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Benefits from upgrade to the CP810™ sound processor for Nucleus® 24 cochlear implant recipients

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Abstract The objective of this study was to measure performance benefits obtained by upgrading recipients of the Cochlear™ Nucleus® CI24 cochlear implant to the new CP810™ sound processor. Speech recognition in quiet and in spatially separated noise was measured in established users of the Cochlear ESPrit 3G™ ($n = 22$) and Freedom™ ($n = 13$) sound processors, using the "Everyday" listening program. Subjects were then upgraded to the CP810 processor and were re-assessed after a 3-month period, using both the "Everyday" program and the new "Noise" program, which incorporates several pre-processing features including a new directional microphone algorithm ("Zoom™"). Subjective perceptions were also recorded using the abbreviated profile of hearing aid benefit (APHAB) questionnaire. Mean scores for monosyllables in quiet, presented at 50 and 60 dB SPL, increased by 11 % ($p < 0.0001$) and 8 % ($p < 0.001$), respectively, after upgrade, for all subjects combined. Significant increases were also recorded for both processor groups. In noise, the mean scores were 60.0 and 67.4 % for the original and CP810 Everyday programs, respectively (difference not significant). With the CP810 Noise programs the mean score increased to 82.5 % ($p < 0.01$), with significant increases in both processor groups. There was evidence of slightly greater upgrade benefit in users of the ESPrit 3G processor and in relatively poor performers. The APHAB questionnaire also indicated significant reduction in perceived difficulty in the background noise and reverberation sub-scales after upgrade. The

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findings of the study appear to support the expectation of increased benefit from the new CP810 sound processor.

Keywords Cochlear implant · Sound processor · Upgrade · Speech recognition · Noise

Introduction

Over the last 10–15 years, the series of sound processors from Cochlear Limited (Sydney, Australia) has introduced a number of refinements designed to enhance performance, particularly in noise. At the same time, the processors have generally become smaller and have incorporated additional features such as FM system compatibility and remote control operation. The latest processor from Cochlear, initially introduced with the system 5 implant, is the CP810^{TM}, which is now also compatible with the previous CI24 implants.

From March 2009, the French healthcare system has funded sound processor upgrades every 5 years for CI users. Candidature criteria for upgrades are set by each CI centre, without specific guidelines from health authorities. Considering the high price of a new processor (€6,000) and the important benefits obtained from cochlear implantation, processor upgrades have a potentially significant economic impact and should be recommended only where there are demonstrable benefits. Consequently, it is important to assess any improvement in speech understanding or other benefits provided by new processors in order to determine which patients are the best candidates for upgrade. In particular, it would be useful to know whether or not each successive processor "generation" provides sufficient benefit to indicate upgrade.

The aim of this study was to evaluate speech recognition in recipients of the Nucleus 24CI upgrading from the earlier ESPrit 3G^{TM} and Freedom^{TM} processors to the CP810. The ESPrit 3G was supplied from 2002 to 2011. The Freedom processor was introduced in 2005 and supported several new features and refinements, including the ADRO algorithm, an increase in the default instantaneous input dynamic range (IIDR) and an adaptive directional dual microphone option (Beam^{TM}). The CP810 now features an additional fixed directional microphone option (Zoom^{TM}) and several ergonomic improvements, including smaller size and remote operation. The differences among these processors are outlined in more detail in the "Methods" section below. Studies reporting on some of the individual features of the Freedom and CP810 processors are also discussed later in this report.

Several previous studies have attempted to compare performance obtained from different processor generations. For example, Davidson et al. [1] measured speech understanding in 109 users of the earlier Nucleus 22 implant who used four different processor types (Spectra^{TM}, Sprint^{TM}, ESPrit 3G and Freedom). Better performance was indicated in the users of the newer processors (ESPrit and Freedom) than in those using the older versions, but in such studies the patient groups are not necessarily well matched in terms of pre-implant demographics. Other comparison studies have been performed in the context of clinical processor upgrades, which have the advantage of paired, within-subject comparison. Generally, these have indicated significant improvements with each processor generation. Müller-Deile et al. [2] reported highly significant improvements in speech understanding and subjective benefits in subjects upgrading to the Freedom processors from several earlier versions. Santarelli et al. [3] reported on a study on children upgrading from the SPrint and ESPrit processors to the Freedom. Word recognition in quiet significantly increased with the Freedom processor compared to both the earlier processors, but speech recognition in noise only increased significantly in the subjects upgrading from the SPrint.

