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Speech recognition in reverberation in biomodal cochlear implant users

Christine Alexander

SPEECH RECOGNITION IN REVERBERATION IN BIMODAL COCHLEAR IMPLANT USERS

by

Christine L. Alexander

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**Approved by:
Jill B. Firszt, Ph.D., Capstone Project Advisor
Ruth M. Reeder, M.A., Secondary Reader**

Abstract:* *The purpose of the present study was to evaluate the effects of bimodal (implant plus hearing aid) listening on speech recognition in four different environment conditions. Results indicate that there was little difference in the cochlear implant only and bimodal conditions.

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Literature Review

Effects of Using a Hearing Aid in the Non-Implanted Ear Along With a Cochlear Implant (Bimodal Amplification)

The use of bimodal hearing, defined as the use of a hearing aid in the non-implanted ear and a cochlear implant (CI), has been studied in the literature. Armstrong, et al. (1997) studied both American (n=5) and Australian (n=7) speakers to determine if using a cochlear implant in conjunction with a hearing aid would provide benefit with speech perception in noise. The mean pure-tone average in the non-implanted ear was 107 dB for the Australian listeners and 100 dB for the American listeners. All were fitted with a hearing aid on the opposite ear. Two of the seven Australian subjects had worn a hearing aid consistently since being implanted. Speech perception was evaluated using recorded material with an Australian talker for the Australian listeners and an American talker for the American listeners. Three lists each of City University of New York (CUNY) sentences and Consonant- Nucleus- Consonant (CNC) words were presented at 70 dB SPL in quiet and in noise using four-talker babble with a +10 dB signal-to-noise ratio (SNR) for two conditions: CI alone and bimodal. In addition, American listeners were tested with a +5 dB SNR. There was a significant difference between the mean scores for the CI alone condition and the bimodal condition for all measures and both groups of listeners. The mean scores in quiet were significantly higher than mean scores in noise in every case. The authors concluded that a significant binaural advantage existed for both the American and Australian listeners, although the American listeners showed a greater binaural advantage. The reason for this may be that there was a greater range of residual hearing in the non-implanted ear with the American group. The residual hearing was 75-112 dB and 97-112 dB for the American and Australian listeners, respectively. In addition, the participants reported that wearing a hearing aid along with the CI contributed to more “natural” sound.

Hamzavi, et al. (2004) studied whether there was an improvement in speech recognition provided by bimodal hearing. The participants in the study were seven CI recipients between the ages of 38 and 70 years who had worn a hearing aid for at least twelve months after implantation. All participants were implanted in their poorer ear. Three speech perception tests, the Innsbrucker Sentences, Freiburger Monosyllabic Words, and Freiburgerer Numbers, were administered for two test conditions: CI alone and bimodal. The results indicated improved speech recognition for the bimodal condition over the CI alone condition. Mean scores improved from 79% to 88% for Innsbrucker Sentences, from 37% to 49% for Freiburger Monosyllables, and from 83% to 89% for Freiburger Numbers. These findings are in agreement with Armstrong et al. (1997) and indicate that the addition of a hearing aid to the contralateral ear for CI recipients can improve speech recognition performance.

Morera, et al. (2004) reported on a multi-center study in Spain that evaluated the effects of bimodal stimulation in quiet and noise for twelve post-lingually deafened adults with bilateral, severe-to-profound sensorineural hearing loss. All subjects were implanted in the poorer ear. The mean age at implantation was 46 years and mean duration of deafness in the implanted ear was 11 years. The participants were evaluated before implantation, as well as three and six months after fitting of their speech processors. Each patient consistently used the hearing aid and CI simultaneously during the study. Preoperatively, the subjects were tested in monaural-aided conditions and their best-aided condition. Postoperatively, subjects were assessed in three listening conditions: hearing aid alone, CI alone, and bimodal after optimization of the combined hearing aid and CI fitting. Optimization of the hearing aid involved loudness balancing of the two systems so signals would not interfere with each other. Word and sentence stimuli were presented from a loudspeaker one meter from the subject at 70 dB SPL and 55 dB SPL. The speaker was positioned at a 0 degree azimuth in quiet and noise. Speech recognition in noise was conducted with both speech and noise from this speaker at the front of the subject as well as with speech from the front an noise from 90 degrees to the right or left. The signal to noise ratio was +10 dB for each listening condition with a 4-talker babble.

The authors concluded that in quiet, bimodal stimulation offers the advantage of binaural listening for the majority of experienced hearing aid users at conversational and soft speech levels. For speech and noise coincident in space, superior performance was demonstrated by most of the subjects in the bimodal condition, although this was not significant for the group as a whole. Results from the spatially separated speech in noise conditions suggest that there was successful integration of the CI stimulation and the stimulation from the hearing aid in the opposite ear.

