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Speech Recognition in Quiet and Noise in Borderline Cochlear Implant Candidates

Farah Mohd Alkaf *
Jill B. Firszt†

Abstract

The present study 1) examined speech recognition at three intensity levels and in noise for adults with bilateral hearing loss who wore amplification and were referred for cochlear implant evaluation but did not meet current audiological criteria, and 2) compared their performance to cochlear implant recipients using current implant technology. When tested at 70 dB SPL, hearing aid subjects' word and sentence recognition scores were similar to or greater than the scores of cochlear implant recipients. Compared to their implanted peers, however, subjects' scores were significantly poorer at normal (60 dB SPL) and soft (50 dB SPL) presentation levels for words and at soft levels for sentences; detection thresholds were also significantly poorer at 1000 Hz and above. The assessment of candidates at louder-than-normal levels (i.e., 70 dB SPL) may not correctly portray their day-to-day communication struggles.

Key Words: speech perception, speech recognition, hearing aid, cochlear implant, postlingual hearing loss

Abbreviations: SNR = signal-to-noise ratio; CNC = consonant-vowel nucleus-consonant (test); HINT = Hearing in Noise Test; HA = hearing aid; CI = cochlear implant

Sumario

El presente estudio examina, (1) el reconocimiento del lenguaje a tres niveles de intensidad en adultos con hipoacusia bilateral que usaban amplificación y que fueron referidos para una evaluación de implante coclear, pero que no cumplieron con los criterios audiológicos actuales, y (2) compara el desempeño de sujetos implantados utilizando la tecnología actual de implantes. Cuando se evaluaron a 70 dB SPL, los puntajes de los sujetos con audífonos para reconocimiento de palabras y frases fueron similares o mejores que los puntajes de los sujetos con implante coclear. Comparado con los implantados, sin embargo, los puntajes de los sujetos amplificados fueron significativamente peores a niveles de presentación normales (60 dB SPL) y suaves (50 dB SPL), y a niveles bajos para frases; los umbrales de detección fueron también significativamente bajos a 1000 Hz y en frecuencias mayores. La evaluación de candidatos a niveles por encima del normal (p.e., 70 dB SPL) puede no representar correctamente las dificultades de comunicación cotidianas.

*Department of Otolaryngology and Communication Sciences, Medical College of Wisconsin, Milwaukee; †Department of Otolaryngology-Head and Neck Surgery, Washington University School of Medicine, St. Louis, MO

Jill B. Firszt, Ph.D., Department of Otolaryngology, Washington University School of Medicine, 660 S Euclid Avenue Campus Box 8115, St. Louis, MO 63110; Phone: 314-362-4760; Fax: 314-362-4436; E-mail: firsztj@ent.wustl.edu

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Palabras Clave: percepción del lenguaje, reconocimiento del lenguaje, auxiliar auditivo, implante coclear, hipoacusia post-lingual

Abreviaturas: SNR = tasa señal-ruido; CNC = consonante-núcleo vocal-consonante; HINT = Prueba de Audición en Ruido; HA = auxiliar auditivo; CI = implante coclear

Cochlear implantation is a recommended medical treatment to restore hearing in individuals with bilateral severe-to-profound sensorineural hearing loss. Trends in clinical practice and improvements in technology have extended cochlear implant candidacy from previous criteria of bilateral profound hearing loss to more recent criteria of severe hearing loss and open-set sentence recognition scores of 50% or less in the ear to be implanted and 60% or less in the best-aided condition (Cochlear Americas, 2005). Despite broadened candidacy criteria, there are a number of individuals who report difficulty and frustration in their hearing and communication abilities in real-life situations but have speech recognition scores that surpass the candidacy criteria (i.e., 60% sentence recognition in quiet) when using hearing aids.

During cochlear implant candidacy evaluation, speech stimuli are typically presented at 70 dB SPL and in quiet. Clinical observation suggests that when a person attempts to converse with an individual with substantial hearing loss, the speaker raises the level of his or her voice to compensate for the loss of hearing ability by the listener. The vocal effort required to speak at a raised-to-loud speech level such as 70 dB SPL, however, can not be maintained for more than a few minutes (Pearsons et al, 1977; Skinner et al, 1997, 2002). In addition, although an individual may speak at 70 dB SPL for short time periods when talking directly to a person with hearing loss, he or she will decrease the level of their voice when addressing someone in the group with normal hearing. At that instant, the individual with hearing loss may be unable to hear what was spoken and the ability to follow ongoing conversation among the group diminishes.

Skinner et al (1997) and Firszt et al (2004) demonstrated that, on average, cochlear implant recipients were able to recognize words and sentences not only at 70 dB SPL, but also at 60 dB SPL, a level that represents conversational speech (Pearsons et al, 1977). At soft presentation levels (e.g., 50 dB SPL), some cochlear implant recipients are able to understand speech fairly well. The majority are able to converse on the telephone with familiar and sometimes unfamiliar talkers. Based on the study by Firszt and colleagues (2004) which evaluated speech recognition in 78 cochlear implant recipients at three intensity levels and in noise, it was proposed that the assessment of cochlear implant recipients and perhaps cochlear implant candidates be conducted at 60 dB SPL and include testing in noise in an attempt to replicate listening conditions that better reflect every day communication.

