Comparison of Speech Processing Strategies Used in the Clarion Implant Processor

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Objective: **To evaluate the performance of the various speech processing strategies supported by the Clarion S-Series implant processor.**

Design: **Five different speech-processing strategies [the Continuous Interleaved Sampler (CIS), the Simultaneous Analog Stimulation (SAS), the Paired Pulsatile Sampler (PPS), the Quadruple Pulsatile Sampler (QPS) and the hybrid (HYB) strategies] were implemented on the Clarion Research Interface platform. These speech-processing strategies varied in the degree of electrode simultaneity, with the SAS strategy being fully simultaneous (all electrodes are stimulated at the same time), the PPS and QPS strategies being partially simultaneous and the CIS strategy being completely sequential. In the hybrid strategy, some electrodes were stimulated using SAS, and some were stimulated using CIS. Nine Clarion CIS users were fitted with the above speech processing strategies and tested on vowel, consonant and word recognition in quiet.**

Results: **There were no statistically significant differences in the mean group performance between the CIS and SAS strategies on vowel and sentence recognition. A statistically significant difference was found only on consonant recognition. Individual results, however, indicated that most subjects performed worse with the SAS strategy compared with the CIS strategy on all tests. About 33% of the cochlear implant users benefited from the PPS and QPS strategies on consonant and word recognition.**

Conclusions: **If temporal information were the primary factor in speech recognition with cochlear implants then SAS should consistently produce higher speech recognition scores than CIS. That was not the case, however, because most CIS users performed significantly worse with the SAS strategy on all speech tests. Hence, there seems to be a trade-off between improving the temporal resolution with an increasing number of simultaneous channels and introducing distortions from electrical-field interactions. Performance for some CI users improved when the number of simultaneous channels increased to two (PPS strategy) and four (QPS strategy). The improvement with the PPS and QPS strategies must be due to the higher rates of stimulation. The above results suggest that CIS users are less likely to benefit with the SAS strategy, and they are more likely to benefit from the PPS and QPS strategies, which provide higher rates of stimulation with small probability of channel interaction.**

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The latest cochlear implant processors support several speech coding strategies, providing cochlear implant (CI) users the option to choose either a single or multiple strategies for daily use. Advanced Bionics Corporation (ABC), for instance, offers several speech-processing strategies, some based on simultaneous stimulation and some based on nonsimultaneous pulsatile stimulation (Kessler, 1999; Zimmerman-Philips & Murad, 1999). The Simultaneous Analog Stimulation (SAS) used in the S-Series Clarion processor provides simultaneous stimulation to all electrodes using bipolar electrode coupling in which each electrode is paired with another electrode that is in close proximity. The bipolar electrode coupling provides spatially selective stimulation and minimizes the possibility of electrical interaction. The Continuous Interleaved Sampler (CIS) strategy, a popular strategy used by many manufacturers including ABC, provides nonsimultaneous pulsatile stimulation using monopolar coupling. The monopolar coupling provides relatively broader stimulation compared with the bipolar coupling. Aside from the electrode coupling difference between SAS and CIS, the two strategies differ in the rate by which they stimulate the electrodes. The SAS strategy updates the information on each channel 16 times more frequently than the CIS strategy, thereby providing fine temporal details of the acoustic waveform. This is done, however, at an increased possibility of channel interaction due to the simultaneous stimulation. Channel interaction is an important issue associated with electrical stimulation because it affects the salience of spectral cues important for speech understanding. There is therefore a tradeoff between providing more detailed temporal-envelope information with a higher possibility of channel interaction, and less detailed temporal-envelope information with reduced risk of channel interaction. Not many studies have investigated this tradeoff in terms of speech recognition

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performance. Although several studies were undertaken to study the difference between the CIS and SAS strategies, those studies focused primarily on strategy preference.

