A New Speech Processor Providing Improved Speech Discrimination in Noise and in Quiet for the Mini System 22 Cochlear Implant

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The Spectral Maxima Sound Processor (SMSP) has been developed at the University of Melbourne for use with the mini-system 22 cochlear implant manufactured by Cochlear Pty Ltd. A comparison study with four adult subjects [McKay et al., in press] showed that perception of vowels, consonants, monosyllabic words, and sentences in quiet and in background noise is enhanced with the SMSP when compared with the MSP(MULTIPEAK) processor currently supplied for use with this implant. Qualitative remarks of subjects are consistent with improved perception of speech in background noise and of degraded speech such as with television and telephone use. Subjects also report that environmental noises and music sound more natural and identifiable. Further development of the SMSP strategy and formulation of advanced strategies are being facilitated by a new programmable processor utilising digital signal processing. Speech perception results for five adults (two of whom took part in the earlier comparison study) who are currently using this processor programmed with an SMSP strategy, show that performance is better than or similar to that using the earlier version of the SMSP which employed analog signal processing. This enhancement may be due to such factors as increased dynamic range in the version using digital signal processing.

INTRODUCTION

The Spectral Maxima Sound Processor (SMSP) was developed at the University of Melbourne, initially for use with an advanced cochlear implant (McDermott, 1989), and later modified for use with the Nucleus mini system 22 implant manufactured by Cochlear Pty. Ltd. It was first used by implantees fitted with the
mini system 22 device in 1989, when a study was initiated to compare the speech perception ability of two implantees using the SMSP with that using a prototype of the MSP. The latter processor utilised the same two-formant coding strategy as the earlier WSP III processor, but was implemented on the improved hardware of the MSP processor. The study (McKay, McDermott, Vandali, & Clark, 1991) showed that for these two subjects speech perception ability was considerably improved with the SMSP processor. This encouraging result led to a further study with four implantees comparing their speech perception ability using the SMSP to that achieved using the most recent version of the MSP programmed with the MULTIPEAK strategy. The MSP(MULTIPEAK) processor is manufactured currently by Cochlear Pty. Ltd. for use with the mini system 22 implant. A recent report gives details of the MSP (including the prototype) and WSP III processors and compares their performance in a group of implantees (Skinner, Holden, Holden, Dowell, Seligman, Brimacombe, & Beiter, 1991).

The study comparing the SMSP with the MSP(MULTIPEAK) processor (McKay, McDermott, Vandali, & Clark, in press) showed that the speech perception ability of a group of four adult implantees was significantly improved both in quiet and in the presence of background noise with the SMSP processor. For example, the mean percentage correct scores with electrical stimulation alone for an open-set monosyllabic (CNC) word test were, using the SMSP: words 57.4%, phonemes 76.0%, vowels 82.6%, and consonants 72.7%. The corresponding MSP (MULTIPEAK) mean scores for the same subjects were: words 39.9%, phonemes 64.6%, vowels 72.8%, and consonants 60.5%. For sentences in noise (at 10 dB signal-to-noise ratio), the mean SMSP score was 78.7%, compared to the mean MSP(MULTIPEAK) score of 50.0%. As well as these improvements being statistically significant, it should be noted that they are large enough to be of great practical significance to these implantees, and most likely provide them with greater communication competence and quality of life.

Since the above report, the SMSP strategy has been successfully implemented in a new processor which utilises digital signal processing. In this paper, some preliminary results of speech perception tests are presented for five subjects who are currently using this new processor, and their performance is compared with previous performance with the SMSP(analog) and the MSP(MULTIPEAK) where appropriate.

MATERIALS AND METHODS

The processors

The SMSP processor and sound processing strategy have been described in detail in a recent report (McDermott, McKay, & Vandali, in press). Briefly, sound signals obtained from a microphone are amplified, compressed, and subsequently analyzed by means of a bank of 16 bandpass filters. The filters are incorporated in an analog signal processing chip and encompass a frequency range of from 200 Hz to 6 kHz, approximately. At periodic time intervals, typically every 4 ms, the six filters having the highest amplitudes are selected and six corresponding electrodes in the user's implant are activated. For most implantees, the 16 most-apical electrodes are allocated to the filters in tonotopic order. The current levels and pulse widths of the stimuli generated by the implant are determined from the amplitudes of the signals in the selected filterbank channels. If fewer than
six filters are found to have significant amplitudes then correspondingly fewer stimuli are generated during that processing period. This processor will be referred to as the SMSP(analog) in the remainder of the paper.

