The Influence of Different Speech Processor and Hearing Aid Settings on Speech Perception Outcomes in Electric Acoustic Stimulation Patients

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Objective: **Electric acoustic stimulation (EAS) is an increasingly popular means of treating individuals with a steeply sloping mid-to-high frequency hearing loss, who traditionally do not benefit from hearing instruments. These persons often have too much residual hearing to be considered for a cochlear implant. Several studies have demonstrated the ability both to preserve the remaining low-frequency hearing in these individuals, and to provide significant benefit through combining a cochlear implant with a hearing aid to amplify the same ear. These improvements in performance have been especially noted in noise. Often overlooked is that these outcomes may be influenced by the fitting parameters of both the cochlear implant and the hearing aid.**

Design: **This study assessed four EAS subjects, with a minimum of 1 month's EAS use, on eight different fitting parameters. Sentence testing in different noise levels (+15, +10, and +5 dB SPL) was conducted. Subjects also evaluated each condition using a visual analogue scale.**

Results: **Results demonstrated that a reduced overlap of cochlear implant and hearing aid amplification produced best results across listening conditions.**

Conclusions: **The hearing aid should be fit to a patient-specific modified audiogram at least up to the point where low-frequency hearing is not measurable. The cochlear implant should be fit from a higher frequency point than is standard in patients without residual hearing in the implanted ear, to provide reduced overlap with the amplification provided by the hearing aid. Therefore, a small amount of overlap between the frequency ranges used by the hearing aid and the cochlear implant seems beneficial.**

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There is a group of individuals who have a moderate to severe steeply sloping sensorineural hearing loss who gain minimal benefit from traditional acoustic amplification. The minimal benefit is due to the fact that, at higher degrees of high-frequency hearing loss, acoustic amplification becomes less effective or can even have adverse effects on speech understanding (Ching, Dillon, & Byrne, 1998; Hogan & Turner, 1998). Approximately 2% of a large clinic patient group would fall into this category of patients (Kiefer, et al., 2005).

Electric acoustic stimulation (EAS) is proposed as one technique to provide adequate treatment for such individuals (von Ilberg, et al., 1999). Here the low frequencies are preserved during shallow cochlear implantation, and are amplified with an in-the-ear (ITE) hearing aid. The mid-to-high frequencies are stimulated with a cochlear implant. The success of such a procedure relies, to some degree, on the preservation of the low-frequency hearing during implantation. Recent studies have demonstrated that preservation of residual hearing after standard cochlear implantation is possible (Kiefer, et al., 2002; Skarżyński, et al., 2002). As a result, further extensions of cochlear implant candidacy selection criteria were proposed (Kiefer, et al., 2002; von Ilberg, et al., 1999), and the first individuals were implanted and fitted according to EAS principles (von Ilberg, et al., 1999). Results suggest that hearing preservation after cochlear implantation will allow for postimplant amplification of the low frequencies (Gantz & Turner, 2003; Gstöttner, et al., 2004; Gstöttner, Pok, Peters, Kiefer, & Adunka, 2005; Kiefer, et al., 2002, 2004; Skarżyński, Lorens, & Piotrowska, 2003; Turner & Gantz, 2004a). Speech perception results confirm the significant benefit of EAS, demonstrating a strong synergistic effect of combining the hearing aid (or in cases of normal or near-normal low-frequency thresholds—the use of natural low-frequency hearing) and cochlear implant in the same ear. This effect is most particularly noted in noise (Gantz & Turner, 2003; Gstöttner, et al., 2004; Kiefer, et al., 2004; Turner & Gantz, 2004a,b; Wilson, Wolford, Lawson, & Schatzer, 2002).

Although there is a reasonable amount of literature available detailing the benefits of EAS, there is very little written about the actual fitting of the two devices—particularly, regarding EAS hearing aid fitting. Wilson, et al. (2002) adjusted the cochlear

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implant (CI) in three ways providing a lower cutoff of 350, 600, and 1000 Hz; the upper limit was 5500 Hz in all cases. No information on the hearing aid fitting was provided. Two subjects did best on a group of speech tests with the widest range of frequencies, one subject was variable under different listening conditions and one subject did best with a lower cutoff of 600 Hz. The authors concluded that in some cases, raising the low-frequency boundary, thus reducing overlap between acoustic and electric amplification, provides greater listening benefit.

Gantz and Turner (2003) assessed various cochlear implant frequency mappings. The highest level of speech recognition was achieved when the lower frequency cutoff of electrical stimulation was 1 to 2 kHz or higher; however, there was reportedly no significant difference between these two maps on consonant, monosyllable, and sentence tests. Some subjects used natural acoustic low-frequency hearing, whereas others wore a hearing aid. No information was provided on the hearing aid programming, so levels of overlap between the hearing aid and CI could not be determined. Kiefer, et al. (2005) programmed the cochlear implant with three different programs: (1) a standard map with the default frequency allocation (300 to 5500 Hz); (2) a map with a lower frequency boundary of 650 Hz, and (3) a map with a lower frequency boundary of 1000 Hz. Subjects had 2 to 3 weeks of experience with all the three programs and then an optimum map was chosen based on a series of speech tests. Hearing aids were fit using the half-gain formula in the region of 125 Hz to 1 kHz. All but one subject (of 13) chose the full frequency map of 300 to 5500 Hz. Finally, James, et al. (2005) reported using two CI programs: (1) a standard map with default frequency allocation and (2) a map presenting only high frequencies. The hearing aid was fit using the desired sensation level (i/o) method amplifying frequencies for which thresholds were less than or equal to 80 dB HL—a principle similar to that used as the standard fitting procedure in our study. However, the outcomes of the different fitting parameters were not reported.

