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Acoustic Simulations of Combined Electric and Acoustic Hearing (EAS)

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Objective: **Our aim was to explore the consequences for speech understanding of leaving a gap in frequency between a region of acoustic hearing and a region stimulated electrically. Our studies were conducted with normal-hearing listeners, using an acoustic simulation of combined electric and acoustic (EAS) stimulation.**

Design: **Simulations of EAS were created by low-pass filtering speech at 0.5 kHz (90 dB octave roll-off) and adding amplitude-modulated sine waves at higher frequencies. The gap in frequency between acoustic and simulated electric hearing was varied over the range 0.5 kHz to 3.2 kHz. Stimuli included sentences in quiet, sentences in noise, and consonants and vowels. Three experiments were conducted with sample sizes of 12 listeners.**

Results: **Scores were highest in conditions that minimized the frequency gap between acoustic and electric stimulation. In quiet, vowels and consonant place of articulation showed the most sensitivity to the frequency gap. In noise, scores in the simulated EAS condition were higher than the sum of the scores from the acoustic-only and simulated electric-only conditions.**

Conclusions: **Our results suggest that both deep and shallow insertions of electrodes could improve the speech understanding abilities of patients with residual hearing to 500 Hz. However, performance levels will be maximized if the gap between acoustic and electric stimulation is minimized.**

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In the newest application of neural prostheses for deafness, electrical stimulation from a cochlear implant is used to complement residual, low-frequency hearing. Using the technique of "soft surgery" (Lehnardt, 1993), electrodes are inserted into the scala tympani with the hope of preserving neural elements in the apical region of the cochlea. When hearing is preserved, the combination of acoustic hearing in low frequencies, commonly between 125 Hz and 500 to 750 Hz, and electrical stimulation of high frequencies can lead to very high levels of speech understanding, especially in noise (Gantz & Turner, 2003; Skarzynski, Lorens, & Piotrowska, 2003; Turner, Gantz, Vidal, Behrens, & Henry, 2004; Wilson, Wolford, Lawson, & Schatzer, Reference Note 1; Kiefer, et al., Reference Note 5). The combination of electric and acoustic hearing is termed electric/acoustic hearing, or EAS (von Ilberg, et al., 1999).

One of the central issues in the new field of EAS is the effect on speech understanding of the gap in frequency between low-frequency acoustic hearing and the most apical place (or frequency) of electrical stimulation. At present, trials are underway with electrodes inserted a relatively short distance (10 mm) into the cochlea (e.g., Gantz & Turner, 2003) and with electrodes inserted a longer distance (20 mm) into the cochlea (e.g., Baumgartner, Reference Note 2; Kiefer, et al., Reference Note 5). Stimulation from both electrode arrays has been found to add to the intelligibility of speech. A 10 mm insertion will, of course, leave a larger gap than a 20 mm insertion between the region of low-frequency acoustic hearing and the lowest frequency elicited by electrical stimulation. In EAS patients, the magnitude of the gap is not well defined because the relationship between electrode insertion depth and place pitch, or frequency, is not well understood. If the Greenwood equation (Greenwood, 1990) is appropriate for cochlear implant stimulation, then electrical stimulation 10 mm into the cochlea should be near the 4 kHz place, and stimulation 20 mm into the cochlea should be near the 1 kHz place. However, pitch matching data from patients with residual acoustic hearing in the ear contralateral or ipsilateral to an implant suggest that the Greenwood equation is not always appropriate and that electrical stimulation results, for at least some patients, in pitch percepts lower than those predicted by the Greenwood equation (James, Blamey, Shallop, Incerti, & Nicholas, 2001; Boex, Baud, Cosendai, Sigrist, Kos, & Pelizzone, Reference Note 3; Brill, Lawson, Wolford, Wilson, & Schatzer, Reference Note 4).

Whatever the exact place or frequency of stimulation from an electrode, we might suppose that large gaps in frequency between acoustic and electric stimulation would depress speech understand-

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ing relative to the level achieved with small gaps because critical information about phonetic identity would be omitted from the signal. However, consonants can be identified with high accuracy (89% correct) when mid-frequency information, e.g., between 800 Hz and 4 kHz, has been removed (Lippmann, 1996; see Warren, Bashford, & Lenz, 2004, for studies on frequency band effects on speech understanding). Because consonant recognition is correlated highly (0.90) with sentence recognition (Rabinowitz, Eddington, Delhorne, & Cuneo, 1992), it is possible that leaving out mid-frequency information will have a small effect on sentence recognition in the context of EAS. On the other hand, leaving out any portion of the speech spectrum probably will have a significant effect on vowel recognition because both F1 and F2 are needed for recognition (Delattre, Liberman, Cooper, & Gerstman, 1952). In any event, combined electric and acoustic stimulation creates a novel set of questions about the frequency components of speech that are necessary, or sufficient, for patients to reach a high level of speech understanding.