The purposes of the present study were to 1) examine the speech recognition performance at three intensity levels and in noise for adults with bilateral hearing loss who wore hearing aids and were referred for cochlear implant evaluation but did not meet current audiological criteria and were considered borderline candidates, and 2) compare their performance to that of a large cohort of cochlear implant recipients using more current cochlear implant technology.

METHODS AND PROCEDURES

The protocol completed was reviewed and approved by the Institutional Review Board of the Medical College of Wisconsin, Milwaukee, Wisconsin. The study also fulfilled the principles articulated in the Declaration of Helsinki.

Subjects

A total of 12 postlingually deafened adult subjects who use hearing aids participated in the study. Biographical information for each subject is shown in Table 1. The unaided thresholds obtained in the right and left ear for each subject are shown in Table 2. Six of the twelve subjects had unaided thresholds in the severe-to-profound hearing loss range at 250 Hz for at least one ear, whereas at 2000 Hz and above, 11 of the subjects had thresholds in the severe-to-profound range for both ears and 1 subject for one ear (S07). Among the subjects, 4 had symmetrical hearing losses (defined as less than a 5 dB difference in the pure tone average between ears). For the remaining 8 subjects, the better ear was the right ear for 3 subjects and the left ear for 5 subjects. The better ear was defined as the ear with the lowest unaided pure-tone average threshold. There were large asymmetries noted between ears for S05, S06, S07, S09, S10, and S12. Subject 05 was the only subject for whom one ear (i.e., the right ear) had no detectable hearing with the exception of one threshold of 110 dB HL at 250 Hz. Subject 03 had the steepest slope in hearing; the thresholds in the right and left ears were 20 and 40 dB HL, respectively, at 250 Hz and decreased to 105 and 110 dB HL, respectively at 2000 Hz and above.

Subjects had used hearing aids for a minimum of one month, although 11 of the 12 subjects had used hearing aids for a mean length of 17 years (range 6-43 years).

Table 1. Biographical information for each subject.

Subject	Age	AAO-HL	AAO M-P HF HL	HA Use	Etiology
S01	33	16	22	14	Familial
S02	69	53	69	16	Noise Exposure
S03	56	49	53	6	Autoimmune
S04	60	9	47	12	Familial
S05	47	30	44	17	Unknown
S06	73	51	61	12	Middle Ear Pathology
S07	47	44	46	0.08	Meniere's
S08	61	37	58	24	Familial
S09	61	0	44	17	Unknown
S10	72	40	52	14	Unknown
S11	47	3	41	43	Ototoxicity
S12	68	49	67	15	Noise Exposure
Mean	57.8	31.8	50.3	15.8	
StDev	12.3	19.7	12.8	10.4	

Age = age at test in years; AAO-HL = age at onset of hearing loss in years; AAO M-P HF HL = age at onset of moderate-to-profound hearing loss in the high frequencies in years; HA Use = length of hearing aid use in years

Table 2. Unaided pure tone thresholds for each subject in the right and left ears.

	Right Ear Thresholds (dB HL)						Left Ear Thresholds (dB HL)					
Subject	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz
S01	75	90	100	95	95	95	70	95	100	95	90	90
S02	45	50	65	80	95	105	45	45	60	85	85	95
S03	20	40	65	105	105	105	40	50	85	110	115	115
S04	80	80	85	80	90	100	75	70	85	85	90	95
S05	110	125	125	125	125	125	85	100	95	85	85	85
S06	100	85	85	90	90	105	50	50	55	85	100	110
S07	55	55	55	60	55	65	70	75	95	120	125	125
S08	45	65	80	110	110	110	40	55	80	85	80	80
S09	110	105	100	105	105	115	80	80	80	80	75	80
S10	60	75	110	110	120	120	40	55	70	105	120	100
S11	75	80	95	105	125	125	75	80	90	120	125	125
S12	55	65	80	80	85	90	55	105	105	120	120	120
Mean	69.2	76.3	87.1	95.4	100.0	105.0	60.4	71.7	83.3	97.9	100.8	101.7
StDev	27.9	23.8	20.2	18.0	19.8	16.8	17.1	20.9	15.4	16.0	18.9	16.8

Table 3. Aided sound-field thresholds for each subject in the right and left ears and type of amplification worn.

	Right Ear Aided Thresholds (dB HL)							Left Ear Aided Thresholds (dB HL)						
Subject	.25k	.5k	1k	2k	3k	4k	Hearing Aid	.25k	.5k	1k	2k	3k	4k	Hearing Aid
S01	25	35	45	45	60	65	Widex Senso C18	20	40	40	45	55	50	Widex Senso C18
S02	30	25	25	35	60	80	Siemens Prisma Power	30	25	25	35	60	70	Siemens Prisma Power
S03	20	30	30	60	70	70	Phonak P4 AZ	20	25	40	65	80	85	Phonak P4 AZ
S04	50	45	40	45	70	85	Oticon 380P	45	30	45	50	65	70	Oticon 380P
S05								45	45	30	30	35	45	Telex BiCros 350
S06	45	40	45	50	65	75	Oticon 380P	45	15	20	40	50	60	Oticon 380P
S07	35	30	35	35	35	40	ReSound Canta 780D	45	45	55	65	85	85	Oticon 380P
S08	35	35	45	65	70	65	ReSound BZ5	30	25	35	30	35	35	ReSound BZ5
S09	50	45	35	40	65	70	Oticon 380P	75	55	40	35	35	45	ReSound BZ5
S10	25	40	60	60	65	70	Oticon 380P	25	20	20	35	55	60	Oticon 380P
S11	30	30	40	45	65	60	Oticon 380P	25	30	35	45	60	65	Oticon 380P
S12	30	35	40	35	35	45	ReSound BZ5	40	55	45	55	60	65	Oticon 380P
Mean	34.1	35.5	40.0	46.8	60.0	65.9		37.1	33.2	36.4	44.2	56.3	61.3	
StDev	10.2	6.5	9.2	10.8	12.8	13.6		15.6	13.7	11.0	12.4	16.3	15.5	

