Performance of Patients Using Different Cochlear Implant Systems: Effects of Input Dynamic Range

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Objective: **To determine, for patients who had identical levels of performance on a monosyllabic word test presented in quiet, whether device differences would affect performance when tested with other materials and in other test conditions.**

Design: **For Experiment 1, from a test population of 76 patients, three groups ($N = 13$ in each group) were created. Patients in the first group used the CII Bionic Ear behind-the-ear (BTE) speech processor, patients in the second group used the Esprit3G BTE speech processor, and patients in the third group used the Tempo+ BTE speech processor. The patients in each group were matched on (i) monosyllabic word scores in quiet, (ii) age at testing, (iii) duration of deafness, and (iv) experience with their device. Performance of the three groups was compared on a battery of tests of speech understanding, voice discrimination, and melody recognition. In Experiments 2 ($N = 10$) and 3 ($N = 10$) the effects of increasing input dynamic range in the 3G and CII devices, respectively, was assessed with sentence material presented at conversational levels in quiet, conversational levels in noise, and soft levels in quiet.**

Results: **Experiment 1 revealed that patients fit with the CII processor achieved higher scores than Esprit3G and Tempo+ patients on tests of vowel recognition. CII and Tempo+ patients achieved higher scores than Esprit3G patients on difficult sentence material presented in noise at +10 and +5 dB SNR. CII patients achieved higher scores than Esprit3G patients on difficult sentence material presented at a soft level (54 dB SPL). Experiment 2 revealed that increasing input dynamic range in the Esprit3G device had (i) no effect at conversational levels in quiet, (ii) degraded performance in noise, and (iii) improved performance at soft levels. Experiment 3 revealed that increasing input dynamic range in the CII device improved performance in all conditions.**

Conclusions: **Differences in implant design can affect patient performance, especially in difficult listening situations. Input dynamic range and the method by which compression is implemented appear to be the major factors that account for our results.**

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In a previous report (Spahr & Dorman, 2004), we described the outcomes of a study that assessed the perception of speech, voice, and music by two groups of cochlear implant patients. One group of patients was fit with the Advanced Bionics Corporation's Hi-Focus electrode array with positioner, the CII Bionic Ear behind-the-ear (BTE) speech processor and the Hi-Resolution sound processing strategy. The second group was fit with the Cochlear Corporation's Nucleus 24 electrode array, the Esprit3G BTE speech processor (3G), and the Advanced Combination Encoder (ACE) speech coding strategy. The patients in each group were matched on monosyllabic word (CNC) scores in quiet and on age at testing, duration of deafness, and age at onset of deafness. The outcomes indicated that the 3G patients were significantly more affected by difficult listening situations than the CII patients. We withheld interpretation of this result until we had data from a third group of patients—patients fit with Med El Corporation's Combi40+ Cochlear Implant System, the Tempo+ behind-the-ear speech processor (Tempo+), and the CIS+ speech coding strategy.

This report is an extension of our previous report (Spahr & Dorman, 2004) in two ways. First, we provide the results of a comparison among three groups of patients (CII patients, 3G patients and Tempo+ patients) instead of between two. Our rationale for adding a third group is that signal processing in the Med El device is more similar to CII signal processing than to 3G signal processing. If aspects of signal processing were responsible for the differences in performance found in Spahr & Dorman (2004), then, in the present experiment, performance should be similar for patients fit with the CII and Tempo+ devices. That is, in difficult listening situations, the Tempo+ patients should behave more like CII patients than like 3G patients. Second, we provide an evidence-based account for differences in signal processing that are most likely responsible for the performance differences found in our previous experiment (Spahr & Dorman, 2004) and in the present experiment.

In Experiment 1, we describe the performance of the three groups on tests of speech and melody recognition and on voice discrimination. In Experiment 2, we explore the effects of input dynamic range (IDR) and microphone sensitivity on the performance of patients who use the 3G device. In

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TABLE 1.
Design aspects of three cochlear implant systems available in the United States

	Manufacturer		
	Advanced Bionics Corporation	Cochlear Corporation	Medical Electronics Corporation (Med El)
Speech processor	CII BTE (CII)	Esprit 3G BTE (3G)	Tempo+ BTE (Tempo+)
Electrode array	CII HiRes with positioner	CI24m or CI24rcs	Combi 40+
Input dynamic range (IDR)	20–80 dB	30–40 dB	55 dB
IDR default setting	60 dB	30 dB	55 dB
Intra-cochlear electrodes	16	22	12
Maximum pulse rate	5200 pps	1800 pps	1500 pps
Default stimulation strategy	HiRes (CIS)	ACE (n-of-m)	CIS

Experiment 3, we describe the effects of varying input dynamic range on the performance of patients who use the CII device.

EXPERIMENT 1

As shown in Table 1, the three cochlear implant systems described in this study use very different programs and electrode arrays to code acoustic signals into signals appropriate for electrical stimulation. It is reasonable to suppose that the differences in device hardware and software could lead to different levels of patient performance on one or another task of speech, voice, or melody recognition. Because our patients were matched on absolute levels of performance, we anticipated that between-group differences, if present, might be relatively small. Therefore, the following elements were crucial to the design of this study: (i) a battery of tests sensitive to various aspects of speech perception, (ii) a battery of tests with which the three patient groups were equally familiar, and (iii) homogeneity in the patient samples. To achieve the latter goal, we matched patients on CNC recognition in quiet and on hearing history.

Test Battery

The test battery included (i) traditional single-word and sentence tests, i.e., the CNC word test (Peterson & Lehiste, 1962) and the CUNY sentences (Boothroyd, Hanin, & Hnath, 1985), (ii) original sentence material (AzBio sentences) presented in quiet at conversational levels, at a low input level, and in noise, (iii) tests of spectral (frequency) resolution and amplitude-envelope (temporal) resolution in the context of vowel and consonant recognition, (iv) a test of voice discrimination and (v) a test of melody recognition. New sentence material—the AzBio sentences—was recorded to avoid an advantage for patients in one or another group who may have been tested repeatedly with traditional sentence materials, i.e., CUNY or HINT sentences. These new sentences were from multiple talkers who spoke at a conversational rate. Experienced patients described these sentences as less predictable and more realistic than traditional materials.

Firszt et al. (2004) described the results of a large-scale study investigating speech understanding for cochlear implant patients when material was presented at conversational levels, soft levels, and in noise. One conclusion was that patient testing should include measures of performance that reflect "real-life" listening conditions. To increase the probability that our results would be relevant to real life, we presented the AzBio sentences in noise (at +10 and +5 dB SNR) and at a low conversational level (54 dB SPL) in quiet. These conditions are of particular importance in this study as previous studies have shown that details of signal processing can have a significant effect on speech perception in these environments (Cosendai & Pelizzone, 2001; Fu & Shannon, 1999; James et al., 2003; Zeng et al., 2002).

To aid our evaluation of performance in real-life circumstances, we created a performance index to quantify the level of difficulty experienced by patients in noise and at soft presentation levels. The Robustness Index reflects the relative decrease in level of performance when moving from an optimal listening environment (comfortably loud speech presented in a quiet background) to difficult listening environments. The index is calculated by averaging test scores in noise and for soft speech then dividing that score by the score obtained in quiet.

Design

The purpose of this study was to determine, for patients who had achieved identical levels of performance on a monosyllabic word test presented in quiet, whether device differences such as system hardware and speech coding strategy would affect performance when tested with other materials and in other test conditions and if so, to determine why. A repeated-measures design, which allowed patients equal experience with each device, would be ideal. However, such a design requires three implant surgeries for each patient. An alternative would be to use a repeated-measures design in which the signal processing of all three processors was implemented on a single implant platform. However, it is extremely unlikely that all aspects of signal processing from one or another device could be reproduced in detail on a third device because some aspects of signal processing are conditioned by a specific piece of hardware. Moreover, when using this design it is commonly the case that patients have had long-term experience with one of the strategies and little experience with the others (see Tyler et al., 1986).

For the reasons detailed above, it was decided that a three-way, between-group comparison was the most appropriate design for this study. Patients from each group were tested with their "everyday" device settings so that all patients would be equally familiar with their signal processor. Device settings were not changed during the test sessions. Thus, we assessed the level of performance patients commonly experienced and not the level of performance they might have achieved if they had been allowed to manipulate the settings of their device in one experimental condition or another. We revisit this issue later in this report.

