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Original Articles

Multichannel Cochlear Implants

Channel Interactions and Processor Design

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• **Multichannel electrical stimulation of the cochlear nerve can generate complex interactions between the individual channels. Two types of channel interactions have been investigated: those that occur when two or more electrode channels are simultaneously stimulated and those that occur when the stimuli from each channel are not temporally coincident. Experiments with three human subjects, implanted with scala tympani electrode arrays, indicate that responses are a strong function of the spacing between the channels, the subject, and the electrode geometry (ie, bipolar or monopolar geometries).**

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Multichannel cochlear prostheses are currently being investigated as aids in speech reception for the profoundly deaf. It is hoped that multichannel speech processors that divide the speech spectrum in contiguous bands may allow the subject to discriminate between the higher-frequency spectral components of speech. Multichannel stimulation as compared with single-channel stimulation may more accurately mimic normal auditory nerve excitation patterns. However, when two or more electrode channels are stimulated, strong interactions between the channels can occur. Psychophysical experiments indicate that such interactions can greatly alter the loudness and quality of the sensation evoked during multichannel stimulation. In this report, we will describe strategies by which the nature and the extent of interchannel interactions can be measured, and then we will consider methods for controlling these interactions.

One type of interchannel interaction can occur when two or more channels are stimulated at precisely the same time. This type of interaction is described as a "simultaneous interaction" or as an "electric field interaction" because it may be the result of electric field summation and cancellation within the volume-conducting tissues of the cochlea. Figure 1 illustrates how a representative single neuron in the central nucleus of the inferior colliculus responded to two-channel stimulation.[1,2] When the two channels were stimulated simultaneously and with the same polarity (closed circles), the response was greater than that elicited when the polarity of the first channel was reversed (open circles). Reversing the polarity of the first channel presumably causes a net reduction in the electric field strength at the excitable neural structures. Biphasic pulses with 200-μs total duration (100 μs per phase) were used in these experiments. Threshold derived for stimulation of the first channel alone at one polarity was within 1 dB of threshold for the opposite polarity.

Figure 2 illustrates typical auditory brain-stem responses (ABRs) in the cat evoked by single-channel and two-channel stimulation.[1,2] Electrode channels "1" and "2" were bipolar pairs approximately 2 mm apart. In this series, each electrode channel was stimulated with single 200-μs biphasic pulses at current levels near threshold. The response to stimulation of channel 1 alone (2,000 trials) is shown by the first trace at the top of Fig 2 and of channel 2 alone by the second trace. With stimuli delivered simultaneously and with "opposing" polarities, the response was negligible (third trace). With stimuli delivered simultaneously but with the same polarity, a strong response was generated (fourth trace). The difference between the pair of two-channel responses (fifth trace) is a measure of the extent of interelectrode interaction. This example illustrates a relatively simple strategy by which such electric field interactions might be

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evaluated in patients.[3] The application of such an ABR test in a patient is shown in Fig 3. The two middle sets of response averages (labeled "++") represent responses to two-channel stimulation in which the two electric fields presumably "sum" in more regions of the excitable tissue than for those "opposing polarity" stimuli whose response averages are labeled "+ −".

Psychophysical experiments described herein by Eddington et al[4] and by Shannon[5] indicate that behavioral responses (ie, loudness and threshold measures) are also substantially affected by changing the stimulus polarity of one channel when more than one channel is being stimulated simultaneously. Since interactions generated during simultaneous stimulation can be quite severe, it might be useful to avoid them by stimulating each channel separately in time (ie, temporally interlacing the stimuli across the channels). This technique should at least eliminate those interactions that are due solely to the simultaneity of stimuli. However, in some subjects, there are channel interactions that occur even though the stimuli from the channels are not simultaneous. Substantial changes in threshold and loudness occur when stimulation of the second channel follows stimulation of the first channel by less than 2 to 5 ms. In these same subjects, single-channel thresholds are substantially reduced when the delay between identical biphasic pulses is decreased below 2 to 5 ms.

SUBJECTS AND METHODS

At the University of California, San Francisco, three profoundly deaf subjects were implanted with scala tympani intracochlear electrode arrays in an effort to partially restore their ability to understand speech. Each subject had become deaf after acquiring the English language. A comprehensive set of speech perception and basic psychophysical experiments were conducted over the experimental period. In one set of speech reception experiments, a selected set of speech processors was evaluated to determine which processor would be most useful for each subject.

Subject A, aged 60 years, had a gradual onset of hearing loss starting after the age of 10 years, that gradually increased until her loss was profound, about 30 years later. There is no family history of deafness nor any other known reason for this subject's hearing loss. Subject B, aged 61 years, had a gradual onset of hearing loss after measles at age 8 years that gradually increased until the loss was profound when she was in her 20's. Both subjects A and B participated in tests over separate three-month periods. Subject C, aged 51 years, had a sudden loss of hearing after an automobile accident (at age 20 years) in which he sustained a bilateral fracture. Subject C underwent psychophysical testing over a period of approximately 1½ months.

Prior to implantation, all subjects exhibited a greater than 110-dB loss across the 100-Hz to 8-kHz frequency range (subjects were tested at octave intervals). Each of the three subjects was unable to use high-power hearing aids in standard speech discrimination tests. A thorough psychologic evaluation was conducted to estimate how the subjects would respond to the consequences of the implantation. The subjects were also selected on the basis of their willingness and ability to participate in intensive psychophysical studies.