Of importance in each of these studies was that the patient was offered a choice of either a full or a restricted frequency map. An important consideration overlooked in previous studies is that each patient presents with a distinctly different range of auditory thresholds. Rather than one overall approach to all patients, it may be better to develop a fitting process that takes into account the individual nature of each subject's hearing loss.

This study aimed to compare various combinations of cochlear implant and hearing aid fittings for a small group of subjects to ascertain EAS fittings that would allow for a higher level of speech recognition.

METHOD

Subjects

Four subjects (1 women, 3 men), participating in the MED-EL European EAS M-Electrode Clinical Investigation, were included in this study. To participate in the clinical investigation, subjects were required to have normal hearing or a mild to moderate hearing loss in the low frequencies, sloping to a high-frequency hearing loss greater than or equal to 75 dB HL at 1000 Hz and monosyllable scores poorer than 45% in the best aided condition. Subjects included in this study had a mean monosyllabic discrimination score (Nederlandse Vereniging Audiology-test, Wouters, Damman, & Bosman, 1994) of 15%, a score of 33% on sentence recognition tests in quiet (Plomp sentences, Plomp & Mimpen, 1979), and 18% on sentence recognition tests in noise [Plomp sentences at a signal-to-noise ratio (SNR) of +10 dB] preoperatively. Subjects presented with an average of 7.25 months (range, 1 to 16 months) of EAS experience (this is over and above the 2 months of cochlear implant experience before EAS fitting). Etiologies were ototoxicity in two cases, DFNA9 (genetic) in one case, and head trauma in the other. Individual subject data are shown in Table 1. Subject 1 showed complete hearing preservation at the 6-month test interval (9 months postsurgery). Subjects 2 and 3 showed an initial drop of 15 to 20 dB HL at the CI fitting test interval (1 month postsurgery), with relatively stable hearing thereafter. Subject 4 showed changes between surgery, cochlear implant fitting, and the EAS fitting session (2 months after CI-fitting,

TABLE 1. Demographic data of individual subjects showing etiology, preoperative aided speech test scores and length of EAS experience

	Subject 1	Subject 2	Subject 3	Subject 4
Etiology	Ototoxicity	Head trauma	Ototoxicity	DFNA9
Preoperative monosyllable score (%)	25	17	17	0
Preoperative sentence score in quiet (%)	46	34	4	47
Preoperative sentence Score in noise (%)	2	0	0	69
EAS experience at testing for the current study	7 months	4 months	1 month	1.4 years

Note: All subjects were fitted with a CI 1-month after surgery and then had 2 month's CI experience before being fit with EAS.

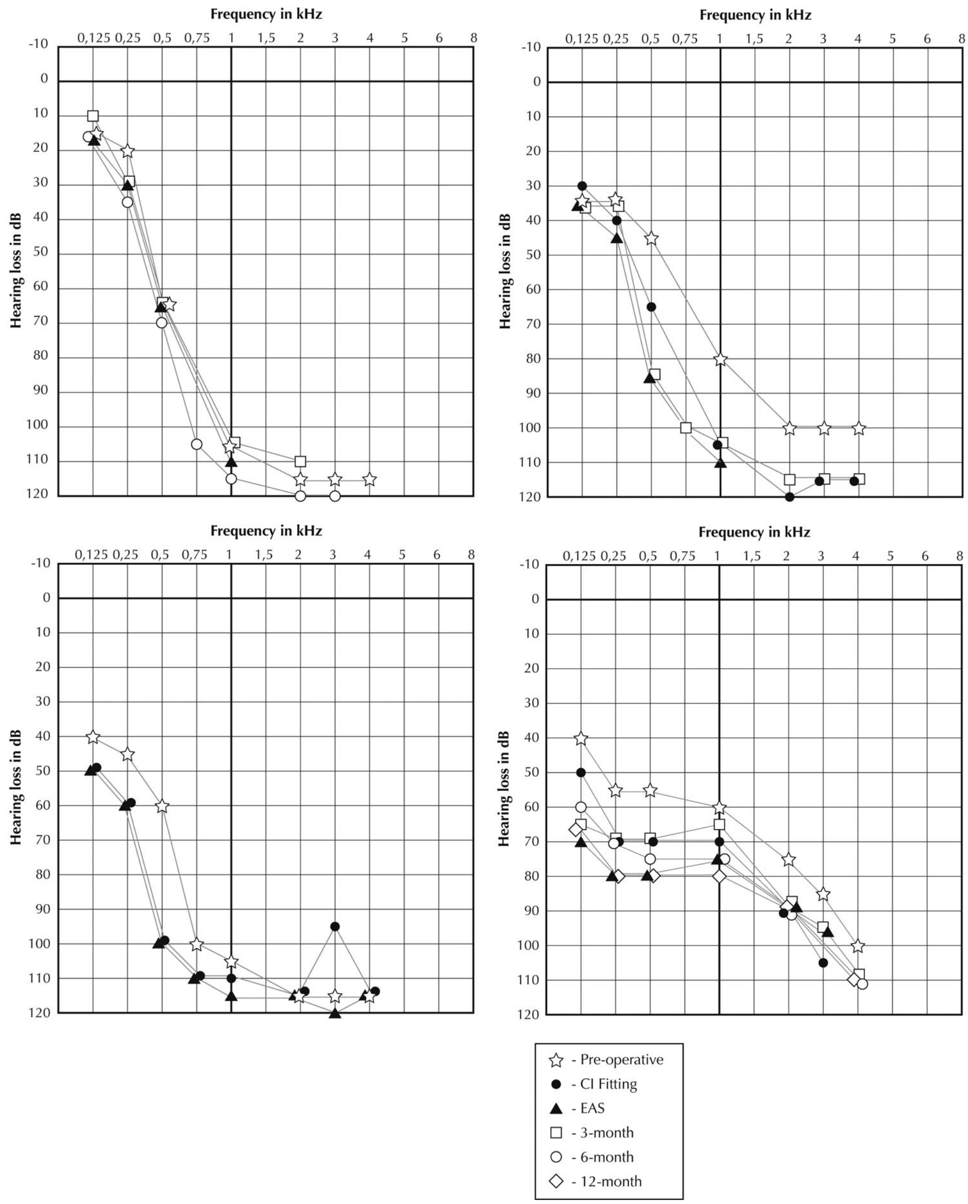


Fig. 1. Individual audiograms showing unaided hearing over time. Left to right in a clockwise direction: subjects 1, 2, 4, and 3. Note: test intervals 3, 6, and 12 months are related to the first EAS fitting period. The EAS fitting period takes place 2 months after CI fitting. Thus, 12 months of EAS experience equates to 14 months of device experience.