Matching Criteria

Biographic factors such as duration of deafness (Gantz, Woodworth, Abbas, Knutson & Tyler, 1993; Kileny, Zimmerman-Phillips, Kemink & Schmaltz, 1991; van Dijk, Olphen, Langereis, Mens, Broks & Smoorenburg, 1999; Waltzman, Fisher, Niparko & Cohen, 1995), age at implantation (Waltzman et al., 1995), experience with electrical stimulation (Helms et al., 1997), pre-operative hearing (Gantz et al., 1993; Rubenstein, Parkinson, Tyler & Gantz, 1999; van Dijk et al., 1999), pre-operative speech understanding (Rubenstein et al., 1999), speech reading abilities (Gantz et al., 1993; van Dijk et al., 1999; Waltzman et al., 1995), and spiral ganglion survival (Fayad & Linthicum, 2006) have been correlated with performance of cochlear implant patients. Although some of this information (e.g. duration of deafness, age at implantation, and experience with electrical stimulation) is readily available, other information is not commonly reported (e.g., speech-reading abilities), or inaccessible (e.g., spiral ganglion survival). Given that we were unable to use a within-subjects design and that we were unable to match groups on all factors shown to affect performance, we chose to control first for the level of performance achieved on a common test of speech understanding and second for biographic factors that were easily obtained.

We created groups by first matching the patients among the groups on absolute levels of performance using a monosyllabic word test (CNC words) presented at a comfortably loud level in a quiet background. For example, a triad of patients was created by pairing a CII patient with a 70% CNC score with a 3G patient and Tempo+ patient who also scored 70% correct. Another triad was created by pairing a CII patient with a 50% CNC score with a 3G patient and Tempo+ patient with a 50% correct score.

Patients within each triad were also matched on three biographic factors, i.e., age at testing, duration of deafness, and experience with electrical stimulation. In cases in which more than one "match" could be made on the basis of CNC scores, patients with the closest set of biographic factors were chosen.

Because we matched patients on level of CNC recognition in quiet, our design was not intended to answer the question of which device would allow the highest level of performance for a random sample of patients. That is, our results do not speak to the question of whether patients would function at a higher level with device A, B, or C. Rather, our aim was to determine, for patients who had identical levels of performance on CNC words in quiet, whether device differences would affect performance when tested with other materials and in other test conditions.

Methods

Patients • A total of 76 unilateral cochlear implant patients were recruited for this study (CII = 26, 3G = 32, Tempo+ = 18). Patients were recruited through letters mailed from implant centers in the United States and Canada. Patients needed to score greater than 40% correct on a CNC word test administered by their clinic to be contacted. Pilot tests with patients with CNC scores lower than 40% correct showed a floor effect when tested on sentence material in noise. All patients completed the CNC word test at Arizona State University as part of the standard test battery and this score was used as our matching criterion.

The 3G and CII patients tested for this project were drawn from the same pool as used in Spahr & Dorman (2004). The patients described in the results section are not identical to those described in the results section of Spahr & Dorman (2004) because the matching procedure in this report considered CNC scores and biographic factors for the entire pool of CII, 3G, and Tempo+ patients.

Test Materials • During testing, listeners were seated in a sound-treated booth. All signals were presented from a single loud speaker located at 0° azimuth, approximately 1 meter from the listener.

To ensure that patients from one group did not have more experience with the test materials than patients from the other groups, a battery consisting of some original test material and some less commonly used materials was used in this project.

CNC Words • All patients were tested with the same 50-item CNC word list (Peterson & Lehiste, 1962) presented at 74 dB SPL in a quiet background. Scores are reported as percent of words correctly identified.

City University of New York (CUNY) Sentences • A total of 24 sentences (two lists) were used in each condition. All lists were taken from the Cochlear Corporation Investigational Test Battery CD (Boothroyd, Hanin, & Hnath, 1985). Sentences were presented at 74 dB SPL in quiet. Scores are reported as the percent of words correctly identified.

The Azbio Sentences • Five hundred sentences, ranging in length from 6 to 10 words, were recorded. A total of five speakers (two male and three female) were used. All sentences were normalized to be of approximately equal intensity re: dBA peak level. The sentences were then processed as a five-channel, cochlear-implant simulation (Dorman, Loizou, & Rainey, 1997) and presented to 10 normal-hearing subjects for identification. Mean percent correct scores were then calculated for each of the 500 sentences. Nine lists of 40 sentences each were constructed. An equal number of sentences from four speakers (two male and two female) were included. The mean intelligibility of the lists was 89% correct for normal-hearing subjects listening to the five-channel simulation. The lists differed in intelligibility by less than 2 percentage points.

After presentation of a single sentence, patients were asked to repeat back any words that were understood and were encouraged to guess when unsure. All sentences were scored as words correct, and an overall percent correct was computed for each list. All words were scored in each sentence. Sentences were presented at 74, 64, and 54 dB SPL in quiet and at 74 dB SPL at +10 and +5 dB SNR (four-talker babble).

Consonants In /e/ Environment • Twenty consonants were recorded in "eCe" format (e.g., "a bay," "a day," "a gay," etc.). A single male talker made five productions of each token. The pitch and durations of the vocalic portion of each token was intentionally varied. During a practice session, patients heard each signal twice while the word was visually displayed on the computer screen. Patients then completed two repetitions of the test procedure (20 alternative, forced choice procedure), with feedback, as a final practice condition. In the test condition, patients heard all 100 tokens (5 productions of each consonant). The order of items was randomized in the test list. Items were scored in terms of percent correct and in terms of speech feature information transmitted. Consonants were presented at 74 dB SPL in quiet.

Vowel Recognition Without Duration Cues • Thirteen vowels were created with the use of KLATT software (Klatt, 1980) in /bVt/ format ("bait, Bart, bat, beet, Bert, bet, bit, bite, boat, boot, bought, bout, but"). The vowels were brief (90 msec) and of equal duration so that vowel length would not be a cue to identity (Dorman, Dankowski, McCandless & Smith, 1989). During a practice session, patients heard each vowel presented twice while the word was visually displayed on the computer screen. Patients then completed two repetitions of the test procedure (13 alternative, forced choice procedure), with feedback, as a final practice condition. In the test condition, there were five repetitions of each stimulus. The order of the items was randomized in the test list. Vowels were presented at 74 dB SPL in quiet.

Voice Discrimination • The stimuli were drawn from a digital database developed at the Speech Research Laboratory at Indiana University, Bloomington. One hundred eight words produced by five male speakers and five female speakers were selected. Patients were presented with pairs of words. Within each condition, half of the pairings were produced by the same talker and half were produced by different talkers. The words in the pairings always differed, e.g., one male talker might say "ball" and the other male talker might say "brush." Across the different talker pairs, each talker was paired with every other talker an equal number of times. After each of the 172 presentations, participants responded "same" or "different" by pressing one of two buttons. Responses were scored as the percentage of correct responses for all contrasts, for across-gender contrasts, and for within-gender contrasts (Kirk, Houston, Pisoni, Sprunger, & Kim-Lee, 2002). Tokens were presented at 74 dB SPL.

