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Research paper

Effects of electrode design and configuration on channel interactions

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Abstract

A potential shortcoming of existing multichannel cochlear implants is electrical-field summation during simultaneous electrode stimulation. Electrical-field interactions can disrupt the stimulus waveform prior to neural activation. To test whether speech intelligibility can be degraded by electrical-field interaction, speech recognition performance and interaction were examined for three Clarion electrode arrays: the pre-curved, enhanced bipolar electrode array, the enhanced bipolar electrode with an electrode positioner, and the Hi-Focus electrode with a positioner. Channel interaction was measured by comparing stimulus detection thresholds for a probe signal in the presence of a sub-threshold perturbation signal as a function of the separation between the two simultaneously stimulated electrodes. Correct identification of vowels, consonants, and words in sentences was measured with two speech strategies: one which used simultaneous stimulation and another which used sequential stimulation. Speech recognition scores were correlated with measured electrical-field interaction for the strategy which used simultaneous stimulation but not the strategy which used sequential stimulation. Higher speech recognition scores with the simultaneous strategy were generally associated with lower levels of electrical-field interaction. Electrical-field interaction accounted for as much as 70% of the variance in speech recognition scores, suggesting that electrical-field interaction is a significant contributor to the variability found across patients who use simultaneous strategies.

Keywords: Cochlear implants; Channel interaction; Speech perception

1. Introduction

Variability in the speech recognition abilities of cochlear implant users may be partly attributed to channel interactions (Hanekom and Shannon, 1998; Shannon, 1985; White et al., 1984; Wilson et al., 1991). One form of channel interaction, namely electrical-field interaction, occurs when electric fields add together during simultaneous electrode stimulation. The electrical-field summation, occurring prior to the activation of nerve fibers, produces a stimulus which differs in intensity from the original (Shannon, 1983, 1985; White et al., 1984). The result is an altered amplitude envelope for the frequency bands allocated to electrodes with interacting current fields. This altered stimulus is subsequently represented in the neural firing pattern. Electrical-field interactions are generally greatest between adjacent electrodes, but can occur between non-adjacent electrodes if the electric field emanating from the electrodes is extensive. It is reasonable to assume that electrical-field interactions can lead to a highly distorted speech signal; however, few studies have directly compared speech recognition performance and electrical-field interaction.

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One of the primary aims of the present study was therefore to examine whether or not there was a significant relationship between electrical-field interactions and speech perception in cochlear implant users.

Two types of channel interaction can occur with nonsimultaneous stimulation. These have been referred to as: (1) neural interaction and (2) interaction resulting from residual polarization of the nerve membrane. Neural interaction applies when sequential stimulation occurs at suprathreshold levels within a short time interval. Due to neural refractoriness the threshold of a probe signal would be elevated when it rapidly follows the masking stimulus. Forward masking tasks have been used to assess this type of interaction in electric hearing. For example, White et al. (1984) demonstrated that substantial changes in psychophysical threshold occurred when electrodes were stimulated within 2–5 ms of each other. In contrast to neural interaction, studies examining the effects of residual polarization present the preceding stimulus at a sub-threshold level, sufficient to 'sensitize' the nerve fiber but not enough to cause it to fire on its own. If a supra-threshold stimulus of the same polarity shortly follows the sub-threshold stimulus, the two together can provide sufficient neural summation to elicit an action potential at thresholds significantly lower than that obtained with the supra-threshold signal presented alone.

A number of variables can influence channel interaction in cochlear implant users. These include, but are not limited to, the electrode configuration used to generate the electrical field, the pattern of stimulation delivered by the electrodes (i.e., the order of electrode stimulation: simultaneous versus sequential), the design of the electrode array (e.g., the distance between electrodes and spiral ganglion cells), nerve survival, and the site or sites of neural activation.

Consider a simplified model of how electrical-field interaction can be affected by the electrode configuration. With bipolar electrode configurations, two intracochlear electrodes, the active and the ground electrode, are closely spaced. Electric fields generated between two narrowly spaced electrodes (e.g., a bipolar pair) will, theoretically, produce localized neural activation whereas wider bipolar electrode separations will lead to broad electric fields with a wider area of neural activation (Kral et al., 1998; Miller et al., 2003; van den Honert and Stypulkowski, 1987). However, this is not to imply that bipolar coupling is always more selective, since even a closely spaced electrode pair can activate a broad region of the cochlea if neural survival within the region of the electrode is low (Chatterjee, 1999; Pfingst et al., 1997; van den Honert and Stypulkowski, 1987). In such cases, the current level and thus the electric field around the electrode pair must increase to excite the surviving cells which can respond to the stimulus (Frijns et al., 1996). The widest electrode separation used in present cochlear implants, called the monopolar electrode configuration, has the active electrode within the cochlea and the ground electrode located outside the cochlea at the mastoid. Monopolar stimulation typically produces greater current spread than bipolar stimulation, however it also reduces current levels required to elicit an auditory sensation. This effect has been demonstrated in both humans (Chatterjee, 1999) and animals (Miller et al., 2003; Rebscher et al., 2001; van den Honert and Stypulkowski, 1987). Monopolar stimulation therefore exchanges neural specificity for lower current level requirements. However, the broader electric fields of monopolar stimulation are problematic when electrodes are stimulated simultaneously since they have a greater probability of overlapping and interacting prior to reaching the neurons within the modiolus. With simultaneous monopolar stimulation, the representation of the stimulus waveform could be disrupted by electrical-field summation over a wide range of the cochlea.

The second way electrical-field interactions can be minimized is by using sequential, non-overlapping, electrode stimulation (Eddington et al., 1978). This method is employed in most speech coding strategies, such as the Continuous Interleaved Sampling (CIS) strategy (Wilson et al., 1991). The use of interleaved stimuli avoids the problem of electrical-field interaction common to speech strategies with simultaneous stimulation, such as the Compressed Analog (CA) speech strategy, because biphasic pulses delivered to each electrode are interleaved to prevent instantaneous vector summation of the electric fields. Comparisons between the CIS and CA speech strategy have demonstrated that higher speech recognition scores could be attained with the interleaved strategy, CIS, even when patients had only a few days of CIS experience and 1–6 years of daily use with the CA strategy (Boëx et al., 1996; Schindler et al., 1995; Wilson et al., 1991).

A third means of reducing electrical-field interaction is through cochlear implant electrode positioning. Electrically evoked auditory brainstem responses (Shepherd et al., 1993) and single-fiber data (van den Honert and Stypulkowski, 1987) have shown that when the electrode array was placed along the lateral wall of the cochlea, current thresholds were elevated relative to those found when the electrodes were placed closer to the modiolar wall. Furthermore, electrically evoked compound action potential measures by Cohen et al. (2003) indicate that electrodes closer to the neural elements within the modiolus produce a more restricted range of neural excitation than those farther from the inner wall. The restricted range of current spread would reduce potential overlap between the electric fields of simultaneously stimulated electrodes.

