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The Effect of Instantaneous Input Dynamic Range Setting on the Speech Perception of Children with the Nucleus 24 Implant

Lisa S. Davidson[1], **Margaret W. Skinner**[1], **Beth A. Holstad**[2], **Beverly T. Fears**[3], **Marie K. Richter**[4], **Margaret Matusofsky**[4], **Christine Brenner**[2], **Timothy Holden**[1], **Amy Birath**[2], **Jerrica L. Kettel**[4], **Susan Scollie**[5]

[1]Department of Otolaryngology-Head and Neck Surgery, Washington University School of Medicine, St. Louis, Missouri

[2]Department of Audiology, The Moog Center for Deaf Education, St. Louis, Missouri

[3]St. Joseph Institute for the Deaf, St. Louis, Missouri

[4]Department of Audiology, Central Institute for the Deaf, St. Louis, Missouri

[5]School of Communication Sciences and Disorders, University of Western Ontario, Ontario, Canada

Abstract

Objective—The purpose of this study was to examine the effects of a wider instantaneous input dynamic range (IIDR) setting on speech perception and comfort in quiet and noise for children wearing the Nucleus 24™ implant system and the Freedom™ speech processor. In addition, children's ability to understand soft and conversational level speech in relation to aided sound-field thresholds was examined.

Design—Thirty children (age, 7 to 17 years) with the Nucleus 24 cochlear implant system and the Feedom speech processor with two different IIDR settings (30 versus 40 dB) were tested on the Consonant Nucleus Consonant (CNC) word test at 50 and 60 dB SPL, the Bamford-Kowal-Bench Speech in Noise Test, and a loudness rating task for four-talker speech noise. Aided thresholds for frequency-modulated tones, narrowband noise, and recorded Ling sounds were obtained with the two IIDRs and examined in relation to CNC scores at 50 dB SPL. Speech Intelligibility Indices were calculated using the long-term average speech spectrum of the CNC words at 50 dB SPL measured at each test site and aided thresholds.

Results—Group mean CNC scores at 50 dB SPL with the 40 IIDR were significantly higher ($p < 0.001$) than with the 30 IIDR. Group mean CNC scores at 60 dB SPL, loudness ratings, and the signal to noise ratios-50 for Bamford-Kowal-Bench Speech in Noise Test were not significantly different for the two IIDRs. Significantly improved aided thresholds at 250 to 6000 Hz as well as

Address for correspondence: Lisa S. Davidson, PhD, Washington University School of Medicine, 4560 Clayton Avenue, St. Louis, MO 63110. davidsonl@ent.wustl.edu.

REFERENCE NOTE
1. Bass-Ringdahl, S. (2002). The relationship of audibility and the development of canonical babbling in young children with hearing impairment. Unpublished doctoral dissertation, the University of Iowa - Iowa City.

higher Speech Intelligibility Indices afforded improved audibility for speech presented at soft levels (50 dB SPL).

Conclusion—These results indicate that an increased IIDR provides improved word recognition for soft levels of speech without compromising comfort of higher levels of speech sounds or sentence recognition in noise.

INTRODUCTION

The fitting goals for cochlear implants are no different from those for hearing aids in that the processor should be adjusted to provide audibility and comfort for a variety of input levels from soft to loud in a variety of listening environments. Therefore, audiologists must select speech processor map parameters that provide access to the intensity, spectral, and timing cues of sound that occur at the child's implant microphone, i.e., very soft to very loud sounds that include all of the spectrum from about 200 to 7000 Hz. The end result of these fittings should be that very soft sounds are recognizable; very loud sounds tolerable; average conversational speech comfortable; and speech spoken at many levels and distances in everyday situations understandable for children. Achieving optimal audibility for young children is essential given that they are active and passive listeners and language learners in a variety of auditory environments throughout the day (Bess et al. 1998; Flexer 1999).

The critical role of audibility is reflected in articulation theory, initially developed by French and Steinberg (1947), to predict the amount of information transmitted through different telecommunication devices for individuals with normal hearing sensitivity. The basic premise of this theory is that speech energy from 180 to 8000 Hz should be sufficiently above threshold to be maximally intelligible. The Speech Intelligibility Index (SII; American National Standards Institute [ANSI] S3.5 1997) has been used to predict the intelligibility of speech, given frequency-specific levels in $\frac{1}{3}$-octave bands across the speech spectrum. A calculated value of 1 indicates complete audibility, and a value of 0 indicates no audibility. This concept has been used by audiologists to predict speech intelligibility in unaided and aided listening conditions and in fitting and adjusting hearing aids (Amlani et al. 2002; Studebaker & Sherbecoe 1993). The basic procedure for calculating these indices involves comparing the peak levels of the speech stimulus with audiometric thresholds to determine band-specific sensation levels for speech and also for maskers. Audibility, as quantified by the sensation levels as a proportion of 30 dB, is then summed across bands to derive the overall audibility index. Based on articulation theory, hearing aid fitting methods predict that aided thresholds across the frequency range from 250 to 6000 Hz, which approximate 20 to 30 dB HL, provide the best opportunity to hear the acoustic cues of soft speech (Humes et al. 1986; Mueller & Killion 1990; Pavlovic 1986; Pavlovic et al. 19851).

Studies by Skinner et al. (1997, 1999) demonstrated the utility of using sound-field thresholds as a guide for fitting cochlear implant processors and verifying the audibility, intelligibility, and comfort of speech at levels ranging from soft to loud. Specifically, aided sound-field thresholds are used to determine the minimum audibility of speech provided to cochlear implant recipients. If aided thresholds are higher than the target of 20 to 30 dB HL, then adjustments in the map parameters are made in an attempt to achieve this target. More recently, Firszt et al. (2004) investigated the speech recognition abilities of 78 adult implant patients using three cochlear implant systems at three different presentation levels in quiet and in noise. Frequency-modulated (FM) tones were used to determine the sound-field threshold levels from 250 to 4000 Hz. Aided sound-field thresholds were inversely related ($p < 0.01$) to scores on the Consonant-Nucleus-Consonant (CNC) monosyllabic word test (Peterson & Lehiste 1962) and the Hearing in Noise test sentences (Nilsson et al. 1994) administered at 50 and 60 dB SPL. Scores on the Hearing in Noise test at +8 dB SNR were correlated ($p < 0.05$) with aided sound-field thresholds. James et al. (2003) evaluated the effects of increasing the microphone input sensitivity on aided sound-field thresholds for 12 adults using the Nucleus 24 SPrint™ cochlear implant processor. Increasing the microphone sensitivity by 10.5 dB lowered (improved) the thresholds by the same amount and significantly improved the perception of consonants and vowels presented at 40 and 55 dB SPL. In a study of infants by Bass-Ringdahl (Reference Note 1), the SII was used to measure the audibility of speech using a hearing aid before implantation and a cochlear implant after implantation. SII values were calculated for both the hearing aid and cochlear implant conditions using the ANSI 1997 standard (ANSI S3.5—1997). The preimplant SII values were calculated using the child's unaided thresholds, real ear insertion gain measured with the child’s hearing aid and $\frac{1}{3}$ octave band sound pressure levels for long-term average speech spectrum levels from the Situational Hearing Aid Response Profile software (Stelmachowicz et al. 1994). SII values with the cochlear implant were calculated by substituting the child’s aided sound-field thresholds obtained with the cochlear implant for the unaided thresholds and using the levels of unaided speech when quantifying audibility. The author found that earlier ages of canonical babble onset were related to greater audibility of the speech signal as measured by the SII. In summary, the better the sound-field thresholds are, the more likely it is that the cues of speech from soft to loud will be audible to the implant recipient.