Melody Recognition • A total of 33 common melodies (e.g., Yankee Doodle, London Bridge) were created for this test. Each melody consisted of 16 equal-duration notes, synthesized with MIDI software that used samples of a grand piano (Hartmann & Johnson, 1991). The fundamental frequencies of the notes ranged from 277 Hz to 622 Hz. The average note was concert A (440 Hz) ±1 semitone. The melodies were created without distinctive rhythmic information. Before testing, patients were asked to select five familiar melodies from a list of 33 melodies. Patients then completed two repetitions of the test procedure (five alternative, forced-choice procedure), with feedback, as a practice condition. In

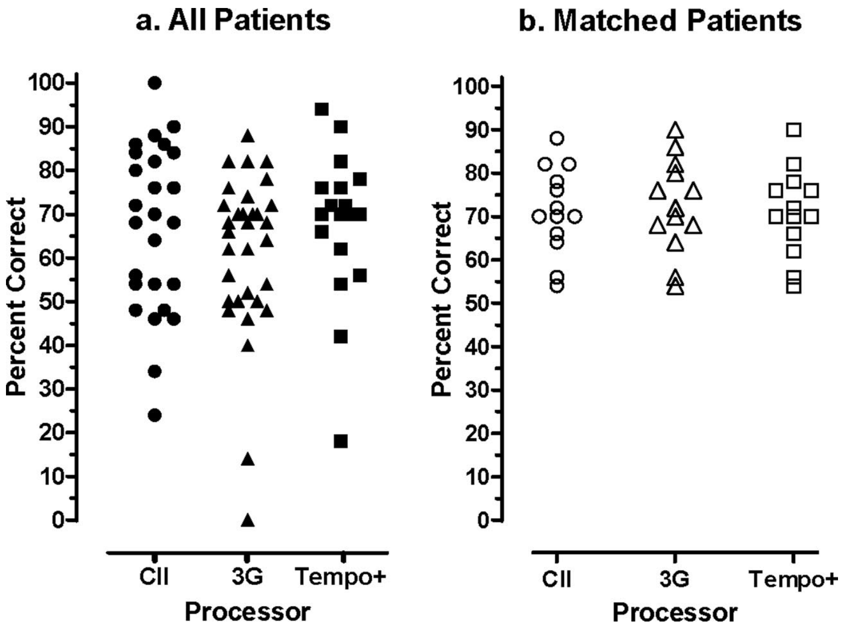

Fig. 1. Individual CNC word scores for (a) all 76 patients tested and (b) the 39 matched patients.

the test condition, there were five repetitions of each stimulus. The order of the items was randomized in the test list. Melodies were presented at 74 dB SPL.

Results

Matching Criteria • A total of 76 patients were tested under this protocol. Matching patients on CNC word scores and biographic factors produced 13 triads of CII, 3G, and Tempo+ patients. 12 triads were matched within 4 percentage points on the CNC word test. One triad was matched within 6 percentage points (Fig. 1). The groups did not differ significantly in mean CNC score (CII = 71%, 3G = 72%, Tempo+ = 71%, $F_{(2,36)}$ = .08, p = 0.93). Further, the groups did not differ significantly in terms of mean age (CII = 55.0 yr, 3G = 50.5 yr, Tempo+ = 52.2 yr, $F_{(2,36)}$ = 0.35, p = 0.70), mean duration of deafness (CII = 13.1 yr, 3G = 9.9 yr, Tempo+ = 12.6, $F_{(2,36)}$ = 0.29, p = 0.75), or mean duration of experience with electrical stimulation (CII = 1.5 yr, 3G = 2.1 yr, Tempo+ = 2.2 yr, $F_{(2,36)}$ = 1.19, p = 0.32).

Recognition of Words in Sentences • As shown in Figure 2 (a and b), no significant main effect of device was found for CUNY sentences presented at 74 dB SPL in quiet (CII = 98%, 3G = 99%, Tempo+ = 97%, $F_{(2,36)}$ = 1.44, p = 0.25) or for AzBio sentences presented at 74 dB SPL in quiet (CII = 85%, 3G = 79%, Tempo+ = 82%, $F_{(2,36)}$ = 0.95, p = 0.40).

Consonant Identification and Feature Transmission • As shown in Figure 2c, a one-way ANOVA revealed no significant effect of device for consonant identification (CII = 77%, 3G = 71%, Tempo+ = 77%, $F_{(2,36)}$ = 0.72, p = 0.49). Additional analyses of feature transmission revealed no significant effect of device for consonant place of articulation (CII = 63%, 3G = 53%, Tempo+ = 63%, $F_{(2,36)}$ = 0.184, p = 0.17), for consonant manner of articulation (CII = 89%, 3G = 81%, Tempo+ = 88%, $F_{(2,36)}$ = 1.74, p = 0.19), or for consonant voicing (CII = 77%, 3G = 72%, Tempo+ = 72%, $F_{(2,36)}$ = 0.38, p = 0.68).

Vowel Identification • As shown in Figure 2d, a one-way ANOVA revealed a significant difference for vowel identification as a function of device (CII = 70%, 3G = 52%, Tempo+ = 55%, $F_{(2,36)}$ = 3.93, p = 0.02). Post hoc Fisher's protected LSD tests revealed that vowel identification scores of the CII group were significantly higher than vowel scores of the 3G and Tempo+ groups.

Voice Discrimination • As shown in Figure 2e, one-way ANOVAs revealed no significant effect of device for within-gender speaker discrimination (CII = 68%, 3G = 68%, Tempo+ = 68%, $F_{(2,36)}$ = 0.02, p = 0.98) or for across-gender speaker discrimination (CII = 94%, 3G = 95%, Tempo+ = 94%, $F_{(2,36)}$ = 0.16, p = 0.85).

Melody Recognition • As shown in Figure 2f, a one-way ANOVA revealed no significant effect of device for melody recognition (CII = 51%, 3G = 31%, Tempo+ = 40%, $F_{(2,36)}$ = 2.55, p = 0.09).

Speech Understanding in Difficult Listening Situations • The results for tests conducted in difficult listening conditions are shown in Figure 3 (a and b).

Speech Understanding in Noise • Figure 3a shows group mean scores for AzBio sentences as a function of signal-to-noise ratio. Repeated-measures ANOVAs revealed significant main effects of noise

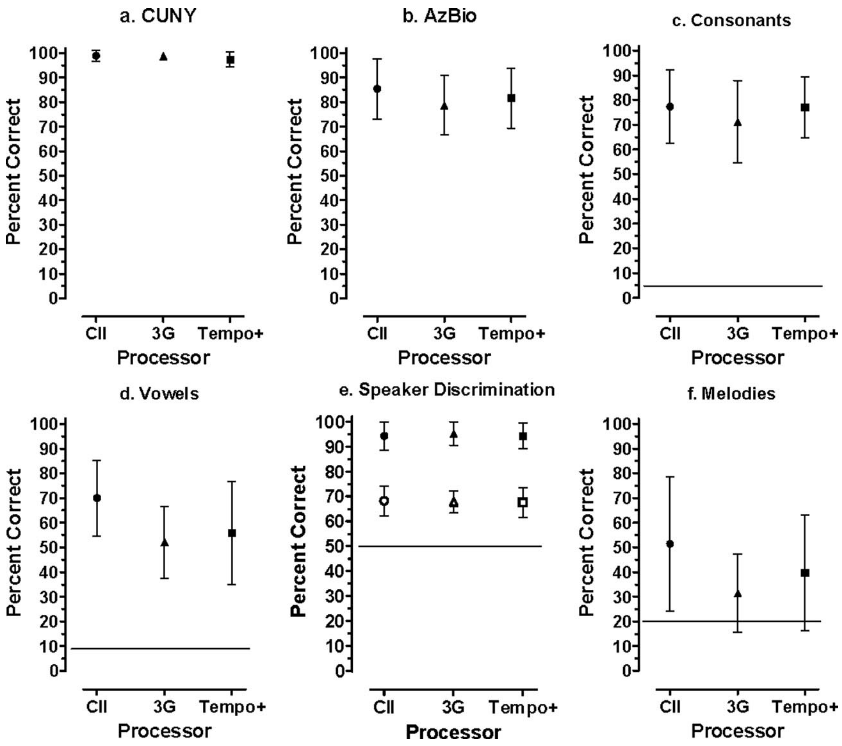

Fig. 2. Results from three groups of cochlear implant patients on tests of (a and b) sentence understanding, (c) consonant identification, (d) vowel identification, (e) across-gender (closed symbols) and within-gender (open symbols) speaker discrimination and (f) melody identification. Horizontal lines indicate chance levels of performance. Error bars represent ±1 standard deviation of the mean.

level on performance for all groups. Post hoc Fisher's protected LSD tests revealed scores in quiet were higher than scores at +10 dB SNR, which, in turn, were higher than scores in +5 dB SNR.

A one-way ANOVA revealed significant main effect of device for AzBio sentences presented at +10 dB SNR (CII = 64%, 3G = 42%, Tempo+ = 58%, $F_{(2,36)} = 4.39$, $p = 0.02$). A Fisher's protected LSD test revealed performance of the CII and Tempo+ groups was significantly higher ($p < 0.05$) than performance of the 3G group.