The CLARION® Electrode Positioning System™ (EPS) was developed to reduce electrical-field interaction by moving the electrode array closer to the modiolus. The EPS consists of a shim inserted behind the electrode array that pushes the electrode array away from the outer wall of the scala tympani and closer to the inner wall. Due to the potential role of the EPS in a spate of Meningitis cases, the EPS has since been withdrawn from the market and is no longer included with the newer CLARION electrode arrays. Clinical results with the standard, precurved Clarion electrode with the EPS showed lower stimulation levels and better speech perception scores than in patients without the EPS (Osberger and Fisher, 1999). Advanced Bionics subsequently developed a newer electrode design, the Hi-Focus electrode, to be used in combination with the EPS. Clinical results suggested that further benefit was achieved with this design at the 6-month test interval (Zwolan et al., 2001) and that patients with the Hi-Focus with EPS performed well with the simultaneous speech processing strategy (SAS) while those with the pre-curved, enhanced bipolar electrode design preferred and performed best with sequential strategies (Battmer et al., 2000a,b). The present study, therefore, had two overall aims: first, to measure electrical-field interaction in patients with the Clarion multichannel cochlear implant using different electrode array designs and electrode configurations; and second, to relate these measures of electrical-field interaction to speech intelligibility.

In this study, electrical-field interaction was determined by measuring the subjects' detection threshold from stimulation of a single electrode and comparing that with the threshold obtained from stimulating two electrodes simultaneously (electrical simultaneous masking). This task is commonly used to measure the degree of electrical-field summation produced by two electrodes stimulated simultaneously (Boëx et al., 2003; Shannon, 1983, 1985; White et al., 1984). If currents from the two electric fields interact, they will either add together or cancel each other depending on the relative phase of the current. Specifically, when same-phase current pulses overlap, they add electrically, thereby lowering thresholds below that found with the probe electrode stimulated in isolation. For the out-of-phase condition, overlapping current pulses cancel and thresholds tend to be higher relative to the probe electrode stimulated alone. The amount of electrical-field overlap therefore determines how much current summation (in-phase) or cancellation (out-of-phase) occurs. The difference in thresholds for the in-phase and out-of-phase conditions represents the degree of current pulse overlap, or electrical-field interaction. The degree of electrical-field interaction can be expressed by the following formula (Eddington and Whearty, 2001):

$$\text{Interaction Index} = (T_{(-)} - T_{(+)})/2 * C \quad (1)$$

where $T_{(-)}$ is the threshold of the probe with an out-of-phase perturbation signal, $T_{(+)}$ is the threshold of the probe with an in-phase perturbation signal, and C is the stimulation current level of the perturbation signal. In the present study, C was set at a sub-threshold level.

When there is virtually no electrical-field interaction, the phase of the current will not differentially affect threshold (Shannon, 1983, 1985). Thresholds in this case are simply lower than when only one electrode is activated. With complete electrode independence, what matters most is the additive neural activity arising from multiple electrode stimulation sites and not the relative phase of the current. Under these circumstances, both out-of-phase and in-phase stimuli will lower thresholds, and roughly to the same degree. Therefore, the Interaction Index would approach zero as the amount of electrical-field overlap decreased.

The potential relationship between electrical-field interaction, as measured by the Interaction Index, and speech recognition performance was evaluated in this study. The study consisted of three groups of patients implanted with one of three generations of Clarion electrode arrays: the standard electrode array, the standard array with an electrode positioner, and the Hi-Focus I electrode array with an electrode positioner. Each generation of electrode array was designed to further reduce electrical-field interaction. Speech recognition performance was measured with two speech processing strategies: one that used simultaneous stimulation and another that used sequential stimulation. It was predicted that only those subjects with less electrical-field interaction would be able to perform well with a speech processing strategy that used simultaneous stimulation.

2. Materials and methods

2.1. Subjects

Eight postlingually deafened cochlear implant users (20–69 years of age) were selected for these experiments. The subjects were assigned to one of three groups on the basis of electrode design: (1) the standard, precurved Clarion Enhanced Bipolar electrode (ENH), (2) this same electrode with the Electrode Positioning System™ (ENH + EPS), or (3) the Clarion CI Hi-Focus™ electrode with the EPS (HF + EPS). There were two HF + EPS subjects and three subjects in each ENH group. All were native English speakers with at least five months of experience with their device. The subjects were regular users of the sequential strategy, CIS, or the partially simultaneous strategy, MPS. Subjects were recruited from the House Ear Clinic in Los Angeles, California and from the Callier Center for Communication Disorders in Dallas, Texas. Approval from the Internal Review Boards was obtained from both centers. Informed consent was obtained and participants were paid on an hourly basis. Patient demographics are shown in Table 1 and electrode array parameters are shown in Fig. 1 and Table 2.

2.2. Stimuli and equipment

2.2.1. Electrical-field interaction

Electrical-field interaction was measured between a sub-threshold perturbation signal and a supra-threshold probe signal delivered simultaneously. The stimuli were driven by custom-designed software developed by Advanced Bionics Corporation, called the Electrode Interaction Tester (EIT). The EIT software runs on a personal computer and interfaces with the patient's S-Series speech processor through the Clarion Processor Interface (CPI).

The stimuli consisted of a series of charge-balanced, biphasic pulses (300 μs/phase, 200-ms burst duration, at a 1000-Hz rate). The initial phase of the biphasic pulse delivered to the probe electrode was cathodic, while that of the perturbation electrode varied depending on the condition. Thresholds were compared for pulses presented either to the probe electrode alone or simultaneously to the probe electrode and a second

Table 1
Subject demographics

Subject	Age	Electrode type	Speech strategy used in everyday speech processor	Duration of hearing loss (years)	Duration of deafness (years)	Duration of CI use (years)
S7	66	ENH	MPS	43	5	2.2
S8	67	ENH	CIS	0.2	0.2	2
S9	55	ENH	CIS	18	8	2.1
S6	57	ENH + EPS	CIS	35	18	1.4
S5	46	ENH + EPS	CIS	0.2	0.2	0.4
S4	47	ENH + EPS	CIS	20	10	1.7
S2	68	HF + EPS	MPS	34	26	0.4
S1	57	HF + EPS	MPS	39	8	1.1

The duration of hearing loss was defined as the amount of time from which the patient first noticed a hearing loss to the time the patient was implanted. The duration of deafness was the amount of time the patient had a pure tone average (e.g., average threshold for frequencies of 500, 1000, and 2000 Hz) greater than 90 dB HL bilaterally to the time the patient was implanted. All subjects in this study used the CI implanted receiver/stimulator with eight analysis channels.

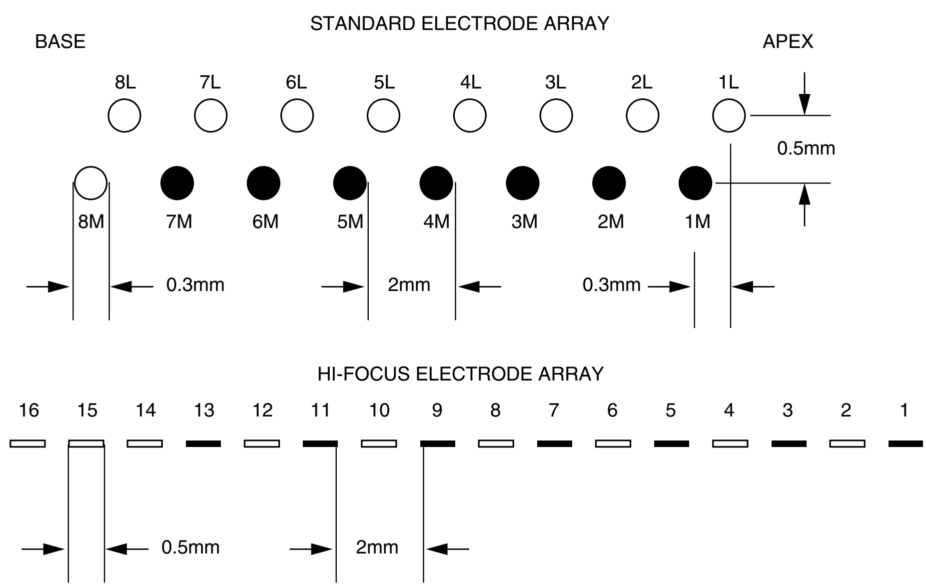

Fig. 1. Electrode array parameters for the standard Enhanced Bipolar electrode array (top panel) and Hi-Focus array (bottom).

