of the new conditions developed may potentially be effective in aiding the hearing impaired understand speech.

4.1.1 One-Envelope Monaural

Though the One-Envelope Monaural was generally preferred by subjects during training, it was consistly among the least effective in conveying speech (85.4% during training and 62.8% during testing). Also, as testing progressed, subjects noted that they were becoming more uncomfortable with this presentation (see section 3.4.4 for more details).

Nevertheless, the One-Envelope Monaural was found to be more effective than the similar presentation developed by Grant et al.(62.8% vs. 38%)[4]. Though the subjects in this project may have been better speechreaders than those in Grant et al.'s study, the enhanced performance may also be attributed to the wider bandwidth used in both the prefilter and the smoothing filter (refer to Sec. 2.4.1 for details). If this is the case, then a significant improvement in the efficacy of the envelope cues can be achieved by simply incorporating larger bandwidth filters.

It is interesting to note that the One-Envelope Monaural condition was found to be as effective as the two-envelope condition developed by Grant et al.(62.8% vs. 60%). This suggests that enhanced performance seen in this project is due to the filter bandwidths, as it is unlikely that subjects' speechreading abilities were markedly higher than those of the subjects who participated in the previous study.

4.1.2 Two-Envelope Monaural

The effectiveness of the Two-Envelope Monaural condition was confirmed in testing and training. It both produced high scores during training (89.9%), and was the most effective presentation during testing (75.7%). Moreover, it was the only monaural condition that was unanimously preferred by subjects during testing (see Table 3.5 at the end of section 3.4.4). Finally, this condition proved more effective than the most successful two-envelope transposed condition developed by Grant et al. (75.7% vs. 60%) [4]. As mentioned above, this enhanced performance may be due to the subject's speechreading abilities, or the filter bandwidths, or both.

4.1.3 One-Envelope "Rough" Monaural

The One-Envelope "Rough" Monaural presentation was neither effective, nor preferred by subjects during testing. Although it was the most effective condition in training (91.2%), it was among the least successful during testing (64.7%). Also, most subjects found this condition considerably uncomfortable. They noted that it sounded like "mush" and too "robotlike" to be an effective condition.

Since this condition incorporated the same prefilter for each of the envelope cues, we can isolate the effects of the "roughening" sensation. Though the average score of this condition was greater than that of the One-Envelope Monaural, the difference is only slight. Thus, it appears that the rough sensation alone does little to improve the efficacy of the envelope cues.

4.1.4 Two-Envelope "Rough" Monaural

The Two-Envelope "Rough" Monaural proved to be a very effective condition. It was one of the most effective presentations during testing (74.1%) and was generally preferred by subjects throughout the project (see Table 3.2 and Table 3.5). Moreover, this condition proved to be more effective than the one-envelope monaural presentation, which was similar to the most effective one-envelope condition developed by Grant, Braida, and Renn [4].

The Two-Envelope "Rough" Monaural appears to have substantial potential to aiding the hearing impaired understand speech. An attractive feature of this condition is that the tones presented span a total bandwidth of 140 Hz (refer to Sec. 2.4.4 for details). Since the hearing impaired usually have a very limited range of residual hearing, this condition may be helpful to many individuals. Hence, the possibility of providing aid to a greater population may make the Two-Envelope "Rough" Monaural more attractive than the Two-Envelope Monaural, which requires a much broader range of hearing to be effective (refer to Sec. 2.4.2 for details).

Since the "roughing" effect was found to do little to enhance performance, it seems that the source of the envelope cues ultimately determines the effectiveness of a presentation. Furthermore, incorporating a wide presentation bandwidth seems unnecessary as this condition performed almost as well as the Two-Envelope Monaural condition.

4.1.5 Simple Binaural

The Simple Binaural condition was somewhat effective. Though it was generally preferred by subjects, the scores attained with this presentation were not as high as were hoped to be (71.7% during testing). Since it is a binaural condition, it was hoped that the “removal” of any masking effects or other perceptual interferences found with monaural presentations would enhance performance. However, this was not the case, as both the Two-Envelope Monaural and the Two-Envelope “Rough” Monaural proved more effective during testing. Thus, the benefits of a binaural presentation may not be as profound as was hoped.

4.1.6 Combination Binaural

The Combination Binaural condition proved more effective than the simple binaural, though it was not as successful as the Two-Envelope Monaural nor the Two-Envelope “Rough” Monaural. Nonetheless, it was the only binaural presentation that was unanimously preferred by subjects during testing. Also, it was among the most effective presentations during training (90.8%) and testing (72.1%). As noted by subjects, the success of this condition may stem from the fact that the tones delivered to each ear sounded more similar than with the other binaural conditions. However, the difference in scores between the Simple Binaural (71.1%) and the Combination Binaural (72.1%) is not significant enough to confirm this relationship. Perhaps the marginal improvement over the Simple Binaural can be attributed to the comfort subjects had when listening to similar tones in each ear.

4.1.7 Low Binaural

Finally, the Low Binaural presentation proved the least effective of the binaural conditions tested. Though it is difficult to ascertain if subjects found this condition comfortable (see Table 3.5), performance scores were among the lowest during training (85.3%) and testing (68.4%). Since the tones presented to subjects span a very narrow bandwidth, it was hoped that this condition would have been more successful in conveying speech. Thus, it appears that the Two-Envelope “Rough” monaural would be more effective than the Low Binaural, especially if the individual listening to the envelope cues has a narrow range of residual hearing.

4.2 Follow-up Testing Reviewed

The purpose of follow-up testing was to isolate each condition's ability to convey speech, irrespective of the sentences used. Since each subject was presented with the same sentences under the same conditions, there may be some correlation between performance and the sentences used (i.e. the sentences may have been particularly difficult or easy, irrespective of the presentation scheme used.) Since the Two-Envelope "Rough" Monaural seemed to be more effective than the One-Envelope Monaural, it was necessary to ensure that the scores seen only reflect each presetentation's ability to convey speech. The Two-Envelope Monaural and the combination binaural conditions were also reviewed during follow-up testing to verify their relative scores seen during testing.

The results of follow-up testing were not conclusive. Because Clarke sentences are relatively simple, performance scores were too high to verify any trend seen in testing (see Table 3.6). Though the Two-Envelope "Rough" Monaural still out-performed the One-Envelope Monaural, the difference is not substantial enough to make any solid conclusions. The same can be said for the Two-Envelope Monaural and the Combination Binaural. Thus, more difficult sentences (like Harvard sentences) need to be used in order to be able to verify any trends already seen.

Chapter 5

Recommendations

Though the Two-Envelope "Rough" Monaural and the Combination Binaural conditions appear promising, future work is needed to verify the trends seen in this project. As mentioned in the discussion above, a new group of subjects need to be tested under these conditions, where each subject is presented with different sentences for a given condition.

Also, it appeared that subjects became increasingly comfortable with binaural presentations, especially when the sounds delivered to each ear sounded similar. Thus, it may prove benefical to present the the tones of the Two-Envelope "Rough" Monaural to both ears. Since the total bandwidth of these tones span only 140 Hz, it is plausible that an adequate portion of the deaf community could derive much benefit from such a condition.

Finally, the envelopes of filtered bands of speech from different spectral regions may be partially correlated. To be an aid to speechreaders, it is not sufficient that the second envelope cue be audible. Rather differences between the two envelopes must be clearly perceived and correctly interpreted. Thus, future work should address the correlation issue and presentation conditions exploiting this correlation should be explored.

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[10] Envs program was written in 1991 by Louis D. Braida.

Appendix A

A.1 SIVO PROJECT

A.1.1 Background

A project to provide hearing-impaired listeners with wearable aids capable of producing audible lipreading cues was commenced by Philip Nadeau, in 1995. The aids were designed to incorporate a monaural presentation of two envelope cues. Nadeau's project was plagued by several problems. One problem that greatly obstructed progress was that the SIVO aids had to be sent to the manufacturers in London to be programmed with the envelope producing code.

The programming interface of the SIVOs was damaged and only the manufacturers of the aid were able to download the code. Thus, Nadeau designed the signal processing conservatively by incorporating few filter stages. Hence, performance of the SIVOs were not tested to the full extent.

My contunuation of Nadeau's work focussed on optimizing the code in order to provide for more substantial filters to improve performance. However, several problems made it prohibitively difficult to progress meaningfully. The following summary will address issues faced in order to facilitate future work on this project.

A.1.2 SIVO Code

The processor within a SIVO aids is a Texas Instrument TMS3205x fixed point processor. The wisdom behind choosing a fixed point processor is that most floating point processors tend to drain battery packs at a much faster rate, making it awkward for subjects to use the SIVOs in their daily activities.

Nadeau programmed the TI DSP chip in its own assembly language. There is a manual in lab that lists all the possible commands and corresponding syntax that will be useful when coding. The key component of the signal processing code is the "Biquad routine", which performs the filtering of input signals. The performance of the SIVO aid depends almost solely on this routine.

Optimizing the Biquad routine can provide more processor time to allow for more substantial filters. These filters would process signals more accurately, leading to improved performance of the SIVO aids. Thus, I spent a good deal of time analyzing the Biquad routine written by Nadeau, in "mitsivo.asm", and trying to identify ways of optimizing the code in order to improve performance.

After much effort, I identified areas of the code that could be optimized and rewrote the biquad routine. This revised code is contained in "sivotest.asm", which differs from the original code only in the biquad routine.

Problems began to arise when I attempted to debug the code. The revised code complied as expected, but produced only noise when downloaded onto the SIVOs. I reviewed the algorithm and syntax of the code several times by hand, but was unable to identify any obvious mistakes. Thus, I attempted to use the "emulator", a tool provided by TI to debug code, in hopes of finding the error(s). However, the emulator was designed primarily to debug C programs, not assembly code, as indicated in the emulator's manual, the "C Source Debugger."

So why write the code in assembly, when you can write it in C? The answer to this question addresses one of the major set backs of this project. The C compiler that TI designed for the TMS3205x is fundamentally flawed. I realized this when I began rewriting the biquad routine. Originally, I attempted to optimize the code by writing it in C, then use the compiler to translate it into assembly. The results were disappointing. The compiler called several subroutines that were later found to be nonsense. For example, the compiler referenced a subroutine to perform a 32 bit multiplication. (This subroutine is different than the 32 bit multiplier code listed in the manual. The one in the manual is correct and was used in the revised code.) This routine was not completed and only produced nonsense for results. For instance, a multiplication of 1 x 1 would produce a result of zero. Thus, if the compiler could not be trusted to correctly translate code from C to assembly, it could not be trusted to translate C into machine language. (I examined the machine language produced by the compiler to verify this assumption. Unfortunately, I was correct.)

Throughout the duration of the project, I was in constant contact with the people at TI. I was hoping that they would offer some words of wisdom about the C compiler's poor design and the limitations of the emulator. Unfortunately, I was unable to obtain any useful information from the "technical experts." They were utterly surprised when I pointed out to them the shortcomings of the compiler and really had no idea how I could use the emulator to debug assembly language. Their response to my questions about the emulator was that it was not really designed for assembly code debugging and suggested that I translate the code into C. As mentioned above, this suggestion would not lead to a meaningful solution; just another class of problems.

A.1.3 Subjects

Another component of the project that proved difficult was the search for subjects suitable for field trials of the aid. As I was redesigning the biquad subroutine, I conducted a search for individuals from the deaf community who would be willing to partake in the SIVO project and who would benefit from the new aid. This search involved testing individuals in the lab to compare their ability to lip-read with their own aid with their ability to lip read while hearing the same processed sound that they would hear in the SIVO aid. If an individual's performance with the envelope cues was better or at least as good as with their own aid (measured over time), then the person was asked to join the project. Though the revised code was not complete, the intention was to provide subjects with SIVOs running the older code until the revised code was ready.

I had no difficulty finding members of the deaf community who were willing to participate in the project. In fact, finding such people was quite easy. Most hearing impaired individuals are always interested in trying new ways of improving their hearing.

However, the SIVO aid was too awkward for people to wear over a long periods of time. One common compliant was that the aid was too large and bulky to wear while interacting with people. Though this is an adjustment that we ask subjects to make, few seemed willing to comply. Another complaint was that the microphone on the aid was not sensitive enough to pick up a sufficient amount of input to produce a meaningful output. One subject claimed that it was necessary to sit directly in front of the television in order understand what was being said. Adjusting the input gain seemed to only increase the background noise, making it more difficult to understand speech.

The limitations of the SIVO aid greatly hindered progress in the project and made it difficult to make accurate measurements of a subject's performance. Whenever a subject was asked for his/her opinion about the aid, he/she would complain about the aid itself and not report much about the actual sound that was delivered.

A.1.4 Summary and Suggestions

To summarize, there were a few fundamental problems faced during the course of the project. Not only was it difficult to use the C compiler to produce meaningful code, it was also difficult to use the emulator to debug the assembly code. Also, the physical features of the aid made it very difficult to retain a subject's interest in the project, as it was too frustrating for them to communicate with other people.

Given these descriptions of the problems faced, it would seem that substantial improvements could be attained if another type of processor could be used in this project. Also, the physical features of the aid (size, output gain, input gain, etc.) need to be addressed in order to retain a subject's interest over the course of the project. This would involve finding a more appropriate case for the processor as well as providing a more powerful microphone what would pick up sufficient inputs. If neither of these options are possible, then it may prove beneficial to incorporate a cordless microphone with the SIVO aid. Though this will not improve the difficulties faced when coding the TMS3205x processor, it may abate subjects' dissatisfaction with the physical features of the SIVO.

Appendix B

B.1 Feedback Form

This form is to give you the opportunity to provide us with some feedback about your experiences thus far in the project. Specifically, we would like to know how you feel about the tones presented to you during training. We encourage you to be completely honest in expressing your opinions. The more detailed your responses, the more helpful they will be to us.

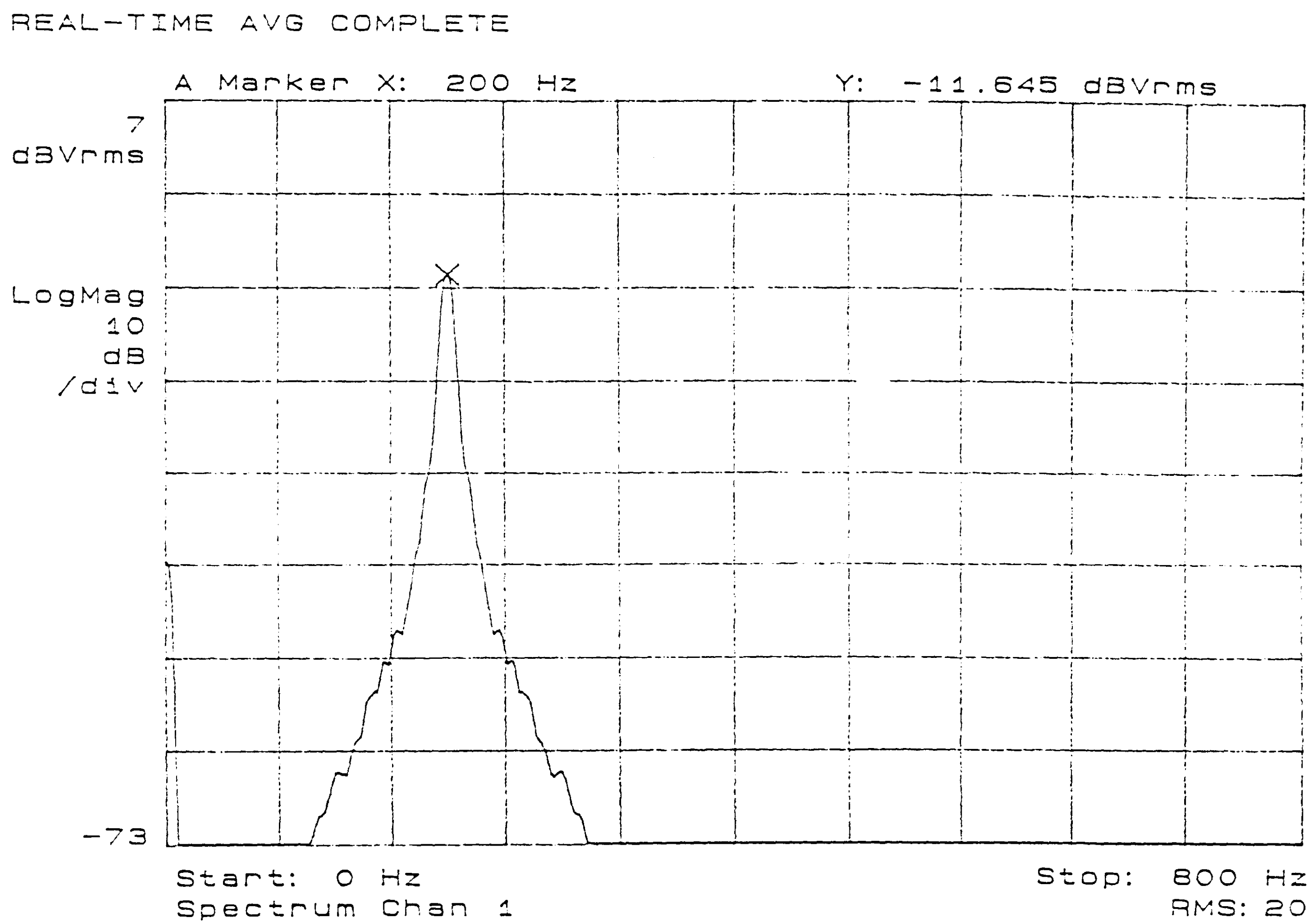
1. Do you feel that the low tones are particularly helpful? How about the high tones?
2. Do you prefer presentations involving both ears or just one? Why?
3. Which presentation conditions do you like or feel most comfortable with?
4. Which presentation conditions do you dislike or feel uncomfortable with?