A one-way ANOVA revealed a significant main effect for device for AzBio sentences presented at +5 dB SNR (CII = 44%, 3G = 22%, Tempo+ = 38%, $F_{(2,34)} = 5.54$, $p = 0.008$). Two 3G patients asked to discontinue testing in this condition, indicating that they could not hear the speech signal at all. Both subjects were dropped from this analysis. A Fisher's protected LSD test revealed performance of the CII and Tempo+ groups was significantly higher ($p < 0.05$) than performance of the 3G group.

Speech Understanding as a Function of Signal Level • Figure 3b shows group mean scores for AzBio sentences as a function of input level. Repeated-measures ANOVAs revealed significant main effects of signal level on performance for all groups. A Fisher's protected LSD test revealed scores in the 74 dB SPL and 64 dB SPL conditions were significantly higher ($p < 0.05$) than scores in 54 dB SPL condition for all groups.

A one-way ANOVA revealed no significant differences as a function of device for sentence material

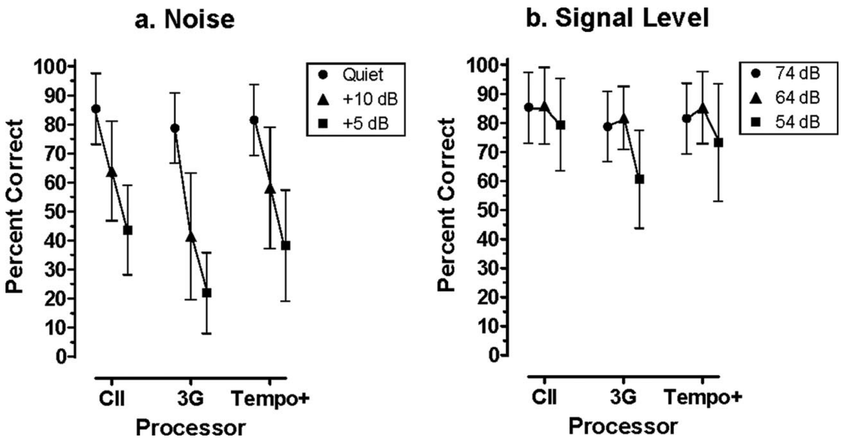

Fig. 3. Results from three groups of cochlear implant patients for AzBio sentence materials presented (a) in noise and (b) at different signal levels. Error bars indicate ±1 standard deviation of the mean.

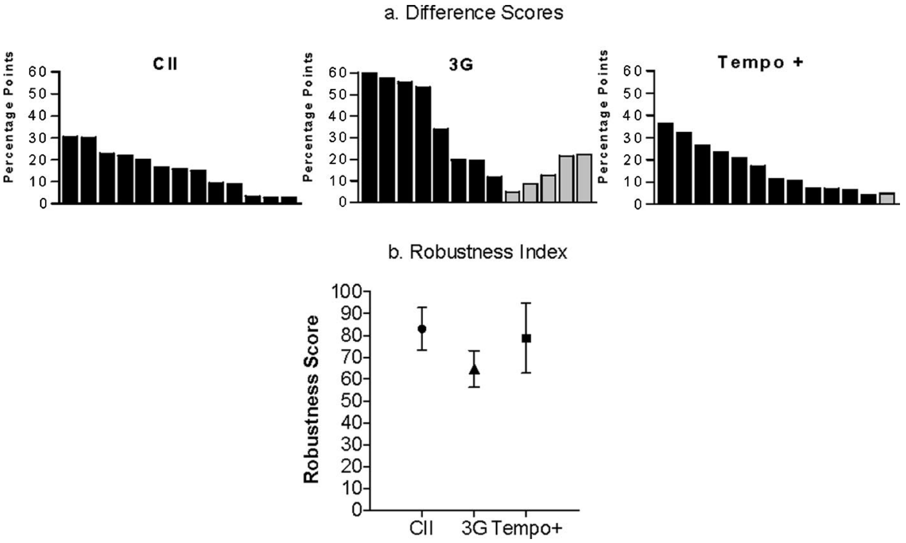

Fig. 4. Relative measures of performance for three groups of patients using different cochlear implant systems. a, Difference scores of individual patients for performance on material presented at low levels (54 dB SPL) and in noise (+10 dB SNR). Dark bars represent patients who achieved higher scores in the low presentation level condition and lighter bars represent patients who achieved higher scores in noise. b, Mean and standard deviations of the three groups on the "robustness score."

presented at an input level of 64 dB SPL in quiet (CII = 86%, 3G = 82%, Tempo+ = 85%, $F_{(2,36)} = 0.42$, $p = 0.66$). Significant differences as a function of device were found for sentences presented at 54 dB SPL in quiet (CII = 79%, 3G = 61%, Tempo+ = 73%, $F_{(2,36)} = 3.77$, $p = 0.03$). A Fisher's protected LSD test revealed a significant difference ($p < 0.05$) between the CII and 3G groups for AzBio sentence scores in the 54 dB condition.

Two Indices of Performance in Difficult Listening Situations

Difference Scores • Figure 4a shows, for each patient, the difference in scores achieved in the +10 dB noise condition and the 54 dB input level condition (soft speech). CII and Tempo+ patients tended to achieve similar scores in both difficult listening environments: The majority of scores differed by 20 percentage points or less. In contrast, 3G patients generally evidenced a greater difference between conditions: For 4 of the 13 patients, the scores differed by greater than 50 percentage points. In most cases. performance in noise was poorer than at a low signal level. These outcomes can be summarized in the following way: The performance of CII and Tempo+ patients was more consistent than 3G patients in the two difficult-listening situations.

Robustness • The scores in Figure 4a represent the difference in performance between two difficult listening conditions The measure of robustness, shown in Figure 4b, provides an estimate of consistency across listening environments by averaging an individual's scores in two difficult listening situations (74 dB SPL at +10 dB SNR and 54 dB SPL in quiet) and by dividing that score by the score from the easy listening situation (74 dB SPL in quiet). The product is then multiplied by 100 to obtain an indexed score with a range of zero to 100.

A one-way ANOVA revealed a significant difference between groups on the robustness index ($F_{(2,36)} = 8.52$, $p = 0.0009$). A Fisher's protected LSD test revealed that CII and Tempo+ patients obtained significantly higher robustness scores than 3G patients (CII average = 83%; 3G average = 65%; Tempo+ average = 79%). Thus, CII and Tempo+ patients were less affected by the difficult listening situations than 3G patients.

Discussion

The aim of Experiment 1 was to assess whether differences in device design would result in different levels of speech understanding, voice discrimination, or melody recognition. By carefully matching patients on a difficult task of speech understanding in quiet and on three biographic factors, we increased the likelihood that differences in performance across different tests among the three cochlear implant groups would be related to device differences and not to sampling error.

Despite similar levels of performance among the three groups of patients on monosyllabic words and sentences presented at comfortable levels in quiet backgrounds, significant differences in performance were found in some conditions. The CII group achieved a higher score than the 3G and Tempo+ groups on a measure of vowel identification. For sentences presented in noise (+10 and +5 dB SNR), the CII and Tempo+ groups achieved higher scores than the 3G group. For sentences presented at soft levels (54 dB SPL), the CII group achieved higher scores than the 3G group. Finally, both the CII and Tempo+ groups achieved higher scores than the 3G group on the measure of robustness. Given our matching procedure, it is unlikely that the between-group differences were related to biographic factors that were not matched in our design. Rather, we should look to differences in implant design for an account of between-group differences in performance.

Aspects of Design • The Tempo+ device addressed the fewest number of intracochlear electrodes—12 versus 16 for the CII device and 22 for the 3G device—but allowed scores equal to or better than that of the 3G device in all conditions. Thus, the number of intracochlear electrodes cannot account for the observed differences in performance.

The mean stimulation rates used by the CII, Tempo+, and 3G systems were 3127 pps, 1016 pps, and 1425 pps, respectively. The mean rate for the CII patients was significantly higher than the mean rate for the Tempo+ patients. Yet, patients fit with the Tempo+ device achieved scores equal to that of patients fit with the CII device in nearly all conditions. Thus, stimulation rate is unlikely to be a factor underlying between-group differences in performance.