and 3 months postsurgery). This loss improved at the 3 and 6-month test intervals, indicating a conductive component as confirmed by bone conduction testing, and then decreased to match the EAS audiogram at the 12-month test interval (15 months postsurgery). Figure 1 shows the audiograms over time for each subject.

Ethical approval for testing with human subjects was granted by the Ethical Committée of the University Hospital Antwerp. After preoperative evaluations (including pure-tone audiometry, speech audiometry, and completion of the APHAB questionnaire) each subject was implanted with a COMBI 40+ Medium (M) electrode array from MED-EL GmbH (Innsbruck, Austria). The COMBI 40+M has a contact extent of 20.9 mm (1.9 mm contact spacing) and is designed for insertion depths covering the basal turn of the cochlea to stimulate mid and high frequencies, suitable for the concept of EAS. Subjects had an electrode insertion depth of 18 mm as reported by the surgeon, based on having electrode 10 placed in the cochleostomy. After surgery, each subject was fitted with a TEMPO+ behind-the-ear speech processor and had 2 months experience with their cochlear implant programmed with the full frequency range before being fitted with an Oticon Adapto P (Smørum, Denmark) ITE hearing aid in the same ear, thus becoming EAS users. This hearing aid is a two-channel seven-band hearing instrument that allows the flexibility to match the gain and compression requirements of the steeply sloping hearing loss. In terms of output characteristics, a peak gain of 60 dB and maximum power output of 127 dB SPL (output sound pressure level for 90 dB SPL input—OSPL90) are available. For all patients, an "open" fitting was provided so that as large a vent as possible was provided. This resulted in a reduction in the occlusion effect, as well as the potential to mix natural and amplified sound. The VoiceFinder (Oticon, Smørum, Denmark) technology was enabled. In this way, the hearing aid reduces gain when speech is not present. This was done to maximize the comfort of amplified sounds when speech information is not present. VoiceFinder is a speech detector that detects synchronicity unique to the human voice, and adjusts the amplification of the hearing aid based on the characteristics of the input signal. When speech is present, the full amplification (gain) of the hearing aid is provided. When speech is absent, the hearing aid will provide less amplification so as to maximize comfort and to reduce long-term listening effort.

Device Fitting

Both the cochlear implant and the hearing aid can be fit in a number of ways. This study aimed to compare various combinations of fittings to determine which provided the most benefit for the subjects.

Cochlear implant fitting parameters • For the purposes of this study, the cochlear implant was programmed in two different ways:

1. The cochlear implant can be programmed using the "full" frequency range that is currently standard for patients who do not have residual hearing in the implanted ear. In this instance, the frequency range is set from 200 to 7000 Hz.
2. The cochlear implant can be programmed using the "reduced overlapping" frequency range, where the programmed CI frequency range starts at the falloff frequency of the audiogram. The falloff frequency is defined as that frequency where the audiogram passes the 65 dB HL point (Kiefer, et al., 2005). This point was selected based on the fact that the maximum hearing loss attributable to outer hair cell loss lies in the range of 50 to 65 dB, with hearing loss of greater than 85 dB HL being likely due to complete loss of inner hair cells (Moore, Huss, Vickers, Glasberg, & Alcántara, 2000). Places of nonfunctioning inner hair cells are termed "dead regions" (Moore & Glasberg, 1997) and would thus be more suitable to electric stimulation.

This is the prescribed fitting for the larger EAS clinical investigation. In this instance, programmed frequencies were

Subject 1: 550 to 7000 Hz
Subject 2: 700 to 7000 Hz
Subject 3: 450 to 7000 Hz
Subject 4: 250 to 7000 Hz.

Hearing aid fitting • For all subjects the Adapto Fast fitting rationale utilized in the Genie Hearing Aid Fitting Software (Oticon, Smørum, Denmark) was used. This rationale basically follows the half-gain rule (the threshold of a given frequency is divided into half to obtain the predicted gain) with adjustable knee-point. The half-gain rule was deemed the most appropriate fitting rationale for EAS, as it would allow for the greatest amount of low-frequency amplification; other fitting rationales are designed to provide less low-frequency amplification.

The hearing aid was fit in one of four ways. All methods required modification of the audiogram. This involved inputting the low frequencies as measured by pure-tone testing, and inputting the mid-to-high frequencies as 10 dB HL, before input into the Genie Hearing Aid Fitting software. Modification of the audiogram was needed to ensure that sufficient gain was provided for the region of hearing loss most requiring acoustic amplification in an EAS fitting—the low-frequency range; while providing no amplification to the high frequencies (which will be stimulated by the cochlear implant). Standard fitting rationales would automatically attempt to boost gain in the higher frequencies in an unmodified audiogram. In EAS, this is not required, as the cochlear implant provides the high-frequency stimulation. In summary, this involved inputting the low-frequency hearing thresholds as tested and modifying the high frequency thresholds. The purpose was to devise an easily replicable method for fitting a hearing aid to the cochlear implant. Four configurations were tested.

