J Am Acad Audiol 18:777–793 (2007)

# Effect of Increased IIDR in the Nucleus Freedom Cochlear Implant System

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**Abstract**

The objective of this study was to evaluate the effect of the increased instantaneous input dynamic range (IIDR) in the Nucleus Freedom cochlear implant (CI) system on recipients' ability to perceive soft speech and speech in noise. Ten adult Freedom CI recipients participated. Two maps differing in IIDR were placed on each subject's processor at initial activation. The IIDR was set to 30 dB for one map and 40 dB for the other. Subjects used both maps for at least one month prior to speech perception testing. Results revealed significantly higher scores for words (50 dB SPL), for sentences in background babble (65 dB SPL), and significantly lower sound field threshold levels with the 40 compared to the 30 dB IIDR map. Ceiling effects may have contributed to non-significant findings for sentences in quiet (50 dB SPL). The Freedom's increased IIDR allows better perception of soft speech and speech in noise.

**Key Words:** Cochlear implant, instantaneous input dynamic range, speech processor map, speech perception

**Abbreviations:** ACE = Advanced Combination Encoder; ADRO = Adaptive Dynamic Range Optimization; AI = Articulation Index; CI = cochlear implant; CIS = Continuous Interleaved Sampling; CL = current level; CNC = consonant-vowel nucleus-consonant; CUNY = City University of New York; F0 = fundamental frequency; F1 = first formant; F2 = second formant; FM = frequency modulated; HINT = Hearing in Noise Test; IDR = input dynamic range; IIDR = instantaneous input dynamic range; pps/ch = pulses per second/channel; RP8 = Research Platform 8; S = subject; SAS = Simultaneous Analog Stimulation; SEM = standard error of the mean; SNR = signal-to-noise ratio; WSP = Wearable Speech Processor

**Sumario**

El objetivo de este estudio fue evaluar el efecto del rango dinámico aumentado instantáneo de ingreso (IIDR) en el sistema de implante coclear (IC) Nucleus Freedom, sobre la capacidad de sujetos implantados para percibir lenguaje a bajo volumen y lenguaje en ruido. Diez sujetos implantados con el IC Freedom participaron. En la activación inicial, dos mapas con una diferencia

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Portions of this manuscript were presented as a poster at the 9th International Cochlear Implant Conference, June 14th-17th, 2006, Vienna, Austria. This research was supported by Grant R01 DC000581 from the National Institute on Deafness and Other Communication Disorders.

en cuanto al IIDR se colocaron en el procesador de cada sujeto. El IIDR fue ajustado a 30 dB para un mapa y a 40 dB para el otro. Los sujetos utilizaron ambos mapas por al menos un mes, antes de una evaluación de percepción del lenguaje. Los resultados revelaron puntajes significativamente más altos para palabras (50 dB SPL), para frases en balbuceo de fondo (65 dB SPL), y niveles umbrales en campo libre significativamente más bajos con el mapa de IIDR de 40 comparado con el de 30. Efectos tope pueden haber contribuido a los hallazgos no significativos para frases en silencio (50 dB SPL). El IIDR aumentado para Freedom permite mejor percepción para el lenguaje a bajo volumen y el lenguaje en medio de ruido.

**Palabras Clave:** Implante coclear, rango dinámico de ingreso instantáneo, mapa del procesador de lenguaje, percepción del lenguaje

**Abreviaturas:** ACE = Codificador de Combinación Avanzada; ADRO = Optimización Adaptativa de Rango Dinámico; AI = Índice de Articulación; CI = implante coclear; CIS = Muestreo Continuo Intercalado; CL = nivel actual; CNC = consonante-núcleo vocal-consonante; CUNY = Universidad de la Ciudad de Nueva York; F0 = frecuencia fundamental; F1 = primer formante; F2 = segundo formante; FM = frecuencia modulada; HINT = Prueba de Audición en Ruido; IDR = rango dinámico de ingreso; IIDR = rango dinámico de ingreso instantáneo; pps/ch = pulsos por segundo/por cana; RP8 = Plataforma de Investigación 8; S = sujeto; SAS = Estimulación Analógica Simultánea; SEM = error estándar de la media; SNR = tasa señal-ruido; WSP = Procesador Usable de Lenguaje

The ability to perceive soft speech allows Cochlear Implant (CI) recipients to converse from across a room and even from a different room than the speaker. It allows them to better understand soft-spoken individuals (e.g. children), to perceive the asides of a conversation, and to expend less effort throughout the day to understand speech (Skinner et al, 2002a). For children using CIs, being able to perceive soft speech is critical for incidental or passive learning (Flexer et al, 1999). Advances in CI technology have improved recipients' detection of soft sound and perception of soft speech over the past 20 years. For example, in 1988 Skinner and colleagues compared the benefit that four postlinguistically deaf adults obtained from a vibrotactile aid and a Nucleus 22 CI. Frequency modulated (FM) tone, sound field threshold levels were obtained with the subjects using the Nucleus 22 Wearable Speech Processor (WSP) and the F0/F1/F2 (Skinner et al, 1991) speech coding strategy. Sound field threshold levels averaged across subjects at 250, 500, 1000, 2000, 3000, and 4000 Hz were 45, 35, 39, 46, 49, and 59 dB HL, respectively. These threshold levels allowed the subjects to detect average conversational speech (long-term overall level ~ 44 dB HL); however, their ability to detect soft speech (long-term overall level ~ 34 dB HL) would have been severely limited with these sound field levels (Skinner et al, 2002a). In a more recent study, FM-tone, sound field threshold levels were obtained for eight Nucleus 24 CI recipients using either the SPrint™ or ESPrit 3G speech processor and the Advanced Combination Encoder (ACE) speech coding strategy (Skinner et al, 2002b). Group mean sound field thresholds at 250, 500, 1000, 2000, 3000 and 4000 Hz were 20, 26, 23, 22, 25, and 25 dB HL, respectively. These threshold levels provided this group of subjects with the ability to detect and perceive soft speech (Holden et al, 2005). Firszt et al (2004) examined the speech perception abilities of 78 cochlear implant users (26 each with the Clarion HiFocus I or II, Med-El Combi 40+, and Nucleus 24R or 24M devices) at three stimulus presentation levels, 70, 60 and 50 dB SPL. These presentation levels correspond to raised, conversational, and soft vocal efforts, respectively (Pearsons et al, 1976). Results showed a statistically significant correlation between lower FM-tone, sound field thresholds and better performance on monosyllabic words, sentences in quiet and sentences in noise at the softer presentation levels of 50 and 60 dB SPL. For these subjects, group mean FM-tone, sound field threshold levels at 250, 500, 1000, 2000, 3000 and 4000 Hz were 29, 27, 25, 25, 29, and 29 dB HL, respectively. This group of implant users was chosen to represent the full range of performance, and although group mean scores on all speech perception measures varied widely, results revealed considerable open-set speech recognition at the softest presentation level of 50 dB SPL (24% for words; 57% for sentences). These results emphasize the need for CI users to obtain sound field threshold levels less than 30 dB HL across the frequency range in order to perceive soft speech.

There have been significant efforts by researchers to improve CI users' ability to perceive soft speech. Skinner et al (1999b) found that raising minimum stimulation levels (T-levels) above counted levels for each electrode in a speech processor program or map significantly improved the perception of soft speech for eight Nucleus 22 CI users. A counted level represents the level at which the CI user can correctly count the number of stimulation bursts presented on each electrode 100% of the time. In the study, two maps were created for each subject that differed only in minimum stimulation levels set for each electrode. Minimum stimulation levels were set at counted levels for one map and were raised above counted levels for the other map. Results revealed significantly better group mean scores for words and sentences in quiet at presentation levels of 50 and 60 dB SPL with minimum stimulation levels raised above counted levels than with minimum stimulation levels set at counted levels.

McDermott et al (2002) evaluated the effect of syllabic input compression that was employed in the microphone circuitry of the Spectra 22 and SPrint™ processors in an effort to improve the perception of soft speech without varying map parameters. Similar compression circuitry is used in the "Whisper" setting with the ESPrit 3G and Freedom speech processors. Subjects were tested with and without input compression. Results revealed significant improvements in sentence recognition with input compression for three presentation levels (45, 55, and 70 dBA SPL) with the greatest improvements seen for the two softest presentation levels. No significant difference was seen between the two conditions in noise; however, the majority of subjects needed higher signal-to-noise ratios (SNRs) when using input compression to maintain sentence recognition in noise at 70% of their score in quiet. Six of the subjects who used input compression in everyday life reported that background sound was louder, and some reported that it was too loud with input compression.

Adaptive Dynamic Range Optimization (ADRO) is a pre-processing scheme used with the SPrint™ and Freedom speech processors that continuously adjusts the gain in each of the filter bands to maintain soft speech and sound in the upper half of the CI user's electrical dynamic range, thus allowing better perception of soft speech and sound without the need to adjust map parameters or the sensitivity control setting (James et al, 2002). James and colleagues compared a standard clinical map with and without ADRO processing on the SPrint™ processor with a group of nine Nucleus 24 users. Significantly higher scores with ADRO were seen for spondees presented at 40 dB SPL, for words presented at 60 and 70 dB SPL and for sentences presented at 50 and 60 dB SPL. No significant difference was seen in scores between the two maps for sentences in noise.

