

Changes in Speech Intelligibility as a Function of Time and Signal Processing Strategy for an Ineraid Patient Fitted with Continuous Interleaved Sampling (CIS) Processors

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Abstract [TOP](#)

Objective: To assess changes in speech intelligibility as a function of signal processing strategy and as a function of time for one of the first two Ineraid patients in the United States fitted with a continuous interleaved sampling (CIS) signal processor.

Design: In Experiment 1, the patient was fitted with a CIS processor and measures of speech intelligibility were taken over a period of 4 mo. These data were compared with data collected with the Ineraid. In Experiment 2, three new signal processing strategies were tested. Measures of speech intelligibility were taken at fitting and after a week's use of the processor. In Experiment 3, the number of channels in the processor was reduced to 5, 4, and 3. Each processor was tested at fitting and after a week's use of the processor.

Results: In Experiment 1, immediately on fitting, the CIS processor produced better speech intelligibility for consonants, vowels, and the CID sentences than did the Ineraid. Performance improved over periods ranging from 1 to 4 mo depending on the test material. In Experiment 2, two processors produced significantly better speech intelligibility than did other processors. Most generally, performance dropped slightly when a new processor was fitted and then improved over the course of a week. All of the processors produced better speech intelligibility than did the Ineraid. In Experiment 3, five channels allowed similar levels of performance as did six channels. The effect of four and three channels varied as a function of test material. Four CIS channels allowed better performance than did the four analogue channels of the Ineraid.

Conclusions: We conclude 1) that CIS processors can provide much better speech intelligibility than can the analogue processor of the Ineraid; 2) that many CIS strategies, not just one, will produce better speech intelligibility than will the Ineraid; 3) that for this patient, five channels can allow as high a level of word intelligibility as can six channels; 4) that when the number of CIS and analogue channels are equated (at four), the CIS strategy provides better speech intelligibility than does the Ineraid; and 5) that speech intelligibility with CIS processors improves over periods as short as a week and as long as several months after fitting of the processor.

In 1991, Wilson, Finley, Lawson, Wolford, Eddington, and Rabinowitz described a new signal processing strategy-continuous interleaved sampling(CIS)-for cochlear implants. Since then a small number of papers have described the changes in speech intelligibility for Ineraid patients that accompany the change in signal processing strategy from analogue to CIS(e.g., [Boex, Pelizzone, & Montandon, 1994](#); [Lawson, Wilson, & Finley, 1993](#); [Wilson, Finley, Lawson, Wolford, & Zerbi, 1993](#); [Wilson, Lawson, Zerbi, & Finley, 1994](#)).

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Wilson and colleagues have identified a number of factors that affect speech intelligibility with a CIS processor. One factor is the pulse duration and pulse rate of the processor. For a given patient, one combination of duration and rate will, most generally, provide better speech intelligibility than will other combinations. However, the combination of duration and rate that provides the best performance varies greatly across patients. For example, some patients perform best with pulse durations as brief as 31 μ sec/phase and rates as high as 2941 pulses per second (pps), whereas other patients perform best with pulse durations of 167 μ sec/phase and a rate of 500 pps ([Wilson et al., 1993](#)). Another factor is the number of channels in the processor. As the number of channels increases from one to six, consonant intelligibility increases in a monotonic fashion (from 45 to 100% for the single patient tested [[Lawson et al., 1993](#)]).

In each of the experiments reported to date, the patients had a few minutes', or at most a few hours', experience with a given CIS processor before measures of speech intelligibility were obtained. In Wilson's experiments, measures were taken at these times because portable CIS processors were not yet available.

Recently a few portable CIS processors have become available for Ineraid patients in the United States. One of our patients has worn a research processor for a year. Over the course of the year, we have performed many experiments on the effects of pulse duration and pulse rate on speech intelligibility performance and on the effects of number of processor channels on speech intelligibility. Our experiments differ from those of Wilson et al. in that measures of performance were taken both immediately after the patient had been fitted with a given processor and after the patient had worn the processor for periods of a week to several months. Thus, we have been able to assess the effects, if any, of learning to use a processor or accommodating to a processing scheme.

The design of Experiment 1 was driven, in the first instance, by necessity. When a portable CIS processor became available, it was not sufficiently flexible to implement the strategy that, in laboratory tests, had been found to produce the best speech intelligibility. Therefore, the patient was given a processor with an approximation of the best strategy, and tests were made over a period of 4 mo to determine whether his performance on tests of speech intelligibility would improve. The patient's test scores varied as a function of test material and time. Most generally, performance at 4 mo was no better than at 3 or 1 mo. At that time several changes in signal processor design were implemented to determine whether one or another design produced better results than did the design to which he had become adapted. In these experiments the patient was tested at fitting and after a week's adaptation to a given processor. The results of these experiments are described in Experiment 2. Experiment 3 began after the patient had achieved 90 to 100% correct scores on tests of consonant intelligibility and on the CID sentences. Given this level of performance, it was possible to assess the effects of reducing the number of CIS channels on performance and, thus, to determine whether all six channels were necessary to maintain the patient's highest level of performance. As in the previous experiment, the patient was tested at fitting and after a week's use of a processor with a given number of channels. Most generally then, the aim of Experiments 1 to 3 was to assess the interaction of processor design and experience with the processor on speech intelligibility.