Adjustment to amplified frequencies

1. For all frequencies with a threshold worse than 85 dB HL, a threshold of 10 dB is input into the audiogram. This means that frequencies where the audiogram is worse than 85 dB are not amplified. This hearing aid modification is the required fitting paradigm for the EAS clinical investigation.
2. For all frequencies where there was no response at 120 dB HL, a threshold of 10 dB HL was input into the audiogram. In this way, all available low-to-mid frequency hearing may be amplified with the hearing aid. This would allow for a larger overlap between the hearing aid and the cochlear implant programs. Thus, in contrast to fitting in point 1, the frequency range where the audiogram was between 85 and 120 dB is now amplified. No amplification was provided where the audiogram is 120 dB or worse.

Adjustments to gain and compression • In each of these conditions the gain and compression were then adjusted.

3. The gain and compression predicted by the fitting software for the given hearing loss were used. This used the Adapto FastFitting rationale, which is based on the half-gain rule.
4. The gain was increased by 6 dB SPL and the compression was reduced, to provide an extra "boost". This was based on the subject opinions, where they stated that they needed more gain in the low-frequency range.

Real ear measurements (REM) for each hearing aid fitting were conducted to obtain an objective measure of the hearing aid fitting and the actual gain that was obtained. These measurements are shown in Figure 2. REMs were conducted using speech spectrum noise presented at 65 dB SPL. For the REMs, noise was presented in free field; the speaker was placed at 0° azimuth at a distance of 1 m from the subject. The output level of the hearing aid was then measured with an insertion tube. The real ear occluded response was measured with the hearing aid in the ear but switched off. The real ear insertion response, the actual output response of the hearing aid is measured for the four different programs. Despite input into the fitting software, real ear gain measurements were not as high as one would hope, given the degree of hearing loss (see Figs. 1, 2). This is a limitation of using ITE hearing aids to boost the low frequencies.

Procedure

Sentence testing in noise • The Dutch "Plomp and Mimpen" sentence lists (Plomp & Mimpen, 1979) were used in testing, all in a background of speech-weighted stationary noise. The test consists of 20 lists of 13 sentences each. The speaker was placed at 0° azimuth at a distance of 1 m from the subject. Both noise and speech were presented from the same speaker. The sentences were presented at 70 dB SPL, with the SNR set at different levels for each test list under each test condition: +15, +10, and +5 dB. One list of 13 sentences was used for each condition and a keyword score was used. The contralateral ear was masked for all testing.

Visual analogue scale • Each subject was asked to complete a visual analogue scale (VAS) (DeVellis, 2003) after each test condition. This was an overall assessment after each test condition and was not answered for each SNR separately. The VAS required each subject to mark with an "X" how easy it was to listen to the speech in noise under each test condition. A 10-point scale was drawn, with the left-hand side (or 0 point) being "very easy, no effort

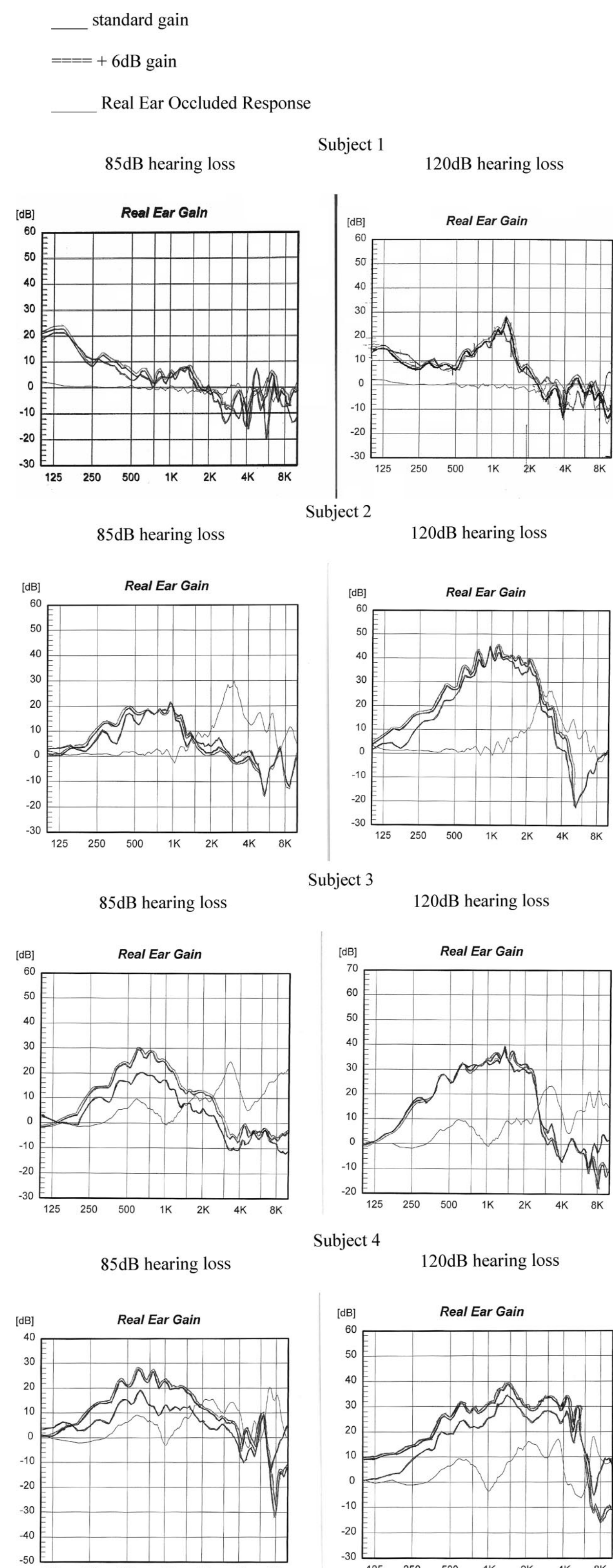
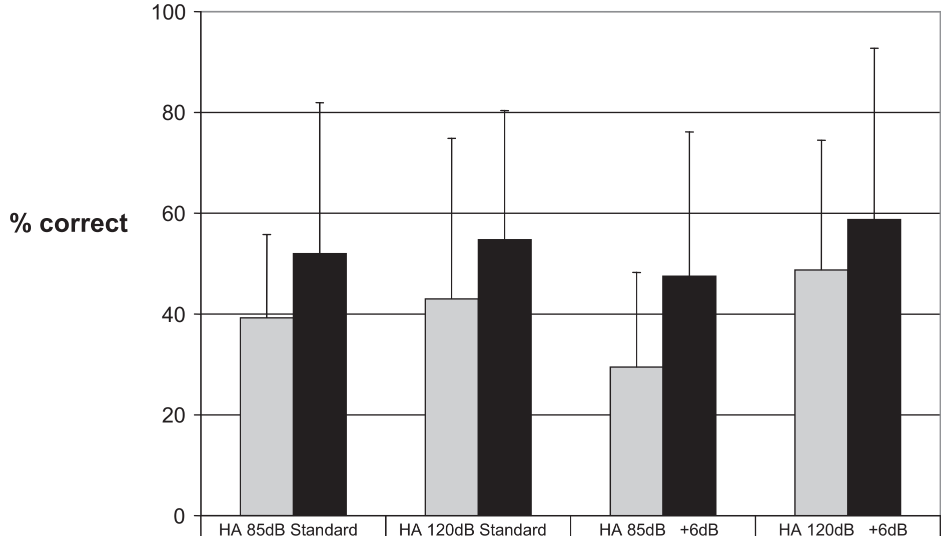