The best-aided condition for each subject was determined during the cochlear implant evaluation prior to study participation with a protocol that combines results of real-ear measurements, aided sound-field thresholds and sound quality judgments by the patient. Given the severity and configuration of the hearing loss among the subjects, the ability to achieve target gains was not always possible, especially in the high frequencies, but was always attempted. For the majority of subjects (n=11), the best-aided condition was represented with binaural hearing aids; however, one subject (S05) was best-aided with a BiCros aid fit to the left ear. Six subjects wore digital hearing aids in one or both ears and one subject wore analog programmable hearing aids in both ears. Five subjects had worn analog non-programmable hearing aids for many years and preferred their current hearing aids to digital amplification following a trial period. The aided sound-field thresholds obtained in the right and left ear for each subject and type of amplification worn are shown in Table 3.

Test Sessions

Subjects were initially seen for a clinical pre-implant evaluation to determine cochlear implant candidacy. For all subjects, adjustments were made to their personal hearing aids or, if necessary, clinic hearing aids were fit and worn for a trial period of one month in order to maximize gain without discomfort. Detection thresholds for pulsed warble-tones in the sound-field were obtained in the best-aided condition and are displayed in Table 4. As part of the clinical protocol, the HINT sentences were administered at 70 dB SPL in quiet to evaluate speech recognition. Based on the test results on the HINT sentences, the subjects scored greater than 60% in the best-aided condition and were considered borderline cochlear implant candidates.

Subjects subsequently returned for two test sessions, Session 1 and 2. During these sessions, pulsed warble-tone sound-field thresholds were repeated. The evaluation of word and sentence recognition was performed at three stimulus presentations levels as well as sentence recognition in noise. Test-retest measures were obtained at Sessions 1 and 2,

Table 4. Best-aided sound-field thresholds (dB HL) for each subject.

Subject	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz
S01	20	40	40	45	55	50
S02	30	25	30	40	55	65
S03	20	30	30	60	70	70
S04	45	30	40	35	55	60
S05	45	45	30	30	35	45
S06	45	15	20	40	50	60
S07	30	30	35	35	30	45
S08	30	30	35	35	35	35
S09	50	40	35	35	35	40
S10	25	20	20	35	55	60
S11	25	20	35	45	60	65
S12	30	40	45	35	40	45
Mean	32.9	30.4	32.9	39.2	47.9	53.3
StDev	10.5	9.4	7.5	7.9	12.5	11.3

which each lasted approximately one hour and were the same except for the use of different lists. Sessions 1 and 2 were completed on the same day for most subjects, otherwise within a two-week period.

Sound-Field Threshold Measures

Sound-field thresholds were obtained in a double-walled soundproof booth via calibrated audiometric and sound-field equipment. Detection thresholds for pulsed warble-tones at .25, .5, 1, 2, 3 and 4 kHz were obtained using the Hughson-Westlake procedure (Carhart and Jerger, 1959) and 5 dB increments.

Speech Recognition Measures

Based on a study of 10 recipients of the Nucleus 22 cochlear implant device evaluated at the Washington University School of Medicine (M.W. Skinner, pers. comm.), specific test lists were used for the current study that provided the closest mean speech test scores. The CNC monosyllabic word (Peterson and Lehiste, 1962) test lists selected were lists #1, 2, 3, 5, 9 and 10. Each list consists of 50 monosyllabic words. For the HINT sentence test, lists #1, 4, 6, 8, 10, 11, 12, 16, 17, 18, 19, 20, 22, 23, 24 and 25 were used for the study. Each HINT list consists of 10 sentences.

During Sessions 1 and 2, one list of the CNC words and two lists of the HINT sentences were presented in quiet at presentation levels 70, 60 and 50 dB SPL. For sentence testing in noise, two lists of HINT sentences were presented at 60 dB SPL with speech-spectrum noise at a +8 dB SNR. The word and sentence test lists were randomized across subjects and test presentation levels. Subjects were tested in a double-walled soundproof booth, seated one meter away from a loudspeaker placed at 0 degrees azimuth. Each subject's hearing aids were set at one volume and program setting, appropriate for speech audibility and most comfortable listening.