Experiment 1 [TOP](#)

Method [TOP](#)

Subject • The subject was a 70-yr-old man who had worn an Ineraid processor for 4 yr. He had participated in many psychophysical experiments before being tested in the present experiment (see [Dorman, Smith, Smith, and Parkin \[1994\]](#) and [Dorman, Smith, and Parkin \[1993\]](#) for descriptions of pitch matching and loudness matching, respectively, for sinusoids presented to the patient's implanted ear and to his nonimplanted ear with residual hearing). The subject is referred to as SR10 in the Wilson et al. progress reports.

Signal Processor Design • The 4-channel Ineraid processor has been described by [Eddington \(1980\)](#) and by [Wilson, Finley, Lawson, Wolford, Eddington, and Rabinowitz \(1991\)](#). The CIS processor was an implementation of the [Wilson et al. \(1991\)](#) processor fabricated at the University of Innsbruck ([Zierhofer, Peter, Bril, Pohl, Hochmair-Desoyer, & Hochmair, 1994](#)). The signal processor was a 6-channel design with 6th order bandpass filters, 400 Hz first order smoother, full wave rectification, logarithmic compression function, and staggered channel-update order. Channel center frequencies were 393 Hz, 639 Hz, 1037 Hz, 1680 Hz, 2730 Hz, and 4440 Hz. The channels were of equal width on a logarithmic scale. Signals were pre-emphasized above 1200 Hz.

Test Materials • Speech intelligibility was assessed with four sets of materials. Consonant intelligibility was tested with the Iowa Medial Consonants-16 consonants in an "aCa" frame spoken by a male talker (Tyler, Preece, & Lowder, 1987). Each consonant was presented five times in a randomized, blocked design. Vowel intelligibility was assessed with 13 signals in a "bVt" frame. The signals, "beet, bit, bait, bite, bet, Bert, bat, bought, Bart, bout, but, boot, boat," were synthesized with a software algorithm (Klatt, 1980) to ensure the stimuli were of equal duration and pitch contour (see Dorman, Dankowski, Smith, and McCandless [1991] for details of the synthesis). Each vowel was presented five times in a randomized, blocked design. Means and standard deviations for consonant and vowel recognition were calculated from the five repetitions of each block. The consonant and vowel stimuli were directed from the laser disk and digital to analog converter of a personal computer, respectively, to a mixer and isolation amplifier before being directed to the auxiliary input of the Ineraid and CIS processor. †

The intelligibility of words in sentences was assessed with 50 key words from the CID sentences. A different set of sentences was used in each of the test sessions. The intelligibility of isolated monosyllables was assessed with 50 words from the NU-6 test. The same list of words was used in each of the test sessions. Both word tests were presented "live voice" by a female speaker in the free field in an IAC booth at 70 dB SPL. Live voice testing was employed because the previous data on performance with the Ineraid had been collected in this manner. The patient adjusted the volume and sensitivity controls to provide a signal that she or he felt would give optimal intelligibility. †

Design • The tests of speech intelligibility with the CIS processor were administered at the time of fitting and at 1, 2, and 4 mo postfitting. Tests of speech intelligibility with the Ineraid were administered the day before fitting of the CIS processor. To provide an estimate of the variability in performance for word level materials, four CID and NU-6 scores collected over the previous 2 yr were added to the scores collected the day before fitting with the CIS processor. Means and standard deviations for the CID sentences and NU-6 words were derived from this set of scores.

Results TOP

The results of speech intelligibility testing for the Ineraid and for the CIS processor, as a function of time, are shown in [Figure 1](#). For consonants, the mean score with the Ineraid was 37% correct. The mean percent correct scores with the CIS processor at fitting, 1 mo, 3 mo, and 4 mo were 66%, 79%, 85%, and 80%, respectively. The score for the CIS processor at fitting was significantly higher than was the score for the Ineraid ($t = 14.2$; $p < 0.002$). A repeated measures analysis of variance (ANOVA) indicated a main effect for time using the CIS processor ($F[3,12] = 9.65$; $p = 0.002$). The scores at 1, 3, and 4 mo postfitting were significantly higher than was the score at fitting (Fisher's LSD, $\alpha = 0.05$). The score at 4 mo was not significantly different from the score at 1 mo.

