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The Just Noticeable Difference in the Clarity Index for Music, C80

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Abstract

A common parameter used in the study concert halls is the clarity index of music, C_{80}. Clarity describes the definition of music or how clear each note sounds. There has been a limited amount of research to determine the smallest change that is perceivable by humans, or the just noticeable difference (JND), and each of these studies has limitations due to a small sample size. An investigation was conducted to try to determine the JND of C_{80} using a larger sample size. The test was performed in the University of Hartford's acoustic laboratory with 51 test subjects. A Yamaha DME64N digital processor engine was used to create different impulse responses achieving different clarity values. Using an array of eight Genelec 8030A loudspeakers, pairs of signals with different clarity values were compared to determine if an audible difference existed. Using the acquired data, a statistical analysis was performed to determine the JND of C_{80}.

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Purpose

The purpose of this investigation was to determine the just noticeable difference in the clarity index for music, C_{80}. The subjective testing included playing pairs of samples to the subject in order to determine if an audible difference exists.

Background

One of the many different parameters to study concert hall acoustics is the clarity index, C_{80}. Clarity is defined as the ratio of early sound energy to late sound energy, expressed in decibels. It is derived from the impulse response *p(t)* (Eqn. 1).

$$C_{80} = 10\log\left(\frac{\int_{0}^{80ms} p^2(t)dt}{\int_{80ms}^{\infty} p^2(t)dt}\right) \tag{1}$$

If the value is high, there will be a sense of definition in the music. A low value will have a decreased definition in the music, but will increase the fullness of the tone. In most cases, clarity is inversely proportional to reverberation time.

There has been a limited amount of research done on this topic in the past. The first study was conducted by Cox *et al* in 1993 [1]. Using eight loudspeakers in an anechoic chamber, a system of delays and effect units were used to create impulse responses. He used two anechoic motifs, the first five bars from Handel's *Water Music Suite*, and a motif from the fourth movement of Mendelssohn's *Symphony no. 3 in A minor*, Op.56. A total of 7 to 10 subjects participated in the studies and the subjects either played a musical instrument or who regularly attended live classical performances, and had normal hearing. The results revealed a different JND for each of the two motifs studied. The JND for the Handel motif was 0.44 ± 0.07 dB and the JND for the Mendelssohn motif was 0.92 ± 0.22 dB. Because of the difference, the two values were averaged, which resulted in an overall JND of 0.67 ± 0.13 dB. The main limitation of the study was the small sample size.

A second study was conducted in this area by Bradley *et al* [2], but for the JND for clarity index in speech, C_{50}, with the results extrapolated for the C_{80} JND. This is similar to the clarity index for music except the integration limit is adjusted to 50 ms instead of 80 ms in Eqn. 1. Bradley *et al* used eight loudspeakers and tested three different base cases: Base Case 1 with a low clarity of -3.0 dB, Base Case 2 with a medium clarity of +1.0 dB, and Base Case 3 with a high clarity of +5.0 dB. For each base case, pairs of signals were presented to the test subjects where the first signal was the base case and the second signal had a positive difference of 0.5, 1.0, 1.5, 2.5, or 4.0 dB. The subject was able to switch between the two signals while the anechoic speech recording continued uninterrupted. A total of 10 test subjects participated in the study. The data analysis revealed a JND of 1.1 dB for C_{50}. Through extrapolation with the C_{50} test data, the

JND for the clarity in music, C_{80}, was predicted to be 0.9 dB. This study also has limitations. The subjects were not musically trained and their hearing was not tested to verify that they had normal hearing thresholds. This study also had a small sample size, and the validity of the extrapolation to C_{80} is unverified given that speech and not music signals were used.

Testing Overview

Signals of different clarity values were created. Two base case signals were created: Base Case 1 with a low clarity value of -3 dB and Base Case 2 with a high clarity value of +1 dB. Once each base case had been generated, eight more signals with positive differences between 0.5 to 3.0 dB were created starting from each base case. Three different musical motifs of approximately 10 s each were used in listening tests. A total of 51 subjects were tested, 30 male and 21 female, with 75% of the subjects between the ages of 18 to 22 years old. The test subjects were asked to indicate if the signals sounded the same or different. The data were analyzed to find the just noticeable difference (JND).

Procedure

Experimental Setup

A Yamaha DME64N digital mixing engine in conjunction with the Yamaha DME Designer software was used to create the signals for the testing. Figure 1 is a simplified flowchart of the processing done in DME Designer.

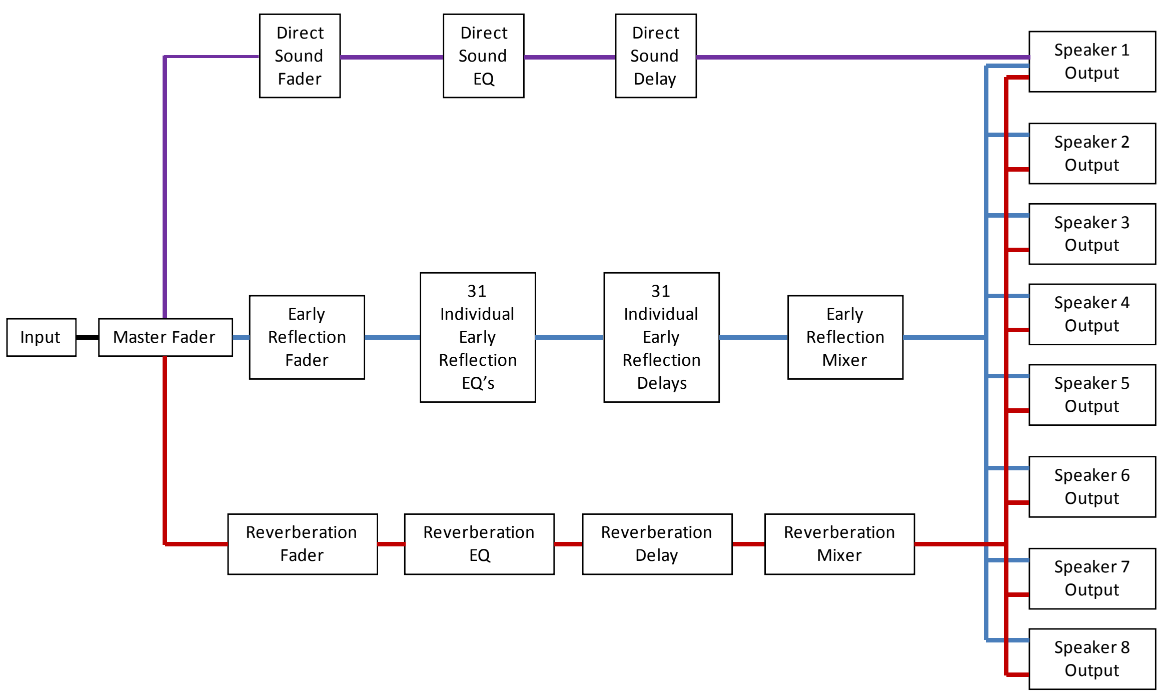

Figure 1 - Summary of Signal Creation using Yamaha DME Designer Software

The input goes to a master fader and splits off into three paths: direct sound, early reflections, and reverberation. The direct sound passes through a separate fader, equalizer, and delay. The direct sound was only presented through speaker number 1, which was the speaker directly in front of the subject (see circled speaker in Figure 2). The next path in the signal processing controlled the early reflections in the first 80 ms. This path had a main fader then branched out into 31 different equalizers and delays controlling, creating four early reflections for each of the eight speakers, with the exception of the speaker no. 1, which had three early reflections and the direct sound. These early reflections were used to create a more realistic impulse response that included specular reflections from various surfaces of the virtual room. The final path controlled the reverberation, which was separated into frequency bands and included a main fader and an equalizer. The signal was mixed across frequency bands and then sent to the eight loudspeakers with short time delays of 1 to 3 ms to further randomize the reverberant signal.

The eight loudspeakers were positioned in the anechoic chamber, such that six of the loudspeakers were positioned in front of the subject (Figure 2) and two were placed behind (Figures 3 and 4). Because the door of the chamber was located in the back corner, one of the speakers was placed on a track so the speaker could be moved to allow access to the chamber and then moved back into position for the test. A camera was mounted to confirm the speaker was in the correct position.

Figure 2 - Front Six Loudspeaker Locations

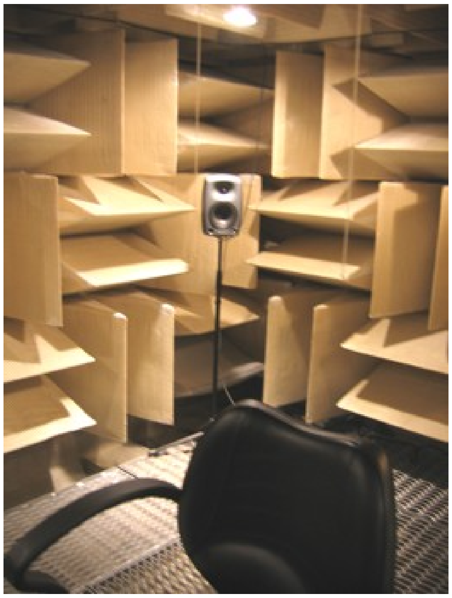

Figure 3 - Right Rear Loudspeaker Location

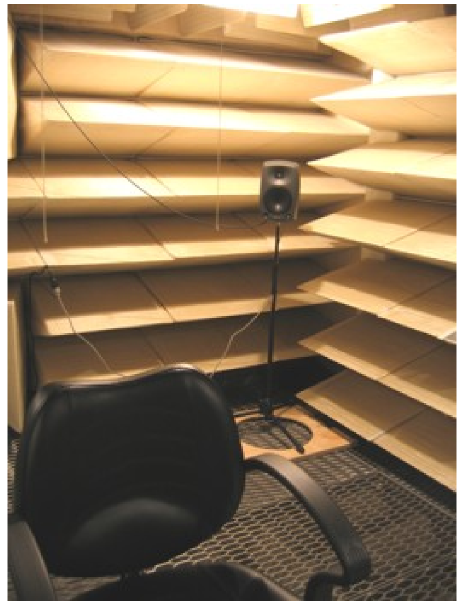

Figure 4 - Left Rear Loudspeaker Location

All testing was conducted in University of Hartford's anechoic chamber, which was completed in early 2006. The chamber contains 100 Hz wedges and is well isolated from the exterior floor below, as it sits on 3 Hz isolation springs. Through independent testing, the chamber has been qualified for free field measurements in one-third octaves between 100 – 20,000 Hz using the method described in ISO 3745 "Test Room Qualification Procedures".

The time delay and sound pressure level of each speaker needed to be normalized. A meter was placed in the chair at ear height and WinMLS 2004, impulse response measurement software, was used to measure the time delay of each loudspeaker. The delays for each loudspeaker were adjusted in the Yamaha Designer software to ensure that the signal from each loudspeaker was reaching the listener at the same time before any signal processing was added. Similarly, the sound pressure level at the receiver position of each loudspeaker was measured using a Brüel and Kjær meter type 2250. Level adjustments were made in the DME Designer software to equalize the levels coming from each loudspeaker before adding in any signal processing.

WinMLS was used to measure the impulse response of the generated signals. Using the room acoustics settings, an exponential sine sweep (one pre-signal, and then two sweeps) was used to measure the impulse response at the listener's position. Using the impulse response, the software computed C_{80} values in one-octave bands from 125 to 8000 Hz.

Initial Measurements to Determine Variations in C_{80} as a Function of Listener Location

From initial measurements, it was observed that the measured C_{80} values varied as a function of small changes in the microphone position. This issue needed to be evaluated due to the differences in the subjects' heights and head sizes. An additional investigation was undertaken to quantify these changes as the microphone was moved left and right, up and down from the "ideal location", which is center point shown in red as shown in Figure 5. A 3" measurement grid was created using the ideal location as the center point for all measurements.

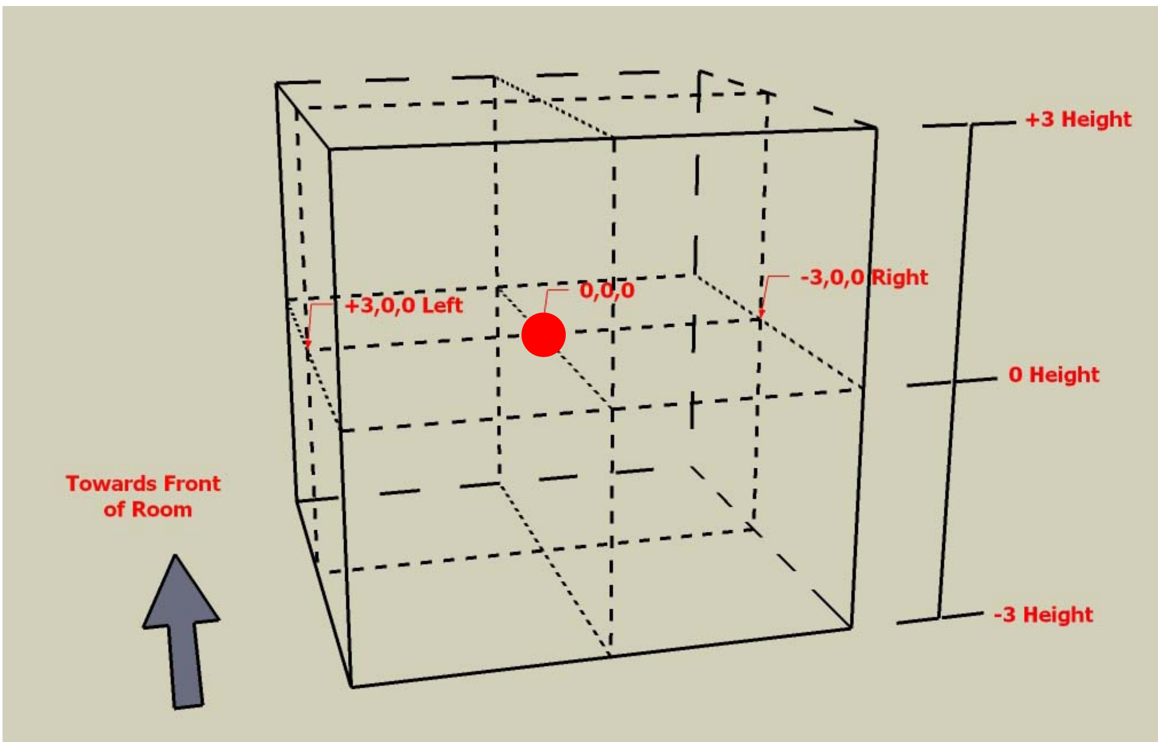

Figure 5 - 3" Measurement Grid for Clarity Test

Figure 6 shows the results taken from the center point (0, 0, 0) and then the variation if the subject moved to the right or to the left (+3,0,0 Left and -3,0,0 Right). The error bars show the normalized change in height, at ± 3”, at each position.