The CP810 processor is relatively recent and fewer upgrade reports are available to date. However, Wolfe et al. [4] reported on a multicentre study on 35 adults upgrading from the Freedom to the CP810 processor. Their study focussed on the new Zoom directional microphone feature, but demonstrated superior performance from the CP810 in quiet as well as in noise. In addition, a White Paper from Cochlear Limited described an internal study conducted in Melbourne and Sydney, comparing speech understanding with the Freedom and CP810 processors and also subjective preferences after a 2-week take-home trial period [5]. Speech understanding in quiet was the same for the two processors, but speech in noise testing and the results of a subjective questionnaire indicated superior performance with the CP810.

The present study was designed to assess the benefits of upgrading Nucleus CI24 recipients from the ESPrit and Freedom processors to the new CP810. Speech recognition in quiet and noise was measured, plus subjective ratings using the abbreviated profile of hearing aid benefit (APHAB) questionnaire.

Methods

Subjects

Subjects enrolled in the study were all recipients of the Nucleus CI24 device who were fluent French speakers and aged over 12 at the time of upgrade. They had all used an ESPrit 3G^{TM} or Freedom^{TM} processor for at least 4 years, and were required to have a minimum of 10 % open set monosyllabic word (PBK or Lafon list) or 20 % open set

Table 1 Demographic details of the subjects comprising group 1 (ESPrit 3G users) and group 2 (Freedom users)

	Group 1 ($n = 22$)	Group 2 ($n = 13$)	Combined ($n = 35$)
Age at testing	48.6 (14–79)	36.0 (12–62)	43.9 (12–79)
Age at implantation	40.0 (3–69)	29.0 (5–56)	35.9 (3–69)
Duration of CI use	8.5 (6–14)	7.0 (5–12)	7.9 (5–14)

disyllabic word (Fournier list) recognition at 65 dB SPL in quiet in the best aided condition (with contralateral hearing aid or CI if used), as indicated by clinical records. Any subject with inappropriate expectations/motivation or who was unable to complete the required assessments for other reasons was excluded.

This was a multi-centre study with subjects recruited at five CI centres in France. Written informed consent was obtained from each subject before enrolment into the study, which was approved by the appropriate Ethics Committee (Comité de Protection des Personnes, Ile de France IV, No. 2010 A01294-35).

From March to August 2011, 35 patients were enrolled into the study. All subjects were implanted with versions of the Nucleus 24 Cochlear Implant: CI24M (7), CI24R (27) and CI24RE (1). 22 subjects were using the ESPrit 3G processor at the time of upgrade (group 1) and 13 were using the Freedom processor (group 2). All subjects used the ACE coding strategy before and after upgrade to the CP810 apart from two subjects (one from each group) who used the SPEAK strategy. The mean age at implantation was 35.9 years (range 3–69 years), mean duration of CI use was 7.9 years (range 5–14 years) and the mean age at testing was 43.9 years (range 12–79 years). Table 1 provides demographic data for all subjects and for the ESPrit and Freedom processor groups. There were no significant differences between the two processor groups on any of these parameters, as assessed using t tests and $a < 0.05$ significance level. Six subjects were pre-lingually deaf (four from group 1 and two from group 2) and the others were post-lingually deafened adults or adolescents. Precise data on the duration of deafness was not available for all the post-lingually deafened subjects.

Four of the subjects (two from each processor group) had a CI on the contralateral side, and twelve subjects (nine in group 1 and three in the group 2) used a contralateral hearing aid.

Speech processors

All three of the sound processors evaluated in the study are behind-the-ear models, and each generation incorporates several features and parameter modifications designed to improve hearing performance. The main differences are summarized in Table 2. In common with the earlier Cochlear processors, the ESPrit 3G uses a single dual port first-order directional microphone, which produces mild attenuation of sounds from the rear. For the Freedom processor, an omnidirectional microphone was added, in addition to the dual port microphone, and this combination was used to implement an adaptive “beam-forming” algorithm, known as Beam™, which modifies its polar characteristics according to the direction of the dominant sound source [6, 7]. In the CP810 processor, the microphones of the Freedom processor are replaced by twin omnidirectional microphones which are precisely calibrated and phase-matched. These enable tighter control of the previous directional modes, and implementation of new algorithm known as Zoom™, which produces a strong directional response, similar to Beam, except that it is fixed, rather than adaptive [4, 8].

In addition to the microphone hardware and processing, there are several other processing differences among the three processors. The default instantaneous input dynamic range (IIDR) was increased from 30 dB in the ESPrit 3G to a default of 40 dB (adjustable up to 75 dB) in the Freedom and CP810 processors. Furthermore, new front-end options were added in the later processors. The ESPrit 3G supports the Whisper™ algorithm, which extends the lower limit of the IIDR in order to improve access to quiet speech, plus Autosensitivity, which reduces the microphone sensitivity when the background noise level reaches a certain pre-set value [9]. The adaptive dynamic range optimization (ADRO) algorithm was also added in the Freedom and CP810 processors, which adjusts gain in multiple frequency channels in order to improve audibility, comfort and intelligibility [10].