Appendix C

C.1 Spectra Plots

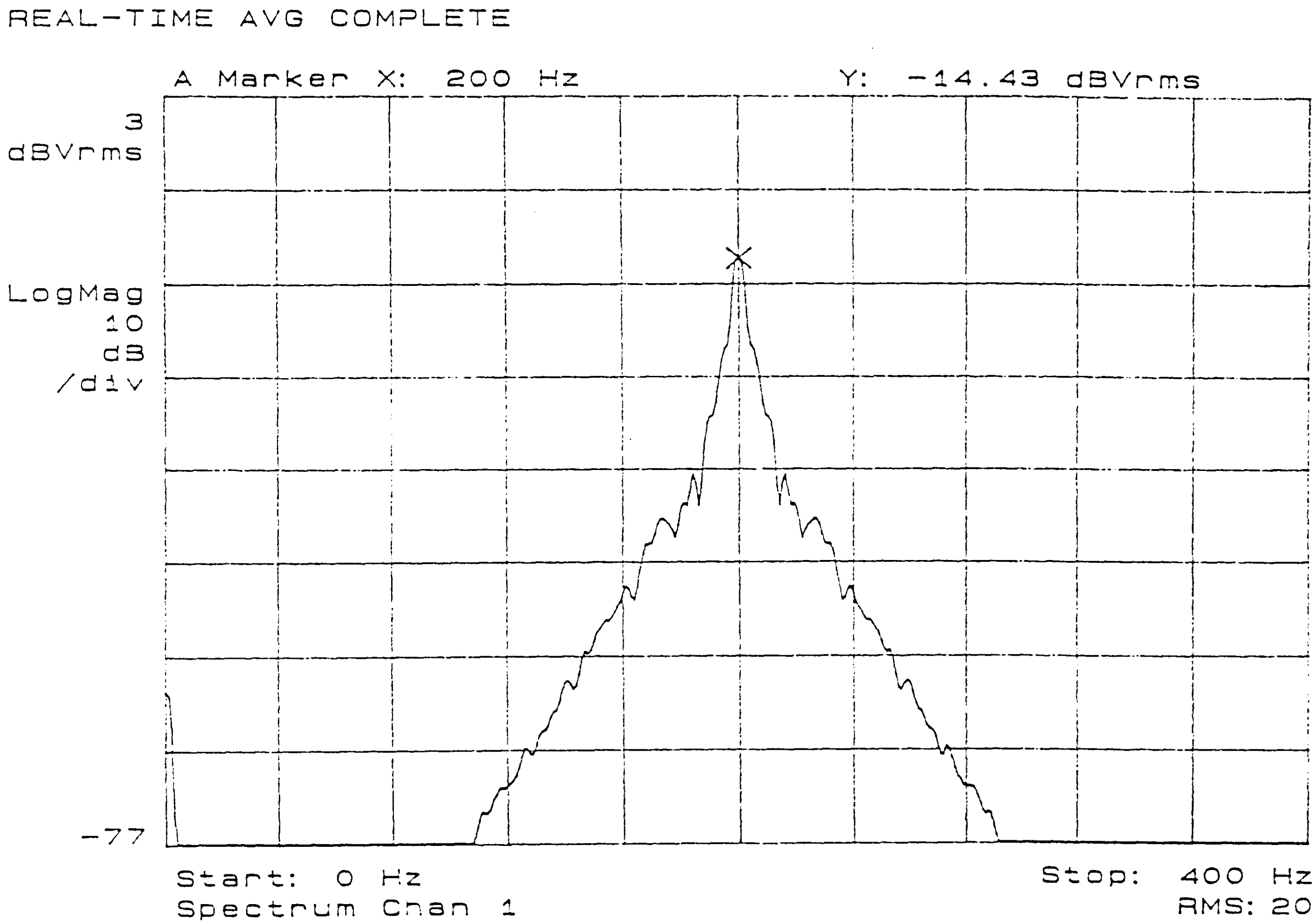
1-env /mon

ONE-ENVELOPE MONOAURAL

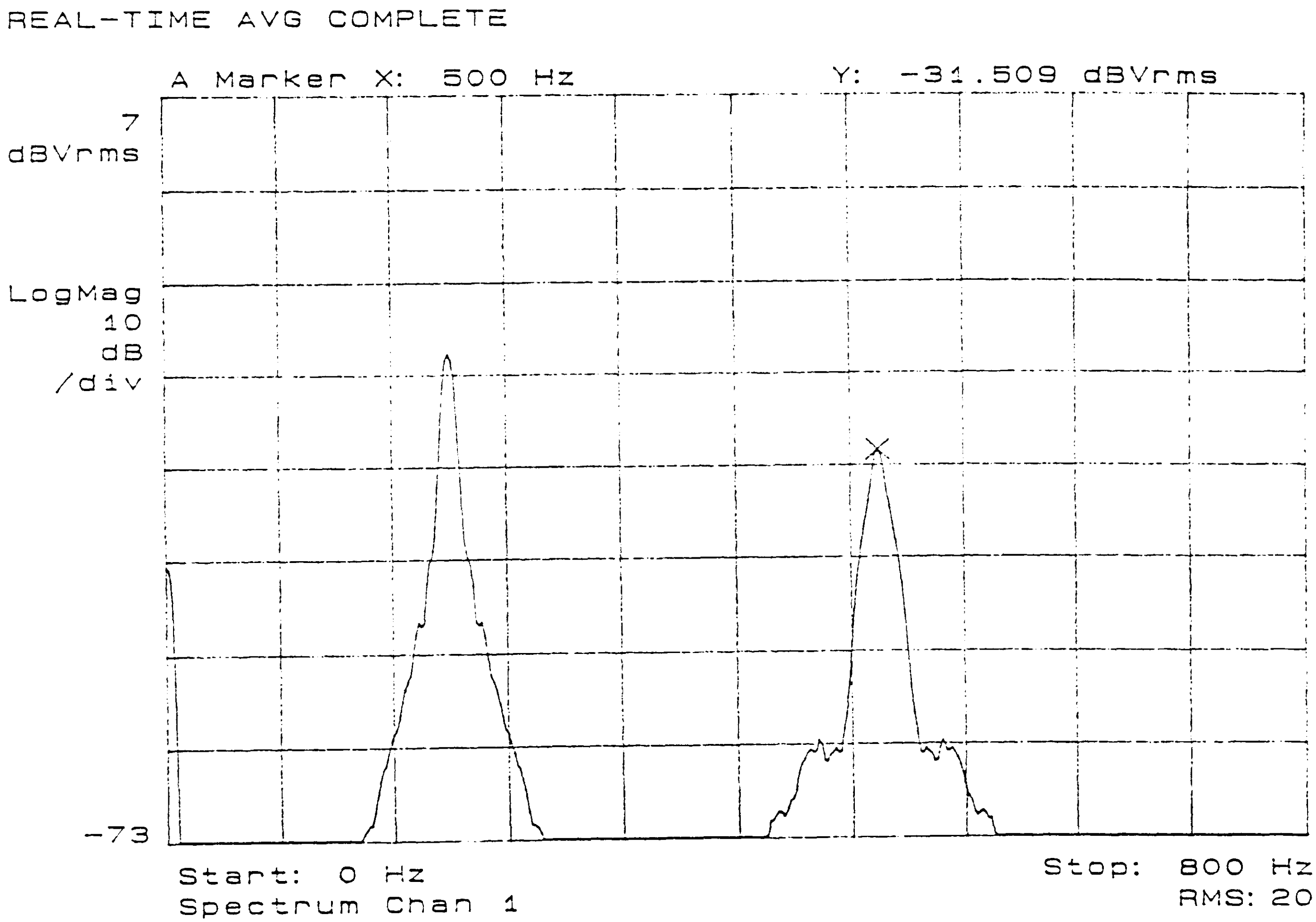


1-env mon

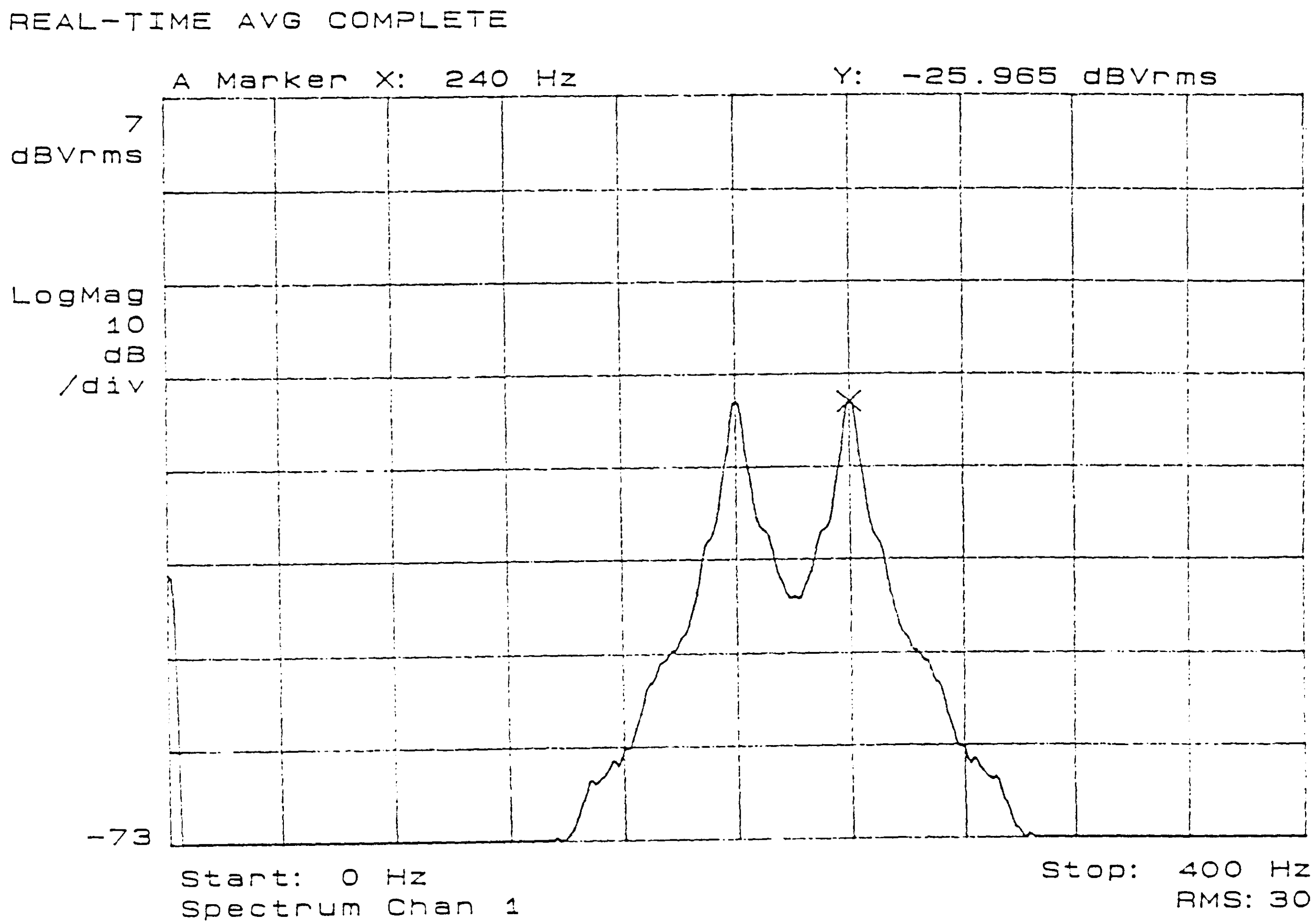
ONE-ENVELOPE MONOAURAL



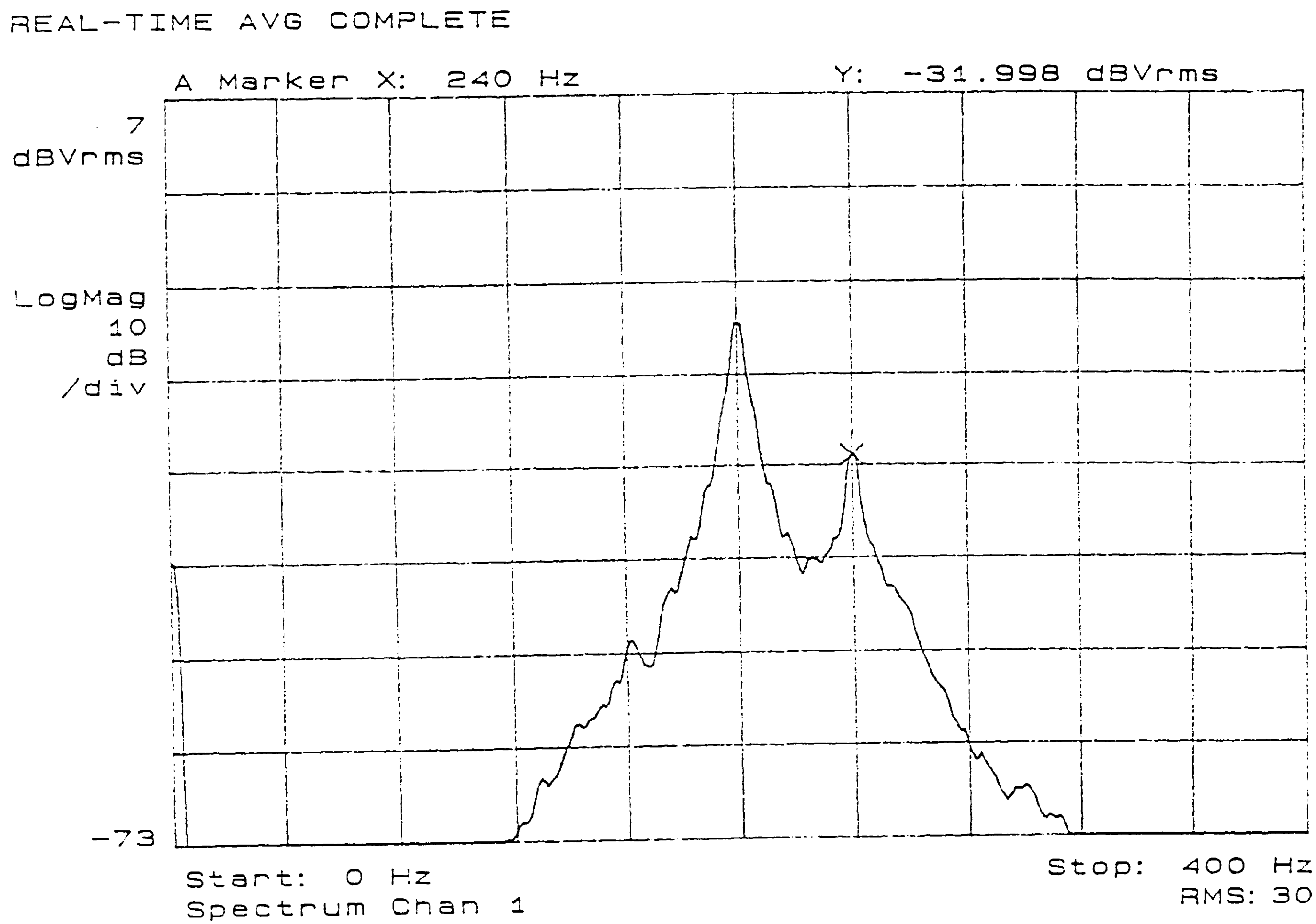
TWO-ENVELOPE MONOAURAL



ONE-ENVELOPE "ROUGH" MONOAURAL

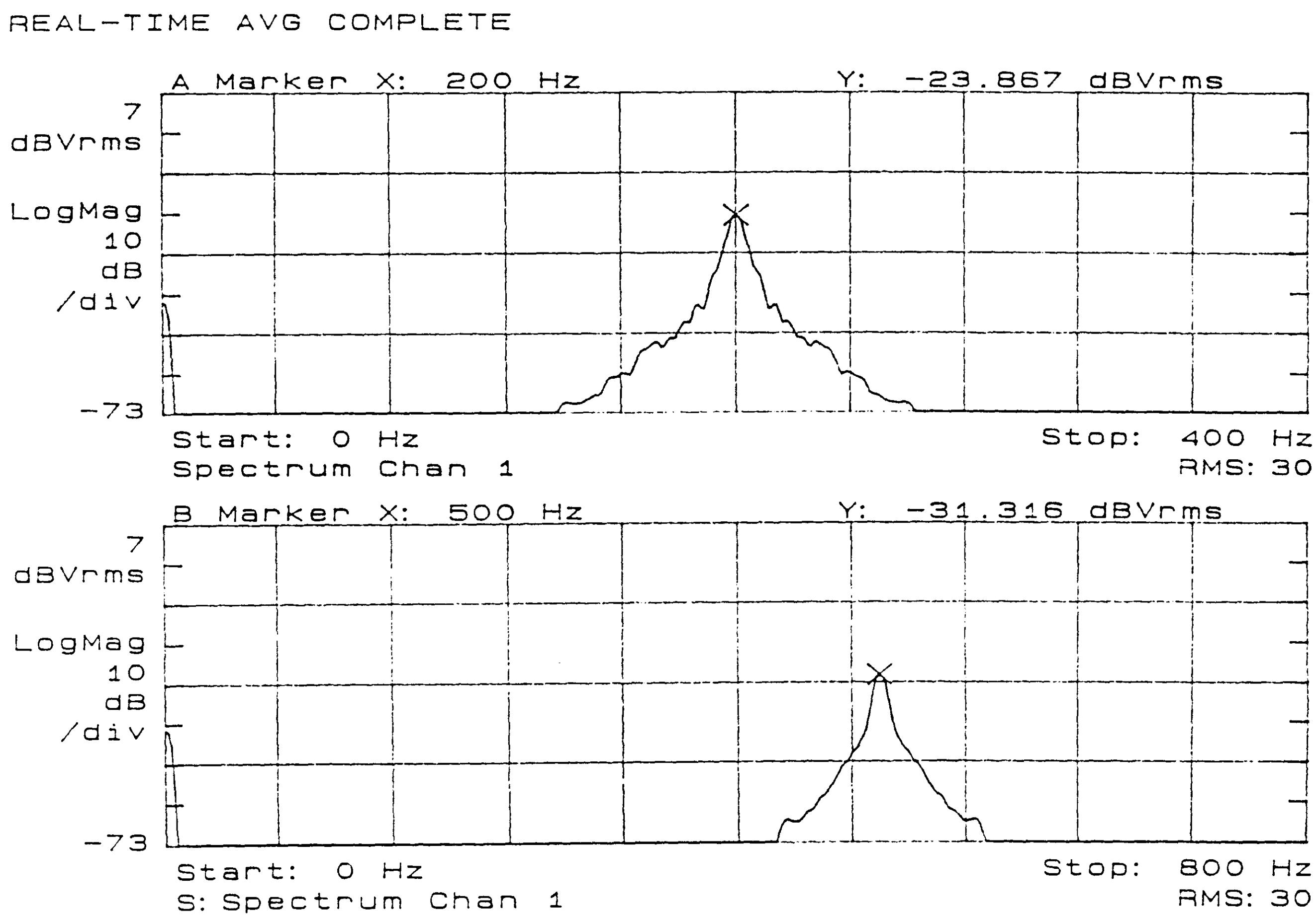


TWO-ENVELOPE "ROUGH" MONOAURAL



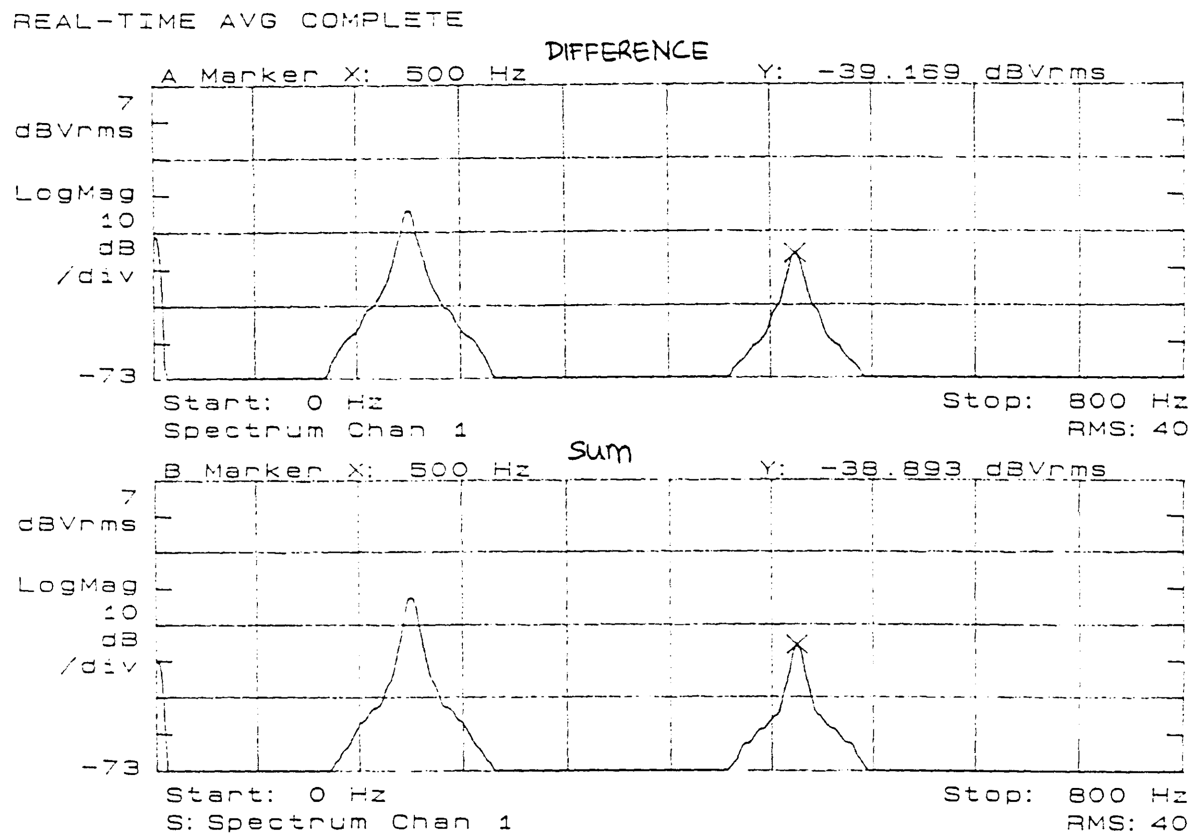
Simple 6/4

SIMPLE BINAURAL



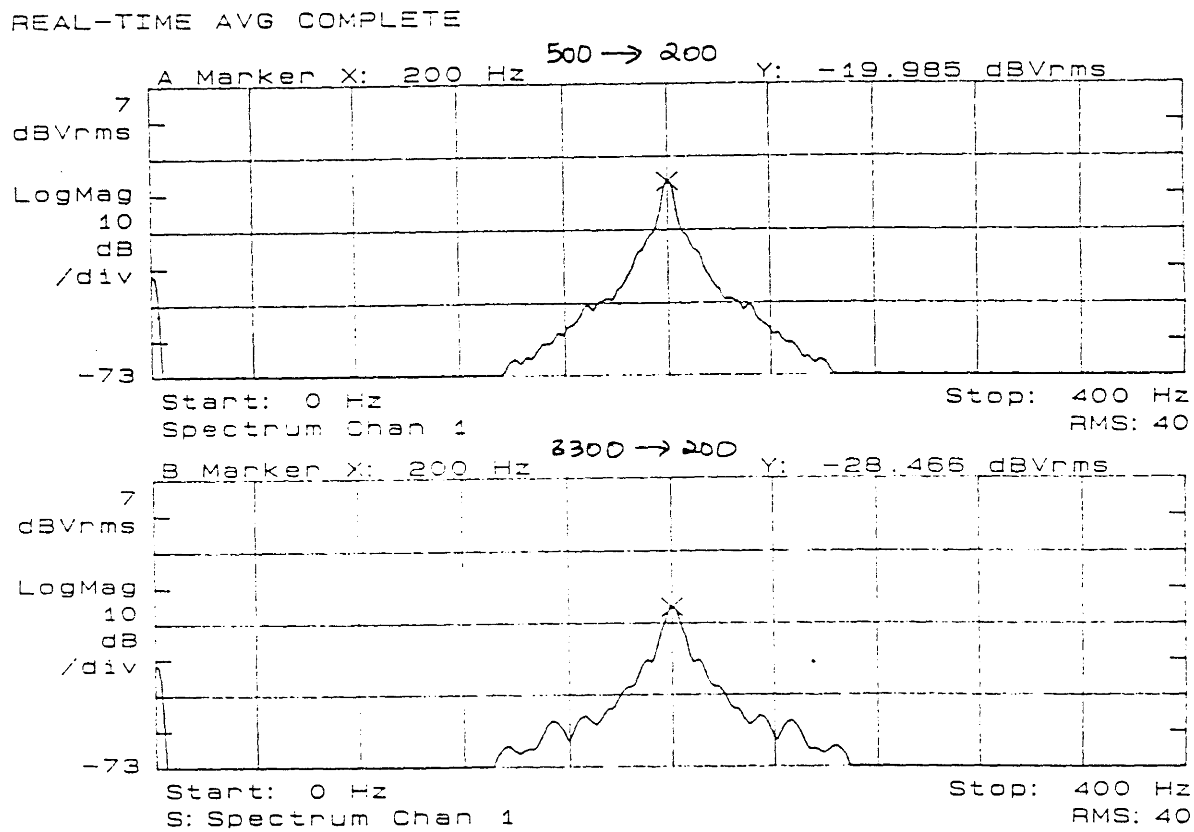
Combo bin

COMBINATION BINAURAL



Low bin

LOW BINAURAL



Appendix D

D.1 "ENVS" Code

```
envs  IDENT 1,0
  page 132,66

; a programmable digital multiple modulated envelope generator
; uses double prcision storage of oscillator parameters 8-june-92
;   and direct upload of these double precision parameters
; uses the five coefficient biquad filter of B.1.50 in dpp96000 manual
; if J_RUN_ME equ 1 run this program after reset

J_RUN_ME equ 1
SLOW equ 1
MAX_BANDS equ 20
MAX_STAGES equ 20
NCOEFS equ 5
NSVARS equ 2
NFILTS equ 1
NBANDS equ 2
IF J_RUN_ME
NADDS equ 64
CYCLE_COUNT equ 0
ELSE
NADDS equ 1
ENDIF
MAX_AMP  equ 1000.0
TWOPI equ 8.0*@atn(1.0)
HMAX equ @POW(2,32)
RANNMC equ 69069
```

```
INVMAX equ 1.0/HMAX
BIAS equ 0.5*NADDS
SRATE equ 24000
SMPLPD equ 1.0/SRATE
FCO equ 200.
WCO equ TWOPI*FCO
OMEGA1 equ WCO*@sin(TWOPI/8.0)
SIGMA1 equ WCO*@cos(TWOPI/8.0)
A11 equ 2.0*@xpn(-SIGMA1/SRATE)*@cos(OMEGA1/SRATE)
A12 equ -1.0*@xpn(-2.0*SIGMA1/SRATE)
B11 equ 0.0
B12 equ 0.0
B10  equ (1+A11+A12)/(1+B11+B12)
FNORM equ 0.1*@pow(2,15)*@sqt(12.0/NADDS) ;adjust the noise amplitude
FREQ equ 1000.0
AMP equ MAX_AMP
FANG equ TWOPI*FREQ*SMPLPD
OSCP equ 2.0*@cos(FANG)
OSV1 equ AMP*@sin(FANG)
OSV2 equ AMP*@cos(FANG)

DECLARE_MY_VECTORS MACRO
JSR >NEW_RATE ;CVR $90 Long ISR to write new ctrl register
MOVE #1,d7.h ;CVR $91 Start command
NOP
ENDM


org l:$1000
osc5tbl
DUP MAX_BANDS
IF J_RUN_ME
ds 1 ;oscp
ds 1 ;ossv1
ds 1 ;ossv2
ds 1 ;ocsv1
ds 1 ;ocsv2
ELSE
dc OSCP ;oscp
dc 1.0 ;ossv1
dc OSV2 ;ossv2
dc 1.0 ;ocsv1
dc OSV2 ;ocsv2
ENDIF
ENDM
```

```
end_osc5tbl

org l:end_osc5tbl
osc3tbl
DUP MAX_BANDS
IF J_RUN_ME
ds 1 ;oscp
ds 1 ;ossv1
ds 1 ;ossv2
ELSE
dc OSCP ;oscp
dc 1.0 ;ossv1
dc OSV2 ;ossv2
ENDIF
ENDM
end_oscps

org x:end_oscps
svrtbl DUP MAX_BANDS
IF J_RUN_ME
ds MAX_STAGES*NSVARS ;ssvars
ds MAX_STAGES*NSVARS ;csvars
ds MAX_STAGES*NSVARS ;osvars
ELSE
bsc MAX_STAGES*NSVARS,0.0 ;ssvars
bsc MAX_STAGES*NSVARS,0.0 ;csvars
bsc MAX_STAGES*NSVARS,0.0 ;osvars
ENDIF
ENDM
end_svrtbl

org y:end_oscps
IF J_RUN_ME
samp ds 1
waits ds 1
nbands ds 1
modsum ds 1
ch1att ds 1
ELSE
samp dc 1000.0
waits dc 0
nbands dc NBANDS
modsum dc 0.0
ch1att dc 1.0
ENDIF
```

```
ybandtbl
DUP MAX_BANDS
IF J_RUN_ME
ds 1 ;nifilt
ds 1 ;nofilt
ELSE
dc NFILTS ;nifilt
dc NFILTS ;nofilt
ENDIF
ENDM
end_ybandtbl

org y:end_ybandtbl
coefftbl
DUP MAX_BANDS
IF J_RUN_ME
ds MAX_STAGES*NCOEFS ;icoeff1
ds MAX_STAGES*NCOEFS ;icoeff2
ds MAX_STAGES*NCOEFS ;ocoeff
ELSE
dc A12 ;icoeff1
dc A11
dc B12
dc B11
dc B10
dc A12 ;icoeff2
dc A11
dc B12
dc B11
dc B10
dc A12 ;ocoeff
dc A11
dc B12
dc B11
dc B10
ENDIF
ENDM
end_coefftbl

NOLIST
IF J_RUN_ME
INCLUDE "JANUS.A"
ELSE
org P:$100
```

```
ENDIF
LIST
; the following parameters are kept in the DSP's registers
; d7.h Start signal
; d7.m scratch storage for $90 CV
; d7.l scratch storage used by do loops
; For the folloing values, first, the data is written to the TX register,
;    then the user host command is called to update the parameter.
; $90 Sample rate/control register
; $91 Start signal

start
IF J_RUN_ME
move #DAU_CR,r7 ;for quick checking of sample clock
move #ADA_DACEN|ADA_N16,d7.m ;Default to 16 kHz with DACs on
move d7.m,y:DAU_CR ;set control register
bclr #5,x:MI_HCR ;Enable Inner Port interface
wait1 move #0,d7.h ;Clear start signal
clr d0.l
wait0 inc d0.l
move d0.l,y:samp
jclr #0,d7.h,wait0 ;Loop until start CVR occurs
ENDIF
move #$ffffffff,m0 ;All indexing is normal
move m0,m4
move m4,m1
move #3,n1
move #2,n2
bra outp0
; bra wait1

mloop
move #osc5tbl,r1
move #osc3tbl,r3
move y:nbands,d7.l
oscs ;uses r1, r3, d0,d1,d3,d4,d5,d6 output in d6
; generates a sine-cosine pair (r1,d1,d4) and another sine (r3,d3,d0)
do d7.l,end_oscs
move l:(r1)+,d1.d ;get s-c osc parameter
move l:(r1)+,d6.d ;get ultimate s-c sine state variable
move l:(r1)-,d5.d ;get penultimate s-c sine state variable
fmpy.x  d5,d1,d4 d5.d,l:(r1)+ ;s-c penult is next s-c ult
fsub.x  d6,d4 l:(r3)+,d3.d ;get s osc parameter
move l:(r3)+,d6.d ;get ultimate s sine state variable
move l:(r3)-,d5.d ;get penultimate s sine state variable
```

```
fmpy.x d5,d3,d0 d5.d,l:(r3)+ ;pen s sv is new ult s sv
fsub.x d6,d0 d4.d,l:(r1)+ ;save new pen s-c sv
move l:(r1)+,d6.d ;get ultimate s-c cosine state variable
move l:(r1)-,d5.d ;get penultimate s-c cosine state variable
fmpy.x  d5,d1,d4 d5.d,l:(r1)+ ;penult s-c csv is next ult
fsub.x  d6,d4 d0.d,l:(r3)+ ;new penultimate s sv
move  d4.d,l:(r1)+ ;new penultimate s-c c sv
end_oscs

move #svrtbl,r0 ;state variables
move #osc3tbl+1,r1 ;output oscillator parameters
move #osc5tbl+1,r2 ;input oscillator parameters
move #ybandtbl,r3 ;numbers of filter sections
move #coefftbl,r4 ;filter coefficients
move #modsum,r6 ;the final result
fclr d0
do d7.l,end_mloop
move l:(r2)+n2,d3.d ;get the sine value
fmpy.x d3,d8,d2 d0.s,y:(r6) ; shift the input down to zero
move y:(r3)+,d7.l ;get the number of input filter stages
; jsr filter
fclr d1 x:(r0)+,d4.s y:(r4)+,d6.s
do d7.l,end_flt1
fmpy d4,d6,d0 fadd.s d1,d2 x:(r0)-,d5.s y:(r4)+,d6.s
fmpy d5,d6,d1 fadd.s d2,d0 d5.s,x:(r0)+ y:(r4)+,d6.s
fmpy d6,d4,d1 fadd.s d1,d0 y:(r4)+,d6.s
fmpy.s d6,d5,d2 d0.s,x:(r0)+ y:(r4)+,d4.s
fmpy d4,d0,d1 fadd.s d1,d2 x:(r0)+,d4.s y:(r4)+,d6.s
end_flt1 fadd.s d1,d2 ;finish up
fmpy.x d3,d2,d2 l:(r2)+n2,d3.d ;shift it up and get cosine
move d2.s,d9.s
; move l:(r2)+n2,d3.d ;get the cosine value
fmpy.x d3,d8,d2 ;shift the input down
; jsr filter
fclr d1 x:(r0)+,d4.s y:(r4)+,d6.s
do d7.l,end_flt2
fmpy d4,d6,d0 fadd.s d1,d2 x:(r0)-,d5.s y:(r4)+,d6.s
fmpy d5,d6,d1 fadd.s d2,d0 d5.s,x:(r0)+ y:(r4)+,d6.s
fmpy d6,d4,d1 fadd.s d1,d0 y:(r4)+,d6.s
fmpy.s d6,d5,d2 d0.s,x:(r0)+ y:(r4)+,d4.s
fmpy d4,d0,d1 fadd.s d1,d2 x:(r0)+,d4.s y:(r4)+,d6.s
end_flt2 fadd.s d1,d2 ;finish up
fmpy.x d3,d2,d2  l:(r2)+,d6.d ;(the move only keeps r2 in sync)
move d9.s,d1.s ;get the sine-modulated result