Tyler, Gantz, Woodworth, Parkinson, Lowder, and Schum (1996) were the first to compare the performance between the SAS and CIS strategies for 19 implant users. At the time, most users could not be fitted with the SAS strategy because adequate loudness growth could not be achieved with the narrowly spaced, radial bipolar electrode coupling. Results obtained using six Clarion users with an acceptable SAS fitting showed higher speech scores with the CIS strategy. After the introduction of the enhanced bipolar coupling mode with the Clarion S-series processor, more subjects could be fitted with the SAS strategy (Battmer, Zilberman, Haake, & Lenarz, 1999). More recently, Osberger and Fisher (1999) conducted a study on SAS-CIS preference with 71 adults who had profound, bilateral, sensorineural hearing loss, postlingual onset of deafness, and no previous implant experience. Speech recognition performance was evaluated using sentences and monosyllabic words preoperatively and postoperatively after 3 mo of implant use. Results showed that 23 users (32%) preferred the SAS strategy and 48 users (68%) preferred the CIS strategy. The study showed that subjects performed better with the strategy they preferred. The study also showed that the mean word recognition scores of the SAS users were significantly higher than that of the CIS users after 3 mo of implant experience. It should be noted that their results were confounded by the fact that the SAS users had a shorter duration of deafness than the CIS users. In a follow-up study, Osberger and Fisher (2000) tested 58 of the 71 users enrolled in the previous study at 6 mo postimplantation. No significant difference was obtained between the performance of the CIS and SAS strategies at the 6-mo interval. The authors concluded that the results of the two studies suggest that the SAS users achieve higher levels of speech recognition in a shorter period of time than the CIS users.

A similar study on SAS-CIS preference was conducted by Battmer et al. (1999). Twenty-two postlingually deafened German-speaking adults participated in the study, and their performance was evaluated up to 3 mo postoperatively. Eleven (50%) users preferred SAS, and 11 (50%) users preferred CIS when tested at 3 mo. No group comparisons were made between the CIS and SAS users because the subjects in each group had different levels of speech understanding; only within-subjects comparisons were made. Consistent with Osberger and Fisher (1999), subjects performed significantly better with the strategy they preferred.

A recent study by Stollwerck et al. (2001) compared the preference and performance of a group of 55 SAS and CIS users at 2, 6, and 12 wk after their initial stimulation session. Subjects were fitted with both CIS and SAS at their initial programming session. Half received the SAS strategy first and the other half received CIS first. Speech strategy preference was apparent at an early stage and did not change with more listening exposure. Of the 55 subjects, 14 (25%) preferred SAS and 41 (75%) preferred CIS. Their results, like those of Battmer et al. (1999) and Osberger and Fisher (1999), also showed that listeners achieve their highest performance with their preferred strategy. Speech recognition results were higher for SAS than CIS users when the duration of deafness was less than 10 yr. However, the CIS users outperformed the SAS users when the duration of deafness was longer than 10 yr.

As discussed above, previous research has focused more on strategy preference between CIS and SAS rather than on strategy performance in terms of speech recognition. The present study compares the performance of CIS and SAS strategies on vowel, consonant and word recognition. At issue is whether CIS users (namely CI patients who use the CIS strategy daily) could benefit from the SAS strategy that preserves more detailed temporal information. If there is such a benefit, it should be evident on the consonant recognition task.

The CIS and SAS strategies represent the two extremes in electrode stimulation: sequential (one electrode at a time) versus fully simultaneous (all electrodes at the same time) stimulation. The Clarion S-series processor supports two other strategies with a stimulation mode that can be considered to be intermediate between sequential and fully simultaneous: the Paired Pulsatile Sampler (PPS) and the Quadruple Pulsatile Sampler (QPS) strategies. These strategies are partially simultaneous; only a subset of the electrodes is stimulated simultaneously. In the PPS strategy only two electrodes (located far apart from each other) are stimulated simultaneously, whereas in the QPS strategy four electrodes are stimulated simultaneously. The PPS and QPS strategies are running at twice and four times the stimulation rate, respectively, of the CIS strategy with a relatively small chance of increased channel interaction because of the distance between the simultaneously stimulated electrodes. Hence, given the higher rates of stimulation with the PPS and QPS strategies we would expect that higher performance would be achieved on consonant recognition compared with the CIS strategy. This hypothesis, motivated in part by previous experiments (e.g., Loizou, Poroy, & Dorman, 2000; Wilson, Wol-

TABLE 1. Biographical data for the nine Clarion users who participated in this study