In this study, we examined some of these questions in three experiments by using normal-hearing listeners and an acoustic simulation of EAS. We have used an acoustic simulation of EAS because we could define with precision the gap in frequency between acoustic stimulation and simulated electric stimulation. In our experiments, speech was low-pass filtered at 500 Hz with a 90 dB/octave roll-off. We chose this cutoff frequency and roll-off because it creates an audiometric configuration similar to that found in the literature for many EAS patients and similar to that of participants in the U.S. clinical trial of a 20 mm electrode insertion. In our experiments, the effects of electrical stimulation were approximated by using *N* amplitude-modulated sine waves as stimulation (e.g., Dorman, Loizou, & Rainey, 1997). The results from several experiments have shown that the level of performance achieved with acoustic simulations of conventional implants is similar to the level of performance achieved by the better-performing patients (e.g., Dorman & Loizou, 1997; Dorman, 1999; Fu, Shannon, & Wang, 1998).

In Experiment 1, we assessed the effects on speech understanding of the magnitude of the gap in frequency between acoustic stimulation and simulated electric stimulation, i.e., the effects of electrode insertion depth. In Experiment 2, we assessed the interaction of the magnitude of the gap in frequency and the type of test material. In Experiment 3, we assessed the contributions of acoustic-only stimulation, simulated electric-only stimulation, and simulated EAS to speech intelligibility in noise and in quiet.

EXPERIMENT 1

Experiment 1 was designed to answer the following questions: (1) What is the effect on sentence understanding of the magnitude of the gap in frequency between low-frequency acoustic hearing and higher-frequency electrical stimulation? (2) What is the effect on sentence understanding of losing acoustic hearing, i.e., what level of understanding could be achieved with electrical stimulation alone if hearing were lost as a consequence of surgery? (3) How does the level of understanding achieved with EAS compare with the level of understanding that could be achieved with a full electrode insertion, i.e., a standard cochlear implant in a patient with no residual acoustic hearing?

Subjects

The subjects were 12 normal-hearing undergraduates at Arizona State University.

Test Material

Sentences from the TIMIT (The DARPA TIMIT Acoustic-Phonetic Continuous Speech Corpus) sentence lists (Lamel, Kassel, & Seneff, 1986) were used as stimuli. The sentences were scored for words correct. To ensure equal difficulty among sentence lists, 950 sentences were processed through a five-channel, cochlear implant simulation and were presented to 10 listeners for identification. We used a five-channel simulation to avoid ceiling effects in sentence intelligibility. The sentences were combined into 20-sentence lists with equal intelligibility (75% correct ± 1%). The lists were randomly assigned to a test condition, and no list was used twice.

Signal Processing

The acoustic-hearing alone condition was created by passing speech through a 500 Hz, low-pass filter with a roll-off of 90 dB/octave. The filter was implemented by using the MATLAB signal-processing toolbox.

To create the signals for the simulation of electric stimulation, a software version of a cochlear implant signal processor was implemented, using MATLAB (Dorman, et al., 1997). Signal processing was implemented in the following manner: Signals were first processed through a pre-emphasis filter (low pass below 1200 Hz, −6 dB octave) and then band-passed into *N* frequency bands, using sixth-order Butterworth filters. The envelope of the signal was extracted by using a 4 msec rectangular window, by full-wave rectification, and low-pass filtering (second-order Butterworth) with a 400 Hz cutoff frequency. Sinusoids were generated with amplitudes

TABLE 1. Center frequencies of filters used to create sine wave stimulation for each frequency gap condition

Gap (kHz)	Center Frequencies (kHz)						
0.5	1.073	1.485	2.037	2.777	3.770	5.100	6.683
1		1.485	2.037	2.777	3.770	5.100	6.683
1.5			2.037	2.777	3.770	5.100	6.683
2.2				2.777	3.770	5.100	6.683
3.2					3.770	5.100	6.683

equal to the root-mean-square energy of the envelopes (computed at 4 msec intervals) and frequencies equal to the center frequencies of the bandpass filters. The sinusoids of each band were summed and presented to listeners at 72 dB SPL (re: vowel peaks) through headphones.

The acoustic-plus-electric hearing simulations were created by adding sine waves, created in the manner described above, to the output of the 500 Hz low-pass filter. The sine wave frequencies were chosen by using the Greenwood equation for stimulation at distances of 19, 17, 15, 13, and 11 mm into AQ: 1 the cochlea. These frequencies are summarized in T1 Table 1. To create stimuli that simulated the output from a fully inserted electrode array with 2, 4, 6, 8, and 10 channels, signals were processed in the manner described earlier. The frequencies for the 2 to T2 10 channel simulations are summarized in Table 2.

