Interactions between cochlear implant electrode insertion depth and frequency-place mapping

Deniz Başkent[a)]
Department of Biomedical Engineering, University of Southern California, Los Angeles, California 90089 and House Ear Institute, 2100 West Third Street, Los Angeles, California 90057

Robert V. Shannon
Department of Biomedical Engineering, University of Southern California, Los Angeles, California 90089 and House Ear Institute, 2100 West Third Street, Los Angeles, California 90057

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While new electrode designs allow deeper insertion and wider coverage in the cochlea, there is still considerable variation in the insertion depth of the electrode array among cochlear implant users. The present study measures speech recognition as a function of insertion depth, varying from a deep insertion of 10 electrodes at 28.8 mm to a shallow insertion of a single electrode at 7.2 mm, in four Med-El Combi 40+ users. Short insertion depths were simulated by inactivating apical electrodes. Speech recognition increased with deeper insertion, reaching an asymptotic level at 21.6 or 26.4 mm depending on the frequency-place map used. Başkent and Shannon [J. Acoust. Soc. Am. **116**, 3130–3140 (2004)] showed that speech recognition by implant users was best when the acoustic input frequency was matched onto the cochlear location that normally processes that frequency range, minimizing the spectral distortions in the map. However, if an electrode array is not fully inserted into the cochlea, a matched map will result in the loss of considerable low-frequency information. The results show a strong interaction between the optimal frequency-place mapping and electrode insertion depth. Consistent with previous studies, frequency-place matching produced better speech recognition than compressing the full speech range onto the electrode array for full insertion ranges (20 to 25 mm from the round window). For shallower insertions (16.8 and 19.2 mm) a mild amount of frequency-place compression was better than truncating the frequency range to match the basal cochlear location. These results show that patients with shallow electrode insertions might benefit from a map that assigns a narrower frequency range than patients with full insertions. © *2005 American Institute of Physics.* [DOI: 10.1121/1.1856273]

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I. INTRODUCTION

Recent studies on cochlear implants and simulations of cochlear implants have suggested that speech recognition is optimized when the frequency information is presented to the normal acoustic tonotopic cochlear location (Dorman *et al.*, 1997; Fu and Shannon, 1999a, b; Başkent and Shannon, 2003, 2004). Frequency-place maps that are shifted or distorted relative to the normal tonotopic map reduce speech recognition. However, if an electrode array is not fully inserted, the lowest frequency represented by the most apical electrode of that array may be 2000 Hz or higher. Matching frequency information to the acoustic tonotopic place in this case will result in the loss of a range of frequencies that is critical for speech recognition. The present study investigates the trade-off between such loss of low-frequency information when the acoustic input range is matched to the stimulation range, and distortion in the frequency-place mapping when a wider range of input acoustic range is assigned compressively.

More speech information could theoretically be delivered with longer and more deeply inserted electrode arrays. Blamey *et al.* (1992) and Skinner *et al.* (2002) found a significant correlation between open-set speech recognition scores of Nucleus 22 users and the insertion depths of the electrode arrays. Yet, Hodges *et al.* (1999) found no correlation between speech recognition and electrode insertion depth for insertion depths ranging from 17 to 25 mm. One complicating factor in these studies was that the speech performance was compared across different subjects with different array insertions rather than within subjects. If different pathologies contributed to the differences in electrode insertion depth, those pathologies might have also affected the residual nerve survival, and so speech recognition. In such a case poorer speech recognition with short electrode insertion may not be due to the short insertion *per se*, but rather due to the covarying pathology. Studies that simulated different insertion depths within subjects by selective activation of more apical electrodes found that deeper insertion generally resulted in improved speech recognition (Kileny *et al.*, 1998; Hochmair *et al.*, 2003).

Even though current electrode designs are intended to achieve array insertions as deep as 30 mm (Gstoettner *et al.*, 1999; Hochmair *et al.*, 2003), obstructions in the cochlea as a result of new bone formation, cochlear otosclerosis, or anatomical abnormalities might still prevent the full insertion of the array (Cohen and Waltzman, 1993). For example, three studies that used imaging methods to assess actual electrode

[a)]Electronic mail: dbaskent@hei.org

insertion depth (Cohen *et al.*, 1996; Ketten *et al.*, 1998; Skinner *et al.*, 2002) observed a range of insertions of Nucleus patients from 2 to 26 mm from the round window. There are also cases where a short array is used on purpose to preserve the residual acoustic hearing for a combined electric-acoustic stimulation (Kiefer *et al.*, 2004).

With such large variation in electrode insertion depths it becomes crucial to customize the frequency-place map for the individual implant user to achieve the best speech perception. Başkent and Shannon (2003) measured speech recognition by normal-hearing (NH) listeners in conditions that simulated cochlear implant processing. Their results suggested that implant users with full electrode array insertions (from 20 to 25 mm) would have the best speech recognition when the acoustic information was mapped onto the matching tonotopic range in the cochlea, even if that mapping resulted in the elimination of a considerable amount of acoustic information. A second study confirmed this finding with Med-El Combi 40+ users (Başkent and Shannon, 2004). In an earlier study, Whitford *et al.* (1993) modified the frequency-place map to match the characteristic frequencies of the electrode locations in the cochlea. They assigned the acoustic input at 3 kHz to the electrode at the cochlear location with the characteristic frequency of 3 kHz. The remaining acoustic input range was redistributed over the remaining electrodes around the matched electrode. Nucleus-22 users with array insertions from 20.5 to 23.5 mm had improved open-set sentence recognition scores in low levels of noise with the modified map. However, Eyles *et al.* (1995) did not observe significant improvement with Nucleus-22 patients with shallower insertion depths (from 14 to 21.5 mm) when tested with similar mapping strategy.

These studies imply that there is a strong interaction between the optimum frequency-place map and the electrode array insertion depth. It is important to quantify this interaction, considering that the electrode array insertion depth varies widely across individual patients. Speech recognition performance is generally very low for patients with shallow insertions. Many implant speech processors map the full range of frequencies onto the electrodes compressively even in cases of short electrode insertions, which might result in substantial frequency-place compression and shifting. One reason for a compressed map is to provide the patient with the full range of acoustic information with the assumption that she would eventually learn to make use of the information even if it is distorted in terms of cochlear tonotopic place. Several studies have shown evidence of partial adaptation (Rosen *et al.*, 1999; Fu *et al.*, 2002), but it is not clear if patients can fully adapt to a large distortion in the mapping and, if so, how much time such an adaptation would require. Studies of frequency-place distortions (Başkent, 2003; Başkent and Shannon, 2003, 2004) or frequency place shifts (Fu and Shannon, 1999b) showed a tolerance of only a few mm for such tonotopic distortions. Trinh *et al.* (2000) observed no significant improvement in speech recognition with five of eight Nucleus 22 users with partial insertions, over periods of time ranging from 12 to 60 months. This finding suggests that patients with short electrode insertions may only have a limited ability to adapt to the frequency-place compression normally assigned in such cases.