fadd.x d1,d2 ;combine sine and cosine
```

```
fabs.s d2 ;rectify the sum
move y:(r3)+,d7.l ;get the number of output filter stages
; jsr filter ;smooth the rectified sum
fclr d1 x:(r0)+,d4.s y:(r4)+,d6.s
do d7.l,end_flt3
fmpy d4,d6,d0 fadd.s d1,d2 x:(r0)-,d5.s y:(r4)+,d6.s
fmpy d5,d6,d1 fadd.s d2,d0 d5.s,x:(r0)+ y:(r4)+,d6.s
fmpy d6,d4,d1 fadd.s d1,d0 y:(r4)+,d6.s
fmpy.s d6,d5,d2 d0.s,x:(r0)+ y:(r4)+,d4.s
fmpy d4,d0,d1 fadd.s d1,d2 x:(r0)+,d4.s y:(r4)+,d6.s
end_flt3 fadd.s d1,d2 ;finish up
move l:(r1)+n1,d6.d ;get the modulating sine
fmpy.x d6,d2,d0 y:(r6),d6.s ;modulate it with the envelope
fadd.x d6,d0
end_mloop

output
move d8.s,d1.s
move y:ch1att,d9.s
fmpy.x d9,d1,d1
intrz d1.s ; d1 contains regular speech
intrz d0.s ; d0 contains summed cues
join d1.l,d0.l ; d1 & d0 delivered to separate channels


outp0
IF J_RUN_ME
IF CYCLE_COUNT
move #waits,r0 ;r0 also used by FILTER
clr d6.l ;to provide a count of free cycles
qr_ads0 inc d6.l
jset #0,y:(r7),qr_ads0 ;read sample interrupt until sample pd.
qr_ads1 inc d6.l
jclr #0,y:(r7),qr_ads1 ;read sample interrupt until sample pd.
move d6.l,y:(r0) ;store the cycle count
ELSE
qr_ads0 jset #0,y:(r7),qr_ads0 ;read sample interrupt until sample pd.
qr_ads1 jclr #0,y:(r7),qr_ads1 ;read sample interrupt until sample pd.
ENDIF
move y:DAU_DATA,d1.l
move d0.l,y:DAU_DATA ;send mixed stereo sample to DACs
split d1,d0
ext d1
float.s d0
move d0.s,y:samp
```

```
ENDIF
move y:samp,d8.s
bra  mloop



filter ;input and output samples are in d2.s
;requires d7.l (unchanged) as well as r0 and r4 (which are updated)
;uses r0,r4,d0,d1,d2,d4,d5,d6 but not d3, d8, d9
fclr d1 x:(r0)+,d4.s y:(r4)+,d6.s
do d7.l,end_flt
fmpy d4,d6,d0 fadd.s d1,d2 x:(r0)-,d5.s y:(r4)+,d6.s
fmpy d5,d6,d1 fadd.s d2,d0 d5.s,x:(r0)+ y:(r4)+,d6.s
fmpy d6,d4,d1 fadd.s d1,d0 y:(r4)+,d6.s
fmpy.s d6,d5,d2 d0.s,x:(r0)+ y:(r4)+,d4.s
fmpy d4,d0,d1 fadd.s d1,d2 x:(r0)+,d4.s y:(r4)+,d6.s
end_flt fadd.s d1,d2 ;finish up
rts



; Long ISR to change the sample rate
NEW_RATE
IF J_RUN_ME
move x:<<MI_HRX,d7.m ;Read data from host
move d7.m,y:DAU_CR ;clear control register
ENDIF
rti

end start



****************************************************************************
```

D.2 “BIENVS” Code

```
envs    IDENT   1,0
page 132,66

;This routine is based on the "ENVS" routine written by LDB. It has been
;modified to present envelope cues on separate channels to provide for
```

```
;binaural presentations. April 3, 1997. Sharieff A. Mansour.

; a programmable digital multiple modulated envelope generator
; uses double prcision storage of oscillator parameters 8-june-92
;   and direct upload of these double precision parameters
; uses the five coefficient biquad filter of B.1.50 in dpp96000 manual
; if J_RUN_ME equ 1 run this program after reset

J_RUN_ME equ 1
SLOW equ 1
MAX_BANDS equ 20
MAX_STAGES equ 20
NCOEFS equ 5
NSVARS equ 2
NFILTS equ 1
NBANDS equ 2
IF      J_RUN_ME
NADDS equ 64
CYCLE_COUNT equ 0
ELSE
NADDS equ 1
ENDIF
MAX_AMP  equ 1000.0
TWOPI equ 8.0*@atn(1.0)
HMAX equ @POW(2,32)
RANNMC equ 69069
INVMAX equ 1.0/HMAX
BIAS equ 0.5*NADDS
SRATE equ 24000
SMPLPD equ 1.0/SRATE
FCO equ 200.
WCO equ TWOPI*FCO
OMEGA1 equ WCO*@sin(TWOPI/8.0)
SIGMA1 equ WCO*@cos(TWOPI/8.0)
A11 equ 2.0*@xpn(-SIGMA1/SRATE)*@cos(OMEGA1/SRATE)
A12 equ -1.0*@xpn(-2.0*SIGMA1/SRATE)
B11 equ 0.0
B12 equ 0.0
B10  equ (1+A11+A12)/(1+B11+B12)
FNORM equ 0.1*@pow(2,15)*@sqt(12.0/NADDS)       ;adjust the noise amplitude
FREQ equ 1000.0
AMP equ MAX_AMP
FANG equ TWOPI*FREQ*SMPLPD
OSCP equ 2.0*@cos(FANG)
OSV1 equ AMP*@sin(FANG)
```

```
OSV2 equ AMP*@cos(FANG)

DECLARE_MY_VECTORS      MACRO
JSR     >NEW_RATE       ;CVR $90 Long ISR to write new ctrl register
MOVE    #1,d7.h         ;CVR $91 Start command
NOP
ENDM


org     l:$1000
osc5tbl
DUP     MAX_BANDS
IF      J_RUN_ME
ds      1       ;oscp
ds      1       ;ossv1
ds      1       ;ossv2
ds      1       ;ocsv1
ds      1       ;ocsv2
ELSE
dc      OSCP    ;oscp
dc      1.0     ;ossv1
dc      OSV2    ;ossv2
dc      1.0     ;ocsv1
dc      OSV2    ;ocsv2
ENDIF
ENDM
end_osc5tbl

org l:end_osc5tbl
osc3tbl
DUP MAX_BANDS
IF      J_RUN_ME
ds      1       ;oscp
ds      1       ;ossv1
ds      1       ;ossv2
ELSE
dc      OSCP    ;oscp
dc      1.0     ;ossv1
dc      OSV2    ;ossv2
ENDIF
ENDM
end_oscps

org     x:end_oscps
svrtbl  DUP     MAX_BANDS
```

```
IF      J_RUN_ME
ds      MAX_STAGES*NSVARS           ;ssvars
ds      MAX_STAGES*NSVARS           ;csvars
ds      MAX_STAGES*NSVARS           ;osvars
ELSE
bsc     MAX_STAGES*NSVARS,0.0       ;ssvars
bsc     MAX_STAGES*NSVARS,0.0       ;csvars
bsc     MAX_STAGES*NSVARS,0.0       ;osvars
ENDIF
ENDM
end_svrtbl

org     y:end_oscps
IF      J_RUN_ME
samp    ds      1
waits   ds      1
nbands  ds      1
modsum  ds      1
ch1att  ds      1
ELSE
samp    dc      1000.0
waits   dc      0
nbands  dc      NBANDS
modsum  dc      0.0
ch1att  dc      1.0
ENDIF

ybandtbl
DUP     MAX_BANDS
IF      J_RUN_ME
ds      1                           ;nifilt
ds      1                           ;nofilt
ELSE
dc      NFILTS  ;nifilt
dc      NFILTS  ;nofilt
ENDIF
ENDM
end_ybandtbl

org y:end_ybandtbl
coefftbl
DUP     MAX_BANDS
IF      J_RUN_ME
ds      MAX_STAGES*NCOEFS           ;icoeff1
ds      MAX_STAGES*NCOEFS           ;icoeff2
```

```
ds      MAX_STAGES*NCOEFS       ;ocoeff
ELSE
dc      A12     ;icoeff1
dc      A11
dc      B12
dc      B11
dc      B10
dc      A12     ;icoeff2
dc      A11
dc      B12
dc      B11
dc      B10
dc      A12     ;ocoeff
dc      A11
dc      B12
dc      B11
dc      B10
ENDIF
ENDM
end_coefftbl

org y:end_coefftbl

;**** Following table allocates space to store env. values before output.
envstbl
DUP MAX_BANDS
IF J_RUN_ME
ds 1
ds 1
ELSE
dc 0
dc 0
ENDIF
ENDM
end_envstbl

NOLIST
IF      J_RUN_ME
INCLUDE "JANUS.A"
ELSE
org     P:$100
ENDIF
LIST
; the following parameters are kept in the DSP's registers
;       d7.h    Start signal
```

```
;       d7.m    scratch storage for $90 CV
;       d7.l    scratch storage used by do loops
; For the folloing values, first, the data is written to the TX register,
;    then the user host command is called to update the parameter.
;       $90     Sample rate/control register
;       $91     Start signal

start
IF      J_RUN_ME
move    #DAU_CR,r7              ;for quick checking of sample clock
move    #ADA_DACEN|ADA_N16,d7.m ;Default to 16 kHz with DACs on