Patient	Age	Electrode Array	Coupling Mode	Speech Processing Strategy Used Daily	Duration of Cochlear Implant Use (months)	Duration of Deafness (years)	Etiology
S1	57	Hi-focus I + EPS	Bipolar	PPS	13	8	Otosclerosis
S2	68	Hi-focus I + EPS	Monopolar	PPS	5	26	Unknown
S3	49	Hi-focus I + EPS	Monopolar	CIS	8	29	Unknown
S4	47	Enhanced + EPS	Monopolar	CIS	20	10	Gradual loss (unknown)
S5	46	Enhanced + EPS	Monopolar	CIS	5	0.2	Bickets
S6	57	Enhanced + EPS	Monopolar	CIS	17	18	Unknown
S7	66	Enhanced	Monopolar	PPS	26	5	Otosclerosis
S8	67	Enhanced	Monopolar	CIS	24	0.2	Unknown
S9	55	Enhanced	Monopolar	CIS	25	8	Meniere's disease

The Electrode Positioning System (EPS) is a piece of material that is inserted lateral to the electrode array, and is intended to push the array closer to the modiolus. Duration of deafness is defined here as the amount of time the subjects' thresholds at 500, 1000, and 2000 Hz exceeded 90 dB HL bilaterally up to the time of initial implant stimulation.

ford, & Lawson, Reference Note 1), is investigated in the present study by fitting and testing CIS users with the PPS and QPS strategies. Finally, for completeness, we investigate the performance of a relatively new strategy, called the hybrid strategy (also available in the Clarion S-Series processor), which is a combination of the CIS and SAS strategies.

METHODS

Subjects

Nine adult Clarion users were recruited based on age (46 to 68 yr of age), electrode type (Clarion Hi-Focus I + EPS, Enhanced, or Enhanced + EPS), and speech processing strategy used in their daily processor (either partially simultaneous, PPS, or sequential, CIS). Information regarding the types of electrode, coupling mode and preferred speech strategy for each patient tested is provided in Table 1. Only one subject (S7) uses a different speech strategy (PPS) from the one preferred at initial hookup (CIS). The speech strategy PPS was not introduced until after subject S7 had been wearing the speech processor for over a year. In the clinical programming software (SCLIN 2000), PPS (now called MPS) typically uses monopolar stimulation. However, a bipolar PPS program was given to subject S1. This is because S1 was the very first Hi-Focus I subject implanted in the U.S.A., and therefore received a much wider selection of speech processing parameters to choose from at the time of his initial stimulation. All CI users had at least 5 mo of experience with the Clarion implant.

Speech Material

The test material included vowels in /hVd/ context, consonants in /aCa/ context, and sentences. The vowel material consisted of 11 vowels in the words: "heed, hid, hayed, head, had, hod, hud, hood, hoed, who'd, heard." The vowels were spoken by seven men, six women, four boys, and five girls. The stimuli were drawn from a set used by Hillenbrand, Getty, Clark, and Wheeler (1995). The consonant test was a subset of the Iowa consonant test (Tyler, Preece, & Lowder, 1987) and consisted of 16 consonants in an /aCa/ environment spoken by a single male speaker. The sentences were taken from the Hearing In Noise Test (H.I.N.T) database (Nilsson, Soli, & Sullivan, 1994). Two different lists (10 sentences per list) were used to evaluate each strategy.

Experimental Setup

The Clarion Research Interface (CRI) hardware was developed by Advanced Bionics Corporation as a research platform to design, implement and test CI speech-processing algorithms. All speech-processing strategies were developed on the CRI platform using the experimental setup shown in Figure 1. The main hardware components of the CRI consisted of the DSP56309 EVM board, the implant speech processor (SP), the PC and the Research Implantable Cochlear Stimulator (RICS), which con-

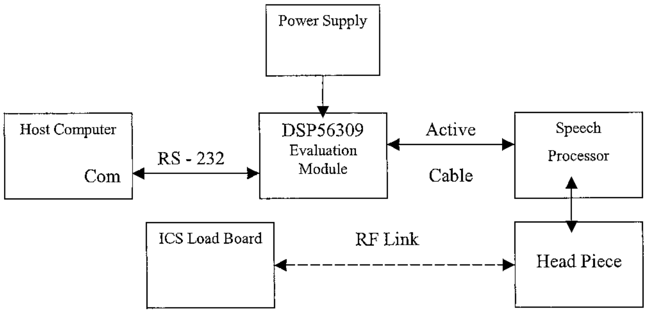

Figure 1. The experimental setup used for developing and testing speech-processing strategies.