On the other hand, a strict matching of frequency information to cochlear place with short insertions would result in the loss of substantial low-frequency information that is important for speech. The Speech Intelligibility Index (SII), which predicts the speech recognition performance from the amount of audible acoustic information available (ANSI, 1997), weights frequency information between 1 and 3 kHz most heavily. When the speech frequency range is converted to cochlear location (Greenwood, 1990), the cochlear region around 14 to 28 mm from the round window receives speech information, with the most critical information concentrated between 18 and 25 mm. The 900-Hz region (21.5 mm) is important for the distinction of the first two formants of vowels, while the 1.5-kHz region (18.5 mm) is important for the distinction of high and low second formants. If the insertion depth is shallower than 19 mm, and frequency information is matched to the normal acoustic tonotopic place, then all frequencies lower than 1.3 kHz will be lost. Such a truncated map might be harmful for speech recognition, even though the acoustic information is delivered to the correct tonotopic location (Faulkner *et al.*, 2003).

The present study measures phoneme and sentence recognition in Med-El Combi 40+ implant users as a function of electrode array insertion depth and stimulation range. Experiment 1 extends the results from Başkent and Shannon (2003, 2004) to a wider range of insertion depths (varying from a shallow insertion depth of 7.2 mm with a single electrode to a deep insertion of 28.8 mm with an array of 10 electrodes), where the performances with compressed and matched maps are compared. Experiment 2 explores an optimum map for the shallow insertions of 19.2 and 16.8 mm by systematically changing the map from matched to fully compressed.

II. EXPERIMENTAL METHOD

A. Subjects

Four Med-El Combi 40+ users, aged 25–62, participated in the experiments. All were reported to have full electrode insertions at surgery. An insertion depth of 31 mm, which complies with company specifications, was assumed for all subjects. Information about subjects, such as duration and type of deafness, duration of implant use, baseline speech recognition scores, and the frequency ranges used in the clinical processor, is summarized in Table I. Table II additionally shows the center frequencies of the clinical maps the subjects use most.

M1, M3, and M4 were postlingually, and M2 was prelingually deafened. All subjects were born into hearing families, used oral communication as their main communication mode, and had been provided with speech correction therapies for long periods of time. Only M2 has used sign language frequently as an additional communication mode. All patients could converse over the telephone with their implants.

TABLE I. Information about Med-El Combi 40+ users.

Subject	Age	Duration of profound deafness (years)—reason of deafness	Experience with CI (years)	Baseline vowel score (corrected for chance)	Baseline consonant score (corrected for chance)	Baseline IEEE sentence score	Overall acoustic input frequency range of the original map and number of the electrodes activated
M1	39	30—High fever	2.5	60.0	55.3	38.2	300–5500 Hz, 6 or 12 electrodes later: 200–8500 Hz, 10, 11, or 12 electrodes
M2	25	From birth—Unknown	5	70.0	85.9	84.5	300–7000 Hz, 9 or 12 electrodes
M3	62	12—Noise exposure	1	68.2	70.2	92.8	300–5500 Hz, all 12 electrodes
M4	46	26—Unknown	2	82.5	86.7	93.9	Map 1 and 2: 300–5500 Hz Map 3: 300–7000 Hz 9 electrodes

B. Speech stimuli

The speech recognition tasks consisted of medial vowel and consonant identification, and sentence recognition.

Vowel stimuli (Hillenbrand *et al.*, 1995) consisted of 12 medial vowels, including 10 monophthongs and 2 diphthongs, presented in /h/-vowel–/d/ context (heed, hid, head, had, hod, hawed, hood, who'd, hud, heard, hayed, hoed) and spoken by five female and five male talkers. Chance level on this test was 8.33% correct, and the single-tailed 95% confidence level was 12.48% correct based on a binomial distribution.

Consonant stimuli (Shannon *et al.*, 1999) consisted of 20 medial consonants (b tʃ d ð f g ʒ k l m n p r s ʃ t v w j z) presented in /a/-consonant–/a/ context and spoken by three male and three female talkers. Chance performance level for this test was 5% correct, and the single-tailed 95% confidence level was 8.27% correct based on a binomial distribution.

IEEE sentences (IEEE, 1969), spoken by a single male speaker, are phonetically balanced across lists and the predictability of the words is relatively low. For each condition, the percent-correct score was acquired from 20 sentences of varying length from each listener. The length of each sentence varied from 5 words to 12 words. Lists of 20 sentences for each condition were prepared such that the average word length per sentence was 7 to 9 words. Sentences were presented without any context information, and no sentences were repeated to an individual listener.

C. Med-El Combi 40+ implant system

Combi 40+ electrode array consists of 12 electrode pairs equally distributed over 26.4-mm total length. The electrodes are numbered 1 to 12 from apex to base. The array is inserted through a cochleostomy around 4 mm from round window. In the study we used a TEMPO+ processor worn behind the ear, which can process frequencies from 200 Hz to 8.5 kHz.

D. Procedures

The study explores the acute effects of frequency-place maps on speech recognition. In both experiments the subjects were tested right after receiving the experimental processor.

The experimental processor was programed with a different frequency-place map before each test condition. All stimuli were presented via a loudspeaker in a sound field at

TABLE II. Center frequencies of clinical maps the subjects used most.

	Bandpass filter center frequencies for 12 electrodes (Hz)											
Subject	1	2	3	4	5	6	7	8	9	10	11	12
M1,M3	338	430	549	701	894	1137	1444	1845	2349	2987	3889	4918
M2	358	507	Off	722	1017	Off	1445	2057	Off	2890	4225	6013
M4	352	487	Off	672	930	Off	1273	1771	Off	2420	3456	4544

70 dB on an A-weighted scale. Phonemes were presented to the listeners in random order via custom software (Robert, 1998). Subjects were asked to select the phoneme they heard from the set of all possible phonemes displayed on the screen. Recognition of words in sentences was evaluated using custom software (TIGER Speech Recognition System developed by Qian-Jie Fu) which presented the sentences in random order. Subjects were asked to type the sentence they heard, and the number of words heard correctly was counted.