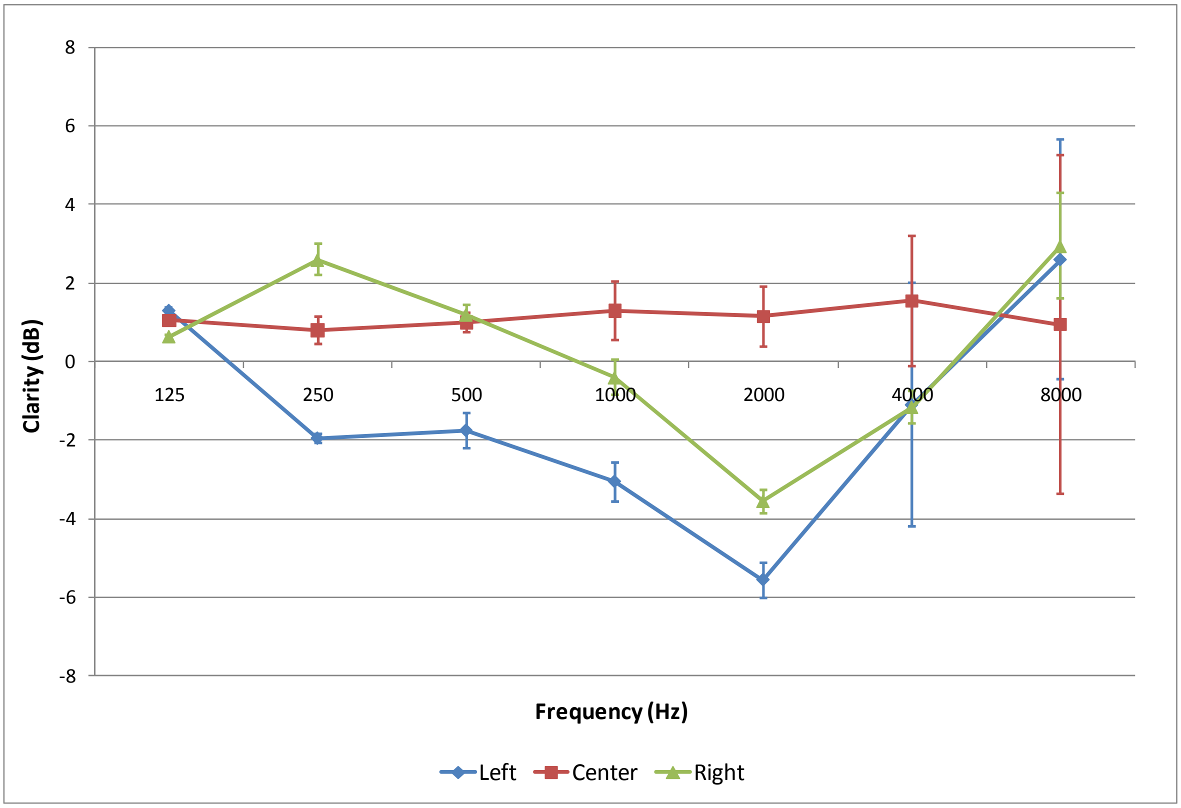

Figure 6 – Variation of Measured C80 in Left and Right Position with 3” Measurement Grid

Figure 7 shows the results from the center point (0,0,0), as well as 3” to the front and 3” to the back. The error bars show the normalized difference from the left and right of each position.

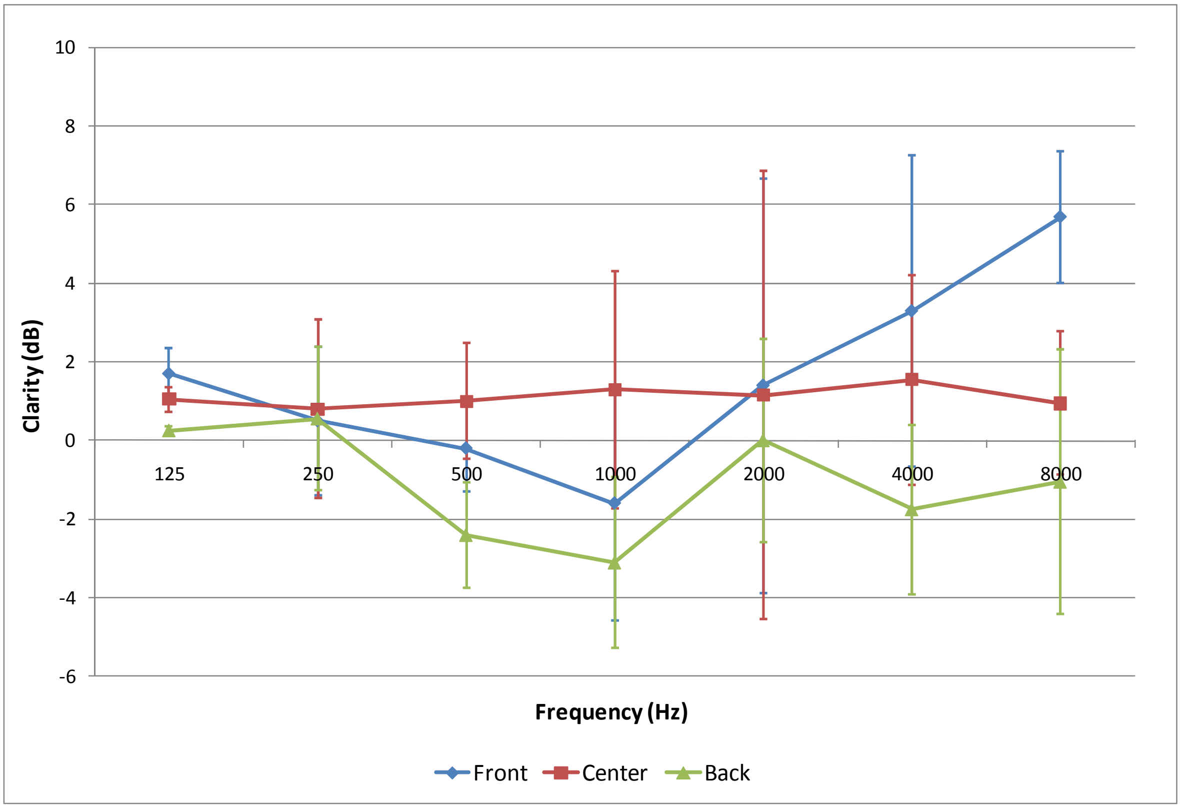

Figure 7 - Variation of Measured C80 in Front and Back Positions with 3” Measurement Grid

From this testing it was discovered that the clarity value changed more with moving left and right (much larger error bars in Figure 7, than in Figure 6) than with variations in height. This was especially true at the higher frequencies. Because of this, the side loudspeakers were tilted so they were directed at the opposite ear, i.e. the left loudspeaker was aimed towards the right ear.

A 3” displacement was thought to be a large distance for one to move their head so the experiment was repeated with a finer resolution grid of 1.5”. Figure 8 shows the clarity values using the 1.5” grid. The error bars show the change in clarity associated with a change in height (± 1.5”).

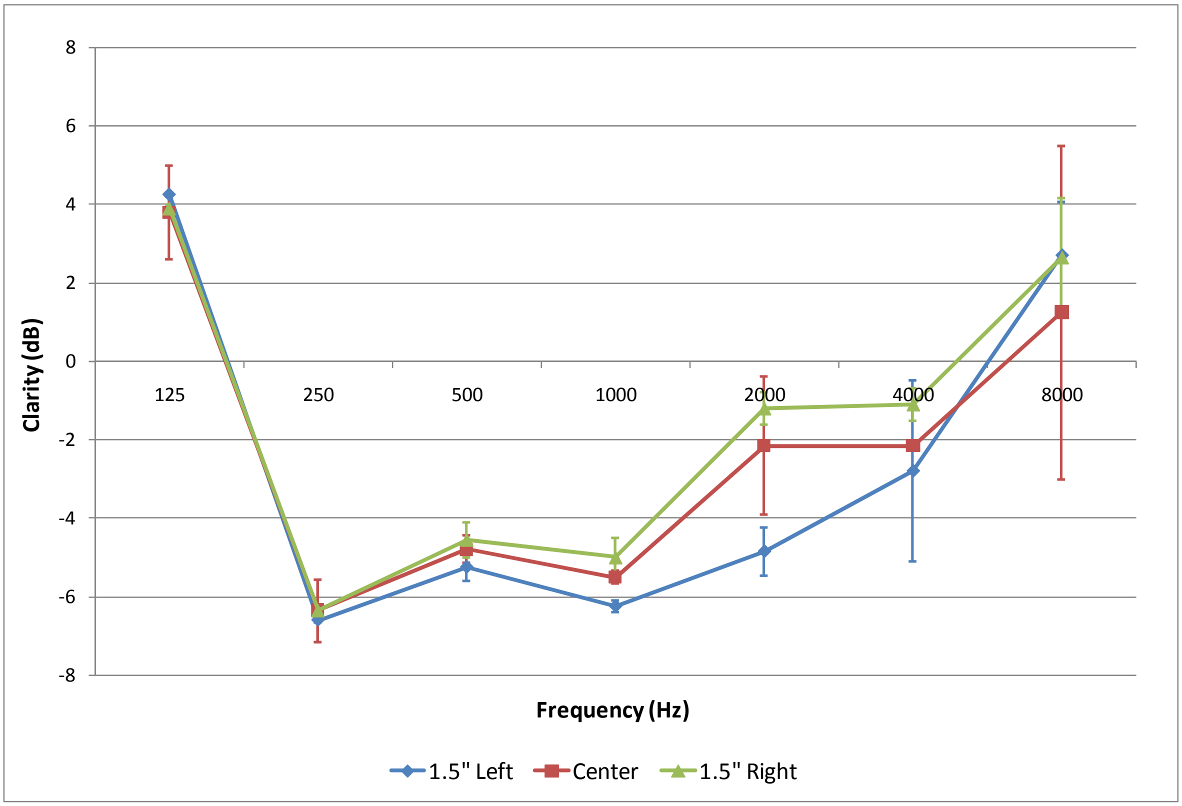

Figure 8 – Variation with 3" Measurement Grid in Left and Right Position with 1.5" Measurement Grid

The effect on clarity with the 1.5" movements was very similar to the 3" plots, but with smaller variations. It was determined that ear placement was very critical for the listener to hear the desired clarity value. A transit was used to measure the final horizontal and vertical angles of the speakers with respect to the listener's position and the values are shown in Table 1.

Table 1 – Speaker locations relative to the listener position, where the listener faces straight ahead at the *center mid-plane* speaker at 0°, 0°

Loudspeaker	Horizontal Angle (°)	Vertical Angle (°)
Center mid-plane	0.00	0.00
Center high	0.00	+16.50
Left mid-plane	-31.75	0.00
Left high	+37.50	+13.00
Right mid-plane	+31.75	0.00
Right high	-37.50	+13.00
Rear left	-136.25	0.00
Rear right	+136.25	0.00

Motif Selection

The motifs were selected from the limited number of available, high quality anechoic recordings. Three different motifs were chosen for several reasons. First, it was desirable to have a piece performed by a large ensemble as well as a solo instrument. Second, the motifs should have somewhat quick moving notes, and be relatively short. An 10.9 s passage from the third movement of Bizet's *L'Arlésienne Suite No. 2* was chosen as a large ensemble motif, Motif 1. For a solo piece, *Theme* by Weber, a solo cello piece, was chosen as Motif 2 with a length of 10.3 s. Motif 3, a 10.3 s passage from the beginning of Handel's *Water Music Suite*, was chosen as the same motif that was also used in the Cox *et al* [1] study. The orchestral anechoic recordings, Motifs 1 and 3 were taken from the DENON *Anechoic Orchestral Music Recordings* CD (1988), while Motif 2 was taken from the Bang & Olufsen *Music for Archimedes* CD (1992).

Signal Creation

Experimental Test Design

Two different base cases were chosen based on Beranek's table of preferred values of acoustical parameters [3]. For a large concert hall for symphonic repertoire, the preferred range of clarity values is -3 to 0 dB with a mid-range reverberation time of 1.6 to 2.1 seconds. A reverberation time of 2.1 seconds was chosen with a clarity value of -3 dB at 1 kHz for Base Case 1. Similarly, the parameters for chamber music were used to establish the second base case, where a range of clarity values of -2 to +2 dB with a reverberation time of 1.6 to 1.8 seconds is preferred. Base Case 2 had a reverberation time of 1.6 seconds and a clarity value of +1 dB at 1 kHz. Similar to Bradley *et al* [2], but with more differences clustered around +1.0 dB, each base case was tested with a positive difference of 0.5, 0.8, 1.0, 1.2, 1.5, 2.0, and 3.0 dB. In addition, the low and high values of each range were tested with a 0.0 dB difference. The signal values at 1 kHz and the specific A/B comparisons tested are shown in Table 2.