Table 2
Electrode statistics

Feature	ENH electrode	HF Electrode
Electrode contacts	Ball electrodes	Plate electrodes
Surface area	0.012 mm^2	0.4×0.5 mm^2
Spacing between active electrodes	2 mm	2.2 mm
Spacing between medial to lateral electrode	0.3 mm (lateral separation) 0.5 mm (radial separation)	–
Spacing between adjacent electrodes	2 mm	1.1 mm

electrode located some distance from the probe (i.e., the perturbation electrode). When both the probe and perturbation electrode were stimulated, the perturbation electrode either delivered biphasic pulses with the same polarity as the probe electrode (Fig. 2: middle) or was 180° out-of-phase with the pulses of the probe electrode (Fig. 2: bottom). The perturbation electrode was located generally in the center of the electrode array at electrode 4 for the ENH and ENH + EPS groups, and at electrode 7 for the HF + EPS group. The probe electrodes were the medial electrodes 1, 2, 3, 5, 6, and 7 for the ENH and ENH + EPS groups, whereas the HF + EPS group used the odd electrodes 1, 3, 5, 9, 11, and 13 as the probe electrodes. As shown in Table 2, the separation between adjacent active electrodes was close to 2 mm for both the standard and Hi-Focus electrode arrays.

Thresholds were measured for bipolar and monopolar configurations. For each configuration condition, the mode of stimulation was the same for the perturbation and probe signal. The electrode array in the ENH and ENH + EPS groups uses offset-radial bipolar coupling. This type of coupling is achieved by pairing the medial (active) electrode with the lateral (ground) electrode from the adjacent basal electrode pair. Referring to Fig. 1, note that this configuration for adjacent, simultaneously stimulated electrodes (e.g., simultaneous stimulation of active electrode 4 M and 3 M) can potentially leak current to the more apical, lateral ground electrode (e.g., between 4 M and 4 L). This is because the separation between the medial active electrode and its corresponding ground electrode is greater than that between the medial electrode and the ground electrode of the more apical pair. For monopolar coupling, the stimulation is applied between the medial electrode and a far-field ground located at the receiver-stimulator case. The Hi-Focus electrode uses lateral bipolar coupling, achieved by pairing longitudinally arranged, odd and even numbered adjacent electrodes. The basal electrode in the bipolar configuration is used as

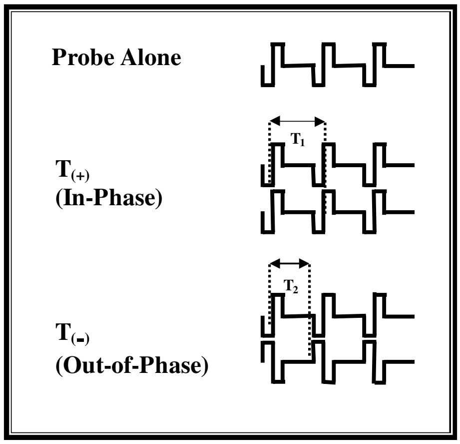

Fig. 2. Simultaneous masking conditions. The top trace shows the condition for biphasic pulses presented to a single electrode in the “probe alone” condition. The middle and lower traces show simultaneous stimulation by two pulses: one pulse is delivered to the probe electrode and the second is delivered to the perturbation electrode. The middle trace represents the “in-phase” condition (T_+), while the lower trace represents the “out-of-phase” condition (T_-). The time interval between pulses for perturbation and probe electrodes with similar polarities is represented by T_1 for the in-phase condition and T_2 for the out-of-phase condition. Note the shorter interval for the out-of-phase condition.

the ground electrode. Monopolar coupling in the Hi-Focus array is achieved by applying stimulation between the intra-cochlear electrode and the far-field ground in the receiver-stimulator case. As was the case for the subjects in this study, the odd numbered electrodes are typically the active electrodes for the Hi-Focus CI electrode array when monopolar stimulation is used.

2.2.2. Speech recognition

To examine the relationship between electrical-field interaction and speech recognition performance, subjects were evaluated with each of two speech processing strategies: one that used sequential electrode stimulation (i.e., CIS) and another that used simultaneous stimulation (i.e., SAS). Speech recognition performance was evaluated for these speech strategies with vowel and consonant identification tasks and with an open-set sentence recognition test. The vowels were a subset of those recorded by Hillenbrand et al. (1995). The subset consists of 11 vowels in /hVd/ context: /ı/ “heed”; /I/ “hid”; / / “hayed”; / / “head”; / / “had”;/ / “hud”;/ / “hod”;/ / “herd”; /o/ “hoed”; / / “hood”; / / “who’d”. The vowel stimuli consisted of a total of 132 vowels spoken by six women, seven men, four boys, and five girls. Ten repetitions of 16 consonants in /aCa/ context, spoken by a single male talker (Shannon et al., 1999), were used for the consonant identification task. Twenty H.I.N.T. sentences (Nilsson et al., 1994), also spoken by a single male talker, were used for the sentence recognition test. A separate set of the 20 sentences were used for the evaluation of each speech processing strategy.

2.2.3. Speech processing strategies

The SAS and CIS strategies were implemented at UT Dallas using the Clarion Research Interface (CRI) (Wygonski et al., 2001). Although SAS and CIS were available with the clinical programming software, SCLIN, this software did not support the additional strategies evaluated in the same subjects for a second study (published in Loizou et al., 2003). The clinical programming software (SCLIN) was used to obtain the threshold and comfortable loudness levels for each speech processing strategy. For the CIS users, these levels were comparable to the levels used in the subjects’ everyday speech processor. The output of each implementation was verified using an oscilloscope. A more detailed description of the CRI and implementation of these strategies can be found in Loizou et al. (2003).

2.2.3.1. Continuous interleaved sampler (CIS). The CIS strategy was developed to avoid electrical-field interactions by stimulating the electrodes sequentially from apex-to-base (i.e., 1, 2, 3, 4, 5, 6, 7, and 8). CIS is a pulsatile speech processing strategy that typically uses a monopolar coupling mode. The Clarion CIS strategy delivers pulsatile stimulation at a rate per channel of 833 pulses per sec (pps) with a pulse duration of 75 μs/phase.

2.2.3.2. Simultaneous analog stimulation (SAS). The SAS speech processing strategy delivers simultaneous analog waveforms to channels 1–7, and therefore is more likely to introduce electrical-field interactions than CIS. SAS uses the bipolar stimulation mode; this is based on the assumption that simultaneous bipolar stimulation is less likely to introduce electrical-field interactions than simultaneous monopolar stimulation. For the standard Clarion electrode (i.e., ENH and ENH + EPS) offset radial bipolar coupling (“enhanced bipolar”) is used, with an active medial electrode referenced to the lateral electrode of the adjacent, basal electrode pair. The Hi-Focus electrode uses two adjacent longitudinal electrodes to generate a bipolar electric field. The most basal electrode is excluded from SAS stimulation because there is no electrode available for bipolar coupling. Studies have shown that speech recognition scores by experienced cochlear implant CIS and SAS users are comparable despite the fact that the SAS strategy uses only seven electrode pairs, whereas CIS uses eight electrode pairs (Friesen et al., 2001).