RESULTS

Figure 1 shows the group mean unaided thresholds and one standard deviation from the mean for the right ear (open circle) and left ear (x symbol) for all subjects at 250 through 4000 Hz. The average thresholds (in dB HL) at frequencies .25, .5, 1, 2, 3, and 4 kHz for the right ear were 69.2, 76.3, 87.1, 95.4, 100.0 and 105.0, respectively and for the left ear were 60.4, 71.7, 83.3, 97.9, 100.8 and 101.7 dB HL, respectively. Four subjects had no response at the limits of the audiometer for at least one frequency. To ensure that the averages calculated for each frequency would accurately represent the severity of the subjects' hearing losses, a no response result was assigned a level 5 dB HL above the limit of the audiometer for each fre-

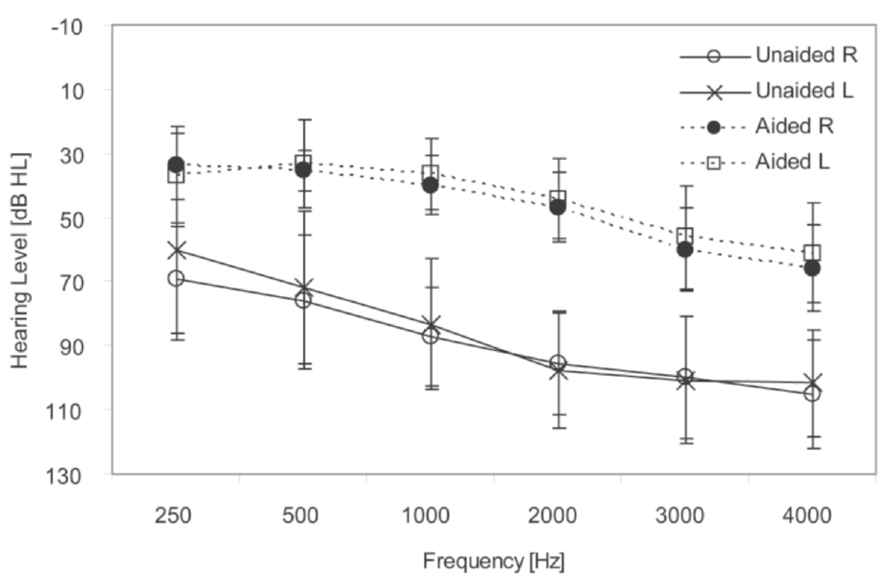

Figure 1. Group mean thresholds are displayed for the unaided right ear (open circle), unaided left ear (x symbol), aided right ear (filled circle) and aided left ear (open square) for subjects. Error bars represent one standard deviation from the mean.

quency. The average unaided thresholds in the right and left ears indicate a moderately-severe hearing loss through 500 Hz and a severe-to-profound hearing loss at 1000 Hz and above.

Figure 1 also displays the group mean aided sound-field thresholds in the right ear (filled circle) and left ear (open square) conditions and one standard deviation. For the right ear aided condition, average thresholds (in dB HL) were 34.1, 35.5, 40.0, 46.8, 60.0, and 65.9 at the respective frequencies (.25, .5, 1, 2, 3, and 4 kHz). At the same frequencies, average thresholds for the left ear aided condition in dB HL were 37.1, 33.2, 36.4, 44.2, 56.3, and 61.3, respectively. The highest aided thresholds are observed at 2000 to 4000 Hz, which can be attributed to greater hearing loss at these frequencies and the limitations of hearing aid technology in providing sufficient gain in the high frequencies without causing acoustic feedback or discomfort to individuals with profound hearing loss.

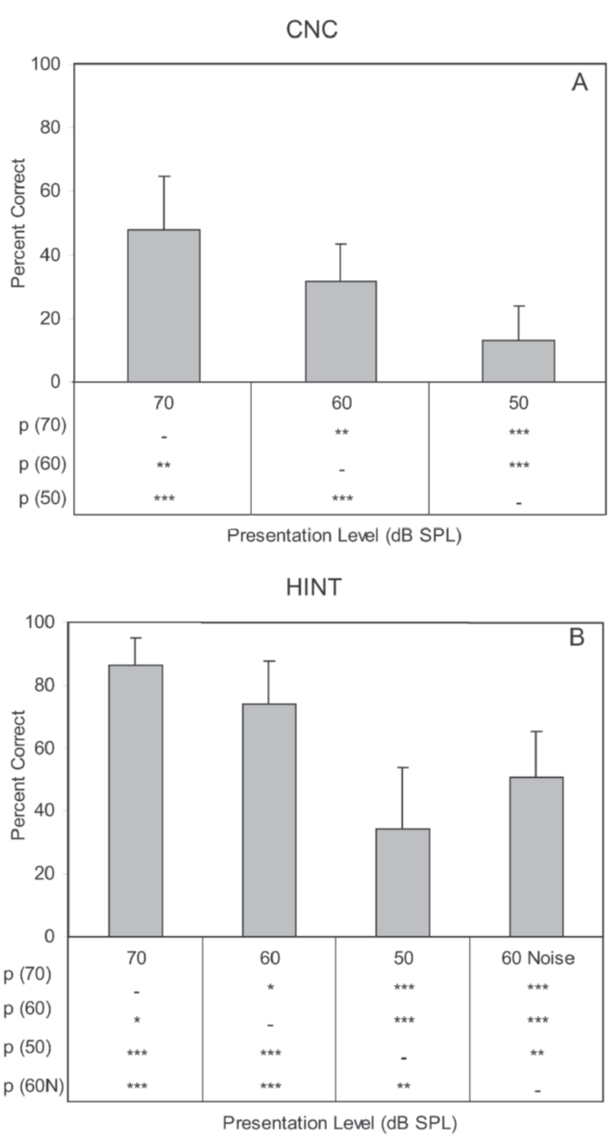

Figure 2. Group mean scores for subjects on the CNC monosyllabic word test (panel A) and HINT sentence test (panel B) at 70, 60, and 50 dB SPL and at 60 dB SPL in noise. Error bars represent one standard deviation from the mean. Asterisks denote statistical significance (*p < 0.05, **p < 0.01, ***p < 0.001).