Table 2 Sound processing features of the processor types evaluated in the study

	Esprit 3G™	Freedom™	CP 810™
Microphones	Dual port directional	Dual port + omnidirectional	Two matched omnidirectional
Frequency range (Hz)	75–10,823	188–7,980	63–7,938
Default IIDR (dB)	30	40	40
SmartSound (front-end processing) options	Autosensitivity Whisper	Autosensitivity, Whisper, ADRO, Beam	Autosensitivity, Whisper, ADRO, Beam, Zoom

Assessment protocol

The subjects attended for two test sessions. At the start of the first session a fitting review was performed, in order to ensure that testing was performed in optimal conditions. A copy of the subject's Everyday map was then loaded into a new processor (ESPrit 3G or Freedom) which was used solely for the study. Speech recognition was then measured as described below, and at the end of the session the new CP810 processor was fitted. The fitting was reviewed at 1 month and the subjects were then re-tested using the CP810 at the second test session 3 months after upgrade. All speech recognition testing was performed in the best aided condition, i.e., using the contralateral hearing aid or cochlear implant, if worn. This is because the aim of the study was to evaluate the impact of upgrading a single processor, no matter what the subjects were using prior to upgrade.

During the first test session, the subjects used their "Everyday" program. In the ESPrit 3G group ($n = 22$), five subjects routinely used Autosensitivity in their Everyday program, and one subject used Whisper, while the other subjects did not use any pre-processing ("SmartSound") options. In the Freedom group ($n = 13$), two subjects used ADRO alone and two used ADRO together with Autosensitivity, while the others did not use SmartSound options. The CP810 processor was fitted with the same SmartSound options in the Everyday program as were used in the original processor, and the subjects also had the option to select the new "Noise" program in difficult listening conditions, which incorporates ADRO, Autosensitivity and the new Zoom™ directional microphone mode. During the second test session, speech recognition measures with the CP810 processor were made using both the Everyday and Noise programs.

Speech recognition in quiet was measured in a sound-treated room using recorded lists of 17 monosyllabic words (Lafon list) presented at 50 and 60 dB SPL from a loudspeaker placed at 0° azimuth and 1 m from the subject. Two lists of words were presented at each level, and responses were scored as the percentage of phonemes and words correctly identified.

Speech recognition in noise was assessed using recorded lists of 15 sentences (MBAA lists) presented at 65 dB SPL from the loudspeaker placed at 0° azimuth, with cocktail-party background noise presented simultaneously from loudspeakers placed at 90°, 180°, and 270° azimuth. In the first session, two lists of sentences were used at signal-to-noise ratios (SNR) of +10, +5, +2, 0, −2 and −5 dB, in order to determine the SNR that produced the score closest to 50 % (speech reception threshold, SRT). Testing commenced at +10 dB SNR and the noise level was then reduced until the subject failed to score over one complete list. In the second session, two lists of sentences were presented at the SRT measured in the first session. The MBAA sentences' results were scored as the percentage of words and sentences correctly identified.

In addition to objective measures, the subjects completed the APHAB questionnaire [11] in order to record subjective impressions of sound quality. This was completed during the first session, prior to fitting of the new processor, and at the start of the second session. The APHAB questionnaire consists of 24 questions in four sections: ease of communication (EC), reverberant listening conditions (RV), background noise (BN) and aversiveness to sounds (AV).

Statistical analysis

Scores are expressed as mean ± SEM. Individual speech recognition scores and APHAB questionnaire scores were compared using paired t tests.

Results

Speech recognition in quiet

Table 3 provides all the mean speech recognition test results for the two subjects groups and for all subjects combined.

Speech recognition in quiet for monosyllabic words with the original SP and the CP 810 (using the Everyday program) is shown in Fig. 1. For the two subject groups combined, % speech scores for words presented at 50 dB SPL were significantly higher with the CP 810 than those obtained with the previous SP (48.0 ± 2.88 versus 37.0 ± 3.92, $p < 0.0001$). At 60 dB SPL the mean % scores (±SEM) were 56.6 ± 3.51 and 64.7 ± 2.50 with the original processor and CP810, respectively ($p < 0.001$), and all mean scores were higher than at 50 dB SPL. Word scores improved by more than 20 % in 19/35 (54 %) of the subjects for words presented at 50 dB SPL, and in 13/35 (37 %) of subjects for words presented at 60 dB SPL. Scoring for phonemes produced an almost identical pattern of scores (Table 3).