Table 2 – Description of Testing Pairs

	C_{80} Signal A [1 kHz] (dB)	C_{80} Signal B [1 kHz] (dB)	Δ C80 (dB)	Comment
Base Case 1: C80 = -3 dB (RT = 2.1s)	-3.0	-3.0	*0.0*	*"Low" 0 dB Difference*
	-3.0	-2.5	*0.5*	-
	-3.0	-2.2	*0.8*	-
	-3.0	-2.0	*1.0*	-
	-3.0	-1.8	*1.2*	-
	-3.0	-1.5	*1.5*	-
	-3.0	-1.0	*2.0*	-
	-3.0	0.0	*3.0*	-
	0.0	0.0	*0.0*	*"High" 0 dB Difference*
Base Case 2: C80 = +1 dB (RT = 1.6s)	1.0	1.0	*0.0*	*"Low" 0 dB Difference*
	1.0	1.5	*0.5*	-
	1.0	1.8	*0.8*	-
	1.0	2.0	*1.0*	-
	1.0	2.2	*1.2*	-
	1.0	2.5	*1.5*	-
	1.0	3.0	*2.0*	-
	1.0	4.0	*3.0*	-
	4.0	4.0	*0.0*	*"High" 0 dB Difference*

Details of Signal Design

With the base case C_{80} values established at 1 kHz, a typical contour across the frequency bands of 125-8000 Hz of concert halls needed to be established. The average contour was determined by averaging C_{80} values over this frequency range of existing concert halls with 2000 seats or less found in Beranek [3]. (See Appendix A for the hall data used in this analysis.) Figure 9 shows the average clarity values and the standard deviation. The clarity value at 1,000 Hz is the clarity value reported for the signal.

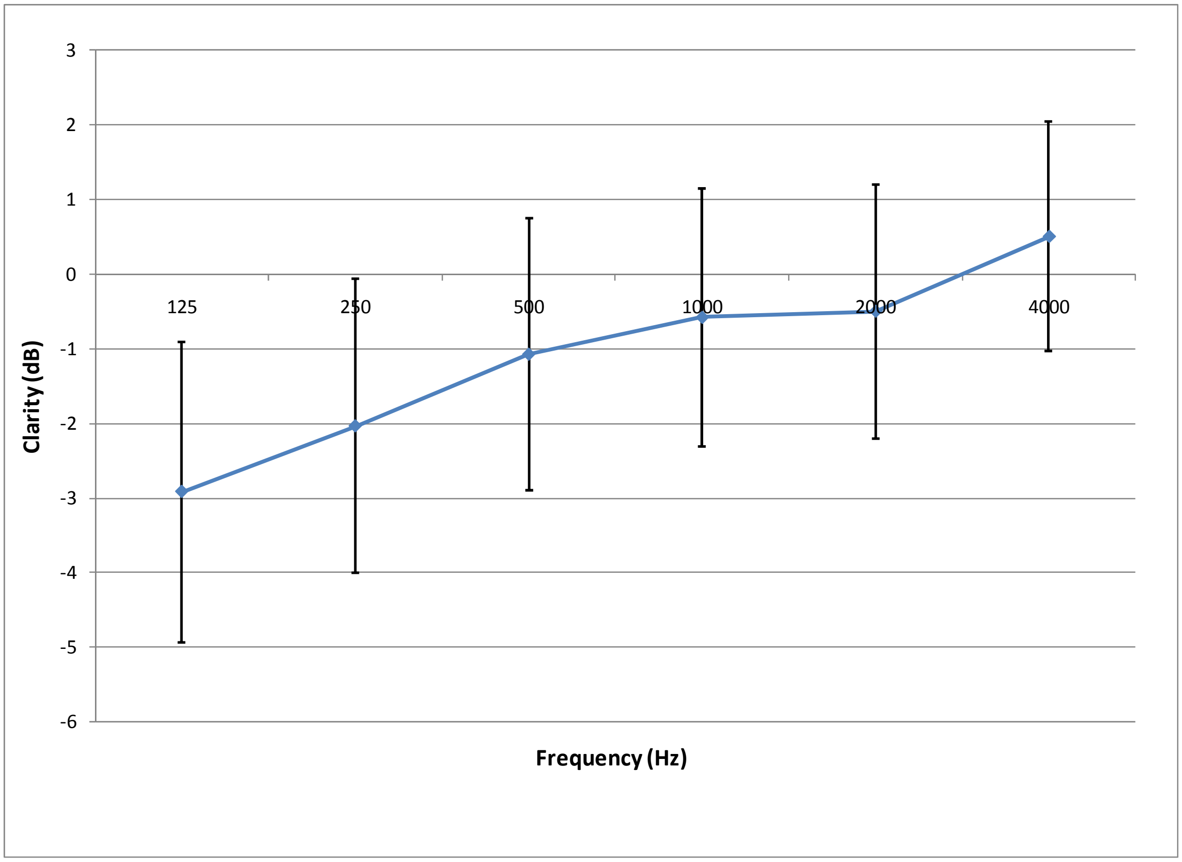

Figure 9 – Average Clarity of Existing Concert Halls with 2000 Seats or Less

Each base case contour was created by adjusting the reverberation time fader and the early reflection equalizer. This very iterative process was conducted for both base cases. To create the other seven signals, the base case was used as a starting point and the reverberation time fader was adjusted by the difference in clarity as a basis. Next, the equalization in each frequency was adjusted as necessary. Every signal was created so that at 1000 Hz, the signal was exactly the clarity value as specified, where as a 0.2 dB margin of error was allowed for all other frequencies. Figures 10 and 11 display the actual clarity values used in testing for Base Cases 1 and 2, respectively.

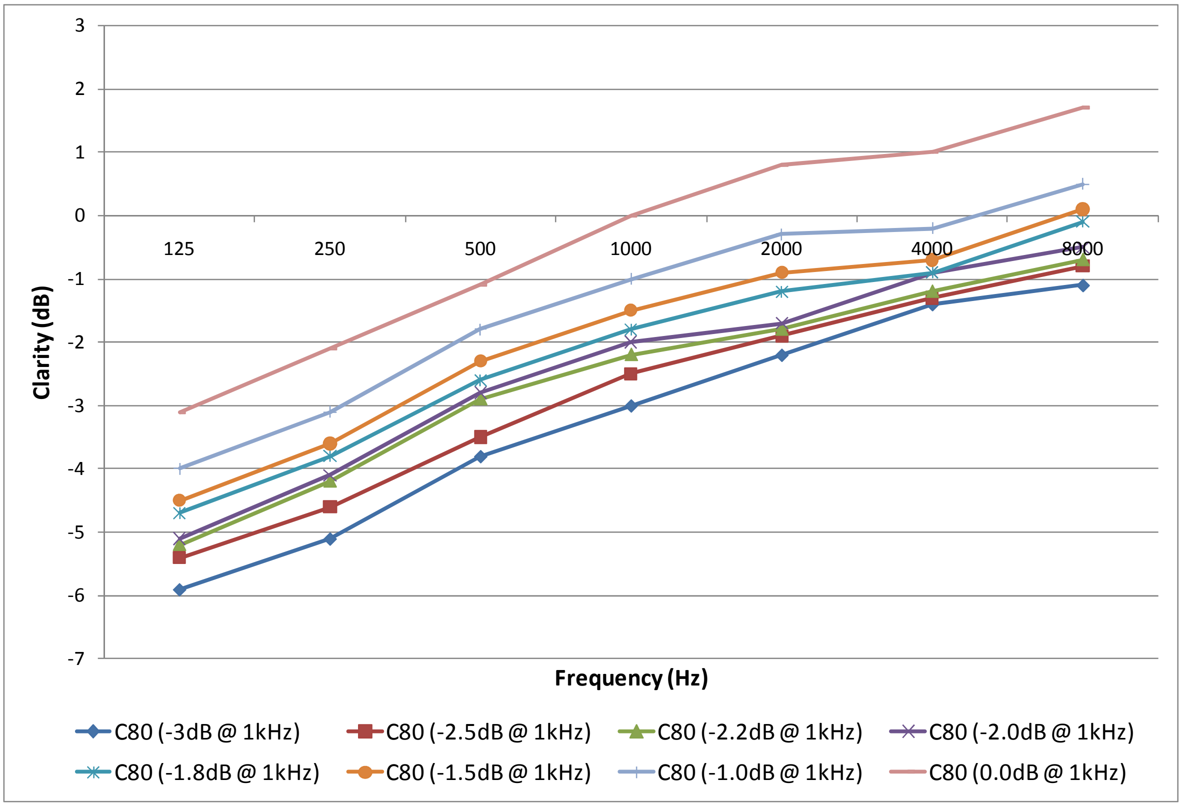

Figure 10 – Actual Clarity Contours of Signal Generated for Base Case 1

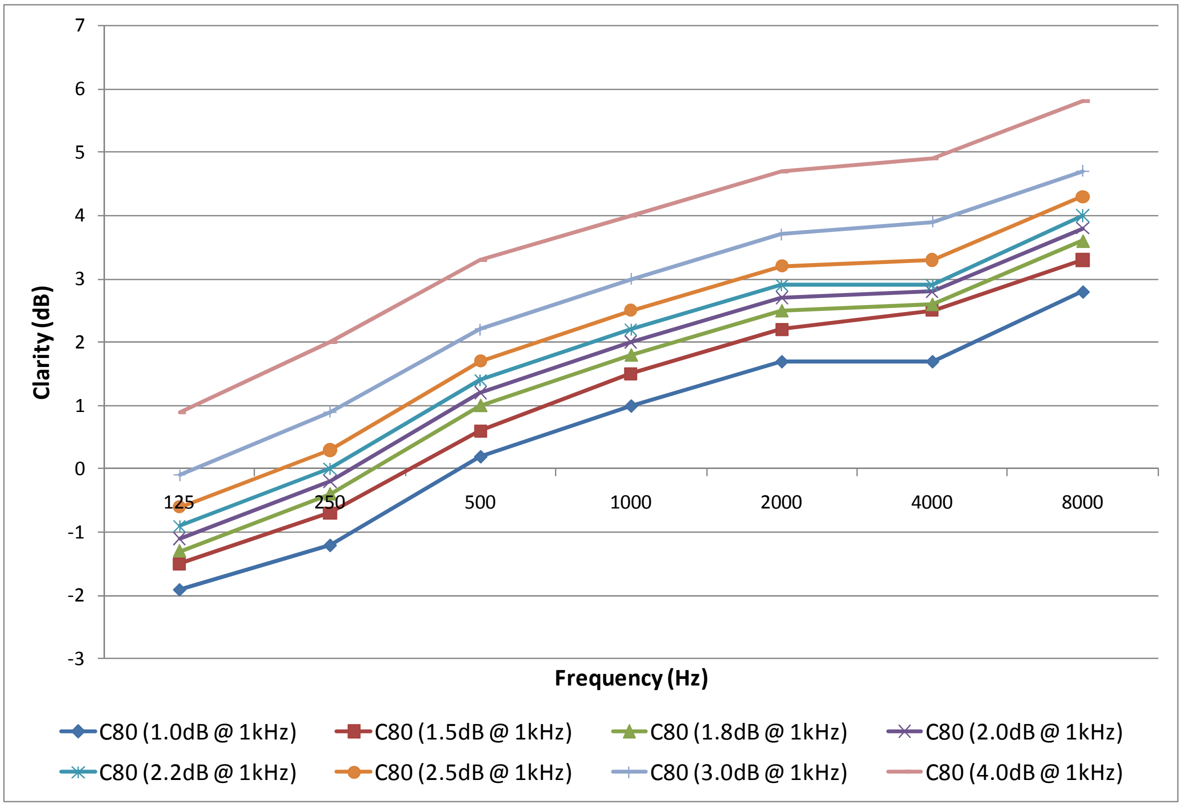

Figure 11 - Actual Clarity Contours of Signal Generated for Base Case 2

To avoid a change in SPL being perceived as a change in clarity, the sound pressure level of each signal needed to be normalized. First, each motif wave file was adjusted to be approximately the same level. Then a motif was played in the chamber and the SPL was measured in dBA and Sones. Each was normalized by adjusting the master equalizer in the Designer. The clarity values were then re-measured to make sure this had no effect on the clarity value.

Testing

The test subjects had to meet two main requirements to participate in the testing. Each participant was required to have a minimum of five years of formal musical training as well as a hearing threshold level of 25 dB HL or lower from 250 Hz to 8000 Hz. Approval to conduct the subjective testing was obtained from University of Hartford's Human Subjects Committee (see Appendix B for the approval letter.)

Since ear placement was determined to be critical, a salon chair was used to adjust the subject's height. Figure 12 shows the correct ear placement that was used during the testing. Since it was not possible to control for changes in head size, the subjects were instructed to remain as still as possible for the duration of the test. A camera was monitored throughout testing to make sure the subject didn't move too much.


Figure 12- Correct Ear Placement

Before testing, each subject was required to fill out an informed consent form. This form was to educate the subject about the details of the experiment, compensation, any risks they may be exposed to, and contact information should they have any questions after the testing has been completed. After agreeing to participate by signing the informed consent form, they were also asked to complete a demographic and music experience form that asked questions about their musical background to insure they met the requirements for the test.

Each subject's hearing was screened in the anechoic chamber before the subjective testing. It was required that each subject must have a hearing threshold of 25dB or lower in each octave band from 250 Hz - 8000 Hz. The testing was performed while sitting behind the subject. The test was started by playing three beeps at 1000 Hz and 50 dB in the right ear. The level in dB was decreased by increments of 10 dB until the subject was unable to detect the sound. At that point, the level in dB was increased by 5 dB until the subject was able to detect the sound again. This process was repeated to confirm the threshold. This was also done at 2 kHz, 4 kHz, 8 kHz, 500 Hz, and 250 Hz in that order. All thresholds were found for each frequency in the right ear first, and then all were found in the left ear using the same procedure.

Once it was verified that the subject met the hearing requirements, they were informed they would hear to two signals to compare, an "A" signal and a "B" signal. The subjects entered a 1 if they thought the signals sounded the same, a 2 if they thought they sounded different, and 3 if they wanted to hear the pair of signals again. A keypad (shown in Figure 13) that was connected to a laptop was given to the subjects to enter their response. The subjects were specifically instructed to focus on how clear each individual note sounded, and also how clear the note sounded relative to the subsequent note. They were informed that the test consisted of seven sets. The first set contained four A-B pairs, and the remaining six sets contained nine A-B pairs.

The briefer first set was a practice set, unbeknownst to the subjects to allow them time to familiarize themselves with the testing procedure. A unique motif was used for the first set. The subjects were also aware that there was a camera for communication purposes and were asked to keeps their heads as still as possible in an upright and forward position.