Subjects were implanted with scala tympani intracochlear electrode arrays of 16 wires. The electrode array and the implantation procedure are described in detail by Loeb et al.[6] The apical-most electrode was inserted approximately 21 to 26 mm into the scala. Each electrode contact was mushroom shaped in order to increase its surface area. The eight bipolar electrode pairs were spaced at 2-mm intervals along the polymeric silicone (Silastic) intracochlear insert. The intercontact spacing between bipolar contacts was approximately 700 μm, center to center. The bipolar electrode pairs were oriented approximately radial (and slightly diagonal) to the axis of the cochlea. Numbering of electrodes begins at the apical-most part of the array and progresses basally, such that the apical-most bipolar pair is labeled 1 and 2 and the basal most bipolar pair is labeled 15 and 16. An odd-numbered electrode represents an electrode contact placed more toward the modiolus (lateral) than the even-numbered (medial) contacts. In the monopolar configuration, only one intracochlear electrode contact was stimulated and the "return" contact was an ear clip located on the earlobe nearest the implanted cochlea. With monopolar stimulation, the same numbering system is used, but only one number is displayed to indicate which intracochlear electrode contact was stimulated.

All stimuli were delivered directly to the subject's electrode contacts via a percutaneous cable. This cable was connected through a set of relays to optically isolated, constant-current stimulators.[7] Each stimulator could generate a maximum of 1 mamp peak of current. Stimuli were generated with a digital-to-analogue converter at a sampling rate of 20 kHz. Both pulsatile and sinusoidal charge-balanced stimuli were generated. For sinusoidal stimuli, an antialiasing filter was used. During pulsatile stimulation, the antialiasing filter was bypassed. During all tests, the subject could immediately terminate stimulation by disengaging a "master" switch that would immediately disconnect all electrodes from the stimulators. As an additional precaution, the computer program used a set of ongoing "consistency checks" that verified that the system components were operating properly. If any one of these consistency checks proved invalid, stimulation immediately ceased.

In most cases, behavioral thresholds were measured with a modified Békésy tracking procedure using a minimum of eight threshold reversals for each stimulus condition. The subject pressed a button when he or she heard the stimulus and released the button when the stimulus was no longer audible. Interstimulus interval was 0.6 s. The average of the last six stimulus current minima and maxima was computed to determine the estimated threshold current. For selected stimuli, psychometric functions were estimated from threshold measurements obtained with a standard two-interval, two-alternative, forced-choice (2I-2AFC) adaptive procedure.

In loudness scaling experiments, subjects adjusted a linear potentiometer to indicate how loud a sound was. The left end of the 32.5-cm linear potentiometer represented a signal that was below threshold (represented by a "0" on the 0 to 100 loudness scale). The right extreme of the potentiometer represented a loudness that was the maximum loudness that was still comfortable (ie, a "100" on the scale). The stimuli were repeated every 700 ms until the subject pressed a button indicating that he had completed the loudness scaling. Stimulus trials were pseudorandomized. Unless otherwise noted, 12 loudness estimates were obtained for each stimulus condition.

Interchannel interactions of temporally overlapping stimuli were measured by determining how much loudness or threshold measures changed when the stimulus polarity of one of the channels was reversed. In most cases, polarity reversal did not substantially alter an individual channel's response. Thus, any changes in the two-channel responses could be attributed to "interactions" between the two channels. However, if an individual channel's response was notably different for the two stimulus polarities, a modification of the previously mentioned measurement technique was used to compensate for the difference in the individual channel's response. The channel's stimulus amplitude was changed when its polarity was reversed, so as to generate the same single-channel response for both polarities. To determine how much the stimulus amplitude should be changed, responses to single-channel stimulation of both stimulus polarities were measured prior to the two-channel interaction experiment.

RESULTS

Single-Channel Threshold Responses

Thresholds for monopolar and bipolar stimulation were measured for all three subjects. Thresholds were measured at several electrode sites in each subject. In one set of threshold measurements, 1,000-Hz, 300-ms sinusoidal stimuli were used. Across all three subjects, monopolar thresholds of 18 to 35 μamp were typical. Bipolar thresholds were a much stronger function of subject than were monopolar thresholds. Average bipolar thresholds for subjects A, B, and C were 90, 30, and 170 μamp, respectively. Subject C's thresholds were about 6 dB greater than those of subject A, and subject A's thresholds were 9 dB greater than those of subject B. The SEMs (in decibels) for subjects A, B, and C were 1.1, 2.7, and 1.6 dB, respectively. Dynamic ranges varied considerably (6 to 40 dB) with the type of stimulus. Dynamic ranges were generally not a strong function of electrode geometry. Dynamic ranges of 6 to 10 dB were common for the 200-μs biphasic pulse stimuli that we used in these studies or subject.

Interactions Involving Simultaneous Stimuli

For measuring simultaneous interaction, subject A adjusted a linear potentiometer to indicate how loud a 100-pulse per second (pps), 300-ms stimulus was (Fig 4). Electrodes 1 and 2 and 3 and 4 were each driven with 200-μs biphasic pulse trains of equal amplitude. The triangles represent the subject's loudness estimates when the two channels were stimulated with the same polarities. The squares represent the subject's loudness estimates when the polarity of electrodes 3 and 4 was reversed. The "reverse-polarity" stimuli generated a relatively weak sensation (eg, a loudness below "10" at 500 μamp) while the "same-polarity" stimuli generated an almost uncomfortably loud sensation at the 500-μamp stimulus level. The two bipolar electrode channels were 2 mm apart. Thresholds for the two channels and two polarities were approximately equal (ie, within 1 dB of 380 μamp).