Mean scores with the original processor were higher for the group 2 (Freedom) subjects than the group 1 (ESPrit 3G) subjects at 50 and 60 dB SPL, but these differences were not significant on a t test ($p = 0.141$ and 0.261, respectively). The increase in word score obtained from upgrading the group 1 subjects was significant at 50 and 60 dB SPL ($p = 0.0003$ and 0.0026, respectively), but the increases for the group 2 subjects were not significant.

Scores obtained using the original and upgrade processors were compared and significant, though relatively

Table 3 Mean scores (SEM) obtained on speech recognition testing for each processor group and for all subjects combined

	Group 1 (ESPrit 3G, $n = 22$)			Group 2 (Freedom, $n = 13$)			Combined ($n = 35$)		
	Original Everyday	CP810 Everyday	CP810 Noise	Original Everyday	CP810 Everyday	CP810 Noise	Original Everyday	CP810 Everyday	CP810 Noise
Monosyllables 50 dB SPL	32.5	47.1***		44.5	49.5		37.0	48.0***	
Word score % (SEM)	(5.04)	(3.55)		(6.13)	(5.28)		(3.92)	(2.88)	
Monosyllables 50 dB SPL	53.4	70.5**		64.6	71.0**		57.54	70.7***	
Phoneme score % (SEM)	(5.84)	(3.08)		(4.98)	(4.44)		(4.17)	(2.51)	
Monosyllables 60 dB SPL	53.6	64.2**		61.8	65.7		56.6	64.7**	
Word score % (SEM)	(4.46)	(2.99)		(5.86)	(4.80)		(3.51)	(2.50)	
Monosyllables 60 dB SPL	74.2	83.3		79.8	83.0		76.3	83.2**	
Phoneme score % (SEM)	(3.61)	(2.15)		(4.08)	(3.40)		(2.73)	(1.82)	
Sentences in noise	58.5	67.1*	82.8***	62.6	68.0	81.8	60.0	67.4	82.5***
Word score % (SEM)	(1.92)	(3.25)	(2.12)	(5.89)	(4.68)	(4.69)	(2.39)	(2.60)	(2.10)
Sentences in noise	39.1	49.2*	69.0***	44.5	52.2	67.5*	41.1	50.3*	68.4***
Sentence score % (SEM)	(2.14)	(3.27)	(2.66)	(5.22)	(4.02)	(5.61)	(2.36)	(2.51)	(2.63)

Comparison to the original SP (paired *t* test): * $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$

weak, correlations were obtained indicating greater levels of improvement in subjects with lower scores using their original processor. Figure 2 illustrates these relationships for the two processor groups at the 60 dB SPL presentation level. The coefficient of determination (R^2) was 0.55 for group 1 ($p < 0.0001$) and 0.33 for group 2 ($p < 0.05$). For the 50 dB presentation level there was a very similar result for the group 1 subjects ($R^2 = 0.5$, $p = 0.002$), but the correlation for group 2 was not significant.

Results were also analysed separately for subjects with ($n = 16$) and without ($n = 19$) a contralateral hearing device (hearing aid or CI). For the subjects without a contralateral device, mean scores for the original processor and the CP810 were 37.5 and 50.0 %, respectively, for the 50 dB SPL level and were 56.0 and 65.0 % for the 60 dB level. Both of these differences were statistically significant ($p < 0.05$). For the subjects who used a contralateral device mean scores for the original processor and the CP810 were 36.3 and 45.6 %, respectively, for the 50 dB SPL level and were 57.4 and 65.0 % for the 60 dB level. The difference for the 50 dB SPL level was significant, but was not for the 60 dB level ($p = 0.075$). Thus, both groups showed significant improvement, though this finding was slightly less robust for the group using a contralateral device.

Speech recognition in noise

Speech recognition in noise for MBAA sentences (scored for words) with the original SP and the CP810 is shown in Fig. 3. For the Everyday programs, mean % scores for all subjects were higher with the CP810 than the original processor (67.4 ± 2.60 versus 60.0 ± 2.39), though this difference did not quite reach statistical significance ($p = 0.069$). There were no significant differences between the two subject groups. Scores for the CP810 Noise program were significantly higher ($p < 0.01$) than either of the Everyday programs, for each group and for all subjects combined, apart from the comparison between the original Everyday and CP810 Noise programs for group 2 ($p = 0.057$). The mean scores for all subjects combined were 60.0, 67.4 and 82.5 % for the original Everyday, CP810 Everyday and CP810 Noise programs, respectively. When comparing the original Everyday program with the CP810 Noise program, 27/35 (77 %) subjects showed an improvement of over 20 %, and when comparing the CP810 Everyday and Noise programs this proportion was 19/35 (54 %).

Scoring for complete sentences produced an almost identical pattern of scores (Table 3).