A separate study by James et al (2003) evaluated two different methods of improving the perception of soft speech with a group of 12 Nucleus 24 CI recipients using either the ACE or SPEAK (Seligman and McDermott, 1995) strategy on the SPrint™ processor. In Part 1 of the study, subjects compared a sensitivity control setting of 8 (manufacturer's recommended setting) to a raised sensitivity control setting of 15. The results revealed that the raised setting produced significantly lower FM-tone, sound field threshold levels, significantly higher scores for closed-set vowels and consonants presented at 40 dB SPL, and significantly higher scores for consonants presented at 55 dB SPL than the recommended setting of 8. For sentences presented at 65 dB SPL in noise, there was no significant difference between the two settings. Many of the subjects, however, reported that background sound was unacceptably loud with a sensitivity control setting of 15. Based on the results from this study, Cochlear Americas changed their recommended sensitivity control setting from 8 to 12.

In Part 2 of the study, the speech processor's instantaneous input dynamic range (IIDR) was increased by lowering the base level parameter from the clinical software's default setting of 4 to 1 or 0. The IIDR is the range in which the incoming acoustic signal is mapped onto the CI users' electrical dynamic range (minimum to maximum electrical stimulation levels). Lowering the base level increased the IIDR from 29.5 dB to 37.5 dB for SPEAK users and from 30.5 to 41 dB for ACE users and resulted in a significant improvement in consonants presented at 40 dB SPL. No significant difference in scores was seen for vowels presented at 40 dB SPL or for vowels or consonants presented at 55 dB SPL. Scores for sentences presented in noise were significantly lower with the base level set to 1 or 0 than with the base level set to 4 suggesting that an increased IIDR is detrimental to speech perception in noise.

The lack of overall improvement for the perception of soft speech with the increased IIDR found by James and colleagues is contradictory to several research studies. Consendai and Pelizone (2001) systematically varied the input dynamic range (IDR) for a group of three Inner Aid CI recipients using the Continuous Interleaved Sampling (CIS) strategy (Wilson et al, 1991). The researchers found vowel and consonant recognition to be best with an IDR of 45 dB. Zeng et al (2002) examined vowel and consonant recognition while varying the IDR for 10 Clarion CI recipients using either the CIS or simultaneous analog stimulation (SAS) (Battmer et al, 1999) strategies. The results revealed that an IDR of 50-60 dB provided the CI users with the highest vowel and consonant scores. Donaldson and Allen (2003) compared the speech perception abilities of seven Nucleus 22 CI recipients using SPEAK and seven Clarion v1.2 CI recipients using CIS across a range of presentation levels (70, 60, 50, 40 and 30 dB SPL). Results revealed that Clarion users scored higher for consonants, vowels and sentences at the softest presentation levels compared to the Nucleus users. These findings were due in part to the differences in IDR between the Clarion (IDR = 60 dB) and Nucleus (IDR = 30 dB) CI systems.

Prior to the development of the Nucleus Freedom CI System, all Nucleus CI systems had a default IIDR of 30 dB. However, many of the above mentioned studies showed that even with this limited IIDR Nucleus CI users have had the ability to perceive soft speech through the use of processing schemes such as "Whisper" and "ADRO" and/or manipulations of map parameters and speech processor settings (i.e. raising minimum stimulation levels, raising the speech processor's sensitivity control setting, and lowering the base level). The Freedom CI system has a maximum IIDR of 45 dB with 40 dB being the default setting within the clinical software. The objective of this study was to evaluate the effect of the increased IIDR in the Nucleus Freedom CI system on recipients' ability to perceive soft speech and speech in noise.

## METHOD

### Subjects

Ten newly implanted adult recipients of the Nucleus Freedom CI system participated in the study. All subjects had postlinguistic onset of hearing loss and used spoken English as their primary mode of communication. Demographic information for the subjects is provided in Table 1. Subjects ranged in age from 36 to 80 years with a mean age of 59 years. Duration of deafness in the implanted ear ranged from 1 to 15 years with a mean duration of approximately 6 years. All subjects had complete insertion of the electrode array into the cochlea according to the surgeon's report.

### Mapping Procedures

At the initial activation of the Freedom CI system, two maps were created for each subject. One map had an IIDR of 30 dB and the other had an IIDR of 40 dB. Both maps were created using the ACE strategy (25 μs/phase, monopolar stimulation), 1200 pulses per second /channel (pps/ch) stimulation rate and 10 maxima. The number of maxima, which are the channels selected based on the filter bands with the highest amplitudes within each analysis cycle, multiplied by the stimulation rate per channel gives the total stimulation rate (12,000 Hz for each subject). The ACE strategy was chosen for each subject as it was preferred by the majority of subjects and was found to provide significantly higher scores for sentences in noise compared to the SPEAK and CIS strategies in two separate research studies (Skinner et al, 2002b; Skinner et al, 2002c). A stimulation rate of 1200 pps/ch was chosen for each

**Table 1. Subject demographic information**

| Subject | Sex | Etiology | Age at Study (yrs) | Age at Id or Onset of Hearing Loss (yrs) | Duration of Deafness (yrs) | Hearing Aid Use Implant Ear (yrs) | Implanted Ear |
|---|---|---|---|---|---|---|---|
| 1 | M | Genetic | 69 | 40 | 1 | 20 | L |
| 2 | F | Genetic/Encephalitis | 56 | 24 | R: 5<br>L: 32 | 20 | R |
| 3 | F | Unknown | 80 | 60 | R: 15<br>L: 20 | 12 | R |
| 4 | M | Genetic | 54 | 44 | 5 | 8 | L |
| 5 | F | Meniere's Disease | 57 | 36 | 6 | 14 | R |
| 6 | F | Ototoxicity | 67 | 64 | 3 | 3 | R |
| 7 | F | Unknown | 36 | 5 | 5 | 0 | R |
| 8 | F | Genetic | 65 | 30 | 2 | 10 | L |
| 9 | F | Genetic | 69 | 22 | 5 | 30 | R |
| 10 | F | Genetic | 43 | 6 | 10 | .5 | R |

subject based on the outcome of the feasibility study for the Nucleus Research Platform 8 (RP8) CI System (Plant et al, 2007) in which this rate was used. The RP8 System was the precursor to the Freedom CI System and all 15 postlinguistically deafened subjects participating in the RP8 feasibility study had considerable open-set speech recognition. In addition, a stimulation rate of 1200 Hz allows longer battery life than faster stimulation rates.

To create the two maps at the initial activation, an ascending loudness judgment procedure was used to set both minimum (T) and maximum (C) stimulation levels for each electrode. Subjects were asked to listen for the stimulus (500-ms biphasic pulse train) that was first presented well below each subject's detection threshold. The stimulus was then increased in two current-level (CL) steps and subjects reported the loudness of the stimulus from very soft to maximum acceptable loudness utilizing an eight-point loudness scale (first hearing, very soft, soft, medium soft, medium, medium loud, loud, maximum acceptable loudness). Minimum stimulation levels were set at the subjects' report of "very soft" and maximum stimulation levels were set at "medium loud" or "loud." Maximum stimulation levels were swept and balanced for equal loudness across electrodes and then globally adjusted in live-voice mode so that speech was comfortably loud. On the first day of initial activation, the two maps were identical except for the IIDR. Subjects were randomly placed into one of two groups, group A or group B. The five subjects in group A had the 40 and 30 dB IIDR maps placed in locations P1 and P2 on their Freedom processors, respectively, and the five subjects in group B had the maps in the reverse order on their processors. Subjects were blinded to the location of each map to prevent bias. All subjects had both the volume and sensitivity control settings activated on their Freedom processors and were encouraged to wear volume control settings between 6 and 9 and sensitivity settings between 8 and 12. On the first day of initial activation, most subjects were more comfortable wearing the sensitivity at a lower setting (i.e., 8 or 9) with the goal being to increase the sensitivity to 12 over the next several weeks. Each subject was counseled on the importance of hearing soft speech and sound to their communication abilities in everyday life. Subjects were asked to use the same sensitivity and volume control settings for both maps for all listening situations throughout each day. They were allowed to adjust the volume and sensitivity settings from their general use settings if necessary (i.e., listening at a noisy restaurant); however, they were asked to adjust both maps to the same volume and sensitivity control settings for each listening situation.