The wearable DSP speech processor recently developed at the University of Melbourne for use in cochlear implant research has the computing power, precision and flexibility to enable the implementation of a broad range of sound processing strategies. The processor incorporates an analog preprocessor, the DSP (digital signal processor) core, an encoder, and a radio frequency (RF) transmitter. The analog front end preprocesses signals obtained from an ear-level microphone. The signals are amplified and digitised at a rate of 12000 samples per second using a 12-bit analog-to-digital converter which is interfaced to the DSP core. The DSP core includes a Motorola DSP56001 integrated circuit which typically is programmed to perform processes such as real-time spectral analysis and filtering of incoming signals. The outputs of these processes are converted into electrical stimulus parameters that are transferred to the encoder. The encoder then formats the stimulus parameters into appropriate RF signals for transmission to the cochlear implant.

The DSP processor has been programmed to implement a sound processing strategy which is very similar to that embodied in the earlier (analog) version of the SMSP. The use of digital signal processing techniques has provided some advantages, including an increase in the usable dynamic range of the system. As a result of the dynamic range improvements, it has been possible to avoid compressing signals in the front-end of the processor. Furthermore, the analog filters in the previous version of the SMSP have been replaced by a filterbank based on a real-time fast Fourier transform. The effects of modifying the design of the filters may thus be investigated more easily in future variations of the SMSP strategy. However, the results reported below for the DSP processor were obtained using a DSP program which emulated the SMSP(analog) as closely as was practical and which will be referred to in the remainder of the paper as the SMSP(digital).

Subjects

Two of the subjects whose results are reported below (Subjects 3 and 4) were also involved in the study comparing the SMSP(analog) with the MSP (MULTIPEAK) and are fully described in that report (McKay, et al., in press). For ease of reference, they have the same designated subject numbers in this report. Both of these subjects continued to use the SMSP(analog) after the completion of the comparison study, and so had considerable experience with the SMSP strategy before proceeding to the SMSP(digital) processor.

Subjects 5 and 6 had a relatively short period of time using the SMSP(analog) before going on to try the SMSP(digital), as described below. Subject 5 is 52 years old and has been profoundly deaf since the age of 11 years. She was implanted 12 months before the start of this study and had been using the MSP (MULTIPEAK) since implantation. Subject 6 is 50 years old and has had a progressive loss since the age of 20 years, being profoundly deaf for four years prior to implantation. He was implanted 13 months before the start of the study and had also been using the MSP(MULTIPEAK) since the time of implantation. Subject 7 is 64 years old and has had a severe loss since the age of 13 years, pro-
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gressing to profound by age 40 years. He was implanted 5 years before the start of this study. He used the WSP III processor for 4 years, and changed to the MSP (MULTIPEAK) 13 months before the start of this study.

Speech test material

Two types of speech test are reported below. Monosyllabic (CNC) word tests were used to monitor the speech perception performance of each subject over time. Each test consists of 50 CNC words which are phonemically balanced. A total of 40 such lists, recorded by Australian speakers, were available for testing so that subjects were unlikely to become familiar with the material over time. The lists were presented in the auditory alone condition in a sound treated room at a level of 65 to 70 dBA. The tests were scored by the percentage of correct phonemes in the responses. The latest results for the SMSP(digital) processor are presented below in the context of the performance over time of each subject when using various processors since they started to participate in speech processing research.

Sentence testing was used to test the effect of varying amounts of background noise on the ability to understand speech. The sentence material used was adapted from the CUNY sentences (Boothroyd, Hanin, & Hnath, 1985). Sixty lists were constructed with each having 12 sentences of varying length and context with a total of 102 words per list. The sentences were recorded by Australian speakers and presented in the auditory alone condition in a sound treated room at a level of 65 dBA. The CUNY sentence scores are the percentage of words correct for each sentence list. The background noise used was multi-talker babble.