TABLE 2. Frequency boundaries for the band-pass filters used

Number of Channels	Channel Number 1		2		3		4		5		6		7		8	
	F_l	F_h	F_l	F_h	F_l	F_h	F_l	F_h	F_l	F_h	F_l	F_h	F_l	F_h	F_l	F_h
7	250	500	500	875	875	1150	1150	1450	1450	2000	2000	2600	2600	6800	—	—
8	250	500	500	875	875	1150	1150	1450	1450	2000	2000	2600	2600	3800	3800	6800

F_l indicates the lower 3-dB cutoff frequency (Hz), and F_h indicates the higher 3-dB cutoff frequency of the band-pass filters.

tained the implanted electronics (Fig. 1). Attached to the RICS were resistors, which served as a dummy load for examining the stimulating pulses on an oscilloscope. The speech processing strategies were implemented on Motorola's DSP56309 board and the data were transmitted to the implant via the SP, which was used in a pass-through mode. The SP was connected to a head-piece that transmitted data to the RICS via an RF link.

Speech Processing Strategies

A total of five different speech-processing strategies were implemented on the Clarion Research Interface platform: CIS, SAS, PPS, QPS and Hybrid. These speech-processing strategies varied in the degree of electrode simultaneity, with the SAS strategy being fully simultaneous (all electrodes are stimulated at the same time), and the CIS strategy being completely sequential (only one electrode is stimulated at a time). The PPS and QPS strategies were partially simultaneous, with the PPS strategy stimulating two electrodes at a time, and the QPS strategy stimulating four electrodes at a time. In the hybrid strategy, some electrodes were stimulated using SAS, and some were stimulated using CIS (Kessler, 1999).

Continuous Interleaved Sampler (CIS) • Signals were first processed through a pre-emphasis filter (2000 Hz cutoff), with a 3-dB/octave roll-off, and then band-passed into eight frequency bands using sixth-order Butterworth filters. The center frequencies and bandwidths of the eight band-pass filters are given in Table 2. The envelopes of the filtered signals were extracted by full-wave rectification and low-pass filtering (second-order Butterworth) with a 400 Hz cutoff frequency. The eight envelope amplitudes A_i ($i = 1, 2, \ldots, 8$) were mapped to electrical amplitudes E_i using a logarithmic transformation:

$$E_i = c \log(A_i) + d$$

where c and d are constants chosen so that the electrical amplitudes fall within the range of threshold and most comfortable level (MCL). The mapped envelope amplitudes were finally used to modulate biphasic pulses of duration 75 μsec/phase at a stimulation rate of 833 pulses/second in a monopolar-coupling mode. The electrodes were stimulated sequentially in the same order as in the subject's daily processors. For most subjects, the electrodes were stimulated in apex-to-base order, i.e., 1-2-3-4-5-6-7-8.

Paired Pulsatile Sampler (PPS) • The signal processing involved in the PPS strategy is identical to that in the CIS strategy. The main difference is in the way the electrodes get stimulated. The PPS strategy is a partially simultaneous pulsatile strategy in which the electrode pairs 1-5, 2-6, 3-7, and 4-8 are stimulated simultaneously. These pairs were chosen to be further apart to avoid any deleterious effects due to electrode interaction caused by the summation of current fields. Due to the partial overlap of pulses on adjacent electrodes, the pulse rate increased to 1445 pulses/second/channel.

Quadruple Pulsatile Sampler (QPS) • The signal processing involved in the QPS strategy is also identical to that in the CIS strategy. In the QPS strategy, four electrodes were stimulated simultaneously in the order of 1-3-5-7 and 2-4-6-8. QPS used monopolar stimulation. Due to the increased possibility of channel interaction, the threshold levels were set to very small values (less than 10 μA). With the simultaneous stimulation of four channels, the pulse rate increased to 3300 pulses/second/channel.

Simultaneous Analog Stimulation (SAS) • In the SAS strategy, all the electrodes are stimulated simultaneously. To avoid interactions between the electrical fields, a bipolar electrode configuration was chosen because it provides a smaller and more focused area of stimulation. Note that the SAS strategy is not the same as the compressed analog (CA) strategy used in the Ineraid device (Eddington, 1980). The CA strategy provides a purely analog waveform for electrical stimulation, whereas the SAS strategy approximates the analog waveform in a staircase-type fashion using a 75-μsec temporal resolution. The SAS scheme is similar to that used for the CIS strategy with two notable differences: only seven channels are stimulated and no envelope detector is used. Only seven channels are stimulated because of the "enhanced" bipolar coupling arrangement. In this coupling mode, a medial electrode contact is paired with the next lateral contact to make a bipolar electrode pair (i.e., medial 1 with lateral 2, medial 2 with lateral 3 and so on). The center frequencies of the band-pass filters are different in this case to accommodate for the change in number of channels (see Table 2).