Fig. 2. The real ear insertion gain measurements for each subject and each hearing aid fitting are shown on the graphs. The single dark line indicates real ear gain for the standard hearing aid fitting. The double line shows the hearing aid fitting measurement with an additional gain of 6 dB. The real ear occluded response is shown by the lighter single line.



	HA 85dB Standard	HA 120dB Standard	HA 85dB +6dB	HA 120dB +6dB
□ CI Full Fr.	39,3	43,0	29,5	48,8
■ Reduced overlapping Fr.	52,0	54,8	47,5	58,8

Fig. 3. Mean scores (percent correct) for the sentence tests with a signal-to-noise ratio of 15 dB are shown for each test condition. The error bars represent standard deviations.

required" and the right-hand-side (or 10 point) being "very difficult, I needed to concentrate a lot."

Listening conditions • Subjects were tested under eight different cochlear implant and hearing aid program combinations. Subjects were fit with the program, had a short period of time (½ hour) to adjust to the new program and underwent a practice list for each section before testing. All test conditions were randomized.

Data analysis • Data were analyzed descriptively and are expressed as mean and standard deviations.

In addition, two-factorial analyses of variance (ANOVA) for repeated measurements (general linear model) with HA fitting condition, CI condition, and the interaction of HA fitting and CI condition as factors were performed for all test parameters (sentence tests in noise with SNR's of 15, 10, and 5 dB and the VAS). Beforehand, Mauchly's tests of sphericity were applied. If sphericity could not be assumed, a Greenhouse-Geisser correction was used as part of the ANOVA. With Kolmogorov-Smirnov-tests, data were checked for their distribution. Missing values were replaced through single mean imputation, whereas those imputed data were only used for the ANOVA. Statistical significance is defined as $p < 0.05$. SPSS for Windows 14.0 software (Chicago, IL) was used for all analyses. Microsoft Office Excel 2003 was used for all graphs.

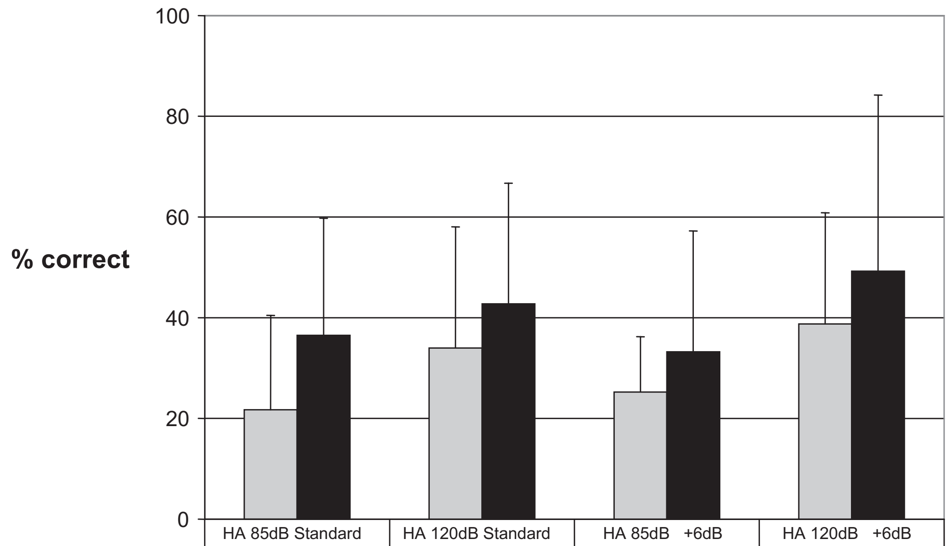
RESULTS

Keeping the Cochlear Implant Constant and Manipulating the Hearing Aid

CI Program: full frequency • The highest level of performance found for all noise conditions, and the VAS, was where the audiogram was modified from where hearing was lost at 120 dB, with +6 dB gain provided (Hearing Aid 120 dB – +6 dB Gain). Figures 3 to 6 show mean scores for all test conditions. Individual scores are shown in Table 2. The next highest level of speech understanding was observed in the condition where acoustic hearing was amplified up to 120 dB, but with no extra gain than that prescribed by the fitting software (Hearing Aid 120 dB – Standard Gain). However, the VAS did not reflect this outcome. There was no preference for more or less gain with the audiogram modified to the point of 85 dB loss. The VAS showed that the "Hearing Aid 85 dB – Standard Gain" condition was the most difficult listening condition.