move    d7.m,y:DAU_CR           ;set control register
bclr    #5,x:MI_HCR             ;Enable Inner Port interface
wait1   move    #0,d7.h                 ;Clear start signal
clr     d0.l
wait0   inc     d0.l
move    d0.l,y:samp
jclr    #0,d7.h,wait0           ;Loop until start CVR occurs
ENDIF
move    #$fffffff,m0            ;All indexing is normal
move    m0,m4
move    m4,m1
move    #3,n1
move    #2,n2
bra     outp0
;       bra     wait1


mloop
move    #osc5tbl,r1
move    #osc3tbl,r3
move    y:nbands,d7.l
oscs    ;uses r1, r3, d0,d1,d3,d4,d5,d6 output in d6
; generates a sine-cosine pair (r1,d1,d4) and another sine (r3,d3,d0)
do      d7.l,end_oscs
move    l:(r1)+,d1.d    ;get s-c osc parameter
move    l:(r1)+,d6.d    ;get ultimate s-c sine state variable
move    l:(r1)-,d5.d    ;get penultimate s-c sine state variable
fmpy.x  d5,d1,d4        d5.d,l:(r1)+    ;s-c penult is next s-c ult
fsub.x  d6,d4           l:(r3)+,d3.d    ;get s osc parameter
move    l:(r3)+,d6.d    ;get ultimate s sine state variable
move    l:(r3)-,d5.d    ;get penultimate s sine state variable
fmpy.x  d5,d3,d0        d5.d,l:(r3)+    ;pen s sv is new ult s sv
fsub.x  d6,d0           d4.d,l:(r1)+    ;save new pen s-c sv
move    l:(r1)+,d6.d    ;get ultimate s-c cosine state variable
```

```
move    l:(r1)-,d5.d    ;get penultimate s-c cosine state variable
fmpy.x  d5,d1,d4        d5.d,l:(r1)+    ;penult s-c csv is next ult
fsub.x  d6,d4           d0.d,l:(r3)+    ;new penultimate s sv
move    d4.d,l:(r1)+    ;new penultimate s-c c sv
end_oscs

move    #svrtbl,r0      ;state variables
move    #osc3tbl+1,r1   ;output oscillator parameters
move    #osc5tbl+1,r2   ;input oscillator parameters
move    #ybandtbl,r3    ;numbers of filter sections
move    #coefftbl,r4    ;filter coefficients
move    #modsum,r6      ;the final result
move    #envstbl,r5     ;table to store first envelope
fclr    d0
do      d7.l,end_mloop
move    l:(r2)+n2,d3.d  ;get the sine value
fmpy.x  d3,d8,d2        d0.s,y:(r6)     ; shift the input down to zero
move    y:(r3)+,d7.l    ;get the number of input filter stages
;       jsr     filter
fclr    d1                              x:(r0)+,d4.s    y:(r4)+,d6.s
do      d7.l,end_flt1
fmpy    d4,d6,d0        fadd.s  d1,d2   x:(r0)-,d5.s    y:(r4)+,d6.s
fmpy    d5,d6,d1        fadd.s  d2,d0   d5.s,x:(r0)+    y:(r4)+,d6.s
fmpy    d6,d4,d1        fadd.s  d1,d0                   y:(r4)+,d6.s
fmpy.s  d6,d5,d2                        d0.s,x:(r0)+    y:(r4)+,d4.s
fmpy    d4,d0,d1        fadd.s  d1,d2   x:(r0)+,d4.s    y:(r4)+,d6.s
end_flt1                        fadd.s  d1,d2   ;finish up
fmpy.x  d3,d2,d2        l:(r2)+n2,d3.d  ;shift it up and get cosine
move    d2.s,d9.s
;       move    l:(r2)+n2,d3.d  ;get the cosine value
fmpy.x  d3,d8,d2        ;shift the input down
;       jsr     filter
fclr    d1                              x:(r0)+,d4.s    y:(r4)+,d6.s
do      d7.l,end_flt2
fmpy    d4,d6,d0        fadd.s  d1,d2   x:(r0)-,d5.s    y:(r4)+,d6.s
fmpy    d5,d6,d1        fadd.s  d2,d0   d5.s,x:(r0)+    y:(r4)+,d6.s
fmpy    d6,d4,d1        fadd.s  d1,d0                   y:(r4)+,d6.s
fmpy.s  d6,d5,d2                        d0.s,x:(r0)+    y:(r4)+,d4.s
fmpy    d4,d0,d1        fadd.s  d1,d2   x:(r0)+,d4.s    y:(r4)+,d6.s
end_flt2                        fadd.s  d1,d2   ;finish up
fmpy.x  d3,d2,d2         l:(r2)+,d6.d ;(the move only keeps r2 in sync)
move    d9.s,d1.s       ;get the sine-modulated result
fadd.x  d1,d2           ;combine sine and cosine
fabs.s  d2              ;rectify the sum
move    y:(r3)+,d7.l    ;get the number of output filter stages
```

```
;       jsr     filter          ;smooth the rectified sum
fclr    d1                              x:(r0)+,d4.s    y:(r4)+,d6.s
do      d7.l,end_flt3
fmpy    d4,d6,d0        fadd.s  d1,d2   x:(r0)-,d5.s    y:(r4)+,d6.s
fmpy    d5,d6,d1        fadd.s  d2,d0   d5.s,x:(r0)+    y:(r4)+,d6.s
fmpy    d6,d4,d1        fadd.s  d1,d0                   y:(r4)+,d6.s
fmpy.s  d6,d5,d2                        d0.s,x:(r0)+    y:(r4)+,d4.s
fmpy    d4,d0,d1        fadd.s  d1,d2   x:(r0)+,d4.s    y:(r4)+,d6.s
end_flt3                        fadd.s  d1,d2   ;finish up
move    l:(r1)+n1,d6.d  ;get the modulating sine
fmpy.x  d6,d2,d0        y:(r6),d6.s ;modulate it with the envelope
; fadd.x  d6,d0
move    d0.s,y:(r5)+    ; *****stores envelope cue(s) in envstbl
end_mloop

output
move    #envstbl,r5
nop
move    y:(r5)+,d1.s ;***** d1 contains one envelope cue
move    y:(r5)+,d0.s ;***** d0 contains the other envelope cue
intrz   d1.s ;convert to integer
intrz   d0.s ;convert to integer
join    d1.l,d0.l ;***** each envelope is delivered to SEPARATE channels.
outp0
IF      J_RUN_ME
IF      CYCLE_COUNT
move    #waits,r0               ;r0 also used by FILTER
clr     d6.l                    ;to provide a count of free cycles
qr_ads0 inc     d6.l
jset    #0,y:(r7),qr_ads0       ;read sample interrupt until sample pd.
qr_ads1 inc     d6.l
jclr    #0,y:(r7),qr_ads1       ;read sample interrupt until sample pd.
move    d6.l,y:(r0)             ;store the cycle count
ELSE
qr_ads0 jset    #0,y:(r7),qr_ads0       ;read sample interrupt until sample pd.
qr_ads1 jclr    #0,y:(r7),qr_ads1       ;read sample interrupt until sample pd.
ENDIF
move    y:DAU_DATA,d1.l
move    d0.l,y:DAU_DATA         ;send mixed stereo sample to DACs
split   d1,d0
ext     d1
float.s d0
move    d0.s,y:samp
ENDIF
move    y:samp,d8.s
```

```
bra     mloop



filter  ;input and output samples are in d2.s
;requires d7.l (unchanged) as well as r0 and r4 (which are updated)
;uses r0,r4,d0,d1,d2,d4,d5,d6 but not d3, d8, d9
fclr    d1                            x:(r0)+,d4.s    y:(r4)+,d6.s
do      d7.l,end_flt
fmpy    d4,d6,d0        fadd.s  d1,d2  x:(r0)-,d5.s    y:(r4)+,d6.s
fmpy    d5,d6,d1        fadd.s  d2,d0  d5.s,x:(r0)+    y:(r4)+,d6.s
fmpy    d6,d4,d1        fadd.s  d1,d0                  y:(r4)+,d6.s
fmpy.s  d6,d5,d2                       d0.s,x:(r0)+    y:(r4)+,d4.s
fmpy    d4,d0,d1        fadd.s  d1,d2  x:(r0)+,d4.s    y:(r4)+,d6.s
end_flt                         fadd.s  d1,d2   ;finish up
rts


; Long ISR to change the sample rate
NEW_RATE
IF      J_RUN_ME
move    x:<<MI_HRX,d7.m         ;Read data from host
move    d7.m,y:DAU_CR           ;clear control register
ENDIF
rti

end     start
```