The implant processor, fitting software STUDIO+, and the fitting box were provided by Med-El for use in the experiments. The threshold and maximum comfort levels were measured with the research processor for each patient before testing and these levels were used throughout the experiments. Maximum stimulation rate was limited to 2 kpps per electrode. The electrodes were stimulated in monopolar mode and the processing strategy was continuous interleaved sampling (CIS).

The STUDIO+ software allows the programmer considerable flexibility in manually entering the bandpass filter cutoff frequencies that are assigned to each electrode. In every condition the acoustic input range was converted to cochlear distance in mm by the Greenwood mapping function. The range was divided into bandpass filters with equal bandwidths in mm, which were then converted to frequency in Hz with the Greenwood mapping function.

Greenwood's function describes the characteristic frequency along the organ of Corti as a function of cochlear place. In healthy cochlea, the maximum displacement on the basilar membrane shifts as a function of sound level. However, in implants, the place information does not come from the basilar-membrane motion. Instead, it is conveyed by selective stimulation of the spiral ganglia electrically. In our calculations, we assumed that Greenwood's function similarly holds at the level of spiral ganglia, and ignored effects of stimulation level.

We also assumed an average length of 35 mm for the cochlea in the calculations. Ulehlova *et al.* (1987) measured a range of 28 to 40 mm, with an average length of 34.2 mm, for human cochleae. However, Başkent and Shannon (2004) showed that a change of a few mm in the assumed length for the cochlea did not have a significant effect on speech recognition.

A third assumption in the study is uniform distribution of the nerve survival pattern. Any possible dead regions in the auditory nerve would be difficult to locate with implant users. Since we have not observed any abnormal threshold patterns during the fitting, we assumed the simplest case of uniform distribution for nerve survival pattern.

III. EXPERIMENT 1: FREQUENCY-PLACE MAPPING WITH VARYING INSERTION DEPTH

A. Experimental setup

In experiment 1, we changed the effective insertion depth by turning off the most apical electrode for each successive condition.

In the baseline condition, the 10 middle electrodes (numbered 2 to 11) were activated. We assumed an insertion depth of 31 mm for full insertion of the entire array. With this assumption, the middle 10 electrodes cover a cochlear range between 7.2 and 28.8 mm from the round window, which, according to the Greenwood frequency-place function, corresponds to a range of acoustic frequencies between 244 Hz and 7.5 kHz. Thus, the baseline condition simulates a deeply inserted (at 28.8 mm) array of 10 electrodes with a stimulation range of 21.6 mm. From this deep insertion condition the most apical electrode was turned off for each successive experimental condition. Because the electrode separation is 2.4 mm, each condition created an insertion depth that was 2.4 mm shallower than the previous condition. Note the number of the electrodes decreases by one with each successive condition as well.

In the first part of the experiment the acoustic input range was kept the same for all insertion depths (244 Hz–7.5 kHz). Starting from the baseline condition of 10 electrodes, where the acoustic input range matched the stimulation range, the map becomes increasingly compressive with each successive condition, as shown for the partial insertion condition of 6 electrodes in the upper part of Fig. 1. The acoustic input range assigned onto the electrodes is shown by the frequency bands on top, while the stimulation region covered by the actual electrode array is shown in the bottom of the map. These conditions simulate the clinical approach where the patient gets the same standard input frequency range in the map regardless of the actual location of the electrode array or the number of electrodes activated in her cochlea.

In the second part of the experiment, the acoustic input frequency range was truncated to match the stimulation range for all insertion depth conditions. In such a matched map, as the stimulation range gets smaller with each condition, the patient receives less acoustic information, as shown in lower portion of Fig. 1.

All compressed and matched conditions for all number of electrodes are summarized in Table III. The frequencies in the table show the actual frequencies STUDIO+ used rather than the theoretical values calculated with Greenwood mapping function.

B. Results and discussion

The individual percent-correct scores are shown in Fig. 2 as a function of insertion depth, expressed both in cochlear distance from the round window and in number of electrodes activated. The top, middle, and bottom rows present vowel, consonant, and sentence recognition scores, respectively. Vowel and consonant scores were corrected for chance level. M1 was excluded from the sentence recognition test due to her inability to recognize IEEE sentences at a reasonable level with the experimental maps. The open symbols show the percent-correct scores with the compressed map (upper part of Fig. 1) and the filled symbols show scores with the matched map (bottom part of Fig. 1). The dashed lines show the performances of subjects with their own processor maps, for which the center frequencies are shown in Table II. The baseline condition of 10 electrodes is slightly different from this map. Some subjects performed as well with the baseline condition of 10 electrodes as they did with their own map,

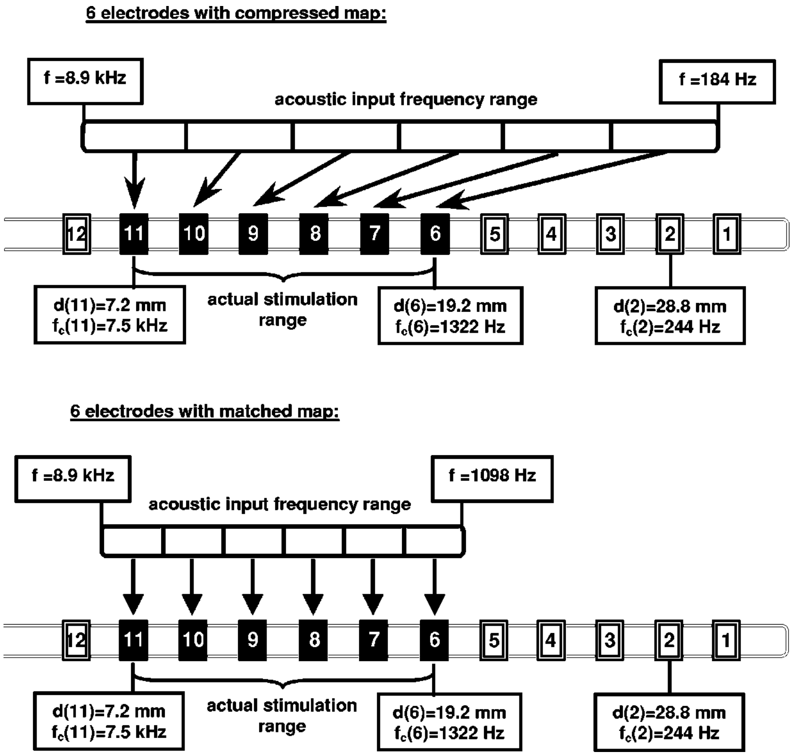

FIG. 1. Compressed and matched maps for the partial insertion condition of 6 electrodes, simulated by activating electrodes 6–11. In each map, the frequency bands on top show the acoustic input range. The lowest and highest frequencies are given at both ends of the input range. The bottom row of each map shows the electrode array with all 12 electrodes, with active electrodes shown in black. The stimulation range in the cochlea is determined by the position of the active electrodes. Assumed distances of the electrodes 2, 6, and 11 from the round window and the center frequencies calculated by Greenwood function based on these distances are shown under the electrodes. The upper part of the figure shows the compressed map, where the wide acoustic range is assigned onto the stimulation range compressively. The lower part of the figure shows the matched map, where the acoustic input range is truncated to match the stimulation range.