Speech Effects of Reverberation and Noise on Listeners with a Hearing Impairment

The effects of reverberation and noise on speech recognition by adults who had a sensorineural hearing loss was investigated by Harris and Swenson (1990). The subjects were placed into three groups of ten consisting of normal hearing, mild sensorineural hearing loss, and moderately-severe sensorineural hearing loss. Speech understanding was measured using the CID W-22 word lists and for testing in noise, speech spectrum noise was used. Words were presented at 40 dB SL for normal hearing subjects and at the most comfortable level for hearing impaired subjects in three listening environments: quiet or sound suite, reverberation time of 0.54 seconds, and a reverberation time of 1.55 seconds. The reverberation times were manipulated by removing or adding carpeting and/or absorbent panels from the ceiling and walls. Speech stimuli were presented from 0 degrees azimuth one meter away from the subject. A second loudspeaker stacked on top of the first was used to present the noise. Speech recognition was adversely affected by the increase in reverberation and noise for all groups. As expected, the subjects with hearing impairment were more adversely affected than the subjects with normal hearing. The difference in speech recognition scores between the sound suite and most reverberant condition (1.55 seconds) decreased by 27.2% for the normal hearing listeners, 44.2% for listeners with mild hearing loss, and 43% for the listeners with moderate hearing loss. In normal and hearing impaired subjects the combination of noise and reverberation creates an interaction in which word recognition scores are poorer than with reverberation or noise alone. Speech recognition for participants with normal hearing decreased by 10.6% when noise was added to the environment consisting of a reverberation time of 0.54 seconds. In the same listening environment, performance decreased by 21.6% and 23.0% respectively for the mild, and moderately-severe hearing impaired groups.

Nabelek and Pickett (1974) studied both monaural and binaural speech perception with normal listeners and hearing aid users with a sensorineural hearing loss in reverberation and noise. Ten college students served as subjects for this experiment, five with a sensorineural hearing loss and five with normal hearing. The speech material used was the Modified Rhyme Test presented at 50 dB SPL for subjects with normal hearing, and 60 dB SPL for subjects with a hearing impairment. Subjects were tested in a sound booth in which the reverberation time was manipulated by adding or removing reflecting panels on the walls and ceiling. Reverberation times of 0.3 seconds and 0.6 seconds were used in this study. Both the signal and noise were presented through separate loud speakers at ear level, 11 feet from the subject's head, and at a 60 degree angle relative to the subject. Subjects' non-test ears were plugged (rubber ear plug) and masked (a circumaural earphone delivering broad-band random noise at 82 dB SPL) when testing in the monaural condition. Hearing impaired listeners used two hearing aids for the binaural condition, and one hearing aid for the monaural condition. Results from this study indicated a significant difference between speech recognition for 0.3 seconds and 0.6 seconds of reverberation for both normal and hearing impaired subjects. Overall, the subjects with normal hearing had better performance than the group with the hearing impairment. Subjects with normal hearing had a significant difference in scores between the binaural and monaural listening condition, whereas, for subjects with a hearing impairment this difference was significant at certain signal to noise ratios. These results indicate that an increased reverberation time adversely affects the speech understanding of listeners with normal and impaired hearing, but the effects are greater for those with a hearing impairment.

Binaural and monaural speech discrimination under reverberation was investigated by Gelfand and Hochberg (1976) using the Modified Rhyme Test. Thirty listeners with normal hearing and thirty with bilateral sensorineural hearing loss listened monaurally and binaurally to the Modified Thyme Test at artificially induced reverberation times of 0, 1, 2, and 3 seconds. As reverberation time increased, the monaural and binaural scores of both groups decreased, except for the 2 and 3 second reverberation time condition in the group with normal hearing. The scores obtained in the monaural condition decreased at a more rapid rate than those obtained in the binaural condition.

Specific vowel errors made in the presence of noise and reverberation by listeners with a hearing impairment were studied by Nabelek and Dagenais (1986). All fifteen vowels in the English language, monophthongs and diphthongs, were spoken by a male talker in the context of /b-t/. The stimuli were presented through a room reverberation time of 1.2 seconds and in the presence of a twelve talker babble. The subjects in this study were ten adults with binaural sensorineural hearing loss acquired in the teenage years or adulthood. The stimuli were presented in three conditions: no noise or reverberation, reverberation only, and in noise at a signal to noise ratio of 0 dB. Results show that there was a significant difference between average correct answers in the quiet condition from the other two listening conditions. However, the vowel recognition scores were not significantly different between the noise and reverberation conditions. The errors made in noise and reverberation for the monophthong vowels were different for the two conditions. On the other hand, the errors were similar for the diphthongs. The authors predict that because reverberation causes a prolongation of sounds, this affects the duration of the vowels and may also affect the spectrum of formant frequencies as they change over time. This indicates how reverberation may interfere with a listener's ability to use acoustical cues to determine the vowel spoken.

The vowel confusions of ten middle aged to elderly adults with binaural sensorineural hearing loss with and without the interference of reverberation were studied by Nabelek and Letowski (1985). Fifteen vowels and diphthongs found in the English language were presented by a male talker in a /b-t/ context. Reverberation times of 1.2 seconds at 250, 500, and 1,000 Hz. were selected. The participants had a mean vowel identification score in reverberation that was significantly lower than the mean score with no reverberation. In reverberation, diphthtongs were often identified by the subjects as initial monophthong, which may be explained as masking by the preceding sounds.