2.3. Procedure

2.3.1. Electrical-field interaction

Prior to testing, thresholds for perturbation and probe electrodes were obtained separately for monopolar and bipolar stimulation. The clinical programming software developed by Advanced Bionics Corporation (i.e., Software CLINician, or SCLIN) was used to obtain the initial threshold values that were entered into the EIT program. The SCLIN threshold was estimated by using the modified Hussen–Westlake technique (Carhart and Jerger, 1959). This adaptive procedure estimates the amount of stimulation capable of evoking a response 50% of the time. The step size was 5 μA. In the EIT program, the pulse amplitude delivered to the perturbation electrode was then fixed at 70% of its threshold, while the amplitudes of the probe electrodes were initially set to 10 μA above their respective thresholds. Only the current amplitude was adjusted during the test session to produce a change in loudness.

In the test session, a 3-interval, forced-choice adaptive tracking procedure was used to obtain thresholds for pulses presented to the probe electrode alone and for pulses presented to the probe and perturbation electrodes simultaneously. Only the pulse amplitude of the probe electrode was varied adaptively. In the simultaneous condition, pulses delivered to the perturbation electrode were either “In-Phase” or “Out-of-Phase” with the probe electrode. Therefore, there were three simultaneous masking conditions (Probe Alone, In-Phase, and Out-of-Phase) for each electrode configuration (monopolar and bipolar) and for each of the six probe electrodes. All conditions were randomized.

Subjects were seated in a sound-attenuated chamber for the duration of the task. Subjects responded by directing the cursor on the computer monitor and clicking the mouse button to indicate which interval contained the stimulus. Two consecutive correct decisions led to a decrease in the probe electrode’s pulse amplitude and one error resulted in an increase in pulse amplitude. The step size was initially 12% of the current amplitude and was gradually decreased (linearly) to 3% of the current amplitude. Visual feedback was provided after each trial. This procedure estimated the amount of stimulation current required for 70.7% correct responses (Levitt, 1971). The last eight reversals were averaged to compute the threshold for each condition.

2.3.2. Speech recognition

The clinical programming software, SCLIN, was used to obtain T-levels (thresholds) and M-levels (most comfortable loudness) for each speech processing strategy. These parameters are used to compress the speech signal into the audible dynamic range for each patient and speech strategy. The patient was then fitted with the speech strategy implementation and the volume level and sensitivity of the microphone were adjusted to a comfortable listening level. The subjects were given approximately 10 min to adjust to the sound with each strategy prior to testing. Once the volume and sensitivity settings were established, the levels were recorded and the subject was asked not to adjust these settings for the duration of the experiment. The speech strategy software was implemented on a personal computer and interfaced with an S-Series speech processor through the CRI circuit board. Speech processing strategies were selected and modified with a custom MATLAB-based user interface[1] The interface allowed the user to enter patient parameters, such as threshold and comfort levels, the electrode configuration, and electrode stimulation order. Another custom MATLAB-based software package, Speech Identification Utility (SPID), was used to administer the speech tests. SPID has a graphical user interface that allows the user to select the speech task and automatically scores the results once the test session is completed. Subjects were seated in a soundproof chamber for the duration of the experiment. All speech material was presented at a 0° azimuth in the soundfield at 65 dB SPL. Subjects were given a practice session with the test materials prior to the test session.

Testing was divided into acute listening sessions (20–30 min) with each speech coding strategy. The speech processing strategies were counterbalanced across subjects to avoid possible order effects. Following the presentation of a vowel or consonant, the subject was asked to select the button on the computer monitor identifying one of the possible responses. For the sentence recognition task, the subject was asked to repeat as many words in the sentence as possible. The subject was instructed to guess if unsure and no feedback was given during the test session. Results were calculated in percent correct and scored separately for vowel, consonant, and sentence stimuli. The speech tasks were repeated for each speech strategy session, however, a new list of H.I.N.T sentences was used for each session.

3. Results

3.1. Electrical-field interaction

3.1.1. Thresholds for simultaneous stimulation

Averaged thresholds with or without a sub-threshold perturbation signal are shown separately for each electrode design in Fig. 3 (top panels: monopolar; bottom panels: bipolar). Thresholds shown in the left panels are for the HF + EPS group, the middle panels show the results for the ENH + EPS group, and the panels on the right show thresholds for the ENH group. Thresholds were 15–20 μA higher for bipolar stimulation than for monopolar stimulation in the probe alone condition. With monopolar stimulation, all the electrode types had thresholds indicative of electrical-field interaction (i.e., the highest thresholds occurred for the Out-of-Phase condition and lowest thresholds occurred for the In-Phase condition, and the relative increase/decrease in threshold magnitude in relationship to the Probe Alone threshold were similar). This relationship was not observed with bipolar stimulation, where the Out-of-Phase condition could produce similar or lower thresholds than the Probe Alone condition. This is discussed further in the following section.

3.1.2. Pattern of interaction

The pattern of interaction is represented by the change in interaction magnitude as a function of the distance (in mm) between the probe and perturbation electrode. Figs. 4 and 5 show the individual and mean interaction patterns for monopolar and bipolar stimulation, respectively.

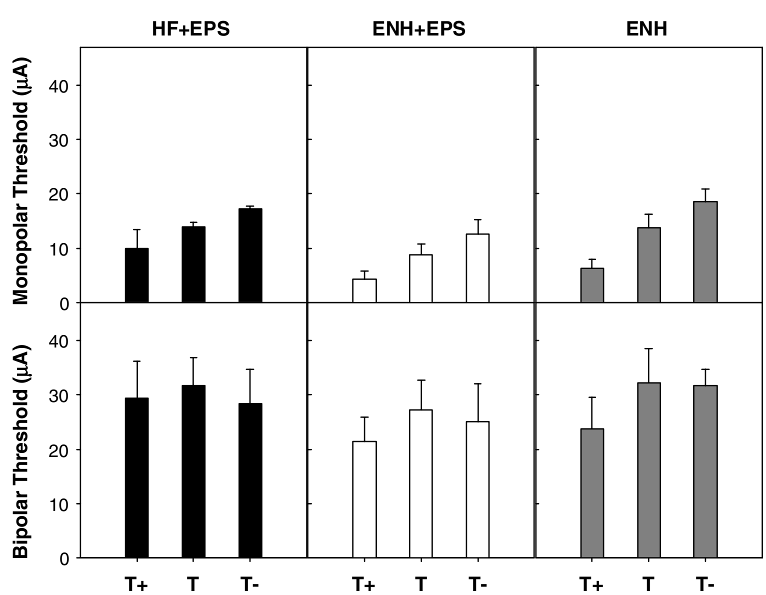

Fig. 3. Monopolar (upper panels) and bipolar (lower panels) simultaneous masked thresholds for each of the three electrode designs and phase conditions. The thresholds shown are the average of all probe electrode thresholds in each of three masking conditions: "in-phase", "probe alone", and "out-of-phase", represented as T_+, T_-, and T, respectively. The perturbation electrode was electrode 4 for the ENH and ENH + EPS groups. The perturbation electrode for the HF + EPS group was electrode 7. Error bars represent the standard error of the mean across the three subjects per group and six perturbation + probe pairs.