Test Conditions

Twenty-six test conditions were created. The major grouping variables for the conditions were (1) acoustic-hearing only, (2) acoustic-plus-electric hearing, (3) electric hearing only, i.e., a simulation of losing residual hearing after implantation, and (4) full electrode insertion. For (2) and (3), the parameter was the gap in frequency between acoustic and electric hearing. For (4), the parameter was the number of channels.

Results

F1 **Acoustic Hearing Only** • As shown in Figure 1, the mean level of speech understanding achieved in the low-pass filter condition was 17% correct (s.d. = 6).

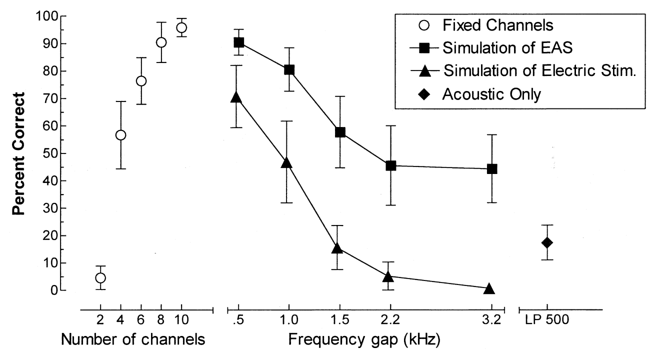

Fig. 1. Sentence understanding (from left to right on the *x*-axis) as a function of (1) the number of channels in simulations of a full electrode insertion, (2) the frequency gap between acoustic and simulated electric stimulation, and (3) low-pass filtering at 500 Hz. For the frequency gap conditions, the parameter is the type of signal: a simulation of EAS or a simulation of electrical-only stimulation.

Simulation of Electric-Plus-Acoustic Hearing • The results of a repeated-measures analysis of variance (ANOVA) revealed a significant effect of frequency gap ($F_{3,33} = 78.8$, $p < 0.00001$) for the electric-plus-acoustic condition. As shown in Figure 1 and confirmed by post-tests (Tukey-Kramer with $\alpha = 0.01$), the best speech understanding occurred in the 0.5 kHz and 1.0 kHz gap conditions (90 and 80% correct, respectively). A significant reduction in speech understanding was found with a 1.5 kHz gap (58% correct) and then again with a 2.2 kHz gap (45% correct). Speech understanding with a 2.2 kHz gap was not significantly different than the speech understanding with a 3.2 kHz gap (44% correct). All gap conditions allowed a higher level of performance than the low-pass-filtered speech condition (17% correct).

Simulation of Electric-Only Hearing • As shown in Figure 1, performance was poorer with simulated electric stimulation only than with simulated EAS. For the electric-only simulation post-tests revealed significant changes in speech understanding with each change in starting frequency (71% correct, 47% correct, 16% correct, 5% correct, and 1% correct). Electric-only stimulation was significantly better than acoustic-only stimulation for speech understanding in the 0.5 and 1.0 kHz gap conditions, i.e.,

TABLE 2. Center frequencies of filters used to create sine wave stimulation for simulations of processors with 2 to 10 channels

Channels	Center Frequencies (kHz)									
2					0.792	3.392				
4				0.460	0.953	1.971	4.079			
6			0.393	0.639	1.038	1.685	2.736	4.443		
8		0.365	0.526	0.756	1.088	1.566	2.252	3.240	4.661	
10	0.321	0.545	0.814	1.136	1.523	1.987	2.544	3.212	4.014	4.975

when stimulation started at 1073 Hz and 1485 Hz. Electric-only stimulation was not significantly different than acoustic-only stimulation in the 1.5 and 2.2 kHz gap conditions, i.e., when stimulation started at 2037 Hz and 2777 Hz. Electric-only stimulation starting at 3770 Hz produced significantly poorer speech understanding than acoustic-only stimulation.

Full Electrode Insertion • The results from a repeated-measures ANOVA indicated a significant effect of the number of channels of stimulation ($F_{4,44} = 608.7$, $p < 0.00001$). As shown in Figure 1, performance increased as the number of channels of stimulation increased. Post hoc tests indicated that 10 and 8 channels allowed a higher level of performance than 6 channels (96% and 90% correct versus 76% correct), that 6 channels allowed a higher level of performance than 4 channels (76% correct versus 57% correct), and that 4 channels allowed a higher level of performance than 2 channels (57% correct versus 5% correct).

Discussion

The aim of Experiment 1 was to probe, using normal-hearing listeners and simulations of combined acoustic and electric stimulation, the consequences of electrode insertion depth when acoustic hearing was limited to 500 Hz. We found a clear advantage in EAS for minimizing the gap between frequencies stimulated acoustically and frequencies stimulated electrically. A gap of 500 Hz allowed 90% correct sentence recognition for difficult sentence material. A gap of 3.2 kHz allowed only 45% sentence recognition. From this result, we infer that patient performance with EAS would be maximized if the gap between acoustic and electric stimulation were minimized.