Effects of Reverberation on Speech Understanding in the Elderly

Helfer and Wilber (1990) studied the effect of reverberation on hearing loss in the elderly. A group of younger subjects, less than 36 years, and an older group, over 60 years of age, participated in this study. The two groups were further divided into younger hearing impaired, younger normal hearing, older hearing impaired, and older normal hearing impaired subjects. The Nonsense Syllable Test served as speech stimuli in reverberant conditions of 0.6 seconds, 0.9 seconds, and 1.3 seconds. The subjects listened to the three reverberation conditions in quiet and at a +10 dB signal to noise ratio. The results from this study show that the elderly group of listeners had a more difficult time understanding the nonsense syllables in noise and reverberation. Hearing loss also contributed negatively to speech understanding with reverberation and noise combined.

Plomp and Duquesnoy (1980) investigated the elderly’s susceptibility to reverberation and noise. In this study, monaural speech reception threshold for elderly subjects were obtained using ten lists of thirteen sentences with reverberation and background noise. The noise had the same spectrum as the long-term average spectrum of the sentence. Recordings of the sentence lists and the noise were made for a reverberation time of 0 seconds, as well as various reverberation times between 0.4 and 2.6 seconds. The authors suggest that the elderly should be conversing in rooms with reduced reverberation times for maximum communication ability.

Reverberation Effects Using a Cochlear Implant Simulator

Qin and Oxenham (2003) used a CI simulator to test the effect of fluctuating maskers on speech understanding. Thirty-two participants with normal hearing listened to sentences with 4, 8, or 24 channels or unprocessed speech. Steady-state speech-shaped noise, speech-shaped noise modulated with a speech envelope, single male talker, and single female talker were used as sentence maskers. The CI simulator was implemented using MATLAB (Mathworks, Natick, MA) by bandpass filtering (sixth-order Butterworth filters) the target and masker into 4, 8, or 24 contiguous frequency bands, or channels, between 80 and 6000 Hz. The envelopes of the signals were extracted by half-wave rectification and lowpass filtering at 300 Hz in order to preserve the F0 cues. These envelopes were used to modulate narrowband noises, filtered by the same bandpass filters that were used to filter the original stimuli, and modulated narrowband noises were summed and scaled to have the same level as the original stimuli. The authors concluded that using the simulated CI processing led to a large deterioration in speech reception when a masker was present. The single-talker masker proved to be more detrimental to speech recognition than steady-state noise, which is the opposite of what was found when the stimuli is unprocessed, or a CI simulator is not used.

Qin and Oxenham (2005) studied the effects of envelope-vocorder sound processing on listeners' ability to discriminate changes in the fundamental frequency in reverberant conditions. The first experiment consisted of measuring the formant frequency (F0) difference limens as a function of number of envelope-vocorder frequency channels and no, mild, and severe reverberation using four listeners with normal hearing. Vowel identification was measured in the second experiment as a function of the F0 difference between two different vowels with a varied number of vocoder channels with six listeners with normal hearing serving as participants. The stimuli in both experiments were digitally generated, treated, processed, and stored on computer disk using Matlab. First, the stimuli were treated to simulate various reverberation conditions, and then processed to simulate cochlear implant sound processing effects. Noise-excited envelope vocoder processing was used to simulate the effects of cochlear implant processing by using the method discussed in Qin and Qxenham (2003). The authors used a two-alternative forced-choice paradigm in which the listeners had to indicate the interval that contained the stimulus with the higher pitch. In the second experiment, the participants were asked to identify five American English vowels which were synthesized and processed under 24-channel, 8-channel, and unprocessed (no CI simulations used) conditions. There was a significant difference between the unprocessed condition and the two processed conditions as well as between the two processed channels. Reverberation was found to be more detrimental when a small number of channels were simulated. The authors suggest that, "… reverberation is likely to smear out envelope-based F0 information, particularly at the higher F0, where the envelope fluctuations are more rapid."

Cochlear implant simulation and reverberation were also studied by Poissant et al (2006). This study investigated the effects of reverberation and masking on speech intelligibility for listeners with normal hearing using a CI simulator implemented by Matlab. The implementations of the vocoder systems followed that used by Qin and Oxenham, 2003. Sixteen listeners with normal hearing were asked to identify key words in sentence recordings processed under one of four reverberant conditions using methods developed by Zurek et al. (2004). The simulation times were 0.425, 0.266, 0.152, and 0.0 seconds. Unprocessed stimuli, as well as six, twelve, twenty-four CI channel processing were simulated for this study. Speech understanding in reverberation was affected the most in the six channel simulation. However, speech understanding was not affected for the unprocessed and twenty-four channel conditions. There was a significant effect between the reverberation time and the number of channels used. As the reverberation time increased there, speech understanding became significantly poorer. In a second experiment, ten different subjects with normal hearing were tested with the same simulations with an electronically added speech-spectrum noise or a two talker babble consisting of two female talkers speaking nonsense syllables. These maskers were presented at a +8 or +18 target-to-maker ratio before reverberation and the different number of channels in an implant electrode was reproduced with CI simulation. As noise was combined with reverberation, speech understanding became worse for the participants. There was a significant effect for reverberation time, number of channels, and noise and no significant interaction effects were found.

Because of broadened candidacy criteria, the number of cochlear implant recipients using a hearing aid in the non-implant ear is increasing. Many of these bimodal listeners will encounter listening environments that have various levels of reverberation and noise. Therefore, it is our objective in the present study to evaluate the effects of reverberation on bimodal listening and to evaluate the effects of noise combined with reverberation on bimodal listening.