For both the CNC and HINT measures at each of the three stimulus presentation levels, differences in mean scores obtained at Sessions 1 and 2 were non-significant, and therefore the data were averaged across sessions in the following analyses. When averaged across the two sessions, the CNC word scores are 48% (SD=17), 32% (SD=12) and 13% (SD=11) at 70, 60 and 50 dB SPL, respectively, and are shown in Figure 2(A). Paired t-tests indicate a statistically significant difference in CNC word scores for 70 versus 60 dB SPL ($p < 0.01$), 70 versus 50 dB SPL ($p < 0.001$), and 60 versus 50 dB SPL presentation levels ($p < 0.001$). In Figure 2(B), the average group scores for HINT sentences are 87%, 74% and 34% at 70, 60, and 50 dB SPL (SD = 9, 14 and 20), respectively. Similar to that observed with the CNC word test, there was a significant difference ($p < 0.05$ for 70 versus 60 dB SPL, $p < 0.001$ for 70 versus 50 and 60 versus 50 dB SPL) for scores at each of the three presentation levels in quiet. The average score on the HINT sentence test at 60 dB SPL with +8 dB SNR is 51% (SD=15). Scores were also significantly different for presentation levels 70 versus 60+Noise ($p < 0.001$), 60 versus 60+Noise ($p < 0.001$) and 50 versus 60+Noise ($p < 0.01$). Subjects' scores were lower at soft levels (50 dB SPL) compared to listening in noise at an increased level of 60 dB SPL.

The relation between average (.5, 1, 2, 3, 4 kHz) sound-field thresholds in the best-aided condition and CNC word and HINT sentence scores for all test conditions was assessed. Pearson correlations between sound-field thresholds and speech recognition scores were not statistically significant in this subject sample, perhaps due to ceiling effects for the sentence recognition measure and a relatively narrow range of best-aided sound-field thresholds among the subjects as shown in Table 4.

Figure 3 displays the average scores for subjects using hearing aids (HA) in the current study and the average scores of the postlingually deafened cochlear implant (CI) recipients who were evaluated with the same protocol in Firszt et al (2004). In that study, data were reported for 78 subjects using current implant technology. Because 10 subjects had prelingual hearing loss, their data are excluded from the current comparison with postlingually deafened subjects using hearing aids. Figure 3(A) shows that the average CNC word scores at 70 dB SPL were fairly similar for both groups (CI = 44%, HA = 48%). At lower levels, the mean scores were 41% and 32% for the CI and HA groups respectively at 60 dB SPL, and 25% and 13% for the CI and HA groups at 50 dB SPL. Statistical analysis indicates a significant difference for scores between the groups at 60 ($p < 0.05$) and 50 dB SPL ($p < 0.01$). The HA subjects perform progressively poorer than the CI subjects with each decrease in presentation level from 70 to 50 dB SPL.

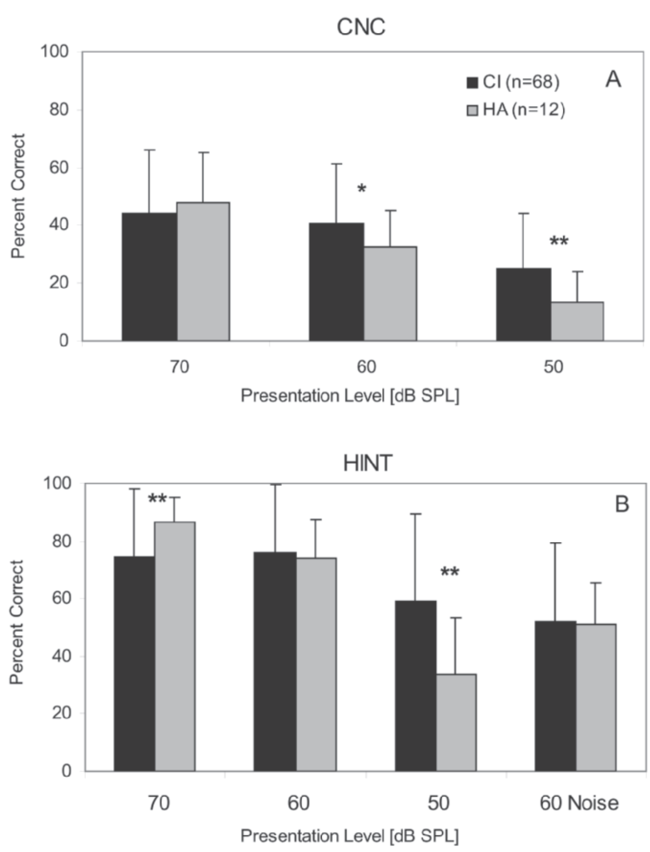

Figure 3. Group mean scores for hearing aid (HA) subjects (light bars) in the current study and a subset of cochlear implant (CI) subjects (dark bars) reported in Firszt et al 2004 on the CNC monosyllabic word test (panel A) and HINT sentence test (panel B) at 70, 60, and 50 dB SPL and at 60 dB SPL in noise. Error bars represent one standard deviation from the mean. Asterisks denote statistical significance (* $p < 0.05$, ** $p < 0.01$).