Figure 13- Keypad Used by the Subjects to Enter Their Responses

Results and Discussion

The data were analyzed using Statistical Package for Social Sciences (SPSS) software. The data were plotted as a function of percent of subjects who heard a difference as a function of the actual difference in the pairs in dB. The error bars represent the 95% confidence intervals for the mean values.

Phase I – All Data

Figure 14 displays the overall average percentages of subjects who indicated they heard a difference between the signals as a function of the actual C_{80} differences in dB. The x-axis displays the positive differences in the clarity (C_{80}) value between the A-B pairs, and the y-axis displays the percentage of subjects that responded they heard a change between the two signal pairs.

When there was no difference in clarity at the low 0 dB difference, approximately 48% of subjects responded that there was a difference in clarity. When there was no difference in clarity at the high 0 dB difference, approximately 49% of subjects responded that there was a difference in clarity. These results were unsettling results as these percentages should have been close to 0%. At the other extreme, the highest difference of clarity (3 dB), should have corresponded to very high percentages of difference, close to 100%, but these results yielded only approximately 61% of the subjects reporting hearing a difference.

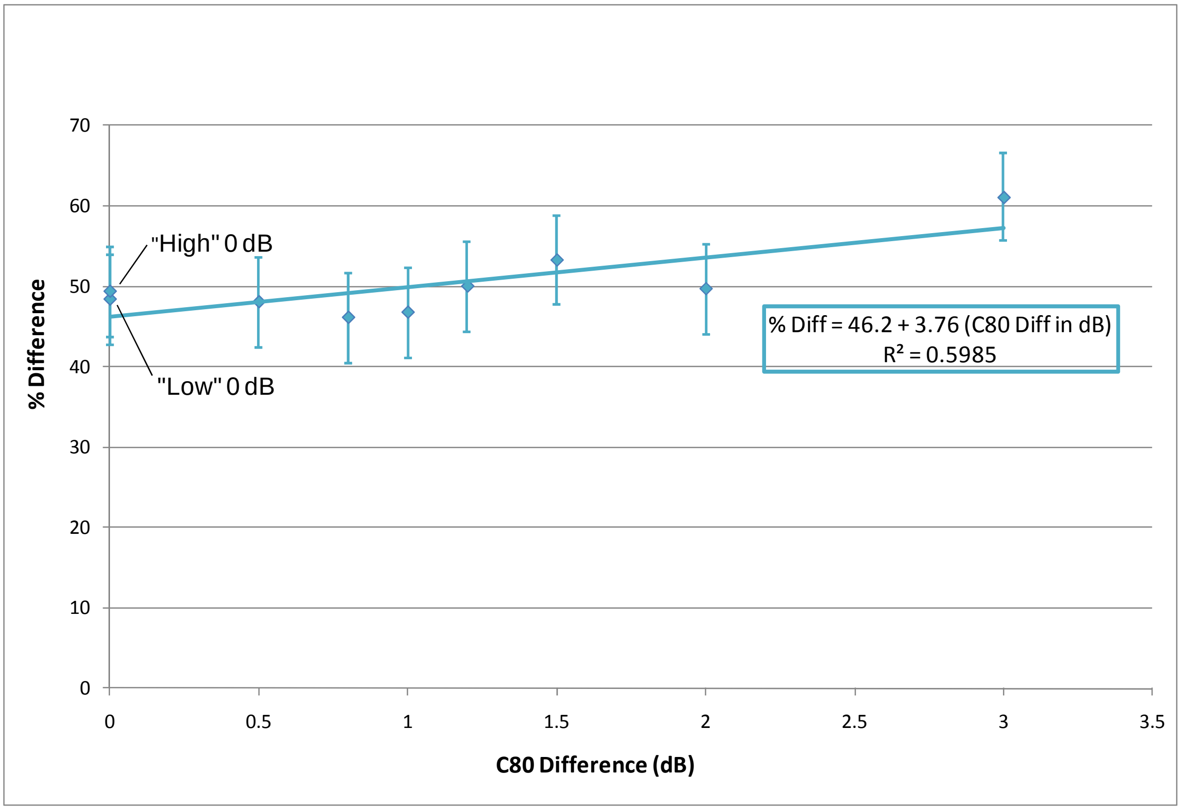

Figure 14 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Averaged Over All Conditions

The results were analyzed with respect to motif and base case. Figure 15 displays the data separated into the results for each motif used. This graph displays that fewer number of people detected a difference consistently through all clarity values during the cello piece, Motif 2. The responses during the piece by Bizet, Motif 1, consistently showed that a higher percentage of people responded that there was a difference in clarity through all clarity values, and the responses during the piece by Handel, Motif 3, were consistently between the solo and other orchestral motif. The trends of the responses are quite similar across the three motifs.

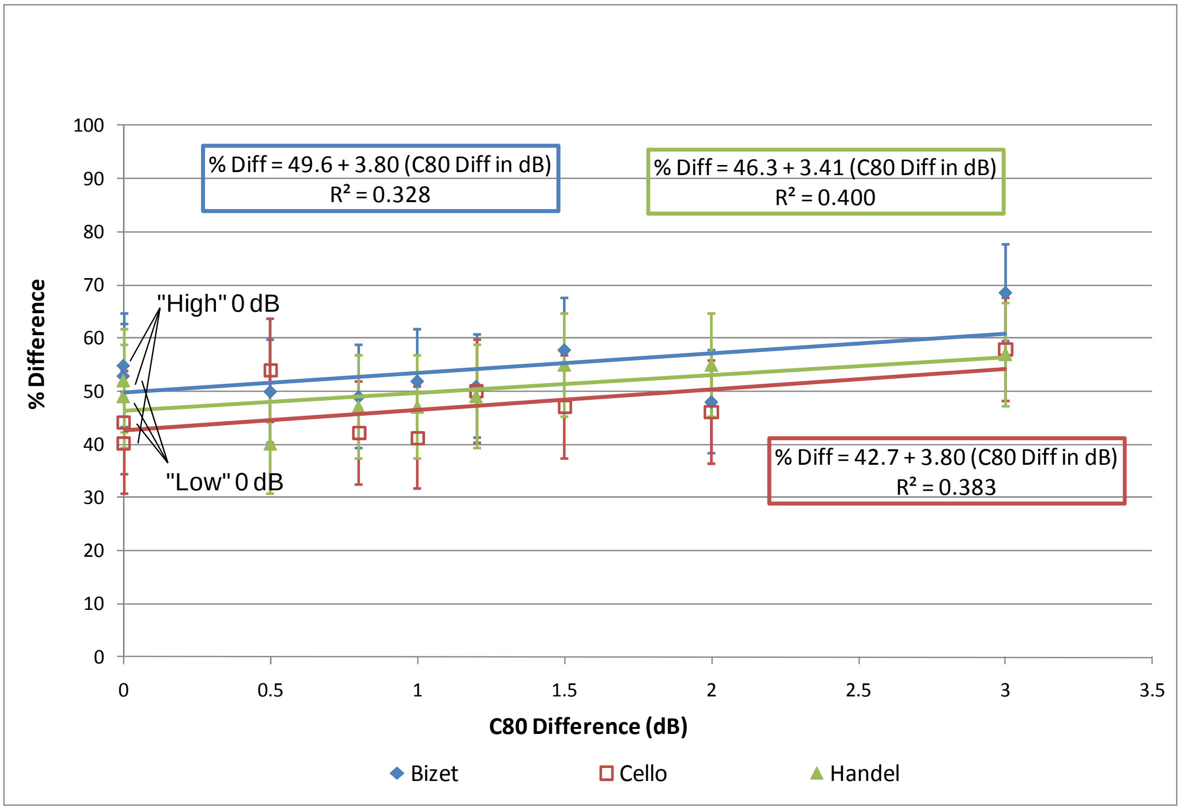

Figure 15 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Averaged Over the Base Cases

The graph in Figure 16 displays the results averaged over motif and separated by C_{80} base case. The responses for Base Case 1, with the low clarity value of – 3 dB at 1 kHz and RT of 2.1 s, are shown in blue, while the responses for Base Case 1, with the high clarity value of +1 dB at 1 kHz and RT of 1.6 s, are shown in red. This graph displays that in the 0 dB clarity difference, Base Case 1 is more accurate showing less subjects detected a difference when there was none.

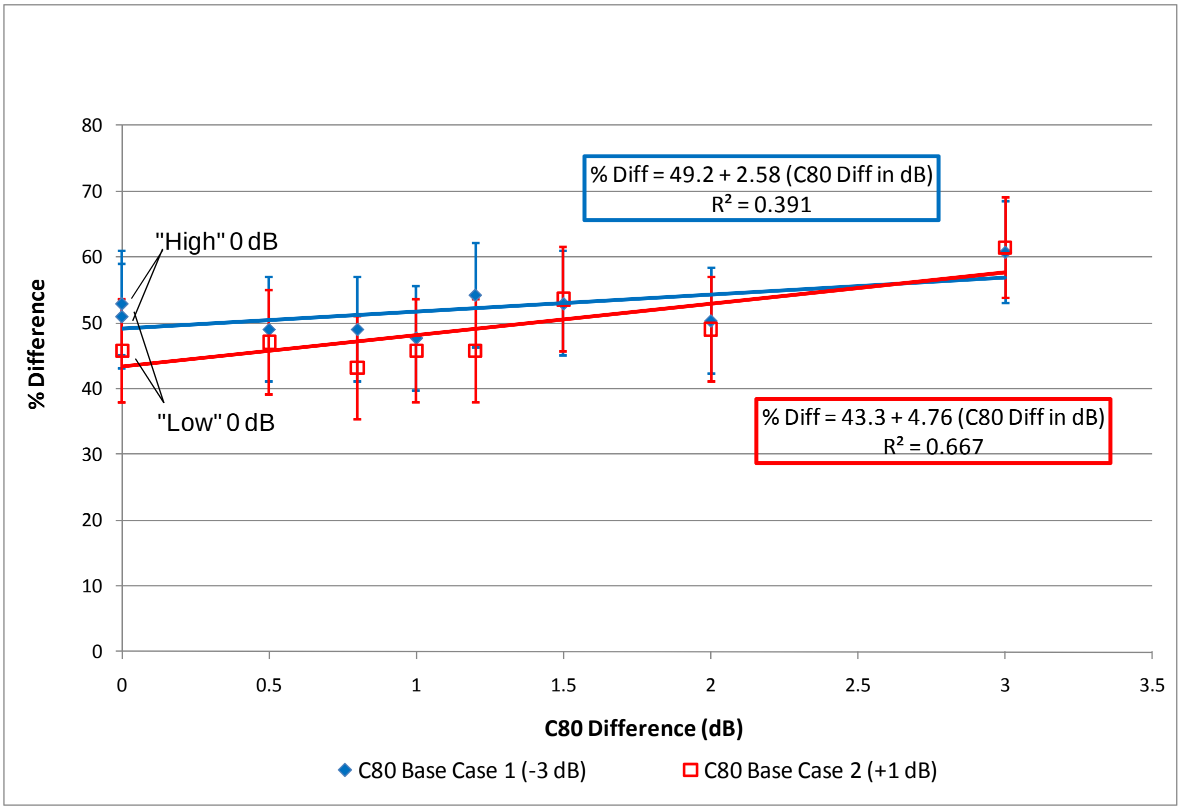

Figure 16 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Averaged Over the Motifs

The results were also further separated by each individual motif and base case, and these figures are given in Appendix C.

The data were analyzed using linear regression, with two key variables to indicate the strength of the trend line: R^2 and *p* values. The closer the R^2 values are to 1.0, the better the data fit the linear regression. Another indication of the goodness of fit of the data is the significance value, or *p* value, of the slope. In statistics, it is generally accepted that a *p* value less than 0.05 is considered to be a statistically significant result.

A summary of all of the results is shown in Table 3, including the equation to the linear regression, the R^2 value and the significance of the slope. Most of the cases analyzed had low R^2 values and *p* values > 0.05, which indicates that the trend lines did not fit the data very well. The data also didn't reveal very steep slopes, as expected based on previous work by Bradley *et al* [2]. The trend was anticipated to go from a low percentage of subjects (close to 20-30 %) hearing a difference to a high percentage (close to 80-90%) hearing a difference when the largest change in clarity occurred. From the data, only three cases had possible merit and are highlighted in the table.

Table 3 – Regression Analysis of All Data

Case	*Equation to Predict JND*	*R^2*	*Significance of Slope (p value)*
ALL DATA	46.2 + 3.67 (C80 Diff)	0.6	0.007
Motif 1 - Averaged over Base Cases 1&2	49.6 + 3.80 (C80 Diff)	0.328	0.054
Motif 2 - Averaged over Base Cases 1&2	42.7 + 3.80 (C80 Diff)	0.383	0.038
Motif 3 - Averaged over Base Cases 1&2	46.3 + 3.41 (C80 Diff)	0.400	0.034
Base Case 1 - Averaged over Motifs 1,2&3	49.2 + 2.58 (C80 Diff)	0.391	0.036
Base Case 2 - Averaged over Motifs 1,2&3	43.3 + 4.76 (C80 Diff)	0.667	0.004
Motif 1 & Base Case 1	50.9 + 5.90 (C80 Diff)	0.513	0.015
Motif 1 & Base Case 2	48.3 + 1.60 (C80 Diff)	0.037	0.311
Motif 2 & Base Case 1	47.0 + 1.80 (C80 Diff)	0.059	0.265
Motif 2 & Base Case 2	38.3 + 5.90 (C80 Diff)	0.477	0.020
Motif 3 & Base Case 1	49.5 + 0 (C80 Diff)	0.000	0.488
Motif 3 & Base Case 2	43.2 + 6.80 (C80 Diff)	0.715	0.002

NOTE: Highlighted cases are the only ones with possible merit from the unfiltered data analysis.

Feedback from the Subjects

The vast majority of subjects reported on their feedback forms that they found it difficult to hear differences between the signals A and B. They especially thought Base Case 1 was harder to distinguish than Base Case 2. Of those who reported a difference in difficulty as a function of motif, there were approximately equal numbers of subjects that preferred the motifs with large ensembles to those who preferred the solo motif. (Motifs 1 and 3 had large ensembles, while Motif 2 had a solo cello.) Most subjects found the test very repetitive and some found it hard to stay attentive towards the end of each set.