The range of acoustic input levels that are mapped onto the cochlear implant user’s electrical dynamic range are commonly referred to as the input dynamic range. The subject’s electrical dynamic range is defined as the difference in clinical units from threshold to maximum comfortable loudness level (T and C levels) on individual electrodes. This input dynamic range (IDR) varies across implant systems and can range from approximately 30 to 80 dB. In general, studies have shown that an IDR wider than 30 dB is needed in cochlear implant systems for optimal speech recognition (Cosendai & Pelizzone 2001; Wilson et al. 1991; Zeng et al. 2002). Specifically, perception of soft-speech levels has been shown to improve with wider IDRs. Donaldson and Allen (2003) evaluated the speech perception abilities of recipients of the Nucleus 22 cochlear implant system (N = 7) and recipients of the Clarion vl.2 system (N = 7). Speech recognition was assessed across a range of presentation levels that varied from soft to loud (i.e., 30, 40, 50, 60, 70 dB SPL). The Nucleus recipients demonstrated higher (poorer) aided thresholds and lower scores for consonants, vowels, and sentences at the softest presentation levels compared with recipients with the Clarion system. These differences were attributed primarily to the fact that the I DR for this particular Nucleus System was 30 dB, whereas the IDR for the Clarion system was 60 dB.

The Freedom™ Cochlear Implant System, the most recent Nucleus system, has an instantaneous IDR (IIDR) that can be increased to 45 dB; however, the manufacturer recommends a default setting of 40 dB. Note that although the other studies above use the term IDR in referring to the range of frequencies that are mapped onto the cochlear implant user's electrical dynamic range, the Nucleus system uses the term IIDR. The new IIDR is increased from past, commercially available Nucleus cochlear implant systems that had an IIDR of approximately 30 dB. A study by James et al. (2003) found that although an increased IIDR on the SPrint processor with the Nucleus 24 system resulted in improved perception of consonants presented at soft levels (i.e., 40 dB SPL), perception of sentences at 65 dB SPL in multitalker background noise was poorer. Dawson et al. (2007) compared IIDRs of 31,46, and 56 dB in a Nucleus research processor with nine adult implant recipients using the Nucleus 24 implant system. Two different programs were used for each expanded IIDR program. One program used T and C levels obtained on each electrode using standard clinical procedures; i.e., T levels were set at 100% detection and C levels were set at a maximum comfortable loudness level. The other program used reduced T levels to reduce the loudness of low-level signals. Subjects were given two 2-week take-home periods with each of the three IIDRs with a single IIDR used during each trial period. Speech perception testing was conducted after each trial period. The CNC word test (Peterson & Lehiste 1962) was conducted in quiet at two levels (45 and 55 dB SPL, root mean square [RMS]), and the City University of New York sentences were presented at individually determined signal to noise ratio (SNR) using multitalker babble. The results revealed improvements in CNC scores at soft speech levels (45 and 55 dB SPL) with the 46 and 56 IIDRs compared with the 31 IIDR, although no significant differences were seen between the 46 and 56 IIDRs. No decrement in speech in noise scores was seen with the wider IIDRs. Although the benefits were greater for the standard programs compared with the reduced T-level programs, two subjects indicated that they would be unable to tolerate the standard program with the wider IIDRs for an extended period of time. Holden et al. (2007) determined that 10 adult subjects with the new, commercially available Nucleus Freedom cochlear implant system demonstrated improved sound-field thresholds and recognition of soft speech using a map with an IIDR of 40 dB compared with 30 dB. Word recognition scores in quiet (50 dB SPL), sentence recognition scores in multitalker babble (speech at 65 dB SPL, SNRs ranging from 10 to 20 dB), and aided sound-field thresholds were improved with the 40 dB versus the 30 dB IIDR. In addition, most subjects preferred the IIDR of 40 dB. They concluded that the increased IIDR of 40 dB provided better detection of soft speech and sound with no detriment to understand speech in noise at relatively high levels.

Although these studies support the use of the extended IIDR for the Freedom processor for adults, no such studies have been conducted on children. The benefit of the extended IIDR for recognition of soft speech for children is especially important for incidental language learning, self-monitoring of speech, and ease of communication. However, children may be more susceptible than adults to issues of added noise and comfort related to an extended IIDR. Given that children require a greater SNR than adults (Elliot 1979; Nabelek & Robinson 1982), added low-level signals allowed by a wider IIDR may create greater difficulties for speech understanding in noise. In addition, the children in this study had T and C levels set for the 30 dB IIDR Nucleus system according to protocols established at the Washington University (Holstad et al. 2009; James et al. 2003; Potts et al. 2007; Skinner et al. 1999). That is, T levels were increased above 100% detection to achieve aided sound-field thresholds of 30 dB HL or better, and the C levels were often decreased globally to avoid speech and noise becoming uncomfortably loud. This mapping technique reduced the electrical dynamic range; however, it improved aided thresholds and perception of low-level inputs and addressed reported problems of comfort of higher level sounds in quiet and noise. Recall that two of the adults in the study of Dawson et al. (2007) reported tolerance problems with the wider IIDR and standard maps where T levels were set at 100% detection. The children in this study had T levels above 100% detection, and no changes were made to the T and C levels when the maps were converted from 30 to 40 dB IIDR. Although it is the case that the Nucleus system maps the top 10 dB of the speech signal to the same current levels for both the 30 and 40 dB IIDR, the added low-level inputs allowed by the expanded IIDR would be mapped to higher current levels in the electrical dynamic range. The added stimulation at these higher levels may cause issues with comfort in noise as well as with comfort and loudness of higher-level inputs.

Aim of the Study

The aim of this study was to examine the effects of a wider IIDR on the recognition and comfort of speech in quiet and noise for children wearing the Nucleus 24™ implant system and the Freedom speech processor. Word recognition at soft and conversational speech levels (50 versus 60 dB SPL), sentence recognition in noise, and loudness ratings for four-talker babble were examined with two IIDRs (30 and 40 dB). In addition, children’s ability to understand soft and conversational levels of speech in relation to audibility was examined on the basis of aided sound-field thresholds and the Speech Intelligibility Index.