RESULTS

CNC word tests

The phoneme scores over time for the five subjects are shown in Figs. 1 to 5. The time axis in each case is the number of months since the beginning of MSP use. For all subjects except 3 and 7, this is also the time since implantation. Subject 3 used the WSP III and the MSP prototype (both with the two-formant strategy F0F1F2) for approximately three years before first trying the MSP (MULTIPEAK), and Subject 7 used the WSP III processor for 4 years before changing over to the MSP(MULTIPEAK). The scores shown in these figures represent the mean scores and 95% confidence intervals of the mean scores for each period of use with a particular processor. In general the scores from the first few weeks of experience with a processor were not used in calculating the means.

Subject 3 (Fig. 1) first used the MSP(MULTIPEAK) for three months and his average score over this time is shown as the first point on the graph. This score was close to his performance over the previous six months with the MSP prototype. He then used the SMSP (analog) for three months and exhibited a marked increase in his scores during this time (second point). He then went back to the MSP(MULTIPEAK) for two months (third point), and subsequently back to the SMSP (analog) for two months (fourth point). These last two points were significantly different from each other and show that Subject 3 performed better when using the SMSP(analog) than when he was using the MSP(MULTIPEAK) (McKay, et al., in press). He then continued to use the SMSP(analog) for the next 9 months as he greatly preferred it to his MSP. The fifth point represents the
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average performance over this extended period of use and shows a further improvement in performance over this time with the SMSP(analog). It is not possible to say whether this increase was due to further experience with the strategy or whether his scores were affected by his improvement in self confidence with the new processor. After this time he was given the new DSP processor programmed with experimental modifications of the SMSP strategy, and finally with the standard SMSP(digital) strategy. The final point is his average score with the SMSP(digital) over a period of several weeks. This score is significantly better than the last SMSP(analog) score (t-test, p<0.05), however, in view of the time difference of the two scores and the improvement over time seen previous to these scores, it cannot be said whether the improvement is due to the digital processor or further learning over time.

Subject 4 (Fig. 2) used the MSP(MULTIPEAK) since implantation. Her scores were monitored until they were stable and then her MSP scores were obtained over several weeks (first point). She was then given the SMSP(analog) to use and the second point is her SMSP score averaged over the last seven weeks of a 14 week period. This score is significantly higher (t-test, p<0.001) than her MSP (MULTIPEAK) score (McKay, et al., in press). After the completion of the comparison study, she continued to use the SMSP (analog) in preference to her MSP, and the third point is the average of four scores over a six month period. She then used the SMSP (digital), and the last point is her average score over a two month period with this processor. Unlike Subject 3, her scores have not changed significantly since shortly after changing over to the SMSP(analog), showing no learning effect over time. This is not surprising given that her scores were averaging close to 90% correct with both SMSP versions.

Fig. 1. Subject 3: Performance over time for the CNC word test. Each bar represents the mean score (in percentage of phonemes correct) for a particular test period and the 95% confidence interval of the mean. The time scale denotes the number of months since the subject first used the MSP(MULTIPEAK) processor.

Fig. 2. Subject 4: Performance over time for the CNC word test. Each bar represents the mean score (in percentage of phonemes correct) for a particular test period and the 95% confidence interval of the mean. The time scale denotes the number of months since the subject first used the MSP(MULTIPEAK) processor.
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Subject 5 (Fig. 3) had worn the MSP(MULTIPEAK) since she was implanted 12 months prior to the beginning of this study. Her MSP scores were monitored over five weeks and showed no learning effect after the first week. The first point shows the scores from the last three test sessions. She then used the SMSP (analog) for eight weeks and the second point shows the scores from the second half of this period. She then went back to using the MSP (MULTIPEAK) for an eight week period and the third point shows the scores from the second half of this period. Then she used (and continues to use) the SMSP (digital) and the fourth point represents the scores from weeks 2 to 5 with this processor. Her performance in the two periods with the MSP (t-test) were not significantly different although there may have been a small learning effect obscured by the variability of the scores. These two periods were combined and a one way analysis of variance showed a significant difference between processors (p<0.001) with both SMSP scores being significantly higher than the MSP(MULTIPEAK) score, and the SMSP(digital) score being significantly higher than the SMSP (analog) score (Tukey multiple comparison test).