Methods

The study was approved by the Institutional Review Board and the Human Studied Committee at Washington University School of Medicine and all participants signed an informed consent. Twelve adults, seven female and five male, participated in the study. Each had at least six months of consistent bimodal use and English as their primary language. The average age of participants was 65 years with a range of 28 to 85 years. Onset of hearing loss for the participants ranged from early childhood, after language was acquired, to 65 years of age, five years prior to implantation. The mean length of CI use was two years and nine months with a range from eight months to five years and eleven months. The range of hearing aid use was from early childhood to two years and four months before their implant surgery. Four females, twenty three to twenty five years of age, served as pilots participants. Hearing of the pilot participants was screened using TDH-50 headphones to confirm normal hearing.

For each bimodal participate, there was a test session and retest session, each lasting about one and a half to two hours. Unaided air conduction thresholds were obtained in the non-implanted ear using TDH-50 headphones and a Grason-Stadler (Welch Allyn Co.) audiometer at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Aided sound field thresholds were obtained using frequency modulated tones at 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz. Sound field thresholds for the CI ear were gathered from the Washington University Cochlear Implant Department patient files.

Participants were tested in a standard Industrial Acoustics Company (Bronx, NY) sound suite using an R-Space speaker array. The R-Space™ is an eight speaker array which encircles the listener. The eight speakers were 10 inches in height, 6 ½ inches wide, and 8 inches in depth on a 36 inch tall stand. The speakers are equally spaced and all are approximately 2 feet from the listener as shown in Figure 1. Four different environment conditions were simulated using MOTU Performer 5 software with e-Verb Module on an iMAC desktop computer. The Digital Performer software controlled the output to each loudspeaker in the R-Space™ system.

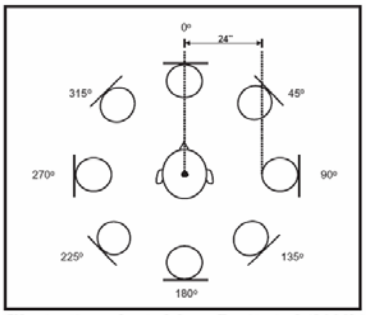


Illustration adapted from Revit et al (2002b).
Figure 1

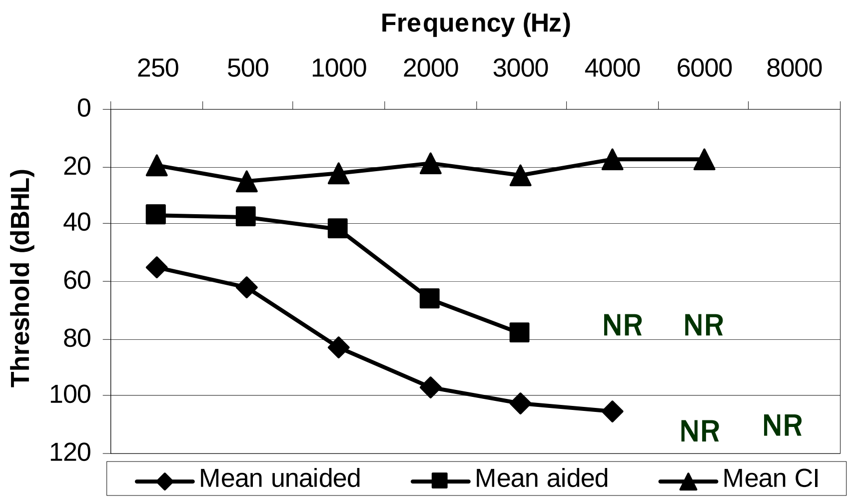
The four environment conditions simulated for this study were named “Large Room with No Reverberation”, “Large Room with Reverberation”, “Large Room with Reverberation plus Noise”, and “Concert Hall with Reverberation.” The software used acoustic modeling of various room sizes. These models replicated the initial sound reflections that would be expected from the walls, floors and furniture. In addition a room size could be selected with 1 being a smaller room and 4 being a larger room. The simulations were chosen based on feedback by several listeners with normal hearing, the pilot participants and a bimodal pilot subject. Consensus was obtained that the effect was consistent with the description used, e.g. the settings for the “Large Room with Reverberation” indeed sounded like a large reverberant room. The noise was four-talker babble (Auditec of St. Louis) consisting of three females and one male which were recorded separately and then mixed together. The male was quite intelligible while the females varied in intelligibility. The noise was presented from speakers located directly above and below the subject's chair at a +10 dB signal to noise ratio. The noise was not presented through the R-Space™ system, and therefore, there was no reverberation effect on the noise. In a real-life environment, noise would also be affected by reverberation.

Testing was conducted with three device conditions: hearing aid only, CI only, and bimodal. Three lists of CUNY sentences, which use a male talker, were presented at 60 dB SPL for each listening condition. Thirty-six of the sentence lists were used during the first test session, and a different thirty-six sentence lists were presented at the re-test session. The list order, device condition, and environmental condition were randomized for each subject. The pilot participants attended one test session, listening to 36 of the CUNY lists in the same four environmental conditions and three ear conditions: right ear only, left ear only, and both ears. In the monaural conditions, the subjects' non-test ear was muffed with TDH-50 headphones or plugged with an Eartone 3A foam insert earphone.