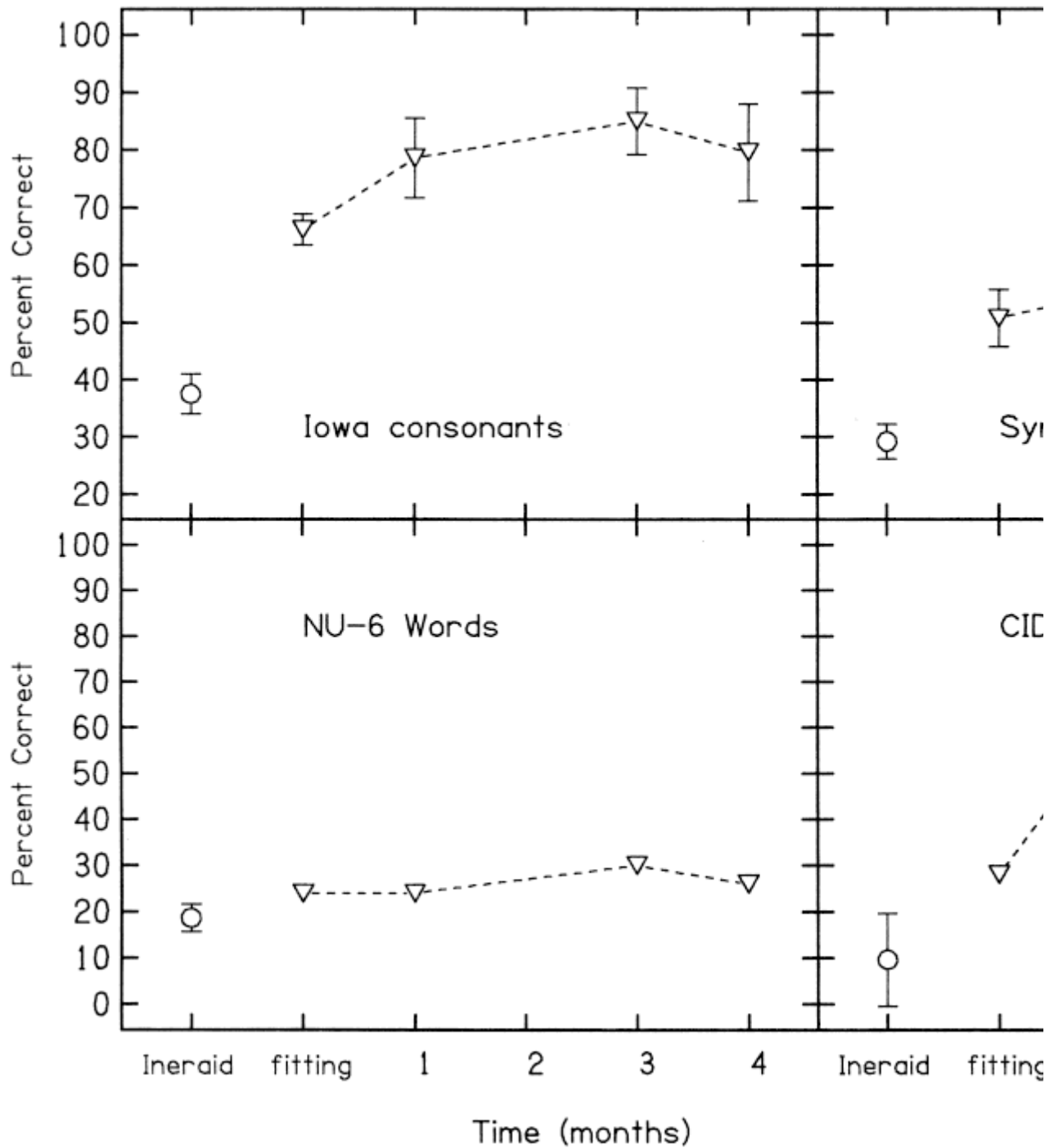


Figure 1. Speech intelligibility, in terms of percent correct, as a function of processor type (Ineraid = open circles; CIS= open triangles) and as a function of the time using the processor. Error bars indicate standard deviations.