while some subjects performed worse. The subjects who performed worse might be more sensitive to spectral changes in the frequency-place mapping.

Figure 2 shows that performance dropped with both matched and compressed maps as the insertion depth became shallower. Findings from previous studies imply that there are several factors contributing to the decrease in performance: decrease in the number of electrodes (Friesen *et al.*, 2001), transmitting a smaller portion of the speech spectrum with the matched map (Faulkner *et al.*, 2003; Hochmair *et al.*, 2003), spectral distortions with the compressed map (Başkent and Shannon, 2003, 2004).

The matched and compressed maps produced similar scores for the deep insertion condition of 26.4 mm, probably due to the minimal difference in the acoustic input ranges of these two maps (Table III). At insertion ranges from 19.2 to

TABLE III. Frequency-place mapping conditions with compressed and matched maps for varying insertion depths. The conditions also used in experiment 2 are denoted by symbols Δ, *, +, and ◊.

Condition	Number of active electrodes, electrodes employed	Length of the active electrode array	Insertion depth of the active electrode array (mm)	Input frequency range: center frequency range (Hz), total analysis range (Hz)	
				Compressed map	Matched map
10	10	21.6 mm	28.8	273–7.3 k	273–7.3 k
	(2–11)			214–8.4 k	214–8.4 k
9	9	19.2 mm	26.4	272–7.3 k	393–7.3 k
	(3–11)			212–8.5 k	312–8.4 k
8	8	16.8 mm	24	269–7.3 k	609–7.3 k
	(4–11)			206–8.5 k	496–8.4 k
7	7	14.4 mm	21.6	265–7.2 k	906–7.3 k
	(5–11)			199–8.6 k	745–8.4 k
6	6	12 mm	19.2	275–7.1 k	1332–7.3 k
	(6–11)			201–8.8 k$^{\Delta}$	1108–8.4 k*
5	5	9.6 mm	16.8	293–6.4 k	1896–7.3 k
	(7–11)			207–8.1 k^{+}	1583–8.4 k$^{\diamond}$
4	4	7.2 mm	14.4	342–6.4 k	2676–7.3 k
	(8–11)			238–8.1 k	2250–8.4 k
3	3	4.8 mm	12	461–5.8 k	3803–7.3 k
	(9–11)			315–7.5 k	3199–8.4 k
2	2	2.4 mm	9.6	1.0 k–4.8 k	5557–7.3 k
	(10–11)			682–6.5 k	4673–8.4 k
1	1	single	7.2	4.4 k	—
	(11)	electrode		3.1 k–6.1 k	