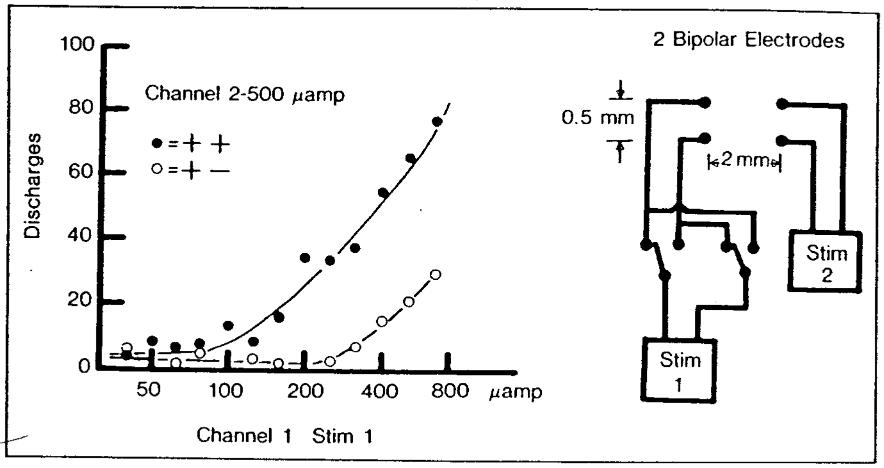


Fig 1.—Field interaction. Single-unit responses to two-channel stimulation (Stim) in central nucleus of inferior colliculus.[3,10] Basic conditions of experiment are indicated schematically on right. Closed circles indicate when two channels were stimulated simultaneously and with same polarity; open circles, polarity of second channel was reversed.

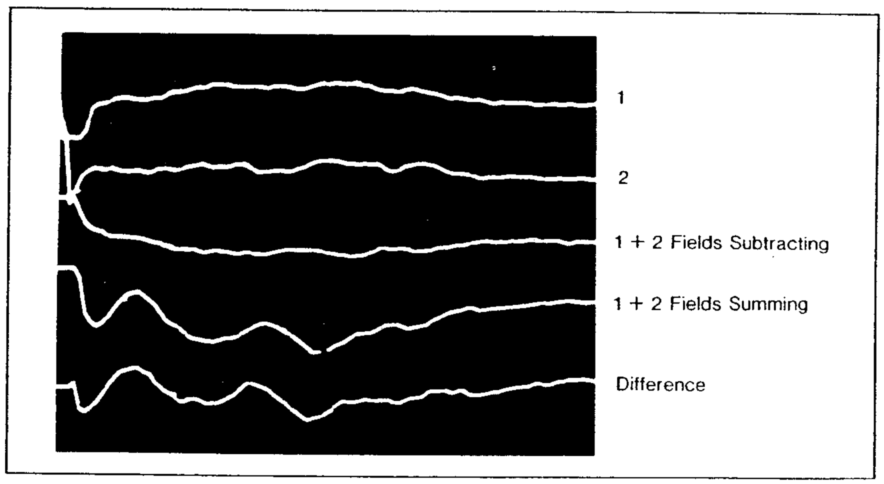


Fig 2.—Interelectrode interaction, as exhibited in auditory brain-stem response recording in cat.[3,10] Averaged responses are displayed during initial 10-ms period after stimulus onset.

This experiment suggested an efficient method for measuring simultaneous channel interactions as a function of interchannel separation. The stimulus amplitudes of both channels were varied such that each channel's amplitude was maintained at the same fraction of its threshold. Thresholds were measured for the same polarity and reverse polarity conditions. Differences between the subjects were particularly apparent in these measurements. When the polarity of the nearest monopolar electrode (ie, approximately a 700-μm interchannel separation) was reversed, two-channel thresholds increased by an average of 11, 5, and 14 dB over single-channel thresholds in subjects A, B, and C, respectively. Suprathreshold measurements were consistent with these threshold measurements. Shannon[5] found that subject

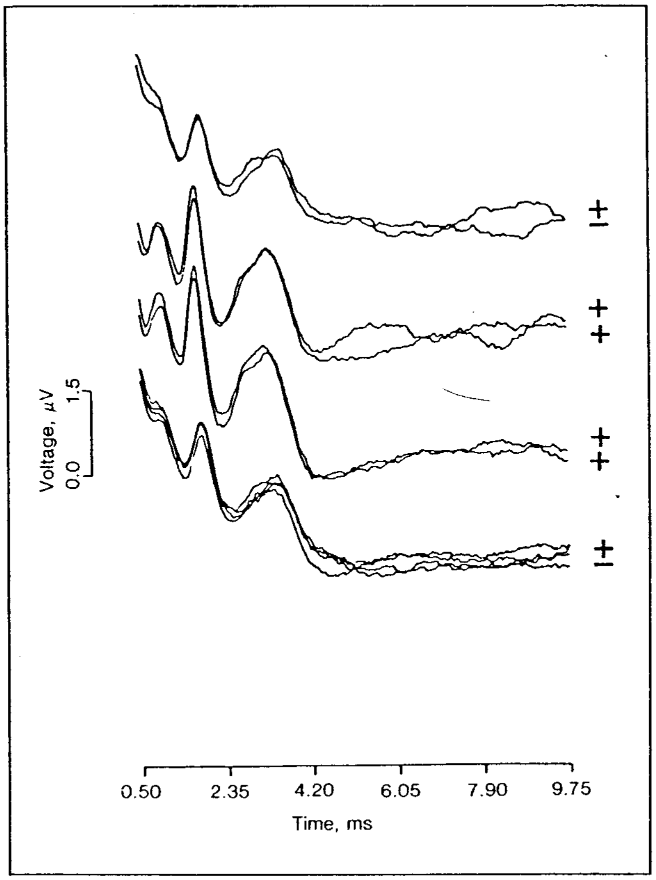
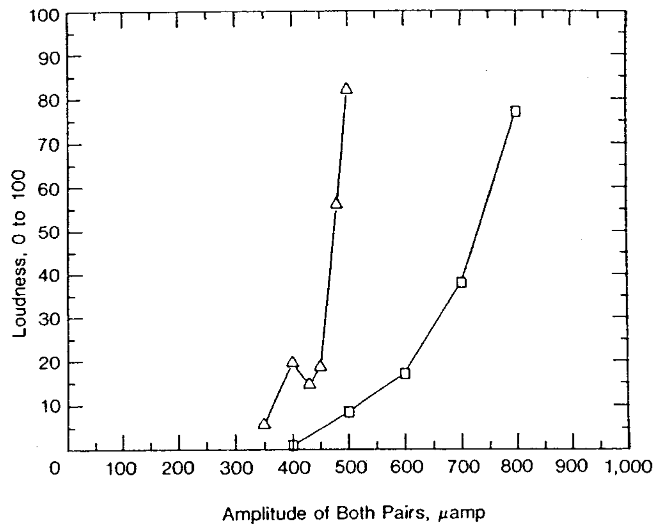


Fig 3.—Auditory brain-stem response averages (2,000 trials) that exhibit interelectrode interactions in subject B. Third and fourth most apical bipolar pairs (2 mm apart) were stimulated simultaneously with 100 μs per phase, 300-μamp biphasic pulses.