The CII and Tempo+ devices used the same stimulation strategy (CIS), and both used a large input dynamic range (55 dB or greater) in the default setting. In contrast, the 3G device implemented a channel-picking strategy (ACE) and a smaller input dynamic range (30 dB). Of stimulation strategy and IDR, stimulation strategy appears to be the least likely factor underlying differences in performance. Previous studies have shown that CIS and channel-picking strategies allow similar levels of performance in acoustic simulations with normal-hearing listeners (Dorman, Loizou, Spahr, & Maloff, 2002) and in cochlear implant patients (Zeise et al., 2000). Zeise et al. (2000) allowed patients extended periods of experience with each strategy and found no significant differences in performance for vowel identification, consonant identification, or sentence understanding in quiet or noise as a function of strategy.

If the number of intracochlear electrodes, stimulation rate, and stimulation strategy can be minimized as factors contributing to between-group differences in performance, then IDR remains, as a primary candidate, to account for some, or most, of the outcomes of the present study.

Input Dynamic Range • For the purposes of this study, IDR is used to describe the range of acoustic input levels coded by the speech processor and presented within the patient's electrical dynamic range. For all three devices, the peak input value processed by the device is determined by a slow-acting compression circuit, a sensitivity control setting, or both. The peak input value is presented at the upper limit of the electrical dynamic range or the maximum comfort level (M). Input values above the peak value are subjected to high-level compression to avoid presenting signals at uncomfortably loud levels. The IDR value describes the range of input levels below this peak value to be presented between the M-level and electric threshold (T). Figure 5 shows how different IDR values (dB) are mapped to the electrical dynamic range (μA): Because the x-axis is logarithmic and the y-axis is linear, logarithmic mapping functions are seen as straight lines.

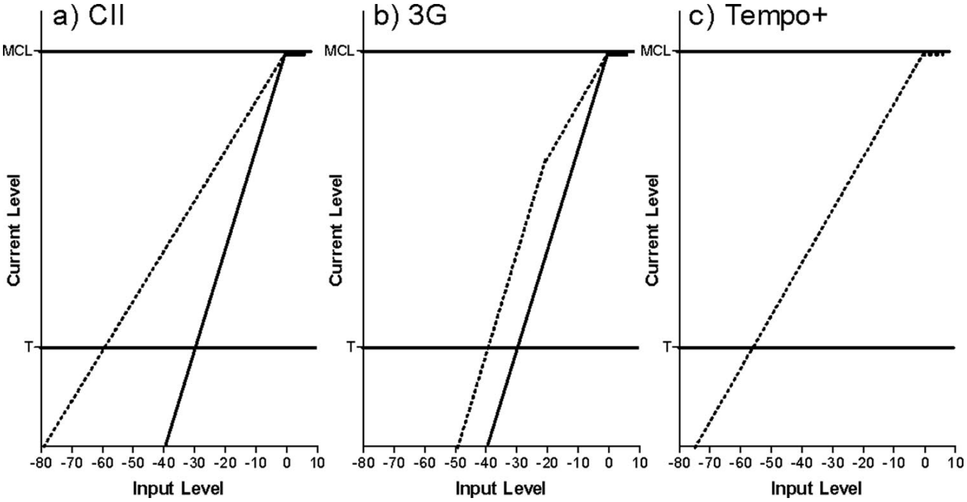

Fig. 5. Mapping functions for the three cochlear implant systems. Current level has been displayed as a range of values between threshold (T) and maximum comfort level (MCL) in logarithmic steps. The peak input value mapped to the patients MCL has been set to 72 dB SPL. a, Mapping function for the CII device shows IDR settings of 30 dB (solid line) and 60 dB (dashed line). b, Mapping function for the 3G device shows IDR settings of 30 dB (solid) in the Microphone Setting and 40 dB (dashed) in the Whisper Setting, where signals above 52 dB SPL are subjected to higher levels of compression. c, The mapping function for the Tempo+ device shows a fixed IDR of 55 dB.

CII Input Dynamic Range • The CII device allows IDR to be adjusted within the clinical software to values of 80 dB and lower with a default setting of 60 dB—the mean IDR setting for the patients described in Experiment 1 was 60.8 dB, with a range of 55 dB to 70 dB. A slow-acting compression circuit determines the peak input value processed by the device. This peak input value will be mapped to the patient's M-level. The range of input levels defined by the IDR setting will be mapped between the M-level and T-level. As shown in Figure 5a, the compression ratio is constant throughout the IDR, such that increasing IDR from 30 dB to 60 dB appears as a change in slope. Note that increasing the IDR from 30 dB to 60 dB has no effect on the peak input value but should improve audibility of softer sounds (–30 dB to –60 dB) by mapping them within the patient's electrical dynamic range.

3G Input Dynamic Range • A toggle switch at the base of the 3G device allows patients to select the Microphone setting, Whisper setting, or Telecoil setting. The Microphone setting is the recommended setting for everyday use and the setting used by all patients in Experiment 1. For the Microphone setting, the IDR is fixed at 30 dB. The peak input level processed by the device and mapped to the patient's M-level is determined by the sensitivity setting of the device (Cochlear Limited, 2002; James et al., 2003). The sensitivity setting can be fixed within the clinical software or controlled by the patient using a dial on the processor. The clinical software is used to determine if the dial will control volume or sensitivity.

The Whisper setting is offered as an alternative to the adaptive dynamic range optimization (ADRO) feature available on the body worn processor. ADRO improves audibility of soft sounds by maintaining a 30 dB IDR but adapting the level of gain applied to the signal based on average input levels (James et al., 2002). Unlike ADRO, the Whisper setting improves audibility of soft sounds by increasing the IDR from 30 dB to 36 dB at the highest sensitivity setting and to 51 dB at the lowest sensitivity setting.

As shown in Figure 5b, in the Microphone setting, constant compression is applied so that the 30 dB IDR can be mapped to the patient's electrical dynamic range. In the Whisper setting, the compression ratio applied to input levels below 52 dB is identical to that used in the Microphone Setting. Higher levels of compression are applied to input levels above 52 dB SPL (Cochlear Limited, 2002). Increasing IDR from 30 dB to 40 dB (without altering the sensitivity setting) has no effect on the peak input value, but does improve audibility of softer sounds (–30 dB to –40 dB) by mapping them within the patient's electrical dynamic range.

Tempo+ Input Dynamic Range • The Tempo+ uses a fixed IDR of 55 dB. The peak input value is controlled by a slow-acting compression circuit and can also be influenced by a sensitivity dial on the processor. This peak input value is mapped to the patient's M-level. As shown in Figure 5c, constant compression is applied to the signal below the peak value so that the 55 dB IDR is mapped between the M-level and the T-level (Stöbich et al., 1999).

IDR as an Account for Differences in Performance • All of the 3G patients in this experiment used the Microphone setting on their devices as the "everyday" setting and thus used a 30 dB IDR in each test condition. Some patients had devices with a sensitivity control. Others had sensitivity fixed and used the dial to control volume. We propose that individual differences in settings of the sensitivity control in conjunction with a narrow IDR combined to create relatively poorer group-mean scores for 3G patients in noise, for low-level input signals, and on the measure of robustness.

Our reasoning is as follows: If IDR is narrow, then patients must adjust sensitivity to compensate for different listening environments. If they do not, then either soft sounds will be inaudible (presented below threshold) or conversational level sounds will be compressed. A high sensitivity would lower the peak input value processed by the device and improve audibility of soft sounds and perhaps depress performance in noise. On the other hand, a low sensitivity setting would increase the peak input value processed by the device and could maximize performance in noise but reduce the audibility of soft speech. If some patients chose a high sensitivity setting and others a low setting, then, on average, performance would not be optimal for soft speech, for speech in noise, or for the measure of robustness.