Subjects returned the following day and counted levels were obtained for each active electrode in the map. For the 40 dB IIDR map, minimum stimulation levels were set at the counted level for each active electrode. For the 30 dB IIDR map, minimum stimulation levels were set above the counted level. Table 2 shows each subject's dynamic range (range between minimum and maximum stimulation levels) averaged across electrodes at the initial activation. In addition, the initial increase in minimum stimulation levels, above counted levels, for the 30 dB IIDR map is shown for each subject. Minimum stimulation levels were raised between 2-5 levels for each subject except for S5 who had minimum stimulation levels raised by 10 levels. Subject 5 had a wide dynamic range of 61 CLs and needed minimum stimulation levels

**Table 2. Each subject's dynamic range (DR) and increase in minimum stimulation levels above counted levels averaged across electrodes for the 30 dB IIDR map at initial activation.**

| Subjects | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| DR | 31 | 31 | 46 | 48 | 61 | 28 | 27 | 33 | 29 | 33 |
| Increase in Minimum Stimulation Levels | 2 | 2 | 2 | 2 | 10 | 2 | 3 | 5 | 3 | 5 |

raised by 10 CLs in order for sound to be comfortably loud with the 30 IIDR map. FM-tone, sound field threshold levels were obtained with each map and minimum stimulation levels were raised further for the 30 dB IIDR map if sound field threshold levels were ≥ 30 dB HL at any frequency from 250-6000 Hz. With the 40 dB IIDR map, sound field levels were always ≤ 30 dB HL; therefore, minimum stimulation levels were never adjusted from the counted level except for Subject (S) 2. Subject 2 reported background sound to be loud with minimum stimulation levels set at counted levels; consequently, minimum stimulation levels on all electrodes were lowered by 5 CLs from the counted level for the 40 dB IIDR map and then raised by 3 CLs for the 30 dB IIDR map. With these levels, S2 reported that background sound was comfortable. It is worth noting that when sweeping across electrodes set at counted levels, S2 reported the overall loudness to be "soft," whereas all other subjects reported the overall loudness to be "very soft."

Subjects returned to the clinic once a week for 4-6 weeks. During these visits counted and sound field threshold levels were monitored and changes were made to the minimum stimulation levels of both maps. The minimum stimulation levels for the 40 dB IIDR map continued to be set at counted levels and minimum stimulation levels for the 30 dB IIDR map were raised above counted levels so that sound field threshold levels fell below 30 dB HL from 250-6000 Hz. Minimum stimulation levels for the 30 dB IIDR map were initially raised above counted levels equally across all electrodes. For most subjects, minimum stimulation levels then needed to be raised further on individual electrodes within a specific frequency region to decrease the sound field threshold level in that region. Maximum stimulation levels were globally adjusted in live-voice mode and then swept and balanced during these visits to ensure that speech and sound were comfortably loud at a volume control setting of 6 to 9 and a sensitivity control setting of 12. Sensitivity and volume control settings were checked weekly to ensure that each subject was wearing appropriate settings. Seven subjects (S1, S2, S3, S5, S6, S8, and S10) used maps with 22 active electrodes; S4 had 2 electrodes removed from his map due to short circuits. Subject 9 had one basal electrode removed and S7 had two basal electrodes removed to improve sound quality. All parameters remained identical for both maps except for IIDR and minimum stimulation levels. Speech processing schemes such as "Whisper" or "ADRO" were not used during the study. After each visit, subjects were instructed to wear each map every other day and were given a written schedule to follow. They were also encouraged to compare both maps during a variety of listening situations (e.g. watching TV, conversing at the dinner table or at a restaurant) and to keep notes as to which map sounded best for specific situations.

### Procedures

Each subject's open-set speech recognition was monitored every two weeks after initial activation using the Consonant-Vowel-Nucleus-Consonant (CNC) Monosyllabic Word Test (Peterson and Lehiste, 1962). The recording of the CNC word test used to monitor speech recognition is part of the Minimum Speech Test Battery for Adult CI Users (Luxford et al, 2001). Formal testing with both maps was begun at one month post initial activation if the subject's CNC word score had reached 20%. For subjects whose CNC score did not meet the 20% criteria, formal testing was delayed until a score of 20% was obtained. Subjects 1, 5, 6, 8 and 9 began formal testing at one month, S10 at five weeks, S2 and S4 at six weeks, S7 at seven weeks, and S3 at eight weeks. Formal testing consisted of two test sessions one week apart. A practice test session to familiarize subjects with the speech perception measures was carried out the week before the first formal test session. Both maps were tested at each session. For the first test session, subjects assigned to Group A were initially tested with the 40 and then with the 30 dB IIDR map, and subjects assigned to Group B were initially tested with the 30 and then with the 40 dB IIDR map. The order of testing with each map was reversed for the second test session. The volume and sensitivity control settings used for testing were the same for both

**Table 3. Listing Situations Listed on the Questionnaire**

1. Conversation on the telephone
2. Message on the answering machine
3. News on TV
4. Movies/dramas/sitcoms on TV
5. Radio in the car
6. Radio at home in a quiet room
7. Lyrics to music
8. Conversation with several friends around dinner table
9. Conversation in a quiet room with one person
10. Conversation in a quiet room with several people
11. Conversation in a car
12. Conversation with friends at a social gathering
13. Conversation at a restaurant
14. Conversation with a cashier at the grocery store
15. Conversation with a child
16. Conversation outside
17. Someone speaking from a distance
18. Church service
19. Meeting in a large room

maps and were the settings that each subject used most often in everyday life. All subjects used a volume control setting of 8 or 9, except S2 who used a volume setting of 6. Seven of the 10 subjects used a sensitivity setting of 12; S2 used a sensitivity setting of 10 and S4 and S8 used a sensitivity setting of 14. FM-tone, sound field threshold levels were obtained from 250-6000 Hz with each map at the beginning of each test session. Threshold levels were obtained in 2 dB steps using a standard Hughson-Westlake procedure (Carhart and Jerger, 1959).

## Test Materials

The FM tones were sinusoidal carriers modulated with a triangular function over the standard bandwidths recommended for use in the sound field (Walker et al, 1984). The modulation rate was 10 Hz. A conversion in the sound field from dB SPL to dB HL was made according to the ANSI (American National Standards Institute) standard for audiometers (ANSI s3.6-1996 [ANSI, 1996]).

Four lists of the Hearing in Noise Test (HINT) sentences (Nilsson et al, 1994) and four lists of the CNC monosyllabic words (Skinner et al, 2006) were presented at a soft level of 50 dB SPL with each map at each of the two test sessions for a total of eight lists of sentences and words with each map. The HINT sentences consist of 25 lists with 10 sentences per list and are part of the Minimum Speech Test Battery for Adult CI Users (Luxford et al, 2001). The CNC word test used during the formal test sessions consists of 30 lists of 50 words per list and is on the average 22% more difficult than the original CNC word test used as part of the Minimum Speech Test Battery. As noted above, the original CNC word test was used to monitor open-set speech recognition prior to formal testing. Four lists of the City University of New York (CUNY) Sentences (Boothroyd et al, 1988) were presented at 65 dB SPL in 8-talker babble with each map at each test session for a total of eight lists of sentences with each map. There are 72 lists of CUNY sentences with 12 sentences per list. The SNR varied for each subject to prevent ceiling or floor effects and was chosen for each subject so that the CUNY sentence recognition score would fall between 50 and 75% correct. The SNRs for Ss 1-10 were as follows: +10, +16, +20, +15, +12, +10, +15, +12, +12, and +15 dB. All test lists were presented in a pseudorandomized order and each subject had a unique randomization.

Prior to the first test session, subjects were given a questionnaire to complete at home over a two week time period. The questionnaire asked subjects to rate, on a 5 point scale (1 = poor, 5 = excellent), how well they perceived speech for 19 listening situations with both maps. In addition, they were to rate how well they detected environmental sounds and enjoyed music with each map. Finally, they rated their overall speech understanding with each map. Table 3 provides a list of the 19 listening situations on the questionnaire.

## Equipment/Test Environment

All test materials were presented in a double-walled sound attenuating booth (IAC; model 1204-A; 254 cm x 264 cm x 198 cm) through a loudspeaker placed at ear-level at 0 degrees azimuth and 1.5 meters from the center of the subjects' heads in their absence. The test materials were presented via an IBM compatible, Pentium II computer that controlled a mixing and attenuation network (Tucker-Davis Technologies) to present stimuli through a power amplifier (Crown model D-150) and loudspeaker (JBL; model LSR32). FM tones as well as the speech perception materials were stored as wave files on the hard disk played through a soundcard (Lynx Studio Technology; model LynxONE). The microphone (Brüel and Kjaer, Model 4155) of a sound level meter (Brüel and Kjaer, Model 2230) was placed at what would be the center of the subject's head during testing and used to measure the sound pressure level of the stimuli. A slow (250 ms integration time) RMS detector and wide bandpass filter (20 Hz to 20 kHz) were used to measure the SPL of the words and sentences for all test materials, and an average overall SPL was computed for each of the test materials separately.

## RESULTS

### Minimum Stimulation Levels and FM-Tone, Sound Field Threshold Levels

A two-tailed, paired t-test was performed on subjects' minimum stimulation levels for all active electrodes for each of the two maps. Results revealed significantly higher minimum stimulation levels (N = 215, t = 2.134, p< .05) for the 30 (mean = 130.3 CLs) compared to the 40 dB IIDR map (mean = 125.1 CLs). For the group, the mean increase in minimum stimulation levels across electrodes was 5 CLs. Figure 1 shows the mean increase in minimum stimulation levels across electrodes for individual subjects (range: 2.3-8 CLs). Subjects 5 and 9 had minimum stimulation levels for all electrodes raised equally by 8 and 3 CLs, respectively, whereas S1 had a mean increase in minimum stimulation levels across electrodes of 7.5 CLs with increases on individual electrodes ranging from 2-17 CLs. The other seven subjects also had minimum stimulation levels raised higher for some electrodes than for others; however, the range was smaller for these subjects than for S1.