Analysis of the results obtained in subjects with and without a contralateral device showed a significant improvement with the Everyday CP810 program as compared to that

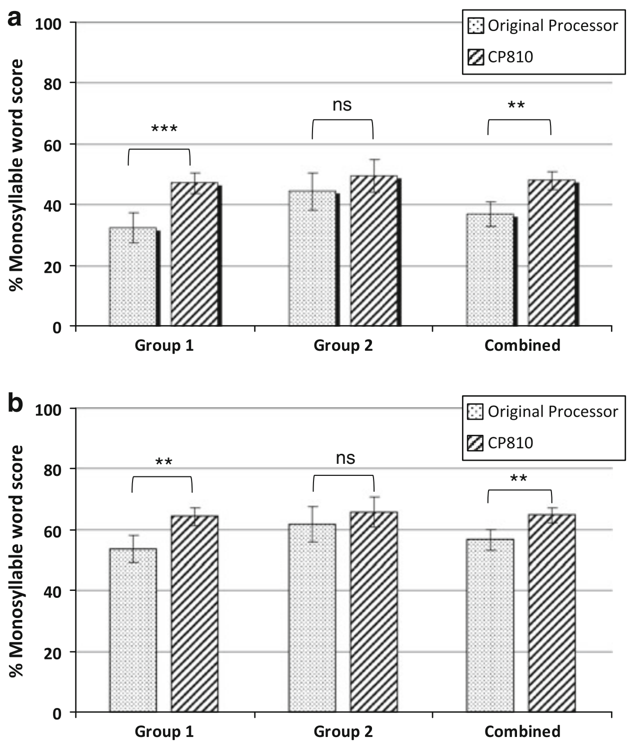


Fig. 1 Speech recognition in quiet with the original SP (ESPrit 3G for group 1 and Freedom for group 2) and the CP 810. Test material was monosyllabic words presented at 50 SPL (**a**) and 60 dB SPL (**b**). Results are expressed as mean ± SEM for words. Significance levels: **$p < 0.001$, ***$p < 0.0001$

in the original processor in the subjects without a contralateral device ($p = 0.494$), but not in those who used a contralateral hearing aid or CI ($p = 0.680$). However, the improvement with the CP810 Noise program was similar and highly significant in both groups ($p < 0.001$).

Subjective sound quality ratings

The APHAB questionnaire was completed by 27 of the subjects (fifteen from group 1 and eleven from group 2), and results are summarized in Fig. 4. Mean scores were lower (fewer perceived problems) with the CP810 globally and for all sub-scales, and this improvement was

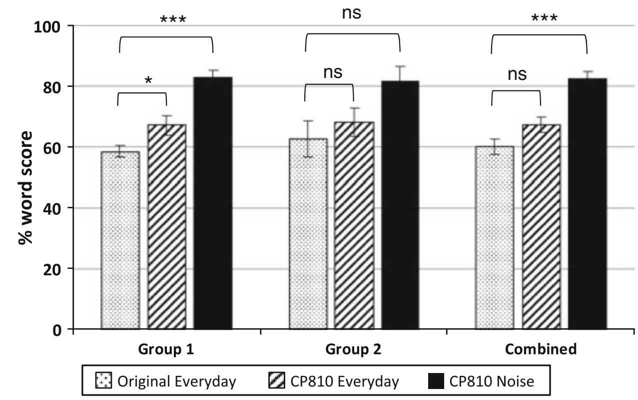


Fig. 3 Speech recognition in noise obtained with the original SP (ESPrit 3G for group 1 and Freedom for group 2) and the CP810 using the Everyday programs in both processors, and also using the Noise program with the CP810. Test material was sentences presented at 65 dB SPL with the noise level adjusted to produce a score around 50 % at the initial session (original Everyday). Results are expressed as mean ± SEM for words. Significance levels: *$p < 0.05$, ***$p < 0.0001$

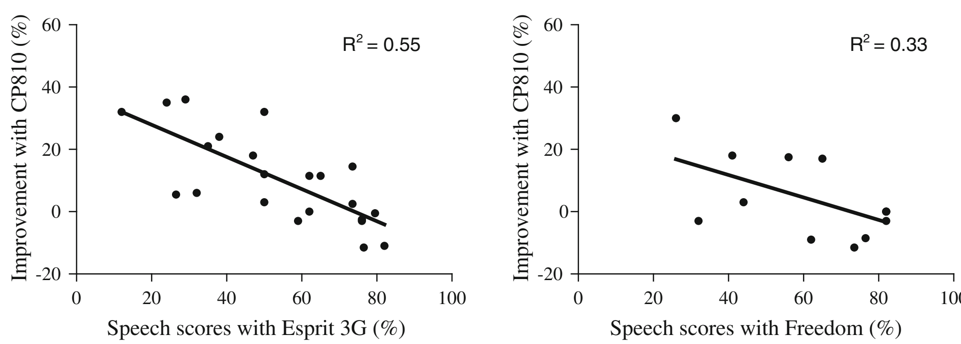
statistically significant ($p < 0.001$) for the global score and the BN and RV sub-scales ($p = 0.168$ and 0.092 for the EC and AV sub-scales, respectively). There were no significant differences between the scores in the two subject groups.