On the other hand, it is important to note that a simulation of a very shallow insertion, one that left a gap of 3.2 kHz between acoustic stimulation at 500 Hz and electric stimulation beginning at 3.7 kHz, produced higher scores than acoustic stimulation alone. This is an encouraging finding because if a very shallow insertion were the only way to reliably preserve residual hearing, then patients would still benefit from electrical stimulation.

There is, however, a significant risk associated with a very shallow insertion: If hearing is lost, then speech understanding with electrical stimulation alone may be no better than, or may be worse than, the level of speech understanding achieved before the surgery. For example, our simulation of electrical stimulation with a starting frequency of 3.2 kHz elicited a level of performance poorer than that elicited with acoustic hearing alone. In contrast, our simulation of electrical stimulation with a starting frequency of 1.0 kHz resulted in a mean score of 70%.

The mean score in the 1.0 kHz electrical-stimulation-alone condition (70% correct) fell between the mean scores for a 4- and a 6-channel full insertion. Previous studies have shown that patients with conventional implants receive, on average, the equivalent of 4 to 6 channels of stimulation even if the number of electrical contacts is much larger (Dorman, 1999; Fishman, Shannon, & Slattery, 1997; Wilson, 1997). Given this outcome, if stimulation from the most apical electrode in an EAS array reaches the 1 kHz place, then EAS patients who lose hearing after surgery should, on average, perform at the level of patients with conventional implants. This appears to be the case. Kiefer, et al. (Reference Note 5) report that EAS patients with a 20 mm insertion, when tested with electric stimulation alone, perform, on average, at the level of a large sample of patients with a conventional cochlear implant.

Earlier in this discussion, we concluded that speech intelligibility under conditions of EAS stimulation would be maximized if the gap in frequency between acoustic and electric stimulation were minimized. This is hardly a surprising outcome—the larger the gap, the more spectral information that is removed from the signal. We wonder what would happen if the frequency components were not removed but rather remained in the signal and were up-shifted in frequency to a higher-than-normal place on the cochlea. We have explored this issue in a supplementary experiment. The outcome was poorer speech understanding than when "holes" were left in the spectrum. The mean scores for the "holes" conditions were 90, 80, 57, 45, and 44% correct. The mean scores for the corresponding up-shifted conditions were 74, 60, 42, 36, and 37% correct. The mean scores in the two conditions differed significantly ($F_{1,11} = 121.6$, $p < 0.00001$). We conclude that leaving "holes" in the spectrum is less detrimental to speech intelligibility than up-shifting frequency components. Our experiment was acute, not chronic, and a different outcome might have been obtained if our listeners had more practice with the up-shifted conditions.

EXPERIMENT 2

The aim of Experiment 2 was to assess the interaction of the gap between frequencies stimulated acoustically and frequencies stimulated electrically and the type of test material. We wished to determine which type of test material would be most sensitive to the effects the gap (or of electrode

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insertion depth). In the Introduction, we noted that consonants could be identified with high accuracy when mid-frequency information was eliminated from the spectrum. On the other hand, vowels need information in both the region of F1 (approximately 300 to 700 Hz for a male voice) and in the region of F2 (approximately 900 to 2200 Hz for a male voice). Thus, we expected to find differences in performance as a function of the test material.

Methods

Subjects • Twelve normal-hearing undergraduates at Arizona State University served as subjects.

Test Material • Consonants, vowels, HINT sentences (Nilsson, Soli, & Sullivan, 1994), and AzBio sentences (Spahr & Dorman, 2004) were used as stimuli. Sixteen consonants in /aCa/ environment were taken from the Iowa consonant test (Tyler, Preece, & Lowder 1987). A male speaker recorded the stimuli. The test sequence was created by randomizing the presentation of six tokens of each consonant. Thirteen vowel stimuli were synthesized in "bVt" format from the parameters reported in Dorman, Dankowski, McCandless, & Smith (1989). All signals were created with equal duration to eliminate duration as a cue to vowel identity. The test sequence was created by randomizing the presentation of six tokens of each vowel. The HINT sentence material consisted of 20 sentences per list recorded by a single male talker. AzBio sentence material consisted of 40 sentences per list recorded by 2 male and 2 female informants speaking in a conversational style (Spahr & Dorman, 2004). The AzBio sentences are more difficult than the HINT sentences. For a group of better-than-average cochlear implant patients, Spahr & Dorman (2004) report HINT scores of approximately 95% correct and scores of 75% correct for the AzBio sentences. The increased difficulty for the AzBio sentences probably is due to (1) the greater number of speakers, (2) the conversational speaking style, and (3) less predictable sentence content. The assignment of a list to a condition was randomized for each subject.

Procedures • The order of tests was randomized across participants. Within a test, the order of conditions was fixed. Half of the tokens in each test were presented in the order minimum gap to maximum gap, and the other half were presented in the reverse order.