Due to the difficulty most subjects reported, it is possible that their responses were in fact randomly decided. This would be consistent with the displayed results as the percentage of people who heard a difference across differences in C_{80} was generally around 50% (Figure 14).

Phase II – Filtered Data Analysis

Due to the results giving weak trends and subject feedback indicating the overall difficulty level of the test, data were filtered to only include some of the subjects. It was decided to examine the participant's response to the 0 dB low, 0 dB high, and 3 dB cases. Because these are the extremes, it was expected that the participant would respond they heard no difference for the 0 dB change and that they heard a difference between the 3 dB change. From this, the subjects were graded on how often they were correct on these cases. The subjects that were correct 65% of the time for these cases ONLY were selected for a filtered analysis. This process resulted in using 17 subjects' data from the original 51.

Using this data yielded trends more in agreement with the expected results. Figure 17 shows the overall average of the filtered subjects. When there was no difference in clarity at the low 0 dB difference, approximately 24% of people reported a difference as opposed to 48% in the unfiltered data. When there was no difference in clarity at the high 0 dB difference, approximately 28% of subjects responded that there was a difference in clarity as opposed to 49% in the unfiltered data. The number of people reporting that they heard a difference in clarity at the highest clarity difference in the filtered data is 68%, as opposed to the 61% in the unfiltered data. The predicted clarity index JND from this data set is 1.55 dB.

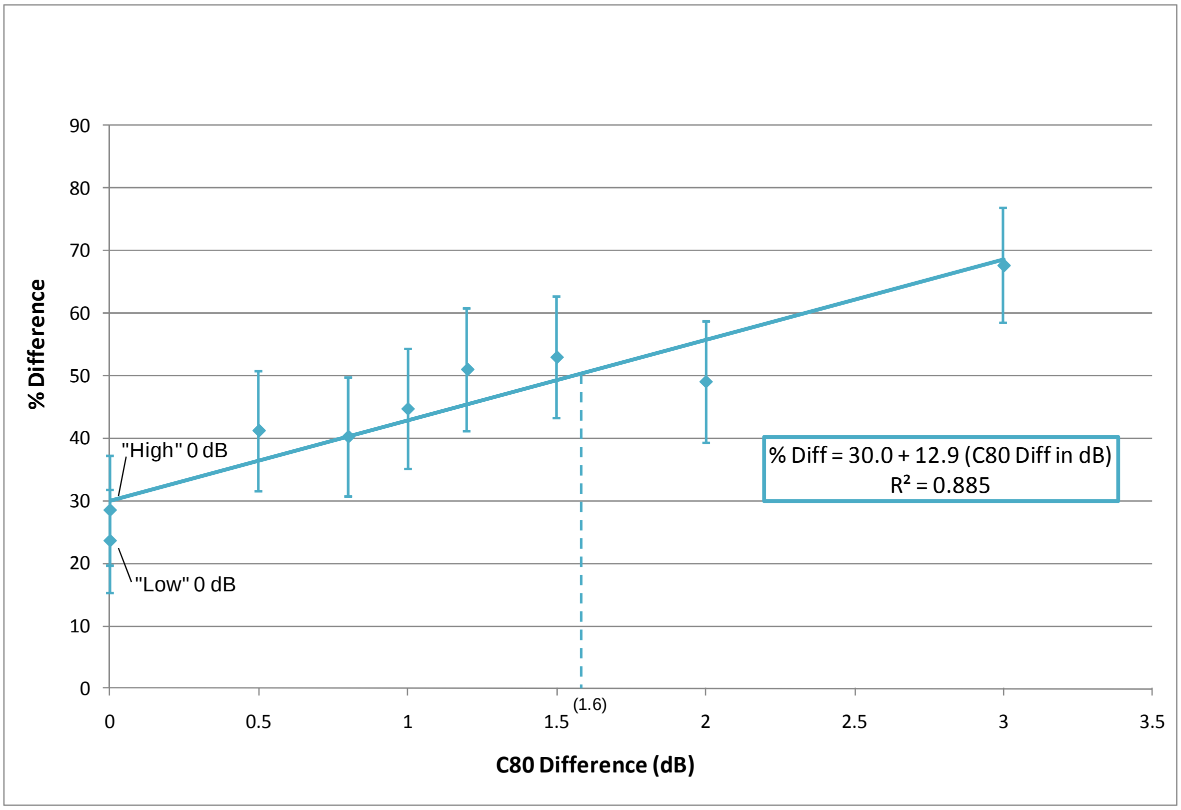

Figure 17 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Averaged Over All Conditions

The results as a function of motif for the unfiltered data (Figure 18) differ from the results with all data (Figure 15). Motif 1, Bizet orchestral piece, had the highest slope value and Motif 2, Weber solo cello piece, had the lowest. These trends show that motif could have had an influence on the JND of the clarity index. The solo cello piece had the highest predicted C_{80} JND of 2.03 dB with p= 0.002 while the both orchestral motifs, 1 and 3, predicted lower JNDS of 1.36 dB (p=0.000) and 1.47 dB (p=0.002), respectively.

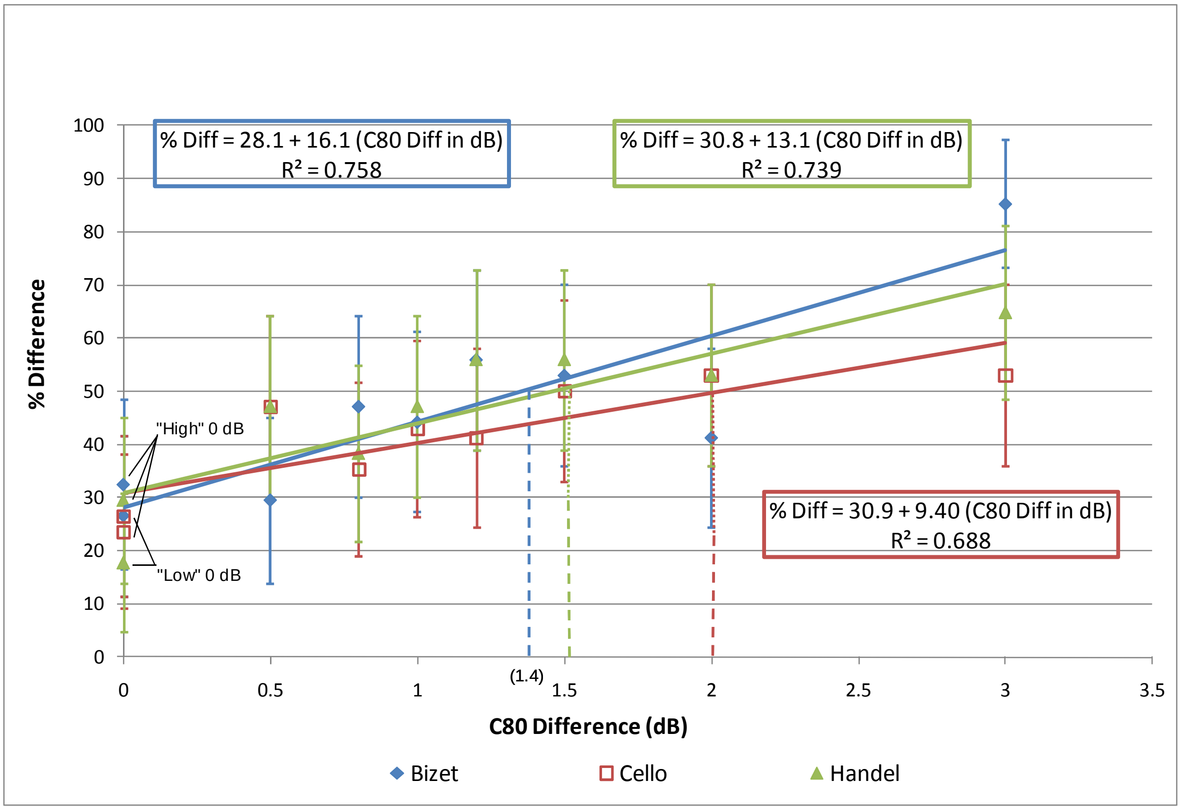

Figure 18 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Averaged Over the Base Cases

Figure 19 shows the filtered data separated by the two base cases. There does not seem to be a different trend between the two base cases as there was with the motifs, as compared to the analysis with all of the data. Again, the graph displays a greater difference in base case at the low differences of clarity, where base case 2 shows fewer numbers of people reporting they heard a difference in clarity when there was none, which perhaps indicates that people find it easier to determine the signals are same when there is a higher clarity index and a lower reverberation time.

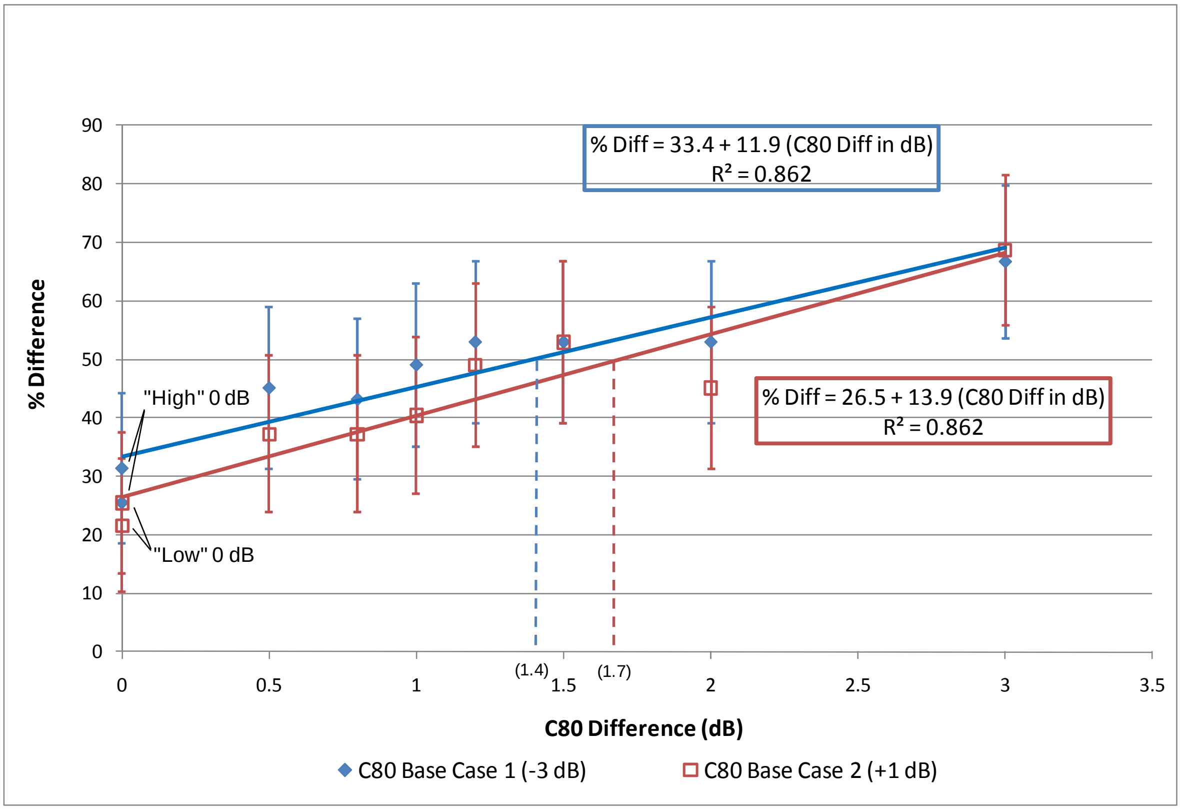

Figure 19 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Averaged Over the Motifs

The remaining figures for the filtered data are shown in Appendix D. Table 4 summarizes the results for the filtered data. The R^2 values are higher than the unfiltered data and the significance values are smaller. The cases that are crossed out have R^2 values less than 0.6. The average predicted JND, not including the crossed out values, is 1.6 ± 0.3 dB.

Table 4 – Regression Analysis of Filtered Data and Predicted JND

Case	*Equation to Predict JND*	R^2	*Significance of Slope (p value)*	*JND*
ALL DATA	30.0 + 12.9 (C80 Diff)	0.885	0.000	1.55
Motif 1 - Averaged over Base Cases 1&2	28.1 + 16.1 (C80 Diff)	0.758	0.001	1.36
Motif 2 - Averaged over Base Cases 1&2	30.9 + 9.40 (C80 Diff)	0.688	0.003	2.03
Motif 3 - Averaged over Base Cases 1&2	30.8 + 13.1 (C80 Diff)	0.739	0.002	1.47
Base Case 1 - Averaged over Motifs 1,2&3	33.4 + 11.9 (C80 Diff)	0.862	0.000	1.39
Base Case 2 - Averaged over Motifs 1,2&3	26.5 + 13.9 (C80 Diff)	0.883	0.000	1.69
Motif 1 & Base Case 1	25.6 + 21.0 (C80 Diff)	0.807	0.001	1.16
~~**Motif 1 & Base Case 2**~~	~~30.6 + 11.3 (C80 Diff)~~	~~0.525~~	~~0.014~~	~~1.72~~
~~**Motif 2 & Base Case 1**~~	~~37.2 + 6.00 (C80 Diff)~~	~~0.334~~	~~0.049~~	~~2.13~~
Motif 2 & Base Case 2	24.7 + 12.8 (C80 Diff)	0.633	0.005	1.98
~~**Motif 3 & Base Case 1**~~	~~37.4 + 8.70 (C80 Diff)~~	~~0.323~~	~~0.055~~	~~1.45~~
Motif 3 & Base Case 2	24.3 + 17.6 (C80 Diff)	0.827	0.001	1.46

NOTE: The crossed out cases have R squared values less than 0.6. The average predicted JND, not including the crossed out values, is 1.6 ± 0.3 dB.

Recommendations and Conclusions

After testing, analyzing the data, and reviewing the feedback forms, it was clear the subjects had a difficult time determining if an audible difference was present. Future studies should incorporate changes to make the test more manageable in terms of both time and difficulty. Some of subjects found it hard to focus by the end of the test; thus the number of A/B pairs presented in one session should be reduced. If more pairs need to be presented, they should be given in a different session after a break or even on a different day.