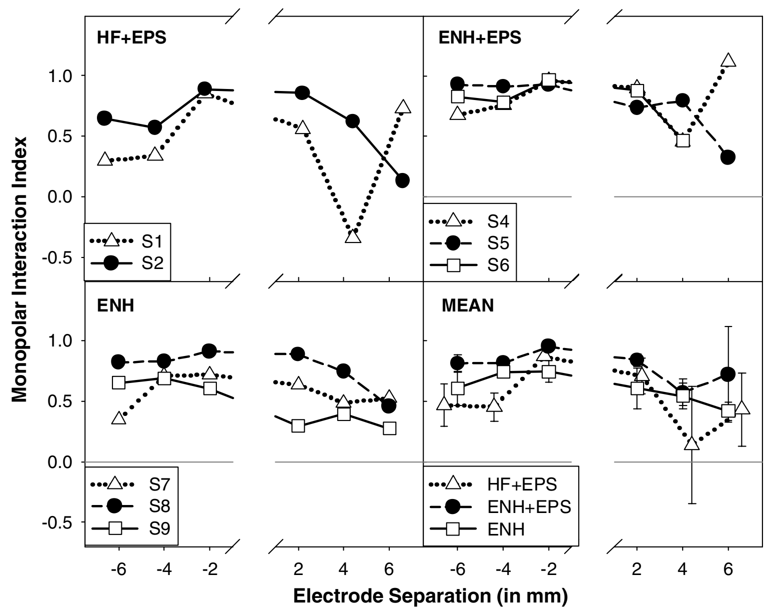

Fig. 4. The monopolar interaction pattern. The vertical axis presents the magnitude of electrode interaction given by the formula for the Interaction Index. The horizontal axis represents the probe electrode location in mm relative to the location of the perturbation electrode. The perturbation electrode was located in the center of the electrode array. There is a 2.2-mm separation between adjacent probe electrodes in the Hi-Focus design and a 2-mm separation in the Enhanced Bipolar design. Negative numbers on the horizontal axis indicate that the probe electrode was apical to the perturbation electrode, while positive numbers indicate the probe was basal to the perturbation electrode.

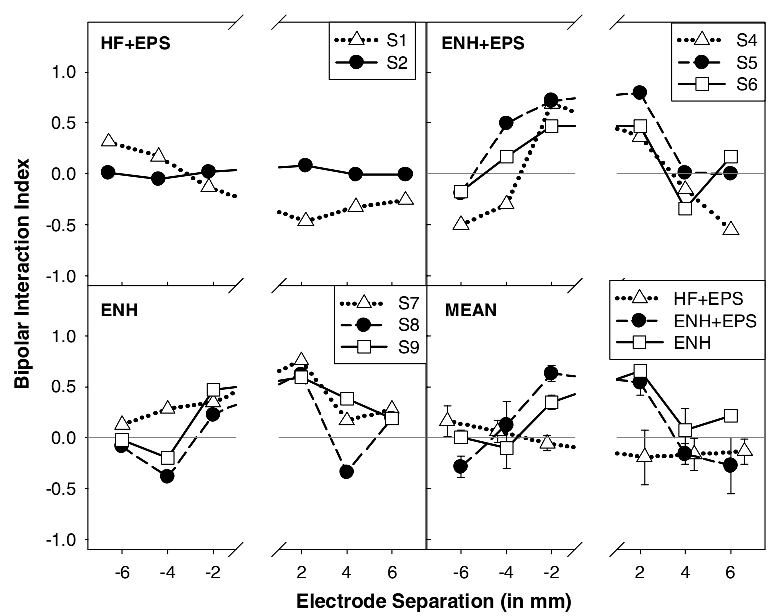

Fig. 5. The bipolar interaction pattern. The vertical axis presents the magnitude of electrode interaction given by the formula for the Interaction Index. The horizontal axis represents the probe electrode location in mm relative to the location of the perturbation electrode. The perturbation electrode was located in the center of the electrode array. There is a 2.2-mm separation between adjacent probe electrodes in the Hi-Focus design and a 2-mm separation in the Enhanced Bipolar design. Negative numbers on the horizontal axis indicate that the probe electrode was apical to the perturbation electrode, while positive numbers indicate the probe was basal to the perturbation electrode.

A mixed design ANOVA was conducted with electrode array as the between subjects factor and all other conditions as within subjects factors. The Interaction Index was found to be significantly greater with simultaneous monopolar stimulation compared to bipolar stimulation [$F(1,4) = 31.85$, $p < 0.01$]. The Interaction Index was also found to decrease as a function of the separation between the perturbation and probe electrodes for both monopolar and bipolar stimulation [$F(2,3) = 24.75$, $p < 0.05$], indicating reduced interaction. Bonferroni-adjusted (Dunn, 1961) planned comparisons showed significant decreases in the Interaction Index from 2 to 4 mm [$F(1,4) = 26.04$,

$p < 0.025$], but not from 4 to 6 mm. Additionally, there was a significant three-way interaction between electrode configuration, separation, and array type [$F(4,6) = 6.41$, $p < 0.05$]. Separate ANOVAs were performed for monopolar and bipolar configurations. Though only approaching significance [$F(1,4) = 7.49$, $p < 0.052$], monopolar stimulation showed some differences between the Interaction Index measured at apical compared to basal electrodes, with basal electrodes generally showing lower Interaction Index measures compared to apical electrodes.

Note also in Figs. 4 and 5 that the Interaction Index could be less than zero, meaning that the Out-of-Phase thresholds were sometimes lower than In-Phase thresholds. This occurred more frequently with bipolar stimulation and typically at greater separations between the perturbation and probe electrodes. Resampling statistics (Kaplan, 1999) were performed on the eight reversals used to calculate threshold in all instances where the Out-of-Phase condition was producing lower thresholds than the In-Phase condition. These reversal values were resampled 1000 times to compute the 95% confidence interval for each threshold. The results confirmed that the measured threshold was within the range of thresholds specified by the confidence interval.

Last, the ANOVA for the bipolar configuration demonstrated a significant interaction between the electrode array and the perturbation and probe separation [$F(4,6) = 6.21$, $p < 0.05$]. An analysis at each electrode separation showed that the Interaction Indices for the electrode arrays differed at the 2-mm separation with the bipolar configuration. Post hoc analyses showed a significantly reduced mean Interaction Index for subjects with the Hi-Focus array at this separation compared to subjects with the Enhanced Bipolar array ($p < 0.05$). No differences in Interaction Indices were observed between the two groups with the Enhanced Bipolar array.

3.2. Speech recognition

Separate mixed design ANOVAs were performed for each of the three speech tasks, with the electrode array group as the between-subjects factor and speech processing strategy as the within subjects factor. An arc-sine transformation was applied to the raw scores and the rau values were used in the ANOVA (Studebaker, 1985).