The participants were given practice before the start of each test condition. For example, for the test of consonant identification, participants were first given practice with stimuli in the 500 Hz gap condition. The stimuli were played twice in a fixed order with the identity of the consonant displayed on the computer screen. The stimuli were then played twice in a randomized order with feedback. Finally, the stimuli were presented in the test sequence without feedback. This sequence of practice and test sessions was repeated for each gap condition for all tests. Practice for the tests of sentence identification consisted of five sentences without feedback.

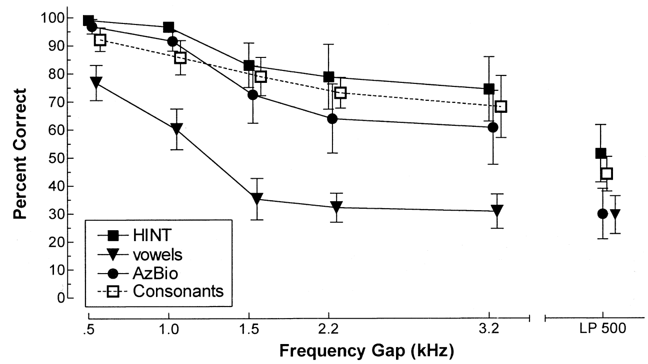

Fig. 2. Speech understanding as a function of frequency gap. The parameter is type of speech material.

A software interface was used by patients to control the presentation of test material and to record subjects' responses. Overall percent correct scores were calculated from the responses.

Each type of test material was tested by using the gap conditions of Experiment 1.

Results

The mean percent correct scores for all conditions are shown in Figure 2. A repeated-measures ANOVA indicated a main effect for type of material ($F_{3,33}$ = 171.07, $p < 0.00001$); a main effect for gaps ($F_{4,44}$ = 143.1, $p < 0.00001$); and an interaction of material and gaps ($F_{12,132}$ = 9.35, $p < 0.0001$). F2

When performance was collapsed over frequency gap, the mean scores were 86% correct for HINT sentences, 79% for consonants, 77% correct for AzBio sentences, and 47% correct for vowels. A post hoc test (Tukey-Kramer with α = 0.01) indicated that scores from the HINT sentences were significantly higher than scores from the AzBio sentences and from the test of vowel identity.

Consonant scores were analyzed further in terms of the features manner, voicing, and place of articulation. Mean scores as a function of gap are shown in Figure 3. Repeated-measures ANOVAs revealed a significant effect of gap for identification of place of articulation ($F_{4,44}$ = 57.12, $p < 0.0001$) and for voicing ($F_{4,44}$ = 3.08, p = 0.02). The effect of gap was not significant for manner ($F_{4,44}$ = 2.11, p = 0.09). The magnitude of the gap effect (the score at the 0.5 kHz gap minus the score at the 3.2 kHz gap) was large (44% points) for place of articulation, smaller F3

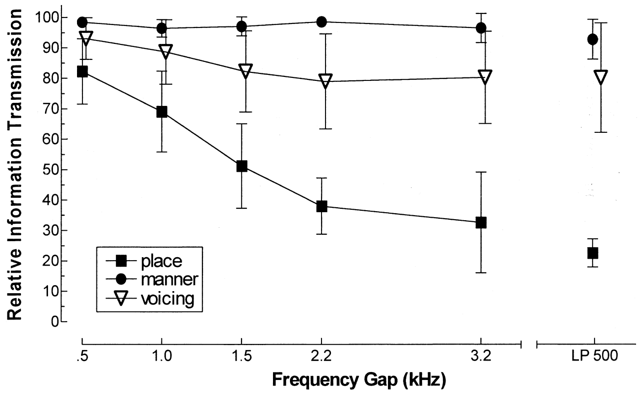

Fig. 3. Information transmission as a function of frequency gap. The parameter is consonant feature: place, manner, and voicing.

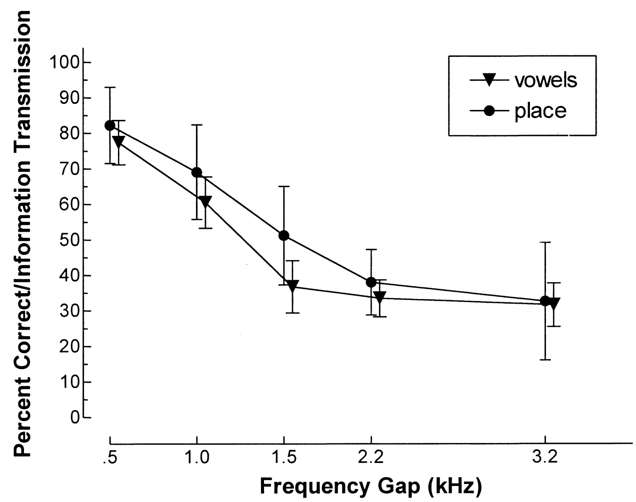

Fig. 4. Speech understanding as a function of frequency gap. Data points are for vowels and consonant place of articulation.

for voicing (15% points), and negligible for manner (2% points).