In terms of reducing the difficulty, many steps could be taken. First, subjects should be given some explicit training with very obvious A/B pairs with no difference and large differences in clarity index. Based on the subject's feedback, the test design should include pairs with larger differences in clarity and with shorter motifs (shorter than 10 seconds). Another important change is to emphasize to subjects that they should not hesitate to report that they did not hear a difference, as the data suggest that when the subjects were unsure if they heard a difference, they would report that they did. Another recommendation is to set up an apparatus that gives the subjects' the ability to switch back and forth between the two signals in each pair, as Bradley *et al* did in their study [2]. This measure should help to make it easier to detect differences or readily observe no differences in the signals, and likely result in a steeper slope in the trend line of the results. Finally, a different testing approach could be implemented based on the commonly practiced hearing threshold testing procedure. A single signal could be initially presented with the subsequent signal having a large difference in C_{80}. The subject would indicate if they hear a difference. The next signal would have a smaller difference in C_{80} and signals with decreasing differences in C_{80} would be presented until the subject no longer detected a difference.

The conclusions drawn from the filtered data set is a C_{80} JND of 1.6 ± 0.3 dB. This result is a higher value than the current commonly reported JND of 1.0 dB, which was used as a basis for the design of this test. The JND of 1.6 ± 0.3 dB, found in this test, could be used to redesign the test with larger increments of clarity.

References

[1] Cox, TJ., Davies, W.J., and Lam, Y.M. (1993). "The sensitivity of listeners to early sound field changes in auditoriums." *Acustica* **79**(1):27-41.

[2] Bradley, J.S., Reich, R., and Norcross, S.G. (1999). "A just noticeable difference in C-50 for speech." *Applied Acoustics* **58**(2): 99-108.

[3] Beranek, L. (2004). *Concert Halls and Opera Houses: Music, Acoustics, and Architecture. 2nd Edition* (Springer-Verlag, New York, NY), pg. 526-527, 536.

Appendix A –C80 Values of Existing Concert Halls

Table A.1 – C80 Values of Existing Concert Halls

	C80 Averages (dB)					
Concert Hall	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Baltimore Symphony	-3.35	-3.31	-2.31	-1.69	-0.89	0.35
Symphony Hall	-2.42	-2.63	-2.76	-2.52	-2.97	-2.31
Costa Mesa	-3.15	-1.48	-0.98	-0.5	-0.1	0.8
McDermott Concert Hall	-0.9	-4.2	0.7	-0.7	0.2	0.4
Ft Worth	-2	-2	-2	-2	-1.5	-1
Worchester	-1	-2	-2	-1	0	1
Buenos Aires	-4.3	-2.3	-3	-3.5	-1.7	-0.8
Salzburg	-2.14	-1.71	-0.9	0.47	-0.42	0.81
Musikvereinssaal	-5.28	-5.47	-4.72	-3.95	-3.32	-1.57
Vienna Konzerthaus 1997	-3.5	-2.2	-2	-0.5	0	1.9
Vienna Konzerthaus 2001	-2	-0.9	-0.6	-0.3	-0.7	1.1
Staatsoper So	-0.2	1.5	2.5	2.8	2.7	4.3
Staatsoper Pit	-2.1	-0.7	-0.7	-0.6	-0.2	1.2
Brussels after ren	-1.41	-0.99	-0.29	-0.75	-0.97	1.13
Toronto	-4.48	-1.58	0.01	0.95	0.74	2.92
Hong Kong no absorp blinds	-3.29	-1.8	-0.26	-0.8	-0.47	0.02
Hong Kong with absorp blinds	2.74	1.2	1.59	2.32	3.24	2.29
Copenhagen	0.83	-0.36	-0.35	-0.26	-1.53	-0.52
Odense	-2.7	-2.2	-2.4	-1.1	-2.9	-0.7
Birmingham open reverb door	-4.8	-1.3	-0.6	1.1	0.9	1.9
London Barbican	-1.04	1.14	0.55	-0.02	1.73	3.31
Salle Pleyel	-5.41	-0.78	0.45	2.21	2.03	0.78
Baden-Baden	-2	-1.6	-0.6	0.2	0.6	1.4
Berlin Konzerthaus	-4.2	-4.3	-3.9	-2.3	-1.3	-0.5
Barlin Philharmonie	-2.2	-0.7	-0.7	-0.6	-0.5	0
Munich Philharmonie Bradley	-4.51	-1.11	-0.44	0.38	-0.71	0.61
Munich Philharmonie Gade	-5.02	-2.8	-0.51	-0.82	-1.95	-0.3
Stuttgart Gade	-2.72	-0.36	2.09	2.01	-3.1	-0.54
Stuttgart Bradley	-1.85	-0.99	-1.04	-1.03	-1.15	-0.34
Belfast	-4.2	-2.6	-0.4	0.4	1.5	
Milan	1	1.4	2	3.8	4.7	4.4
Naples	-2.3	-2.3	-0.25	-0.1	0	0.1
Sapporo	-4.7	-1.1	0.3	1	0.3	1.3
Tokyo Bunka Kaikan Nagata	-2.9	-1.24	-0.08	-1.72	-1.23	-0.08
Tokyo Bunka Kaikan Tacenaka	-1.3	-0.8	-0.3	-1	-0.8	0
Tokyo Metropolitan Art Space	-5.88	-3.55	-0.85	-1.5	-1.07	-0.3
Tokyo Suntory Hall	-0.381	-2.68	-0.85	-0.91	-1	-0.31
Amsterdam Concertgebouw	-5.4	-4.67	-4.19	-3.07	-2.65	-1.47
Christ Church Town Hall	-2.5	0.2	1.3	1.9	1.3	2
Madrid	-3.03	-1.97	-1.21	-0.06	0.06	2.3
Valencia	-4.98	-7.55	-5.45	-3.51	-2.12	0.98
Gothenburg	-1.86	-2.02	-1.31	0.16	0.95	1.25
Basel	-4.1	-4.5	-3.2	-2	-1.7	-0.7
Zurch	-5.8	-6.8	-4.4	-3.6	-2.8	-1.5
Taipei	-7.71	-5.87	-4.65	-3.28	-2.74	-2.7
Cardiff Barron	-4.2	-1.5	-0.7	-0.5	-0.9	
Cardiff Gade	-2.31	-2.14	-1.04	-0.73	-0.88	-0.08

Table A.2 – C80 Differences Using Value at 1000Hz as a Reference

	Delta (1000Hz) (dB)					
Concert Hall	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Baltimore Symphony	-1.66	-1.62	-0.62	0	0.8	2.04
Symphony Hall	0.1	-0.11	-0.24	0	-0.45	0.21
Costa Mesa	-2.65	-0.98	-0.48	0	0.4	1.3
McDermott Concert Hall	-0.2	-3.5	1.4	0	0.9	1.1
Ft Worth	0	0	0	0	0.5	1
Worchester	0	-1	-1	0	1	2
Buenos Aires	-0.8	1.2	0.5	0	1.8	2.7
Salzburg	-2.61	-2.18	-1.37	0	-0.89	0.34
Musikvereinssaal	-1.33	-1.52	-0.77	0	0.63	2.38
Vienna Konzerthaus 1997	-3	-1.7	-1.5	0	0.5	2.4
Vienna Konzerthaus 2001	-1.7	-0.6	-0.3	0	-0.4	1.4
Staatsoper So	-3	-1.3	-0.3	0	-0.1	1.5
Staatsoper Pit	-1.5	-0.1	-0.1	0	0.4	1.8
Brussels after ren	-0.66	-0.24	0.46	0	-0.22	1.88
Toronto	-5.43	-2.53	-0.94	0	-0.21	1.97
Hong Kong no absorp blinds	-2.49	-1	0.54	0	0.33	0.82
Hong Kong with absorp blinds	0.42	-1.12	-0.73	0	0.92	-0.03
Copenhagen	1.09	-0.1	-0.09	0	-1.27	-0.26
Odense	-1.6	-1.1	-1.3	0	-1.8	0.4
Birmingham open reverb door	-5.9	-2.4	-1.7	0	-0.2	0.8
London Barbican	-1.02	1.16	0.57	0	1.75	3.33
Salle Pleyel	-7.62	-2.99	-1.76	0	-0.18	-1.43
Baden-Baden	-2.2	-1.8	-0.8	0	0.4	1.2
Berlin Konzerthaus	-1.9	-2	-1.6	0	1	1.8
Barlin Philharmonie	-1.6	-0.1	-0.1	0	0.1	0.6
Munich Philharmonie Bradley	-4.89	-1.49	-0.82	0	-1.09	0.23
Munich Philharmonie Gade	-4.2	-1.98	0.31	0	-1.13	0.52
Stuttgart Gade	-4.73	-2.37	0.08	0	-5.11	-2.55
Stuttgart Bradley	-0.82	0.04	-0.01	0	-0.12	0.69
Belfast	-4.6	-3	-0.8	0	1.1	-0.4
Milan	-2.8	-2.4	-1.8	0	0.9	0.6
Naples	-2.2	-2.2	-0.15	0	0.1	0.2
Sapporo	-5.7	-2.1	-0.7	0	-0.7	0.3
Tokyo Bunka Kaikan Nagata	-1.18	0.48	1.64	0	0.49	1.64
Tokyo Bunka Kaikan Tacenaka	-0.3	0.2	0.7	0	0.2	1
Tokyo Metropolitan Art Space	-4.38	-2.05	0.65	0	0.43	1.2
Tokyo Suntory Hall	0.529	-1.77	0.06	0	-0.09	0.6
Amsterdam Concertgebouw	-2.33	-1.6	-1.12	0	0.42	1.6
Christ Church Town Hall	-4.4	-1.7	-0.6	0	-0.6	0.1
Madrid	-2.97	-1.91	-1.15	0	0.12	2.36
Valencia	-1.47	-4.04	-1.94	0	1.39	4.49
Gothenburg	-2.02	-2.18	-1.47	0	0.79	1.09
Basel	-2.1	-2.5	-1.2	0	0.3	1.3
Zurch	-2.2	-3.2	-0.8	0	0.8	2.1
Taipei	-4.43	-2.59	-1.37	0	0.54	0.58
Cardiff Barron	-3.7	-1	-0.2	0	-0.4	0.5
Cardiff Gade	-1.58	-1.41	-0.31	0	-0.15	0.65

Appendix B – University of Hartford Human Subjects Committee Subjective Testing Approval Letter

UNIVERSITY OF HARTFORD

Human Subjects Committee

March 5, 2009

Michelle Vigeant
Department of Mechanical Engineering
Acoustics Program
University of Hartford
West Hartford, CT 06117

Dear Dr. Vigeant:

Upon review by the Human Subjects Committee, your proposal, *Just noticeable difference in clarity index, C80,* has been approved for one year according to expedited guidelines governing the use of human subjects in research as set forth in federal regulation 45 CFR 46.110(b). Keep in mind that it is your responsibility to notify and seek approval from this Committee of any modifications to your project, and that it is your responsibility to report within 48 hours to this Committee, any adverse events that occur related to this evaluation.

This institution has an Assurance of Compliance on file with the Office of Human Research Protections (Federalwide Assurance FWA00003578).

Congratulations and good luck.