Our inference that with a fixed sensitivity setting, 3G patients should demonstrate an advantage for either speech understanding in noise or at low signal levels is confirmed by an analysis of the differences in performance in the +10 dB SNR condition and in the 54 dB condition for subgroups of the entire group of 3G patients ($N = 32$) who participated in this project. Although 9 of the original 32 patients demonstrated similar performance (difference <10 percentage points) in quiet and noise, the remaining 23 patients could be divided into two groups: those who achieved higher scores in the soft speech condition than in the noise condition ($N = 13$) and those who achieved higher scores in the noise condition than in the soft speech condition ($N = 10$). It follows that any sample of 3G patients probably would be composed of (i) patients whose microphone sensitivity is relatively high and who perform better with soft speech than with speech in noise and (ii) patients

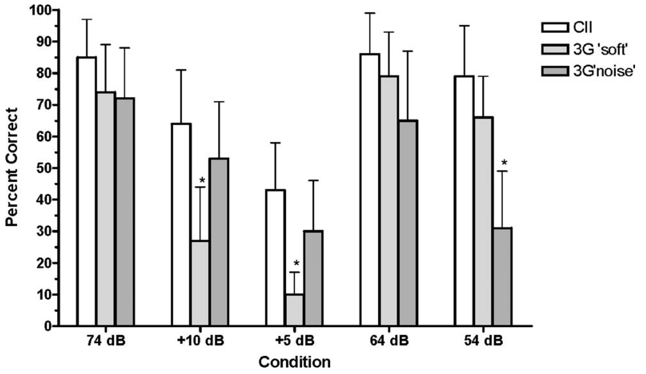

Fig. 6. Comparison of performance on AzBio sentences for CII and 3G patients. 3G patients were divided into patients (*N* = 13) who performed better at low signal levels (3G "soft") and patients (*N* = 10) who performed better in noise (3G "noise"). Error bars indicate ±1 standard deviation of the mean. Asterisk indicates a significant difference between that condition and the other conditions.

whose microphone sensitivity is relatively low and who perform better with speech in noise than with soft speech.

Figure 6 displays the performance of the 13 CII patients (described in Experiment 1) and the two subgroups of 3G patients (described above) on tests of sentence understanding in quiet and in noise. All groups achieved similar levels of performance when sentences were presented at conversational levels in quiet. 3G patients with a tendency for better performance at soft levels achieved a similar level of performance as CII patients in the 54 dB condition, but their performance was significantly worse than CII patients in both the +10 dB and +5 dB noise conditions. 3G patients with a tendency for better performance in noise achieved a similar level of performance as CII patients in the +10 dB and +5 dB noise conditions, but their performance was significantly worse than CII patients in the 54 dB condition. This observation suggests that, had we allowed the 3G patients to change their sensitivity settings, at least for the patients who had sensitivity enabled on their devices, the performance of the 3G group could have equaled the performance of the other groups for the soft speech and noise conditions. Note, however, that the other two groups did not need to manipulate their devices, which used wide IDRs, to achieve high levels of performance in both difficult listening situations.

The analyses framed above do not speak to the issue of between-group differences in vowel recognition. It is difficult to tie IDR and sensitivity to vowel recognition, and we have no other principled account for differences in level of vowel recognition.

Research Design • Finally, we comment on a significant aspect of our research design: matching patients not only on biographic factors but also on CNC scores in quiet. Our motivation was to create homogenous groups of patients fit with the three devices. We chose CNC word scores as an added matching variable because they are commonly used to estimate performance and because they do not suffer from ceiling effects. At the conclusion of our study, we were left to consider that, had we matched on a different variable, we might have obtained a different outcome—a circumstance faced by all researchers in all fields. For example, if we had matched on sentence performance at soft levels or in noise, then we would have found that 3G patients achieved higher scores than CII and Tempo+ patients on CNC words and AzBio sentences presented at conversational levels in quiet. This pattern of results would occur because 3G patients exhibited a greater difference between performance in an easy listening condition and performance in difficult listening conditions than CII and Tempo+ patients. As a consequence, the matched CII and Tempo+ patients would have lower CNC and AzBio scores. Although this is an interesting exercise, it does not alter our interpretation of the results. The results revealed lower robustness scores, i.e., a greater change in performance between easy and difficult listening conditions, for 3G patients than for CII and Tempo+ patients. This outcome would have been present regardless of our matching procedure.

EXPERIMENT 2

We have speculated that differences in the setting of microphone sensitivity played a significant role in the performance of patients who use the 3G device when tested in noise and with low-level signals. These speculations led us, in Experiment 2, to directly manipulate sensitivity in two 3G-processor configurations—the Microphone configuration with a 30 dB IDR and the Whisper configuration with a wider IDR. At issue was the effect of sensitivity and IDR on the perception of soft speech and speech presented in noise.

Methods

Patients • Ten adult patients who used the Nucleus 3G device were selected from the patients in the Section of Audiology at Mayo Clinic Scottsdale. Four patients had previously participated in Experiment 1. For these patients, a minimum period of 6 mo elapsed between test periods. The criterion for selection was greater than 50% correct scores on the CNC word lists distributed by Cochlear Corporation. All patients who agreed to participate signed an informed consent form approved by the Institutional Review Board at Mayo Clinic Scottsdale.

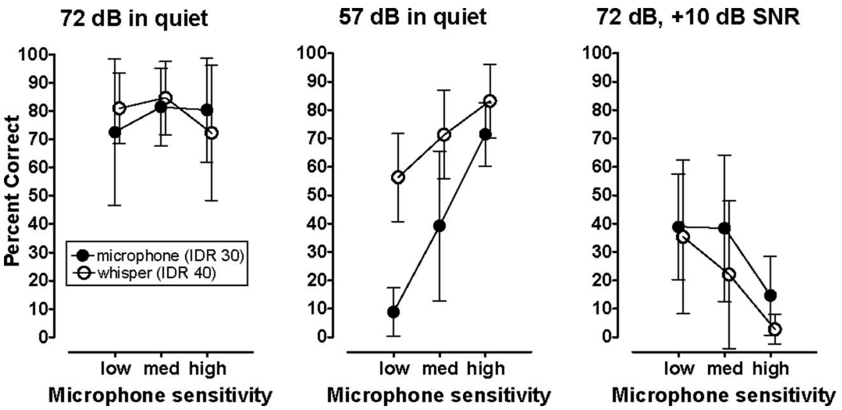

Fig. 7. Performance levels of cochlear implant patients for AzBio sentence material presented at 72 dB SPL in quiet, 57 dB SPL in quiet, and 72 dB SPL at +10 dB SNR, using the Microphone (●) and Whisper (○) settings of the 3G device. Error bars indicate ±1 standard deviation of the mean.

Conditions • Patients were tested in using the Microphone setting, which uses an IDR of 30 dB, and the Whisper setting, which uses an IDR of approximately 40 dB at medium sensitivity settings. Three settings of microphone sensitivity were used in each of the two IDR conditions: low (3.5), medium (5), and high (7). The order of test conditions was randomized for each patient by the use of a random number generator. Patients were allowed approximately 5 minutes to adjust to each IDR and sensitivity setting.

Test Materials • The AzBio sentences were presented in three conditions: 72 dB SPL in quiet, 57 dB SPL in quiet, and 72 dB SPL at +10 dB SNR (4-talker babble). The AzBio sentences used in Experiment 2 were taken from a novel batch of 1000 sentences recorded, processed, and organized in an identical manner as described in Experiment 1. In total, 33 lists of 20 sentences were created. The patients had no previous exposure to this material.

Procedures • The patients were seated in an IAC booth facing a loudspeaker at a distance of 1 meter. The patients listened to five practice sentences before each of the 15 test conditions, and one sentence list (20 sentences) was used in each test condition. Sentences were scored as total words correct, and the score was reported as the overall percent correct for the sentence list.

Results

The results are shown in Figure 7. Performance in the 72 dB condition is shown in the left panel, performance in the 52 dB condition is shown in the middle panel, and performance in the 72 dB at +10 dB SNR condition is shown in the right panel. In each panel, performance is shown as a function of microphone sensitivity. Performance with IDR settings of 30 dB and 40 dB is shown by filled and open symbols, respectively.

For sentences presented at conversational levels in a quiet background (72 dB SPL) a repeated-measures ANOVA showed no significant effect of microphone sensitivity or IDR on performance ($p > 0.05$) but a significant interaction ($F_{(2,28)} = 4.29, p = 0.029$). Performance at conversational levels in quiet was worst when patients used extreme device settings (i.e., high sensitivity with high IDR or low sensitivity with low IDR).

For sentences presented at a soft level in a quiet background (57 dB SPL), a repeated-measures ANOVA showed a main effect for IDR ($F_{(1,9)} = 157$, $p < 0.0001$), a main effect for microphone sensitivity ($F_{(2,18)} = 79, p < 0.0001$), and a significant interaction ($F_{(2,18)} = 12.8$, $p < 0.001$). Performance was worst in one extreme condition (i.e., low sensitivity with low IDR) and best in the other extreme condition (i.e., high sensitivity with high IDR).