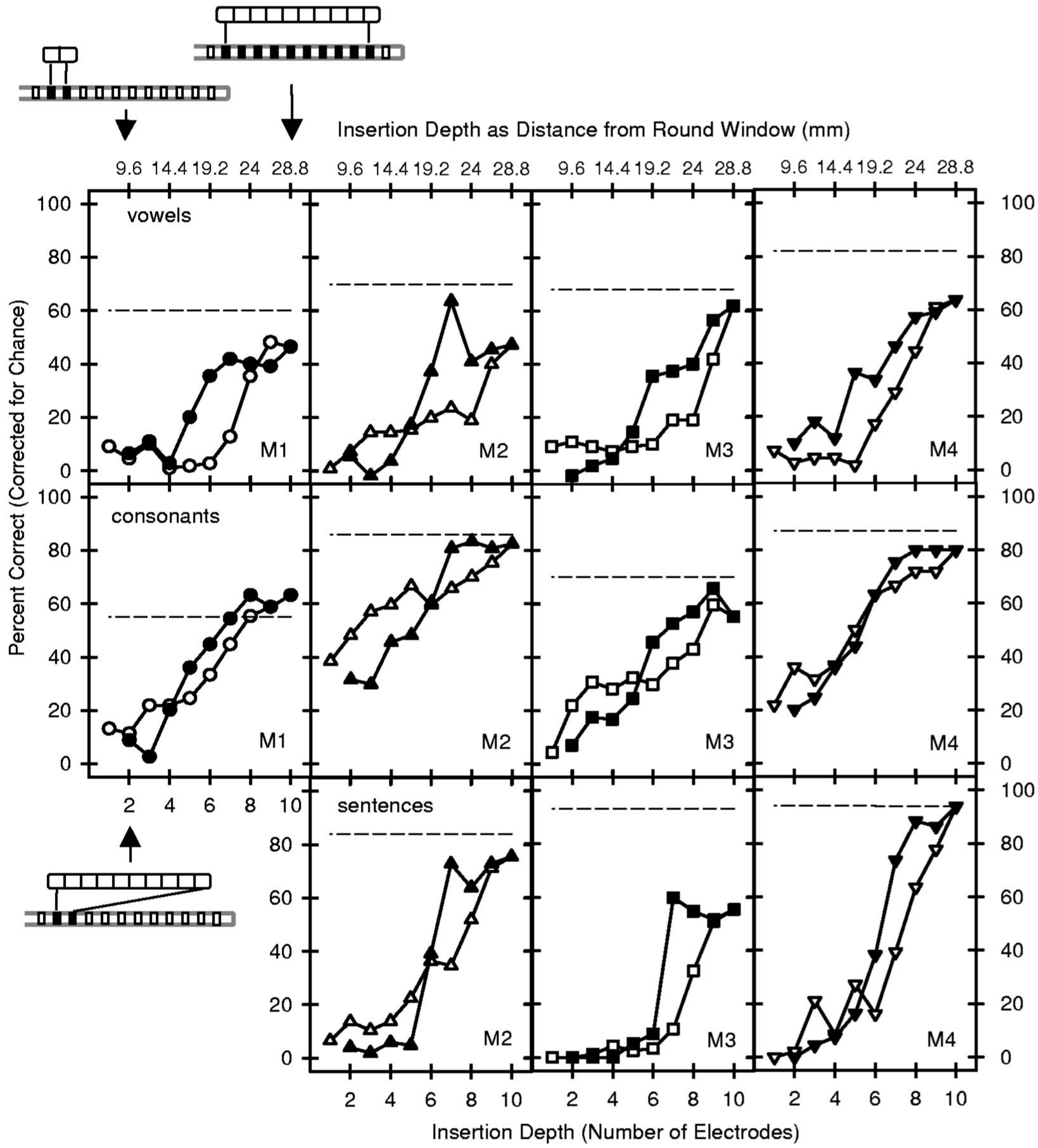

FIG. 2. Individual percent-correct scores from Med-El Combi 40+ users. Filled symbols show the scores when the acoustic frequency range was matched to the cochlear stimulation region (matched map). The figures on top of the first column show the matched maps with 2 and 10 electrodes. Open symbols show the scores when the entire acoustic bandwidth was compressed into the shorter stimulation region (compressed map). The compressed map with the full acoustic input frequency and two apical electrodes activated is shown in the figure under the first column. Dashed lines show the scores the subjects obtained with the map they used most with their own processors. Vowel and consonant recognition scores are corrected for chance level.

24 mm, all subjects performed better with the matched map, consistent with previous studies with fully inserted electrode arrays. Even though the compressed map assigned a larger frequency range, it produced poorer speech recognition due to the distortion in the frequency-place mapping. However, the advantage of the matched map vanished at shallow insertions and compression usually produced better performance. The crossover point was at the insertion depth of 14.4 mm for M1, in the range of 16.8–19.2 mm for M2, and 14.4–19.2 mm for M3 and M4. This transition demonstrates the trade-off between the frequency range delivered to the electrodes and the accuracy of the frequency-place mapping.

A minor but interesting point is that subjects M2 and M4 had higher consonant recognition scores than M1 and M3, which probably also contributed to their higher sentence recognition scores. Note that M2 still identified 40% and M4 identified 20% of consonants correctly even when they had only one electrode active (in Fig. 2). In this condition there is no spectral resolution; the entire spectral range is provided to a single electrode. The carrier pulse rate on the single electrode is simply modulated by the broadband envelope of the speech signal. This observation suggests that M2 and M4 make better use of temporal cues.

To explore a common pattern, the average scores of the subjects are plotted in Fig. 3. Similar to Fig. 2, filled circles show the average percent-correct scores of all patients for phonemes, and average scores of M2, M3, and M4 for sentences, with the matched map. Open circles show the average scores when the subjects were tested with the compressed map. Performance levels with both maps dropped significantly ($p<0.001$) with decreasing insertion depth, for vowels, consonants, and sentences, as shown by one-way repeated measures ANOVAs.

A paired t-test was applied to the scores to compare the

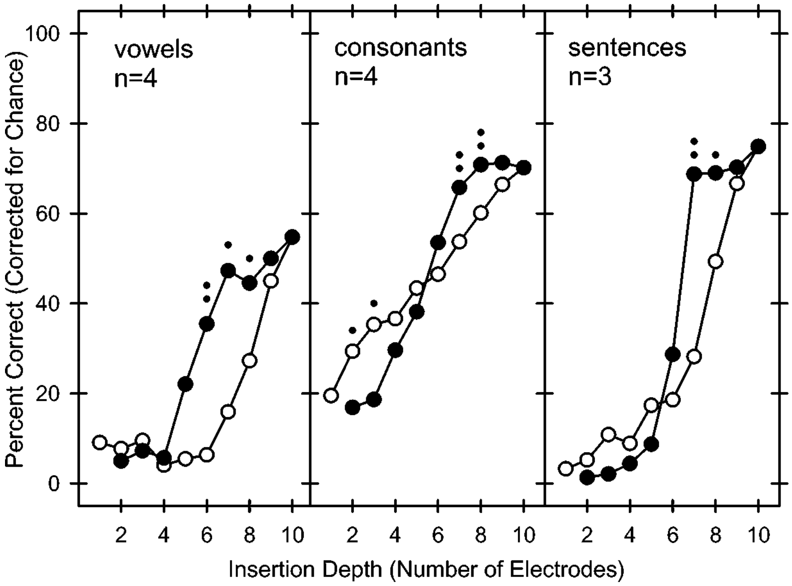

FIG. 3. Average percent-correct scores of M1, M2, M3, and M4 for phonemes, and M2, M3, and M4 for sentences. The open circles show the scores when a wide acoustic range was mapped to electrodes (compressed map), whereas the filled circles show the scores when the acoustic range was truncated to match the stimulation range (matched map). Small dots on top of the scores show the significance level of the difference between the scores from two maps with paired t-test: one dot for $p<0.05$, two dots for $p<0.01$.

two mapping conditions. The level of significance is shown by small dots in Fig. 3. The t-test shows a significant advantage of the matched map for moderate insertion depths (6–8 electrodes for vowels, and 7–8 electrodes with consonants and sentences) and a significant advantage in consonant recognition for the compressed map at very shallow insertions (2–3 electrodes). At insertion depths shallower than 4 electrodes vowel and sentence recognition performances are at floor level and there is no significant difference between compressed and matched maps.

An interesting observation is that scores for both maps reach an asymptotic level with increasing insertion depth (and hence increasing number of electrodes) before the baseline condition of 10 electrodes. The improvement in the performance stops at the insertion depth condition of 9 electrodes for the compressed map, and 7 electrodes for the matched map, as shown by a *posthoc* Tukey test. The frequencies corresponding to these ranges contain useful spectral information for vowel recognition. Therefore, their inclusion in the overall acoustic input range would be expected to increase the performance. On the other hand, this result is consistent with previous implant studies that showed little improvement in speech recognition as the number of electrodes was increased above 7 (Fishman *et al.*, 1997; Friesen *et al.*, 2001). The lack of a significant improvement with further insertion than 7 electrodes (21.6 mm in cochlear distance) might also reflect decreased frequency selectivity in the middle and apical turns of the cochlea when stimulated electrically. Spiral ganglia are located near the habenula perforata, near the medial wall of the scala tympani in the basal turn, but are located more centrally in the modiolus apically. The modiolus gets narrower at the apex so the spiral ganglia are packed in a tight bundle, making selective tonotopic activation difficult. As a result, the anatomy of the cochlea might also be limiting the potential improvement with deeper insertions (Cohen *et al.*, 1996).