Descriptive statistics and visual inspection of the test results were used initially to gain an initial understanding of the data. Test-retest comparisons were conducted using a Pearson Product Moment correlation. Differences between device conditions and between room conditions for each device were evaluated with a one-way ANOVA. For conditions that were significantly different, a post-hoc Tukey test was used to identify mean differences that were significant.

Results

Figure 2 shows the average threshold in dB HL for the bimodal subjects with their non-implanted ear unaided, hearing aid, and CI. Not surprisingly, the CI thresholds are the lowest, followed by the aided non-implanted ear. There is aidable hearing for the average subject at 250, 500, and 1000 Hz. in the non-implanted ear.



The average mean threshold for all participants is shown in Figure 2. The mean score for the non-implanted ear unaided is shown with diamonds. The mean score for the non-implanted ear with a hearing aid is shown with squares. The mean score for the cochlear implant is shown with triangles.

There was good correlation between the test and retest scores for the CUNY sentences (.96, .82, and .90 Pearson correlation for hearing aid only, CI only, and bimodal, respectively). Because of the good test-retest reliability, the results from the first and second test session were averaged. The pilot participants had scores over 95% for the three ear conditions in all four of the different room conditions. This suggests that the levels of reverberation and noise used in this study did not affect our listeners with normal hearing's ability to understand sentences.

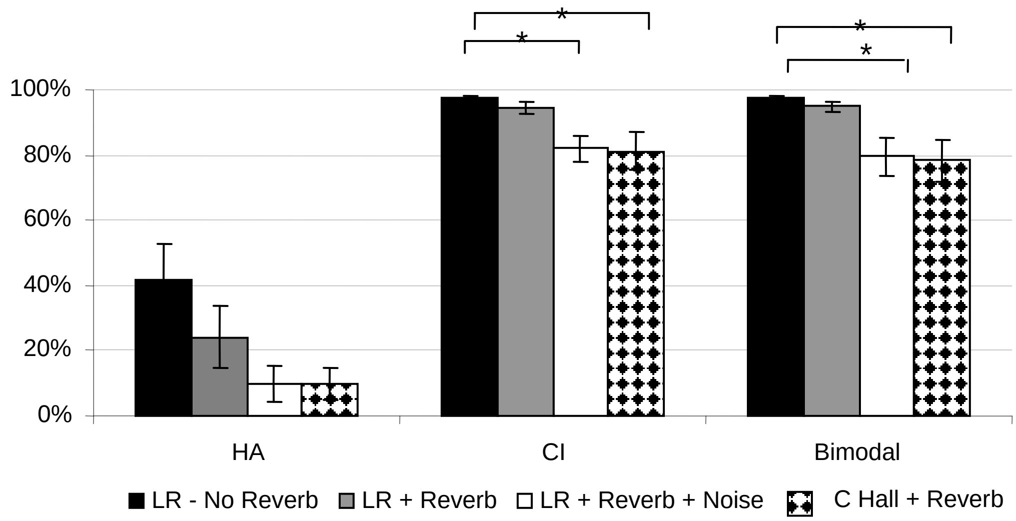
The mean bimodal subject scores in percent correct and standard deviation for the four room conditions and the three listening conditions are shown in Table 1. Within each device condition, the participants' mean scores are the highest in the Large Room with no Reverberation condition compared to the other three conditions. As reverberation and noise are introduced, the mean scores decrease.

	Large Room with No Reverb	**Large Room with Reverb**	**Large Room with Reverb + Noise**	**Concert Hall with Reverb**
HA Only	**38** **(SD=37)**	**28** **(SD=30)**	**9** **(SD=17)**	**9** **(SD=16)**
CI Only	**97** **(SD=3)**	**93** **(SD=7)**	**80** **(SD=15)**	**78** **(SD=22)**
Bimodal	**98** **(SD=2)**	**94** **(SD=7)**	**78** **(SD=20)**	**75** **(SD=24)**

Table 1 shows mean score in percent correct and standard deviation (SD) for all four of the room conditions in the three listening conditions

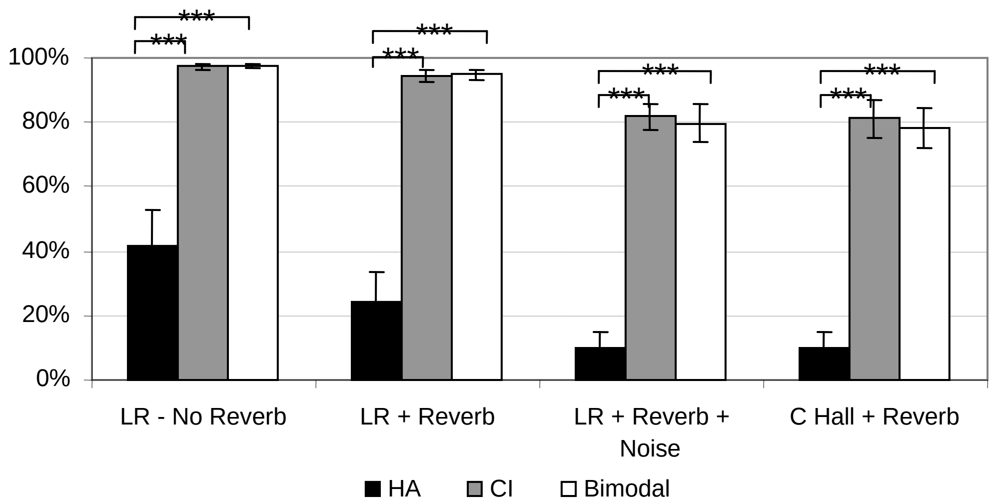
The results for the effects of each device for all room conditions are depicted in a graph in Figure 3. Based on a one-way ANOVA, performance differed across room conditions for the CI [F (3, 36) = 4.99, p = .005] and Bimodal [F (3, 36) = 5.63, p = .003] devices but not the HA device [F (3, 36) = 2.84, p = .051]. Tukey post-hoc comparisons of room conditions for the CI device and for the Bimodal device indicated that the Large Room without Reverberation (shown in black), had significantly higher scores than the Large Room with Reverberation and Noise (shown in white) (CI, p = .027; Bimodal, p = .022) and than the Concert Hall (shown with diamonds) (CI, p = .021; Bimodal, p =