CI program: reduced overlapping frequency • As for the full frequency condition, the highest average level of performance was found for the hearing aid program: "Hearing Aid 120 dB – +6 dB gain". The program "Hearing Aid 120 dB – Standard Gain" provided the next highest level of performance. However, with the reduced overlapping cochlear implant frequency, the "Hearing Aid 85 dB – +6 dB" gain was slightly worse (Figs. 3 to 6).

Comparing the two cochlear implant programs • Having determined which hearing aid program provided the highest level of listening benefit in noise, and ease-of-listening results as determined by the VAS (namely HA 120 dB – + 6 dB gain), the two cochlear implant programs were compared. Data are shown in Figures 3 to 6. This comparison shows that the reduced overlapping frequency range program provides the highest outcome in all assessed hearing aid programs, except for the hearing aid condition of Hearing Aid 85 dB – Standard Gain

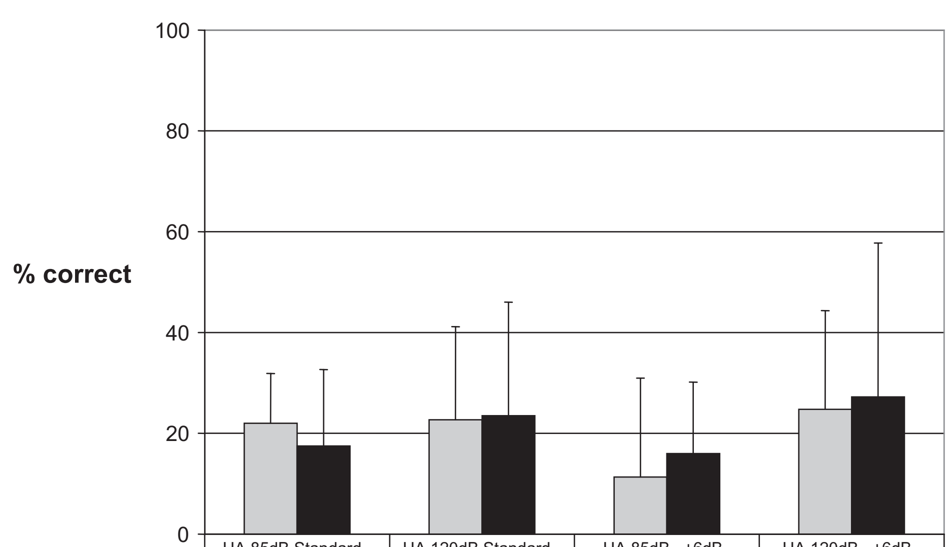


	HA 85dB Standard	HA 120dB Standard	HA 85dB +6dB	HA 120dB +6dB
CI Full Fr.	21,8	34,0	25,3	38,8
Reduced overlapping Fr.	36,5	42,8	33,3	49,3

Fig. 4. Mean scores (percent correct) for the sentence tests with a signal-to-noise ratio of 10 dB are shown for each test condition. The error bars represent standard deviations.

at 5 dB (Fig. 5). This need not be considered as an unusual result, which might have some bearing on overall outcomes, as it is the third highest of four hearing aid programs in this listening condition. Two of the subjects did not test at the 5 dB S/N, we could speculate that they would score at or near zero. The average score could thus be less than the 10% recorded in this study, thus showing that the CI reduced overlapping condition might be even poorer than is currently reflected. The VAS scores (Fig. 6) also indicate that the reduced overlapping frequency range provided the easiest listening outcome.

Statistical analyses • An ANOVA for repeated measurements revealed a significant effect of the HA fitting condition ($p < 0.001$), the CI condition ($p = 0.05$), but no significant interaction of HA fitting condition and CI condition ($p = 0.87$) for sentence testing with an SNR of 15 dB. Sentence testing with an SNR of 10 dB using an ANOVA for repeated measurements revealed a significant effect of the HA fitting condition ($p = 0.03$), but no significant effect of the CI condition ($p = 0.15$) or the interaction of HA fitting condition and CI condition ($p = 0.66$). An ANOVA for repeated measurements revealed no significant effects for sentence testing with an SNR of 5 dB for the HA fitting condition ($p = 0.36$), the CI condition ($p = 0.88$), and the interaction of HA fitting condition and CI condition ($p = 0.89$). Finally, an ANOVA for repeated measurements revealed no significant effects of the HA



	HA 85dB Standard	HA 120dB Standard	HA 85dB +6dB	HA 120dB +6dB
CI Full Fr.	22,0	22,7	11,3	24,8
Reduced overlapping Fr.	17,5	23,5	16,0	27,3

Fig. 5. Mean scores (percent correct) for the sentence tests with a signal-to-noise ratio of 5 dB are shown for each test condition. The error bars represent standard deviations.