For vowels, the mean score with the Ineraid was 29% correct. The mean percent correct scores with the CIS processor at fitting, 1 mo, 3 mo, and 4 mo were 51%, 55%, 61%, and 63%, respectively. The score for the Ineraid and for the CIS processor at fitting differed significantly ($t = 5.24$; $p < 0.01$). A repeated measures ANOVA indicated a marginal effect for time using the CIS processor ($F[3,12] = 3.21$; $p = 0.061$). The score at 4 mo was significantly higher than were the scores at fitting and at 1 mo (Fisher's LSD, $\alpha = 0.05$)

For NU-6 words, the score with the Ineraid was 19%. The percent correct scores with the CIS processor at fitting, 1, 2, and 4 mo were 24%, 24%, 30%, and 26%, respectively. All of these scores were higher than the highest score recorded for the Ineraid over 4 yr of testing but were not statistically different when viewed with the binomial expansion ([Thornton & Raffin, 1978](#)).

For the CID sentences, the mean score with the Ineraid was 10% correct. The percent correct scores with the CIS processor at fitting, 1, 2, and 4 mo were 28%, 60%, 80%, and 68%, respectively. If we consider the mean score for the Ineraid as a data point, when viewed with the binomial expansion, at fitting the CIS processor produced significantly higher scores than did the Ineraid. The score at 1 mo was significantly different from that at fitting, and the score at 3 mo was significantly different from that at 1 mo. The score at 4 mo did not differ from that at 3 mo or at 1 mo.

Discussion [TOP](#)

The results of Experiment 1 indicate that both the type of processor (Ineraid versus CIS) and experience with the CIS processor significantly affected scores on tests of speech intelligibility. The effect of experience, or time wearing the CIS processor, interacted with test type in determining scores. The CID sentence scores and the consonant scores were higher at 1 mo postfitting than at fitting. Vowel scores were higher at 4 mo relative to fitting. Overall, our results indicate that the results of [Wilson et al. \(1991\)](#) and [Boex et al. \(1994\)](#) show only the promise of benefit that CIS processors can provide to Ineraid patients. Over time, the benefit can be significantly greater than that shown in the laboratory.

The improvement over time was greatest for the CID sentences. This improvement is consistent, in principal, with the gains, over time, in consonant and vowel intelligibility. That is, by 4 mo postfitting, scores for the CIS sentences, consonants, and vowels had increased significantly. The extremely small change in NU-6 scores, in the face of a large change in CID sentence scores, suggests that the improvement in the CID sentences scores arose out of the interaction of increased consonant and vowel information and sentence context. This is to say, small improvements in the availability of information that specifies consonant and vowel identity, can, in sentence context, lead to large changes in word intelligibility.

Experiment 2 [TOP](#)

At 4 mo postfitting, most scores were not significantly better than at 1 or 3 mo postfitting. This outcome was interpreted as an asymptote in performance, and experiments were begun to find a better signal processor. The choice of processors to be tested was based on previous experiments conducted by Wilson's group. As noted in the introduction, pulse rate and pulse duration have been shown to affect performance on tests of speech intelligibility. Therefore, three pulse rates and durations were tested. Wilson et al. also have shown that the stimulation order along the electrode array makes a difference in performance for some patients. Curiously, a sequential order of stimulation from apex to base (the reverse of normal stimulation along the basilar membrane) has been shown to produce good results, for this patient in particular, in the laboratory. This strategy also was tested in Experiment 2.

Method [TOP](#)

Signal Processors • Three signal processor designs were tested. The first (Processor #1) was a 100 $\mu\text{sec}/\text{phase}$, 823 pps processor with an apex to base stimulation order. This processor differed from the CIS processor used in Experiment 1 (Processor #0) only in the order of stimulation. The second (Processor #2) was a 40 $\mu\text{sec}/\text{phase}$, 2020 pps processor with an apex to base stimulation order. The third (Processor #3) was a 70 $\mu\text{sec}/\text{phase}$, 1070 pps processor with an apex to base stimulation order.

Design • Because performance had changed over time in Experiment 1, processors were tested at fitting and then at 1 wk postfitting. The 1 wk interval between test sessions was chosen as a compromise. Four mo, or even 1 mo, would be a very long period to wear a processor if that processor was clearly worse than the first CIS processor. The patient verbalized that 1 wk's experience with a new processing scheme probably was enough for him to "learn to use" the processor. Because we have learned to trust the intuition of our very

experienced patients, 1 wk was chosen as the period for adaptation to a given processor. After testing processors #1, #2, and #3, the patient was fitted, again, with the strategy used in Experiment 1 (i.e., Processor #0) to assess whether the baseline for performance had changed. Finally, the patient was fitted with Processor #3, yet again, to determine whether the previous level of performance with this processor could be replicated.

Procedure • At the time of fitting a new signal processor, the patient was tested with the Iowa consonants. One wk later he was tested again with the consonants and, also, with the vowel and word materials. We chose this design to minimize the patient's exposure to the words in the CID sentences and in the NU-6 list. A different CID sentence list was used when testing each of the processors. The stimuli were presented in the manner described in Experiment 1.