PATIENTS AND METHODS

Subjects

Thirty children ranging in age from 8 to 18 yr (mean age, 11.5 yr) participated; all children were required to have worn the Nucleus 24 Cochlear Implant System for a minimum of 1 yr. The average age at implantation was 4.5 yr and ranged from 1.5 to 13.7 yr. To be eligible for the study, all children were required to have scores of ≥40% on monosyllable word tests presented at 60 dB SPL. This was done to avoid floor effects when testing at low input levels for speech (50 dB SPL). In addition, all children were required to have surgical reports confirming that all stimulating electrodes were inside the cochlea with a minimum of 16 electrodes activated in each child’s current map (confirmed by programming audiologists at the three schools). Eighty percent of the children had 20 to 22 active electrodes with the remaining having no fewer than 17.

All children attended or graduated from one of three private oral schools in the St. Louis area.

Cochlear Implant Systems

All children entered the study using SPrint or the ESPrit 3G™ external speech processor with the Nucleus 24 internal implant system. The majority used the ESPrit 3G processor with only six children using the SPrint. All but two children used the Advanced Combination Encoder speech coding strategy. These two children used the Spectral Peak coding strategy. All students using the SPrint processor were encouraged to use a sensitivity setting of 12 or the dial equivalent of 12 (~6 to 7) on the ESPrit 3G. The 30 dB IIDR on this system coupled with the sensitivity setting of 12 allows acoustic input levels from 35 to 65 dB SPL to be mapped linearly onto the subject's electrical dynamic range on each electrode. The subject's electrical dynamic range is defined as the difference in clinical units from threshold to maximum comfortable loudness level on individual electrodes. Specifically, for a speech-like signal presented at 65 dB SPL in the sound field, stimulation in the 1 kHz channel occurs at the set comfort level (C level), and stimulation for signals 30 dB below occurs at the threshold levels (T levels). Sounds above 65 dB are infinitely compressed by the microphone automatic gain control (AGC), and sounds lower than 35 dB would likely not get mapped onto the electrical dynamic ranee and thus would not be audible.

The ESPrit 3G behind-the-ear processor has a similar AGC system; however, when the Whisper setting is used, the IIDR is increased from approximately 30 to 40 dB. When the Whisper setting is used with a sensitivity dial setting of 6 to 7, the acoustic input levels from 25 to 52 dB are processed linearly, and higher levels up to approximately 65 dB SPL are compressed at a ratio of 2:1. Input levels above 65 dB are infinitely compressed. The input processing of the Nucleus processor uses AGC processing similar to the SPrint processor; however, the IIDR can be increased from 30 to 40 dB in the commercial fitting software. Assuming a default sensitivity setting of 12, the IIDR of 40 dB will process input levels between 25 and 65 dB SPL linearly, and input levels above 65 dB will be infinitely compressed. It should also be noted that the Whisper setting can also be used in the processor, and the effect on the IIDR is very similar to the ESPrit 3G processor. The SPrint and the Freedom processors also allow the use of preprocessing strategies such as Adaptive Dynamic Range Optimization (ADRO®). The goal of the ADRO processing scheme was to place the incoming speech signal into the optimal range of the cochlear implant user's electrical dynamic range (i.e., from threshold to comfort levels for electrical stimulation) by continuously adjusting the gain of the input signal (Dawson et al. 2004; James et al. 2002). A study by James et al. (2002) revealed improved sentence and word recognition for soft to level speech (i.e., 40 to 50 dB SPL) in adults using the ADRO strategy. Similarly, Dawson et al. (2004) evaluated the ADRO processing strategy in 15 children ranging in age from 6 to 15 years and found improvements for word recognition in quiet and sentence recognition in noise. For the current study, two children used the Whisper preprocessing strategy on their processor, and one child used the ADRO strategy with both the 30 and 40 dB IIDR settings.

Test Equipment

Testing took place at three different test sites in the audiology department at three area oral schools for the deaf. Two of the schools had a single-walled booth, and one school had a double-walled booth. The child was positioned at 0° azimuth and 1 m from the loudspeaker. The FM tones and narrowband noise stimuli were presented with an audiometer (Grason-Stadler, Model GSI 16 or GSI 61).

The speech stimuli and the four-talker broadband babble were digitized and stored on a Dell Laptop or Desktop computer at each test site. The computer was used to deliver the speech stimuli via an audiometer and loudspeaker in the sound field.

Test Materials

FM tones—FM tone stimuli at 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz were produced by the audiometer at each testing site.

Narrowband noise—Narrowband noise stimuli were produced by the audiometer at each testing site. These noise bands are intended to be used for masking the nontest ear. For this study, they were delivered through the loudspeaker for sound detection testing.

Recorded four-talker babble, broadband signal—These stimuli were digitized and stored on a laptop computer and presented at each testing site. They were recordings from Auditec of St. Louis.

Ling 6 Sounds—The Ling 6 Sound test (Ling 1976, 1988) was developed by Daniel Ling and uses isolated phonemes including three vowels and three consonants to make up the frequency range of speech from 250 to 8000 Hz. The vowel sounds (/ah/, /oo/, /ee/) represent the extreme resonant frequencies of the vocal tract and articulators for vowel production (Raphael et ah 2007). The consonants (/m/, /s/, /sh/) cover the consonant frequency information from lowest to highest. These sounds are often used by audiologists, teachers, and therapists as a detection and recognition task to assess frequency-specific audibility with hearing aids and cochlear implants. These sounds were spoken by a female speaker and recorded using an Audio-technica headset microphone connected to Roland UA-30 USB audio interface, which was connected to a Dell Latitude laptop computer. The sampling rate was 44.1 kHz with 16 bits per sample. The speaker produced the six Ling sounds using different speaking styles (long, short, pulse, and infant directed); long stimuli were used for this study. Typical durations for these waveforms were approximately 800 msec. All six waveforms were normalized to the same total RMS level. The RMS level was then calibrated through the audiometers at each site to determine the sound pressure level (see the specific calibration procedure described below). These recorded Ling 6 sounds (/ah/, /oo/, /ee/, /sh/, /s/, and /m/) were stored on a laptop computer and presented via the audiometer at each testing site.

CNC word lists—The CNC monosyllabic word lists (50 words/list) were digitized and stored on a laptop computer and presented via the audiometer at each test site (Peterson & Lehiste 1962). This recording is part of the Minimum Auditory Abilities test from Cochlear Corporation. Pairs of lists that yielded equally intelligible scores were used (Skinner et al. 2006).

Bamford-Kowal-Bench Speech in Noise Test—Recorded Bamford-Kowal-Bench Speech in Noise (BKB-SIN) sentence lists 9 to 18 were presented via the audiometer in the sound field (Killion et ah 2004). Pairs of sentences that yielded equal SNRs were used.

Children's Home Inventory of Listening Difficulties—The Children’s Home Inventory of Listening Difficulties (CHILD) allows the child or a family member familiar with the child’s listening habits to rate the ability to hear in 15 different listening situations that are likely to occur in the child’s home environment (Anderson & Smaldino 2000).