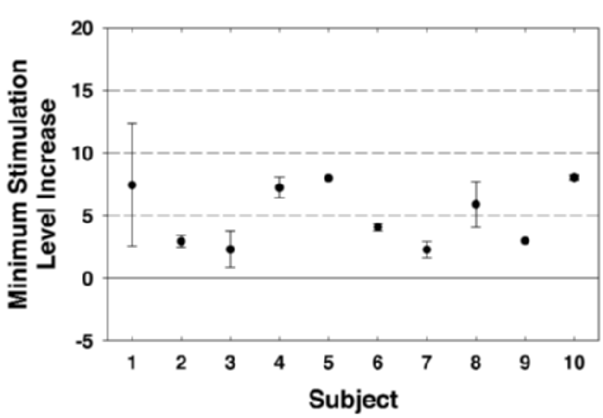


**Figure 1.** Mean increase in minimum stimulation levels across electrodes for each subject with the 30 dB IIDR map compared to the 40 IIDR map. Error bars represent ±1 standard deviation (SD).

Despite the increase in minimum stimulation levels with the 30 compared to the 40 dB IIDR map, group mean FM-tone, sound field threshold levels from 250-6000 Hz were significantly lower with the 40 compared to the 30 dB IIDR map. A univariate analysis of variance (ANOVA) was performed on sound field threshold levels for each frequency with subject and map as fixed factors. A significant effect for map was seen at all frequencies (250 Hz [F = 62.3, p<.0001]; 500 Hz [F = 12.2, p<.0001]; 750 Hz [F = 291.1, p<.0001]; 1 kHz [F = 238.2, p<.0001]; 15 kHz [F = 177.2, p<.0001]; 2 kHz [F = 71.2, p<.0001]; 3 kHz [F = 186.8, p<.0001]; 4 kHz [F = 88.2, p<.0001]; 6 kHz [F = 177.8, p<.0001]). A subject by map interaction was seen at three frequencies (500 Hz, 750 Hz, and 1500 Hz); however, for all subjects, thresholds were lower with the 40 compared to the 30 dB IIDR map. Figure 2 shows the group mean FM-tone, sound field threshold levels for each map plotted on Mueller & Killion's (1990) count-the-dot matrix for the calculation of the articulation index (AI). The AI was .97 for the 40 dB IIDR map and .75 for the 30 dB IIDR map.

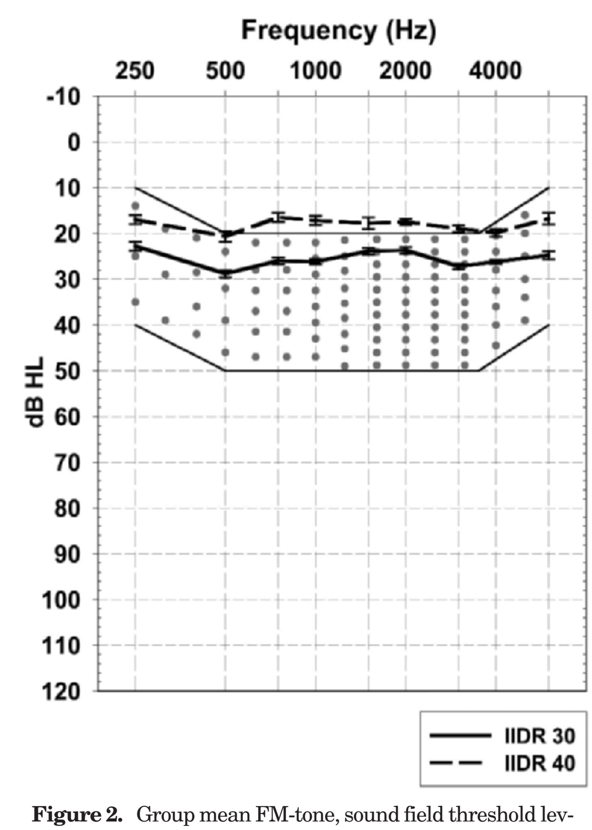


**Figure 2.** Group mean FM-tone, sound field threshold levels for the 30 and 40 dB IIDR maps plotted on Mueller and Killion's (1990) count-the-dot matrix for the calculation of the articulation index. Error bars represent ±1 standard error of the mean (SEM).

### Speech Perception Measures

Speech perception scores were converted from percent correct to arc sine units for statistical analysis. A univariate ANOVA was performed for each of the speech perception measures with subject, map, and session as fixed factors. The analysis showed significant main effects for map for all speech perception tasks except HINT sentences with no significant subject by map or subject by session interactions. Group mean scores averaged across both test sessions with the 30 and 40 dB IIDR maps for each of the speech perception measures are shown in Figure 3. Group mean scores for CNC words presented at a soft level of 50 dB SPL were 12% and 18% for the 30 and 40 dB IIDR maps, respectively; for CNC phonemes, group mean scores were 41% and 47% for the 30 and 40 IIDR maps, respectively. The scores were significantly higher for both words ($F = 59.0$, $p<.0001$) and phonemes ($F = 110.5$, $p<.0001$) with the 40 compared to the 30 dB IIDR map. Group mean scores for HINT sentences presented at 50 dB SPL were 67% and 69% with the 30 and 40 IIDR maps, respectively. No significant difference in group mean scores for the two maps was seen for HINT sentences. Group mean scores for CUNY sentences presented at 65 dB SPL in 8-talker babble were 62% for the 30 dB IIDR map and 66% for the 40 dB IIDR map. The 40 dB IIDR map provided a small but statistically significant advantage for listening in noise ($F = 4.43$, $p<.05$) over the 30 dB IIDR map. Individual subject data for CNC words and phonemes and for HINT and CUNY sentences are shown in Figures 4-7, respectively. All subjects had higher mean CNC word and phoneme scores with the 40 compared to the 30 dB IIDR map. The group means as well as individual subject word and phoneme scores reflect the difficulty of this CNC word test. As can be seen from Figure 6, half the subjects' scores were higher than 70% with both maps for HINT sentences at the soft presentation level of 50 dB SPL. Subjects 8 and 10 scored slightly lower with the 40 compared to the 30 dB IIDR map. For the rest of the subjects, scores were equivalent or slightly higher with the 40 than the 30 dB IIDR map. Individual data for CUNY sen-

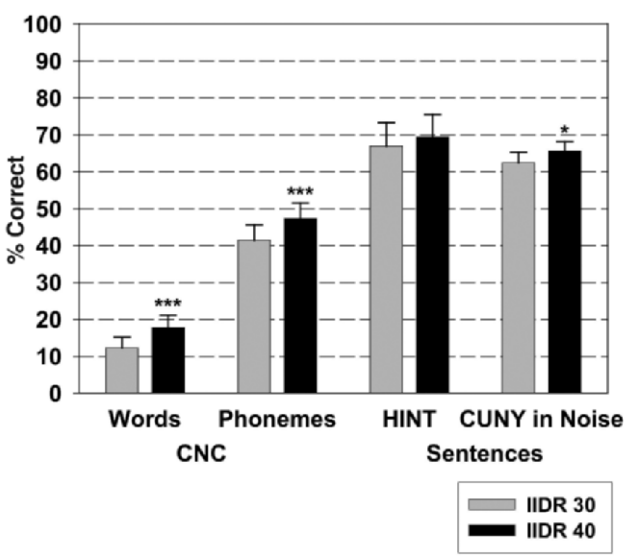


**Figure 3.** Group mean scores for CNC words and phonemes (50 dB SPL), HINT sentences (50 dB SPL), and CUNY sentences in noise (65 dB SPL) with the 30 and 40 dB IIDR maps. Asterisks denote significantly higher scores (*** = p<.0001, * = p<.05). Error bars represent 1 SEM.

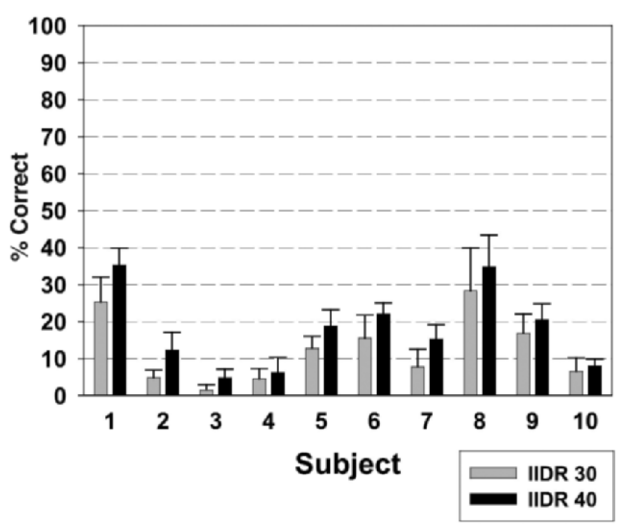


**Figure 4.** Individual mean scores for CNC words (50 dB SPL) for the 30 and 40 dB IIDR maps. Error bars represent 1 SD.