Hybrid Strategy • The hybrid strategy is a combination of CIS and SAS and is only available on the CRI. Some channels are implemented as CIS and some are implemented as SAS. The CIS channels used monopolar stimulation, whereas the SAS channels used bipolar stimulation. The threshold and MCL levels were the same as with the regular implementation of that strategy for each channel. In the hybrid strategy (HYB), channels 1 to 3 were SAS and channels 4 to 7 were CIS.

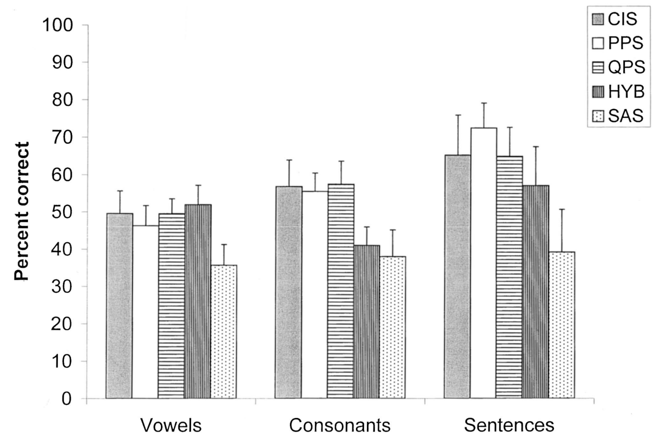

Figure 2. Mean performance of the CIS users (*N* = 9) on vowel, consonant, and word recognition with the various speech processing strategies. Error bars indicate standard errors of the mean.

Procedure

The ABC's clinical programming software (SCLIN) was used to obtain T-levels (thresholds) and M-levels (most comfortable loudness) for each speech processing strategy. The patient was then fitted with the CRI speech strategy implementation (i.e., CIS, PPS, QPS, HYB, or SAS) and the volume level and sensitivity of the microphone was adjusted to a comfortable listening level. Subjects were familiarized with the test materials before each test session.

Testing was divided into five acute listening sessions with each speech processing strategy. The subjects in this study were generally given only 20 to 30 minutes of exposure to each strategy before testing. Each speech strategy session was counterbalanced across subjects to avoid possible order effects. Each session consisted of a consonant, vowel and a sentence recognition test. The speech materials were also counterbalanced among subjects. In the vowel test, there were nine repetitions of each vowel, and in the consonant test there were nine repetitions of each consonant. The stimuli were presented in blocks of three repetitions each. The HINT sentences were presented only once. Two different HINT lists (20 sentences) were used for each strategy. A total of 10 HINT lists were used to test the five speech processing strategies. The vowels and the consonants were completely randomized. All test sessions were preceded by one practice session in which the identity of the vowels/consonants was indicated to the listeners. After the presentation of a vowel or consonant token, 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. Sentences were scored in terms of percentage of words identified correctly.

The test material was played to the CI users through speakers in a sound booth at a mean level of 65 dB SPL. The tests were carried out at two locations: 1) House Ear Institute, Los Angeles, California, and 2) Advanced Hearing Research Center/Callier Center, University of Texas at Dallas, Texas. All tests were performed in double-walled sound booths.

RESULTS

Figure 2 shows the mean performance of the nine CI users with the CIS, PPS, QPS, HYB and SAS speech processing strategies on vowel, consonant and sentence recognition.

Vowels

The results for vowel recognition are shown in Figure 2 (left panel). Chance performance is 9% correct. Repeated measures analysis of variance showed a significant effect of speech processing strategy [F(4,32) = 5.43, p = 0.002]. Post hoc tests according to Fisher's LSD showed that the performance obtained with the CIS, PPS and QPS strategies was not significantly different from the performance obtained with the SAS strategy. The performance obtained with the HYB strategy, however, was significantly (p = 0.036) higher than the performance obtained with the SAS strategy.