Fig 4.—Subject A's loudness estimates during simultaneous two-channel stimulation as function of stimulus amplitude and interchannel polarity. Triangles indicate subject's loudness estimates when two channels were stimulated with same polarities; squares, subject's loudness estimates when polarity of electrodes 3 and 4 was reversed.



B's midrange loudness estimates changed considerably less than those of subject A's when the stimulus polarity was reversed.

In subject C, interactions at threshold were measured as a function of interchannel separation and as a function of electrode configuration (ie, monopolar or bipolar). Figure 5 illustrates such a "mapping" of channel interactions. Each data point represents the ratio of two thresholds: threshold with the polarities reversed divided by the threshold with the "polarities summing." Thresholds were measured on a linear scale of current. For all data points in this example, the first (and most apical) channel's polarity was altered. The second channel was separated by 2, 4, 6, 8, 10, 12, or 14 mm from this most apical channel.

Figure 5 demonstrates that simultaneous channel interactions decline with interchannel distance and that these channel interactions are reduced with bipolar stimulation. However, even with bipolar stimulation, subject C exhibited a substantial amount of channel interaction. Even with bipolar stimulation and 6-mm channel separations, the two-channel threshold can change by nearly a factor of two with a change in the polarity of the apical channel, although the change was considerably less pronounced than that incurred under monopolar stimulation.

Interactions Involving Nonsimultaneous Stimuli

In subjects A and B, there were substantial channel interactions that occurred even though the stimuli from the two channels were not simultaneous. Figure 6 illustrates subject A's loudness estimates as a function of the delay between two biphasic stimulus pulses. Each pulse was delivered to a separate monopolar electrode channel. Each data point represents the average of six loudness estimates. Standard error of the mean was about 2.7 for loudnesses above 10 and about 2.2 for loudnesses below 10. Loudness changed most substantially when the interchannel delay was decreased below 5 ms.

We have measured channel interactions involving nonsimultaneous stimuli as a function of interchannel distance in three subjects and with two types of electrodes (ie, bipolar and monopolar). We often refer to channel interactions that occur during nonsimultaneous stimulation as "temporal interactions." Figure 7 summarizes the results of these studies. The temporal interaction data have been summarized by calculating the "percentage change in loudness" for a given change in interchannel delay. Specifically, the "temporal interaction index" is defined by the following equation: $\text{Index} = 100 \times \{(\text{Lmax} - \text{Lmin})/([\text{Lmax} + \text{Lmin}]\}/2)$, where, Lmin is the loudness for an interchannel delay of 5 ms and Lmax is the loudness for an interchannel delay of 1 ms. Each channel was stimulated at a level that evoked a loudness of 10 to 20 (on the 0 to 100 loudness scale) when the channel was stimulated alone. In Fig 7, the distance between the horizontal dashed line and the horizontal axis represents the average SE of the temporal interaction index-

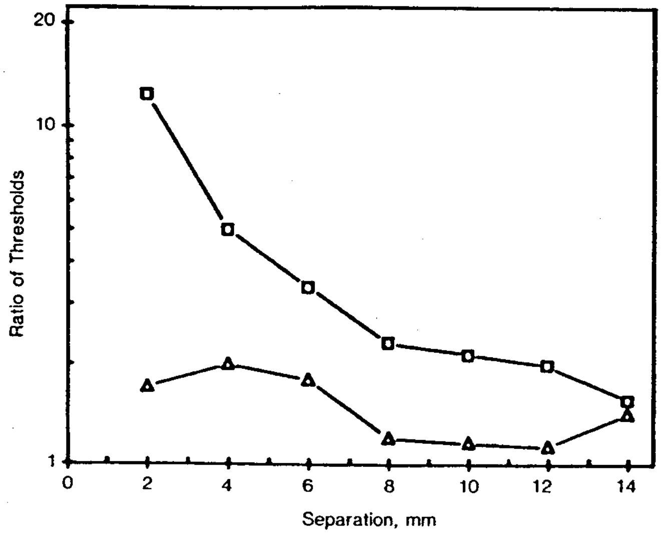


Fig 5.—Ratio of thresholds (for two stimulus polarities) as function of interchannel separation and electrode type (ie, monopolar [squares] or bipolar [triangles]) for subject C.

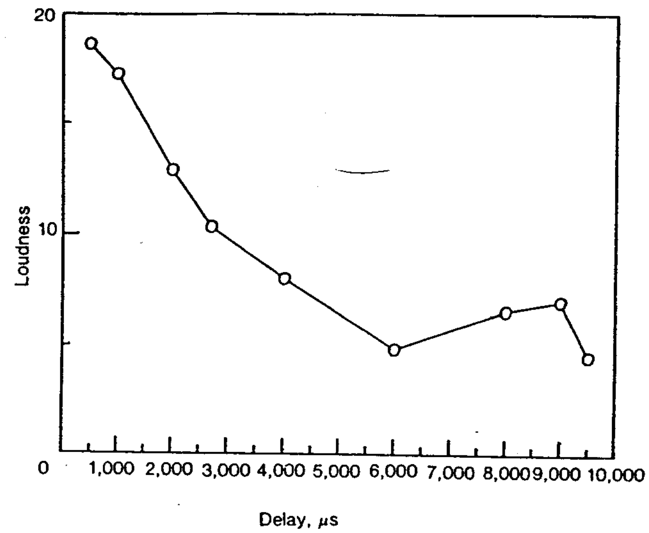


Fig 6.—Subject A's loudness estimates as function of delay between stimulation of monopolar electrodes 12 and 13, spaced 2 mm apart. Two monopolar electrodes were each stimulated with single 200-μs biphasic pulse.