.014), but not the Large Room with Reverberation (shown in gray), p > .05. In addition, mean scores were significantly worse for the Concert Hall compared to the Large Room with Reverberation, p = .046. There was not a significant difference between the Large Room with Reverberation plus Noise and the Concert Hall, p > .05.



In Figure 3, the bars represent the mean scores in each room condition with the hearing aid, cochlear implant and bimodal condition. Large Room with No Reverberation is shown in black, Large Room with Reverberation is shown in gray, Large Room with Reverberation plus Noise is shown in white, and Concert Hall with Reverberation is shown with the black diamonds. *= p<.05 (Error bars represent ±1 SEM)

Figure 4 shows the mean performance for each device condition by room condition. A one-way ANOVA was used to test for differences in performance among the three device conditions and four room conditions. Performance differed significantly across the three device conditions [F (2, 117) = 119.01, p = .000]. Tukey post-hoc comparisons of the three device conditions indicated that the HA condition had significantly lower scores than the other two groups, p = .000. Comparisons between the CI and Bimodal conditions were not statistically significant at p < .05.



In Figure 4 the bars on the graph represent the mean scores of the participants for the hearing aid in black, cochlear implant in gray, and bimodal condition in white. ***=p<.001 (Error bars represent ±1 SEM)

The individual subject data is shown in Figure 5 with the mean group results shown on the far right in each graph. The hearing aid condition results in the worst sentence understanding for every subject in every room condition. In the Large Room with No Reverberation there is a ceiling effect for all subjects, with scores over 90% for the CI only and bimodal conditions (Figure 5a). Using the hearing aid alone, the addition of reverberation to the large room results in decreased performance for all subjects. There is only a slight decrease for ten of the twelve subjects in the other two device conditions. Subject 4 had a 15 % decrease in both the CI only condition and the bimodal condition and subject 12 with a 14% decrease in the CI only condition and a 16% decrease in the bimodal condition when reverberation was added to the Large Room. The mean for all the subjects only decreased 4% and 3% for the CI only and bimodal condition, respectively in this condition. When noise is added to the Large Room with Reverberation condition the mean score for all subjects decreased in all the device conditions. There was a 13 % decrease in the mean score of all the subjects in the hearing aid only conditions, 13% decrease in the CI only condition, and 16% decrease in the bimodal condition from the Large Room with Reverberation condition. In the concert hall condition the hearing aid only mean score for all the participants did not change. The hearing aid only condition and bimodal condition are almost identical to the scores in the Large Room with Reverberation plus Noise condition. There is no significant difference between the CI only and the bimodal condition for any subject in any of the device or room conditions.