Sincerely,

Monica J. Hardesty, Ph.D.
Chair, Human Subjects Committee

Appendix C – Additional Plots of Subjective Testing Results for ALL Data

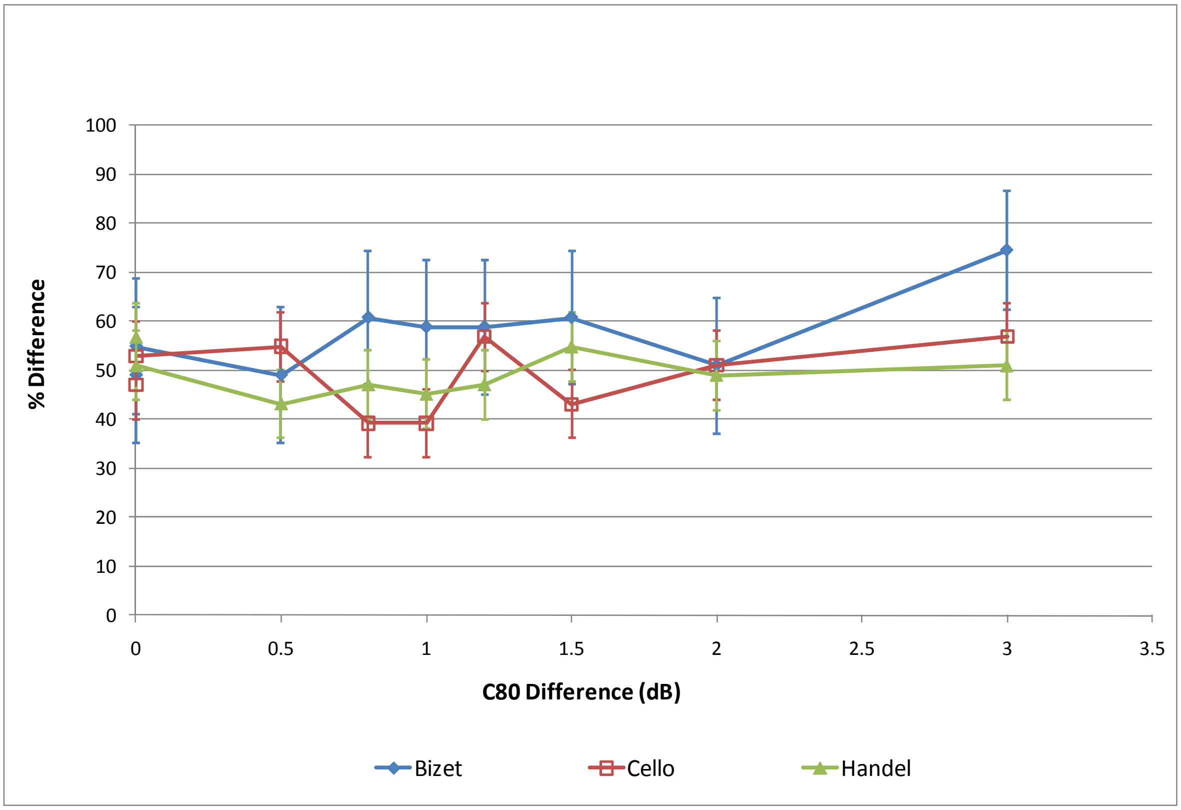

Figure C.1– Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Base Case 1 Only

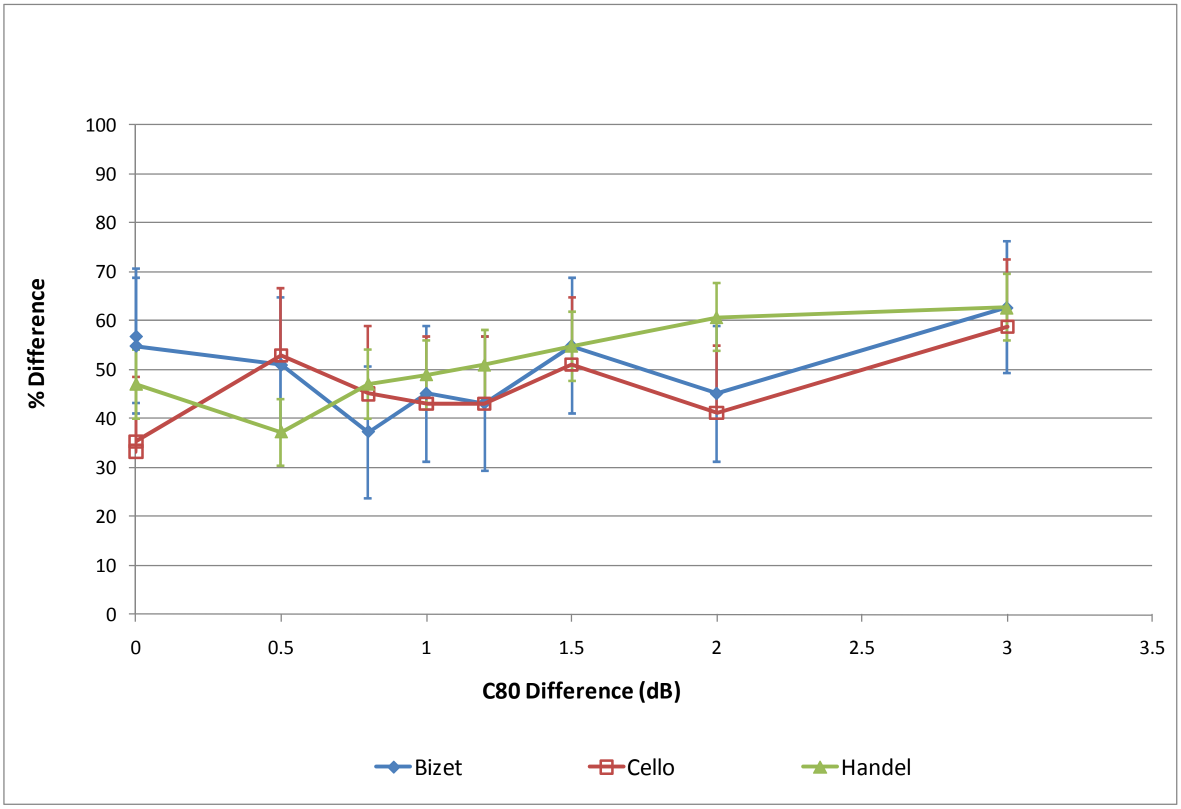

Figure C.2 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Base Case 2 Only

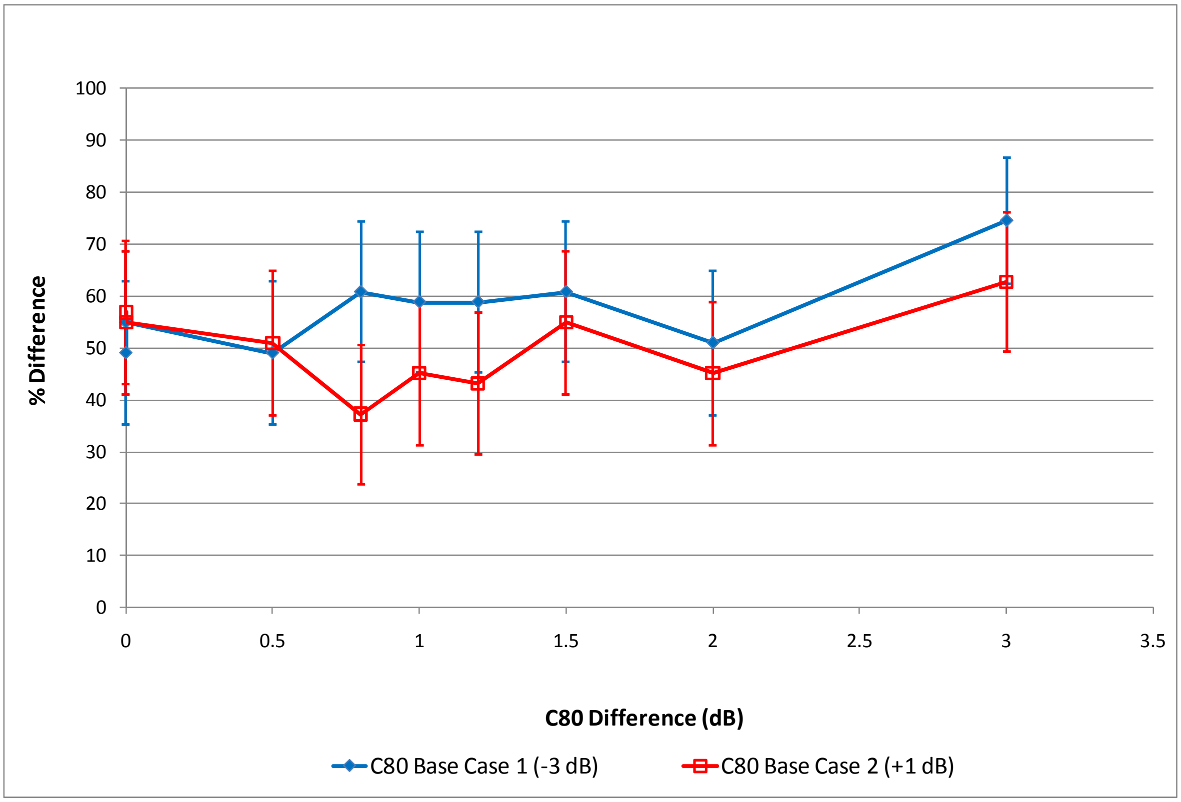

Figure C.3 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Bizet Motif

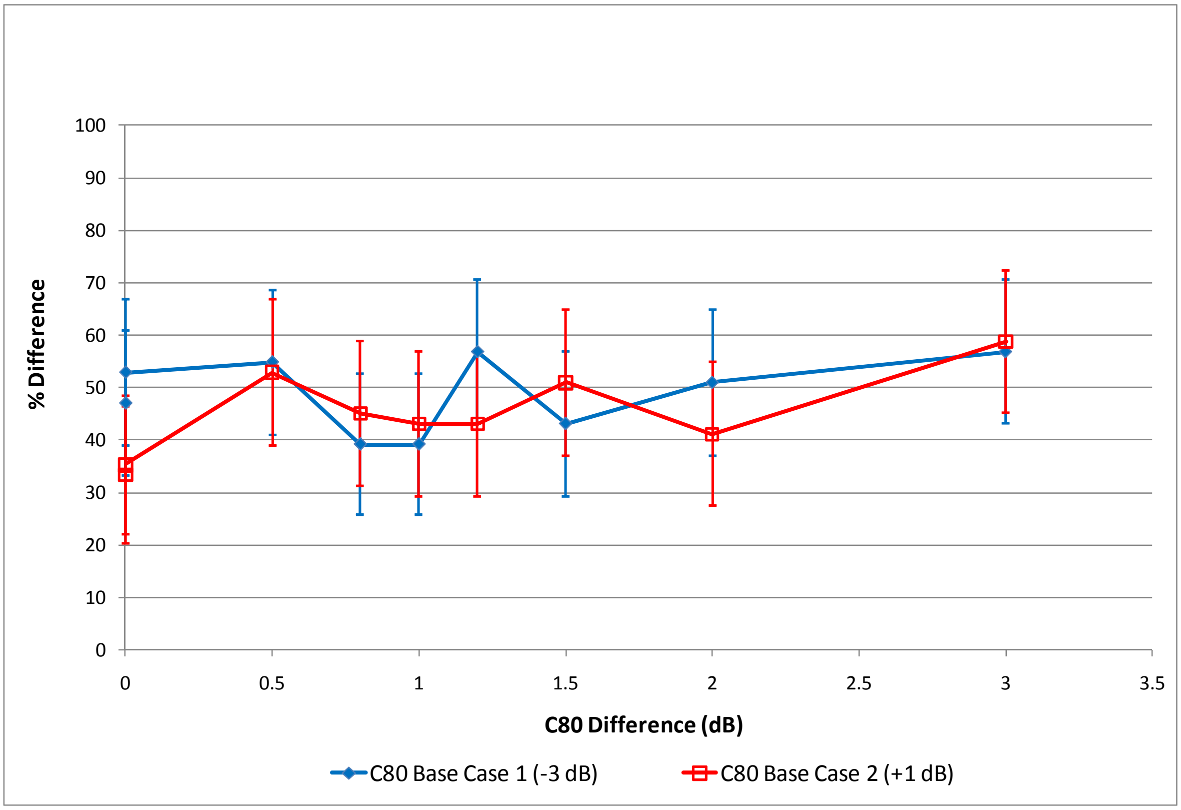

Figure C.4 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Weber Motif

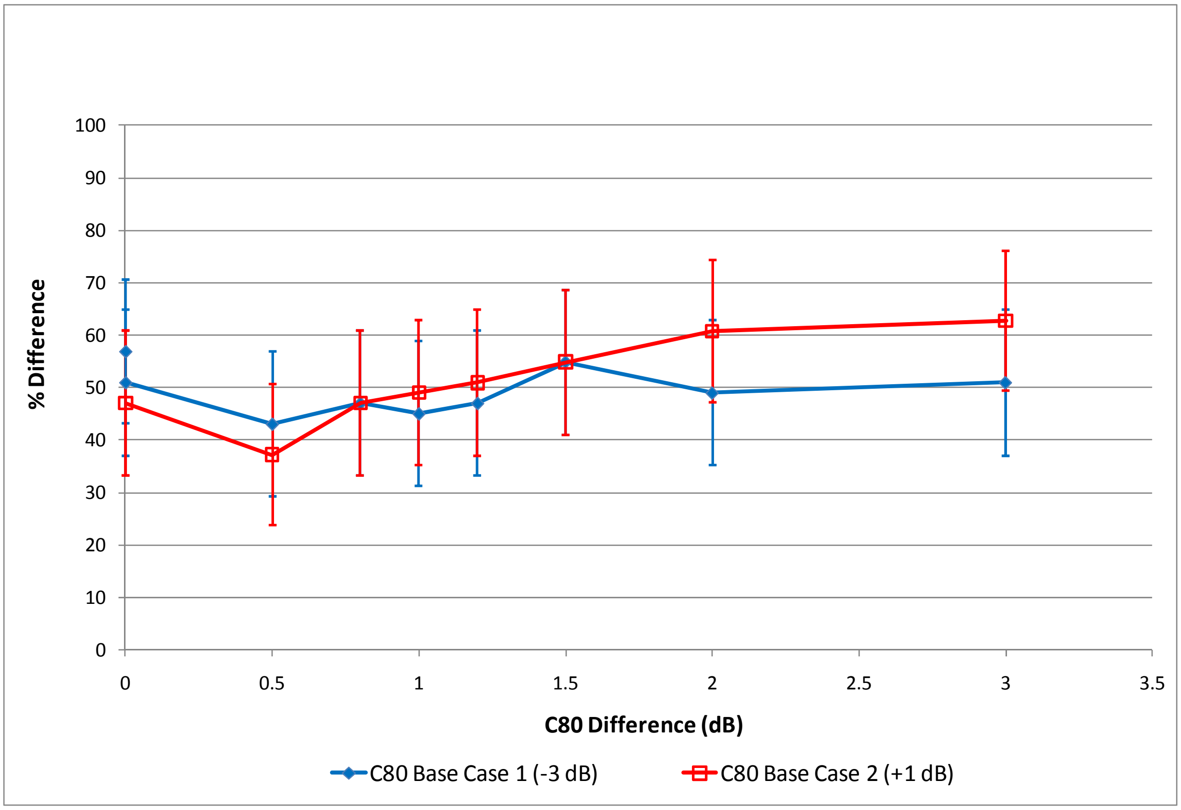

Figure C.5 – Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Handle Motif

Appendix D – Additional Plots of Subjective Testing Results for FILTERED Data

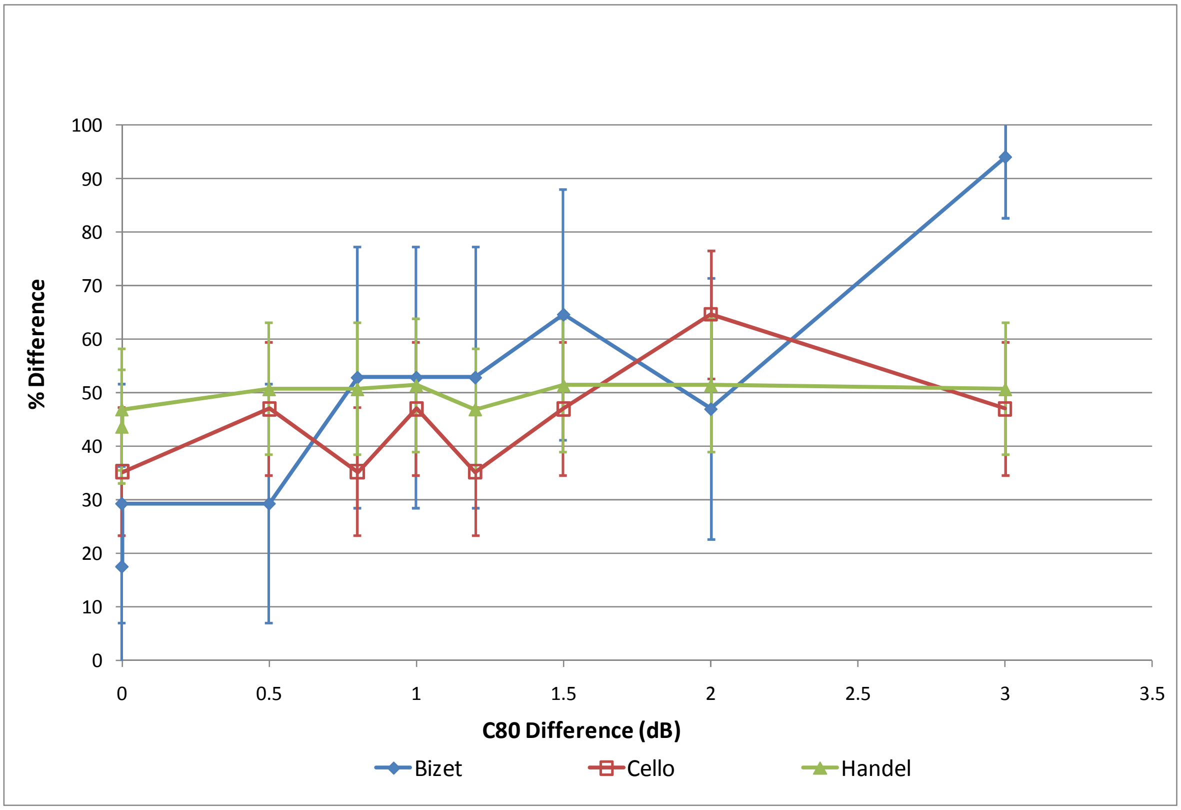

Figure D.1 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Low Base Case Only