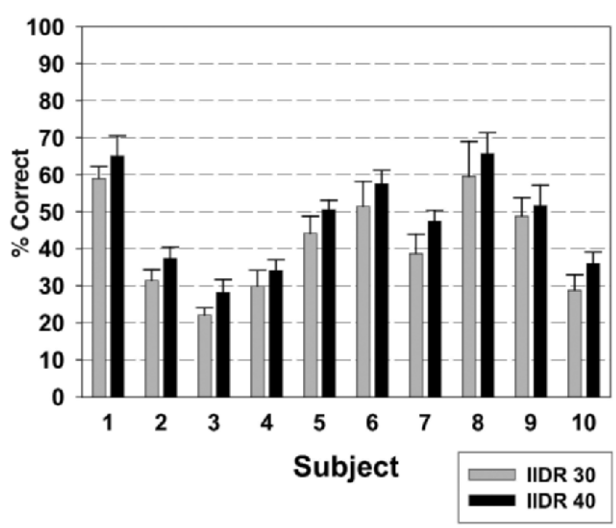


**Figure 5.** Individual mean scores for CNC phonemes (50 dB SPL) for the 30 and 40 dB IIDR maps. Error bars represent 1 SD.

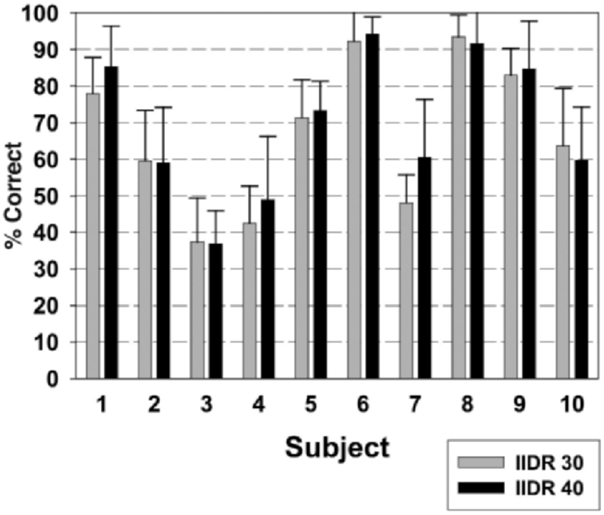


**Figure 6.** Individual mean scores for HINT sentences (50 dB SPL) for the 30 and 40 dB IIDR maps. Error bars represent 1 SD.

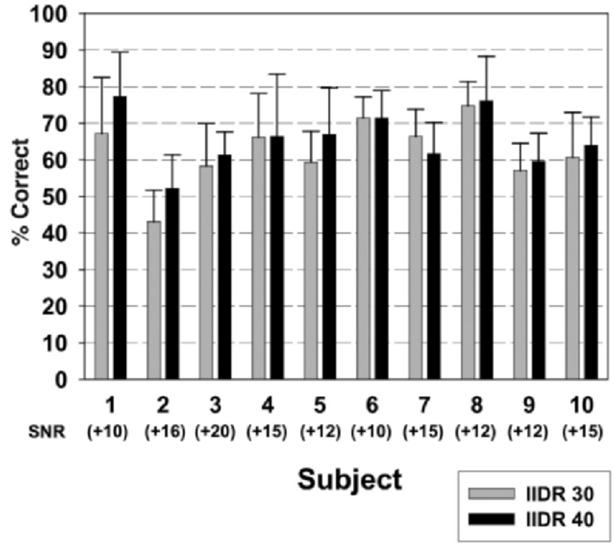


**Figure 7.** Individual mean scores for CUNY sentences (65 dB SPL) in noise for the 30 and 40 IIDR maps. The numbers in parentheses are the SNRs used for each subject. Error bars represent 1 SD.

tences in noise revealed all but one subject (S7) had either equivalent mean scores with the two maps or higher mean scores with the 40 than with the 30 dB IIDR map.

### Information Transmission Analysis

All responses to CNC words were transcribed into machine readable modified two symbol ARPABET notation (Garofolo et al, 1993) and confusion matrices were created for initial consonants, medial vowels, and final consonants within the CNC words. These matrices were then submitted to information transmission analysis (Wang and Bilger, 1973). The feature matrix used for consonants was described in Skinner et al (1999a) while the matrix used for vowels was described in Skinner et al (1996). It was hypothesized that this kind of analysis would provide a more detailed description regarding the transmission of information in the acoustic signal of speech.

Figure 8 shows the group mean percent correct identification scores for each phoneme position (initial consonant, vowel, and final consonant) for the 30 and 40 dB IIDR maps. A paired t-test using arcsine transformed values of the percent correct scores was performed on the vowels and initial and final consonants for the two maps for all subjects and revealed significantly higher initial consonant scores ($t = -7.714$, $p<.001$) as well as significantly higher final consonant scores ($t = -8.05$, $p<.001$) for the 40 compared to the 30 dB IIDR map. Vowels scores were not significantly different between the two maps. Specifically, the group mean scores for initial consonants were 32% and 41% with the 30 and 40 dB IIDR maps, respectively, and group mean scores for final consonants were 36% and 45% for the 30 and 40 dB IIDR maps, respectively. The significant improvement in performance for the consonants (whether initial or final) indicates that the 40 dB IIDR map provided better transmission than the 30 dB IIDR map of low amplitude consonant sounds whose production involves partial or complete obstruction of the airflow with a resulting drastic decrease in overall amplitude relative to vowel sounds.

However, the overall amplitude of consonant sounds can vary as a function of the relative degree of obstruction. Stops [p, b, t, d, k, g] are the weakest. Fricatives and affricates [f, v, th (unvoiced), th (voiced), s, z, sh, zh, ch, j] are next, while sonorant consonants [m, n, ng, l, r, y, w] are the consonants with the highest overall amplitude. The confusion matrices for initial and final consonants (see Appendix) were examined separately for each class of consonants in order to determine whether the use of the increased IIDR affected all consonant identification similarly with no regard to the overall amplitude level typically characteristic of each class. For initial consonants, the 40 dB IIDR map provided a 10% increase in the correct identification score for stops, an 8.2% increase for fricatives, and an 8.5% increase for sonorants relative to the 30 dB IIDR map. Thus, the benefit of using an increased IIDR was spread evenly across all three classes. For consonants

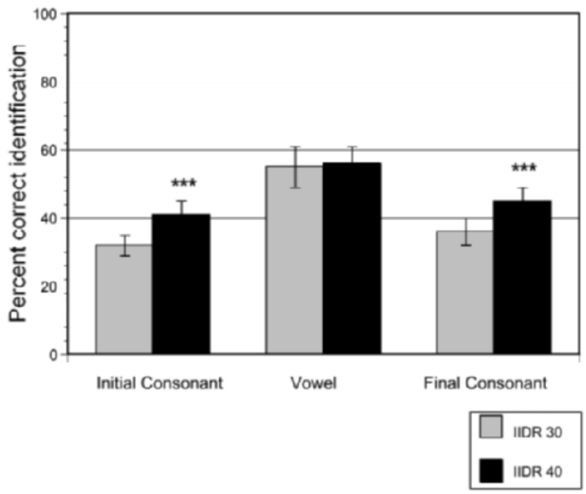


**Figure 8.** Group mean scores for initial consonants, medial vowels and final consonants within CNC words for the 30 and 40 dB IIDR maps. Asterisks denote significantly higher scores (*** = p<.001). Error bars represent ±1 SEM.

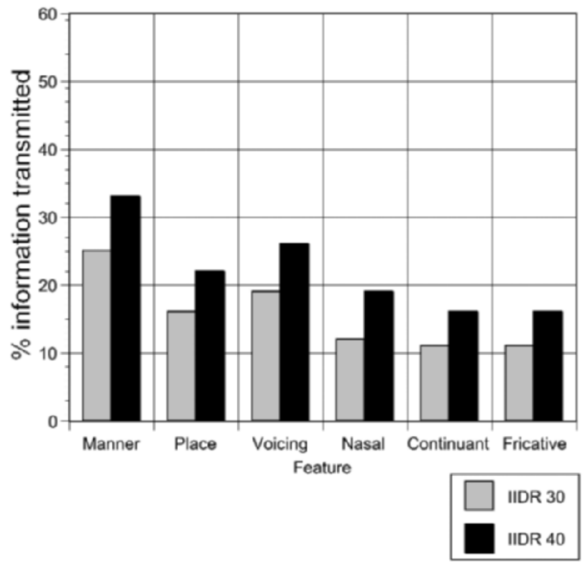


**Figure 9.** Group mean percent correct information transmitted for each consonant feature in the initial position within CNC words for the 30 and 40 dB IIDR maps.

in the final position, the 40 dB IIDR map provided a 7.8% and a 6.9% increase in correct identification of stops and sonorants and a 13.6% increase in the identification of fricatives relative to the 30 dB IIDR map. It is hypothesized that this uneven result was due to the fact that stops in the final position have very little, if any, energy, so the increased IIDR improved identification by a relatively small amount; whereas, sonorants have sufficient energy so that an increased IIDR may not be necessary for correct identification. The overall amplitude of fricatives falls between the overall amplitude of stops and sonorants; therefore, the increased IIDR improved the identification of fricatives by almost twice as much as the other two classes.