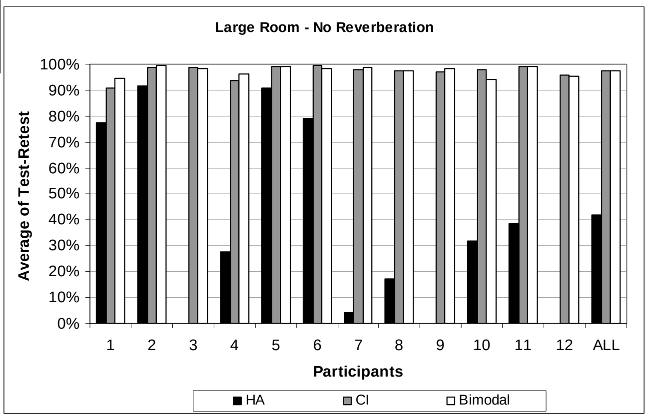


Figure 5a

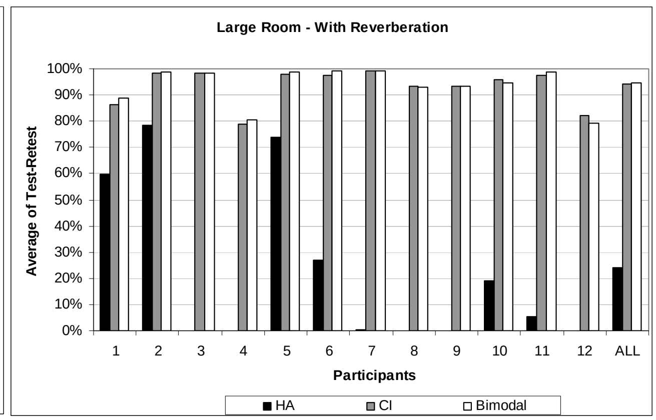


Figure 5b

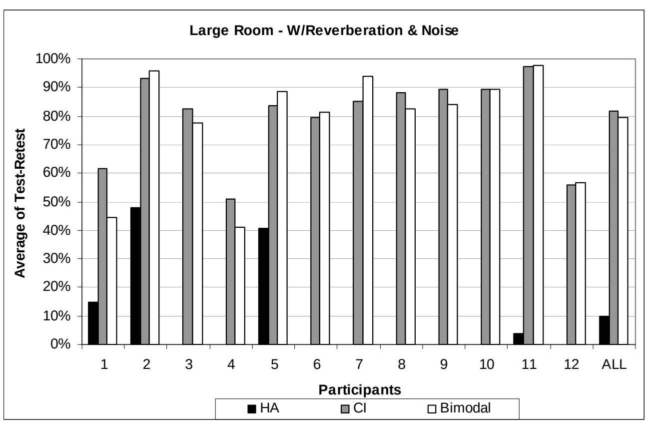


Figure 5c

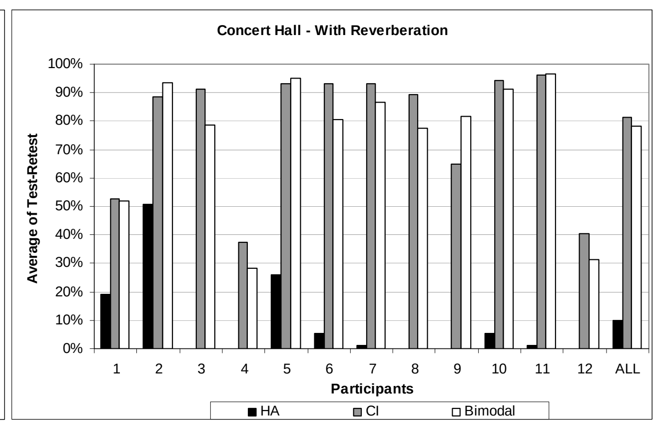


Figure 5d

Figure 5 depicts the individual scores for each participant for room and device condition. The mean for all the participants is shown on the abscissa with the word "ALL." The hearing aid only condition is in black, cochlear implant only in gray, and bimodal condition in white. Figure 4a shows the individual data in the Large Room with No Reverberation condition. Figure 4b shows the individual data in the Large Room with Reverberation condition. Figure 4c shows the individual data for the Large Room with Reverberation plus Noise. Figure 4d shows the individual data for the Concert Hall with Reverberation.

In summary, the subjects performed best in the bimodal device condition and the Large Room with No Reverberation room condition. The subjects performed the poorest when listening with their hearing aid alone and in both the Large Room with Reverberation plus Noise and the Concert Hall room conditions. As reverberation increased from the Large Room with Reverberation to the Concert Hall with Reverberation, the mean score for the subjects decreased for all device conditions. The addition of the four talker babble to the Large Room with Reverberation also resulted in a decrease in the mean score for subjects in all device conditions.

Discussion

To date, there has not been extensive research conducted to test the performance of bimodal listeners or listeners using only a CI in different amounts of reverberation and with reverberation and noise. Cochlear implant simulation studies have suggested that reverberation will affect the speech understanding of CI users, especially those devices with a smaller number of channels. This study was designed to evaluate whether different levels of reverberation and the addition of noise affected speech recognition in bimodal implant recipients.

First, with respect to device conditions, group data indicates there were no significant differences in performance between using bimodal hearing or a CI alone in reverberant conditions. However, there were ceiling effects observed in the scores for the CUNY sentences. Sentence recognition was over 90% for all subjects in the Large Room with No Reverberation, and all but three subjects in the Large Room with Reverberation condition. There was a significant difference between the hearing aid only condition and the other two device conditions. A floor effect was observed: three subjects received 0% sentence recognition in the hearing aid alone condition for the Large Room with No Reverberation, and only two subjects obtained a speech score over 10% in the Concert Hall condition. These floor and ceiling effects may have limited the ability to detect differences in the three device conditions in this study.

Second, with respect to room environment conditions, group data suggest that as reverberation increases, sentence recognition decreases for all device conditions. In the condition with no reverberation, the mean scores were the highest for all three device conditions. As noise was added to the reverberation, speech recognition also decreased for the three device conditions. The increase in reverberation had a more dramatic effect on the hearing aid ear than the CI ear, or with bimodal use.

There was a wide range of aided speech recognition ability in the non-implanted ear for the participants. Three participants (3, 9, and 12) had no speech recognition ability with their hearing aid only in the Large Room with No Reverberation, while participants 1, 2, 5, and 6 had scores over 75%. There was almost no variability with the CI alone and with the use of bimodal listening in the Large Room with No Reverberation since the participants all scored above 90%. When reverberation was added to the Large Room, participants 4 and 12 each had the largest decrease in speech recognition for the CI only and bimodal device conditions, deceasing about 15% in each. The scores in the hearing aid alone condition decreased for all subjects and continued to decrease in the Large Room with Reverberation plus Noise, with only two participants scoring above 10%. When noise is added to the Large Room with Reverberation, only participants 2 and 11 maintain speech recognition scores above 90% for both the CI only and bimodal conditions. In the Concert Hall condition participants 5, 10, and 11 have speech recognition scores for both the CI only and bimodal conditions above 90%. In the Large Room with Reverberation plus Noise and the Concert Hall conditions, a separation of the CI only and bimodal scores is evident in some of the participants, but none are significantly different from each other.