For sentences presented at a conversational level in noise (72 dB SPL at +10 dB SNR), a repeated-measures ANOVA showed a main effect for IDR ($F_{(1,9)} = 9.07, p = 0.014$), a main effect for sensitivity ($F_{(2,8)} = 15.01$, $p < 0.0001$), and no significant interaction ($p > 0.05$).

Discussion

The aim of Experiment 2 was to assess the effects of sensitivity and IDR on the sentence recognition abilities of patients who use the 3G device. Specifically, we wondered if some of the outcomes of Experiment 1 could be accounted for by IDR and sensitivity settings.

Sensitivity Settings • Sentence understanding at comfortably loud levels in a quiet background was unaffected by sensitivity setting. There was, however, a significant and opposite, effect of sensitivity setting in both of the difficult listening environments. We speculated in Experiment 1 that the better performance for some patients when listening to soft speech (3G soft) could be attributed to a higher sensitivity setting and the better performance for other patients when listening to speech in noise (3G noise) could be attributed to a lower sensitivity setting. As shown in Figure 7, we found that a high sensitivity setting produced a mean advantage of nearly 55 percentage points for understanding soft speech, a medium sensitivity allowed similar scores in both conditions, and a low sensitivity setting produced a mean advantage of nearly 30 points for understanding speech in noise. These differences in performance are remarkably similar to those observed in individual 3G patients at the far left, center, and far right of Figure 4a. With respect to Experiment 1, this outcome suggests that the pattern of results observed in individual 3G patients and the group performance differences in noise and at soft levels probably were related to the sensitivity settings used by 3G patients.

Input Dynamic Range • At comfortably loud levels in a quiet background (72 dB SPL), performance was unaffected by IDR setting. For sentences presented at a soft conversational level, we found, as expected, significant benefits of a wide IDR. When microphone sensitivity was medium, increasing the IDR from 30 dB to 40 dB IDR improved performance by an average of 35 percentage points. In contrast, when microphone sensitivity was medium, increasing the IDR from 30 dB to 40 dB produced an 11-point drop in performance for sentence understanding in noise.

Thus, with the 3G system, increasing IDR improves performance for soft speech but hinders performance for speech in noise—an outcome consistent with previous reports (Cochlear Limited, 2001, 2002; James et al., 2003). In contrast, there was no evidence from Experiment 1 to suggest that patients using a wide IDR, the CII and Tempo+ patients, had sacrificed performance in noise for better performance at low signal levels. This outcome was most noticeable for the CII group, who achieved high scores at soft presentation levels and in noise.

General Discussion • The outcomes of Experiment 2 suggest that performance with the 3G device (i) is significantly influenced by IDR and sensitivity settings, (ii) is improved for soft speech using a wider IDR and/or a higher sensitivity setting, and (iii) is improved in noise with a narrow IDR and/or a low to medium sensitivity setting. The relation between intelligibility of soft speech and IDR or sensitivity setting is directly related to audibility and provides a reasonable account for the performance differences reported in Experiment 1.

The outcomes of Experiment 2 demonstrate that if the 3G patients in Experiment 1 had been tested with a wider IDR to improve performance at soft presentation levels, then their performance in noise would have suffered. Given this outcome, we should wonder why, in Experiment 1, the effects of noise on speech understanding were not more pronounced for the CII and Tempo+ patients, as these devices used a wider IDR than the 3G device. To find out, we conducted a third experiment.

EXPERIMENT 3

The outcome of Experiment 2, i.e., that for speech in noise, a narrow IDR allowed higher levels of performance than a wide IDR, was not consistent with the outcome of Experiment 1. In that experiment, devices with a wide IDR (55 dB or greater) allowed relatively high levels of performance for both soft speech and for speech in noise.

Given the contradictory views of the effects of a wide IDR on speech recognition in noise offered by the results of Experiments 1 and 2, in Experiment 3 we varied IDR over the range 30 to 60 dB for patients fit with the CII device. Our aim was to assess whether variations in IDR affected patients fit with this device in the same manner as patients fit with the 3G device.

METHODS

Patients

Ten patients, using the CII BTE speech processor, the CII Bionic Ear cochlear implant system and the HiResolution speech coding strategy, were recruited for this study. All 10 patients had previously participated in Experiment 1. A minimum period of 6 mo elapsed between test periods. A unique set of sentence lists was used in this study to ensure that no patient had prior exposure to the test material.

Before testing, patients were asked to use the device setting they most commonly used for everyday situations. With the exception of IDR, alterations to the device settings were not allowed during testing. Patients were allowed approximately 5 minutes to adjust to each IDR setting.

Material

The AzBio sentence lists used in Experiment 3 were taken from the same sentence corpus described in Experiment 2. The patients had no previous exposure to this material. A total of 12 AzBio sentence lists were used in this test (one list per condition). Each list consisted of five practice sentences and 20 test sentences. Patients were asked to repeat back the sentences and were encouraged to guess when unsure. All sentences and lists were scored as words correct and overall percent correct was computed. Patients were seated in a sound-treated booth. Sentences were presented at 77 dB SPL in quiet, 57 dB SPL in quiet, and 77 dB SPL at +10 dB SNR (four-talker babble) through a clinical audiometer using a single speaker located at 0°

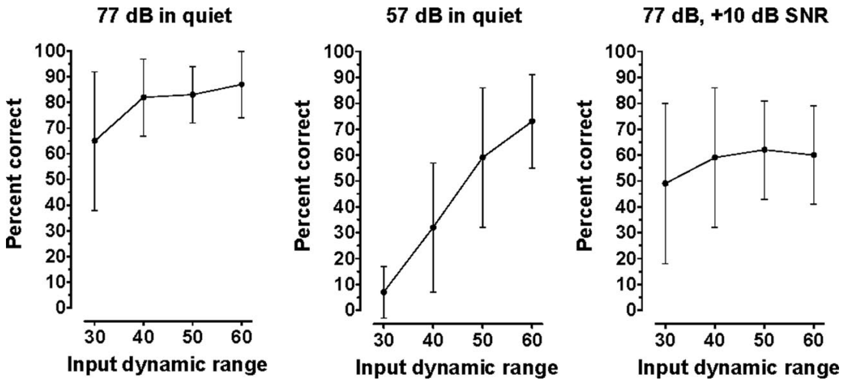

Fig. 8. Performance levels of patients using the CII cochlear implant system for AzBio sentence material presented at 77 dB SPL in quiet, 57 dB SPL in quiet, and 77 dB SPL at +10 dB SNR as a function of IDR setting. Error bars indicate ±1 standard deviation of the mean.

azimuth, approximately 1 meter from the listener. The list order was randomized for each patient.

Input Dynamic Range • Patients were tested by using their everyday program with IDR settings of 30, 40, 50, and 60 dB. The condition order was randomized for each patient.

Results

Group mean scores achieved on tests of sentence understanding are shown in Figure 8. Performance on sentences presented at a loud conversational level in quiet (77 dB SPL) is shown in the left panel, performance on sentences presented at soft levels in quiet (57 dB SPL) is shown in the middle panel, and performance at conversation levels in noise (+10 dB SNR) is shown in the right panel.

A repeated-measures ANOVA revealed a significant main effect of IDR on sentence understanding for material presented at a conversational level in quiet ($F_{(3,27)} = 5.68$, $p = 0.003$). A post hoc Fisher's protected LSD test revealed performance in the 30 dB IDR condition (mean = 65.5%, SD = 27.7%) was significantly ($p < 0.05$) lower than performance in both the 50 dB IDR (mean = 83.0%, SD = 11.5%) and 60 dB IDR (mean = 87.5%, SD = 12.7%) conditions. There were no significant differences in performance for IDR settings of 40 dB (mean = 78.9%, SD = 15.2%), 50 dB, or 60 dB.

A repeated-measures ANOVA revealed a significant main effect of IDR on understanding of AzBio sentence material presented at a soft level in quiet ($F_{(3,27)} = 58.75$, $p < 0.0001$). A post hoc Fisher's protected LSD test revealed a significant improvement in performance as IDR was increased from 30 dB (mean = 6.9%, SD = 10.4%) to 40 dB (mean = 31.9%, SD = 25.1%), from 40 dB to 50 dB (mean = 58.6%, SD = 27.1%) and from 50 dB to 60 dB (mean = 72.9%, SD = 17.97%). With an IDR setting of 60 dB, performance on sentences presented at a soft level was significantly worse than performance on sentences presented at a conversational level ($t = 4.3$, $p < 0.0001$).