Consonants. Fig. 6 (top panel) illustrates the higher performance found with the CIS speech processing strategy compared to SAS [$F(1,6) = 21.35$, $p < 0.01$]. Although this finding could be attributed to differences in subject experience with the two strategies, since most of the subjects in this study were regular users of the CIS strategy, it may also be due to actual differences in susceptibility to electrical-field interactions with the simultaneous speech processing strategy, SAS. This will be discussed further in Section 4: "Speech Perception and Electrical-field Interaction". Of particular interest was the significant interaction between electrode array type and speech processing strategy [$F(2,6) = 10.63$, $p < 0.05$]. In Fig. 6, it can be seen that the amount of improvement from the SAS to the CIS strategy was generally less for the HF + EPS group compared to

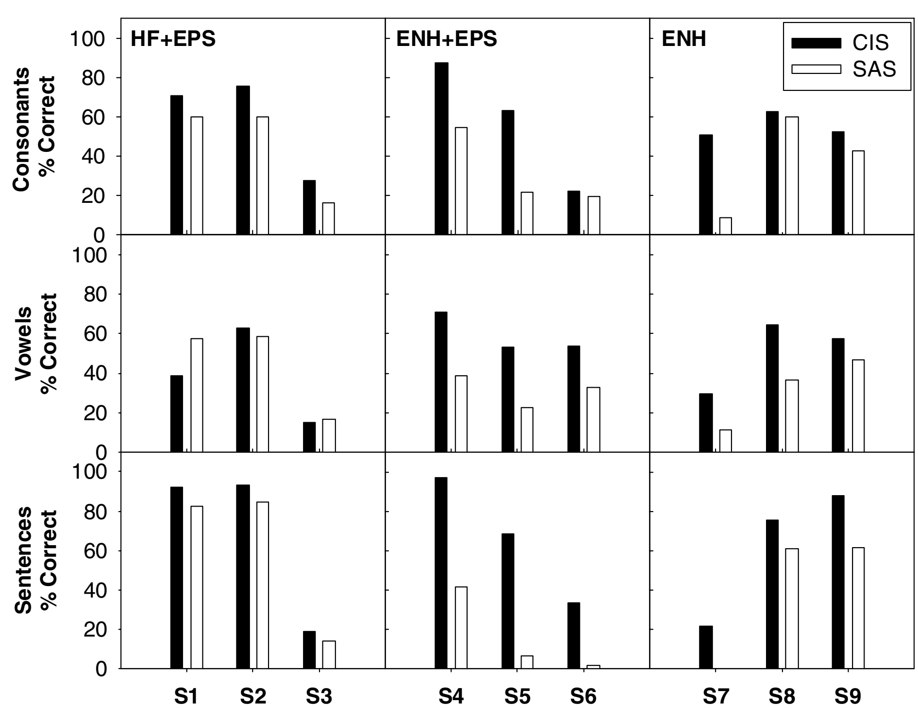

Fig. 6. Individual speech recognition scores are shown for consonants (top), vowels (middle), and sentences (bottom). Speech recognition scores were obtained using the SAS (white bars) and CIS speech processing strategies (black bars). Results for each of the three electrode array groups are shown in columns. Chance performance was 6% for consonants and 9% for vowels.

the ENH and ENH + EPS groups. The average improvement from SAS to CIS was 18%, 26%, and 12% for the ENH, ENH + EPS, and HF + EPS groups, respectively.

Vowels. The results for vowel speech recognition are shown in the middle panel of Fig. 6. Again there was a main effect of the speech processing strategy [$F(1,6) = 21.35$, $p < 0.01$], with CIS producing higher vowel recognition scores than SAS, and there was a significant interaction between electrode array and speech processing strategy [$F(2,6) = 2.63$, $p < 0.05$]. The average improvement from SAS to CIS was 19%, 28%, and −5% for the ENH, ENH + EPS, and HF + EPS groups, respectively.

Sentences. Sentence recognition scores are shown in the bottom panel of Fig. 6. Significantly higher scores were observed for the CIS strategy compared to the SAS strategy [$F(1,6) = 82.08$, $p < 0.001$] and there was a significant interaction between electrode array and speech processing strategy [$F(2,6) = 14.33$, $p < 0.01$]. The average improvement from SAS to CIS was 21%, 49%, and 7% for the ENH, ENH + EPS, and HF + EPS group, respectively.

3.3. Correlation between electrode interaction and speech recognition performance

The relationship between electrode interaction and performance with the sequential (CIS) and fully simultaneous (SAS) strategy was examined. Separate correlations were calculated for vowel, consonant, and sentence recognition. Since in the present study, CIS used monopolar stimulation and SAS used bipolar stimulation, CIS speech recognition performance was correlated with the monopolar interaction measure and SAS speech recognition performance was correlated with the bipolar interaction measure. The mean Interaction Index value for each subject was calculated for monopolar and bipolar stimulation and used in the correlation analysis. Since speech perception involves pattern recognition across the entire array, the measure of interaction used for the correlation was calculated as the average of the six Interaction Index values at each perturbation and probe separation.

Fig. 7 shows the significant negative correlation between bipolar interaction and SAS speech recognition (vowels: $r(6) = -0.74$, $p < 0.05$; consonants: $r(6) = -0.83$, $p < 0.05$). Correlations for sentences were not significant at this alpha level. There was also no significant relationship between monopolar interaction and CIS speech recognition, possibly because CIS uses sequential stimulation and therefore avoids electrical-field interaction. The relationship between bipolar electrical-field interaction and the consonant features of place, manner, and voicing was also examined. Fig. 8 demonstrates that SAS consonant place-of-articulation had the strongest correlation, $r(6) = -0.84$,

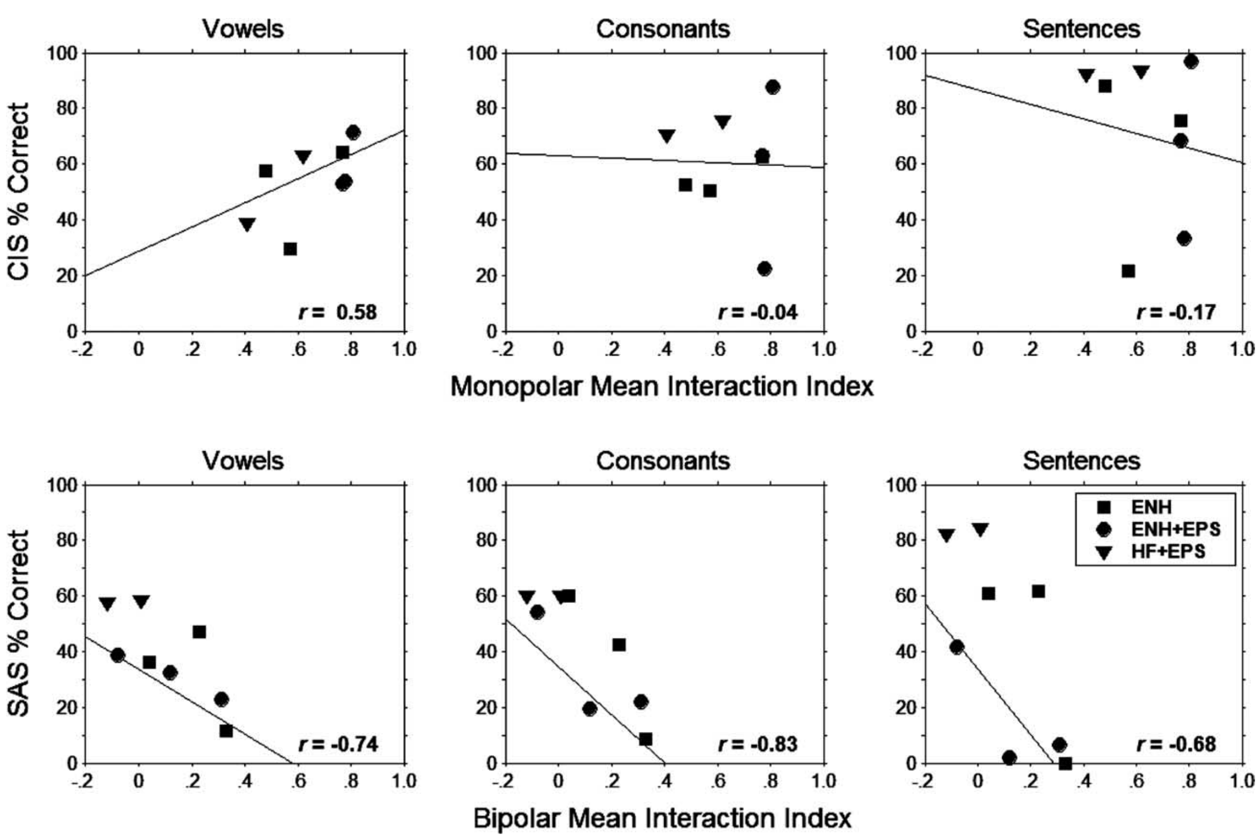

Fig. 7. Correlations show the relationship between CIS and SAS speech recognition scores and interaction spread for the eight cochlear implant subjects: vowels (left panel), consonants (middle panel), and sentences (right panel). The *x*-axis is the average Interaction Index for each subject. The vertical axis is the percent correct score for the CIS (upper panels) or SAS strategy (lower panels). Monopolar interaction spread was used for CIS correlations and bipolar interaction spread was used for SAS correlations.