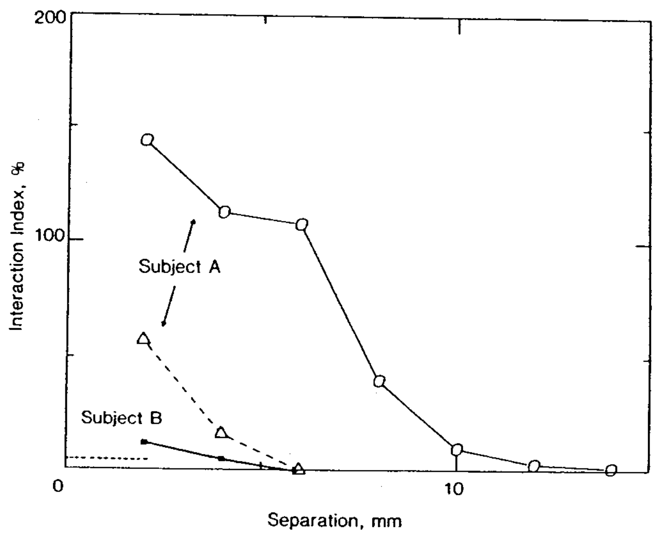


Fig 7.—Index of temporal interaction as function of interchannel separation, electrode geometry, and subject (A or B). Straight line indicates two-channel interaction monopolar; dashed line, bipolar.

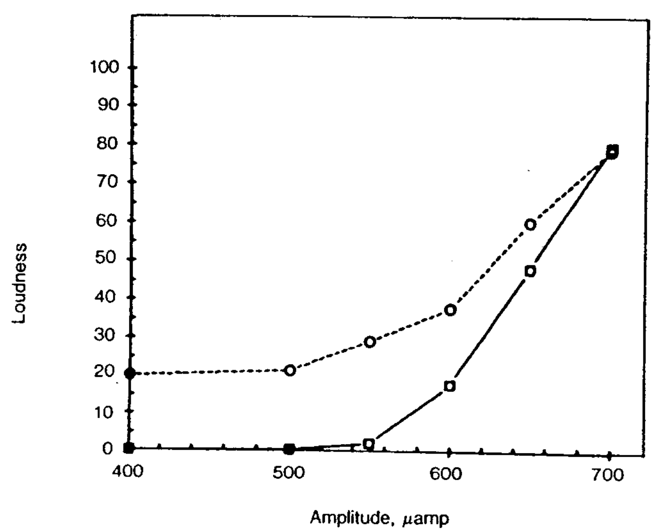


Fig 8.—Subject A's loudness estimates for single- and two-channel stimulation when "electric field" and temporal interactions were minimized. Dashed line and circles indicate subject A's loudness estimates for two-channel stimuli as function of stimulus amplitude on electrodes 7 and 8 and 3 and 4; solid line and squares, subject's loudness estimates as function of stimulus amplitude for stimulation of electrodes 7 and 8 alone.

es measured in subject B.

Subjects A and B exhibited substantial levels of temporal interaction between two nearby monopolar channels. However, the two subjects were different in the spatial extent of these interactions. Subject B exhibited much less channel interaction than subject A. In subject B, there was no measurable nonsimultaneous interaction with bipolar electrodes. In both subjects, the bipolar electrode reduced the change in loudness that occurred for a given change in interchannel stimulus delay. In both subjects, the index of temporal interaction decreased as the distance between the two channels was increased.

Subject C was different from subjects A and B in that his loudness estimates never changed substantially over the range of interchannel delays examined, even with monopolar electrodes and minimal separation between the channels. This is particularly important because other measures indicate that this subject had relatively little "isolation" between channels. Subject C also was different from subjects A and B in a closely related, single-channel threshold measurement. Single-channel thresholds to four biphasic pulses dropped