Listening abilities are rated on a scale of 1 to 8 as follows: 8 (great), child can hear every word, understand everything; 7 (good), hear it all, miss part of an occasional word, still understand everything; 6 (pretty good), hear almost all the words and usually understand everything; 5 (okay but not easy), hear almost all the words, sometimes misunderstand what was said; 4 (it takes work but usually can get it), hear most of the words, understand more than half of what was said; 3 (sometimes get it, sometimes not), hear words but understand less than half of what was said; 2 (tough going), sometimes does not know right away that someone is talking, miss most of message; 1 (huh?), does not know that someone is talking, miss all of the message.

Calibration

The calibration of all speech stimuli (with the exception of the BKB-SIN test), narrowband noise, and Ling 6 sounds was conducted by the same person in collaboration with each audiologist at the three test sites. This ensured that the presentation level of these stimuli across test centers and subjects was consistent. The standard functions (i.e., FM tones, speech levels through tape inputs) were calibrated to the ANSI S3.6—1996 standard by the laboratory that maintains the audiometers at all three sites. For this calibration, the gain for each FM tone is adjusted so that the level in dB SPL at the center of the child's head at 0° incidence was that specified for 0 dB F1L for monaural sound-field listening by the ANSI standard. This adjustment did not affect the dB SPL of the noise bands in the sound field because they are intended for masking the nontest ear. Corrections using dB SPL measurements have to be made manually for the sound-field thresholds obtained with these noise bands. The ambient noise levels in each sound booth were also measured and documented. The BKB-SIN test was set up and calibrated as directed by the provider. A B&K (Brüel & Kjaer, Denmark) 2230 sound level meter, 1625 filter set, and 4155 microphone were used to measure the SPL of the test stimuli and document the frequency response of the sound-field loudspeaker using ⅓ octave bands. The level (in dB SPL, slow RMS, C weighting) for each of the CNC words, Ling 6 sounds, FM tones, and narrowband noise was measured, and a recording was made in the sound field at a microphone position that approximated the center of a subject's head when positioned 1 m from the speaker. These data were used to provide the audiometer attenuations required to present the CNC word stimuli at the prescribed levels of 50 and 60 dB SPL in quiet. In addition, the specific attenuator dial settings for the FM tones, narrowband noise, and Ling 6 sounds could be converted to SPL values for comparisons across clinics.

Testing Protocols

Mapping—On enrolling in the study, all children attended a mapping session to optimize their current processor (Nucleus 3G ear level processor or SPrint body processor). For optimum detection of soft speech levels, T levels were set above a 100% detection level. These were obtained by setting thresholds above counted thresholds or obtained through loudness scaling at levels that were reported above first hearing. Verification of the map included obtaining aided thresholds for FM stimuli at levels of 30 dB HL or better from 250 to 4000 FM. C levels were set using loudness scaling procedures in which the child indicated that the stimulation levels on various electrodes were loud but okay. In addition, the C levels were further modified by having the child judge the loudness of live speech.

Although the loudness scaling techniques and the terminology used (e.g., soft versus loud, big versus little, perfect versus okay) varied, the goal of the mapping session was to obtain a map that was optimized for the detection and comfort of speech at various iimut levels (50 to 80 dB SPL).

Testing schedule—All children participated in four test sessions. The practice test session and test session 1 were conducted with the child's current processor. Test sessions 2 and 3 were conducted with the new Freedom Processor with the two IIDRs (i.e., 30 and 40 dB). The test sessions occurred approximately 1 month apart and included a battery of speech perception tests, aided threshold tests, and loudness scaling tasks.

Test session 1 was scheduled once the child's current map had been optimized and the practice session had been completed. This test session served as the baseline session with the child's current processor and map. Each child was tested with the volume and sensitivity settings that had been recommended by the fitting audiologist (all children used a volume setting of 8 to 9 and a sensitivity of 12 or equivalent dial settings [~6 to 7] on the ear-level device).

On completion of the first test session with their current processor, all children were fitted with the Nucleus Freedom Speech Processor. The map was converted from the SPrint processor, and the processor was programmed to have an IIDR of 30 or 40 dB.

The starting IIDR was randomized across subjects. Children were asked to wear the new processor for a period of 1 month. All children used a volume setting of 8 to 9 and a sensitivity setting of 12.

Children returned in 1 month for test session 2. The processor was then programmed with the second IIDR. The child wore this map for a period of 1 month. Test session 3 was scheduled at 1 month postfitting.

Testing Procedures

1. Sound-field detection thresholds were obtained using FM tones and narrowbands of noise centered at the following frequencies: 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz. The child was seated at approximately 1 to 1.5 m from the loudspeaker at 0° azimuth. A standard Hughson-Westlake procedure (Carhart & Jerger 1959) in increments of 2 dB was used to obtain thresholds.
2. Sound-field detection thresholds for the recorded Ling 6 sounds (/ah/, /oo/, /ee/, /sh/, /s/, /m/) were obtained in the same manner as listed above for the FM tone and narrowband thresholds.
3. A five-point loudness rating task (nothing, very small, small, perfect, and big) was administered using the four-talker broadband stimuli. The intensity was presented in 5 dB increments at levels ranging from 50 to 80 dB SPL. Each intensity level was presented a total of three times in a randomized order for a total of 21 presentations. The children pointed to a picture card stimuli or word cards depicting perceived loudness using the following five-point rating scale: 0,

no sound; 1, very soft; 2, soft; 3, perfect; and 4, big. The rating for each intensity level was averaged across the three presentations, and an average rating was assigned. The average rating for stimuli presented at each level was computed for each child.

4. Paired CNC lists (50 words/list) were presented at each test level (50 and 60 dB SPL) for a total of 200 words at each test session. The original CNC word lists (31 to 40) were paired based on the results of Skinner et al. (2006). List 39 (paired with list 38) was used as a 50-word practice list with the remaining pairs rotated across the two test levels and three test sessions. The lists used at each level and each test session were randomized across subjects.

5. BKB-SIN lists 9 to 18 (developed for cochlear implant users) were paired and randomized across the three test sessions and subjects. The sentences were presented at 65 dB SPL in the presence of four-talker babble. The SNR was automatically decreased in 3 dB steps for each sentence starting with an SNR of +21 dB SNR and ending at 0 dB SNR. The SNR for 50% correct was computed for each list and averaged across the two lists.

6. The CHILD (Anderson & Smaidino 2000) was given to each subject/parent to complete for each test condition (current processor, Freedom with IIDR 30 and 40). The questionnaire was completed before each test session.