Information transmission analysis focused on initial and final consonants. Figure 9 shows the percent correct information transmitted for each consonant feature in the initial position. Scores are consistently higher for the 40 relative to the 30 dB IIDR map. The "manner" feature had the greatest improvement in percent information transmitted (8.5%) with the 40 compared to the 30 dB IIDR map. This feature distinguishes the different levels of airflow obstruction in the oral tract during consonant articulation (i.e. complete for stops and nasals, partial but severe for fricatives, and relatively free, although less so than for vowels, for [l, r, y, w]), and therefore, affects the amount of energy present in the signal. Figure 10 shows the percent correct information transmitted for each consonant feature in the final position. Scores are also consistently higher in this position with the 40 relative to the 30 dB IIDR map. The "fricative" feature, which distinguishes all sounds with high frequency noise (fricatives and affricates) from all others, had the greatest improvement in percent information transmitted (about 15%). This result from information transmission analysis agrees with the difference in overall percent correct identification between the two maps for fricatives in the final position (13.6% in favor of the 40 dB IIDR map).

Examination of the individual CNC word scores revealed that subjects could be divided into two groups on the basis of their scores. For the higher performers (S1, S5, S6, S8, S9) the mean word score averaged across the two maps was 23% (standard deviation [SD] = 7.3) while for the lower performers (S2, S3, S4, S7, S10) the same score was 7.2% (SD = 3.2). This difference in performance was spread across sound type and position regardless of the IIDR used. Initial consonant scores were 45% correct for the higher performers and 27% correct for the lower performers. The information transmission analysis revealed that the use of the 40 dB IIDR map aided higher performers in the recognition of initial consonants just slightly more than it aided lower performers (about a 2% difference in improvement across all initial consonant features). Final consonant scores were 49% correct for the higher performers and 30% correct for the lower performers. Information transmission analysis showed that the use of the 40 dB IIDR map aided both groups equally for all final consonant features except the "fricative" feature. For the higher performers this feature had

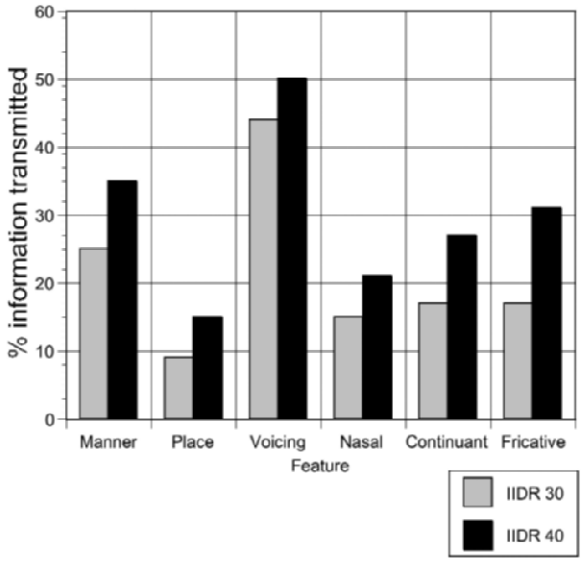


**Figure 10.** Group mean percent correct information transmitted for each consonant feature in the final position within CNC words for the 30 and 40 dB IIDR maps.

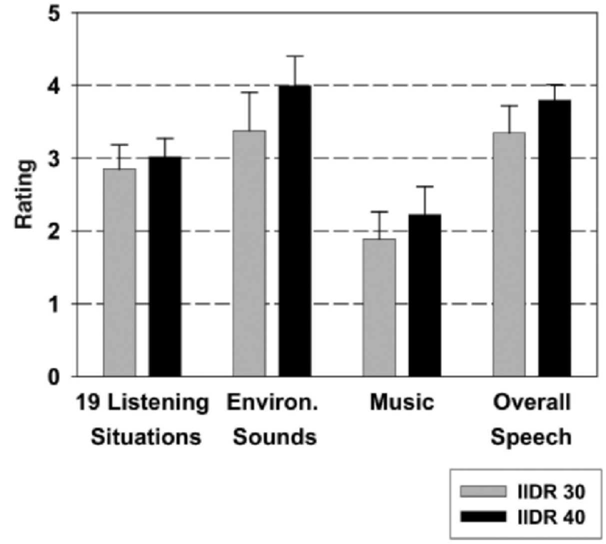


**Figure 11.** Group mean ratings across the 19 listening situations as well as group mean ratings for environmental sounds, enjoyment of music, and overall speech understanding for the 30 and 40 dB IIDR maps. Error bars represent 1 SEM.

a 17.6% improvement when using the 40 relative to 30 dB IIDR map while for the lower performers the improvement was 11.3%.

The greatest difference between the two groups was in vowel identification. The group mean vowel identification score, averaged across the two IIDR maps, for the higher performers was 69.5% and 40.5% for the lower performers. There were no significant differences in the percent correct information transmitted for any vowel feature between the two maps for either group. The first and second formants (F1 and F2) distinguish vowels in terms of height (high, mid, low) and frontness (front, back), respectively. For the lower performers the average percent correct transmission of the F1 feature was 18% while for the higher performers it was 43.3%. For the lower performers the average percent correct transmission of the F2 feature was 29.5% while for the higher performers it was 68%. Considering that most of the energy in vowel sounds lies in the F1 and F2 frequency ranges, this indicates a problem for the lower performers which cannot be resolved through the use of a wider IIDR.

### Questionnaire

Figure 11 shows group mean ratings averaged across the 19 listening situations listed on the questionnaire for both maps. Group mean ratings for questions regarding detection of environmental sound, enjoyment of music and overall speech understanding are also shown for each map. Paired t-tests revealed no significant difference in ratings between the two maps. Seven subjects (S2, S3, S4, S5, S7, S8, S10) rated the 40 dB IIDR map highest for overall speech understanding. Subjects 1 and 6 rated both maps the same for overall speech understanding, and S9 rated the 30 dB IIDR map highest for overall speech understanding. Subject 2 was the only subject who expressed a strong preference for either map. She gave the 40 dB IIDR map a rating of 4 and the 30 dB IIDR map a rating of 1 for overall speech understanding. Oddly enough, S2 originally reported background sound to be loud with the 40 dB IIDR map; therefore, minimum stimulation levels for all electrodes were set slightly below counted levels for the 40 dB IIDR map.

## DISCUSSION

Sound field threshold levels from 250-6000 Hz need to fall below 30 dB HL for CI users to be able to perceive soft speech (Skinner et al, 2002a). To ensure that sound field levels fell below 30 dB HL across the frequency range for all ten Freedom CI users participating in this study, manipulation of minimum stimulation levels was necessary with the 30 dB IIDR map. This additional step in mapping was time consuming; however, an AI of .75 was achieved making most speech cues audible for these subjects. For maps with an IIDR of 40 dB and minimum stimulation levels set at counted levels, sound field thresholds levels for this group of subjects consistently fell well below 30 dB HL and provided an AI of .97 (Figure 2) making almost all speech cues audible. The results of speech perception testing are consistent with the AI being higher with the 40 compared to the 30 dB IIDR map. For easier listening tasks such as HINT sentences in quiet, both maps provided enough audible speech cues so little difference in scores was seen between the maps even at a soft presentation level; however, when more difficult listening situations were encountered (e.g. CNC words and CUNY sentences in noise), the 40 dB IIDR map provided the subjects with the additional speech cues necessary for better speech perception compared to the 30 dB IIDR map. The small but significant improvement to speech perception in noise as demonstrated by the CUNY sentence results demonstrate that the ability to detect softer sound with the 40 compared to the 30 dB IIDR map was not detrimental to speech perception in background noise. Therefore, the soft speech cues made available with an increased IIDR are not all masked by background sound and many CI users will be able to take advantage of these additional cues for better speech perception in difficult listening situations.

These results are consistent with previous research studies that have shown better speech perception with a wider IDR (Consendai and Pelizone, 2001; Zeng et al, 2002; Donaldson and Allen, 2003). The significantly higher scores for sentences in babble with the 40 compared to the 30 dB IIDR map were a bit surprising given that James et al (2003) found lower group mean scores for sentences in babble when the IIDR of the Nucleus 24 CI system was increased by lowering the base level. Differences in subjects' sensitivity control settings between the two studies may have contributed to the disparity between results. In the James et al (2003) study, subjects used a sensitivity control setting of either 8 or 15 on their SPrint™ processors. The choice of these two sensitivity settings was controlled by Part 1 of the study. In the present study, maps were created and sensitivity control settings were selected to ensure that soft sound was audible and that loud sound was comfortable in everyday life for each subject. In addition, the higher scores in the present study may be related to improved front-end processing in the Freedom speech processor. The results of the present study for sentences presented in babble are also in contrast to the results found by McDermott et al (2002). When using syllabic input compression, the subjects in that study needed higher SNRs to maintain their sentence scores in noise at 70% of their scores in quiet. Subjects in the McDermott study reported that background sound with input compression was at times too loud and three of the subjects stated that they would like to be able to turn off the input compression in certain situations. Of the ten subjects in the present study, only S2 reported that background sound was too loud with an early 40 dB IIDR map; therefore, map minimum stimulation levels for each electrode were lowered by 5 CLs from counted levels to make background sound comfortable for S2 with the 40 dB IIDR map. At the conclusion of the study, S2 had a strong preference for the 40 compared to the 30 dB IIDR map. Subjects in the present study had used both the 30 and 40 IIDR maps since the initial activation of the Freedom CI and as noted above, both maps were created so that soft speech and sound were audible and loud sound was comfortable. In addition, the subjects were counseled on the importance of hearing sound that they may not have heard for a long time (e.g. creak in the floor board) to their ability to understand speech in everyday life. Consequently, the subjects in the present study may have been better able to adjust and tolerate background sound than those in the earlier study.