A repeated-measures ANOVA revealed a significant main effect of IDR on understanding of AzBio sentence material presented in noise ($F_{(3,27)} = 3.33$, $p = 0.03$). A Fisher's protected LSD test revealed performance in the 30 dB IDR condition (mean = 47.2%, SD = 31.0%) was significantly ($p < 0.05$) worse than performance with IDR settings of 40 dB (mean = 59.4%, SD = 27.1%), 50 dB (mean = 61.9%, SD = 19.3%), and 60 dB (mean = 59.7%, SD = 19.3%).

Discussion

Increasing input dynamic range with the CII cochlear implant system significantly improved sentence understanding for material presented at conversational levels in quiet, conversational levels in background noise, and low input levels in quiet. As we found for the 3G patients in Experiment 2, the greatest effect of increasing IDR settings was found for speech presented at soft levels. For speech presented at conversational levels in quiet and in noise, performance only improved as IDR was increased from 30 dB to 40 dB. The degraded performance in the 30 dB IDR condition is likely a combination of the decreased audibility of the speech signal and the patients' lack of familiarity with the setting, as all patients used an IDR of 60 dB or greater in their everyday processor. For CII patients, these outcomes indicate that to achieve high levels of performance for speech presented in quiet, noise, and low input levels, a large IDR of 60 dB is useful.

The results from Experiment 2 and Experiment 3 demonstrate that increasing input dynamic range, in both the CII and 3G device, improves speech understanding for sentences presented at low input levels. However, increasing input dynamic range did not have a uniform effect on patients for sentence material presented in background noise. As input dynamic range was increased, sentence understanding in noise improved for patients using the CII device and decreased for patients using the 3G device. This pattern of results suggests that the effects of IDR on speech understanding vary by device. It is unlikely that improving the audibility of low-level noise should be beneficial to one group of patients and detrimental to another based on some biographic factor. More likely, the different patterns of behavior are due to differences in how IDR is expanded in each system.

As shown in Figure 5a, the CII device applies a constant level of compression to inputs mapped between threshold and maximum comfort levels (Zeng et al., 2002). A similar procedure is used in the Tempo+ speech processor (Figure 5c), although the IDR mapped between minimum and maximum stimulation levels is fixed at 55 dB (Spahr & Dorman, 2005; Stöbich, Zierhofer, & Hochmair, 1999). Such a compression function has been shown to have minimal effect on the signal-to-noise ratio of the processed signal (Souza, Jenstad & Boike, 2006).

When increasing the IDR of the 3G speech processor using the Whisper setting, the overall shape of the compression function applied to the input signal is altered (Figure 5b). Specifically, the Microphone setting applies no compression (1:1) to signal levels up to 30 dB below the knee-point for infinite compression. The Whisper setting applies higher level compression to input levels above 52 dB SPL (Cochlear Limited, 2002).

Boike & Souza (2000) investigated the effect of different compression-amplification schemes on speech understanding for normal-hearing and hearing-impaired listeners. They found that applying compression to input signals above 45 dB SPL had no effect on normal-hearing listeners in quiet or noisy backgrounds and no effect on hearing-impaired listeners in quiet backgrounds but significantly degraded understanding for hearing-impaired listeners in noise. They speculated that the decrements in performance observed with hearing-impaired listeners for speech in noise were due to differences in gain applied to low-level noise (1:1) and compression applied to the higher amplitude portions of speech. Differences in compression would effectively reduce the level of the high-amplitude peaks of the waveform (speech) relative to the medium (speech and noise) and low (noise) amplitude components, potentially decreasing the signal-to-noise ratio and creating a more difficult listening environment.

Given the results of Boike & Souza (2000), it is reasonable to ascribe the different trends in performance for the CII and 3G patients, found with increasing input dynamic range, to differences in the manner by which IDR is increased. Specifically, increasing IDR in the 3G device applies additional compression to signal levels above 52 dB SPL. This compression is detrimental to speech understanding in noise as the peaks of speech are reduced relative to the less compressed noise. This increased difficulty understanding speech in noise may also explain why the 3G patients in Experiment 1 preferred to use the Microphone setting and not the Whisper setting as their "everyday" program.

Further, the performance differences found in 3G patients for sentences presented at a soft level and for sentences presented in noise in Experiment 1 probably are related to the individual preferences for sensitivity settings. We suggest that because these patients were unable to increase the IDR of their device without experiencing greater difficulty understanding speech in noise, they relied on sensitivity setting to maximize the audibility of the target signal. Because patients were not able to adjust processor settings during the testing in Experiment 1, those who preferred high sensitivity experienced difficulty in noise and those who preferred low sensitivity experienced difficulty at low presentation levels. This trade-off in performance probably accounts for the degraded group performance when sentences were presented in noise and at low levels. In contrast, applying a constant compression ratio at wide IDR settings in the CII and Tempo+ speech processors allowed patients to perform well in noise and at low input levels without the need for adjustments to processor settings.

General Discussion • The patients in this study were chosen on the basis of high scores on a test of CNC recognition in quiet. The motivation for this criterion was to prevent floor effects in performance when the patients were tested in noise. As a result of this criterion, we have tested patients who score above average, and sometimes far above average, on tests of speech understanding (see, for example, Helms et al., 1997; Wilson, 2006). We discuss first, what we have learned about the speech perception skills of this group of patients.

The best performing patients achieved scores on CNC recognition near 90% correct, achieved scores on CUNY sentence recognition of 100% correct, and achieved scores on the AzBio sentences near 90% correct. The latter score demonstrates that the best patients can function at a very high level in a quiet environment even when material includes multiple speakers, all speaking with normal conversational inflection and rate. However, when signals were presented at signal-to-noise ratios that have no or little effect on sentence intelligibility for normal hearing listeners, e.g., at +10 and +5 dB SNR, performance for the most successful patients fell by approximately 20 and 40 percentage points, respectively. Thus, modern cochlear implants can restore very high levels of speech understanding in quiet but allow poor speech understanding in levels of noise commonly found in the workplace (National

Institute for Deafness and Other Communication Disorders, 1990).

Performance on speech material that emphasized temporal/envelope cues, e.g., consonant voicing and manner, was better than performance on tests that emphasized cues in the spectral domain (e.g., consonant place of articulation). This type of outcome has been reported for many years (e.g., Blamey, Dowell, Brown, Clark & Seligman, 1987; Dorman, Dankowski, McCandless & Smith, 1990; Rosen, Walliker, Brimacombe & Edgerton, 1989). Over time, both scores for speech material that emphasized temporal/envelope cues and scores for material that emphasized spectral cues have improved. However, because temporal/envelope information could be received at a modest level by patients fit with a single channel implant (Rosen et al., 1989), it is receipt of spectral information that has changed the most over time.

All patients achieved high scores on the test of between-gender (male-female) speaker discrimination. This indicates that patients find it easy to discriminate between signals with large F0 differences, e.g., 100 Hz. However, patients were much worse at discriminating speakers within a gender. Patients were also very poor at melody recognition—a task that required coding of small frequency differences in low-frequency signals. These two outcomes indicate that even cochlear implant patients who achieve very high levels of speech understanding receive only modest amounts of low-frequency information, either spectrally or temporally.

As we noted in the introduction, the three devices tested here differed along multiple dimensions—type of signal processing, the number, depth, and location within the scala tympani of intracochlear electrodes, the maximum pulse rate, the default setting of the IDR, and, without doubt, a host of other engineering details not available in the public record. Much attention has been given, in the research literature and in advertising, to the type of signal processing, the number, type, and location of electrodes, and the pulse rate. Yet, if our interpretation of our data is correct, none of these factors played significant roles in the differences in performance we have found. Instead, the IDR, the setting of microphone sensitivity, and the methods for implementing compression appear to be the major factors responsible for the differences in performance. Our findings suggest a versatile speech processor would (i) use a wide IDR (55 dB or greater) and (ii) apply constant compression throughout the IDR.

Finally, we note that the newest member of the Nucleus family of speech processors, the Freedom 4, which became available after this research was completed, uses a larger input dynamic range (45 dB) than the 3G.

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