Speech Intelligibility Index Calculations

An SII was computed tor each child with two ditterent IIDRs (30 versus 40 dB). The SII served as an index of audibility for soft-speech levels (i.e., CNC words at 50 dB SPL) and was calculated with a computer program that used the ANSI standard for SII (ANSI S3.5L 1997) as a guideline. The $\frac{1}{3}$ octave band method was used. The long-term average speech spectrum for the CNC words at 50 dB SPL was measured in $\frac{1}{3}$ octave frequency bands for each test site. The CNC words were concatenated to create a 1 min wave file that was presented in each sound field at 50 dB SPL and the output recorded via the air conduction output of a B&K 2230 SLM with a B&K 4155 microphone and digitized through a Roland ED UA-30 audio interface to Dell L400 laptop. The $\frac{1}{3}$ octave band dB SPL levels were calculated for each recording using spectral analysis software from Yoshimasa Electronic Incorporated with the following parameters: 44.1 kHz sample rate; 16,384 fast Fourier transform sample size; a Hanning time window; flat frequency weighting; and a fast 125 msec time constant and averaged over the entire length of the recording. The average sound pressure levels of the CNC words from 160 to 8000 Hz were entered along with the aided FM thresholds at the following frequencies: 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz. Interoctave frequencies were interpolated by averaging the thresholds for the adjacent frequencies that were tested. The thresholds at 250 and 6000 Hz were entered for 160 and 8000 Hz, respectively. An equal-importance function for frequency weighting was used for the CNC speech spectrum as no specific functions are provided in the standard for CNC words. The standard estimates of 30 dB for the dynamic range and 15 dB for the crest factor were used (ANSI 1997).

Data Analysis

Speech perception scores, aided tnresnolds, loudness ratings, and survey results for the two processor IIDRs (30 and 40 dB) were analyzed using a repeated-measures analysis of variance (ANOVA).

RESULTS

Figure 1 shows the group mean CNC correct score for the two IIDRs at 50 and 60 dB SPL. Group mean scores for CNC words presented at a soft level of 50 dB SPL were 47.8% and 59.2% for the 30 and 40 dB IIDR maps, respectively, and group mean scores presented at a normal conversational level of 60 dB SPL were 65.1% and 68.2% for the 30 and 40 dB IIDR maps, respectively. Results from the repeated-measures ANOVA revealed a significant effect for IIDR condition for CNC score at 50 dB SPL (F[l,29] = 49.75, $p < 0.001$) but not for 60 dB SPL (F[l,29] = 3.67, $p < 0.07$). That is, the scores were significantly higher for the 40 dB IIDR condition than the 30 dB IIDR for CNC word scores at 50 dB SPL; however, the scores at the two IIDRs for 60 dB SPL were not significantly different.

The group mean SNR for 50% correct on the BKB-SIN was compared for the two IIDR conditions (30 versus 40 dB) using a repeated-measures ANOVA. Figure 2 shows that the mean SNR for the two IIDR conditions was 10.4 and 10.7 for the 30 and 40 dB IIDRs, respectively. The SNRs for the two IIDR maps were not significantly different (F[1,29] = 0.41, $p < 0.54$).

A repeated-measures ANOVA was performed on sound-field threshold levels for each frequency with subject and IIDR condition (30 versus 40 dB) as fixed factors. A significant effect for IIDR condition was seen at all frequencies {250 Hz (F[1,29] = 55.1, $p < 0.001$); 500 Hz (F[l,29] = 62.6, $p < 0.001$); 1000 Hz (F[l,29] = 61.6, $p < 0.001$); 2000 Hz (F[1,291 = 45.3, $p < 0.001$); 3000 Hz (F[l,29] = 24.8, $p < 0.001$); 4000 Hz (F[l,29| = 32.3,$p < 0.001$); 6000 Hz (F[l.29| = 41.6, $p < 0.001$)}. Figure 3 shows group mean thresholds for FM tones at frequencies 250 to 6000 Hz. The thresholds are significantly lower (better) with the 40 versus 30 dB IIDR.

Results from the repeated-measures ANOVA for the detection thresholds of the Ling 6 sounds and the speech noise revealed a significant effect for the IIDR {/m/ (F[l,29] = 61.5, $p < 0.001$); /ah/ (F[l,29] = 72.1, $p < 0.001$); /oo/ (F[l,29] = 96.8,$p < 0.001$); /ee/(F[l,29] = 55,$p < 0.001$); /sh/(F[l,29] = 41.8, $p < 0.001$); /s/(F[91,29] = 100.7, $p < 0.001$); speech noise (F[l,29] = 113.97, $p < 0.001$)}. Figure 4 shows that the group mean thresholds for each Ling sound and the speech noise is lower (better) with the 40 versus 30 dB IIDR.

Panel A in Figure 5 shows the threshold contours in dB HL dial readings for the FM tones (circles) and narrowband noise (diamonds) at the 40 dB IIDR from 250 to 6000 Fiz. The dB HL dial readings are calibrated with the ANSI 3.6 1996 standard for the FM notes, but not for the noise bands. Panel B shows the FM and noise band threshold contours measured in dB SPL with a sound-level meter. Although the thresholds in dB dial readings show that the threshold contour for the narrowband noise is approximately 8 dB better than the FM tones, the contours in panel B in dB SPL are overlapping. This ~8 dB difference is due to the higher output level of the noise bands compared with the FM tones.

The loudness ratings (i.e., 0 = nothing, 1 = very soft, 2 = soft, 3 = perfect, and 4 = big) were averaged across subjects for each 5 dB input level ranging from 50 to 80 dB SPL. Figure 6 shows the loudness growth function for the two IIDRs. On average, for each 5 dB increase in intensity, there is approximately a ½ rating point in perceived loudness. There are no significant differences in overall loudness ratings for any input level with the two IIDRs. Note that conversational and raised speech levels (i.e., ≥70 dB SPL) are rated on average from 3.34 to 3.91 (between perfect and big) for both IIDR levels, indicating that the upper range of input levels are reported to be appropriately loud as judged by the loudness scaling task.

The CHILD questionnaire ratings (1 to 8; 1 = poor listening skills; 8 = very good) recorded by each child and each parent for the 15 different listening conditions were averaged tor each group for the two IIDR conditions. Figure 7 shows the average ratings for the two IIDRs by the children and the parents. The average rating for the children was 6.0 (rated as pretty good) for both the 30 and 40 dB IIDR conditions. The average rating for the parents was 5.5 and 5.6 (between okay but not easy and pretty good) for the 30 and 40 db IIDR, respectively. There were no significant differences between the two IIDR conditions for the parents or the children. There was a trend for the children to rate their listening skill slightly higher than the parents; however, this difference was not statistically significant.