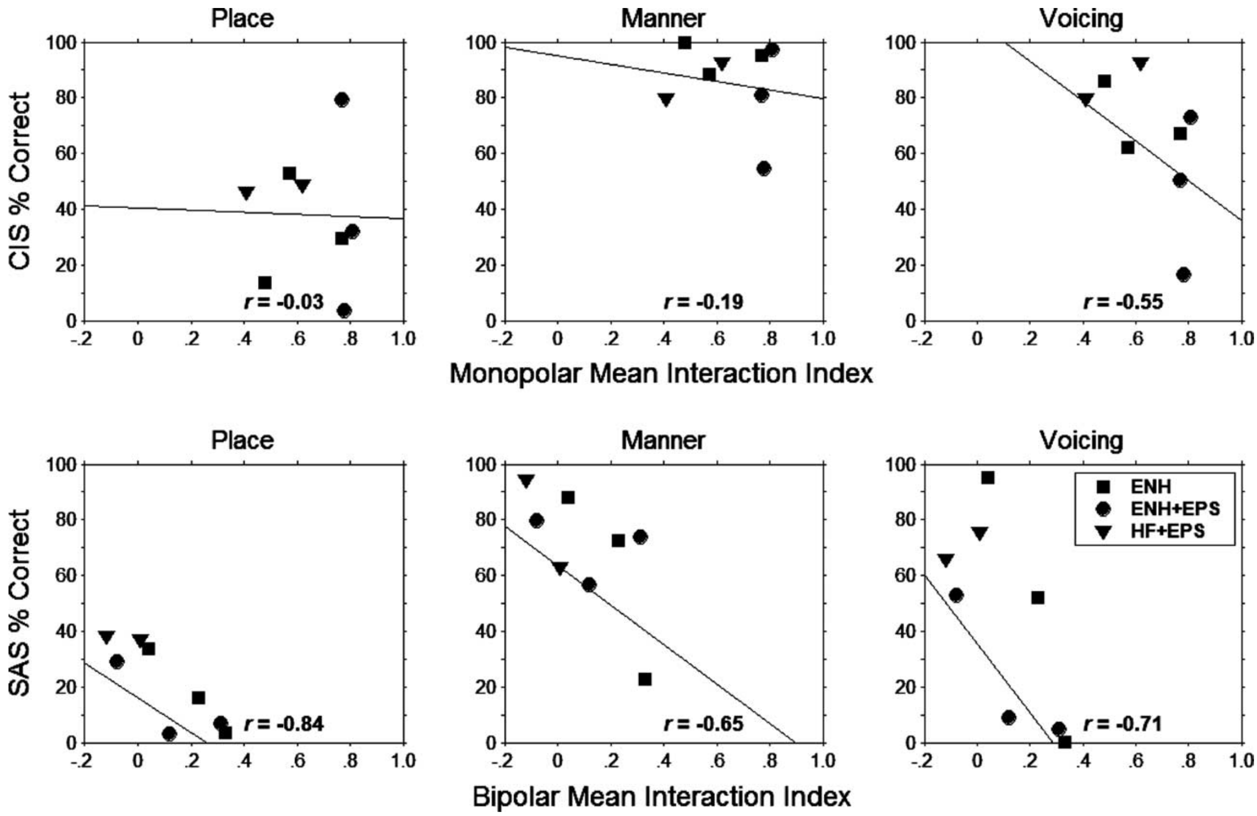

Fig. 8. Separate correlations are shown for the consonant features of place (left panel), manner (middle panel), and voicing (right panel). Correlations between the average monopolar Interaction Index (x-axis) and the % correct scores (y-axis) for the three consonant features are shown in the top panels for the CIS speech processing strategy. The bottom panels show correlations for the average bipolar Interaction Index and % correct scores using the SAS strategy.

$p < 0.01$. Voicing was also significant with $r(6) = -.71$, $p < 0.05$. There was no significant relationship between bipolar electrical-field interaction and manner, nor was there a significant relationship between monopolar interaction and any of the CIS consonant features.

4. General discussion

4.1. Asymmetrical interactions at the apex and base

Electrical-field interaction generally decreased with increasing separations between the perturbation and probe electrodes. This is likely related to the decrease in current field strength with increasing distance from the current source (Frijns et al., 1996; Kral et al., 1998), though the overall degree and pattern of electrical-field interaction was greatly dependent on the electrode configuration. For example, in monopolar configurations, the magnitude of interaction was reduced for basal electrodes compared to apical electrodes, whereas bipolar stimulation produced fairly symmetrical interaction magnitudes. A study by Kral et al. (1998), which used direct current field measurements from monopolar and bipolar stimulation in cat cochleae, provides some insight into these results. They measured the potential distribution at several distances from the round window and noted increasing radial current field potentials at more apical electrode locations as well as steeper, longitudinal potential gradients for bipolar than monopolar configurations. In both the cat and human cochlea the cross-sectional area of the scala tympani at the base of the cochlea is greater than the apex, which can reduce the current field strength for comparable inter-electrode distances at the base relative to the apex. The results in the present study combined with the current field measurements by Kral et al. suggest that the reduced electrical-field interaction observed in the base of the cochlea for monopolar stimulation is dependent on the relationship between cochlear geometry and current field strength.

4.2. Interaction patterns for monopolar and bipolar stimulation

Simultaneous monopolar stimulation between a perturbation and probe electrode was much more likely than bipolar stimulation to produce higher thresholds for out-of-phase stimuli, the lowest thresholds for in-phase stimuli, and thresholds for the probe alone condition that were approximately half-way between (Fig. 3) a threshold pattern indicative of current field summation. Boëx et al. (2003) have also observed this pattern in subjects with the same electrode arrays using simultaneous monopolar stimulation on adjacent electrodes. The psychophysical results from the present study demonstrate that there is a greater likelihood that broad current fields, a characteristic of monopolar stimulation, will have more current field overlap during simultaneous stimulation than the potentially narrower current fields generated by bipolar configurations.

The threshold pattern for bipolar stimulation did not generally show higher probe thresholds for out-of-phase compared to in-phase stimuli. Instead, several subjects either had similar out-of-phase and in-phase thresholds or the out-of-phase stimulation produced the lowest thresholds. In the latter case, the Interaction Index was negative. This result contrasts with the Interaction Indices measured from two Hi-Focus subjects in Boëx et al. (2003) who showed patterns similar to those with monopolar stimulation. It is possible that, if examined at greater separations, the pattern observed in Boëx et al. might have changed since, in the present study, negative Interaction Indices were mostly observed at greater electrode separations and Boëx et al. tested interactions between adjacent electrodes.