The individual subjects' performance on vowel

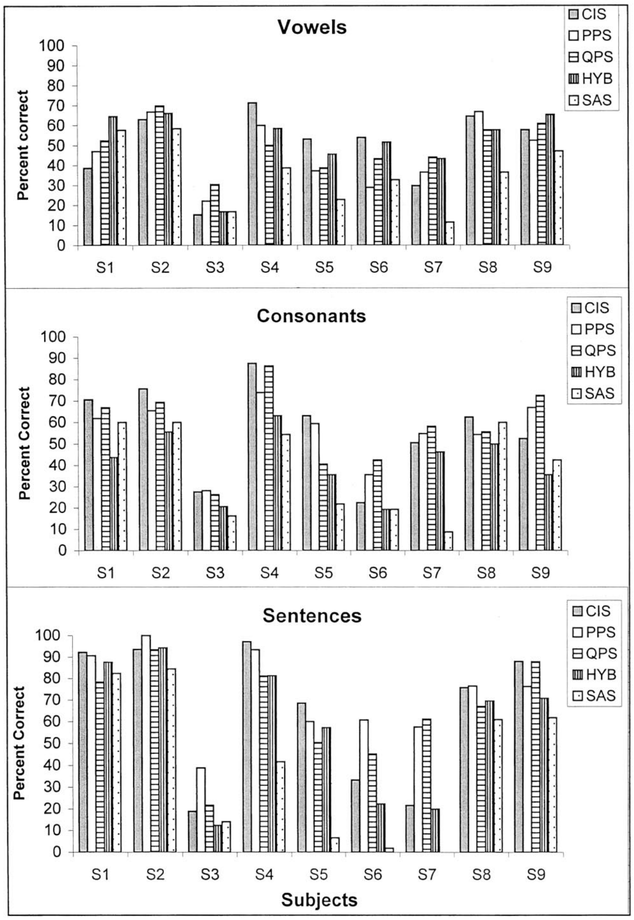

Figure 3. Individual performance of the CIS users on vowel, consonant, and word recognition.

recognition is shown in Figure 3 (top panel). Overall, there was a large variability in performance among subjects with the various speech processing strategies. Some subjects received a large benefit with the QPS and HYB strategies. Subject S1's score, for instance, improved from 38% correct with the CIS strategy to 64% correct with the HYB strategy. He also benefited with the SAS strategy. With the exception of subjects S1, S2 and S3, most of the subjects performed worse with the SAS strategy compared with the CIS strategy. For subjects S5 and S7, the difference was as much as 41%.

Consonants

The results for consonant recognition are shown in Figure 2 (middle panel). Chance performance for this task is 6.2% correct. Repeated measures analysis of variance showed a significant effect of speech processing strategy [$F(4,32) = 9.51$, $p < 0.005$]. Post hoc tests according to Fisher's LSD showed that the performance obtained with the PPS and the HYB strategies was not significantly different from the performance obtained with the SAS strategy. The performance obtained with the CIS and QPS strategies, however, was significantly ($p < 0.05$) higher than the performance obtained with the SAS strategy. Although one would expect that the performance obtained with the SAS strategy would be the highest because it transmits a wealth of temporal-envelope information, we did not find that to be the case. In fact, the performance with the SAS strategy was the lowest on consonant recognition. This was probably due to channel interaction caused by simultaneous stimulation.

The individual subjects' performance on consonant recognition is shown in Figure 3 (middle panel). The performance of some subjects (S4, S5) decreased as the number of electrodes stimulated simultaneously increased. Some subjects (S6, S7 and S9) benefited with the PPS and QPS strategies.

Sentences

The results for sentence recognition are shown in Figure 2 (right panel). Repeated measures analysis of variance showed a significant effect of speech processing strategy [$F(4,32) = 10.16$, $p < 0.005$]. Post hoc tests according to Fisher's LSD showed that the performance obtained with the CIS, QPS and the HYB strategies was not significantly different to the performance obtained with the SAS strategy. The performance obtained with the PPS strategy, however, was significantly ($p < 0.05$) higher than the performance obtained with the SAS strategy. The highest performance was obtained with the PPS strategy.

The individual subjects' performance on sentence recognition is shown in Figure 3 (bottom panel). Subjects S6 and S7 benefited with the PPS and QPS strategies. Subject S7's scores jumped from 27% correct with the CIS strategy to 61% correct with the QPS strategy (subject S7's score with the SAS strategy was 0% correct). Subjects S3 and S6 obtained the highest performance with the PPS strategy. Most subjects (except subjects S1, S2 and S3) performed significantly worse with the SAS strategy. This is consistent with the vowel data.