Appendix E

Training and Test Results

E.1 Training

NN								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	83.3	91.2	81.4	86.3	94.1	82.4	87.3
2	8-14	87.3	87.3	92.2	90.2	83.3	81.4	87.3
3	15-21	85.3	99	89.2	83.3	94.1	91.1	90.2
4	22-28	97.1	91.2	95.01	99	89.8	96.1	73.5
5	29-35	72.5	96.1	83.3	84.3	82.4	86.3	83.3
Average		85.1	92.9	88.2	88.6	88.8	87.5	84.3

Table E.1: NN's Training Results (scores represent percentage correct)

EL								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	77.5	83.3	86.3	87.3	92.2	88.2	81.4
2	8-15	89.2	82.3	86.3	78.4	84.3	93.1	87.6
3	16-21	89.2	88.2	98	99	84.3	94.1	93.1
4	22-28	96.1	98	94.1	87.3	93.4	100	73.5
5	29-35	77.5	88.2	91.2	77.5	89.2	90.2	95.1
6	36-42	86.3	83.3	94.1	95.1	90.2	94.1	93.1
Average		85.9	87.2	91.7	87.4	88.9	93.3	87.3

Table E.2: EL's Training Results (scores represent percentage correct)

AC								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	72.5	90.2	92.2	88.2	87.3	91.2	73.5
2	8-14	73.5	86.3	88.2	82.4	93.1	97.1	98
3	15-21	80.4	98	87.3	88.2	94.1	91.2	89.2
4	22-28	96.1	88.2	100	88.2	97.1	99	82.4
5	29-35	80	93.1	94.1	84.3	86.3	92.2	87.3
6	36-42	81.4	92.2	95.1	96.1	90.2	89.2	92.2
Average		85.9	87.2	91.7	87.4	88.9	93.3	87.3

Table E.3: AC's Training Results (scores represent percentage correct)

RB								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	80.4	75.5	85	89.2	96.7	85.1	85.3
2	8-14	98	79.4	86.3	85.3	87.3	98	90.2
3	15-21	88.2	93.1	93.5	91.2	91.2	95.1	88.2
4	22-28	95.1	92.2	98	93.1	97.1	91.2	83.3
5	29-35	84.3	90.2	87.3	89.2	73.5	90.2	81.4
6	36-42	92.2	97.1	92.2	87.3	82.4	89.2	82.4
Average		89.7	87.9	90.4	89.2	88	91.5	85.1

Table E.4: RB's Training Results (scores represent percentage correct)