The paradoxically lower thresholds for out-of-phase stimulation relative to in-phase stimulation can be explained by residual polarization of the nerve membrane. In two separate electrical forward masking paradigms, both de Balthasar et al. (2003) and Eddington et al. (1994) noted that a sub-threshold perturbation signal produced patterns indicative of residual membrane charge (higher thresholds for in-phase stimulation relative to out-of-phase stimulation) for temporal delays less than 200 μs. de Balthasar et al. note that this pattern cannot be dependent on neural recovery from prior stimulation (i.e., the absolute refractory period), since the perturbation signal was presented below threshold and would not elicit an action potential. Instead, they mention that the second phase of the biphasic perturbation signal could polarize the nerve membrane, priming it for an action potential if the subsequent stimulus occurs within a narrow temporal window. The present results suggest that simultaneous stimulation using biphasic pulses is also sensitive to the relative timing of each phase of the perturbation and probe signal. With simultaneous stimulation, similar phases of the probe and perturbation signals occur within a much shorter time interval with out-of-phase than in-phase stimulation (see Fig. 2). With fully simultaneous out-of-phase stimulation, the depolarizing phase of the perturbation electrode would immediately precede the depolarizing phase of the probe electrode. This short time interval would allow for residual polarization. However, as shown in Fig. 5, it was peculiar that a negative Interaction Index measure was more commonly observed with nonadjacent perturbation, probe combinations, where electrical-field interactions were less likely to occur. At these separations, the electric fields from the perturbation electrode and probe electrode could activate the same neuron and yet avoid electrical-field interaction if the stimulation from each electrode was applied at different sites of excitation (e.g., stimulation at the soma and also along the nerve fiber). This may occur, for instance, with ectopic stimulation where electrodes can cause stimulation of nerve fibers traversing the modiolus from more apical turns (Frijns et al., 1995; Frijns et al., 2001). Future research is certainly needed to better understand the potential usefulness of sub-threshold ectopic stimulation. The present study showed that thresholds can be reduced with this type of stimulation in the absence of electrical field interactions. A reduction in threshold will increase the dynamic range and could enhance speech recognition performance.

4.3. The influence of electrode geometry

The magnitude of interaction was also influenced by the electrode array. Subjects using the Hi-Focus electrode array tended to have lower levels of interaction than either of the two subject groups with the Enhanced bipolar array. However, contrary to our hypothesis, subjects with the Enhanced bipolar array with an electrode positioner (EPS) were not found to have less electrode interaction than subjects without the EPS; this was observed both in the present results and in the study by Boëx et al. (2003). It is likely that differences in electrode geometry contributed to these results. The longitudinal electrodes of the Hi-Focus array produce a current field with a different geometry than the off-radial electrode pairs in the Enhanced Bipolar array and would therefore stimulate a different region along the membrane (Frijns et al., 1996; Hartmann et al., 1984; Pfingst et al., 1995; van den Honert and Stypulkowski, 1984). Because the peripheral process takes a transverse course from the spiral ganglion cell body to the hair cells, its orientation is perpendicular to the current field generated by longitudinally paired electrodes. Cochlear modeling results by Frijns et al., 1996 suggest that longitudinal arrays would therefore be less effective than radial bipolar pairs placed close to the modiolar wall for stimulation of these neural elements. However, in most persons with profound deafness, the peripheral dendrites are no longer intact (Lithicum et al., 1991), and the majority of the subjects in the present study had a long duration of deafness. In such cases, the stimulation site would be the spiral ganglion cell body – a stimulation site best targeted by the current field generated from modiolar placement of longitudinally arranged electrode pairs (Frijns et al., 1996). Thus, the possibility for electrical-field interaction should be decreased for the longitudinally arranged electrodes of the Hi-Focus array than with most placements of radial, or even offset-radial, bipolar electrode pairs. Electrodes placed close to the excitation point of the nerve fiber may lead to the rare selectivity observed in some subjects using monopolar stimulation (Liang et al., 1999; Ryan et al., 1990). This is demonstrated in Fig. 4, particularly for HF + EPS subjects.

4.4. Speech perception and electrical-field interaction

The average level of electrical-field interaction was related to speech recognition performance with the simultaneous speech processing strategy (SAS). The SAS correlations are consistent with the hypothesis that subjects with lower levels of electrical-field interaction will attain higher speech recognition scores. This relationship was not found with the speech perception results using the sequential speech processing strategy (CIS). There are two possible explanations why the SAS conditions produced higher correlations than the CIS conditions: (1) CIS is a sequential strategy and therefore avoids electrical-field summation and (2) simultaneous monopolar stimulation produces roughly the same interaction pattern for subjects with the same electrode array, yet there was a wide range of speech recognition abilities.

It is important to note that the HF + EPS subjects had relatively little difficulty with the simultaneous strategy compared to the other two subject groups, and they also had the lowest levels of electrical-field interaction. Despite SAS being a novel strategy, the HF + EPS subjects had only a small percentage drop in score (7–12%) when they were evaluated with SAS compared to the sequential speech processing strategy, CIS. Scores from the other two subject groups, on the other hand, dropped by as much as 49% points for sentences. This finding suggests that electrical-field interactions may interfere with the successful use of speech processing strategies that use simultaneous stimulation.

Electrical-field interaction accounted for 55% of the variance in vowel recognition scores obtained with the simultaneous speech processing strategy and 69% of the variance in consonant recognition scores. The significant correlations found for vowels (Fig. 7) and consonant place-of-articulation and voicing (Fig. 8) suggests that the effects of electrical-field interaction were very disruptive to the representation of spectral patterns. Electrical-field interaction may blur the boundaries between spectral peaks or introduce aberrant peaks, making it difficult to distinguish between neighboring formants. For example, when the subjects were switched to the SAS strategy, confusions were made between / / and vowels with similar F1–F2 values, e.g., sometimes labeling it as / / and other times as /o/ (as in "hoed") or / / as in ("hood"). For the vowel /A/, even more confusions were made with /æ/ with the SAS strategy than when the subjects were tested with CIS. The most common confusions on voicing using the SAS strategy occurred between /f/ and /v/ and between /s/ and /z/. In contrast to vowels and consonant place-of-articulation, consonant voicing can be determined by relatively coarse spectral information: voiced consonants contain greater energy in lower frequency regions whereas unvoiced consonants contain more energy in higher frequency regions. Interactions may have been so disruptive to the spectral distribution of energy that gross spectral cues were distorted. In addition to the spectral disruptions, the electrical-field interactions also alter the temporal waveforms, specifically the amplitude envelope, at the site of excitation. The effects of amplitude envelope distortions are numerous and likely include disruptions of voiced/voiceless distinctions, syllabic patterns, and the perception of speech in noise.

Although electrical-field interaction accounted for a large portion of the results on the speech recognition tasks, the results do not rule out significant contributions from other factors unrelated to interaction, such as cognitive processing abilities, the relationship between cognitive processing abilities and adaptation to novel speech processing strategies (e.g., SAS), and age at implantation. Furthermore, it is possible that cochlear implant users can adapt to some degree of disruption in the speech signal caused by electrical-field interactions. A full examination of electrical-field interactions and long-term exposure to simultaneous speech processing strategies would be beneficial.

5. Conclusions

The results of this study suggest that there is a relationship between psychophysical electrical-field interactions and speech recognition performance. Electrical-field interactions may be one of the factors that limit the success of simultaneous speech processing strategies. As a result, the range of speech processing strategies available to each patient may be limited and the potential benefits of simultaneous strategies or their hybrids may not be fully realized until the deleterious effects of electrical-field interactions are reduced.

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