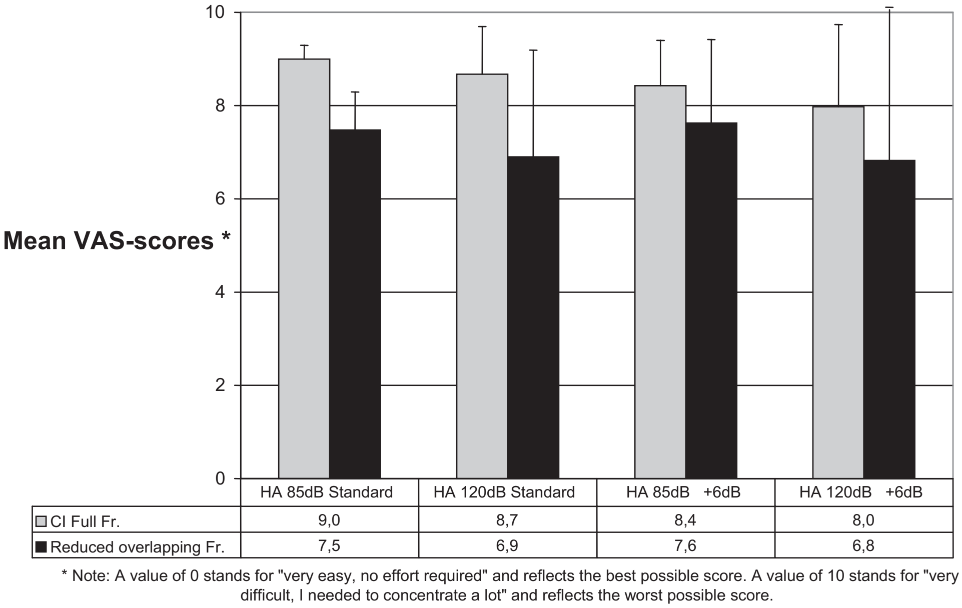


Fig. 6. Mean scores on the visual analogue scale (VAS) are shown for each test condition. The error bars represent standard deviations.

fitting condition ($p = 0.38$), the CI condition ($p = 0.33$), and the interaction of HA fitting condition and CI condition ($p = 0.90$) for the VAS (Table 3).

Audiogram correlations • The audiogram of subject 2 clearly differs from that of the other subjects. Therefore, individual data of subject 2 were compared with mean scores of the other three subjects. Data from speech tests and the VAS were taken into consideration. The results show that in none of the conditions was the mean value of subjects 1, 3, and 4 lower than the individual value of subject 2.

DISCUSSION

Even though there were only four subjects in this study, three of four subjects performed better at the SNR 15 and 10 dB with an EAS fitting program where acoustic hearing is amplified to a wider frequency range (120 dB), with a higher boost of gain (+6 dB), and a reduced, but overlapping cochlear implant frequency range. The results were less consistent at SNR 5 dB. Subject 4 performed best with the wider frequency range (120 dB) with a higher

TABLE 2. Individual scores (in % correct) for the sentence tests with a signal-to-noise ratio of 15, 10, and 5 dB and the visual analogue scale (VAS) are shown for each test condition

		CI: Full frequency				CI: Reduced overlapping frequency			
S	Test	HA 85 dB: Standard	HA 120 dB: Standard	HA 85 dB: +6 dB	HA 120 dB: +6 dB	HA 85 dB: Standard	HA 120 dB: Standard	HA 85 dB: +6 dB	HA 120 dB: +6 dB
1	SNR 15 dB	53.0	56.0	42.0	57.0	73.0	82.0	64.0	87.0
	SNR 10 dB	48.0	53.0	37.0	63.0	63.0	69.0	44.0	80.0
	SNR 5 dB	29.0	23.0	34.0	25.0	28.0	38.0	27.0	66.0
	VAS	9.1	9.5	9.0	8.9	7.5	3.5	5.1	1.9
2	SNR 15 dB	2.0	16.0	12.0	20.0	22.0	30.0	19.0	34.0
	SNR 10 dB	6.0	3.0	14.0	15.0	18.0	32.0	12.0	18.0
	SNR 5 dB	DNT	DNT	0.0	7.0	5.0	0.0	0.0	0.0
	VAS	9.0	9.5	9.5	9.5	8.5	8.5	9.0	8.5
3	SNR 15 dB	54.0	82.0	49.0	80.0	82.0	71.0	79.0	89.0
	SNR 10 dB	22.0	53.0	32.0	51.0	49.0	55.0	62.0	79.0
	SNR 5 dB	15.0	41.0	0.0	52.0	33.0	47.0	21.0	37.0
	VAS	9.3	7.4	7.6	8.0	6.5	7.9	8.8	8.6
4	SNR 15 dB	23.0	18.0	15.0	38.0	31.0	36.0	28.0	25.0
	SNR 10 dB	11.0	27.0	18.0	26.0	16.0	15.0	15.0	20.0
	SNR 5 dB	DNT	4.0	DNT	15.0	4.0	9.0	DNT	6.0
	VAS	8.6	8.3	7.6	5.5	7.4	7.7	7.6	8.3

For the VAS, a value of 0 stands for "very easy, no effort required" and reflects the best possible score. A value of 10 stands for "very difficult, I needed to concentrate a lot" and reflects the worst possible score.
S: subject number; SNR: signal-to-noise ratio; DNT: did not test.

TABLE 3. Results of two-factorial analyses of variance for repeated measurements for sentence tests with a signal to noise ratio of 15, 10, and 5 dB and the visual analogue scale (VAS) are shown

	HA fitting condition		CI condition		Interaction (HA fitting condition × CI condition)	
	F-Statistics	*p*	*F*-Statistics	*p*	*F*-Statistics	*p*
SNR of 15 dB	15.78	**<0.001**	10.05	**0.05**	0.24	0.87
SNR of 10 dB	4.82	**0.03**	3.81	0.15	0.28	0.66
SNR of 5 dB	1.23	0.36	0.03	0.88	0.21	0.89
VAS	1.16	0.38	1.37	0.33	0.19	0.90

F-statistics and *p* are shown for the factors HA fitting condition, CI condition and the interaction between them. *P* values, which show statistical significance, are presented in bold.
SNR: signal to noise ratio.

boost of gain (+6 dB) but with a full cochlear implant frequency range rather than a reduced overlapping frequency range.