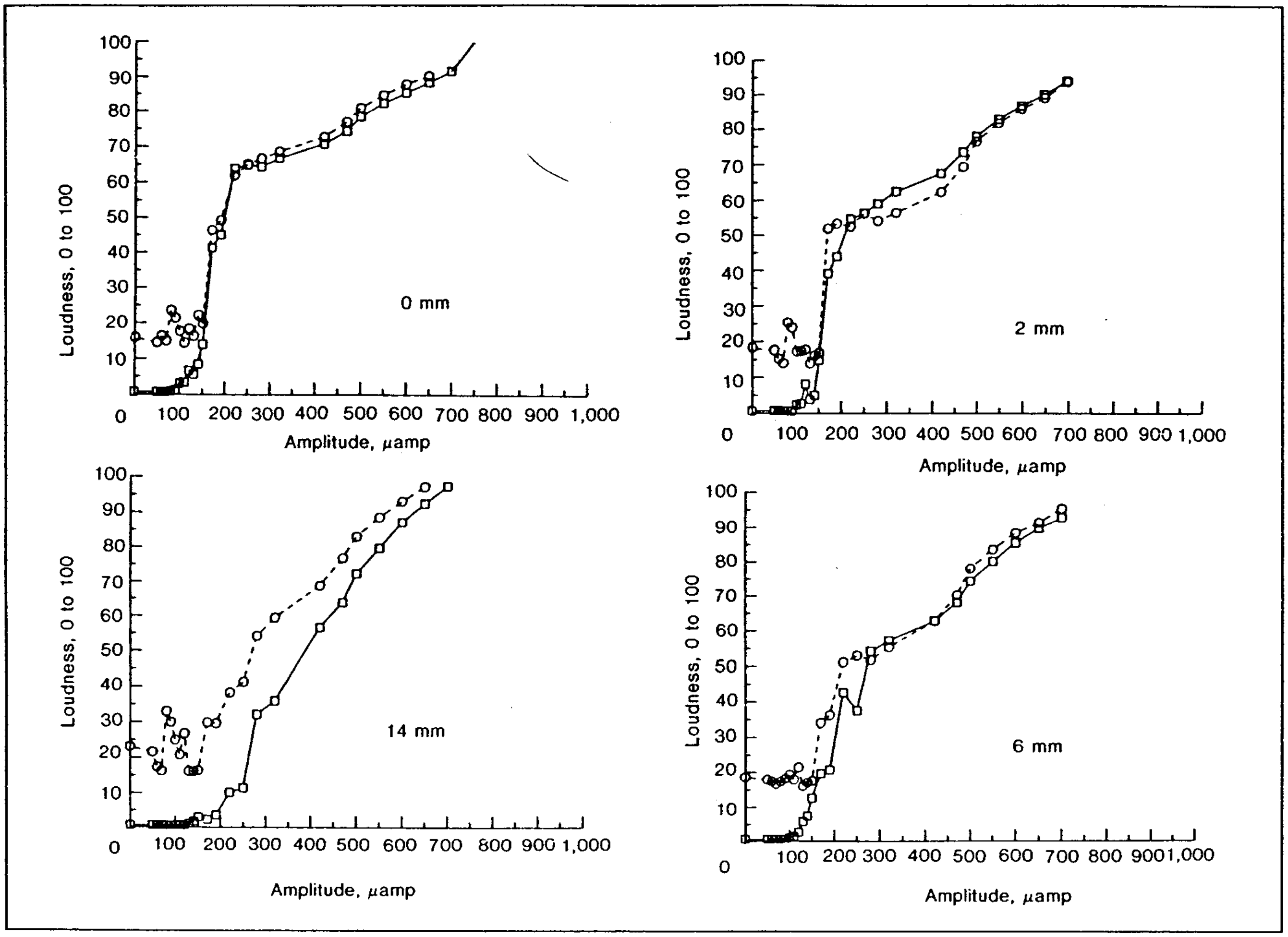


Fig 9.—Subject C's loudness estimates for single- and two-channel stimulation when "electric field" and temporal interactions were minimized. Each graph represents data obtained at different interchannel separations. Solid line and squares indicate subject's loudness estimates for stimulation of second channel alone; dashed line and circles, loudness estimates for stimulation of both channels.

by 2.1 dB for subject A and 2.7 dB for subject B when the interpulse delay was decreased from 10 ms to 1 ms. Thresholds to pairs of biphasic pulses dropped by 1.1 dB for subject A and 1.5 dB for subject B when the interpulse delay was decreased from 10 ms to 1 ms. In all of these cases, thresholds dropped most dramatically as the delay was decreased from 5 ms to 1 ms. However, subject C's thresholds were not measurably affected by interpulse delay. The SD of these threshold measures was approximately 0.2 dB.

Loudness Summation as a Function of Interchannel Separation

Figure 8 illustrates subject A's loudness estimates as a function of stimulus amplitude for single-channel and two-channel stimulation in which interchannel interactions (of the types described previously) have been minimized. Bipolar electrodes 3 and 4 and 7 and 8 were each driven with 200-µs biphasic pulses at 100 pps for 300-ms durations. The stimulus level on electrodes 3 and 4 was held constant while the stimulus level on electrodes 7 and 8 was varied. When electrodes 3 and 4 were stimulated alone at this constant level, the average of the subject's loudness estimates was 20 on the 0 to 100 scale. The interchannel delay between stimulus pulses on the two channels was held constant at 5 ms. The dashed line and circles represent subject A's loudness estimates for these two-channel stimuli as a function of the stimulus amplitude on electrodes 7 and 8. The solid line and squares represent the subject's loudness estimates as a function of stimulus amplitude for the stimulation of electrodes 7 and 8 alone. Each data point represents the average of approximately 12 loudness scalings by the subject.

At loudnesses below about 70, *both channels contribute* to the loudness percept when each of the channels is driven above its threshold level. This assertion is made because the loudness evoked by two-channel stimulation is substantially greater than that loudness evoked by either channel individually. At stimulus levels that evoke a loudness above about 70, electrodes 3 and 4's contribution is not apparent in subject A's loudness estimates. The SEM was approximately constant for loudnesses between 15 and 80. Over this range, the SE was approximately five loudness units. At lower and higher loudnesses, the SEs were substantially smaller. For example, a SE of approximately 0.8 was obtained for a mean loudness of 2.2.

In subject B, two-channel loudness estimates were obtained over a limited loudness range of 0 to 40 on the 0 to 100 loudness scale. At loudnesses greater than 40, subject B experienced facial-nerve stimulation on some electrode channels with these narrow-pulse-width, low-repetition-rate stimuli. Over the measured 0 to 40 loudness interval, subject B's responses indicated that both channels contributed to her loudness estimates when each channel was stimulated above its threshold level.