The mean HINT sentence scores for the HA subjects (87%) was significantly higher ($p < 0.01$) than the CI subjects (75%) at 70 dB SPL, as seen in Figure 3(B). Scores were similar for 60 dB SPL in quiet (CI = 76%, HA = 74%) and 60 dB SPL +Noise (CI = 52%, HA = 51%). HA subjects performed significantly lower at 50 dB SPL ($p < 0.01$) with an average score of 59% for the CI subjects and 34% for the HA subjects.

Several investigators have shown that high speech recognition scores and greater amounts of residual hearing prior to implantation are predictive of higher speech recognition scores with a cochlear implant (Gomaa et al, 2003; Rubinstein et al, 1999; Summerfield and Marshall, 1995). The HA subjects in this study were borderline cochlear implant candidates due to speech recognition scores that were higher than those typically recommended in current candidacy guidelines. For this reason, the average CNC word and HINT sentence scores for the HA subjects were compared to the scores of the upper quartile of CI subjects (n=17, of 68 total) in Firszt et al (2004). As shown in Figure 4(A), the average CNC scores for the upper quartile of postlingual CI subjects were 73%, 64% and 49% at 70, 60 and 50 dB SPL, respectively (SD = 9, 9 and 12, respectively). The average HINT sentence scores for this same group (Figure 4[B]) were 98%, 99% and 92% at 70, 60 and 50 dB SPL, respectively, and 85% at 60+8 SNR (SD = 2, 2, 5 and 8, respectively).

In Figure 4(A), the CNC scores for the HA subjects in the current study are significantly poorer ($p < 0.001$) at the three presentation levels 70, 60, and 50 dB SPL compared to the upper quartile of CI subjects. Although scores in quiet decrease at 60 and 50 dB SPL compared to 70 dB SPL for both HA and CI subjects, the decrease for the HA subjects progressively increased for lower presentation levels. A similar trend is noted in the HINT sentence scores when comparing the two groups (Figure 4[B]); that is, significantly lower scores for the HA subjects are observed compared to the upper quartile of CI subjects ($p < 0.001$), as well as an increase in the decrement across intensity levels in quiet.

DISCUSSION

This study examined the word and sentence recognition scores at three stimulus presentation levels and in noise for adult subjects with postlingual onset and average thresholds in the moderate-to-profound hearing loss range who used hearing aids and were considered borderline cochlear implant candidates. Although the subjects' scores were higher than currently used guidelines for candidacy, these subjects reported continued difficulty in real-life listening situations and frustration with everyday communication. The study results indicate that the stimulus presentation level had a significant effect on word and sentence recognition scores; the lower the presentation level, the poorer the score. Word and sentence score comparisons were significantly different when obtained at 70 versus 60 and 60 versus 50 dB SPL.

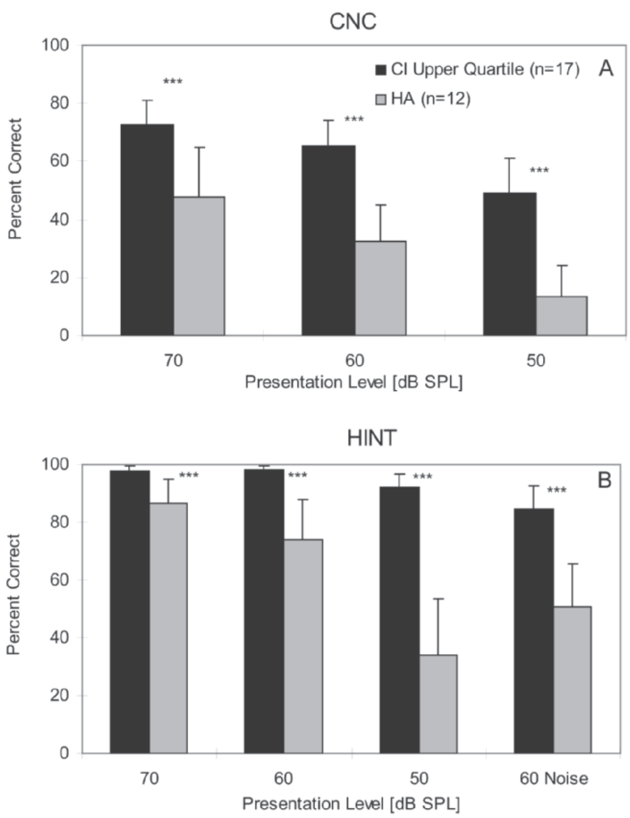

Figure 4. Group mean scores for hearing aid (HA) subjects (light bars) in the current study and the upper quartile of a subset of cochlear implant (CI) subjects (dark bars) reported in Firszt et al 2004 on the CNC monosyllabic word test (panel A) and HINT sentence test (panel B) at 70, 60, and 50 dB SPL and at 60 dB SPL in noise. Error bars represent one standard deviation from the mean. Asterisks denote statistical significance (*** $p < 0.001$).