Results [TOP](#)

Inspection of [Figure 2](#), top left, indicates two trends in performance on tests of consonant identification. One is that each time a new CIS processor was fitted, the score with the new processor was slightly lower than the best score achieved with the previous processor. The second trend is that, for processors with which the patient had a week's experience (i.e., #1, #2, and #3), scores at 1 wk were slightly higher than scores at fitting. To assess these trends statistically, the fitting scores for processors #1, #2, and #3 were collapsed into a group and the scores for these processors at 1 wk postfitting were collapsed into another group. The score (91%) at 1 wk postfitting was significantly higher than the score (78%) at fitting ($t = 5.49$; $p < 0.0002$). To determine whether scores dropped significantly when a new processor was fitted, the scores at 1 wk postfitting were collapsed into one group and the fitting scores for "new" processors were collapsed into another. The mean score (92%) at 1 wk was not significantly higher than the mean score (89%) for the "new" processors ($t = 1.82$; $p = 0.09$).

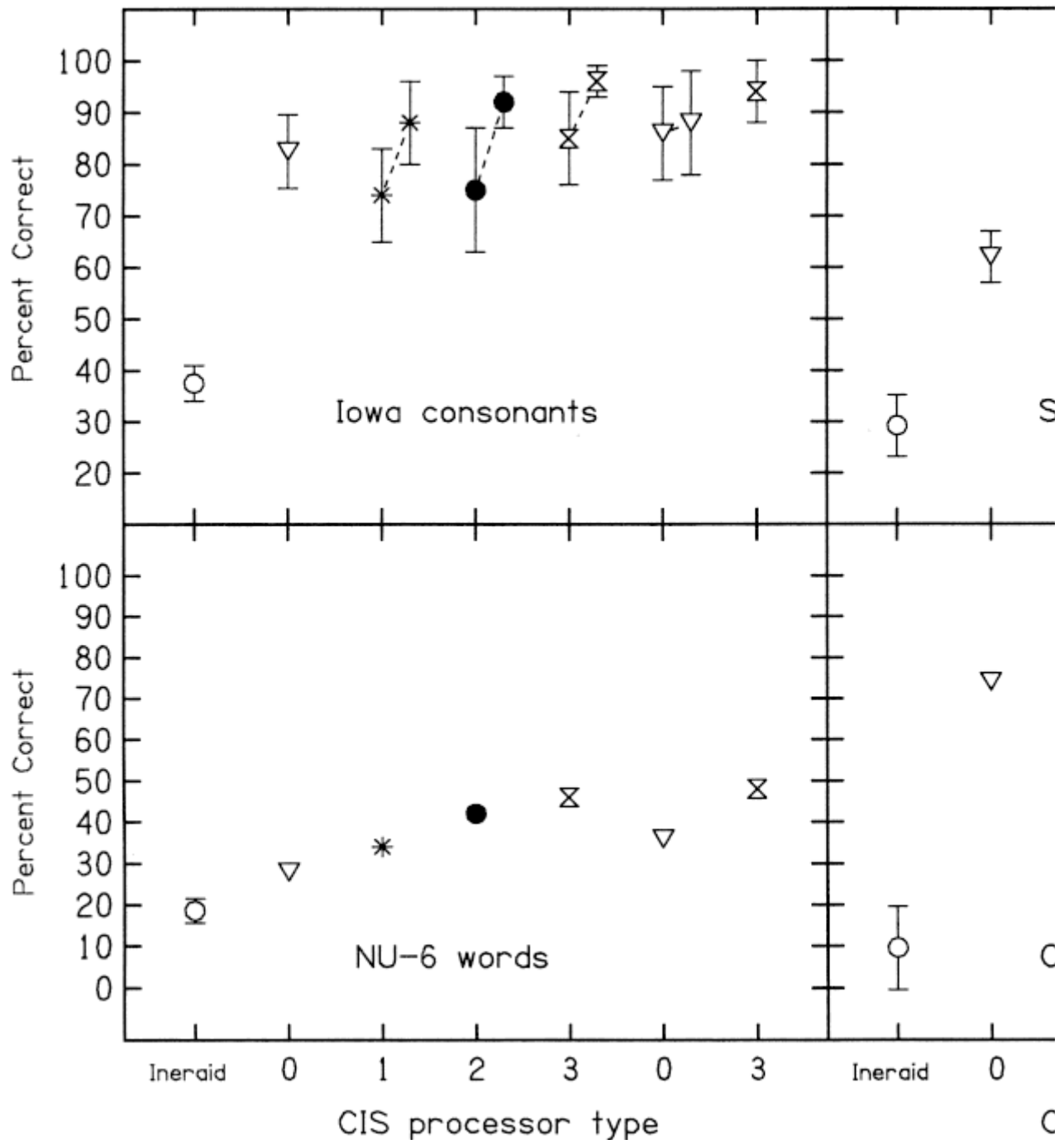


Figure 2. Speech intelligibility, in terms of percent correct, as a function of processor type and as a function of the time using the processor. The processor designs (#0 to #3) are described in the text. Solid lines connect test scores recorded at fitting and after 1 wk's use of a processor. Error bars indicate standard deviations.