Figures 2 and 3 show the trade-off between the amount of acoustic information available versus the accuracy of the location where the information is mapped. The scores in these figures show two extremes, where either the widest acoustic frequency range available was assigned, or it was limited to the matching stimulation range at the expense of losing important acoustic information. It is possible that there might be an optimum range in between where some information is included by truncating the acoustic range less severely and producing a milder distortion in the location where the information is mapped.

The following experiment is designed to explore the possibility of such an optimum map at two insertion depths simulating shallow insertions: 19.2 and 16.8 mm.

IV. EXPERIMENT 2: FREQUENCY-PLACE MAPPING AT 19.2- AND 16.8-MM INSERTION DEPTHS

A. Experimental setup

In the previous experiment, the matched map resulted in significantly better vowel recognition compared to the compressed map at 19.2-mm insertion [with 6 electrodes (6–11) active]. There was little difference between matched and compressed maps for consonant and sentence recognition. When an insertion depth of 16.8 mm was simulated [with 5 active electrodes (7–11)] the performance levels with the matched and compressed maps were not significantly different for all speech materials. Possibly the matched map leaves out too much low-frequency information at these relatively short insertions, while the compressed map introduces too much distortion in the speech patterns. There might be an optimum trade-off between these two extreme maps where a relatively wider acoustic range is assigned onto a relatively accurate cochlear location. To explore this possibility, the frequency-place map was changed from the matched map to the compressed map gradually, while the same set of electrodes was used for each condition.

An insertion depth of 19.2 mm was simulated by activating electrodes 6–11. These electrodes cover 12 mm, from 7.2 to 19.2 mm from the round window, with the assumption of 31 mm for full insertion. The frequency range assigned onto the electrodes was first matched to this stimulation

TABLE IV. Compression conditions for the array of 6 electrodes (electrodes 6–11) inserted 19.2-mm deep and covering 12 mm in the cochlea. The acoustic information assigned onto the array increases as the map changes from 0-mm matching condition to +8-mm compression while the stimulation region remains the same. The maps with * and Δ are same conditions from experiment 1, as shown in Table III.

Frequency-place mismatch condition	Range of acoustic input (mm)	Bandpass filter center frequencies (Hz)						Frequency range of analysis bands (Hz)
		6	7	8	9	10	11	
0 mm (matching)	7.2–19.2	1332	1896	2676	3803	5558	7310	1108–8.4 k*
+1 mm (compression)	7.2–20.2	1132	1664	2472	3597	5146	7290	924–8.5 k
+2 mm (compression)	7.2–21.2	967	1479	2294	3397	5102	7269	773–8.5 k
+3 mm (compression)	7.2–22.2	821	1327	2075	3221	5059	7248	643–8.6 k
+4 mm (compression)	7.2–23.2	695	1160	1894	3051	4695	7226	531–8.6 k
+5 mm (compression)	7.2–24.2	584	1027	1733	2902	4650	7203	438–8.6 k
+6 mm (compression) (clinical setting)	7.2–25.2	489	904	1595	2661	4609	7181	354–8.6 k
+7 mm (compression) (clinical setting)	7.2–26.2	408	787	1446	2535	4300	7158	284–8.7 k
+8 mm (compression) (clinical setting)	7.2–27.2	275	630	1225	2285	4214	7109	201–8.8 k$^{\Delta}$

range, then made wider by adding lower frequencies in steps of 1 mm in cochlear distance. In the second part of the experiment, electrodes 7–11 covering 9.6 mm, from 7.2 to 16.8 mm, were activated to simulate a 16.8-mm insertion depth. The frequency-place map was changed from the matched to the compressed map in 1.5-mm steps. The conditions are summarized in Tables IV and V for insertion depths of 19.2 and 16.8 mm, respectively. The compression conditions from +6 to +8 mm for 19.2-mm insertion depth, and from +7.5 to +10.5 mm for 16.8-mm insertion depth are similar to the clinically available maps.

B. Results and discussion

Figure 4 shows the vowel and consonant recognition percent scores (corrected for chance level) as a function of increasing frequency-place compression. The top panels show the scores with 6 electrodes inserted to 19.2 mm. The bottom panels show the scores with 5 electrodes inserted to 16.8 mm. The thin lines with open symbols show the individual scores, while the thick lines show the average performance of all subjects. The same symbols from Fig. 2 were used to represent scores from individual subjects. In each panel, the area between the vertical dashed lines shows the maps that can be programed in the clinic with the standard fitting procedure. The 0-mm matching condition in Fig. 4 is the same as the matched map shown with filled symbols in Fig. 2 (shown by the maps with * and ◇ in Tables III–V). The +8-mm compression in the upper panels and +12-mm compression in the lower panels are the compressed maps with widest frequency range of acoustic input shown with open symbols in Fig. 2 for 19.2- and 16.8-mm insertion depth conditions (shown by the maps with Δ and + in Tables III–V), respectively. Because the electrode array at 16.8 mm is shorter, the assignment of the full acoustic frequency range effectively results in more compression than the 19.2-mm insertion depth.

A repeated-measures one-way ANOVA shows that compression had a significant effect on the vowel recognition performance at 19.2 mm [$F(8,24)=14.06$, $p<0.001$] and 16.8-mm insertions [$F(8,24)=11.27$, $p<0.001$]. At both insertion depths a clear peak was observed in the vowel recognition performance with an optimal map of a few mm compression.

At 19.2-mm insertion, the peak performance was obtained with a compression of +2 to +3 mm. These optimal maps resulted in a performance level 10% higher than the 0-mm matched map (not significant by paired t-test), 20% higher than the compression map most similar to that offered by the clinical fitting program (+6-mm compression, $p<0.01$), and 35% higher than the compression condition where the full acoustic frequency range was assigned to the electrodes (+8-mm compression, $p<0.01$).

This finding implies that including acoustic information as low as 700 Hz (from Table IV) in the acoustic input range improved the performance, but adding lower frequencies started decreasing the performance. If a patient had a shallow insertion of 19.2 mm, the closest value offered by the clinical program for the low end of the frequency range would be 350 Hz. This mapping is shown by the +6-mm compression

TABLE V. Compression conditions for the array of 5 electrodes (electrodes 7–11) inserted 16.8-mm deep and covering 9.6 mm in the cochlea. The acoustic information assigned onto the array increases as the map changes from 0-mm matching condition to +12-mm compression while the stimulation region remains the same. The maps with ◇ and + are same conditions from experiment 1, as shown in Table III.