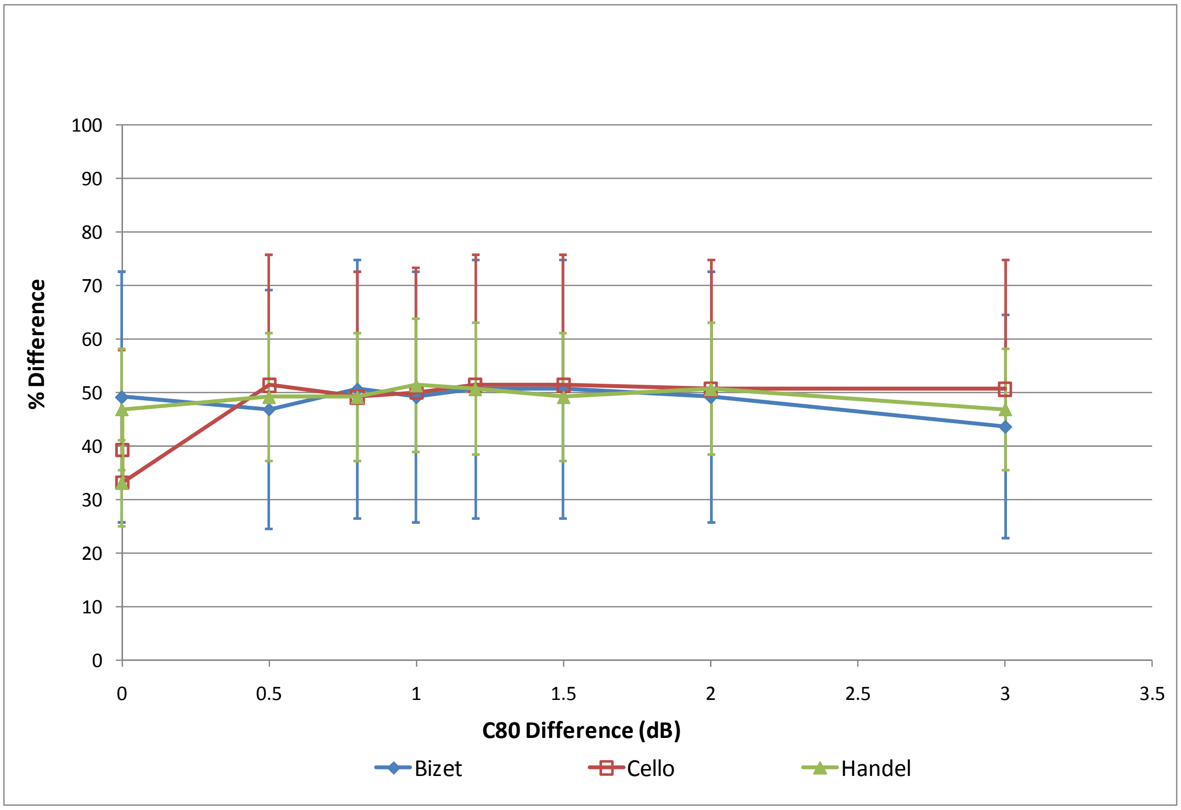

Figure D.2 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Base Case 2 Only

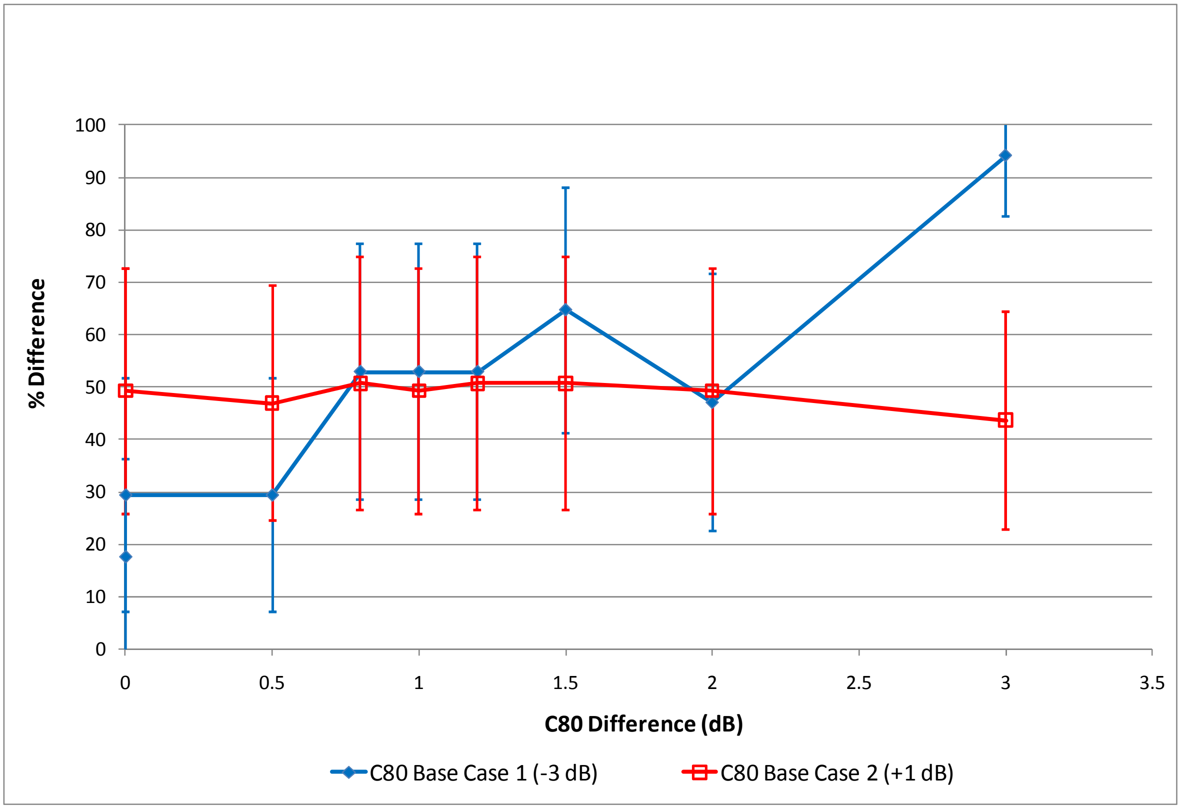

Figure D.3 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Bizet Motif

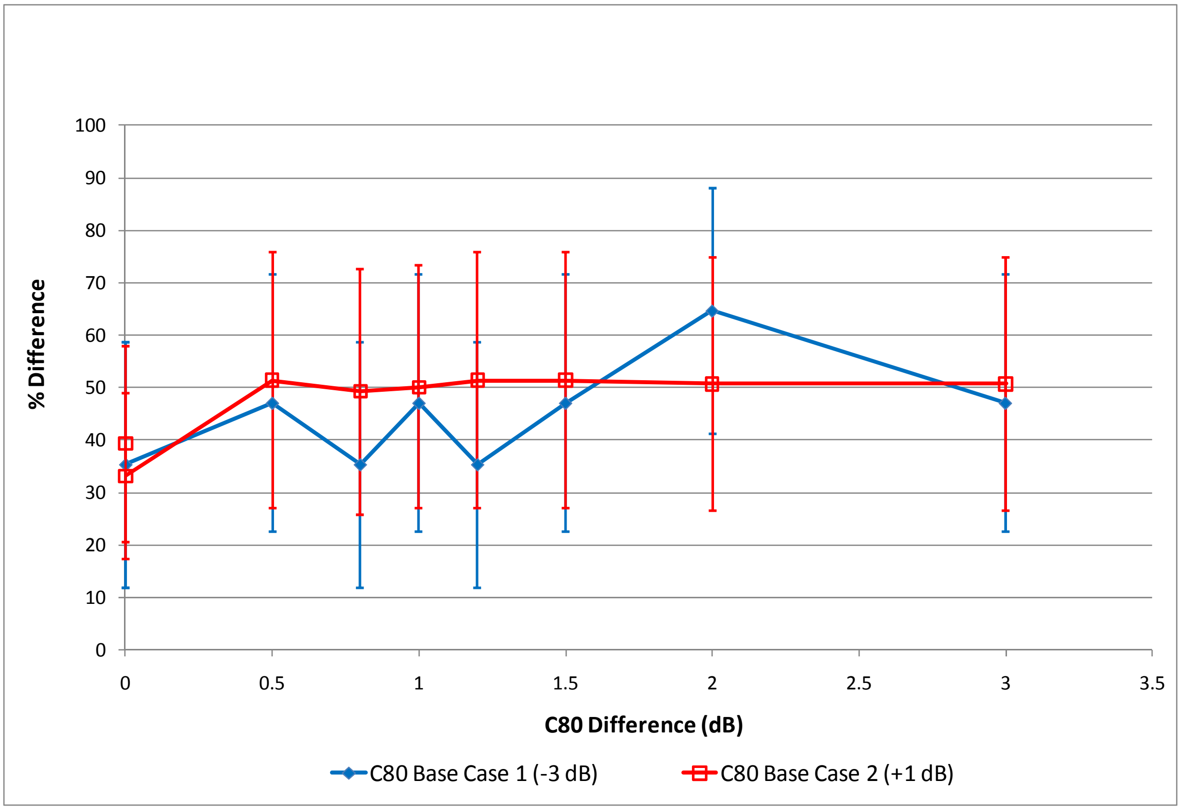

Figure D.4 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Weber Motif

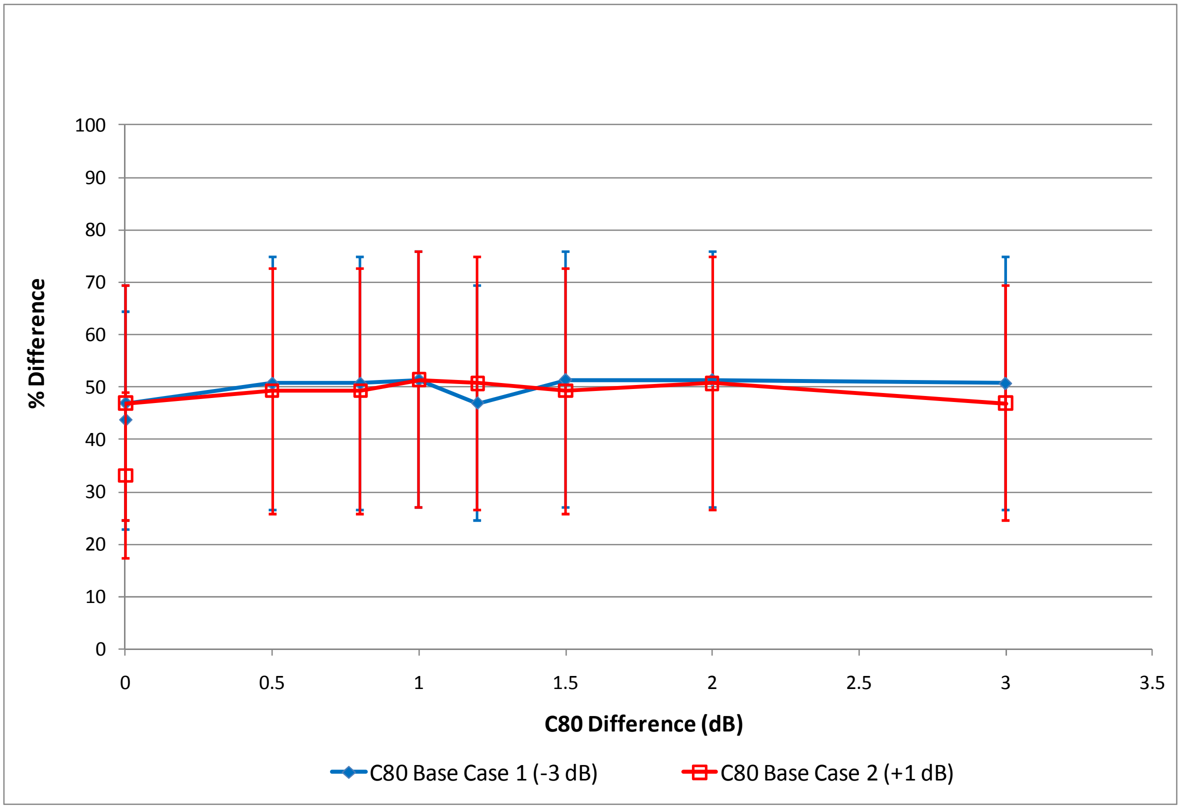

Figure D.5 – Filtered Data: Percentage of Subjects Reporting Hearing a Difference in Signals A and B versus the Actual C80 Difference in dB – Handel Motif