Subject 6 (Fig. 4) used the MSP(MULTIPEAK) since implantation (13 months before the beginning of this study). The first point shows his performance over a three week period with the MSP. Then used the SMSP(analog) over a two month period and the second point shows his performance in the second half of this period. After that he used (and continues to use) the SMSP(digital) and the third point shows his performance over the second month of use. One way analysis of variance showed a significant difference between processors and a Tukey multiple comparison test showed that his performance with the SMSP(digital) was significantly better than the other processors.
than with the SMSP (analog) and with the MSP(MULTIPEAK), the last two processors providing scores which were not significantly different. In this case the learning effect over time could not be evaluated by returning to the MSP processor: this subject strongly resisted the suggestion because of his belief that the SMSP processors were greatly increasing his quality of life. It should be noted however that this subject already had 13 months' experience with the MSP(MULTIPEAK) before being assessed with that processor, and so might not be expected to be improving significantly over the time span of the study.

Subject 7 (Fig. 5) wore the MSP(MULTIPEAK) for 13 months prior to beginning this research. The first point represents his performance over several weeks with the MSP. He then used a prototype version of the SMSP(digital) for eight weeks and his performance with this processor for the second half of this period (second point) was significantly better than that with the MSP. He continued to use the SMSP(digital) over the next six months and his scores remained very stable over this time (third point). He then returned to using the MSP(MULTIPEAK) for six weeks (fourth point) before using the newest version of the SMSP(digital) for another six week period (fifth point). The score with the SMSP(digital) is significantly better than the preceding MSP score, and also significantly better than the score obtained with the prototype version of the SMSP(digital) processor. This latter improvement is likely to be due to hardware improvements in the design of the digital processor.

Sentence tests in noise

Subjects 3 and 4 had previously had their performance in noise using the MSP (MULTIPEAK) compared with that using the SMSP(analog), and it was found that they each performed better with the SMSP(analog) (McKay, et al., in press). The elapsed time to when they received the SMSP (digital) and the necessity of using new sentence material to prevent familiarity, make a direct comparison with their SMSP (digital) performance impractical. However, for the remaining three subjects it was possible to compare their SMSP(digital) performance in noise with that of either the MSP(MULTIPEAK) (Subjects 5 and 7) or both the MSP and the subjects it was possible to compare their SMSP(digital) performance in noise with that of either the MSP(MULTIPEAK) (Subjects 5 and 7) or both the MSP and the SMSP(analog) (Subject 6). The sentence scores are an average of at least two tests at each signal-to-noise ratio tested. These results are shown in Fig. 6 and show that the subjects all performed best with the SMSP
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**SPEECH PERCEPTION IN NOISE (CUNY SENTENCES)**

<table>
<thead>
<tr>
<th>PERCENT WORDS CORRECT vs SIGNAL-TO-NOISE RATIO (dB)</th>
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<tbody>
<tr>
<td>Subject 5 (MSP (digital))</td>
</tr>
<tr>
<td>100</td>
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<tr>
<td>50</td>
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<td>20</td>
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<td>10 Quiet</td>
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*Fig. 6. Performance of Subjects 5, 6, and 7 on the CUNY sentence test in varying levels of background noise. The vertical axes denote percentage of words correct and the horizontal axes denote the signal-to-noise ratio in dB.*

(digital) processor in noise, and that, for Subject 6, the SMSP (analog) provided benefit intermediate between the MSP and SMSP (digital) processors.

**CONCLUSIONS**

Previous studies have shown that the performance of the SMSP (analog) processor in enabling speech perception by cochlear implantees was superior to that of the currently supplied MSP (MULTIPEAK) processor. The present study shows that the implementation of the SMSP strategy in a new DSP processor has provided a group of five implantees with similar or better improvements than seen with the analog version of the processor. In addition, the new processor is easily reprogrammable and will allow research to continue providing perceptual performance improvements to cochlear implantees.

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