Panels A and B in Figure 8 show the long-term average speech spectrum for the CNC words at 50 dB SPL in relation to the group sound-field aided thresholds for FM tones for the 30 and 40 dB IIDRs, respectively. The aided thresholds and the long-term average speech spectrum were averaged across the three sites and the SIIs calculated as discussed previously. Panel A shows the group's SII for the 30 dB IIDR, and the panel B shows the SII for the 40 dB IIDR. Each panel shows the frequency contour for the average SPL level of the CNC words with the heavy solid line and the dashed lines at 15 dB above and below representing SPL levels of the signal occurring above and below this average. The contour line with the circles represents the aided FM thresholds from 160 to 8000 Hz. Note that the SII standard requires that sound-field thresholds at interoctave frequencies as well as 160 and 8000 Hz be entered to compute the SII. As described previously, the aided thresholds at these frequencies were interpolated using aided thresholds that were measured as part of the test protocol. Figure 8 shows that SIIs were 50% and 65% for the 30 and 40 dB IIDRs, respectively. Note that in panel A (30 dB IIDR) the SPL levels (dashed lines) falling below the average level (solid line) are below the aided threshold values in certain frequency regions; thus, they are not audible. The 40 dB IIDR in panel B shows that the lower (better) thresholds allow more of this information to be above threshold. A paired t test revealed that the difference in the SII values was significant ($t[29] = 8.66$, $p < 0.0001$).

DISCUSSION

Children in this study demonstrated improved word recognition at soft levels when using a wider IIDR on the Nucleus Freedom processor. Group mean CNC scores increased approximately 11% with a 40 versus 30 dB IIDR, whereas scores at conversational levels (i.e., 60 dB SPL) remained essentially the same. The widening of the IIDR to include soft-level inputs did not compromise speech recognition in noise by providing excessive low-level background noise. In addition, the loudness scaling task revealed that the upper ranges of input levels are reported to be appropriately loud with the two IIDRs. At the conclusion of the study, all children chose to continue using the IIDR of 40 as their default program.

The results obtained in this study with pediatric patients with the Freedom processor are consistent with those obtained by Holden et al, (2007) and Dawson et al. (2007) with adults with the Freedom processor and are consistent with research obtained on other cochlear implant systems showing better word recognition with a wider IIDR (Cosendai & Pelizzone 2001; Donaldson & Allen 2003; Zeng et al. 2002). It should be noted that two children had the Whisper processing activated on their processor. These two children had poorer aided thresholds and SIIs for the 40 versus 30 dB IIDR conditions. One child had aided thresholds that were poorer by approximately 4 dB at 250 to 3000 Hz, thus lowering her SII from 67% to 59% at 30 and 40 dB IIDR, respectively. The CNC scores at 50 dB SPL and BKB-SIN scores were slightly improved (i.e., CNC scores of 69 and 74% and BKB-SIN SNR of 10.25 and 9.5 dB at 30 and 40 IIDR, respectively). The second child had aided thresholds that were approximately 5 dB worse at 250 to 3000 Hz, thus lowering the SII from 42 to 30% with the 30 and 40 IIDR, respectively. Although the CNC scores at 50 dB remained similar for the two IIDRs (36 and 39% at 30 and 40 dB, respectively), the BKB-SIN SNR was slightly poorer with the 40 dB IIDR (SNR 10.5 and 13 dB at 30 and 40 dB, respectively). Recall that the Whisper setting would in effect add 10 dB to both the 30 and 40 dB IIDRs programmed into the processor; thus, the IIDR would actually be 40 and 50 dB. It is possible that the increased IIDR added by the Whisper processing introduces excessive background noise that does not allow valid assessment of aided thresholds and in some cases may interfere with perception of speech in background noise.

It has been demonstrated that cochlear implant fittings that ensure aided thresholds in the 20 to 35 dB HL range will provide the best opportunity to hear the acoustic cues of soft speech (Firszt et al. 2002; Holden et al. 2007; James et al. 2002; Skinner et al. 1997, 1999). As shown in Figure 3, the aided sound-field thresholds for FM tones from 250 to 6000 Hz for the 40 dB IIDR were approximately 8 dB better than that for the 30 dB IIDR. The same was true for the Ling 6 sound-detection thresholds shown in Figure 4. The improved thresholds enabled the children to have a significantly higher group mean CNC score for words presented at a soft level of 50 dB SPL than with an IIDR of 30 dB. This is further illustrated by the group mean SII computed using the measured long-term average speech spectrum of the CNC words at 50 dB SPL. The panel on the left shows the group's SII for the 30 dB IIDR, and the panel at the right shows the SII for the 40 dB IIDR. Figure 8 shows that the SII average increased 15% when the IIDR was increased from 30 to 40 dB. Note that in panel A (30 dB IIDR) the SPL levels (dashed lines) falling below the average level (solid line) are below the aided threshold values in certain frequency regions; thus, they are not audible. The 40 dB IIDR in panel B shows that the lower (better) thresholds allow more of this information to be above threshold. In summary, the significantly improved FM thresholds with the IIDR of 40 dB made very soft speech more audible; this is reflected by the 15% higher SII values and an 11% higher group mean CNC score for words presented at a soft level of 50 dB SPL.

As audiologists use aided threshold measures to confirm audibility, a cautionary note concerning calibration and the stimuli used for testing is warranted. As noted in the Patients and Methods section, aided thresholds for FM tones and narrowbands of noise both generated by an audiometer were obtained at all three schools. In addition, calibration of speech, FM tone, and narrowband noise stimuli was carried out for each school's sound field. This allowed direct comparison of threshold stimuli in SPL across the three schools. As shown in Figure 5, although the aided sound-field thresholds from 250 to 6000 Hz for the noise bands seem to be approximately 7 to 8 dB better than the FM tones when compared using HL dial readings, the thresholds are nearly identical when thresholds are converted to SPL using the field calibration values. As described above, this difference is due to the fact that the HL dial on audiometers is calibrated for the sound field for FM tones and not for narrowband noise. Many clinicians use noise band stimuli for obtaining thresholds with young children as they seem more attentive to these stimuli compared with FM tones. Although it is desirable to use stimuli that will be of greater interest to the child, audiologists must be aware of these level differences and adjust dB HL values using SPL measures for the noise bands in the sound field.

The CHILD rating data revealed no significant differences in ratings of perceived audibility in daily listening conditions. The listening conditions contained in the CHILD vary from asking parents/children to rate listening ability at home in a quiet room to listening from another room at home or understanding playmates outside. Although the average rating of 5.5 for the adults was slightly lower than the children at 6.0, this difference was not significantly different. Recall that the descriptors for 5 and 6 were as follows: 5 (okay but not easy), hear almost all the words and sometimes misunderstand what was said; 6 (pretty good), hear almost all the words and usually understand everything. These ratings were not significantly different for the 30 versus 40 dB IIDRs for parents (30 dB IIDR 5.5 and 40 dB IIDR, 5.6) or children (30 dB IIDR, 6.0; and 40 dB IIDR, 6.0). It is interesting to note that anecdotal reports from some parents and children indicated increased audibility for soft sounds and speech in the environment. It may, however, be the case that these children were accustomed to hearing soft sounds and speech in their environment with their prior device and the 30 dB IIDR on the SPrint as a result of the mapping strategies and sensitivity settings of the processor. It may also be the case that the questions from the CHILD were not sensitive enough to detect differences in the home environment and that the greatest differences would be seen outside the home listening environments (i.e., classrooms).