The R-Space™ and Digital Performance software have good potential for simulation of reverberant conditions. Surrounding the participant with an 8 speaker array combined with the flexibility of the Digital Performance software allows for several types of listening environments to be tested. Surrounding the participant with an 8 speaker array is an excellent model for what the reverberation in a listening environment would sound like to our participants in their everyday lives.

There was a ceiling effect for the CI only and bimodal conditions indicating that the CUNY sentences were too easy for our participants. A floor effect is seen in the hearing aid only condition with several participants receiving scores of 0% in the room conditions. In the average CI clinic today, different speech materials are used to asses the ability of the hearing aid ear and CI ear which makes comparing the two rather difficult. Speech materials or other evaluation methods are needed that can test both hearing aid speech understanding and CI speech understanding of a recipient without a floor or ceiling effect.

For future research, it may be beneficial to evaluate the effects of other levels of reverberation than those used in the present study to assess bimodal speech recognition abilities with the R-space and Digital Performance Software. Other speech recognition materials should be explored that may reduce ceiling and floor effects. In the present study, criteria for participant enrollment included consistent use of a hearing aid in the contralateral ear, but no criteria for performance in the hearing aid ear were required. As observed, there was a large range of speech understanding ability in the hearing aid ear for the participants. It may be advantageous to define inclusion criteria for the hearing aid ear, for example based on unaided or aided thresholds, or speech recognition scores. This may alleviate floor effects in the hearing aid ear and allow for greater bimodal enhancement when combined with the CI ear.

Conclusions

Reverberation, which is present in many environments, has strong negative effects on speech recognition. This study evaluated the effects of bimodal listening in reverberant environments in adult cochlear implant recipients who regularly wore a hearing aid in the non-implanted ear. As the reverberation increased from no reverberation, to Large Room with Reverberation, to Concert Hall with Reverberation, speech recognition scores decreased for hearing aid alone, CI alone, and bimodal use. This suggests that reverberation is detrimental to CI users whether or not they use a hearing aid in the non-implanted ear. There was little or no difference in speech recognition scores between the bimodal and CI only conditions for the participants in this study. Scores were high for CUNY sentence material in both conditions which did not allow for a bimodal enhancement. In contrast, the sentences were somewhat difficult when listening with the hearing aid alone. When noise was added to one reverberation condition, the mean participant score decreased for all the device conditions, indicating that when noise is present along with reverberation, speech understanding is especially detrimental to our participants. This study suggests that reverberation with and without noise is detrimental to speech understanding for bimodal listeners.

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APPENDIX A

Demographics of Participants

Subject Number	Sex	Age at Testing	Age at Initial Stim	Implant	Processor	P	S	V	Hearing Aid
1	F	69.4	68.1	Nucleus Freedom	Freedom	2	12	7	Widex Vita SV-38
2	F	80.9	79.3	Nucleus Freedom	Freedom	1	11	7	Starkey Destiny 1200
3	F	38.5	32.10	AB Clarion	Hi-Res 120	12:00			Siemens Musik
4	M	85	79.11	Nucleus Freedom	Freedom	1	10	8	Widex Senso C19
5	M	60.7	60.0	Nucleus Freedom	Freedom	1	10	7	Phonak Savia 311
6	M	71.11	69.1	Nucleus Freedom	Freedom	1	10	8	Widex Diva SD
7	F	71.7	69.2	Nucleus Freedom	Freedom	2	12	8	Widex Vita-SV19
8	F	76.8	72.5	Nucleus Freedom	Freedom	3	12	9	Widex P 38
9	M	73.8	73.0	Nucleus Freedom	Freedom	1	12	7	Phonak Perseo
10	F	70.11	68.1	Nucleus Freedom	Freedom	3	12	9	Siemens Prisma
11	F	28.9	23.11	Nucleus Freedom	Esprint 3G	1	13	8	Widex Vita SV-38
12	M	57.3	54.6	Nucleus Freedom	Freedom	2	14	9	Siemens Sigma

M= male
F= female
P= CI processor program used
S= Sensitivity of microphone in CI processor used
V= Volume of CI processor used

APPENDIX B
Instructions to subjects

Instruction to Subjects:

Thank you for volunteering to participate in this study!

[Seat subject in R-Space]

You will be hearing sentences that will primarily come from this front speaker. Please repeat back the sentences that you hear. If you do not understand the entire sentence, repeat back as much as you hear and make a guess if you can. You will hear each sentence only once and will hear "ready?" before each sentence.

You will start listening with: (circle what applies)

only your HA

only your CI

both your HA and CI

This first set of sentences will be: (circles what applies)

in quiet

with some reverberation like in a medium sized room

with reverberation like in a large room

with reverberation and noise

The session will last approximately 2 hours. Please let me know if you need a break.