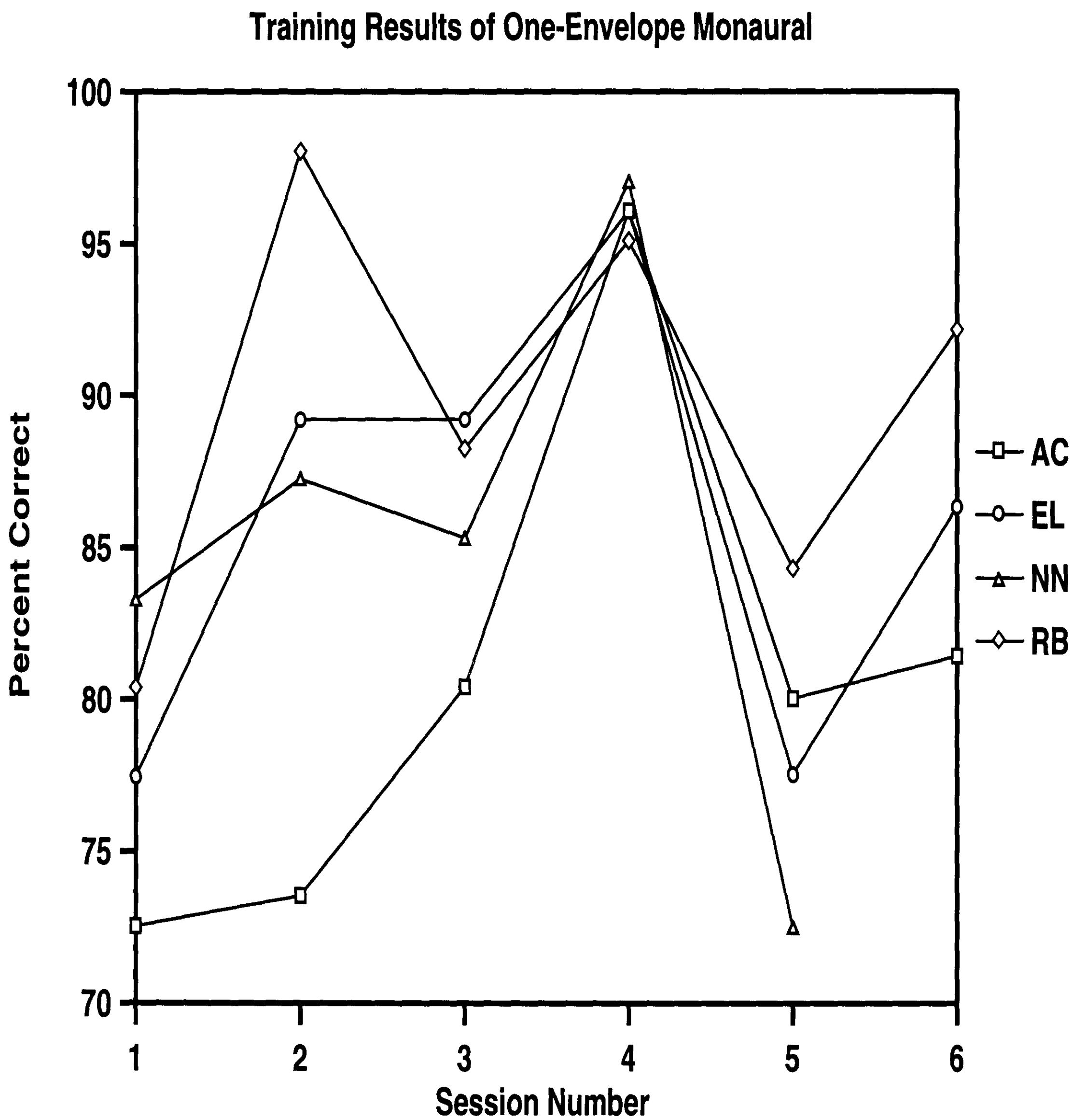


Figure E-1: Training Results of One Envelope Monaural

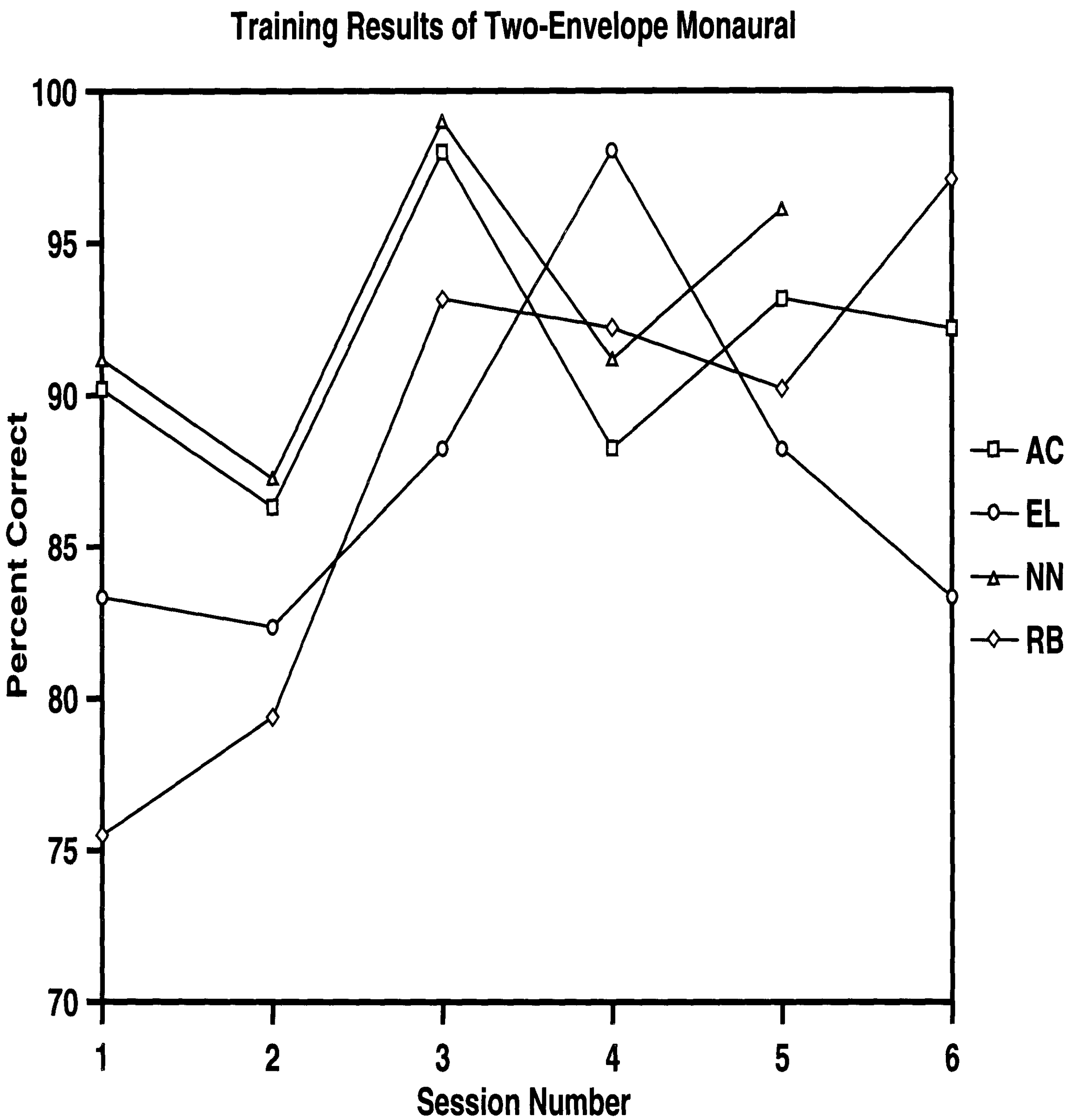


Figure E-2: Training Results of Two Envelope Monaural

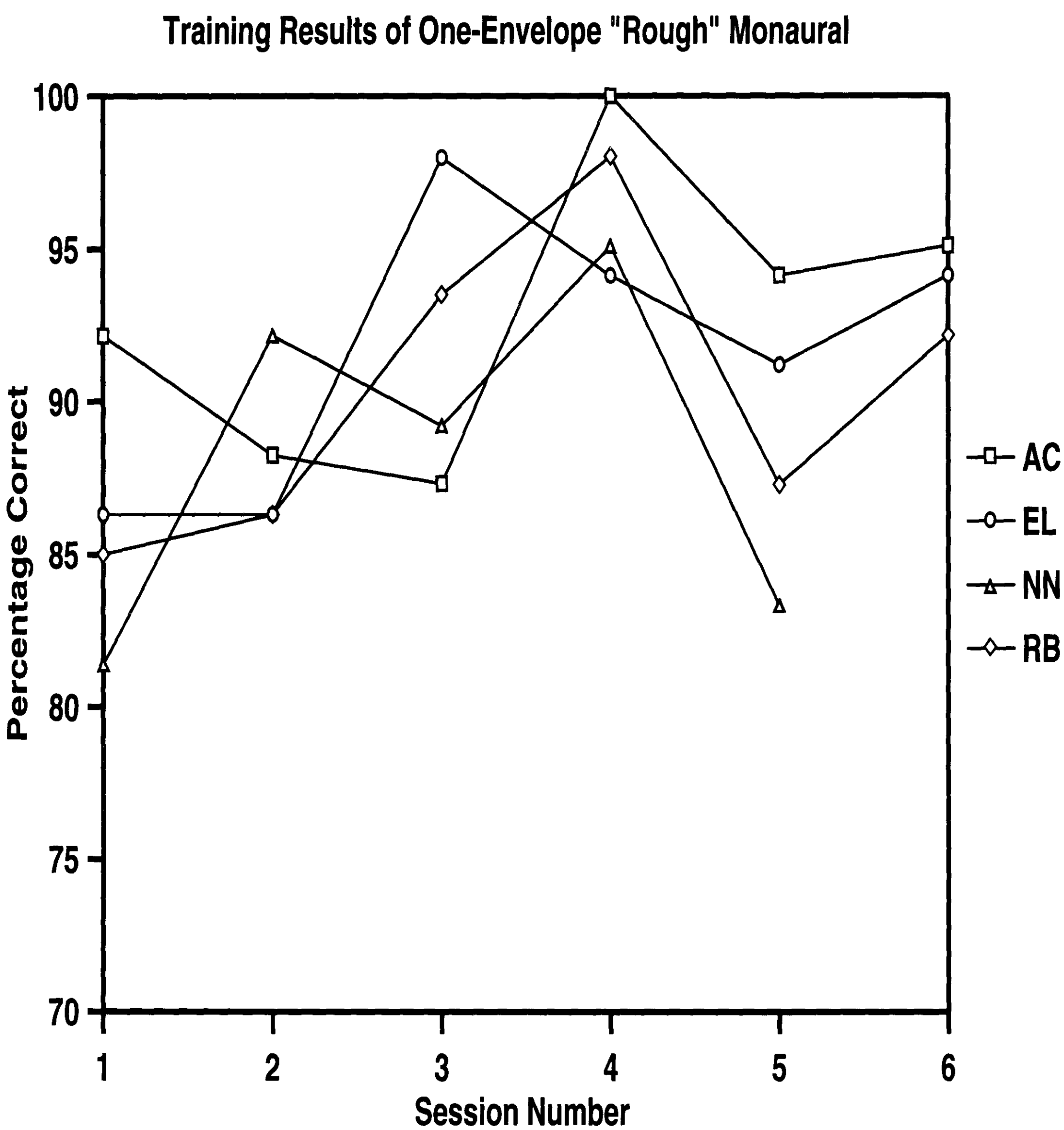


Figure E-3: Training Results of the Rough Monaural

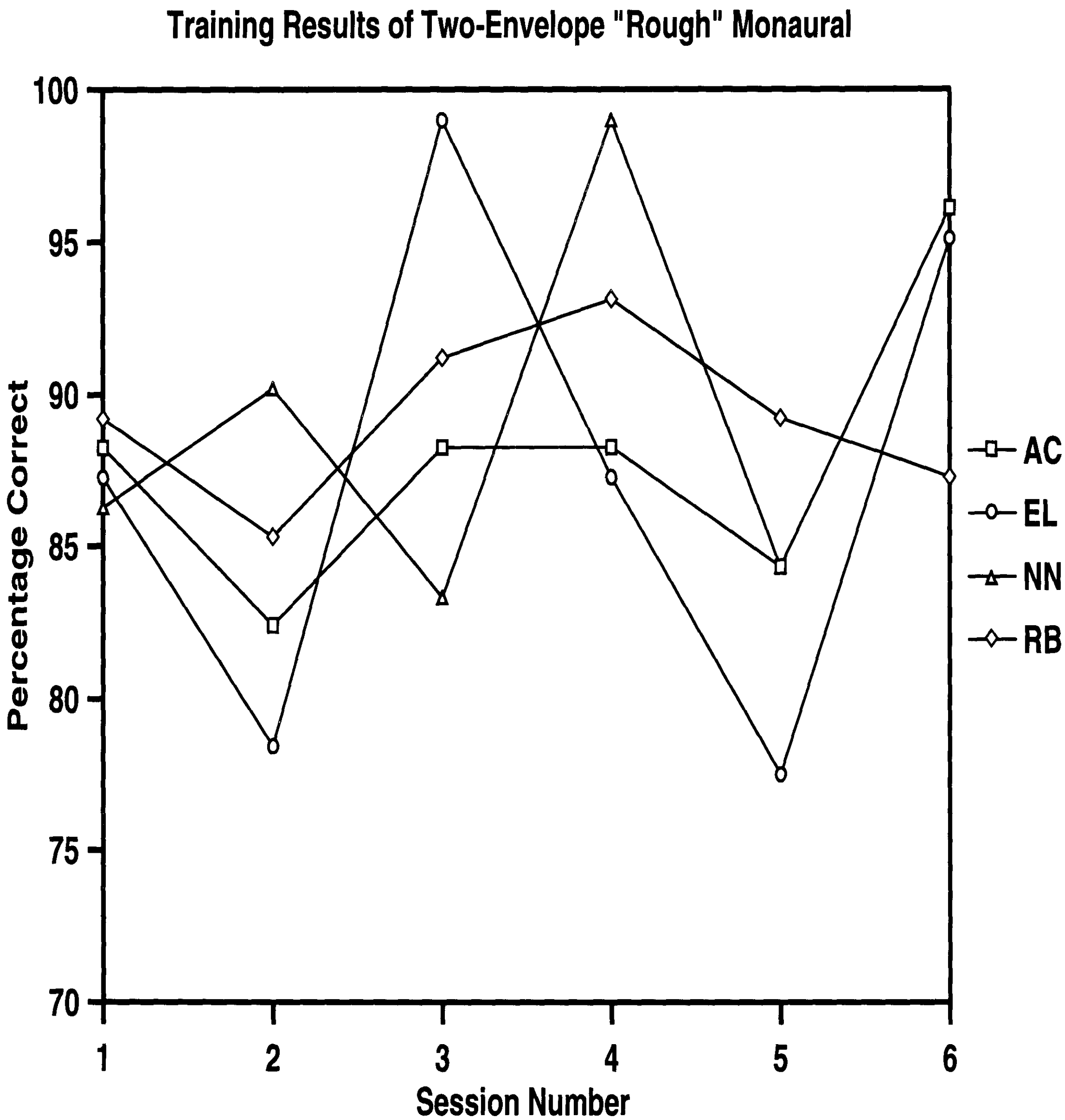


Figure E-4: Training Results of Correlation Monaural

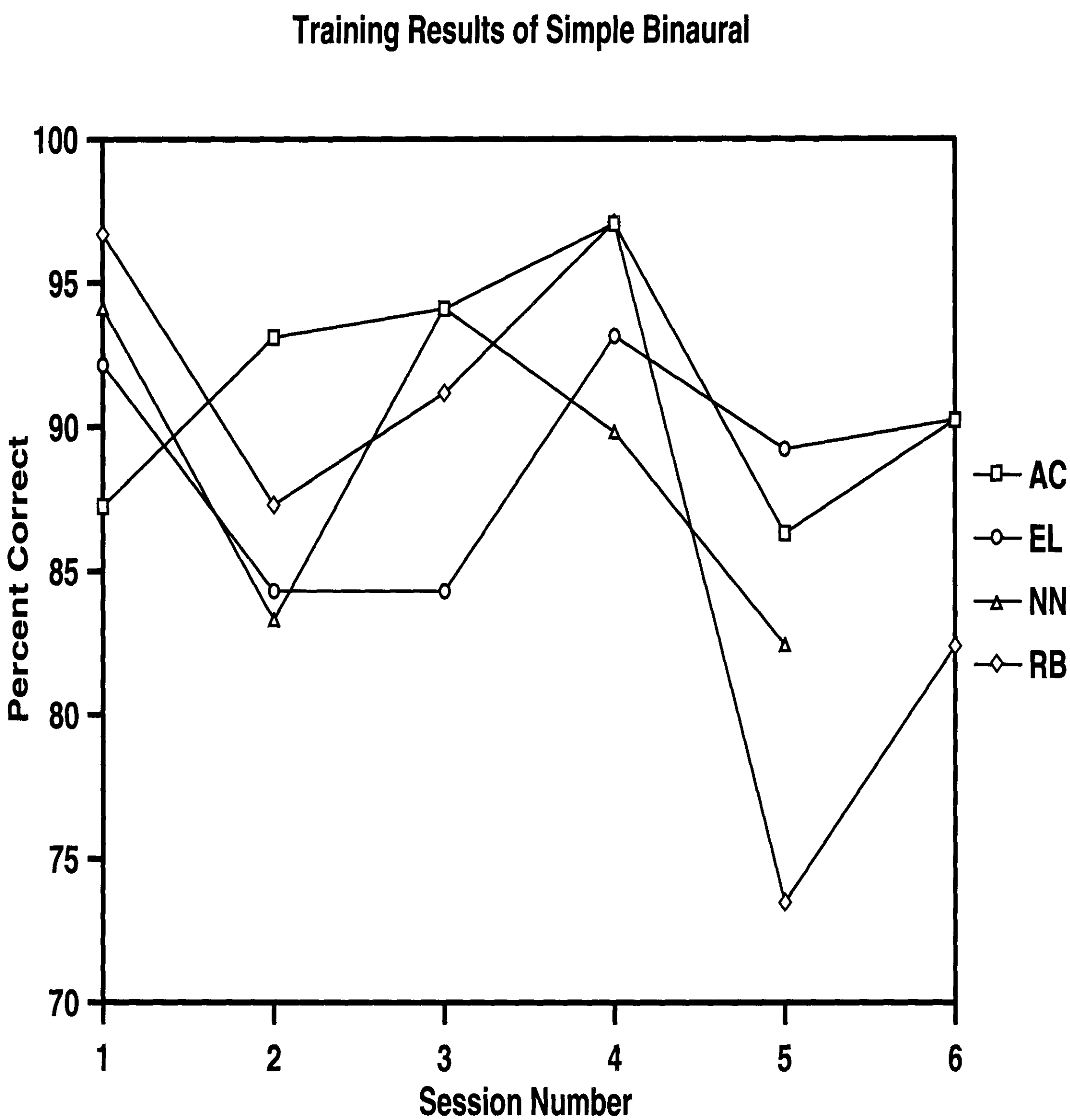


Figure E-5: Training Results of Simple Binaural

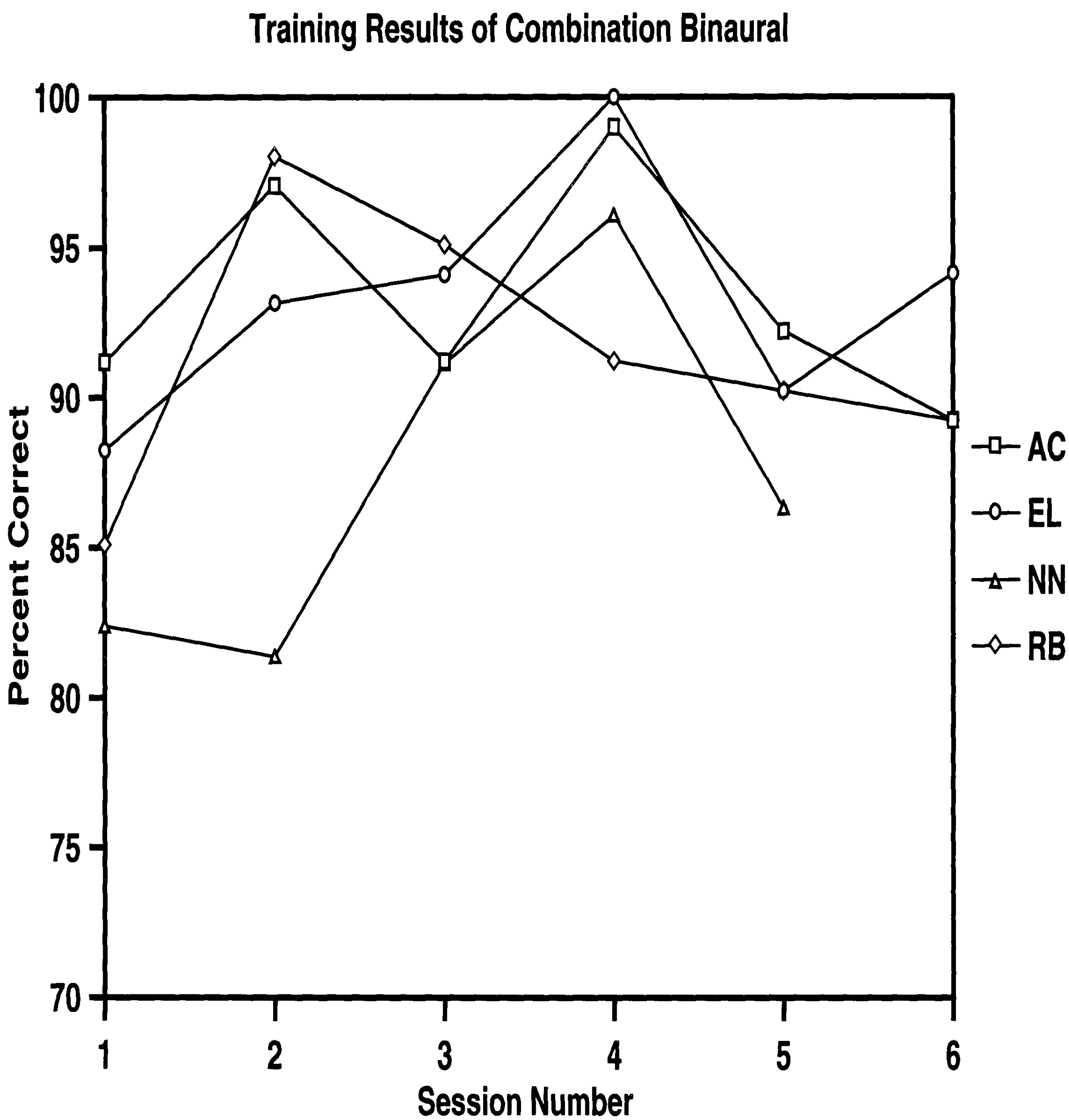


Figure E-6: Training Results of Combination Binaural

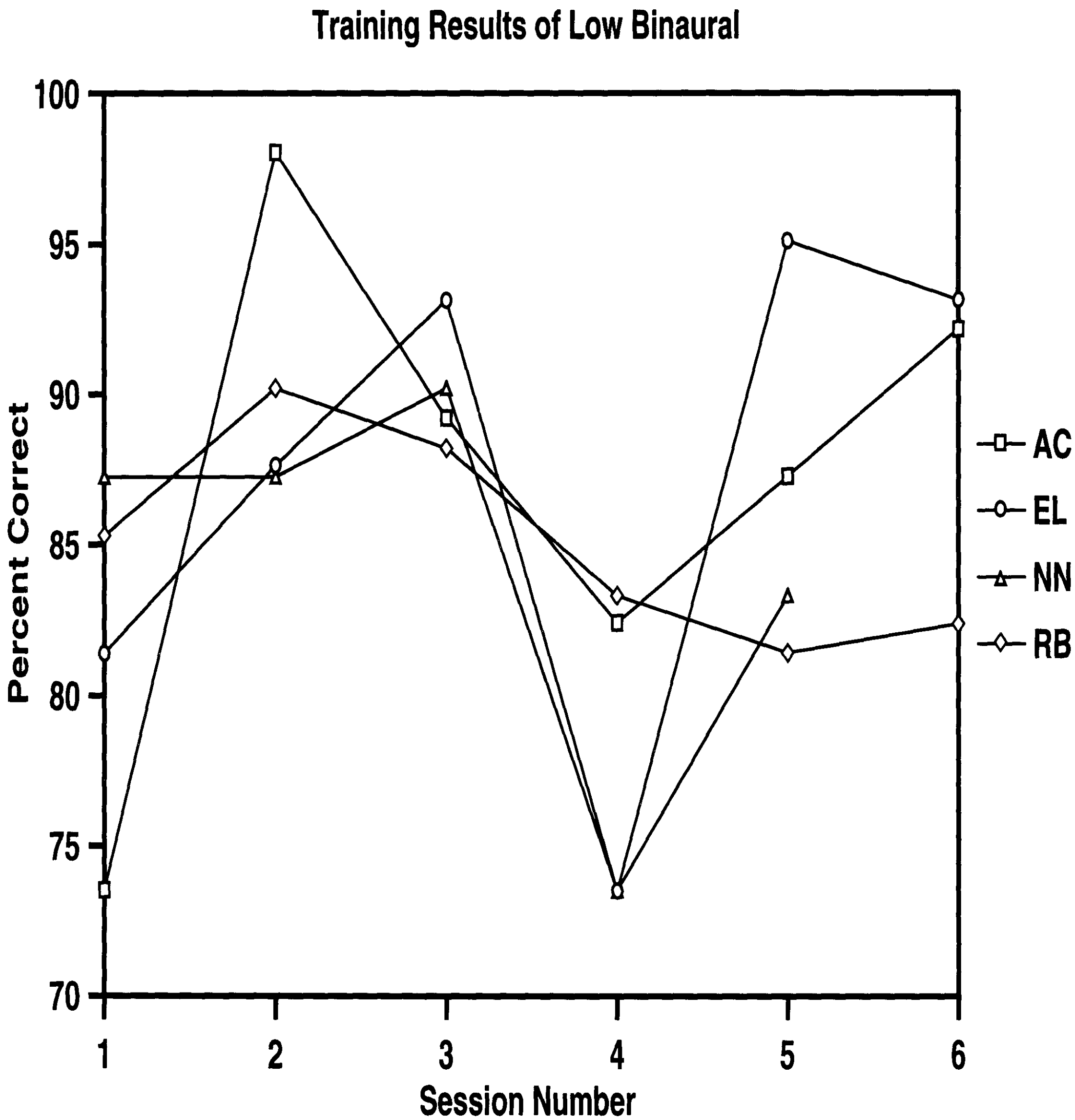


Figure E-7: Training Results of Low Binaural

E.2 Testing

NN								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	54	86	58	64	74	54	74
2	8-14	40	72	36	56	58	50	42
3	15-21	32	64	56	74	62	56	50
4	22-28	54	48	44	68	66	62	84
5	29-35	46	76	64	54	74	74	48
6	36-42	70	82	62	88	68	64	42
7	43-49	66	72	72	82	88	76	84
8	50-56	72	78	68	66	56	86	62
9	57-63	84	96	74	70	68	60	66
10	64-70	62	46	48	92	82	62	88
Average		58	72	58.2	71.4	69.6	64.4	64

Table E.5: NN's Test Results (scores represent percentage correct)

EL								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	46	92	66	66	74	66	72
2	8-14	35.5	80	38	56	70	74	58
3	15-21	54	60	56	66	58	68	72