Comparison of Speech Recognition in Borderline Candidates and Cochlear Implant Recipients

In clinical practice, cochlear implant candidacy is determined on a case by case basis. Considering only the audiometric factor, the recommendation to pursue cochlear implantation is based on a comparison of the individual's speech recognition scores with inclusion criteria from the most recent FDA-approved study, clinical-study inclusion criteria (if appropriate), and average speech recognition scores of cochlear implant recipients. It was of interest, therefore, to compare the scores for the HA subjects to those reported for a large cohort of cochlear implant recipients using current technology who had been evaluated with identical test conditions (Firszt et al, 2004). Compared to the average scores for postlingually deafened adult cochlear implant (CI) recipients when tested at 70 dB SPL, mean scores for the HA subjects were similar for CNC words (49% HA subjects, 44% CI subjects) and significantly higher for HINT sentences (88% HA subjects, 75% CI subjects). Based on this comparison and particularly for scores on the HINT sentences at 70 dB SPL, cochlear implantation for these HA subjects may not be recommended. Since 70 dB SPL does not represent a vocal effort that individuals can maintain (Pearsons et al, 1977; Skinner et al 1997, 2002), determining speech recognition abilities and cochlear implant candidacy at this single speaking level does not represent real-life listening.

Compared to the average postlingual CI subjects in Firszt et al (2004), the HA subjects performed significantly poorer for recognition of words at 60 and 50 dB SPL and for sentences at 50 dB SPL. Sentence scores between the two groups were not significantly different at 60 dB SPL in quiet or in noise. In the noise condition, speech was presented at 60 dB SPL and speech spectrum noise at 52 dB SPL. Given the high frequency aided detection thresholds of the hearing aid subjects, some portion of the noise stimulus may not have been detected and, thus, may not have interfered with the perception of the speech stimulus. It also should be noted that 11 of the 12 HA subjects used binaural hearing aids during testing (i.e., their best-aided condition) which most likely provided an advantage for listening in noise compared to the unilateral CI subjects. Individuals with some residual hearing, such as the subjects in this study, would likely benefit from continued use of a hearing aid in the contralateral ear if cochlear implantation were pursued (Ching et al, 2004; Potts, 2006).

With regard to the HA subjects' poorer speech recognition scores at 50 dB SPL compared to the CI subjects' scores, the groups differed in their auditory detection abilities which is observed in the sound-field test results. Sound-field thresholds for the postlingual cochlear implant recipients in Firszt et al (2004) were 29, 27, 25, 25, 29, and 30 dB HL at .25, .5, 1, 2, 3, and 4 kHz, respectively. A subsequent comparison of the sound-field thresholds for the two groups shows that the HA subjects' best-aided thresholds are poorer than those of the CI subjects by 3.9 dB at 250 Hz, 3.4 dB at 500 Hz, 7.9 dB at 1000 Hz, 14.2 dB at 2000 Hz, 18.9 dB at 3000 Hz and 23.3 dB at 4000 Hz. The differences between groups were statistically significant at 1000 Hz ($p < 0.01$), 2000 Hz ($p < 0.001$) and 4000 Hz ($p < 0.001$).

Comparison of Speech Recognition in Borderline Candidates and the Upper Quartile of Cochlear Implant Recipients

Generally speaking, the vast majority of cochlear implant recipients achieve higher speech recognition scores post-implant compared to their pre-implant performance with hearing aids. When an individual has more residual hearing and high speech recognition scores prior to implantation, it is expected that the individual will obtain higher scores following cochlear implantation, otherwise implantation would not be recommended. Rubinstein and colleagues (1999) conducted a retrospective case review of speech recognition scores combined with mathematical modeling. Pre-implant scores for postlingually deafened adults on the Central Institute for the Deaf (CID) sentence test (Davis and Silverman, 1978) were highly predictive of post-implant scores for CNC words, and pre-implant residual hearing and length of auditory deprivation accounted for 80% of the variance in word recognition scores. Given these findings and clinical observation, it might be appropriate to compare candidates with greater amounts of residual hearing and higher speech recognition scores to higher performing cochlear implant recipients rather than only compare to the "average" cochlear implant recipient. For these reasons, the speech recognition scores for the HA subjects in the present study were compared to the upper quartile of scores for postlingually deafened cochlear implant recipients (n=19 of 68 total) studied by Firszt and colleagues (2004).

The comparison of the mean group data for the HA subjects and the upper quartile of scores for the CI subjects suggested that the HA subjects performed significantly poorer in all test conditions (three presentations levels of 70, 60 and 50 dB SPL for words and sentences in quiet, and sentences in noise at 60 dB SPL). If an individual has more residual hearing pre-implant, comparing a cochlear implant candidate's performance to the average cochlear implant user may not be sufficient and comparisons with recipients who perform at higher levels should be considered. It is well known, however, that cochlear implant outcomes cannot be guaranteed and extensive counseling of the variance in performance should be conducted with each candidate.