Discussion and Conclusions

Group results indicated no statistically significant difference between the CIS and SAS strategies on vowel and sentence recognition. A statistically significant difference was found only on consonant recognition. Individual results, however, indicated that most subjects performed worse with the SAS strategy compared with the CIS strategy on all tests. Six out of the nine subjects performed worse with the SAS strategy on vowel recognition, seven on consonant recognition, and eight on sentence recognition. This outcome is consistent with previous studies (e.g., Battmer et al., 1999; Osberger & Fisher, 1999) that showed that subjects tend to do better with the strategy they prefer—the CIS strategy in our case. So, although CIS users receive more detailed envelope information with the SAS strategy than with the CIS strategy, they did not benefit from it. In fact, their performance deteriorated. We suspect two reasons for that.

First, it could be attributed to lack of familiarity with bipolar, simultaneous stimulation. Novel speech strategies are at a considerable disadvantage with acute listening trials. The subjects in this study were generally given only 20 to 30 minutes of exposure to each of the speech processing strategies, yet had months to years (5 mo to 2 yr) of experience with their own strategy (CIS). The performance drop from sequential (CIS) to simultaneous strategy (SAS) may therefore be due, in part, to the novelty of the stimulus. In that vein, the CIS-SAS comparison results should be viewed with caution, because the outcome might change with prolonged exposure to the SAS strategy.

Second, it could be attributed to the increased channel interaction associated with fully simultaneous stimulation. The distortions from electrical-field interactions can affect the spectral cues important for speech understanding. The SAS strategy uses simultaneous stimulation and has the capability of providing more detailed temporal-envelope information compared with the CIS strategy, which operates at a much lower stimulation rate. If temporal information were the only factor in speech recognition with cochlear implants, SAS would consistently produce higher speech recognition scores than CIS. Speech recognition did not improve, however, as the amount of temporal information increased. This result indicates that there is a tradeoff between improving the temporal resolution by increasing the number of simultaneous channels and introducing distortions from electrical-field interactions.

This tradeoff can be controlled to a certain degree with the use of partially simultaneous strategies like the PPS and QPS strategies. Although we cannot exclude the possibility of channel interaction in partially simultaneous strategies, that possibility is small because the stimulating electrodes are selected to be far apart from each other. Results showed that a few users performed better with the PPS and QPS strategies on consonant and sentence recognition. We believe that the benefit with these strategies stems from the higher rate of stimulation (PPS's rate is twice that of CIS, and QPS's rate is four times that of CIS). The benefits of higher rates of stimulation on consonant recognition are consistent with previous studies (Loizou et al., 2000; Wilson et al., Reference Note 1) with subjects fitted with the CIS strategy and a different electrode array (Ineraid array). In the study by Loizou et al. (2000), consonant and word recognition increased as the stimulation rate increased, but saturated at a certain rate depending on the subject. The consonant and word recognition scores obtained at 1400 pulses/second (roughly the rate of the PPS strategy) were found to be significantly higher than the scores at 800 pulses/second (the rate of the CIS strategy in this study).

The recognition of vowels was improved for some subjects with the HYB strategy. It is not clear why the HYB strategy improved vowel recognition, because it does not improve spectral resolution. One possibility is that some subjects were able to extract F1 (and possibly F2) information from the improved temporal envelope provided by analog stimulation in the low-frequency channels. We suspect that those subjects must have low channel interaction in the low-frequency channels to be able to use that additional information. The HYB strategy is a relatively new strategy and deserves further investigation.

It should be pointed out that the present study focused on the performance of CIS users fitted with various strategies available in the Clarion S-Series processor. The performance of SAS users fitted with these strategies including the CIS strategy was not addressed. Hence, no claim is made that the CIS strategy is the best or the recommended strategy in general for the Clarion S-Series implant patients. That claim needs to be placed in the context of strategy preference in the sense that the strategy preference needs to be taken into account when making comparisons between speech coding strategies. More work needs to be done to investigate why some patients choose the CIS while others choose the SAS strategy. The answer to that question is no doubt related to the individual subject's susceptibility to channel interaction.

In summary, the results of this study showed that CIS users perform as well or worse with the SAS strategy. CIS users are less likely to benefit with the SAS strategy, and they are more likely to benefit from the PPS and QPS strategies, which provide higher rates of stimulation. This outcome has important clinical implications, as the audiologists/clinicians could fit the CIS users with the PPS and QPS strategies in addition to the CIS strategy. It is possible that more CIS users could benefit with the PPS and QPS strategies with prolonged exposure.

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