Frequency-place mismatch condition	Range of acoustic input (mm)	Bandpass filter center frequencies (Hz)					Frequency range of analysis bands (Hz)
		7	8	9	10	11	
0 mm (matching)	7.2–16.8	1899	2676	3802	5558	7310	1583–8.4 k◇
+1.5 mm (compression)	7.2–18.3	1510	2297	3403	5102	7279	1221–8.5 k
+3 mm (compression)	7.2–19.8	1203	1949	3062	4711	7238	941–8.6 k
+4.5 mm (compression)	7.2–21.3	948	1641	2772	4632	7191	715–8.7 k
+6 mm (compression)	7.2–22.8	737	1378	2441	4278	7145	533–8.7 k
+7.5 mm (compression) (clinical setting)	7.2–24.3	582	1155	2215	4191	7096	412–8.8 k
+9 mm (compression) (clinical setting)	7.2–25.8	460	975	1981	3877	7084	326–8.8 k
+10.5 mm (compression) (clinical setting)	7.2–27.3	361	838	1816	3631	7084	256–8.8 k
+12 mm (compression)	7.2–28.8	293	718	1635	3631	6354	207–8.1 k+

(from Table IV). At this condition two subjects performed worse than the matched map even though the matched map discards all information below 1 kHz. The +6-, +7-, and +8-mm compressed maps are the only choices offered by the standard clinical fitting program, and they are clearly not the optimal maps for such shallow insertion.

With a 16.8-mm insertion, a peak performance was observed with +3- and +4.5-mm compression conditions. The performance was 20% higher compared to the 0-mm matched condition ($p<0.05$, by paired t-test), 20% higher than the closest compression map offered by the clinical fitting program (+7.5-mm compression, $p<0.05$), and 30% higher than the compression condition where the full acoustic frequency range was assigned to the electrodes (+12 compression, $p<0.05$). A *posthoc* Tukey test showed that there was no significant difference for conditions between +3- and +6-mm compression on vowel recognition, which corresponds to a range of low-end frequencies for stimulation range from 536 to 941 Hz (Table III). In the +4.5-mm compression condition all frequencies higher than 715 Hz were assigned onto the electrode array, but adding further lower frequencies increased the amount of frequency-place compression and reduced performance.

Consonant scores did not change significantly with compression, but a small peak around +4- and +5-mm compression and a slight drop of 10% for extreme compression of +8 mm were observed at 19.2-mm insertion. At 16.8-mm insertion the effect of compression on consonant recognition was significant [$F(8,24)=7.54$, $p<0.001$, by repeated-measures one-way ANOVA]. At this depth, the optimal range was much wider compared to vowels. Maps from +1.5- to +7.5-mm compression resulted in better consonant recognition compared to 0-mm matched or highly compressed maps ($p<0.05$).

The results support the hypothesis that, for shallow electrode insertions, a compromise between the amount of low-frequency information provided and the accuracy of the mapping of that information to cochlear place might be beneficial. For example, Fig. 4 shows that by choosing a mild frequency-place compression, vowel recognition performance can instantly be increased by 20%–30% compared to the clinical maps, which produce more severe compression. At a low performance level (due to the shallow insertion) such an increase (from 20% to 45% for vowels, and from 40% to 55% for consonants, for example) will have a significant effect on the patient's speech understanding.

V. GENERAL DISCUSSION

The results of the present study mainly show that there is a strong interaction between the frequency range assigned to the electrodes and the distortion in the frequency-electrode mapping for a wide range of electrode insertions.

Speech recognition generally increases as the insertion depth and number of electrodes activated increase, reaching an asymptotic level at an insertion smaller than the baseline condition (10 electrodes, at 28.8-mm insertion). For full insertion ranges of 20 to 25 mm a matched map with less spectral distortions results in better speech recognition. For shorter insertions, however, a map that reduces the input frequency range to preserve the normal acoustic mapping eliminates too much low-frequency information that is important

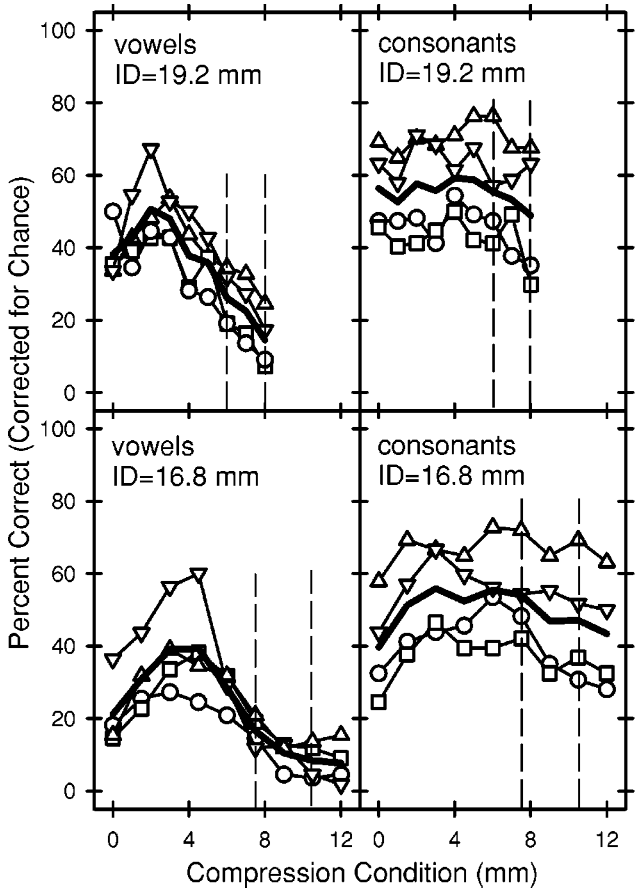

FIG. 4. Individual percent-correct scores (shown by open symbols and thin lines) superimposed with average performances of all subjects (shown by thick lines). In the top row, the frequency-place map is changed from perfect match (0-mm condition) to the compressed map (+8-mm compression) in steps of +1-mm cochlear distance, when 6 electrodes at 19.2-mm insertion depth were activated. In the bottom row the map is changed from perfect match to the compressed map (+12-mm compression) in steps of +1.5 mm when 5 electrodes at 16.8-mm insertion depth were activated. The same symbols from Fig. 2 were used to represent scores of individual subjects. The maps between the vertical dashed lines show the clinically available maps.

for speech. Compressing the full acoustic range onto a short electrode insertion also results in poor speech recognition because of the distortion (compression) in the frequency-place mapping (experiment 1). Optimal recognition of spectrally sensitive stimuli like vowels occurs with a compromise between these two extreme maps (experiment 2).