Two other outcomes also are of importance. The first is that the "retest" score for the processor tested in Experiment 1 (Processor #0) was not significantly different from the score obtained at the end of Experiment 1 (the scores for Months 3 and 4 in Experiment 1 were averaged to produce this datum). Thus, for consonants there was a small, nonsignificant shift in the baseline as a function of time and experience with other processors. The second outcome is that when the 1 wk scores for Processors #1, #2, and #3 and the 1 wk retest score for Processor #0 were entered into an ANOVA, the scores did not differ. However, when the scores for Processor #3 taken just before and just after the test with Processor #0 were collapsed into one

group (mean= 95%) and the fitting and 1 wk scores for Processor #0 were collapsed into another group (mean = 88%), the two sets of scores differed significantly ($t = 2.36$; $p = 0.04$). This outcome suggests that Processor #3 is a better processor than Processor #0 for this patient.

The pattern of results for consonants is seen in various degrees in the data from the other tests. The test-retest scores for Processor #0 for vowels, NU-6 words, and CIS sentences followed the same pattern as those for consonants, i.e., higher, but not significantly higher, scores at retest. If the retest scores are taken as a conservative baseline, for vowels, no processor allowed significantly higher scores than did Processor #0, but Processor #3 produced the highest mean score. For NU-6 words, no processor allowed higher scores than did Processor #0. Once again, Processor #3 produced the highest mean scores. For the CIS sentences, processors #2 and #3 allowed higher scores than did the retest score for Processor #0 (binomial expansion, [Thornton & Raffin, 1978](#)).

Discussion [TOP](#)

The aim of Experiment 2 was to determine whether a better processor could be found than that used in Experiment 1. On the basis of the consonant and CID data, Processors #2 and #3 were so identified. Thus we replicate, in the context of performance over time, the [Wilson et al.\(1994\)](#) laboratory finding that the details in the design of a CIS processor make a difference in performance on tests of speech intelligibility.

Although Processors #2 and #3 produced very similar results, the slightly, albeit not statistically, higher scores produced by Processor #3 led us to adopt this processor as the new "best" processor. The objective data obtained with Processor #3 were matched by the patient's subjective report. The patient reported that he performed better in the "real world" with Processor#3 than with Processor #0 and that he preferred Processor #3 to Processor #2. He noted that voice pitch sounded more normal, i.e., lower, through Processor#3 than through Processor #0. This observation can be rationalized partially by noting that stimulation order, apex to base, allows the most apical electrodes to be stimulated successively rather than in a pattern that alternates between base and apex. The decrease in pitch is important, at least for this patient, because voices processed through 6-channel CIS processors sound higher pitched than do voices processed through the Ineraid.

The "new" processors tested in Experiment 2 produced better scores at 1 wk after fitting than at fitting. The clinical importance of this outcome is that if two processors are to be compared, and if one processor has been used for a period of months, the second must be worn for some time before its performance can be compared with that of the first processor. All of the CIS processors tested in Experiment 2 allowed higher levels of speech intelligibility than did the Ineraid tested in Experiment 1. This outcome is consistent with the success, relative to performance with the Ineraid, reported by [Boex et al. \(1994\)](#) in Switzerland, who fitted all Ineraid patients with a single, "best guess design," CIS processor. It seems that many CIS processor configurations will allow better speech intelligibility than will the Ineraid (see also [Wilson, Lawson, & Zerbi, in press](#)).

Experiment 3 [TOP](#)

In the Introduction we noted that [Lawson et al. \(1993\)](#) report, for a single patient, that the amount of information transmitted about consonant features decreases as the number of channels decreases from six to one. This suggests that if the number of channels were to be reduced for our patient, speech intelligibility would be reduced. On the other hand, there is some evidence that five channels may work as well, or nearly as well, as six channels. [Boex et al. \(1994\)](#) report about the same improvement in transmission of consonant information for Ineraid patients fitted with 5-channel CIS processors as [Wilson et al. \(in press\)](#) report for Ineraid patients fitted with 6-channel CIS processors. To determine the effect of the number of channels on speech intelligibility, the patient was fitted with processors with three channels, four channels, five channels, and six channels, and speech intelligibility was assessed at fitting and after 1 wk's use of a processor.