The importance of the ability to detect soft speech cues from the incoming acoustic signal can not be overemphasized, particularly cues in the high frequency region of the speech spectrum. Studies suggest that the degree and configuration of hearing loss (Hornsby and Ricketts, 2003), the absolute presentation level (Hogan and Turner, 1998) or sensation level (Ching et al, 1998), and presentation of stimuli in quiet compared to noise (Turner and Henry, 2002) affect whether audible speech cues can be beneficial for speech recognition by individuals with hearing loss. The subjects in the current study had varied hearing histories and differed in the degree and configurations of hearing loss, but all subjects had considerable high frequency hearing loss. Subjects also differed in their ability to detect and recognize speech and in their reports of sound quality and ease of communication, but all subjects noted difficulty with speech understanding in everyday life. For example, Subject 01 had faithfully worn bilateral hearing aids for 14 years and obtained adequate gain at least through 2000 Hz in both ears; however, he struggled in daily situations and needed frequent repetition of speech even during one-on-one conversation both at work and home. There were a number of subjects in the study with asymmetric hearing loss that required modification of the hearing aids to optimize clarity and balance with bilateral use. Subject 07, who had an etiology of Meniere's disease, had distinct perceptual differences between the right and left ears with constant fluctuations in hearing that compromised speech understanding. Subject 04 appeared to have symmetrical hearing loss between ears, but subjectively expressed that the right ear was never as clear when listening to speech as the left ear. These examples illustrate the wide range of individual deficits that may occur as a result of sensorineural hearing loss.

A potential weakness in the current study that may have affected the results is that the subjects used different amplification types. As shown in Table 3, some subjects wore digital hearing aids whereas others wore analogue programmable or non-programmable aids. To evaluate the impact of this factor, the data were plotted for individual subjects for each test condition. The group data across conditions with respect to subjects who wore digital versus non-digital hearing aids and WDRC versus non-WDRC hearing aids were analyzed. In these comparisons, neither the individual data nor the group data reveal a clear pattern. Across the test conditions, the subjects with the highest and lowest scores may have used any of the hearing aid types. For example, of the two subjects with the highest scores obtained at 70 dB SPL for the CNC and HINT tests, one wore analog non-programmable amplification and one wore digital aids with WDRC. Of the two subjects with the highest scores obtained at 50 dB SPL for the CNC and HINT tests, one wore analog non-programmable amplification and one wore digital aids without WDRC. Of the four subjects who scored highest on the HINT 60 dB SPL in noise, one wore analog non-programmable amplification, two used digital aids with WDRC and one wore digital aids without WDRC. The heterogeneity of the subject group with respect to hearing loss onset, progression and severity, and length of hearing aid use may also have affected the relation between amplification type and scores at the tested stimulus levels and in noise. A prospective study that controls for subject variables and amplification type may result in a different outcome and is warranted.

Although the goal in fitting bilateral amplification to individuals with substantial hearing loss is to amplify soft and medium loud sounds while maintaining comfort for loud sounds, and for speech to be as clear as possible, the ideal fitting is not always achieved. For example, the steep slope of the hearing loss in Subject 03 made the fitting of amplification challenging due to the difficulty in achieving high frequency gain without over-amplification of the low frequencies. Several subjects had difficulty tolerating the amount of amplification desired in the low frequencies (e.g., S02, S07). The subject with the greatest amount of gain across the frequencies in both ears was Subject 11 who had an early age of onset of hearing loss (i.e., age 3 years) and had worn hearing aids considerably longer (i.e., 43 years) compared to the other subjects. Several subjects liked and wanted traditional power hearing aids and were dissatisfied with the sound quality of digital hearing aids worn during a trial period.

As cochlear implant audiologists, it is important to continue to strive for ideal hearing aid fittings and patient satisfaction to determine cochlear implant candidacy. Given the inability to predict with certainty how well a person with hearing loss will understand speech with hearing aids, evaluation of amplification systems and attempts to obtain low sound-field thresholds and detection of soft speech is recommended. The effect of hearing loss and audibility on speech recognition in varied test conditions and the implications for amplification and cochlear implant candidacy evaluation warrant further study.

CONCLUSIONS

The subjects in the current study had average thresholds in the moderate-to-profound hearing loss range and used hearing aids but did not meet standard cochlear implant candidacy criteria of less than 60% score on the HINT sentence test. When tested at 70 dB SPL, the hearing aid subjects' word and sentence recognition scores were similar to or greater than the scores of postlingual cochlear implant recipients who use current technology (Firszt et al, 2004). Compared to their implanted peers, the hearing aid subjects' performance, however, was significantly poorer at normal (60 dB SPL) and soft (50 dB SPL) presentation levels for words and at soft levels for sentences. This result may be due to the lack of high frequency speech information when the stimulus presentation level was below 70 dB SPL and due to significantly poorer detection thresholds at 1000 Hz and above for the HA subjects compared to the cochlear implant (CI) subjects. Although sentence scores were not significantly different between the two groups when tested at 60 dB SPL in noise (+8 SNR), the majority of HA subjects used bilateral hearing aids to represent their "best-aided" condition in the pre-implant evaluation whereas the CI subjects were unilateral listeners.

This study supports the use of more real-life listening conditions, such as a lower presentation level rather than a raised-to loud level of 70 dB SPL to determine candidacy for cochlear implantation, particularly for candidates with more residual hearing. In clinical settings, recommendations for implantation are based on an expectation that performance with an implant will exceed the individual's performance with hearing aids. The use of test conditions that reflect more real-life listening situations and comparison to recipients with similar hearing histories prior to implantation may assist clinicians when determining cochlear implant candidacy for those individuals who can recognize some speech but still struggle with communication.

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