Several studies have previously shown that speech recognition increases with deeper electrode insertion. For example, Hochmair *et al.* (2003) observed an improvement in speech perception from a shallow insertion of 20 mm to a deep insertion of 30 mm. In the present study we observed an increase in scores up to 26-mm insertion with the compressed map, and 22 mm with the matched map, but no further improvement for deeper insertions. Ideally, inclusion of the lower frequencies in the input acoustic range at deeper insertions would be expected to increase speech recognition. However, the difficulty of selective stimulation of the auditory nerves at such deep apical regions of the cochlea might have a limiting effect. The cochlea is coiled more tightly towards the apical end, physically restricting a deep insertion. Even if the deep insertion is achieved, it is difficult to stimulate spiral ganglia of different characteristic frequencies selectively because they are more densely clustered in the apical turn.

A second factor contributing to the asymptotic performance might be the reduced spectral channels of implant users. It has been shown that implant patients only utilize a limited number of stimulation channels, regardless of the number of stimulating electrodes (Fishman *et al.*, 1997; Friesen *et al.*, 2001). Adding more electrodes (to the 9 electrodes with the compressed map and 7 electrodes with the matched map) similarly did not result in a significant improvement in performance in the present study.

Many studies have shown that speech recognition is adversely affected by spectral distortions such as a spectral shift between the acoustic input range and the stimulation range (Dorman *et al.*, 1997; Fu and Shannon, 1999b), or nonlinear distortions (Shannon *et al.*, 1998), even when the same speech information was used. In more recent studies by Başkent and Shannon (2003, 2004) the acoustic frequency range was systematically made wider or narrower than the tonotopic stimulation range. The results showed that both normal hearing and implant subjects were sensitive to abrupt frequency-place distortions. The subjects had only a limited tolerance of a few mm and performance dropped significantly with further distortion, especially in vowel and sentence recognition tests. These studies generally used an insertion depth ranging from 20 to 25 mm, which represent the ''full-insertion'' range for cochlear implants. Consistent with the previous studies, the present study showed a matched map is advantageous over a compressed map with spectral distortions for full insertion ranges.

Note that there are several assumptions used in the present study. There are many unknown factors with implant users such as individual cochlear length, electrode array insertion depth and its lateral distance from modiolus, nerve survival patterns, and the best frequencies of the nerves actually stimulated by each electrode. We did not have radiographic images of the implants for precise calculations of cochlear dimensions or electrode array positions in the scala tympani. We simply assumed a typical value of 35 mm for the cochlear length, an insertion depth of 31 mm for the full array, a medial location from the modiolus, and functioning nerves uniformly distributed along the organ of Corti. We also assumed that the Greenwood mapping function holds at the spiral ganglia level. Similar assumptions were made by Başkent and Shannon (2004) to match the acoustic input range to the stimulation range in Med-El users. Such studies show that an initial map can be estimated with similar assumptions to the present study, and it can further be fit for the individual patient functionally by using tests with a small set of spectrally sensitive stimuli such as vowels.

The latest generation implants are designed to be inserted much deeper (up to 31 mm) than the conventional full insertion of 25 mm. Despite the improvements in implant designs and surgical techniques, there are still implant patients who receive partially inserted electrode arrays, mostly due to bone and fiber occlusions in the cochlea. In such short insertion cases it is not clear whether it is better to match the acoustic frequencies to the actual electrode tonotopic range, thus losing low-frequency information, or to present a wider acoustic range to the electrodes, resulting in a distortion in the frequency-place mapping. Faulkner *et al.* (2003) showed that matching the frequency to the tonotopic place for insertions shorter than 19 mm was detrimental to speech recognition. The results of the present study also showed that matching was detrimental to speech recognition for short insertions; the best speech recognition was achieved with a compromise between compressing the entire frequency range onto a short insertion electrode and truncating the frequency range to match the short electrode tonotopic place.

The results in the present study show the acute effects of frequency-place maps on speech recognition. An important consideration in actual implant users would be the role of long-term learning. If the frequency range is matched to the electrode tonotopic location the resulting mapping will eliminate low-frequency information. Adding low-frequency information will result in frequency-place distortion. The low-frequency information is presented to the listener in this case, but in a distorted form that might be learned over time. However, it is not clear how flexible the speech pattern recognition in the central nervous system is. Over a lifetime of a normal-hearing listener the brain learns to recognize speech patterns based on the normal tonotopic distribution of frequency information in the cochlea. When hearing is lost and later restored by a cochlear implant, the implant may not provide the brain with the same distribution of tonotopic information as a normal cochlea, depending on the electrode insertion depth and the frequency mapping. Speech pattern recognition in normal hearing is based on a physiological ''hard-wired'' tonotopic representation from the cochlea to the brain. In a cochlear implant any range of frequency information can theoretically be presented to any electrode, so the frequency-place mapping is a manipulable factor in implant fitting. How much distortion in the frequency-place mapping is learnable? What are the trade-offs between frequency range and distortion in frequency-place mapping? The present results suggest several factors that should be considered in selecting the frequency-electrode mapping.

In present clinical practice the general approach is to provide the patient with as much acoustic input as available, regardless of her specific implant configuration such as the insertion depth, in the belief that eventually the patient would learn to make use of this abundant information regardless of any frequency-place distortions. The results of Fig. 4 suggest that this approach may not be optimal. Vowel recognition with the widest frequency range was significantly poorer than the conditions that used a modest amount of compression. The widest frequency range did not add much information that is important for speech and may have degraded the recognition of vowels because it reduces the tonotopic resolution within the most important speech range. So, even if the compressed frequency-place mapping can be learned, the loss of resolution may limit performance with a wide frequency range.

From the present results we infer that there are three factors in frequency-place mapping that determine vowel recognition: the match between frequency and place (especially on the apical end; see Başkent, 2003), the amount of low-frequency information deleted, and the frequency resolution. While cochlear implant listeners might be able to learn a distorted pattern of tonotopic activity, they probably cannot overcome the loss of information caused by truncating the frequency range and the loss of frequency resolution within the speech range. Processor settings to optimize the transmission of spectral cues should include the most important frequency range for speech, should maximize the spectral resolution within that range, and minimize the distortion between the presented frequency place mapping and the original acoustic tonotopic map.

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