Method [TOP](#)

Electrode Characteristics • The patient's dynamic ranges for Electrodes 1 to 6 were 11, 12, 11, 12, 12, and 10 dB. The patient could rank the electrodes appropriately. Thus, Channel 6 was characterized neither by an abnormally small dynamic range nor an by an inappropriate pitch.

Signal Processor Design • Processors with 5, 4, and 3 channels were created by dividing the frequency range 330 Hz to 5500 Hz equally by the number of channels along a logarithmic scale. The other aspects of the processors were the same as those of the 6-channel processor.

Speech Materials • For these experiments, the Speech Perception In Noise (SPIN) sentences from the Minimal Auditory Capabilities battery (used without competing noise) were added to the test battery. The sentences were delivered by audio tape. In addition, the words from one 50 word NU-6 list were delivered by audio tape. The speaker was female and spoke in the manner of "clear speech" ([Picheny, Durlach, & Braida, 1985](#)).

Design • After testing with the 6-channel, 70µsec/phase, 1070 pps processor used in Experiment 2, the patient was fitted, and tested on the same day, with a 5-channel processor of the same design. One week later the patient was tested again with the speech materials. The same day, he was fitted with a 4-channel processor and tested with speech materials. A week later he was tested again and then fitted with a 3-channel processor. A week later he was retested with the speech materials. Consonant and vowel scores were obtained at fitting and after 1 wk's use of a processor. CID, SPIN, and NU-6 scores were obtained only after a week's use of a processor.

Results [TOP](#)

Performance after Adaptation to a Processor • The results for all conditions are shown in [Table 1](#). The intelligibility of consonants, when assessed after a week's adaptation to a processor, decreased systematically from 98% for the 6-channel processor to 90%, 75%, and 65% for the 5-, 4-, and 3-channel processors, respectively. Percent correct scores for place of articulation followed the same pattern: 98%, 91%, 85%, and 69%, respectively. A repeated measures ANOVA on the overall percent correct scores indicated a significant effect of the number of channels ($F[3,12] = 8.71; p = 0.002$). Performance with six channels was significantly better than performance with four channels or three channels (Fisher's LSD, $\alpha = 0.05$). Performance with six channels and five channels did not differ. For vowels, a repeated measures ANOVA indicated a significant effect for the number of channels ($F[3,12] = 11.03; p = 0.0009$). Processors with six channels, five channels, and four channels allowed better scores than did the processor with three channels (Fisher's LSD, $\alpha = 0.05$). For the CID sentences, 5- and 6-channel processors produced identical scores. The change from five channels to four channels was significant (binomial expansion), as was the change from four channels to three channels. Performance on the SPIN sentences was similar for 6-, 5-, and 4-channel processors. The 3-channel processor produced significantly poorer results (binomial expansion). For the words from the NU-6 test, the 6-, 5-, 4-, and 3-channel processors produced scores that were not significantly different.

Test Material	Number of Channels			Fit
	6	5		
		Fitting	1 wk	
Consonants	98 (6)	74 (5)	90 (10)	79
Vowels	69 (9)	74 (7)	71 (11)	65
CID-A	100		100	
SPIN	68		76	
NU-6	46		48	

TABLE 1. Speech intelligibility (percent correct), at fitting and after 1 wk's use of a processor, as a function of the number of continuous interleaved sampling (CIS) channels. Standard deviations are reported in parentheses

Change in Performance over a Week • For consonants, performance varied as a function of experience with a given processor. When the patient was first changed from a 6-channel processor to a 5-channel processor, performance dropped significantly from 98% correct to 74% correct ($t = 10.6; p = 0.0004$). After a week's experience, performance improved significantly to 90% correct ($t = 3.51; p = 0.024$). With a 4-channel processor, performance fell once again at fitting, but the change was not significant ($t = 2.21, p = 0.09$). There was no improvement in performance after a week's experience with the processor. When the patient was fitted with a 3-channel processor, performance fell significantly ($t = 9.41; p = 0.0007$). The 1 wk score was not significantly higher than the score at fitting. For vowels, the change from a 4-channel processor to a 3-channel processor at fitting was significant ($t = 6.69; p = 0.002$), as was the increase in performance after a week's use of the 3-channel processor ($t = 3.26; p = 0.03$).

Discussion [TOP](#)

Performance on tests of consonant, vowel, and words in sentences recognition was affected significantly by the number of channels in the CIS processor. This outcome replicates the laboratory findings of [Lawson et al. \(1993\)](#).