Discussion

The aim of Experiment 2 was to explore the effect of the gap in frequency between low-frequency acoustic hearing and simulated electric stimulation on the recognition of several kinds of test material. As expected, we found an interaction between test material and frequency gap. The use of "easy" material, e.g., sentences from the HINT lists, minimized the effect of the gap in frequency. A relatively high level of recognition, 74% correct, was achieved by using the HINT sentences with a very large gap (3.2 kHz). For the same gap, scores for the more difficult AzBio sentences averaged 61% correct. For the most difficult task, a gap of 3.2 kHz allowed only 31% correct recognition of vowels. Note also that the 500 Hz gap, which allowed 97 to 99% correct recognition of sentences, allowed only 77% correct vowel recognition. Thus, even a small gap in the representation of frequency is detrimental to the recognition of vowels.

We had expected that consonant recognition would be less affected by the removal of mid-frequency information than vowels. This was the case. However, as shown in Figure 3, the effect of the frequency gap on consonant recognition was a combination of a small or no effect of the frequency gap on the recognition of voicing and manner and a large effect on the recognition of place. As shown in Figure 4, scores for vowel identification and consonant place of articulation decreased rapidly with increasing frequency gap, or shorter electrode insertion depth. Over the steepest portion of the function for vowel recognition, between the data points for the 1.0 and 1.5 kHz gaps, performance fell about 12 percentage points per 1 mm of distance.

The shapes of the functions for vowels and consonant place of articulation differed slightly at the larger frequency gaps. This is a consequence of the constrained location of the second formants for the vowels—all of the F2 information fell under 2.1 kHz. Once that information was eliminated, then larger gaps had no effect on performance. On the other hand, larger gaps continued to have an effect on consonant place of articulation because burst cues, some second-formant transitions, third-formant transitions, and fricative cues to consonant place of articulation can reside above 2 kHz.

Overall, we find that both vowel recognition and the recognition of consonant place of articulation are very sensitive to the magnitude of the gap in frequency between acoustic and electric stimulation. The recognition of HINT sentences in quiet is not as sensitive. For this reason, we recommend that tests of vowel and consonant recognition be included in the test battery when assessing the benefits of combined electric and acoustic stimulation.

Gantz & Turner (2003) measured the perception of consonant place of articulation in tests of EAS patients with 10 mm electrode insertions. Because the stimulus material was identical to that used in our experiment, we can use the scores from Gantz & Turner (2003) to make an inference about the effective frequency gap created by a 10 mm electrode insertion. Inspection of Figure 3 in Gantz & Turner (2003) suggests a place score of about 50% for one 10 mm patient. This score is the same as the mean score (51% correct) for a 1.5 kHz gap in our simulations.

The starting frequency for a 1.5 kHz gap was approximately 2 kHz in our simulations. Gantz &

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Turner (2003) note that they explored the best filter center-frequency for the most apical electrode of the patient in question. The best results were found with a 2 kHz center frequency. Thus, our inference and Gantz & Turner's results converge in a striking fashion. Two kilohertz is about an octave lower than the frequency predicted by the Greenwood equation for a 10 mm insertion into the cochlea. This outcome adds evidence to support the view that the effective place of electrical stimulation is more apical than predicted by the Greenwood equation. Evidence from a number of sources suggests the possibility of about an octave offset between the Greenwood frequencies and the pitch elicited by electrical stimulation for laterally placed electrodes inserted 10 to 20 mm into the scala tympani (see, for example, Boex, et al., Reference Note 3; Brill, et al. Reference Note 4).

EXPERIMENT 3

Our experiments with simulations of EAS were predicated on the assumption that the performance of normal-hearing subjects listening to simulations would be similar to the performance of at least some patients using EAS. One way to assess whether this is a reasonable assumption is to ask whether our simulations capture what appears to be a "signature" of EAS. Several authors have noted a distinctive pattern of speech recognition scores for speech presented in noise, i.e., scores in EAS conditions are greater than the sum of the scores from the acoustic-hearing-alone and electrical-stimulation-alone conditions. For example, Kiefer, et al. (Reference Note 5) describe a patient with an acoustic-stimulation-alone score of 25%, an electrical-stimulation-alone score of 5%, and an EAS score of 75%. Another patient's scores for the three conditions were 5%, 40%, and 90% correct. Brill, et al. (Reference Note 4) and Wilson, et al. (Reference Note 1) describe similar results for other EAS patients. This pattern is not commonly seen for material presented in quiet.

In Experiment 3, we created one new stimulus condition (TIMIT sentences at +10 dB SNR) and compared performance in that condition with the performance found in Experiment 1 for the same sentences tested in quiet. Our aim was to determine whether the pattern of results described above for EAS patients would be found by using a simulation of EAS.