4	22-28	82	70	76	76	72	78	78
5	29-35	44	56	42	56	56	46	36
6	36-42	80	70	80	88	62	66	52
7	43-49	66	74	66	74	80	64	84
8	50-56	86	66	54	76	64	78	72
9	57-63	74	86	80	76	76	78	68
10	64-70	60	84	52	82	82	82	84
Average		58	72	58.2	71.4	69.6	64.4	64

Table E.6: EL's Test Results (scores represent percentage correct)

AC								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	52	84	72	68	72	72	82
2	8-14	42.2	76	56	86	90	54	64
3	15-21	72	66	62	78	64	82	70
4	22-28	78	80	64	72	74	94	76
5	29-35	40	86	76	70	76	90	70
6	36-42	74	82	82	86	56	80	70
7	43-49	74	84	84	80	98	84	86
8	50-56	84	88	70	82	70	86	68
9	57-63	90	90	84	66	88	82	88
10	64-70	80	78	58	86	96	90	90
Average		68.6	81.4	70.8	77.4	78.4	81.4	76.4

Table E.7: AC's Test Results (scores represent percentage correct)

RB								
Session	Sent.Lst	1-E.M.	2-E.M.	1-E.R.M.	2-E.R.M.	S.B.	C.B.	L.B.
1	1-7	62	84	68	76	62	70	80
2	8-14	46.67	82	64	69	86	66	56
3	15-21	56	62	72	80	58	72	66
4	22-28	78	60	72	68	64	58	60
5	29-35	32	76	88	76	62	74	50
6	36-42	72	88	66	86	58	78	50
7	43-49	64	62	70	74	84	78	78
8	50-56	82	82	64	70	58	80	70
9	57-63	66	84	78	76	76	78	68
10	64-70	60	76	44	84	84	72	76
Average		61.9	75.6	68.6	75.9	69.2	72.6	65.4

Table E.8: RB's Test Results (scores represent percentage correct)