In conclusion, the IIDR of 40 dB on the Nucleus Freedom processor provided significantly better sound-field thresholds that enabled the children to achieve significantly better CNC word scores at 50 dB SPL by making more sounds audible. The increased audibility of the CNC words at 50 dB SPL was also supported by the increased speech intelligibility indices obtained with the 40 versus 30 dB IIDR. Sentence recognition in noise was not significantly different between the two IIDR settings; thus, improved aided thresholds and recognition of soft speech do not compromise recognition of speech in noise. The fact that all children chose to use the 40 dB IIDR map at the end of the study confirms that the increased audibility was not compromising comfort and audibility in other listening environments. The increased ability of soft speech affords children with cochlear implants the opportunity to hear speech in a variety of listening and learning environments. In turn, they may be better able to hear speech of other classmates with softer voices and more easily converse with classmates at greater distances inside and outside the classroom. It may also facilitate the ability to "over hear" speech or learn language incidentally.

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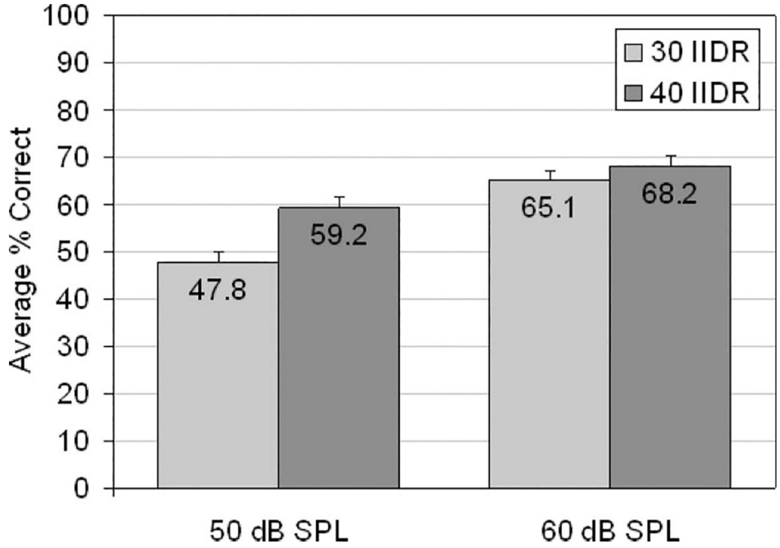

Fig. 1.
Mean CNC percent correct word scores at 50 and 60 dB SPL for the 30 and 40 dB IIDR. Error bars represent ±1 standard error of the mean.

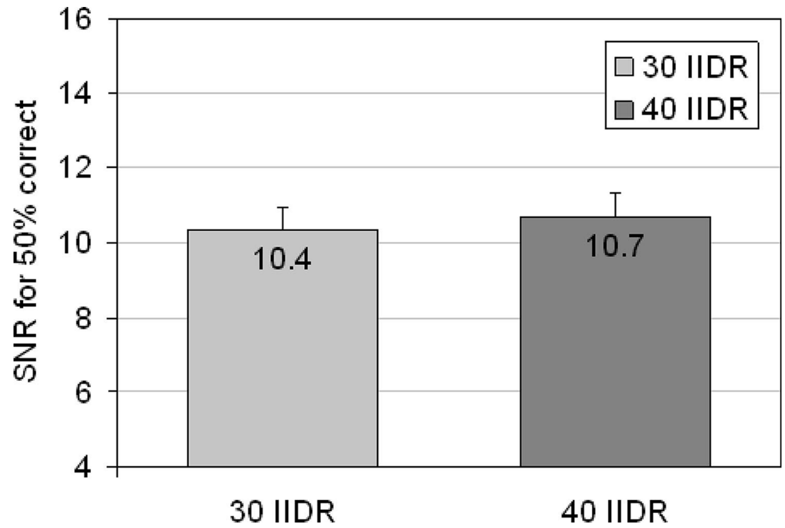

Fig. 2.

Mean group SNR-50 for the BKB-SIN test for the 30 and 40 dB IIDR. Error bars represent ±1 standard error of the mean.

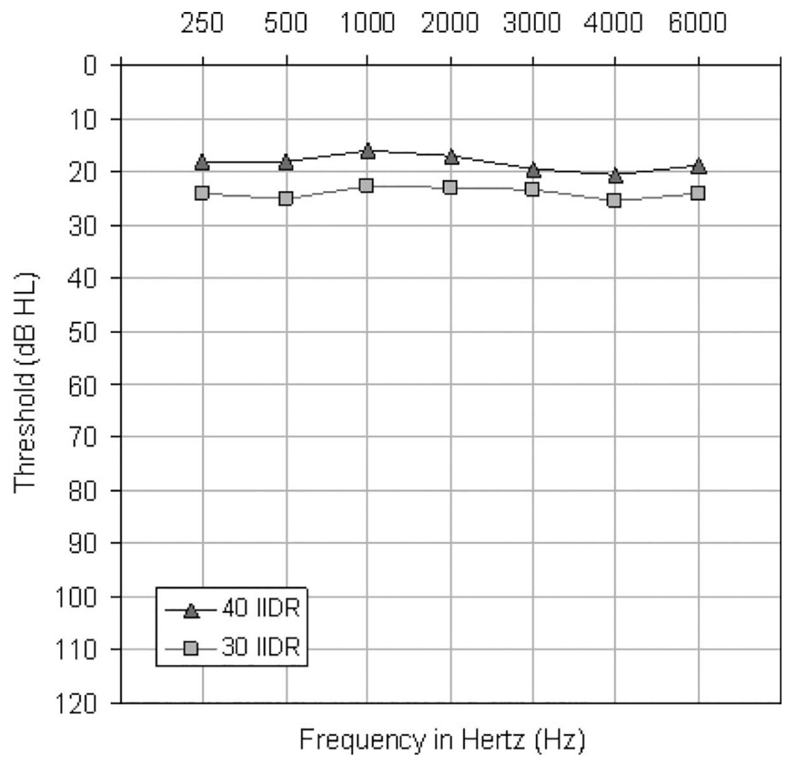

Fig. 3.
Group mean aided FM sound-field thresholds in dB HL at 250 to 6000 Hz for the 30 and 40 dB IIDR.