The first point to note is that the EAS users perform well in noise, scoring nearly 50% correct at an SNR of +10 dB in the best-fit condition, and nearly 30% at +5 dB—a difficult listening condition. This is in comparison with a mean preoperative score of 14% in noise. These results reflect those reported elsewhere. An improvement of 8% in sentences in noise was reported when subjects listened with EAS compared with CI alone (Kiefer, et al., 2005). Two further studies also report improved performance in testing in noise (Gantz, Turner, Gfeller, & Lowder, 2005; James, et al., 2005). Yet, even though we can be impressed by these scores, the VAS scores demonstrate the difficulty of listening in noise. We still need to acknowledge that listening in noise requires a considerable degree of listening effort.

Certain points about programming choice need to be discussed. The hearing aid was not assessed using a full program without manipulating the audiogram, as would be predicted by the fitting software. Baer, Moore, and Kluk (2002) noted in subjects with ski-slope hearing loss that amplifying to one octave above the dead regions would provide benefit, but amplifying more than one octave above the dead region would not. This reinforces the work of Hogan and Turner (1998), stating that amplification in the high frequencies in such cases may actually lead to a decrease in speech recognition. Another issue would be to determine how much overlapping of the frequency range would provide the best outcome. Would reducing the overlap to an adjacent program be better? Results from the current study suggest that a more limited overlap than provided by using a full frequency range fitting of the cochlear implant is more beneficial, but how reduced should this overlap be? The suggested one octave above the dead regions demonstrates that some overlap is beneficial (Baer, et al., 2002). This is further reinforced by Abbas, Miller, Rubinstein, and Robinson (1999), stating that adding acoustical stimulation to electrical stimulation leads to a more "natural" (desynchronized) neural response. Further testing into the degree of overlap needs to be conducted.

Three EAS studies mention cochlear implant and hearing aid fitting. It is not easy to compare these results, as different frequency ranges were used in each study. Also, limited information was provided regarding hearing aid fitting. In one of these studies (Kiefer, et al., 2005), all but one subject preferred the full CI frequency range. Our results are not too dissimilar from this study as two of the four subjects had a less low-frequency cut-off range, which is extremely close to their full-frequency range, yet they still preferred having a slightly reduced overlap. Another influencing factor might be that in our study, the subjects were given a wider acoustic frequency range—which may provide extra information and slightly better hearing in noise. Certainly the best hearing aid fit seemed to be similar to these authors' (Kiefer, et al., 2005), as they used the half-gain rule. The half-gain rule essentially provides a greater boost in the lower frequencies; but it still did not provide sufficient gain, as evidenced by the extra gain required for best outcomes in the present fitting study. However, it is unclear whether, in another report by the same authors (Kiefer, et al., 2002), they modified the audiogram for the hearing aid fit. It is also not so easy to apply the half-gain rule in all cases, especially if digital hearing aids are used. The half-gain rule does provide some guideline of how much extra boost should be provided in the low frequencies; however, the gain needs to be manipulated by the fitting audiologist, as it is clear that more gain is required in the low frequencies than is recommended by the fitting software. Other factors that will influence the fitting are the power of the hearing aid, the degree of remaining low-frequency hearing, and the vent of the hearing aid mold. A fine balance between gain and feedback is required. Ideally an all-in-one device, combining hearing aid and implant technology, would provide the most optimal solution—more gain could be given than an ITE hearing aid could provide. This may now be realized with the availability of the DUET EAS Hearing system (MED-EL GmbH, Innsbruck, Austria).

Results from the subjects tested by Wilson, et al. (2002) are variable; however, they suggest that a reduced overlap between hearing and cochlear implant amplification may best suit EAS users. This seems to be the most common trend in EAS fitting so far. Even though two of our subjects had an extremely low cut-off frequency for their cochlear implant, which closely resembled the full-frequency range of the device; they still preferred a fitting situation with the reduced overlap.

If providing a reduced overlap for EAS users is best, where do we make the low-frequency cutoff for the cochlear implant, an essentially arbitrary decision at this point? More research needs to be conducted on this. It seems that the question of what frequency do we amplify the low-frequency hearing to, has been answered: that is, at least to the point where all low-frequency hearing has been lost. We also do not yet know the influence of dead regions in the cochlea on EAS fitting, and this is an area requiring further research. As can be seen from our data, it is essential to have the best fit possible, as poorer EAS fits can have a remarkable effect on outcomes, both on a sentence-level and as seen in subjective reporting of listening effort.

Although our study used only a small number of subjects, the information generated provides a reasonable starting point to help determine some guidelines for EAS fitting. It is clear when reviewing the published data on EAS fitting that a blanket fitting rule for both the hearing aid and cochlear implant components does not provide the best benefit for each subject. Most of these fitting decisions were based on a decision that was not fully tested to determine the best combination of both the acoustic and electric amplifications. Our study reviewed a number of conditions to determine which one would provide the greatest benefit in noise. The results showed that an individual fitting program, following some broad guidelines, was the most appropriate for all tested subjects. By adjusting the hearing aid to provide extra gain for all the remaining low-frequency hearing, and matching this to the best cochlear implant program, we are able to optimize subjects' listening performance in noise.

In summary, the main findings of this study suggest that the audiogram could be manipulated in the hearing aid fitting software to provide maximum amplification in the low frequencies and no amplification in the high frequencies. It may be better to provide low-frequency gain to the point of no-hearing on the audiogram (determined as 120 dB HL in our study). In addition, extra gain, over and above that recommended by the fitting software, seems to provide greater benefit. Finally, the programmed frequencies of the cochlear implant could be reduced but still provide some overlap of the acoustic and electric amplifications. One note of caution is related to the limited exposure the subjects had to each parameter of configuration. Follow-up studies should allow extensive periods of each parameter configuration to determine the best level of perceptual performance that can be achieved with each one.

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