With subject C, we studied these two-channel responses as a function of the distance between the two electrode channels (Fig 9). The experiment was nearly identical to that described previously. For subject C, a greater interchannel delay was introduced to further reduce possible short-term temporal summation of the excitation generated by both channels together. We increased the interchannel delay from 5 ms to 10 ms, by reducing the pulse repetition rate on each channel from 100 pps to 50 pps. (With single-channel stimulation, loudness did not change substantially when the repetition rate was varied between 50 pps and 100 pps.) The four graphs in Fig 9 represent 0-, 2-, 6-, and 14-mm interchannel separations. Monopolar electrode 1 was always stimulated at the same level during the two-channel stimulation sequences. When electrode 1 was stimulated alone at this level, loudness estimates of approximately 20 were elicited. The second electrode channel was different for each graph: monopolar 2 for the top left graph, monopolar 3 for the top right graph, monopolar 7 for the bottom right graph, and monopolar 15 for the bottom left graph. Monopolar 2 is at approximately the same cochlear "place" (ie, on the longitudinal dimension of the cohlea) as monopolar 1. In each graph, the solid line and squares represent the subject's loudness estimates for stimulation of the second channel alone. The dashed line and circles represent the loudness estimates for stimulation of both channels. Each data point represents the average of four loudness scalings. For loudness estimates between 15 and 60 units, SEMs were approximately 3 to 4 loudness units.

At the largest interchannel separation (ie, 14 mm), both channels measurably contributed to the two-channel loudness estimates at all loudnesses when the second channel was stimulated sufficiently above its threshold level. Interestingly, at this large interchannel separation, the subject consistently and spontaneously reported hearing "two and sometimes three pitches or separate sounds." Subject C never reported this "separation of sensations" when the interchannel separations were small (ie, separations of 0 to 2 mm). For an interchannel separation of 6 mm, both channels might have contributed to the loudness percept, but only over a limited loudness range (ie, approximately 30 to 55 on the 0 to 100 loudness scale). Over this loudness range, the difference in loudness between the one- and two-channel conditions was approximately equal to 2 SEs of the mean loudness differences. At the 0- and 2-mm interchannel separations, there does not appear to be a region in which both channels substantially contributed to the loudness estimates. For the 0- and 2-mm interchannel separations, either the first channel or the second channel "dominated" the loudness estimates.

COMMENT

In this report, we have used a relatively general definition of "interchannel interactions." We have operationally defined interchannel interactions to be phenomena in which response(s) are a function of the separation of the stimulated channels. In the following, we will consider some of the mechanisms that may contribute to these interactions. Further, we will consider the impact of such interactions on the design of multichannel speech processors.

Interactions Involving Simultaneous Stimuli

Interactions involving simultaneous stimuli could be due to electric-field summation in the cochlea. If the fields from each channel substantially overlap, the magnitude of the potential distribution within the cochlea will be notably altered when the stimulus polarity (or phase in the case of sinusoidal components) of one of the channels is changed. As a consequence, the quantity and locus of neural excitation can be substantially altered by a change in stimulus polarity. The results of two-channel threshold experiments offer evidence consistent with an electric-field summation mechanism. When two adjacent channels had the same stimulus polarity, the current delivered to each channel at threshold was as little as one half that current required for either channel alone. When two adjacent channels had opposite stimulus polarities, two-channel thresholds in some subjects were many times that of either channel's threshold (eg, 4 to 6 times single-channel thresholds in subject C). These results are consistent with linear summation (and cancellation) of electric fields within the cochlea. If the electric fields from both channels exactly overlapped and were of the same polarity, we would expect two-channel thresholds to be exactly half those for each channel alone. If the electric fields from both channels exactly overlapped but were of opposite polarity, then theoretically we would never reach threshold.

A number of two-channel thresholds were as much as 2 to 6 dB below respective single-channel thresholds. That this is a sizable change for such stimuli can be seen by examining the psychometric functions for single-channel stimulation. Psychometric functions were derived for single-channel stimuli identical to those used in these interaction experiments. Stimulus levels, only 0.5 to 2 dB below the levels required for a 70% correct response rate, elicited virtually chance detection rates. Without some form of summation across the channels prior to the hypothetical noise source, it seems unlikely that the CNS could detect such low-amplitude stimulation from two channels.

At suprathreshold levels, central mechanisms could be involved in the observed interactions involving simultaneous, two-channel stimuli. For example, a change in stimulus polarity could be signaled to the CNS by a change in the timing of neural discharges and/or by a change in the distribution of excited fibers. Indeed, changes in stimulus polarity might substantially alter which fibers are excited. However, with the stimuli used in this study, detectable changes in the timing of discharges with changes in polarity are unlikely. All stimuli used in these studies were 200-μs (100 μs per phase) biphasic pulses. These stimuli have a cycle duration equivalent to a 5-kHz sinusoidal cycle. It is unlikely that the nerve is capable of transmitting, with sufficient accuracy, such fine-time changes (as might occur with a polarity reversal) at near-threshold levels.

Interactions Involving Nonsimultaneous Stimuli

In single-channel and two-channel experiments, subjects A and B exhibited responses that were consistent with a short-term temporal integration mechanism. With two or four biphasic pulses, their single-channel thresholds decreased as the pulse rate was increased above 200 pps. In two-channel experiments using nonsimultaneous biphasic pulses, the subject's loudness estimates increased when the interchannel delay was decreased below 5 ms. Subject C did not exhibit either of these response characteristics. Subject C may lack such a hypothetical short-term temporal integration mechanism.

For subjects A and B, a comparison of single-pulse threshold with the threshold for two or four biphasic pulses spaced 1 ms apart shows an improvement of 2 to 4 dB for the pulse groups over the singles. That this is a sizable change for such stimuli can be seen by noting that if one derives the complete psychometric function for single 200-μs biphasic pulses (using a 2I-sAFC procedure) the level for 70% correct is only 0.5 to 2 dB below the level for chance detection.

Without some form of temporal summation prior to the hypothetical noise source, it seems unlikely that the CNS could even detect the pulses.