The majority of subjects in this study reported an improvement in their detection of soft sound and their understanding of soft speech in all situations with the 40 compared to the 30 dB IIDR map. One example of improved speech perception in a difficult listening situation was provided by S4 who is a counselor by profession. Subject 4 had used both maps during a counseling session with a client who had a speech impediment, spoke softly and was crying through much of the session. He reported that with the 40 dB IIDR map, he was able to understand what the client said fairly easily; however, when he switched to the 30 dB IIDR map, he noticed an immediate difference. He had to ask his client to repeat several times and the words seemed fuzzy and less distinct. With the 40 dB IIDR map, he reported that he could concentrate on what the client was saying and with the 30 dB IIDR map he had to focus on whether or not he could hear what was said.

Based on the results of this study, it is recommended that Freedom CI users be mapped with an IIDR of 40 dB for use in both quiet and noise. Minimum stimulation levels for all electrodes should be set at a counted level. If a streamlined programming approach is needed, obtaining counted levels on every third electrode and then interpolating across electrodes is advisable. Maximum stimulation levels may be set in live-voice mode and then balanced for equal loudness across electrodes. The CI user should report that speech is between medium and medium loud with a volume control setting of 6-9 and a sensitivity control setting of 12. During the first few weeks after initial activation, volume and sensitivity control settings may need to be gradually increased to allow new users time to become accustomed to hearing speech and sound that they have not heard in a long time, if ever. This may be the case as well for Nucleus 24 CI users who are upgrading to the Freedom processor. These users will be used to listening with an IIDR of 30 dB. The Freedom processor with an increased IIDR of 40 dB may provide better perception of soft speech and detection of sound; however, hearing this soft speech and sound may be annoying at first. CI users will need to be counseled on the importance of hearing soft speech and sound to optimize their ability to understand speech in a variety of listening situations. In this study, neither the "Whisper" or ADRO settings were used by subjects in combination with either of the maps. These processing schemes do, however, have the potential to provide further enhancement to the perception of soft speech and the detection of sound for Nucleus CI users. Based on the results of McDermott et al (2002) and James et al (2002), ADRO may be the better processing scheme to use in conjunction with an increased IIDR when CI users are listening in noisy situations. However, providing CI users with basic guidelines and then letting them try both processing schemes in a variety of different listening situations seems prudent.

**Acknowledgments.** This research was supported by Grant RO1 DC000581 from the National Institute on Deafness and Other Communication Disorders. Appreciation is expressed to our ten subjects who graciously gave their time and effort to participate in this study, to Christine Brenner who helped with data analysis as well as to Lisa Davidson, Karen Mispagel and an anonymous reviewer for their insightful critiques of earlier drafts of this paper. This research was approved by the Human Studies Committee at Washington University School of Medicine (#05-0299).

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**Appendix. Group confusion matrices for the initial and final consonants within CNC words using the 30 and 40 IIDR maps.**

Initial Consonants

a) IIDR 30

| STIMULUS | P | B | T | D | K | G | F | V | TU | TV | S | Z | SH | CH | J | H | M | N | W | Y | L | R | - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | **23** | 91 | 2 | | 3 | 2 | 18 | 2 | | | 2 | | | | | 31 | 11 | 5 | 5 | | 4 | 1 | 32 |
| B | 4 | **130** | | 2 | | 3 | 10 | | 3 | 1 | 1 | | | | | 25 | 9 | 1 | 16 | | 3 | 4 | 23 |
| T | 12 | 63 | **14** | 6 | 6 | 4 | 18 | 2 | 1 | 1 | 2 | | 1 | | | 44 | 8 | 4 | 1 | 2 | 5 | 2 | 44 |
| D | 2 | 52 | 3 | **69** | 1 | 15 | 10 | | 1 | 2 | | | | | 1 | 18 | 7 | 9 | | 9 | 11 | 3 | 27 |
| K | 21 | 62 | 2 | 6 | **48** | 3 | 15 | 1 | | 1 | 3 | 1 | | | | 36 | 9 | 3 | 1 | 1 | 5 | | 22 |
| G | 1 | 30 | | 18 | 5 | **42** | 6 | 1 | | | 2 | | | | | 15 | 7 | 4 | 3 | 3 | 4 | 1 | 18 |
| F | 13 | 64 | | 6 | 1 | 2 | **19** | 1 | 3 | | 2 | | | | | 6 | 7 | | 8 | | 4 | 3 | 21 |
| V | 4 | 26 | | 1 | | 2 | 6 | **1** | | 3 | | | | | | 5 | 4 | 3 | 14 | 1 | 3 | 5 | 7 |
| TU | 1 | 43 | | 2 | | 1 | 6 | | **2** | | | | | | | 8 | 1 | 1 | 3 | 1 | 4 | 3 | 4 |
| TV | | | | | | | | | | | | | | | | | | | | | | | |
| S | 3 | 5 | 10 | | 6 | 1 | 21 | | 3 | 1 | **141** | | 35 | 7 | | 4 | | | | | 2 | 1 | |
| Z | | | | | | | | | | | | | | | | | | | | | | | |
| SH | 3 | 1 | 11 | | 1 | 2 | 9 | | 2 | | 18 | | **59** | 34 | 1 | 9 | 1 | | 1 | 1 | 1 | 4 | 2 |
| CH | 1 | 1 | 49 | 1 | 8 | 2 | 3 | | | | 3 | | 7 | **64** | 8 | 2 | | 1 | | | 1 | 8 | 1 |
| J | | 6 | 5 | 39 | 5 | 32 | 3 | | | | | | 1 | 7 | **36** | 9 | 2 | 2 | | 5 | 1 | 3 | 4 |
| H | 11 | 87 | 1 | 4 | 1 | 3 | 17 | 2 | 1 | | 1 | | | | 1 | **45** | 7 | | 5 | | 8 | 6 | 40 |
| M | 6 | 39 | 1 | 2 | 1 | 5 | 8 | 1 | | | 2 | | | | | 20 | **58** | 22 | 25 | 3 | 19 | 7 | 16 |
| N | | 7 | | 10 | 2 | 7 | | 1 | | 1 | | | | | 1 | 6 | 9 | **67** | 14 | 9 | 19 | 3 | 4 |
| W | | 7 | | 1 | | | 2 | | | | | | | | 1 | 2 | 7 | 1 | **143** | | 38 | 33 | 5 |
| Y | | 1 | 1 | 12 | 3 | 6 | | | | | | | 2 | | 6 | 6 | 1 | 3 | 1 | **32** | 3 | 2 | 1 |
| L | 3 | 14 | | 2 | 1 | 3 | 4 | 1 | | | 1 | | | | | 8 | 64 | 12 | 47 | 1 | **139** | 16 | 9 |
| R | 1 | 10 | 1 | | | 5 | 2 | 1 | | | | | | | | 9 | 23 | 15 | 55 | 2 | 60 | **139** | 5 |