Methods

Subjects • The subjects were 12 undergraduate students at Arizona State University.

Test Material • Multi-talker babble was added to the TIMIT sentences used in Experiment 1 to create sentences at +10 dB SNR. Sentences and babble were presented from the same loudspeaker.

Procedures • The procedures used in Experiment 1 were used also in Experiment 3.

Results

Performance in noise and in quiet for each stimulus condition as a function of frequency gap is shown in Figure 5 (top). Scores for the quiet condition were obtained in Experiment 1 and are replotted here. Scores from the acoustic-only and simulated electric-only conditions were summed and plotted in Figure 5 (bottom), along with performance from the simulation of EAS. A repeated-measures ANOVA for sentences presented at +10 dB SNR indicated a significant main effect for gap ($F_{3,33}$ = 209, $p < 0.00001$), a significant main effect for conditions, i.e., EAS versus E + A ($F_{1,95}$ = 323, $p <$ 0.00001), and a significant interaction ($F_{3,33}$ = 6.71, p = 0.001). The presence of an effect for conditions indicates that scores in the EAS condition were higher than the sum of scores in the acoustic-only and electric-only conditions. F5

A repeated-measures ANOVA for sentences presented in quiet indicated a significant main effect for gap ($F_{3,33}$ = 219, $p < 0.0001$), a significant main effect for condition ($F_{1,11}$ = 47, $p < 0.0001$), and a significant interaction ($F_{3,33}$ = 10.7, $p < 0.0001$). For the 0.5 kHz gap, the mean score in the EAS condition (90% correct) was not higher than the sum of the mean scores in the acoustic-only (17% correct) and electric-only conditions (71% correct). However, for gaps of greater magnitude, scores in the EAS condition were significantly higher than the sum of the constituent scores.

Discussion

The aim of Experiment 3 was to assess whether our simulation of EAS captured a signature of EAS patient performance, i.e., the outcome that EAS scores, for material presented in noise, are higher than the sum of the scores for acoustic stimulation alone and electric stimulation alone. Our simulations do capture this outcome. When sentences were presented at +10 dB SNR, scores in the simulated EAS conditions at each frequency gap were higher than the sum of the scores for the constituent conditions. In quiet, this was not the case for the smallest frequency gap. In that condition, the score for the EAS simulation did not differ significantly from the sum of the scores in the acoustic-only and electric-only conditions.

If we assume that stimulation from a 20 mm electrode insertion reaches fibers at the frequency predicted by the Greenwood equation, i.e., 1.0 kHz,