Discussion

Study design scope and limitations

The study described in this report was designed to run alongside a routine clinical upgrade program. It is possible to compare sound processors in a very controlled manner, for example in acute laboratory conditions, or focussing on specific aspects of speech or other acoustic discrimination. This can be particularly useful for investigation of individual processor features, but it is difficult to predict real-world benefit from the performance of an individual processing feature. A clinical study, especially when including a chronic trial period and subjective evaluation, might be

Fig. 2 Correlations for group 1 (*left*) and group 2 (*right*) between monosyllable word scores obtained with the original processor and increase in score obtained with the CP810, for the 60 dB SPL presentation level



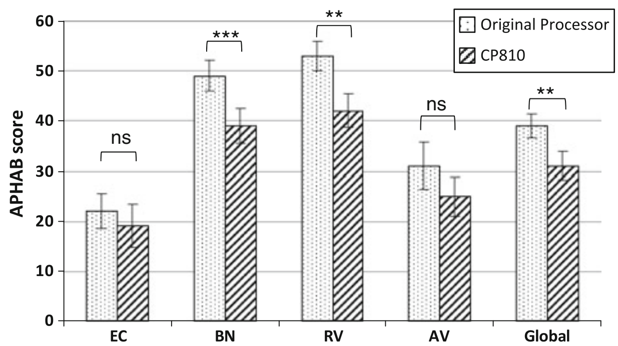


Fig. 4 Mean APHAB scores for all subjects at the initial session (relating to the original sound processor) and after 3 months experience with the CP810 processor. Scores are provided for the 4 sub-scales as well as the global score. *NB* lower scores represent fewer perceived problems. Significance levels: $**p < 0.001$, $***p < 0.0001$

expected to provide data that is more predictive of real-world benefit and cost-utility.

The subjects used in the present study can probably be reasonably considered to be representative of the general CI user population, at least for adults and older children. However, the subject sample was typically heterogeneous, with a wide range of ages and durations of hearing loss. Most were unilateral device users, though there were some using contralateral hearing aids and CIs. The total subject number ($n = 35$) is higher than is often the case in reported upgrade studies, and the fact that the main comparisons are paired increases statistical power. Comparisons between the two individual processor groups are rather less robust, however, largely as the subject number was only $n = 13$ in the Freedom group and as statistical comparisons were not paired. As a result, there were no significant differences between the demographics of the two processor groups, but of course this does not necessarily mean that they were well matched. They contained different proportions of subjects using contralateral devices and differences in pre-processing features in the Everyday programs. Duration of deafness was also not fully documented, though this parameter is often of questionable value as deafness (and use of hearing aids) tends to be progressive in many cases.

Speech recognition in quiet

The results obtained from speech testing in quiet (Fig. 1) show a substantial increase in performance after upgrade to the CP810 processor (all subjects combined), with 11 % increase in mean word score for monosyllables at 50 dB SPL and 8 % improvement at 60 dB SPL. Significant improvements were also observed for both the individual original processor groups. As most of the front-end processing options were the same for all processors (the subjects mostly used the same options in their Everyday program), these improvements may have been due to a variety of subtle hardware and processing refinements in the later processors. For example, each processor uses different microphones and fully digital processing (DSP chip) was not implemented until the Freedom processor. Given the duration of device use (4+ years) it would not be expected that such improvements would occur simply as a result of the additional 3 months of device experience.

Comparison of the two processor groups did not reveal significant differences, but mean scores with the original processor were lower for the group 1 (ESPrit 3G) subjects (Fig. 1), which might be expected in view of the processing refinements in the Freedom processor relative to the ESPrit 3G. It was also notable that poorer performers appeared to show greater improvement than relatively good performers in both processor groups (Fig. 2). The explanation for this effect is not clear, however, but it does not appear to be an artefact of floor/ceiling effects as almost all the individual scores were between 20 and 80 %.

One specific processing feature which likely contributed to the improvement in quiet with the CP810 processor, particularly at the lower presentation level (50 dB SPL) is the instantaneous IIDR. This was increased from 30 dB in the ESPrit 3G to 40 dB in the Freedom and CP810 processors, and this change has been shown to improve recognition of low level speech in several previous studies [12–14]. The greater improvements observed for the 50 dB SPL level and for the ESPrit subject group both fit with this possibility, even though these differences were not statistically significant.