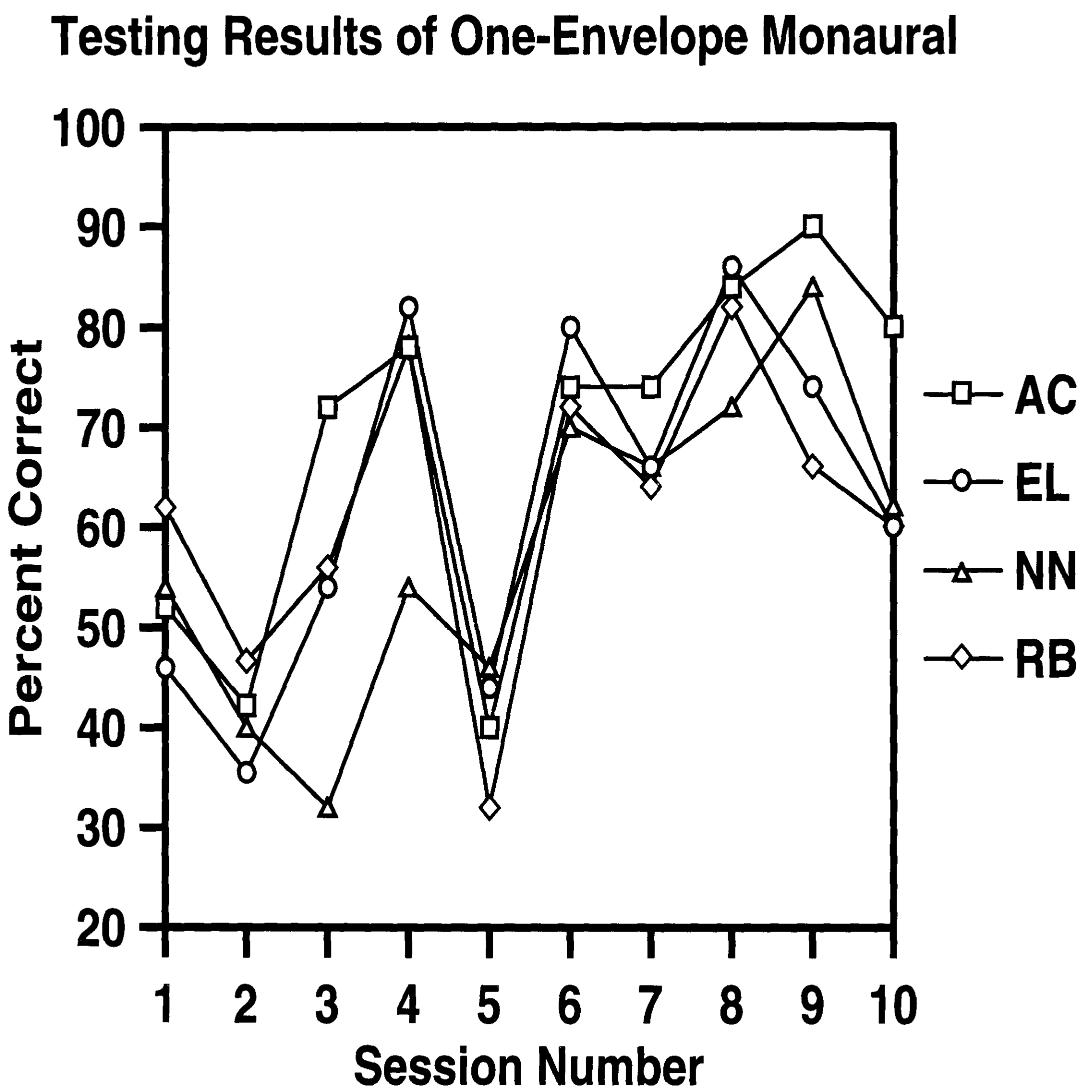


Figure E-8: Testing Results of One Envelope Monaural

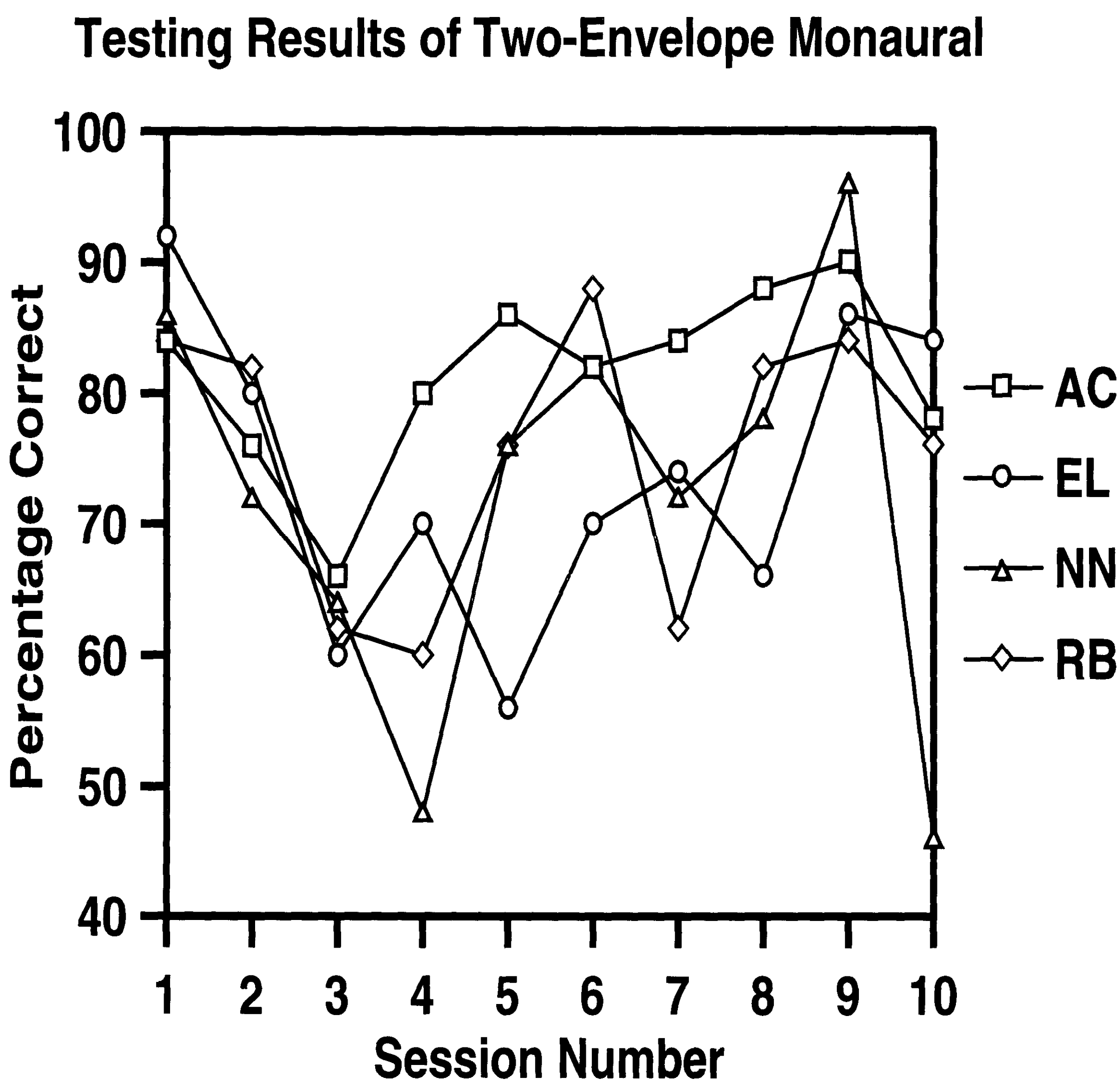


Figure E-9: Testing Results of Two Envelope Monaural

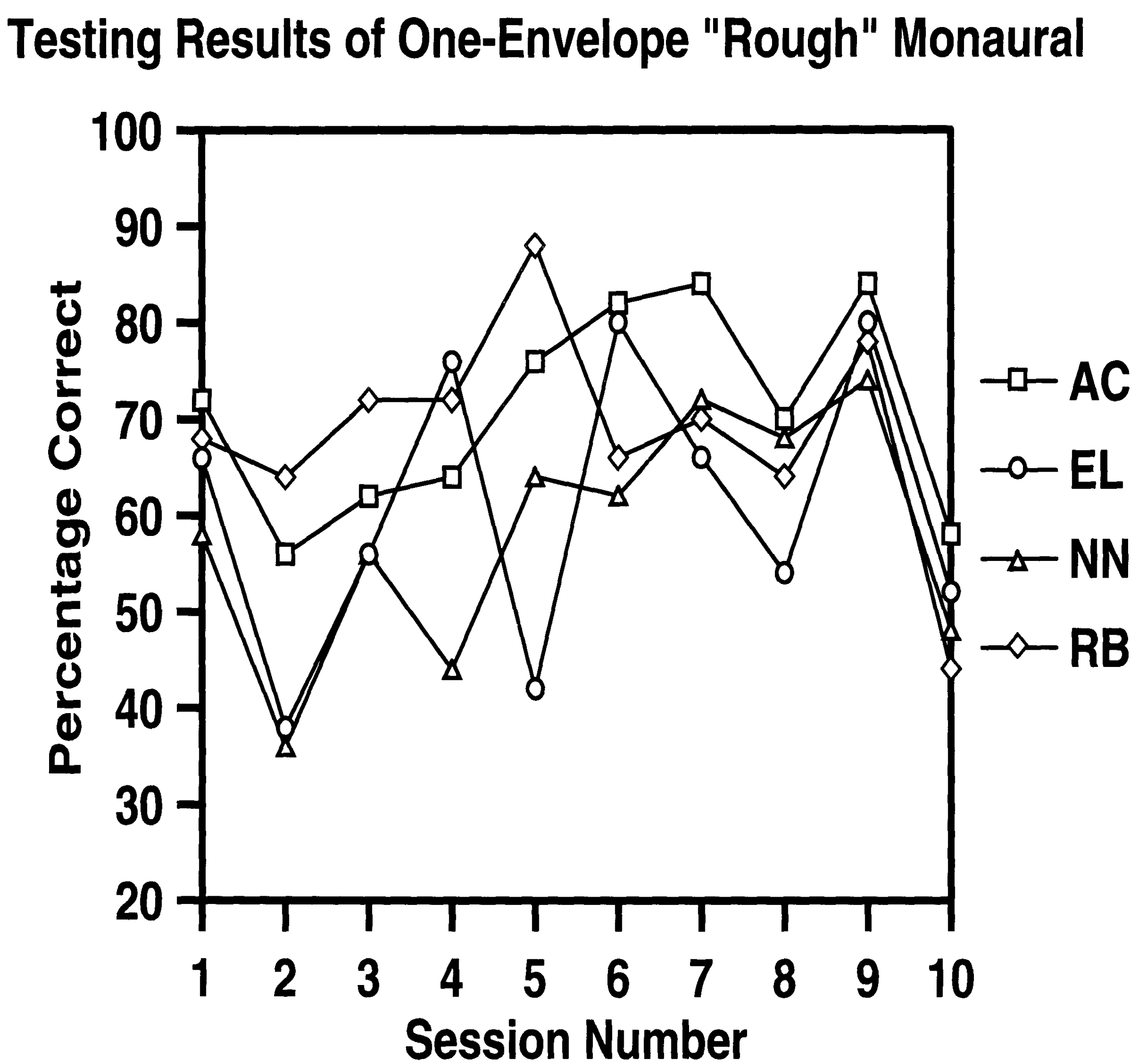


Figure E-10: Testing Results of Rough Monaural

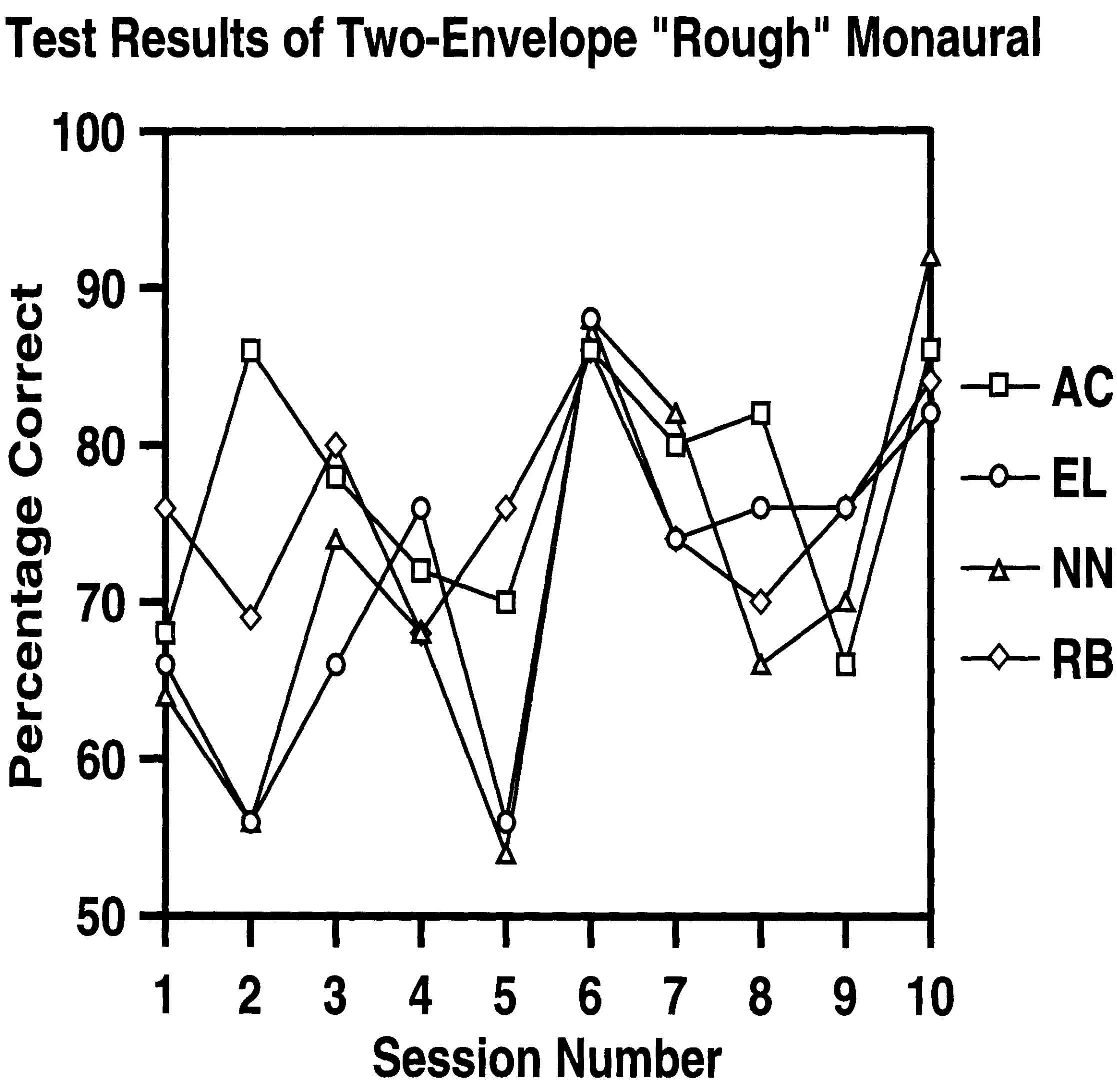


Figure E-11: Testing Results of Correlation Monaural

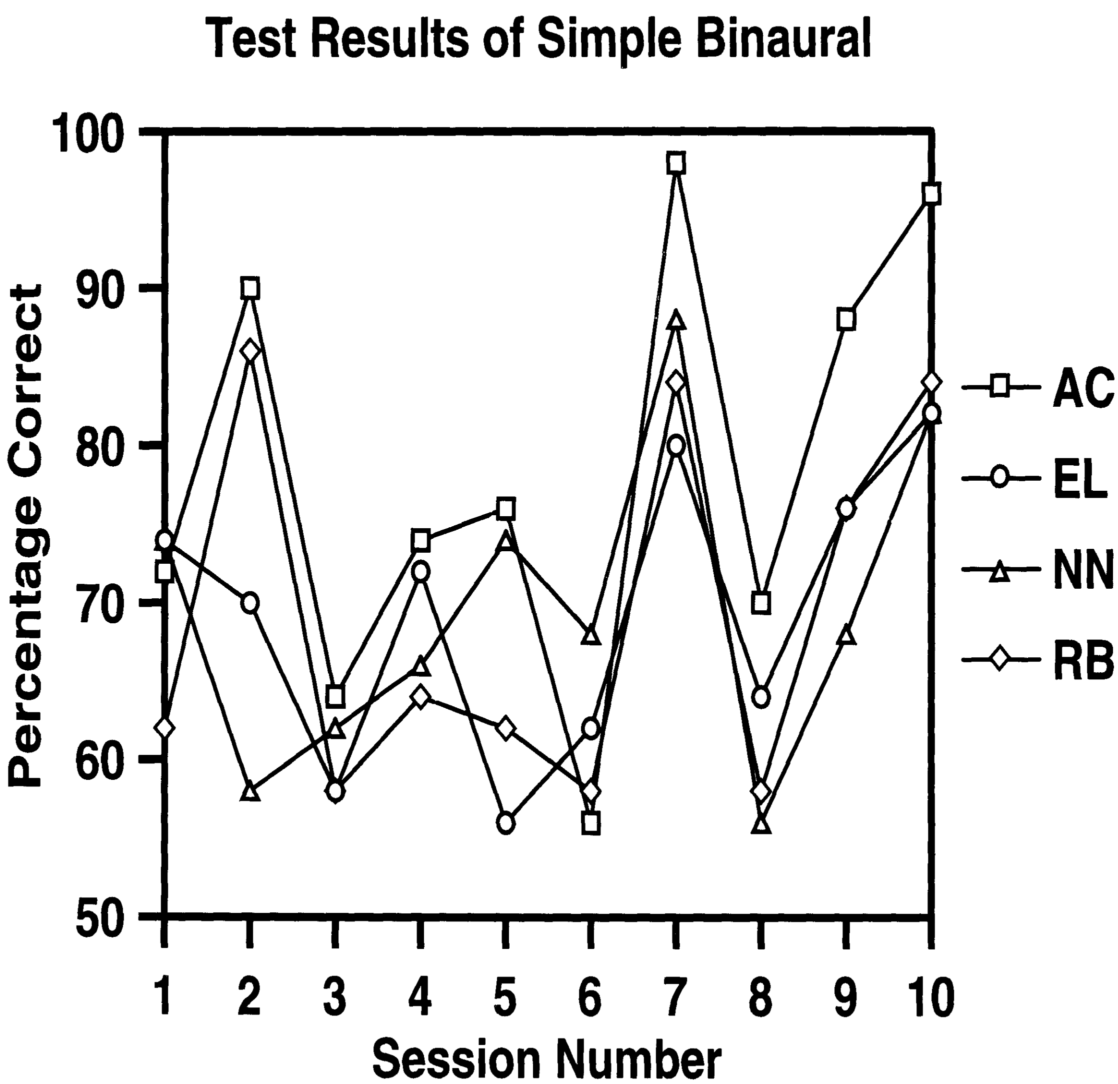


Figure E-12: Testing Results of Simple Binaural

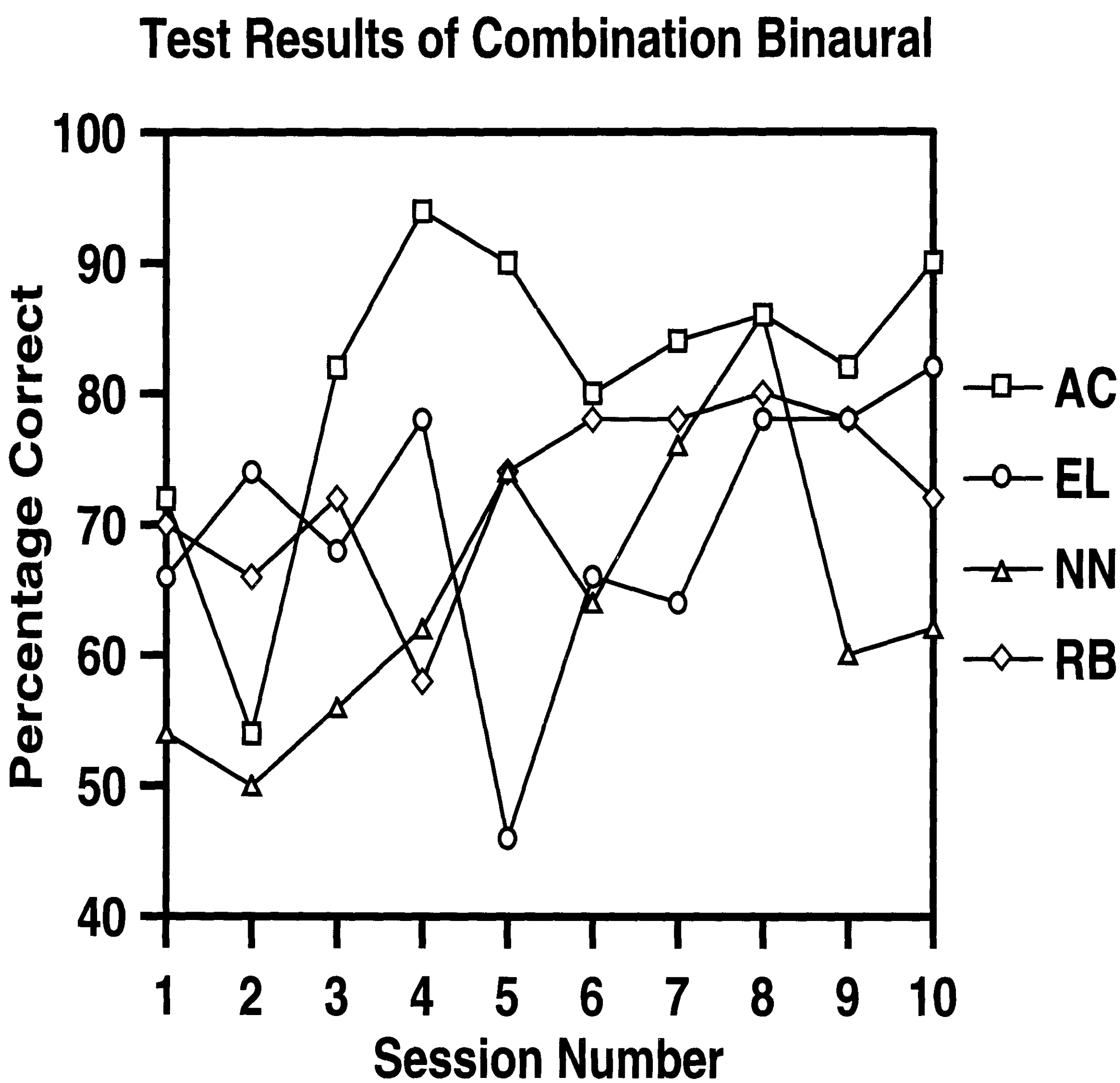


Figure E-13: Testing Results of Combination Binaural

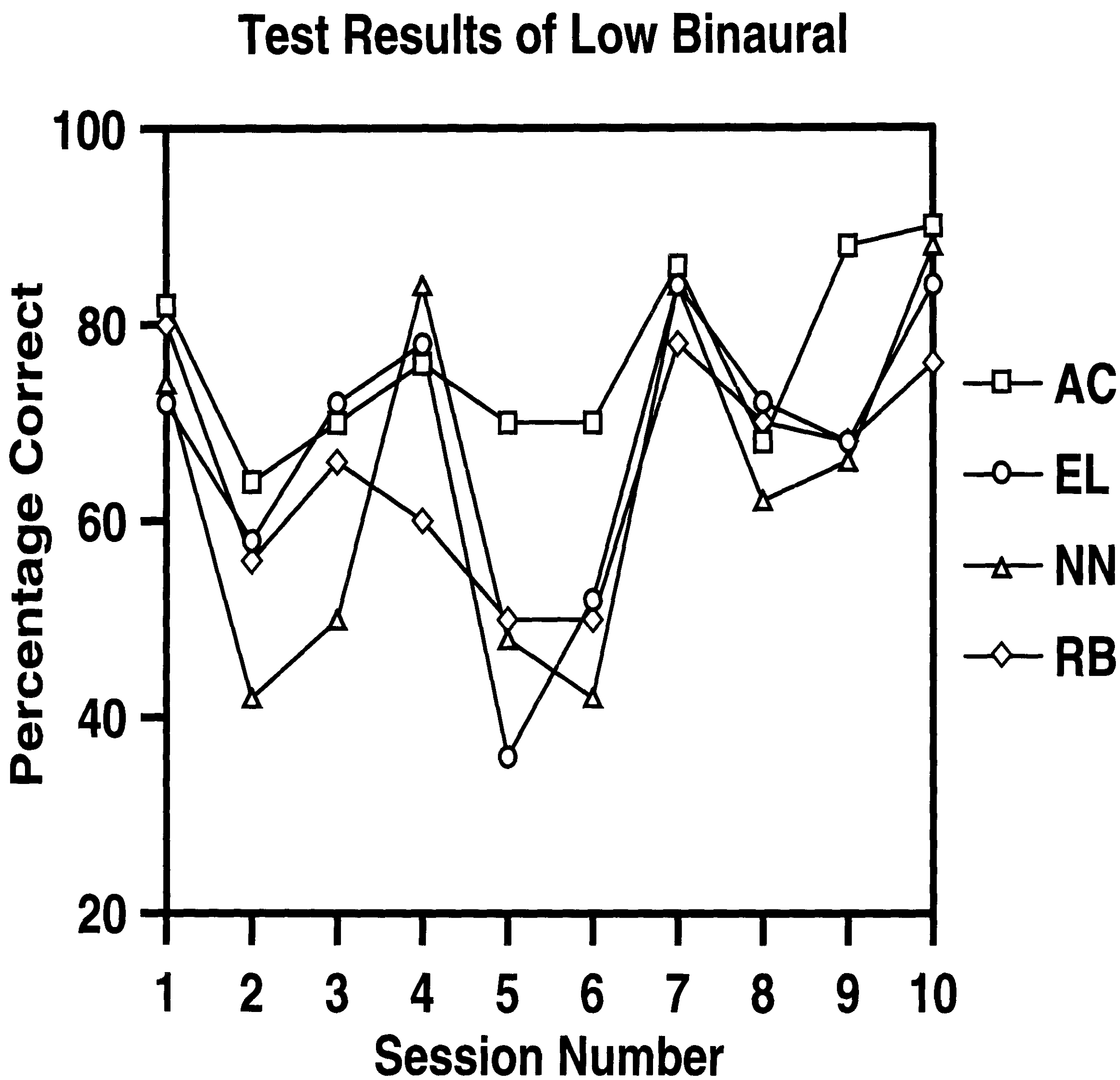


Figure E-14: Testing Results of Low Binaural