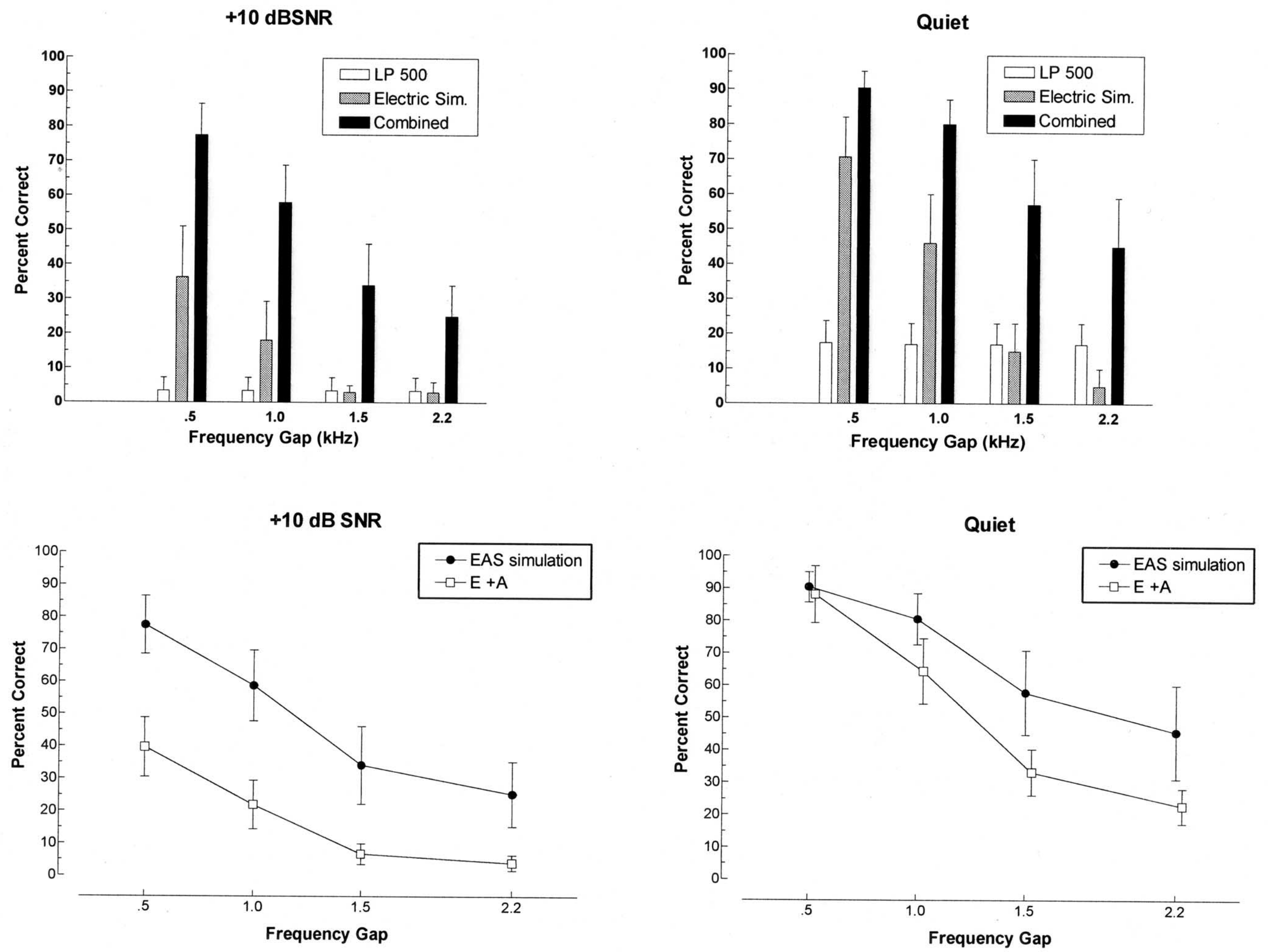

Fig. 5. Top, Percent correct scores in noise and quiet as a function of frequency gap for (1) signals low-pass-filtered at 500 Hz, (2) for simulations of electrical stimulation, and (3) for simulations of EAS. Bottom, percent correct scores in noise and quiet as a function of frequency gap for a simulation of EAS and for the sum of scores from the acoustic-only and simulated electric-only conditions.

or lower, then, given the constraints of our experiment, the 0.5 kHz gap condition most closely approximates the stimulation received by the implant patients studied by Kiefer et al. (Reference Note 5), Wilson et al. (Reference Note 1), and Brill et al. (Reference Note 4). In this condition, our results in noise and quiet mirror the difference in the manner in which acoustic and electric stimulation sum in noise and quiet for implant patients.

For frequency gaps larger than 0.5 kHz, scores in the EAS conditions in quiet exceeded the sum of the scores from the constituent conditions. This is the pattern of results reported for implant patients tested in noise. As shown in Figure 5 (top), as the magnitude of the frequency gap increased, and as the information from electric stimulation (gray bars) decreased, the synergy from the combination of information from the acoustic-stimulation-only and electric-stimulation-only conditions increased. This outcome points to a common link—the amount of information available from electrical stimulation—between our results in noise and our results using large frequency gaps in quiet. Synergy was seen when the information available from our simulation of electric stimulation was relatively low. The amount of information was low in the quiet conditions when the frequency gap between acoustic stimulation and our simulation of electric stimulation was large. The amount of information was low in noise as a consequence of masking. This analysis leads us to predict that the synergy seen in noise for EAS patients will be seen in quiet if the amount of information available from electric stimulation is significantly degraded, for example, by a reduction in the number of active channels of electrical stimulation.

SUMMARY

We have conducted three experiments using normal-hearing listeners and acoustic simulations of combined acoustic and electric stimulation. Our aim was to assess the consequences for speech understanding of the magnitude of a gap between acoustic hearing and simulated electric stimulation.

The results of Experiment 1 suggested that patient performance with EAS would be maximized if the gap between acoustic and electric stimulation were minimized. However, it was also the case that the level of sentence understanding with very large gaps, e.g., 3.2 kHz, was higher than the level of sentence understanding allowed by acoustic hearing alone. There is significant risk associated with a large gap caused by a very shallow insertion—if hearing is lost, then speech understanding with electrical stimulation alone may be no better than, or may be worse than, the level of speech understanding achieved before the surgery. On the other hand, if an electrode insertion is deep and stimulation from the most apical electrode reaches the 1 kHz place, then EAS patients who lose hearing after surgery should perform, on average, at the level of patients with conventional implants.

The results of Experiment 2 demonstrated an interaction between test material and frequency gap. The use of "easy" material, e.g., sentences from the HINT lists, minimized the effect of the gap in frequency. The two types of material most sensitive to frequency gap were vowels and consonant place of articulation.

The results of Experiment 3 indicated that our simulations captured a distinctive aspect of EAS patient performance in noise, i.e., test scores in the EAS condition were higher than the sum of the scores for the acoustic-stimulation-alone condition and the electric-stimulation-alone condition. Our simulation suggests that this form of synergy between acoustic and electric stimulation would also be found for EAS patients in quiet conditions if the information from the electric-stimulation-alone condition were reduced.

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