Performance with a 5-channel processor was not significantly different from performance with a 6-channel processor. For consonants and CID sentences, the absence of a difference in performance could be accounted for by a ceiling effect. There was sufficient room, however, to resolve a difference in performance with the 6- and 5-channel processors with vowels, the SPIN sentences, and the NU-6 words, and no differences in performance were found. It seems that 5- and 6-channel processors allow similar levels of performance for this patient. This outcome is consistent with the report of [Boex et al. \(1994\)](#) that a 5-channel processor can support a high level of speech intelligibility. It also is consistent with the similar levels of information transmission reported by [Boex et al. \(1994\)](#) for a 5-channel processor and by Lawson et al. for a 6-channel processor.

The data collected with the 4-channel processor are of interest because in an appropriate comparison between processing strategies, e.g., analogue versus CIS, the number of channels will be the same. In the comparisons of Ineraid and CIS processors reported by [Wilson et al. \(1991\)](#) and by [Boex et al. \(1994\)](#), both the strategies and the number of channels varied. In the first instance, six CIS channels were compared with four analogue channels, and in the second, five channels were compared with four channels. Unpublished data on two patients from Wilson's group suggest that four CIS channels provide better performance than do four analogue channels. All of our data indicate that performance with the 4-channel processor is superior to that with the Ineraid. Thus, the present data and those of Wilson demonstrate that CIS processors can provide better speech intelligibility than can analogue processors when the number of channels is held constant.

The reduction in channels from six to four had a larger effect on consonant identification than on vowel identification. These data can be rationalized, in part, by noting that the information that specifies vowel identity occupies a more restricted frequency region than does the information that defines consonants. In this circumstance, the addition of Channel 6, or even 5, may be of small benefit. On the other hand, as the number of channels is reduced, the bandwidth per channel must increase, and, we should suppose, frequency resolution must become correspondingly poorer. It is in this light that the robustness of vowel recognition in the face of a reduction in channels is of interest.

Finally, despite of the similar word identification scores with 6-channel processors and 5-channel processors, there may be some benefit of six channels versus five channels. This patient and others have noted a change in sound quality when the number of channels is reduced. If the addition of Channel 6 improves sound quality, of course a 6-channel processor will be preferred. It is also possible that the addition of Channel 6 would aid speech intelligibility in noise. This remains to be tested.

General Discussion [TOP](#)

The aim of Experiments 1 to 3 was to assess the effects of accommodation to, or learning to use, a CIS processing strategy by an Ineraid patient. We have found that learning can take place over time spans ranging from a week to a month or more. Thus, the Wilson et al. reports on improvements in speech intelligibility for Ineraid patients fitted with CIS processors may be only a harbinger of the improvements that may be realized over time.

As Wilson et al. have indicated, processing strategies make a difference in speech intelligibility. The experiments reported here dealt only with strategies that were likely to be of benefit to our patient. In these experiments, differences among processors in terms of speech intelligibility were small. However, many other processors were tested that were summarily rejected by the patient on the grounds of poor sound quality or poor intelligibility. Thus, our experience, and that of Wilson et al., is that the time spent searching for a better processor is well spent. When searching for a better processor, however, it must be kept in mind that if a patient has adapted to a given processor, a period of time may be necessary before a new processor will show its "true" benefit. Thus, if a patient indicates that a new processor "sounds" better in the laboratory, in spite of no change or even poorer scores on tests of speech intelligibility, a week's trial with the new processor may be in order. Even if a new strategy provides better performance immediately in the laboratory, a trial of a week or more will be necessary to assess the benefit from that processor relative to the previous processor.

The pattern of a drop in performance consequent to a change in processor design followed by an increase in performance after a week's experience with a processor was a notable aspect of the data on consonant, and to a lesser extent vowel, identification. These changes in performance bear a resemblance to the changes in the spatial extent of the cortical representation of a sensory surface as a function of learning (e.g., [Merzenich, Recanzone, Jenkins, & Nudo, 1990](#)). Many experiments have shown that the cortical representation of, for example, a finger will increase as that finger's surface is used in an experimental task. Changes in the spatial extent of the cortical representation of frequencies also have been shown as functions of mastering an auditory frequency discrimination task ([Recanzone, Schreiner, & Merzenich, 1993](#)). In the experiments reported here, it might be the case that the drop in performance after a change in processor design, e.g., a change in the number of channels, is a sign of the need to reshape the cortical representation of frequency space. In similar fashion, the increase in performance after experience with a processor may be a sign that the cortical representation of frequency space has been reshaped.

Acknowledgments: [TOP](#)

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* When signals were input via the auxiliary jack to the Ineraid, a special cable was used that disabled the patient's microphone. When signals were directed to the auxiliary input jack of the CIS processor, a switch disabled the microphone input. [\[Context Link\]](#)

† Patients adjust the input and output of their processors depending on the signal level at input (usually between 5 and 20 mv). Patients were given time to adjust their controls before each test began. The relationship between signal level, input amplification, and output amplification and optimal speech understanding is largely unexplored. [\[Context Link\]](#)