Herndon[8] discovered that a subject's single-channel thresholds decreased substantially as the pulse rate was increased above 200 pps in each of two modiolar electrodes. However, under the same stimulus conditions, thresholds did not decrease when using either of the other two modiolar electrodes. The two groups of electrodes might have excited functionally different neural processes. Herndon used standard "square-shaped" biphasic pulses, 250 μs in duration. When he used shorter, highly peaked biphasic pulses, the thresholds of all four electrodes remained essentially constant as the pulse rate was increased. It seems most probable that the time-varying-nonlinear peripheral nerve process is responsible for the difference in threshold response when the stimulus waveform was changed in this manner. Also, these data indicate that some of the simpler nonlinear models (eg, an instantaneous nonlinearity ahead of a "leaky" storage element) would not accurately model this process. However, such first-order models can be useful in the conceptualization of any temporal integration process.

In eighth-nerve recordings, Van den Honert and Stypulkowski[9] found evidence for two distinct sites of electrical excitation in auditory nerve processes. Responses were highly dependent on which site was excited. One site exhibited lower thresholds, longer response latencies, and *substantially longer chronaxies* than the second site. They have been able to eliminate the lower threshold and longer chronaxy responses by destroying the eighth nerve dendrites and ganglion cells while leaving the axons intact.

It is possible that subject C is largely without those neural elements that are normally near the stimulating electrodes. Consistent with this interpretation, subject C's bipolar thresholds were higher than those of the other two subjects. Also, subject C's relatively severe interchannel interactions with simultaneous stimuli are indicative of a relatively large separation between electrode and nerve. It is possible that this hypothetical group of distal neural elements (eg, dendrites) is responsible for the short-term temporal integration seen in subjects A and B, but not in subject C. Since it is likely that the cochlea is the primary site of deterioration in these subjects, it seems plausible that such differences between the subjects are due to differences within the cochlea.

An observed property of peripheral nerve processes may be responsible for the short-term temporal integration observed in these patients.[10] When the current from biphasic, zero-net-charge stimulus pulses enters the nerve cell membrane, "residual excitation" due to the initial pulses can reduce the neuron's threshold such that subsequent pulses can elicit an action potential at normally subthreshold levels of current. In two-channel stimulation, the current from the first channel might reduce the threshold of some neural processes so that a normally subthreshold stimulus from the second channel will be sufficient to excite these neural processes. In this interpretation, each of the two electrode channels must produce a substantial current density at *common* nerve membrane locations. Presumably, as channel separation is increased, the number of fibers that receive current from both channels will decrease.

Loudness Summation as a Function of Interchannel Separation

What are the possible origins of the behavior exhibited in Figs 8 and 9? In the following interpretation, loudness is assumed to be an increasing function of the number of excited fibers. In those cases in which two-channel stimulation does not give a greater than single-channel stimulation, the channels may be stimulating completely overlapping fiber populations. Essentially, the two channels may act as one channel. If this is the case, the two 50-pps stimuli would overlap to form a 100-pps stimulus. (Loudness changes little, if at all, when the pulse rate on a single channel is increased from 50 to 100 pps when using 200-μs biphasic pulses.) If this interpretation is correct, it may not be possible to excite nonoverlapping nerve sectors in subject C at the higher loudness levels with interchannel separations of 6 mm or less. However, at a 14-mm interchannel separation, it should not be difficult to excite at least partially nonoverlapping sectors at all loudness levels. In subjects similar to C, it may be useful to reduce the maximum loudness that can be generated by each channel. This technique could reduce "interference" due to an overlap in excitation patterns. However, the operating range of each channel should not be reduced too much. In such a case, the number of discriminable intensity differences available within each channel would be severely compromised.

Implications for Processor Design

With a good understanding of channel interactions, it might be possible to use simultaneous and nonsimultaneous interactions to expand and improve the transmission of useful information to the nervous system. However, appropriate control of the distribution of the electric fields across the three dimensions of the cochlea and modiolus may be difficult, even to a first order.

In some multichannel processors, the polarity, phase, or interchannel delay relationships between electrode channels can be quite different for different tokens of the same speech segment. With a substantial amount of channel interaction, such intertoken stimulus variations can generate large perceptual differences for the same segment of speech.

One approach has been to avoid channel interactions. Channel interaction that occurs at the peripheral nerve should be a function of the proximity of stimulating elements to excitable neurons and the distance between the channels. Such peripheral interactions can be expected to be less of a problem in patients with many surviving distal neural elements (eg, dendrites intact) since the neural elements are relatively near the stimulating electrodes. In some subjects, relatively few stimulus constraints may be necessary to achieve a relatively low level of channel interaction (eg, subject B with bipolar stimulation). Given poor nerve survival, channel interaction will probably be more substantial. In this latter case, techniques designed to reduce channel interactions should be useful.

There are several ways in which channel interactions can be reduced: (1) The distance between the electrode channels may be increased to reduce interactions, although such alterations may rapidly become self-defeating in a multichannel prosthesis. (2) Bipolar electrodes with closely spaced contacts (0.5 to 1 mm) have been demonstrated to be useful in limiting the spread of excitation when compared with monopolar electrodes.[1] (3) Channel interactions might be reduced by decreasing the distance between the stimulating electrodes and the excited neural tissue. Consistent with this notion, there is a strong positive correlation across subjects between bipolar thresholds and measures of channel interaction (using simultaneous stimuli). (4) Nonsimultaneous stimulation of electrode channels should eliminate the most severe component of channel interaction. In one technique, stimuli are temporally interlaced across the interacting channels. (5) Temporal interactions can be reduced by increasing the minimum delay between stimulation of interacting channels above 2 to 5 ms. (6) In some subjects, it might be necessary to maintain lower loudness levels to prevent some channels from stimulating those fibers that normally carry information from other channels. At one extreme, only one channel would be stimulated during a hypothetical speech analysis interval or "frame" (ie, over a 5- to 30-ms interval).

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