b) IIDR 40

| STIMULUS | P | B | T | D | K | G | F | V | TU | TV | S | Z | SH | CH | J | H | M | N | W | Y | L | R | - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | **28** | 88 | 1 | 3 | 10 | 5 | 28 | 1 | | | 1 | | | 1 | | 33 | 10 | 5 | 5 | | 2 | 1 | 16 |
| B | 9 | **143** | | 2 | 1 | 5 | 16 | | | | | | | | | 16 | 11 | 2 | 10 | 1 | 1 | 1 | 17 |
| T | 26 | 35 | **50** | 5 | 13 | 6 | 26 | 1 | 1 | 2 | 4 | | 1 | 4 | 2 | 37 | 8 | 3 | 1 | 1 | 4 | 1 | 9 |
| D | 2 | 48 | 2 | **93** | 4 | 8 | 12 | 3 | 1 | 1 | 1 | | | | 5 | 15 | 4 | 6 | | 4 | 11 | 2 | 18 |
| K | 28 | 26 | 5 | 2 | **86** | 4 | 9 | | 1 | | 1 | | 2 | 3 | | 43 | 6 | 2 | 3 | 1 | 5 | 4 | 9 |
| G | 3 | 25 | 2 | 17 | 5 | **54** | 2 | 1 | 1 | | | | | | 2 | 11 | 3 | 5 | 3 | 3 | 3 | 1 | 19 |
| F | 6 | 90 | 1 | 2 | | 1 | **21** | | 1 | 2 | | | | | | 6 | 4 | 1 | 4 | | 1 | | 20 |
| V | 1 | 26 | | | | | 9 | **11** | | | | | | | | 5 | 6 | 7 | 7 | | 4 | 2 | 7 |
| TU | 5 | 52 | | | 1 | 1 | 4 | 1 | **2** | 1 | | | | | | 6 | 4 | | | | 2 | | 1 |
| TV | | | | | | | | | | | | | | | | | | | | | | | |
| S | | | 1 | | | | 8 | | 2 | | **176** | | 40 | 9 | | | | | 1 | | 1 | 1 | 1 |
| Z | | | | | | | | | | | | | | | | | | | | | | | |
| SH | | | 4 | 1 | 3 | | 6 | | | 1 | 37 | | **83** | 16 | 4 | | | | | | 1 | 4 | |
| CH | | 1 | 44 | | 2 | | | | | | 4 | | 8 | **82** | 11 | 1 | | | | | | 6 | 1 |
| J | | | 9 | 30 | 2 | 20 | 1 | | | | 2 | | 1 | 4 | **78** | 3 | | 2 | 1 | 1 | 1 | 2 | 3 |
| H | 10 | 83 | 1 | 6 | 2 | 5 | 17 | | | | 1 | | | | | **43** | 14 | 7 | 4 | | 6 | 3 | 38 |
| M | 2 | 15 | 1 | 4 | | 3 | 10 | | | | | | | | | 15 | **66** | 31 | 29 | 2 | 31 | 12 | 14 |
| N | | 3 | | 14 | 1 | 5 | | | | | 1 | | | | 1 | 3 | 15 | **78** | 3 | 6 | 17 | 4 | 9 |
| W | | 5 | | 1 | | 1 | | | | | | | | | | 4 | 10 | | **161** | | 32 | 24 | 2 |
| Y | 1 | 3 | | 5 | | 6 | | 1 | | | | | | | 6 | 4 | 2 | 4 | | **41** | 4 | 3 | |
| L | 4 | 5 | 2 | 1 | | 2 | 1 | | 1 | | | | | | | 6 | 42 | 10 | 68 | 4 | **160** | 14 | 5 |
| R | | 9 | 1 | | 2 | | 1 | 1 | | | 2 | | | | | 4 | 11 | 1 | 66 | | 41 | **177** | 6 |

Final Consonants

a) IIDR 30

| STIMULUS | P | B | T | D | K | G | F | V | TU | TV | S | Z | SH | ZH | CH | J | M | N | NG | L | ER | - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | **59** | 3 | 92 | | 35 | 4 | 10 | 2 | 1 | | 3 | | 1 | | 1 | | 5 | 14 | 1 | 5 | | 9 |
| B | 9 | **6** | 7 | 3 | 3 | 1 | 5 | 6 | | | 1 | 1 | | | | | 8 | 12 | 1 | 8 | 4 | 5 |
| T | 46 | 3 | **195** | 6 | 110 | 4 | 20 | 8 | 9 | | 4 | | 1 | | 3 | | 11 | 26 | 4 | 3 | 7 | 15 |
| D | 4 | 3 | 17 | **69** | 8 | 7 | 1 | 21 | | | 3 | 5 | | | | | 25 | 61 | 3 | 22 | 24 | 46 |
| K | 20 | | 70 | 4 | **158** | 3 | 17 | 3 | 2 | | 3 | | | | 1 | | 4 | 17 | 2 | 6 | 1 | 9 |
| G | 2 | | 22 | 6 | 17 | **40** | 5 | 6 | 2 | | 1 | 2 | | | | | 10 | 20 | 5 | 8 | 2 | 12 |
| F | 31 | 1 | 35 | 2 | 28 | | **21** | 2 | 6 | 1 | 1 | 1 | | | | | 9 | 10 | 1 | 3 | 3 | 4 |
| V | | | 2 | 8 | 3 | 1 | 2 | **13** | 1 | | | 1 | | | | | 12 | 12 | 4 | 6 | 8 | 7 |
| TU | 9 | 1 | 34 | 3 | 7 | 3 | 3 | 2 | **1** | | | | 1 | | | | 3 | 7 | | 2 | | 4 |
| TV | | | | | | | | | | | | | | | | | | | | | | |
| S | | | 12 | 1 | 6 | 1 | 9 | 2 | 7 | | **151** | 2 | 34 | | 5 | 1 | | | | 1 | | 3 |
| Z | 1 | | 3 | 3 | 6 | 4 | | 5 | 1 | 1 | 9 | **73** | | | 1 | 7 | 9 | 17 | | 9 | 5 | 11 |
| SH | 2 | 1 | 5 | | 6 | | 8 | 2 | | | 11 | | **32** | | 8 | | | 1 | | | 1 | 3 |
| ZH | | | | | | | | | | | | | | | | | | | | | | |
| CH | 1 | 1 | 60 | 3 | 26 | 1 | 7 | | 3 | | 3 | | 3 | | **42** | 1 | | 7 | | | | 2 |
| J | | | 11 | 11 | 8 | 4 | 5 | 4 | | 2 | | 1 | | | 5 | **13** | | 9 | 1 | 1 | | 5 |
| M | 1 | 3 | 7 | 15 | 1 | 2 | 5 | 12 | 2 | 3 | 1 | 4 | | | 1 | | **51** | 57 | 8 | 16 | 16 | 35 |
| N | 2 | | 13 | 17 | 14 | 5 | 1 | 17 | 3 | 2 | 3 | 5 | 1 | | 1 | 2 | 42 | **145** | 11 | 30 | 29 | 57 |
| NG | | | 5 | 2 | 3 | 4 | 3 | 2 | 1 | | 1 | | | | | | 16 | 16 | **14** | 5 | 4 | 4 |
| L | | 1 | 4 | 5 | 4 | 1 | | 8 | | | | 3 | | | | | 21 | 40 | 6 | **240** | 27 | 39 |
| ER | | | 2 | 6 | 4 | | | 13 | | | | | | | | | 6 | 28 | 1 | 45 | **126** | 9 |

b) IIDR 40

| STIMULUS | P | B | T | D | K | G | F | V | TU | TV | S | Z | SH | ZH | CH | J | M | N | NG | L | ER | - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | **72** | | 76 | 2 | 42 | 3 | 16 | 1 | | | 2 | | | | 3 | | 8 | 8 | 1 | 5 | 2 | 4 |
| B | 2 | **14** | 5 | 10 | 7 | 1 | 3 | 5 | 1 | | | 2 | | | | | 7 | 4 | 2 | 6 | 4 | 7 |
| T | 49 | 4 | **209** | 6 | 108 | 8 | 12 | 2 | 2 | | 6 | | 1 | | 3 | | 11 | 28 | 1 | 7 | 5 | 13 |
| D | 1 | 3 | 11 | **102** | 8 | 18 | 3 | 16 | 3 | 2 | 1 | 3 | | | | 2 | 18 | 72 | 3 | 17 | 7 | 30 |
| K | 32 | 4 | 41 | | **194** | 2 | 9 | 1 | 1 | | 2 | | | | 3 | | 5 | 8 | 2 | 7 | 1 | 8 |
| G | 5 | 1 | 18 | 12 | 27 | **45** | 1 | 5 | 1 | | | | | | | | 8 | 15 | 3 | 11 | 2 | 6 |
| F | 11 | 2 | 38 | 2 | 28 | 1 | **43** | 1 | 2 | 1 | 3 | | | | 1 | | 10 | 2 | 1 | 2 | 2 | 10 |
| V | | | 1 | 7 | 1 | | | **19** | | 1 | | | | | | | 14 | 13 | 1 | 4 | 8 | 11 |
| TU | 8 | | 17 | 4 | 12 | | 2 | 2 | **9** | | 2 | | | | 1 | | 5 | 7 | 1 | 2 | 2 | 6 |
| TV | | | | | | | | | | | | | | | | | | | | | | |
| S | | | 1 | | 2 | | 2 | | 1 | | **168** | 3 | 51 | | 7 | | | | | | | |
| Z | 1 | 1 | | 2 | 1 | 3 | | 8 | | | 15 | **95** | 3 | | 2 | 14 | 3 | 10 | | 1 | 1 | 5 |
| SH | | | 4 | | 1 | | 11 | 3 | | | 13 | 3 | **40** | | 3 | | | | | 1 | | 1 |
| ZH | | | | | | | | | | | | | | | | | | | | | | |
| CH | 2 | | 42 | 2 | 13 | | | | | | 3 | | 4 | | **85** | 3 | | 2 | | 1 | | 3 |
| J | | | 8 | 8 | 4 | 1 | 1 | 6 | | 1 | | 3 | | | 11 | **23** | 3 | 8 | | 1 | | 2 |
| M | 1 | 2 | 2 | 10 | 3 | 2 | 3 | 12 | 2 | 3 | | 3 | | | 1 | 1 | **75** | 61 | 4 | 25 | 8 | 22 |
| N | 1 | 3 | 9 | 23 | 8 | 2 | 1 | 18 | | 1 | 2 | 3 | | | | | 48 | **184** | 14 | 22 | 25 | 36 |
| NG | | | 1 | 3 | 6 | 3 | 3 | | | | | | 1 | | | | 8 | 21 | **18** | 7 | 2 | 7 |
| L | | 2 | 1 | 4 | 2 | 1 | | 7 | | | 1 | 2 | | | | | 28 | 42 | 2 | **253** | 17 | 38 |
| ER | | | | 2 | | | | 6 | 1 | | | | | | | | 5 | 18 | 1 | 60 | **135** | 12 |