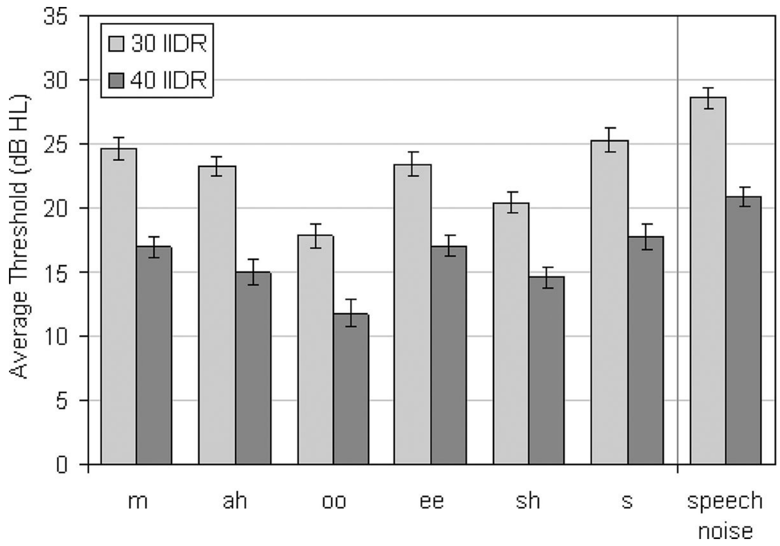

Fig. 4.

Group mean aided detection thresholds for the Ling 6 sounds (/m/, /ah/, /oo/, /ee/, /sh/, /s/) and speech noise for the 30 and 40 dB IIDRs. Error bars represent ±1 standard error of the mean.

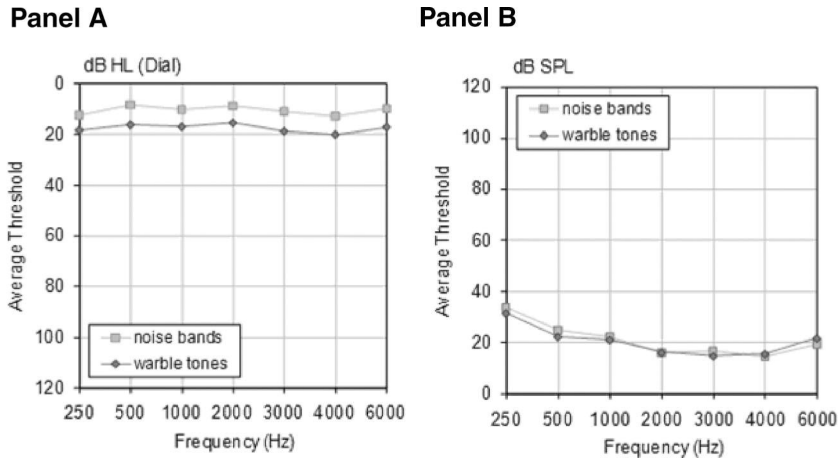

Fig. 5.

Panel A, Group mean aided thresholds in dB HL dial at 250 to 6000 HZ for FM tones and narrowband noise stimuli. Panel B, Group mean aided thresholds in dB SPL for FM tones and narrowband noise.

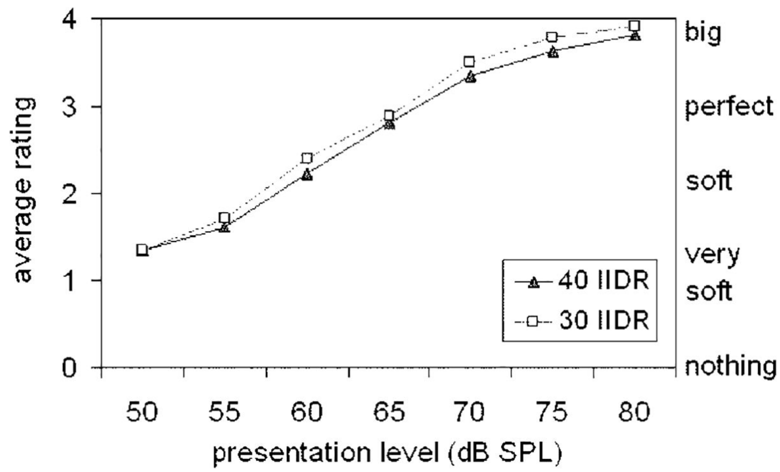

Fig. 6.

Group mean loudness rating for ⅓ octave band stimuli for levels from 50 to 80 dB SPL at 30 and 40 dB IIDRs. Error bars represent ⅓1 standard error of the mean.

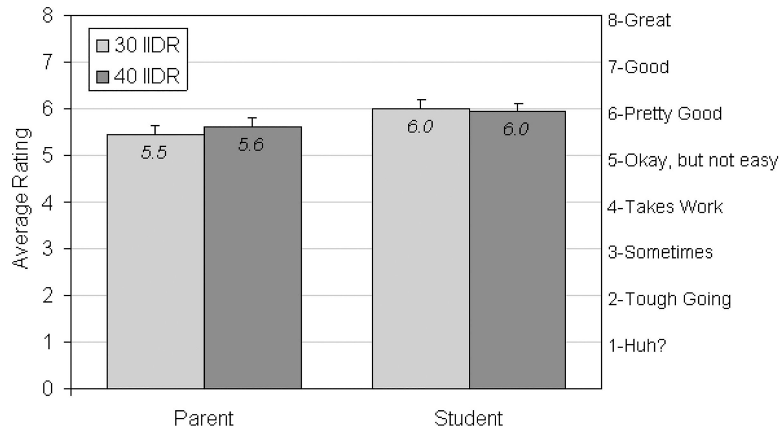

Fig. 7.

Group mean CHILDS questionnaire ratings for parents and students for the 30 and 40 dB IIDRs.

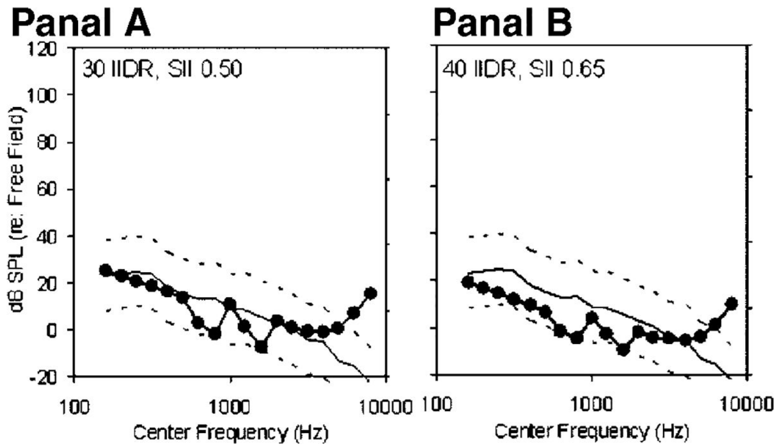

Fig. 8.

Panel A, Long-term average speech spectrum (gray heavy line) and ±15 dB peaks (dashed gray lines) for the CNC words at 50 dB SPL in comparison with group mean aided FM thresholds for 160 to 6000 Hz (dark circles) and the calculated SII for the 30 dB IIDR. Panel B, Long-term average speech spectrum (gray heavy line) and ±15 dB peaks (dashed gray lines) for the CNC words at 50 dB SPL in comparison with group mean aided FM thresholds for 160 to 6000 Hz (dark circles) and the calculated SII for the 40 dB IIDR.