Speech recognition in noise

In noise, there was also a significant improvement in sentence recognition after upgrading to the CP810 when using the Everyday program (which might have been due to similar factors to those affecting performance in quiet), but this improvement was considerably larger when using the Noise program (mean scores were 67.4 and 82.5 % for the CP810 Everyday and Noise programs, respectively). The Noise program in the CP810 incorporates ADRO, Autosensitivity and the Zoom directional microphone mode, whereas the majority subjects did not use any of these in the Everyday program (though a small number used ADRO and/or Autosensitivity).

The present study did not aim to separate the possible contributions of these front-end processing features, but it is possible to speculate in this regard. ADRO is designed to optimize channel-specific gains in order to accommodate fluctuating speech levels [15, 16], but in the test paradigm used in the present study speech levels were constant and so ADRO would not be expected to have a prominent effect. It is possible, however, that the Autosensitivity function might have contributed to the observed improvement. Autosensitivity reduces the input sensitivity when the background level exceeds 57 dB SPL, in order to position the IIDR optimally relative to the level of the speech signal [9]. Most of the subjects were tested in SNR of between 0 and +5 dB (with the speech signal at 65 dB SPL), suggesting that the noise level was probably just above the Autosensitivity threshold for most subjects. However, several studies have demonstrated greatest benefit from Autosensitivity in higher levels of speech and noise [17, 18].

The Noise program also utilizes the new Zoom directional microphone mode, which produces relatively strong attenuation of noise incident from the rear and sides. The Zoom algorithm has been reported to produce advantages over the standard microphone option in situations where the speech and noise sources are spatially separated. Hersbach et al. [8] compared speech in noise performance of the standard, Beam and Zoom microphone options in 14 users of the CP810 processor, using a range of spatially separated noise types. The speech signal was presented frontally and noise (several types) was presented from an array of loudspeakers to the rear of the subject. The Zoom option was found to provide significant benefit over the standard microphone for all noise types, though the effect was strongest for speech weighted noise, with an improvement of 3.9 dB.

Wolfe et al. [4] reported on a study of 35 adult subjects who were upgrading from the Freedom to the CP810 processor. SRT for sentences in noise was measured with the speech presented frontally and multi-talker babble from the 90° ipsilateral direction. Testing of monosyllable understanding in quiet did not show any differences among any of the processor options. For sentences in noise, there was a small but significant improvement when using the standard microphone with ADRO and Autosensitivity with the CP810 as compared with using the same settings with the Freedom processor (mean SRT of 7.8 and 8.6 dB, respectively). When activating the Zoom setting with the CP810, however, the mean SRT showed a very large drop to 1.8 dB.

Subjective perceptions from APHAB data

The data suggest a general improvement from upgrading to the CP810 processor, following a 3-month period. This was evident in the group data, which showed a reduction in mean global score from 39 to 31 % (Fig. 4), and of the individual subjects, 23 out of 27 had a reduced global score. Among the individual sub-scales, the 'background noise' and 'reverberation' categories showed the greatest benefit, with no significant improvement in the 'ease of communication' subscale. However, although statistically significant improvements are indicated by the group data, the improvements are generally smaller than the "critical differences" suggested by Cox and Alexander [11]. Therefore, the results should be interpreted with caution and probably should be viewed as improvement trends, rather than conclusive evidence.

Subjective outcomes, such as those provided by the APHAB, can be affected by the placebo effect, which has been shown to influence reported benefits from "new" hearing aids [19, 20]. In the present study the upgrade (CP810) processor was evaluated after 3 months, however, by which time responses might be more reliable than in the first few weeks when the new processor is very novel. Nonetheless, the APHAB results need to be interpreted with caution for this reason.

The subscales of the APHAB relate to specific listening conditions to some extent (though limited), each of which might correspond to aspects of listening which were reflected in the objective tests performed. 'Ease of communication' might relate to speech understanding in general, while the 'background noise' and 'reverberation' subscales would be expected to relate more to measures of speech recognition in noise. Aversiveness was not assessed by the objective tests performed in the present study, but the Autosensitivity and Zoom features might be expected to contribute to the decrease in aversiveness suggested by the APHAB results.

Clinical implications

The findings of the present study appear to support the expectation of increased benefit from successive Cochlear sound processor generations, most specifically for the new CP810 processor. Clear group improvements were evident for speech understanding in quiet and, in particular, the Noise program (incorporating ADRO, Autosensitivity and Zoom) was highly effective in noise spatially separated from the speech signal.

There was some evidence that some individuals might benefit more than others from processor upgrade. Firstly, there was some suggestion that upgrade to the CP810 resulted in a greater performance benefit for subjects who previously used the ESPrit processor than those using the Freedom, which would be anticipated as some of the design features of the CP810 were already incorporated in the Freedom processor. Secondly, relatively poor performers appeared to benefit more from the upgrade than good performers, though the reason for this trend is not clear.

It is particularly encouraging that significant benefits were recorded in subjects who used a hearing device in the opposite ear, as well as those who used a single CI in isolation. Increases in scores were significant for both processor groups in quiet and in noise, though increases were slightly higher in subjects without a contralateral device, as might be expected. Thus, upgrade of a single processor was shown to provide positive benefit, irrespective of the use of devices in the opposite ear.

The subjective perceptions measured by the APHAB lend some support to the objective test results by their relevance to real-world listening, but it is important to recognize that the APHAB focuses on sound quality, whereas there are other ergonomic factors which also affect user satisfaction.

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References

1. Davidson LS, Skinner MW, Holstad BA, Fears BT, Richter MK et al (2009) The effect of instantaneous input dynamic range setting on the speech perception of children with the nucleus 24 implant. Ear Hear 30:340–349
2. Müller-Deile J, Kortmann T, Hoppe U, Hessel H, Morsnowski A (2009) Improving speech comprehension using a new cochlear implant speech processor. HNO 57:567–574
3. Santarelli R, Magnavita V, De Filippi R, Ventura L, Genovese E, Arslan E (2009) Comparison of speech perception performance between sprint/esprit 3G and freedom processors in children implanted with nucleus cochlear implants. Otol Neurotol 30: 304–312
4. Wolfe J, Parkinson A, Schafer EC, Gilden J, Rehwinkel K et al (2012) Benefit of a commercially available cochlear implant processor with dual-microphone beamforming: a multi-center study. Otol Neurotol 33:553–560
5. Cochlear White Paper (2009) Cochlear™ Nucleus® 5 delivering superior performance in noise
6. Spriet A, Van Deun L, Eftaxiadis K, Laneau J, Moonen M et al (2007) Speech understanding in background noise with the two-microphone adaptive beamformer BEAM in the nucleus freedom cochlear implant system. Ear Hear 28:62–72
7. Gifford RH, Olund AP, Dejong M (2011) Improving speech perception in noise for children with cochlear implants. J Am Acad Audiol 22:623–632
8. Hersbach AA, Arora K, Mauger SJ, Dawson PW (2012) Combining directional microphone and single-channel noise reduction algorithms: a clinical evaluation in difficult listening conditions with cochlear implant users. Ear Hear 33:e13–e23
9. Patrick JF, Busby PA, Gibson PJ (2006) The development of the nucleus freedom cochlear implant system. Trends Amplif 10: 175–200
10. Blamey PJ (2005) Adaptive dynamic range optimization (ADRO): a digital amplification strategy for hearing aids and cochlear implants. Trends Amplif 9:77–98
11. Cox RM, Alexander GC (1995) The abbreviated profile of hearing aid benefit. Ear Hear 16:176–183
12. Davidson LS, Geers AE, Brenner C (2010) Cochlear implant characteristics and speech perception skills of adolescents with long-term device use. Otol Neurotol 31:1310–1314
13. Dawson PW, Vandali AE, Knight MR, Heasman JM (2007) Clinical evaluation of expanded input dynamic range in nucleus cochlear implants. Ear Hear 28:163–176
14. James CJ, Skinner MW, Martin LF, Holden LK, Galvin KL et al (2003) An investigation of input level range for the nucleus 24 cochlear implant system: speech perception performance, program preference, and loudness comfort ratings. Ear Hear 24: 157–174
15. Dawson PW, Decker JA, Psarros CE (2004) Optimizing dynamic range in children using the nucleus cochlear implant. Ear Hear 25(3):230–241
16. James CJ, Blamey PJ, Martin L, Swanson B, Just Y, Macfarlane D (2002) Adaptive dynamic range optimization for cochlear implants: a preliminary study. Ear Hear 23:49S–58S
17. Wolfe J, Schafer EC, Heldner B, Mülder H, Ward E, Vincent B (2009) Evaluation of speech recognition in noise with cochlear implants and dynamic FM. J Am Acad Audiol 20:409–421
18. Brockmeyer AM, Potts LG (2011) Evaluation of different signal processing options in unilateral and bilateral cochlear freedom implant recipients using R-space background noise. J Am Acad Audiol 22:65–80
19. Bentler RA, Neibuhr DP, Johnson TA et al (2003) Impact of digital labeling on outcome measures. Ear Hear 24:215–224
20. Dawes P, Powell S, Munro KJ (2011) The placebo effect and the influence of participant expectation on hearing aid trials. Ear Hear 32:767–774